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Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Coastal Inlets Research Program

Impacts of Navigation Channel Maintenance Dredging on the Coastal Processes of Chatham, Massachusetts

Donald K. Stauble

September 2001

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Coastal Inlets Research Program

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September 2001

Impacts of Navigation Channel Maintenance Dredging on the Coastal Processes of Chatham, Massachusetts

by Donald K. Stauble

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Final report

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Preface

This study was conducted by the U.S. Army Engineer Research and Development Center (ERDC) (formerly U.S. Army Engineer Waterways Experiment Station (WES)), Coastal and Hydraulics Laboratory (CHL), Coastal Evaluation and Design Branch (CE&DB). The study was authorized and funded by the U.S. Army Engineer District (USAED), New England, in 1999. The District POC was Mr. Raymond Francisco. Dr. Donald K. Stauble (ERDC) was the Principal Investigator. The Coastal Inlets Research Program (CIRP) provided additional support for review and publication.

Work was performed under the general supervision of Ms. Joan Pope, Chief, CE&DB, Mr. Thomas Pokrefke, Acting Deputy Director, CHL, and Mr. Thomas W. Richardson, Acting Director, CHL. This report was prepared by Dr. Stauble, who performed the data reduction and GIS analysis and graphics.

The author would like to thank Mr. Theodore L. Keon, Director, Town of Chatham, Department of Coastal Resources, for providing data, base maps, dredging information and discussion on Chatham Inlet. Dr. Lee Weishar, Woods Hole Group, provided scanned aerial photography. Messrs. Carl Boutilier, Raymond Francisco, and William Kavanagh, U.S. Army Engineer District, New England, also provided data and discussion on dredging and inlet evolution. Ms. Jennifer Irish, ERDC, provided data from the SHOALS survey. The report was reviewed by Messrs. Boutilier, Keon, and the staff of the Coastal Inlets Research Program, Geomorphology and Channels Work Unit.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

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Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
cubic yards	0.7646	cubic meters
cubic yards per foot	2.51	cubic meters per meter
degrees	0.01745	radians
feet	0.3048	meters
miles (US statute)	1.6093	kilometers
square feet	0.0929	square meters

1 Introduction

On 2 January 1987, during a severe northeaster, a breach formed through Nauset Spit near Chatham, MA. The initial opening (approximately 20 ft (6 m) wide)[1] was caused by repeated overwash of a narrow section of this barrier spit during this storm. The storm surge allowed waves to cut through a low point in the dune and overwash the barrier spit into the Chatham Harbor/Pleasant Bay estuary. The storm duration was sufficiently long to allow waves to completely breach the spit. This initial opening into the back-barrier bay enabled the ebb and flood tidal flow to further scour out the breach, forming a new inlet. The interaction between waves and tides increased the inlet size to 2 miles (3.2 km) wide within the first 2 years (U.S. Army Engineer Division, New England, 1989).

With the new inlet in place, large changes occurred to the adjacent barrier and mainland shorelines. Major shoal areas developed both on the ocean and bay side of the inlet (Liu et al. 1993). The inlet throat widened as both adjacent barrier shorelines retreated into the bay as recurved spits. The newly formed ebb and flood shoals grew in area and volume indicating a trapping of littoral sediments within the inlet system and an influx of ocean sediments entering the bay through the new inlet. The main ebb channel through the throat of the inlet migrated southward due to the predominant southern longshore drift. From breach formation in 1987 until 1992, Chatham Harbor was part of a four inlet system composed of the established Chatham Bars Inlet opening to the Atlantic Ocean at the south end of the existing Nauset Spit, Morris Island cut between Morris Island and North Monomoy Island, and an unnamed inlet between North and South Monomoy Islands. The new inlet, to the north, bisected Nauset Spit and the southern portion of the barrier spit became a barrier island completely detached from the mainland. As the inlet migrated southward, the north end of this south barrier island retreated into the bay and finally attached to the mainland beach in the vicinity of the Chatham Lighthouse in early 1992. At that time, Pleasant Bay estuary became a one-inlet system, with its entire tidal prism opening to the ocean through the new Chatham Inlet. The main ebb channel continued to migrate south until early 1995 when a new ebb channel opened through the north swash platform. At the present time there are two ebb channels in the ebb shoal.

As the inlet continued to evolve, the north flood shoal increased in size and migrated northward. Navigation into the anchorage at the Fish Pier in Aunt Lydia's Cove became increasingly difficult as the north flood shoal and the Tern

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

Island south shoal, located adjacent to the mainland and Tern Island, changed shape and orientation. Dredging became necessary to maintain a navigable channel access to the Fish Pier and harbor area for Chatham's commercial fishing fleet. Soon after establishment of the inlet, the mainland beach opposite the inlet underwent severe erosion. Several homes were lost, as the mainland shoreline directly across from the new opening retreated landward due to waves and tidal currents impinging on the shoreline. Other areas of the mainland shoreline, both updrift and downdrift of the inlet opening, experienced accretion as longshore currents deposited the newly eroded sand in shore-attached shoals. This report will identify this complex pattern of inlet morphology development, channel migration and shoaling, and shoreline modification. Recommendations to maintain navigation in this highly dynamic environment will be presented.

Project Setting

Chatham Harbor, is a bar-built estuary/lagoon located on the southeastern corner of Cape Cod, MA (Figure 1). The estuary is an elongate, coast parallel feature approximately 4 miles (6 km) long, 1.6 miles (1 km) wide and had a maximum depth of 22 ft (7 m) prior to the breach. The estuary widens into the more shallow Pleasant Bay on the north end.

Prior to the breach, the Chatham Harbor/Pleasant Bay estuary was sheltered from the Atlantic Ocean by a 10-mile- (16-km-) long barrier spit called Nauset Beach, which is attached to the mainland at the north end of Pleasant Bay. This spit averaged 1,250 ft (381 m) wide and contained a sandy beach backed by irregular sand dunes and a back-barrier marsh. The estuary opened to the ocean through what was called Chatham Bars Inlet located between the southern end of Nauset Spit and Monomoy Island. This inlet is now called the South Channel (Figure 1). Monomoy Island was originally an 8-mile- (12.9-km-) long barrier island to the south and west of Chatham Bars Inlet. Monomoy Island was itself breached around 1978 and is now bisected by an unnamed inlet separating North and South Monomoy Islands. The north end of Monomoy Island has been separated from Morris Island by Morris Island Cut. When the new breach formed during an extratropical northeaster on 2 January 1987, the barrier island formed from the southern part of Nauset Spit became known as South Beach. From 1987 to 1992 the Chatham area of southeastern Cape Cod had a complex four-inlet, estuary, and barrier island system.

Cyclic history of inlet system

Historically, this barrier system has an approximate 140-year cycle of barrier spit growth and inlet formation (Giese 1988). The cycle starts with the growth of Nauset Spit southward from the mainland sea cliffs of Eastham and Wellfleet. The spit migrates southward with the prevailing longshore drift until a storm occurs and a breach breaks through a weak point in the barrier, creating a shortened spit and a detached barrier island from the southern portion of the spit. This southern barrier continues to migrate to the south and west and eventually welds to the mainland. Charts and other records dating back to the 1700s indicate that an inlet

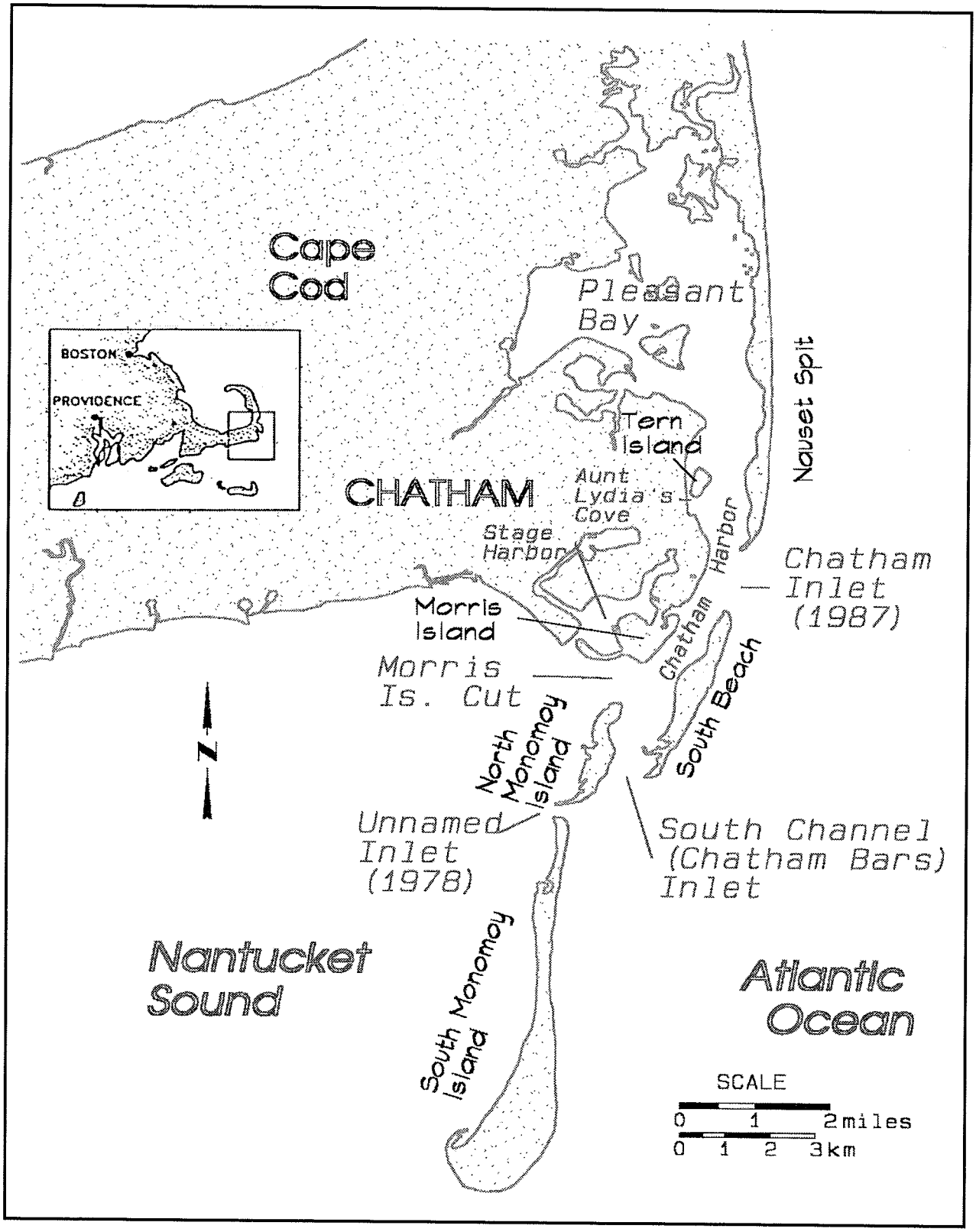


Figure 1. Location map showing main geographic features of Chatham area

formed around 1740 (Giese 1988). Monomoy Island (originally part of the spit) moved west and became attached to Morris Island and the mainland. Nauset Spit migrated to the south again, with its tip approximately at the present new Chatham Inlet (Figure 2). Nauset Spit continued its migration to the south until 1846, when a new inlet broke through the spit approximately 2 miles (3.2 km) north of the 1987 inlet breach. Much of the shoals in the eastern side of Pleasant Bay are remnant ebb and flood shoals of this inlet. In November 1871, a second inlet breached the southern barrier in almost the same place as the present breach, just opposite the Chatham Lighthouse, which had twin light towers at that time (Weishar, Stauble, and Gingerich 1989). The barrier island was breached in numerous places through the 1880s and left the mainland basically unprotected from the ocean waves. Chatham's shoreline suffered severe erosion including the loss of the two lighthouses. Remnants of the southern barrier island at times welded onto the mainland and at other times acted as barrier islands as the entire system migrated west.

Some 50 years after the first breach (between 1910 and 1916) the southern barrier was welded to the mainland. From a 1929 topographic map, a continuous barrier spit connected the mainland to Morris Island and Monomoy Island. Nauset Spit was in the processes of migrating south again, but the shoreline between the present Fish Pier and Pleasant Bay was open to the Atlantic through a roughly 2-mile- (3.2-km-) wide inlet. In the late 1950s Morris Island Cut was formed during a winter storm separating Monomoy Island from the mainland once again. Nauset Spit continued to migrate south and moved past Morris Island Cut, forming the Chatham Bars Inlet. The ebb tidal delta formed at the distal end of Nauset Spit with a large swash platform in front of Monomoy Island (Hine 1975). Morris Island Cut became the flood tidal delta of the Chatham Bars Inlet until it migrated south past the cut. Around 1978, a storm bisected the westward retreating Monomoy Island in the present location of the unnamed inlet forming the North and South Monomoy Islands. This unnamed inlet opened just to the south of the southerly migrating Chatham Bars Inlet/Nauset Spit ebb delta/swash platform complex. This cycle of westward migration of Monomoy Island and southward migration of Nauset Spit continued with the breach of 1987.

Coastal processes

The predominate wave approach direction along Nauset Spit is from the east-northeast (Liu et al. 1993). A mean H_{mo} of 4.92 ft (1.5 m) with a mean T_p of 8 sec, based on the Wave Information Study (WIS) update is presented for sta 91 (Brooks and Brandon 1995). This wave station is approximately 7 miles (11 km) offshore in 299 ft (91 m) of water, so these wave statistics are considered deep-water open-ocean conditions, which have not been transformed to shallow coastal statistics. There is a seasonal trend with the largest waves occurring in the winter months. A resulting southward longshore sediment transport rate has been estimated to be between 4.7×10^5 cu yd/year (3.6×10^5 m^3/year) (Weishar, Stauble, and Gingerich 1989) and 6.5×10^5 cu yd/year (5×10^5 m^3/year) (Liu et al. 1993). The outer coast at Chatham has a mean tidal range of 6.7 ft (2.0 m) at Chatham (National Oceanic and Atmospheric Administration (NOAA) 2000). The tide range has changed significantly in the estuary since the opening of the breach.

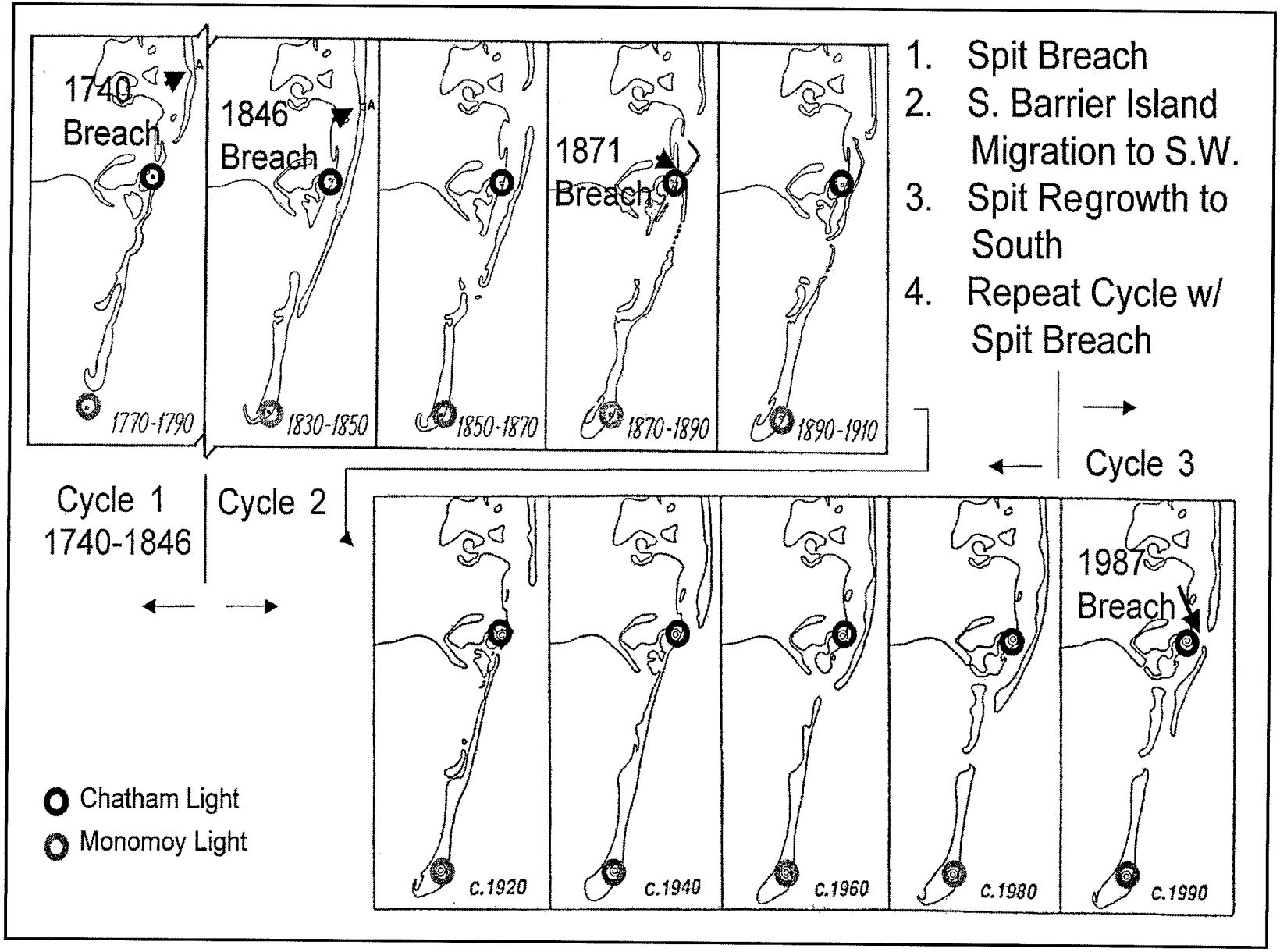


Figure 2. Cyclic change in Chatham shoreline since 1770s (after Giese 1988)

At the Fish Pier the tide range was 3.6 ft (1.1 m) and has increased to 4.6 ft (1.4 m). Tidal currents in the new inlet have been measured at 4.6 ft/s (1.4 m/s) at maximum ebb and 3.2 ft/s (1.0 m/s) at maximum flood (U.S. Army Engineer Division, New England, 1989). The ebb flows reach their maximum near low water and are confined to the main channel, while the maximum flood current occurs near high water and the flows are spread out over the swash platform (FitzGerald and Montello 1993).

Storms have played an important part in shaping the coastline in this area. Extratropical northeasters and tropical storms both have impacted the area. Nauset Spit was breached on 2 January 1987, during a severe northeaster that coincided with a perigean spring tide (Liu et al. 1993). The storm surge allowed overwash of the spit in a low spot with few dunes. As the storm subsided the next day, a meandering surge channel was present in the overwash fan allowing water to flow in and out of Chatham Harbor throughout the entire tidal cycle. Oblique aerial photographs taken a few days after the storm indicated that the dominant flow was toward the bay, with a small flood shoal forming. Two more northeasters occurred in January and February 1987, resulting in the growth of the breach to 1,706 ft (520 m) by March (Liu et al. 1993). Major storms have continued to impact the coast since the breach that have been a driving mechanism in inlet morphology change. Hurricane Bob in August 1991 and the Halloween Storm in October 1991are examples.

Problem

The Town of Chatham's mainland shoreline, located on the west side of the bay, was a relatively stable inner-estuary shoreline before the inlet formed. The Chatham Harbor area and mainland bay shoreline became exposed to the direct force of ocean waves and enhanced tidal currents after the inlet formed. The shoreline from Andrew Hardings Lane to the Hawthorne Hotel (south of Caflin Landing) was eroded some 175 ft (53 m) landward, with the loss of two town landings and nine homes (U.S. Army Engineer Division, New England, 1989), until the shoreline was armored. A complex multishoal flood delta formed in Chatham Harbor and has evolved into a channel shoaling and migrating problem over time. Maintaining a navigation channel to the Fish Pier, Chatham's main commercial fishing port for some 80 commercial fishermen has proven difficult and has restricted the response capability of the U.S. Coast Guard which operates out of the Fish Pier.

In September 1987, Congress requested that the U.S. Army Corps of Engineers undertake a study of the new breach and to determine the feasibility of alternative measures to reduce shoreline damage and navigation hazards (U.S. Army Engineer Division, New England, 1989). The U.S. Army Engineer Research and Development Center's (ERDC) Coastal and Hydraulics Laboratory (CHL), formerly known as the Coastal Engineering Research Center (CERC), had assisted the New England District, formerly New England Division, in a 1989 study of the first 3 years of evolution of the new inlet (Weishar, Stauble, and Gingerich 1989). To maintain a navigation channel, the New England District developed a plan to dredge the anchorage at Aunt Lydia's Cove and to dredge an

access channel leading to the cove through the flood shoal (U.S. Army Engineer Division, New England, 1989). The anchorage and access channel has been dredged one time by the New England District and on several occasions by the Town of Chatham in the 10 years preceding 2000, with most of the dredged material being placed on Tern Island across the anchorage from the Fish Pier and on various mainland beaches within the Town of Chatham.

This report describes a study to update to 1999, the inlet-adjacent mainland and barrier island shoreline response and shoal development and evolution since the initial 3-year study (U.S. Army Engineer Division, New England, 1989) to assess the effects of prior dredging of the flood shoal channel and evaluate potential impacts of future proposed dredging on the Chatham Inlet system. The study area is dynamic and is still evolving. The flood channel has changed orientation and position as the associated flood shoal development has continued to grow in area and migrate northward up-estuary since the 1989 study, creating a problem in maintaining a viable navigation channel for the commercial fishing fleet. Documentation of the sequence of changes will provide a scientific basis for understanding of the mechanisms by which the entire inlet/bay system responds to the inlet processes and dredging.

2 Methods

This study was based on analyses of a series of aerial photographs, taken on roughly a yearly basis from 1987 to 1999. A set of aerial photography taken in 1982 provides a base map of preinlet conditions. Bathymetric survey data is limited, but historic preinlet NOAA data and a Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) from 11/1998 will be used to characterize the vertical component. Aerial photography has been scanned from 22 sets of color and black and white prints (Table 1). The original study on the effects of the new breach at Chatham (Weishar, Stauble, and Gingerich 1989) compared the first eight sets of photography taken approximately every 4 months for the first 2 years after inlet formation. The first postinlet vertical aerials were not flown until May 1987, 5 months after the breach occurred. The 1989 study ended with the analysis of changes as of the May 1989 photography.

For the present long-term study, one set of aerial photographs from every year was chosen from the 22 photo sets in the archive. This subset of 14 photo groups were deemed sufficient to show yearly change. Most of the annual photo sets chosen were collected in the summer months of May, June, July, or August. This temporal coverage reduced the seasonal bias in the analysis. For 1991 and 1996, winter photos were all that were available and had to be used to complete the annual study. The photographs were taken by various aerial photography companies and were collected at several different scales. All photo prints were 9 × 9 in format. Some of the photographs were in color, but all sets were scanned in black and white at 600 dpi to reduce digital file space.

GIS Analysis

A base map was constructed from AutoCad files supplied by the Town of Chatham that contained detailed positioning of streets, buildings, and other physical features. Five sheets covering portions of the mainland coast were supplied and imported into ArcView. The AutoCad base map was in Massachusetts State Plane NAD 83 coordinates. Using the ArcView Image Analysis package, it was possible to import each scanned photo and register them against the control points on the base map. Geo-referenced photo mosaics were constructed from the three or four photographs in each set on a common scale. As a minimum, four control points were used to register each print.

Table 1
Aerial Photographs of Chatham Inlet and Harbor

Date	Scale	Type	Original Source[1]	Location of Prints[2]	Remarks	Air Photo Frame
11/20/82[3,4]	1:18000	Color	Col-East	CHL	Preinlet	9538A-1A-11, 12, 13
01/02/87	**Inlet Formed**					
05/07/87[3,4]	1:9000	B/W	Col-East	CHL	First postinlet partial coverage of mainland	10970-7, 9, 11, 13
09/16/87[3]	1:8000	B/W	ACT/ AEM	CHL	Partial coverage of mainland	AS779 2-5, 2-7, 2-9, 2-11
01/11/88[3]	1:9000	B/W	Col-East	CHL-prints of flight line 2 Chat- flt line 1 scanned WHG	11:55 EST Partial coverage of mainland	11257-2-7, 2-9, 2-11, 2-13 CHL 11257-1-9,1-11,1-13 - WHG
05/05/88[3,4]	1:18000	B/W	Col-East	CHL	11:55 EST	11466-9, 10, 11
09/01/88[3]	1:18000	B/W	Col-East	CHL	10:10 EST	11588-11, 12, 13
12/29/88[3]	1:18000	B/W	Col-East	CHL	11:04 EST	11687-2-4A, 5A, 6A
05/23/89[3,4]	1:18000	B/W	Col-East	CHL	08:20 EST	11964-1-10, 11, 12
12/07/89	1:12000	B/W	Col-East	CHL	Partial coverage of mainland	12401-8, 10, 12
08/15/90[4]	1:18000	Color	Col-East	CHL	12:40 EST	12650-10, 11, 12
02/22/91	1:18000	B/W	ECM	Chat/scanned by WHG	12:36 EST	ECM P819A 11-5, 11-7
12/31/91[4]	1:18000	Color	Col-East	CHL		13309-1-11, 12, 13
05/22/92[4]	1:18000	B/W	ECM	Chat/scanned by WHG	11:20 EST	ECM P00819 11-7,11-8,11-9
06/25/93[4]	1:18000	B/W	ECM	Chat/scanned by WHG		P04043-11-11, 11-12, 11-13
04/23/94	1:18000	B/W	ECM	Chat/scanned by WHG	14:44 EST	ECM P06194 11-5,11-6,11-7
08/08/94[4]	1:18000	Color	James Sewall	CHL	14:20 EST	153.545 1-5,1-6,1-7
09/12/94	1: 38000	Color	NOAA	http:// mapindex. nos.noaa.gov	15:13 GMT	5WKV4769
05/20/95[4]	1:18000	B/W	Col-East	Chat/scanned by WHG		15425-9, 10, 11
03/27/96[4]	1:18000	B/W	Col-East	Chat/scanned by WHG	11:55 EST	16138-10, 11, 12
6/27/97[4]	1:18000	B/W	Aero Tech	Chat/scanned by WHG	12:30 EST	9704004 14-3, 4, 5
07/02/98[4]	1:18000	B/W	James Sewall	Chat/scanned by WHG		13680-2-5, 6, 8
07/15/99[4]	1:18000	B/W	Col-East	Chat/scanned by WHG	08:40 EST	19264-6-4, 5, 6

[1] Col-East, P.O. Box 347, Harriman-West Airport, North Adams, MA 01247
ACT/AEM Co. 14 Cedar Swamp Road, Smithfield, R.I. 02917
James Sewall Company, Old Town, ME, 04468
ECM = East Coast Mapping, 9 Constitution Drive, Bedford, NH 03110
Aero Tech Co.
[2] CHL = U.S. Army Engineer Research and Development Center, Vicksburg, MS (Coastal and Hydraulics Lab).
Chat = Town of Chatham/photos scanned by WHG = Woods Hole Group, Falmouth, MA.
[3] Photo set used in Weishar, Stauble, and Gingerich (1989).
[4] Photo set used in present study.

Barrier island and mainland wet/dry line shoreline positions, channel center lines and shoal areas were then digitized from the aerial images on the screen and entered into the Geographic Information System (GIS) theme layer for each year. There has been a great deal of change in the inlet system. Figure 3a identifies the morphologic features associated with Chatham Harbor in the early years of formation circa 1988 when the South Beach was still detached from the mainland. An example of the prominent morphologic features after the South Beach became welded onto the mainland are shown in Figure 3b from the 1999 photographic set. Details of yearly change will be presented in the next chapter.

Shoreline

Maps have been produced of the north Nauset Spit and South Beach ocean and bay shoreline, and the Chatham mainland shoreline. The shoreline was defined visually on the aerial mosaic as the wet/dry line on the beach, based on the variation in color between the lighter gray tones of the dry beach and the darker gray tones of the more saturated intertidal area. This has been interpreted by some as the high-water shoreline but in reality would be slightly below the actual debris line of maximum runup, which was not visible on most of the photos. Since most of the photos were taken at or around low tide and the same procedure was done on each date, this interpreted shoreline is thought to be a good representation of shoreline change. Each shoreline was stored by date in a separate layer.

Channel Center Line

Channels through the various shoals at Chatham Inlet were readily visible on all of the photographs as darker areas between lighter sand deposits. The approximate center line was digitized as a line feature by visual inspection. The main ebb channel through the ebb shoal was the most prominent channel feature. The pre-inlet 1982 and postinlet 1987 to 1991 had a south Chatham Harbor channel that connected the present opening with the Chatham Bars Inlet and Morris Island Cut. As the north flood shoal evolved, the channels associated with this shoal also changed, evolving from a west and east flood channel around the flood shoal to a channel that was discontinuous through the center of the flood shoal. The entrance channel to the Fish Pier has also evolved with this changing north flood shoal morphology. The channel center lines for each year were placed on a different layer.

Shoals

Several shoals have been identified as the inlet has evolved and the number of shoals has changed as sediment has eroded and accreted with time. The outline of each shoal was digitized using the intertidal and subtidal boundary based on color change and bed forms visible on the photos. Water clarity is for the most part, good in this area, so the interface between the lighter color, shallow shoal and the

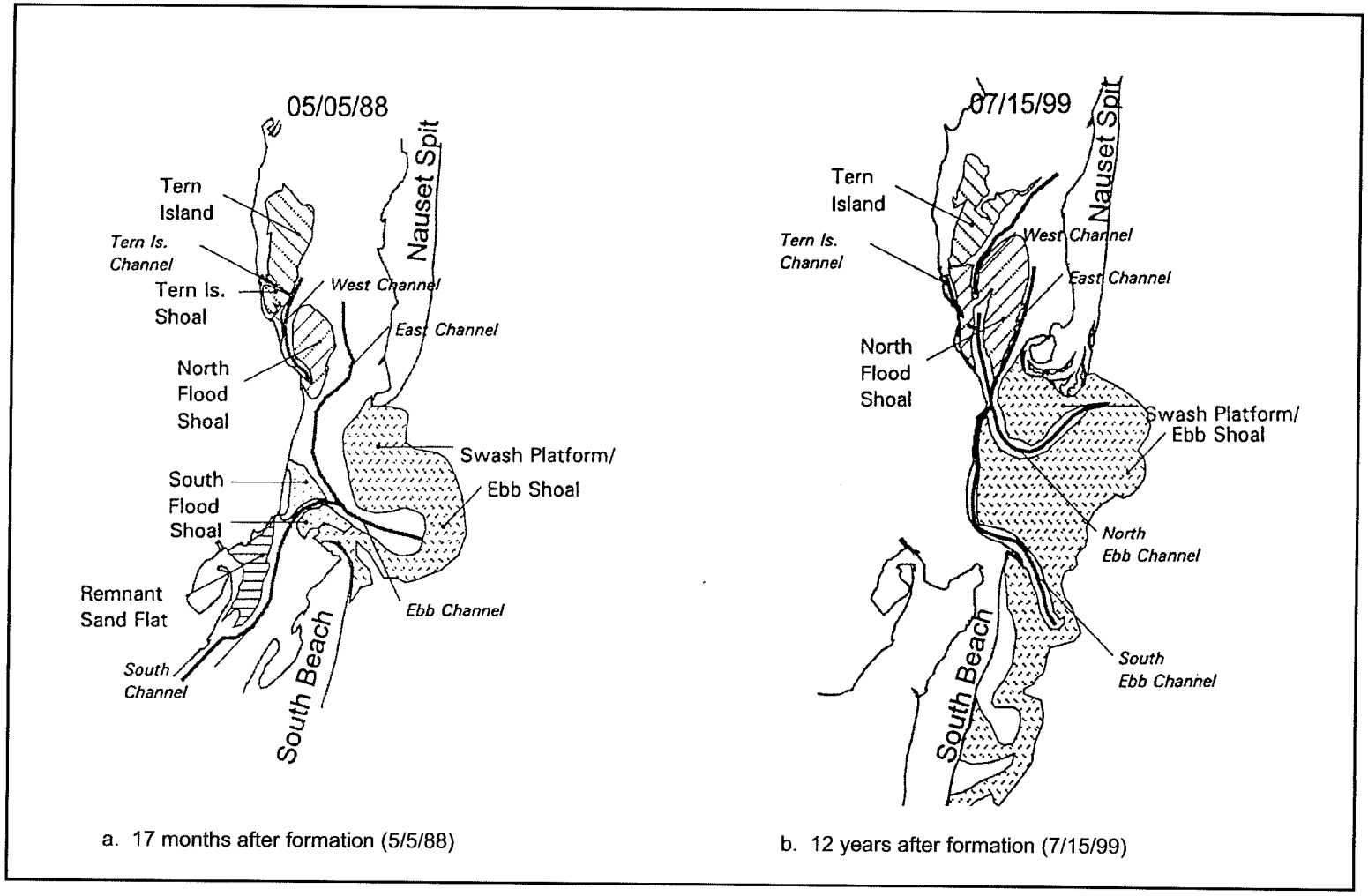


Figure 3. Morphologic features of the ebb and flood shoals, channel center line and shorelines associated with Chatham Inlet

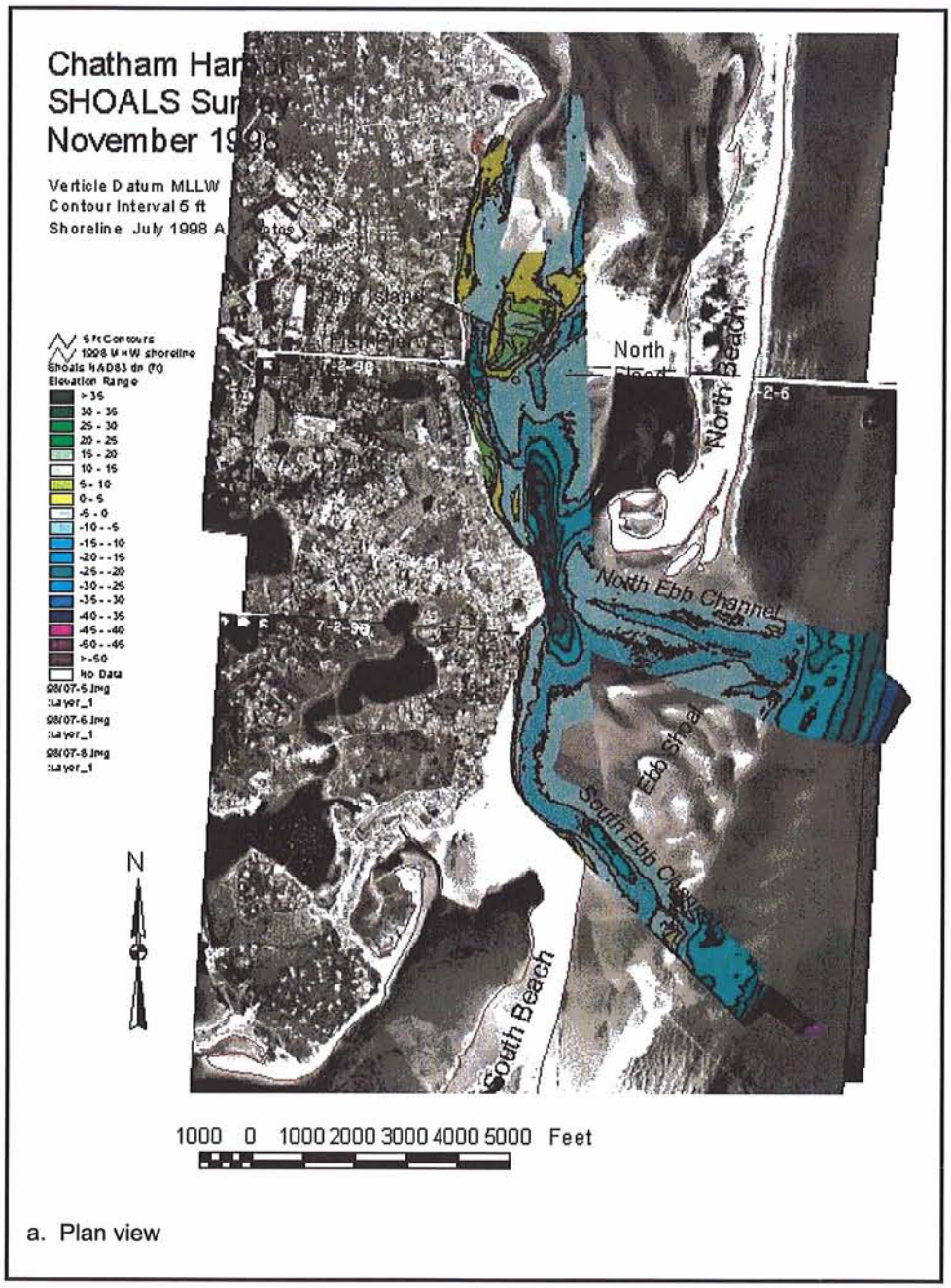
darker, deeper water is visible on all of the photos. Based on the limited bathymetry it was estimated that the digitized shoal boundaries represented the 5 to 10 ft (1.5 to 3.0 m) mean lower low water (mllw) depth contours.

Prior to inlet formation a remnant north and south shoal, and south sand flat were present in Chatham Harbor. Tern Island and its associated south shoal were also present in the vicinity of the Fish Pier. These shoals were probably remnant flood shoal deposits of the last inlet breach in the 1846 to 1926 time period (Giese 1988) and were visible on the preinlet 1982 photographs. An ebb shoal and northern swash platform formed within the first month and was well established by the first set of photography in May 1987. The main ebb channel migrated to the south and the main body of the ebb shoal became asymmetric to the south as it followed the migration of this single channel. As the second ebb channel formed to the north the ebb shoal began to advance seaward on its northern side, beginning in 1995. The bed forms and shapes associated with the ebb shoal and swash platform are easily seen in the photographs.

Because of the long narrow Chatham Harbor shape and close proximity of the mainland shoreline to the inlet, two flood shoal deposits formed. One developed around the north remnant shoal and one around the south remnant shoal, as flood flow entered the estuary and flowed both to the north and south. The south flood shoal eventually overtook the south sand flat. Later, the south shoal/sand flat area was incorporated in the south and westward migrating south beach spit until it finally welded to the mainland in early 1992. The entire flood flow was then forced to the north, resulting in the north flood shoal expanding and moving north toward Tern Island. Tern Island and an associated shoal to its south also migrated to the north as the north flood shoal encroached on the channel to the Fish Pier. This is the area of most concern to maintaining a navigation channel through the shifting shoal deposits. Each shoal outline was stored on a separate layer in the GIS.

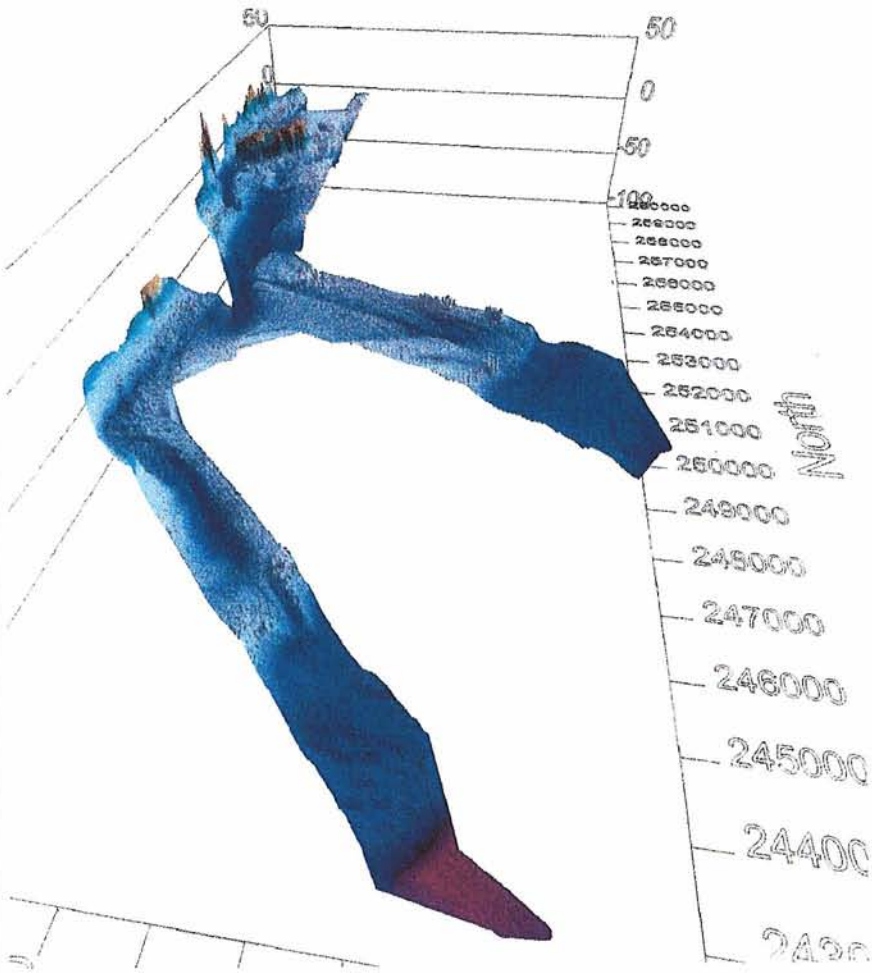
Bathymetry

Only one set of bathymetry was available for the area after the inlet was formed. A SHOALS survey was conducted in November 1998. The SHOALS system is described in Irish, Parson, and Lillycrop (1995). Due to limitations in the lidar system, the survey was limited to the ebb channels. Figure 4a shows a bathymetric map constructed from the SHOALS survey. The predominant south ebb channel and the incipient north channel are visible extending seaward through the ebb shoal as seen on a three-dimensional Digital Terrain Model (DTM) of the SHOALS data in Figure 4b. A large scour hole is prominent just to the bayside of the northern ebb channel. All depths are referenced to mean lower low water (mllw) on the SHOALS survey. Depths reaching to 29 ft (8.8 m) mllw in this scour area. The western side of the flood shoal is also visible showing the location of the west flood channel and the Tern Island channel. An ebb lobe is also present on the edge of the flood shoal where the west channel is trying to re-establish a continuous channel through the ebb shield on the western side of the flood shoal. A maximum depth of 54 ft (16.5 m) was recorded at the seaward end of the ebb shoal at the south ebb channel. Landward elevations reached a maximum height



a. Plan view

Figure 4. Bathymetry of portions of Chatham Inlet collected in November, 1987 by the SHOALS survey system (Continued)



b. A three-dimensional Digital Terrain Model of the bathymetry based on the SHOALS survey

Figure 4. (Concluded)

of 47 ft (14.3 m) on the hills overlooking the Fish Pier. In general, shoal areas of the ebb and flood tidal delta range between 0 and 10 ft (0 and 3.1 m) on this survey. Overlaying the 11/98 SHOALS bathymetry on the 7/2/98 aerial photography indicated that the shoal edge visible on the photography corresponded generally with the 5-ft- (1.5-m-) depth contour in the bay area and the ocean side of the ebb shoal corresponded with the 10-ft- (3.1-m-) depth contour. There would be some change in the bathymetry in the four-month period between the photograph and the bathymetric survey, but the registration of the visible shoal area to a depth relative to mllw was reasonably accurate.

3 Inlet Throat, Shoreline, and Channel Evolution

Chatham Harbor Evolution

Preinlet

Since the mid 1800s breach, the South Beach had migrated westward and merged with the mainland and Monomoy Island. Nauset Spit began its trek southward and the inlet migrated south ahead of the spit. During the early 1980s Nauset Spit was in the southward growth part of the morphologic cycle, with Chatham Bars Inlet located seaward of North Monomoy Island, around 1 mile (1.6 km) south of Morris Island Cut. Figure 5 shows the configuration of Chatham Harbor in its preinlet state on 20 October 1982. Nauset Spit is continuous across the Town of Chatham shorefront. A north and south remnant shoal are present along with a south remnant sand flat in Chatham Harbor. The center line of the main channel through the harbor meanders around these shoals, but is for the most part in the center of the elongate lagoon. The entrance channel to the Fish Pier and Aunt Lydia's Cove is located between the southern end of Tern Island and a shoal, and is orientated in a east-southeast direction. The mainland beach is wide and has a spit oriented to the south, coming off of the shore and attaching to the south remnant shoal.

The approximate location of the 2 January 1987 breach is in a narrow section of Nauset Spit, just across the harbor to the north of the Chatham Lighthouse. This area had few dunes and was bisected by several low spots created by foot traffic and off-road vehicles. The lack of dunes and low elevation allowed the storm surge to cut through to the bay and establish the inlet.

Morphologic evolution of inlet 1987 - 1999

The first vertical aerial photography was flown five months after the breach, on 7 May 1987. Figure 6 shows the early stages of inlet development with the formation of an ebb shoal on the ocean side. At this time, the ebb shoal had a symmetrical crescent shape. A swash platform was beginning to form in the inlet throat just off the northern spit. A south flood shoal formed in the bay and encompassed the southern remnant shoal. Sand was also growing on the north flood shoal that had attached to the north remnant bay shoal. The main ebb channel

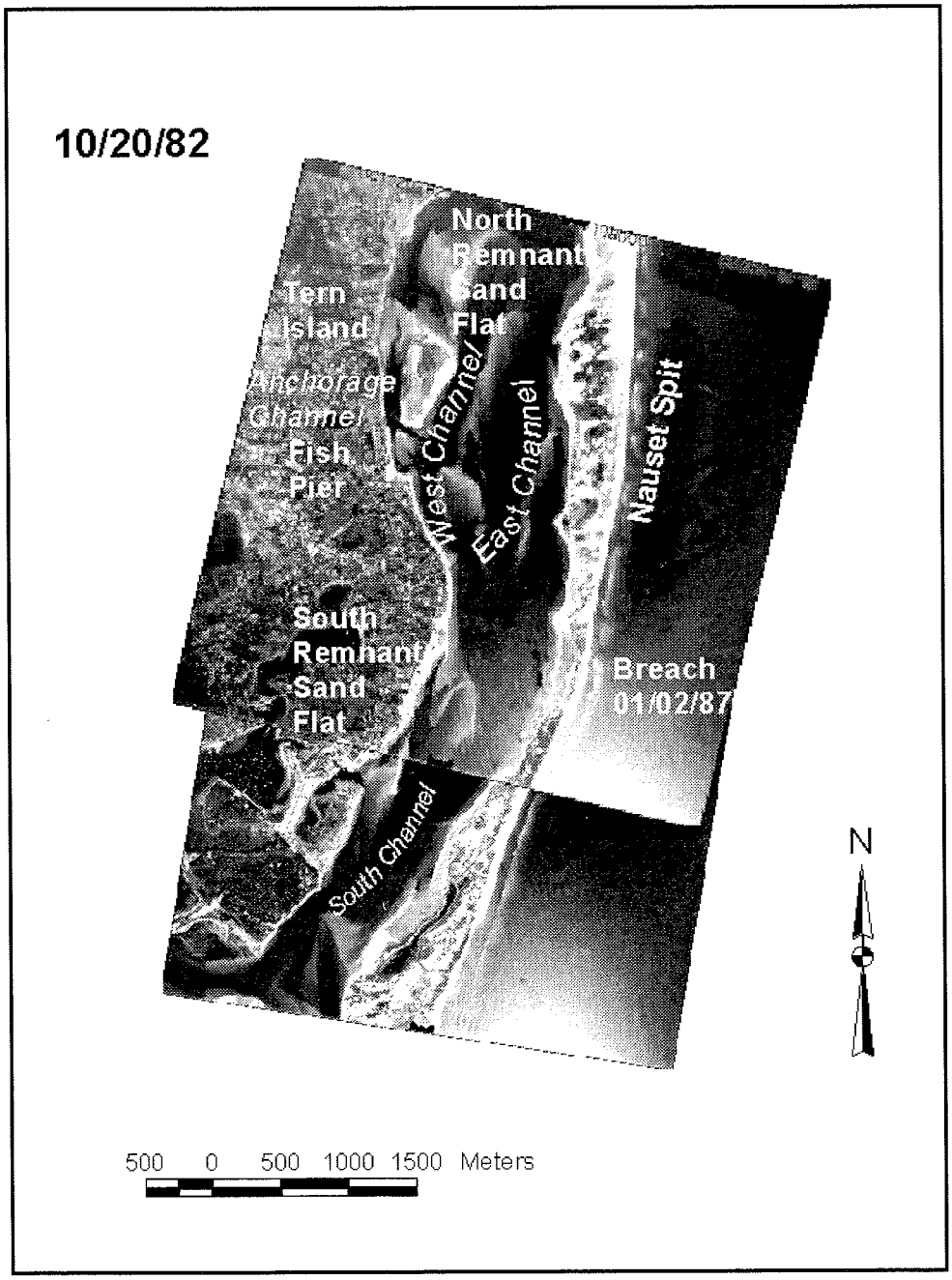


Figure 5. Preinlet morphology of Chatham Harbor, 20 October 1982

exited the inlet in an almost east/west orientation to the south of a small swash platform. The adjacent beaches formed spits at their ends that recurved back into the bay. The channel through Chatham Harbor was being modified by the flood shoal deposits, but there was free access to Chatham Bars Inlet to the south around the south flood shoal. The channel into the Fish Pier was barely in the photograph and changed little from preinlet shape.

The inlet continued to grow through time and details of inlet morphology change in September 1987 and January 1988 are described in Liu et al. (1993).

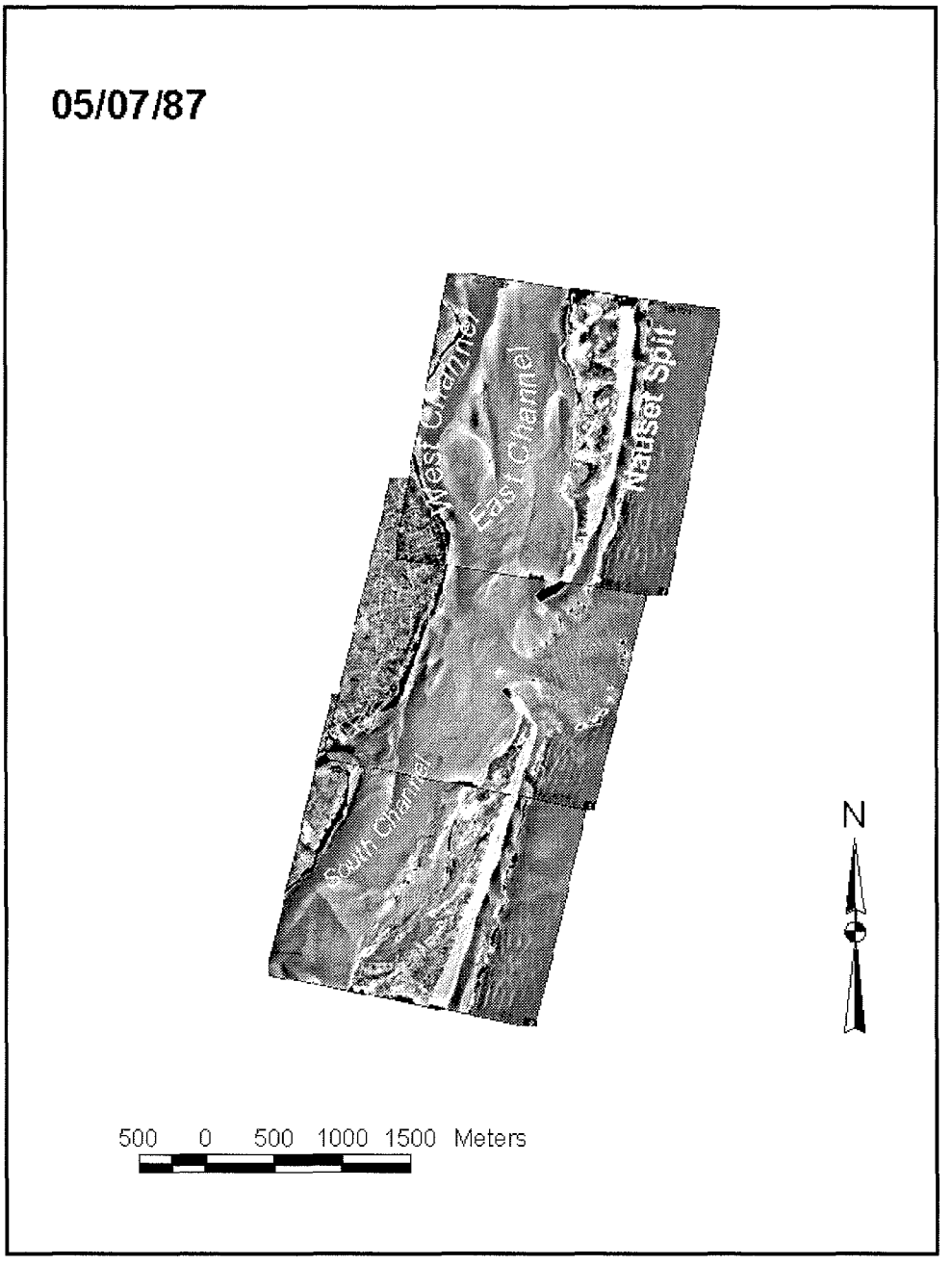


Figure 6. Postinlet morphology of Chatham Harbor, 7 May 1987

The north and south beach spits continued to recurve as the inlet throat widened. Figure 7 shows the inlet 17 months after formation on 5 May 1988. The main ebb channel had migrated to the south and the swash platform on the north end of the ebb shoal had enlarged. The north barrier spit had recurved north-westward into the bay. The south spit continued to recurve westward into the bay. The south beach spit had been described as having five cycles of spit evolution between 1987 and 1989, with spit elongation into the bay, narrowing of the spit and breaching of the spit end (Weidman and Ebert 1993). Sand from this breached spit end was incorporated into the complex south flood shoal sand body.

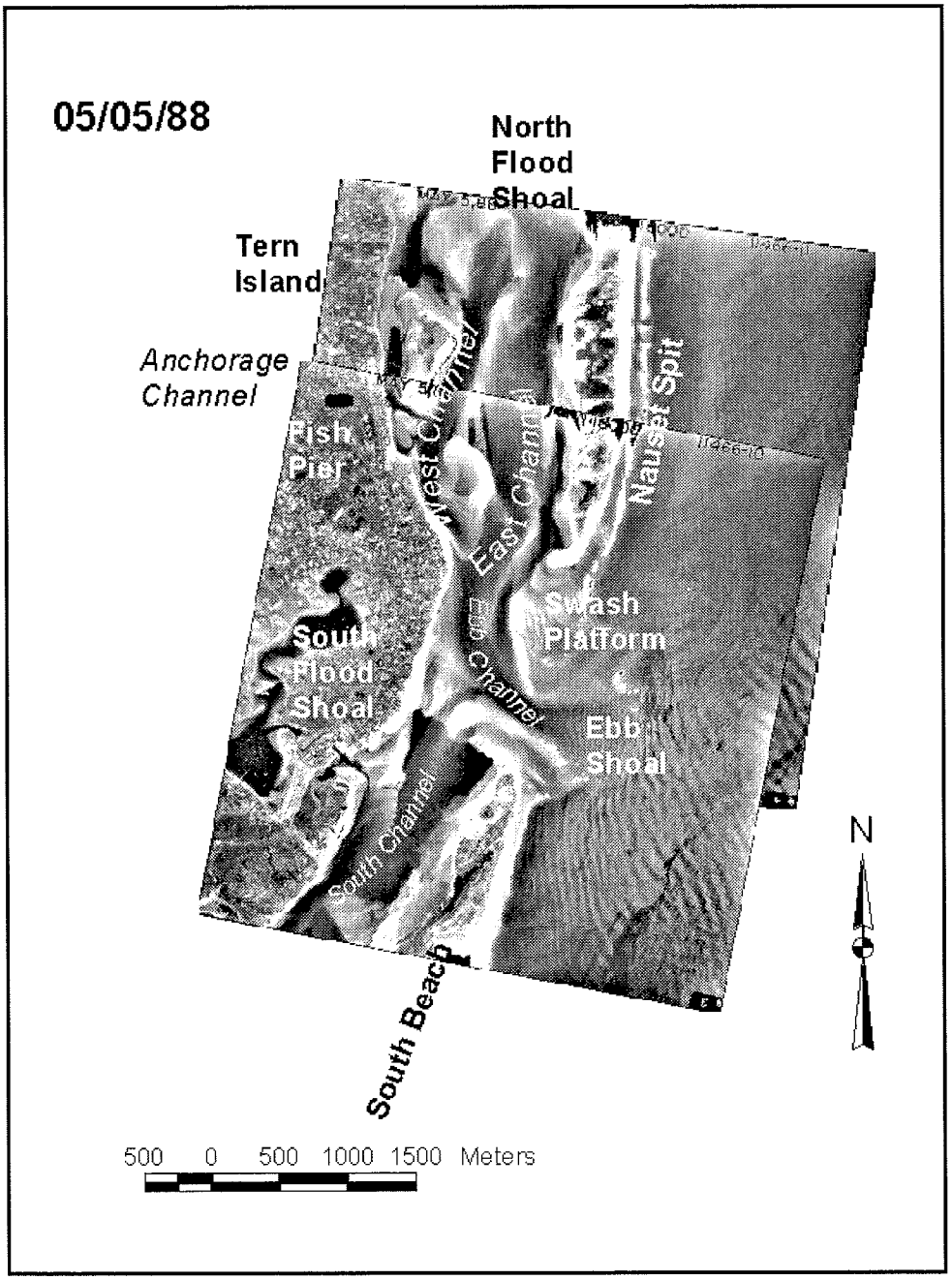


Figure 7. Morphology of Chatham Harbor, 5 May 1988

Navigation to Chatham Bars Inlet and south Chatham Harbor became more difficult with the expansion of the south flood shoal across the entire width of the lagoon. The north flood shoal also grew to the north. The main navigation channel on the west side of the shoal experienced shoaling with the development of an ebb oriented lobe across the channel. The east channel around the north flood shoal also shoaled and became a secondary route to the north. The mainland shoreline began to experience erosion as waves now traveled directly across from the inlet throat. Longshore transport occurred, both to the north and south where sand accreted to the mainland beach adjacent to both the north and south flood shoals.

Additional inlet evolution from October 1988 to December 1988 (described in detail in Liu et al. 1993) showed an ever widening inlet throat and continued recurving of the north and south barrier spits. By 23 May 1989, the south spit breached again and that sand was deposited on the south flood shoal, limiting navigation to the south Chatham Harbor (Figure 8). By this time, the south flood shoal had migrated far enough south to merge with the south remnant sand flat. The main ebb channel continued to migrate southward with the prevailing coastal processes expanding the swash platform and expanding the ebb shoal seaward and to the south. The west channel around the flood shoal into Chatham Harbor was still the predominant channel, but navigation into the Fish Pier became more difficult as the Tern Island Channel narrowed and moved more east-west. The general trend was for the north flood shoal to migrate northward and expand in area. Erosion still continued on the mainland beach, as sand was eroded from in front of the inlet and moved to the north and south mainland beach area just past the expanding inlet opening.

By December 1989, almost two years after inlet formation, the inlet main ebb channel continued to migrate south. A large spit extended westward from South Beach overtaking most of the south flood shoal. At this time a large stone revetment type seawall was being constructed along the most severely eroded section of mainland beach. By 15 August 1990, the South Beach sand spit almost extended across the south Chatham Harbor (Figure 9). Navigation to the south within Chatham Harbor was limited to only small craft through a small channel that still existed adjacent to the mainland through the south flood shoal/south remnant sand flat. The swash platform was becoming very large with development of complex sand waves. The main west flood channel was now close to the recently constructed mainland seawall. The ebb lobe in the west channel was more elongate and presented less obstruction to navigation, and formed a linear shoal in front of the seawall, with a spit extending south toward the ebb channel. Shoaling became more of a problem at the entrance to the Tern Island Channel to the Fish Pier as that channel reoriented more to the east.

In the February 1991 photo mosaic, the inlet configuration was basically the same as in August 1990. By 31 December 1991, almost exactly 6 years after the initial breach, the South Beach spit had continued to enlarge as the seaward tip of the island became more rounded (Figure 10). There was still a small, shallow opening to South Chatham Harbor, as the south flood shoal moved south more into the harbor. The ebb shoal/swash platform, main ebb channel complex continued to grow to the south, with the orientation of the main ebb channel more to the southeast. Nauset Beach Spit was now recurving less into the harbor but more to the southeast. This north swash platform was also extending into the harbor creating a very narrow opening for the main navigation channel between it and the mainland beach. The north flood shoal expanded to the northwest, moving the dominant west navigation channel closer to Tern Island. The Tern Island channel rotated from a east-west orientation to a more northwest-southeast one, with a wider channel. Erosion on the mainland beach progressed south past the Chatham Lighthouse.

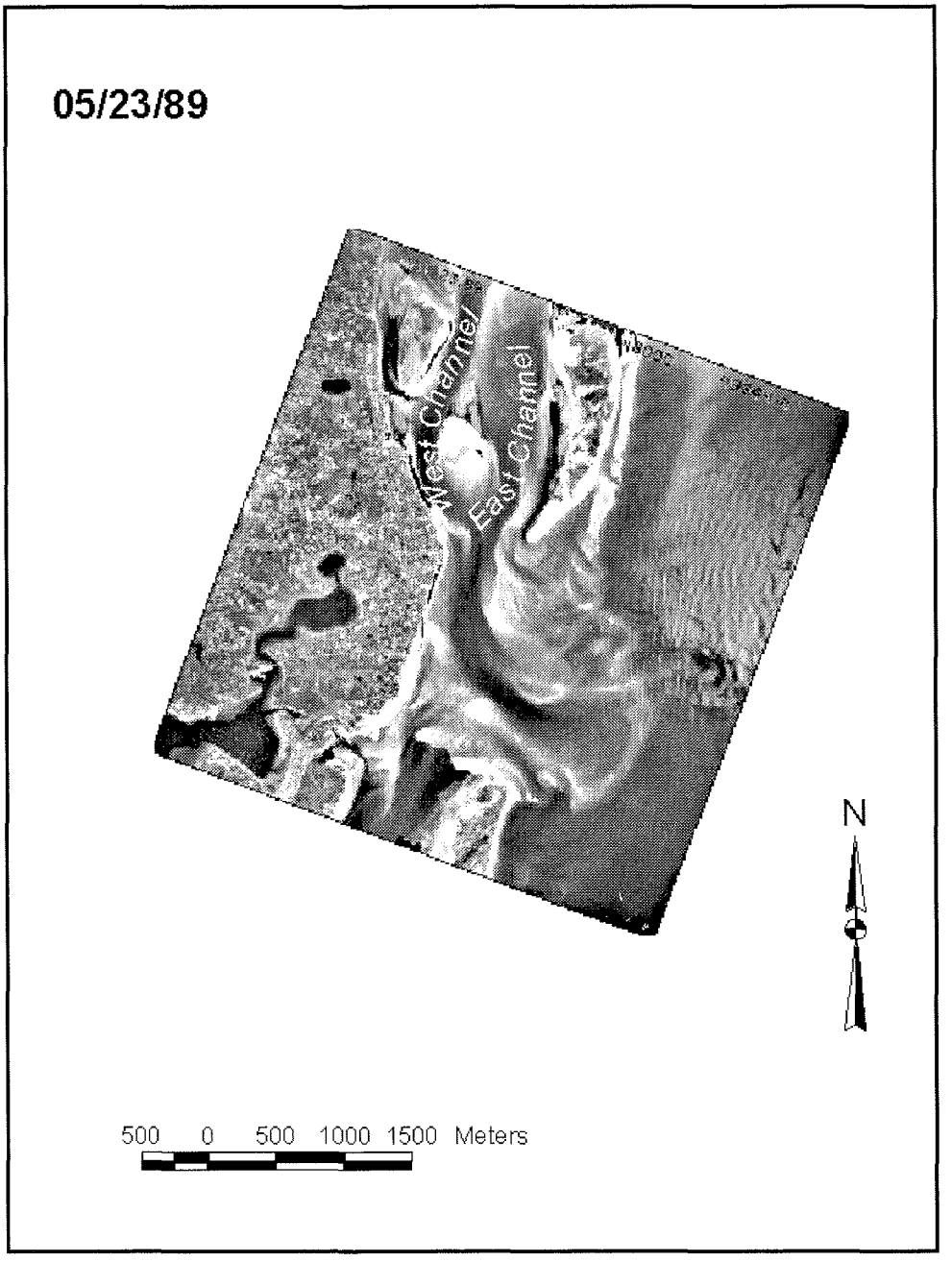


Figure 8. Morphology of Chatham Harbor, 23 May 1989

By 22 May 1992, the South Beach spit finally closed the opening to south Chatham Harbor, as it moved west and welded onto the mainland beach just to the south of the lighthouse (Figure 11). Now all of the tidal prism of north Chatham Harbor/Pleasant Bay flowed out the mouth of Chatham Inlet. Large ebb oriented shoals formed on the southern end of the swash platform, shoaling the main ebb channel. This main ebb channel curved from a southeast orientation inside the swash platform to a more east direction through the throat area. The Nauset Spit (North Beach) developed several finger spits off the ocean side and a large bar system graded into the swash platform. The spit and swash platform continued

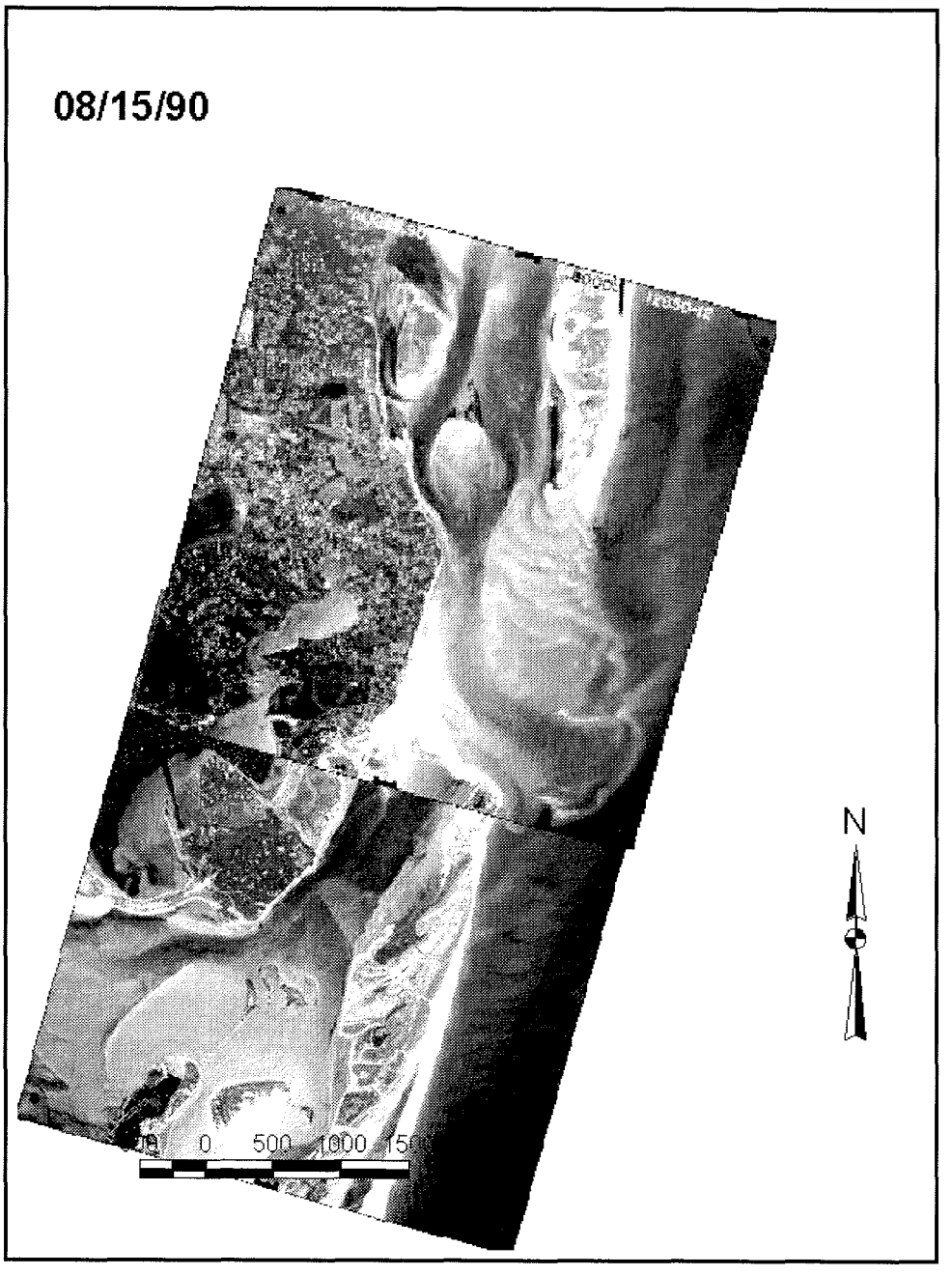


Figure 9. Morphology of Chatham Harbor, 15 August 1990

to move into the bay creating a narrow area of the navigation channel between the mainland point, north flood shoal, and swash platform. The east and west channels around the north flood shoal were both well developed, but the main navigation channel on the west had become shallow from elongation of the western ebb spit of the flood shoal. The Tern Island channel into the Fish Pier also experienced a narrowing due to shoaling.

The South Beach became more substantially attached to the mainland beach (25 June 1993 photo mosaic), with overwash of the former spit adding sand to the

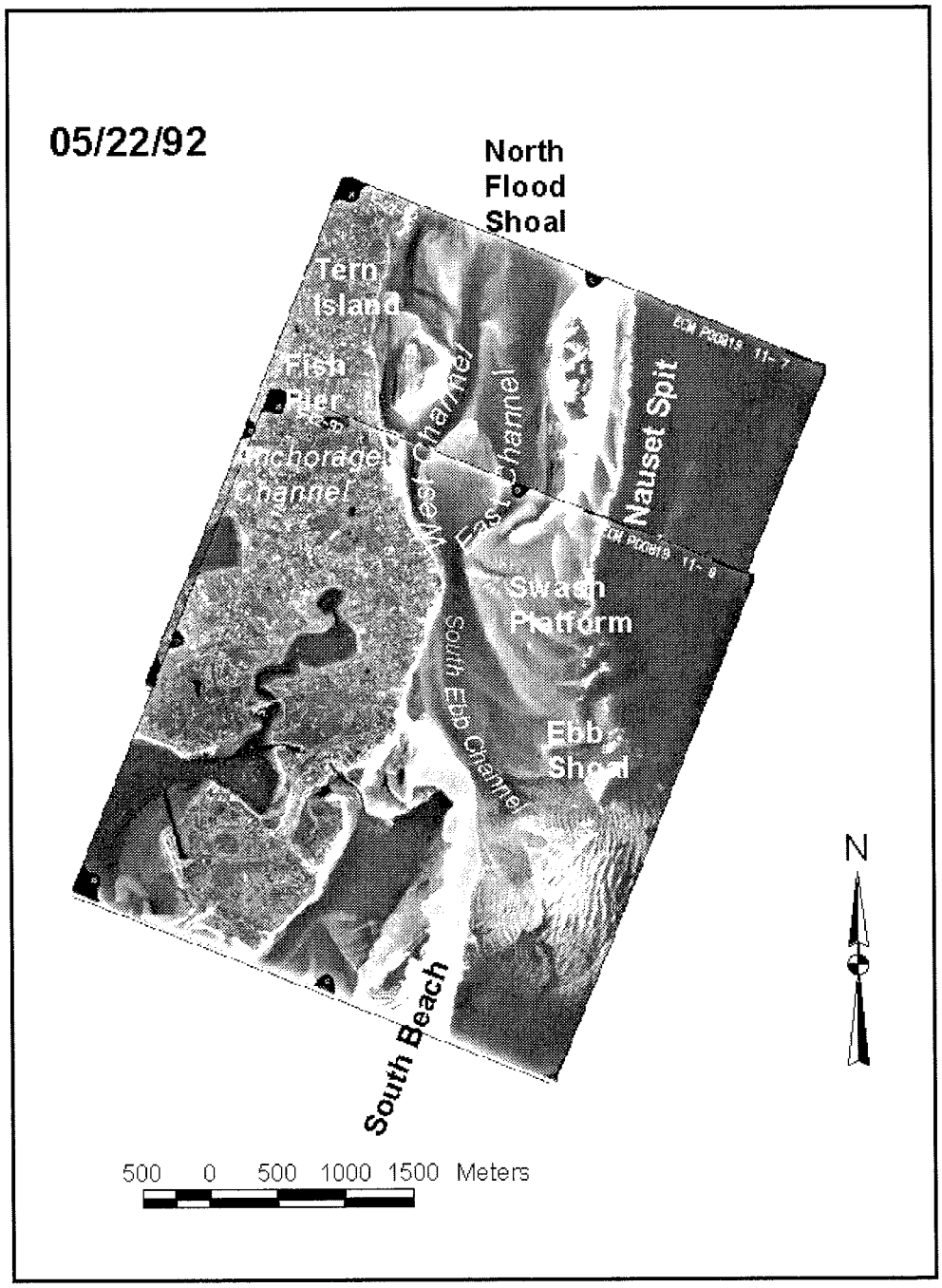


Figure 10. Morphology of Chatham Harbor, 31 December 1991

now large sand flat area (Figure 12). The north end of South Beach had by now migrated one island width toward the mainland. A small ebb oriented spit formed off the tip of the beach defining the south end of the ebb shoal. The main ebb channel was wide and oriented in a northwest-southeast direction, with the expanding swash platform dominating the north side of the ebb shoal. The north flood shoal expanded to the north and increased its width, taking on the classic flood shoal shape described by Hayes (1975) which includes a flood ramp, flood channels, ebb shield, ebb spits and spillover lobes (Figure 13). The west

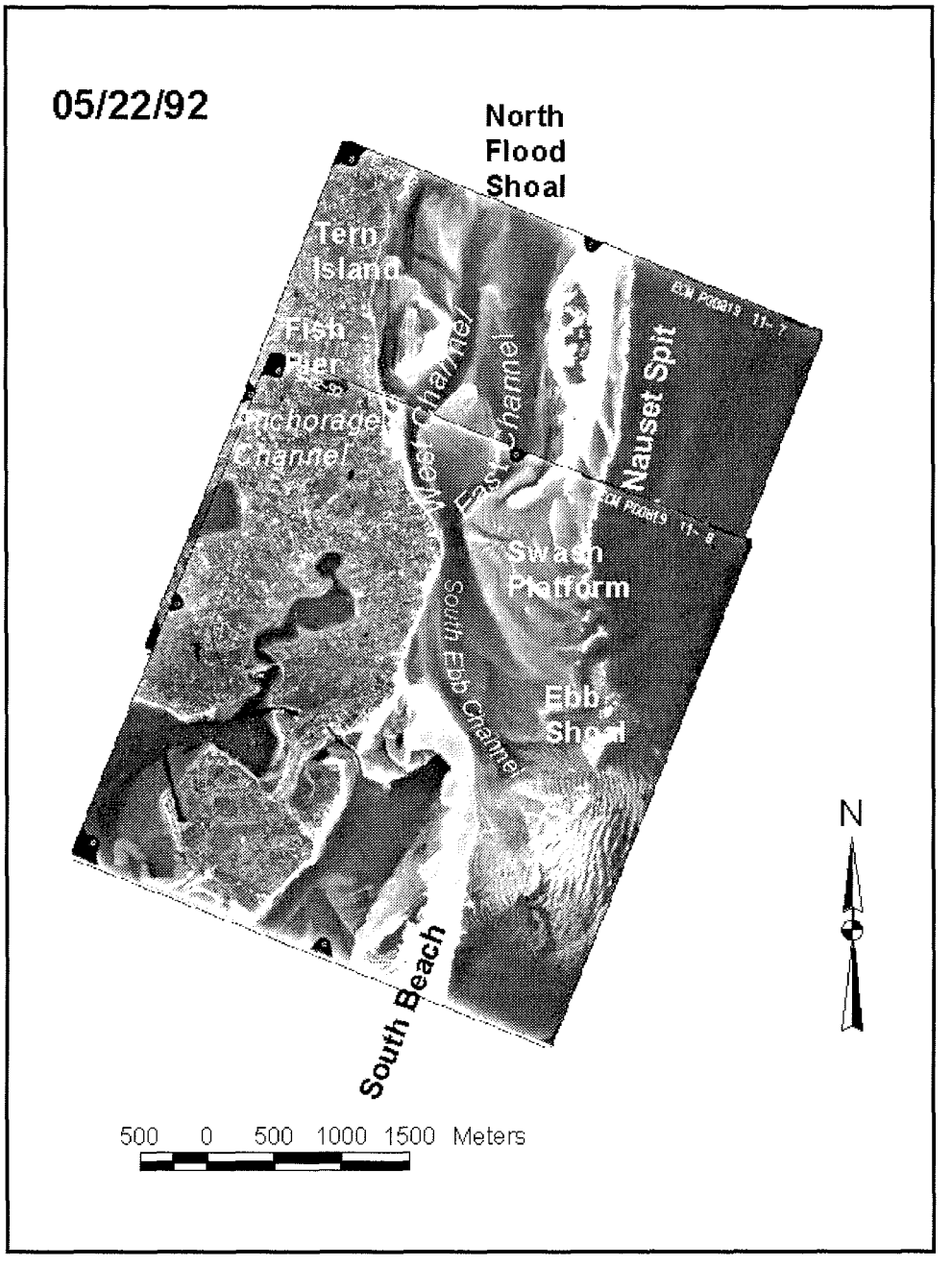


Figure 11. Morphology of Chatham Harbor, 22 May 1992, with south spit attachment to mainland beach

navigation channel moved closer to the mainland beach as the north flood shoal expanded and the Tern Island channel to the Fish Pier continued to a more northwest-southeast orientation. The east channel also moved more to the east around the expanding flood shoal.

The attachment of the South Beach to the mainland became more substantial with overwash of the sand bridge and increased deposition into south Chatham Harbor. This process resulted in increased width and height of the sand bridge

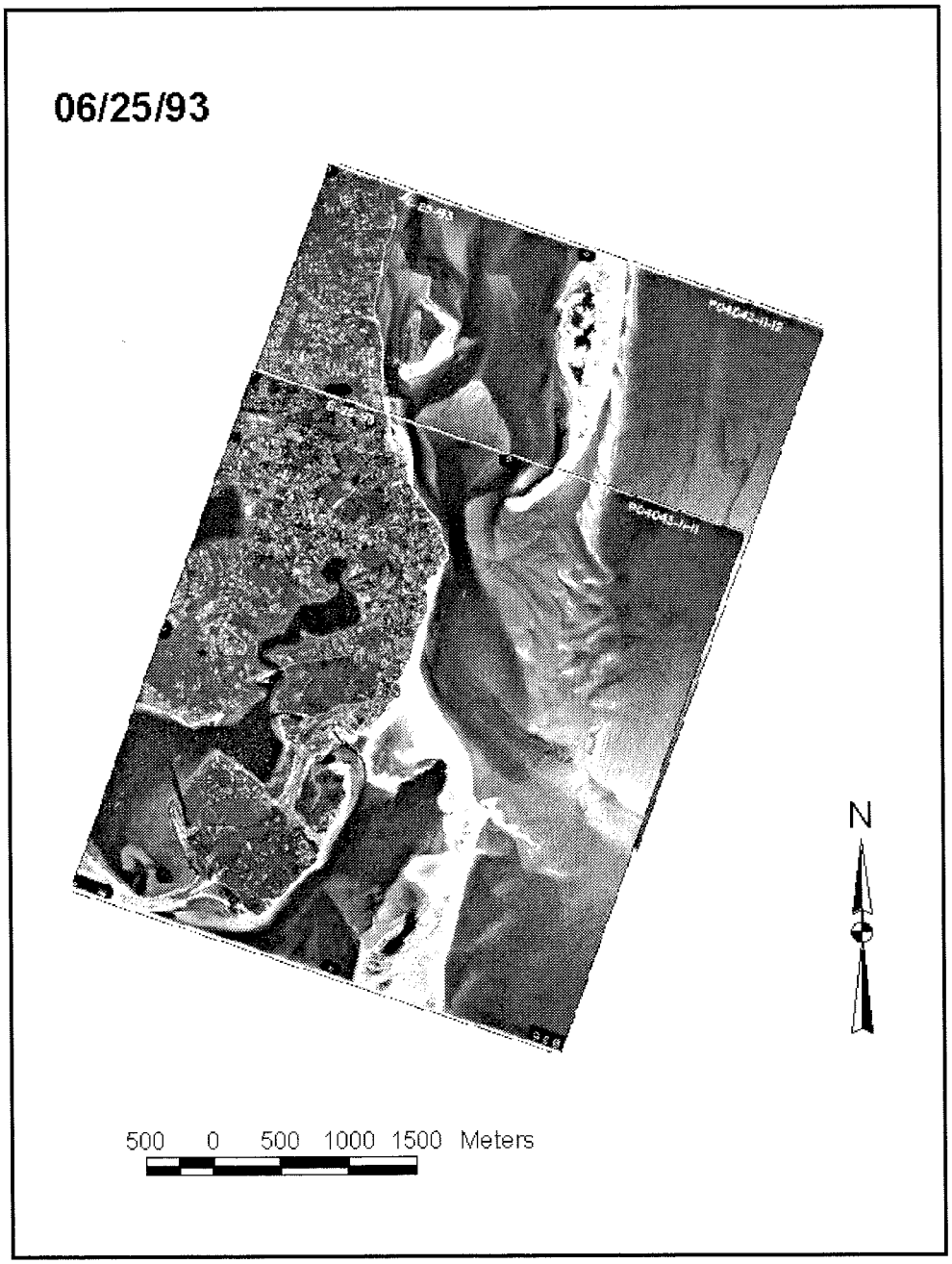


Figure 12. Morphology of Chatham Harbor, 25 June 1993

(23 April 1994 photo mosaic) which continued throughout 1994. As of the 8 August 1994 photography (Figure 14), the attachment was a significant feature of the south side of the inlet. What was an eroding mainland beach a few years earlier now became a wide accretional feature. The shoreline was now an arcuate feature that outlined the western edge of the main ebb channel as it made an almost 90-deg turn from a north-south orientation in the lower harbor to an east-west orientation through the ebb shoal. The north swash platform was now around 7,000 ft (2,100 m) long and filled almost the entire opening into the bay. The

Figure 13. Morphology of the Chatham north flood shoal based on a model of Hayes (1975)

north and only flood shoal continued to grow to the north and the ebb spits on both sides of the shoal almost closed off both the east and west channels around the flood shoal. The west flood channel moved to the west and went almost directly into the Fish Pier. The short Tern Island channel also became shallow as sand was transported into Aunt Lydia's Cove. An ebb-oriented spillover lobe tried to cut the ebb shield of the flood shoal and re-establish the west channel through the flood shoal.

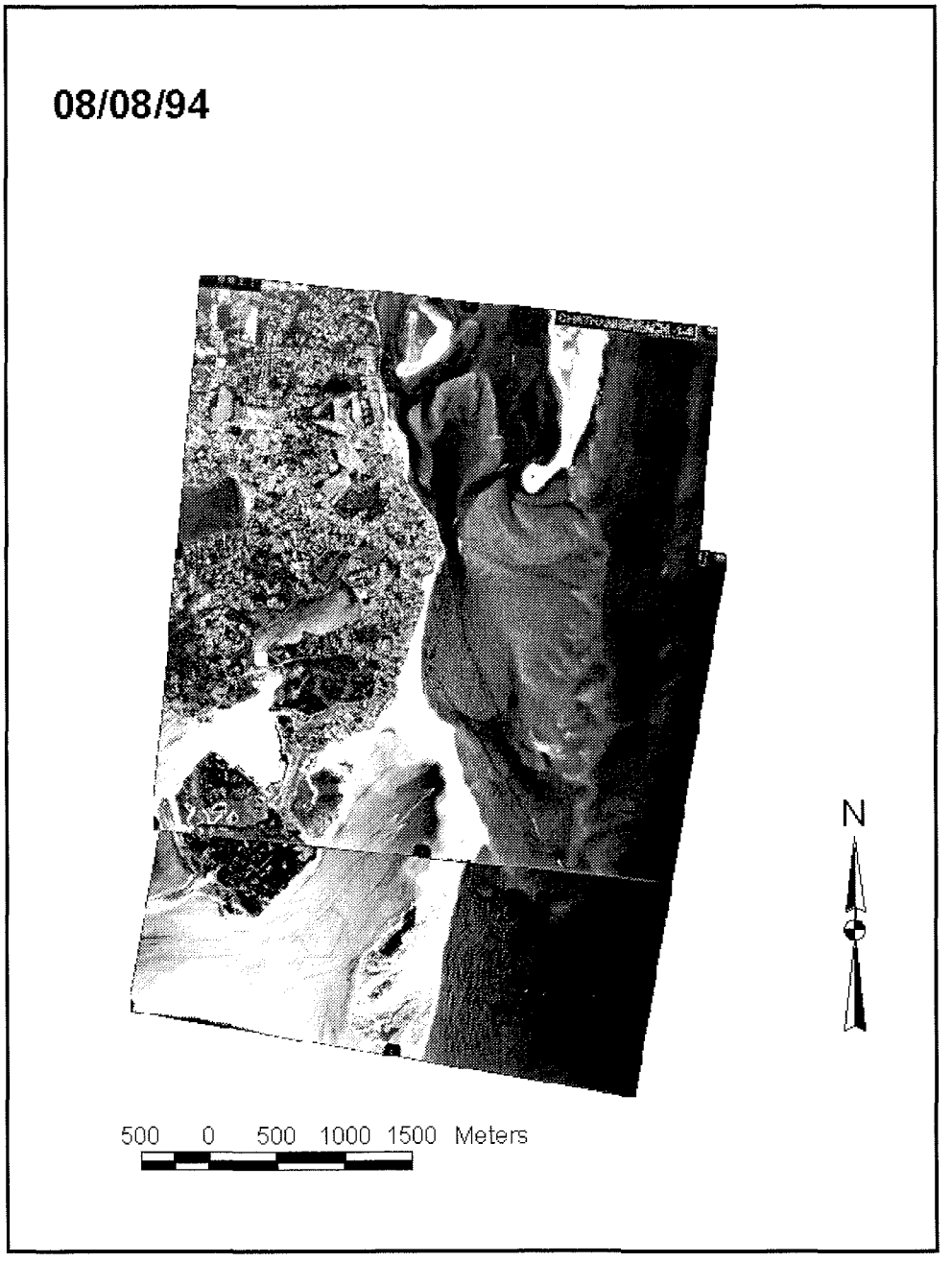


Figure 14. Morphology of Chatham Harbor, 8 August 1994

Eight years and five months after the inlet breach, the inlet was approximately 8,500 ft (2,600 m) wide. The main ebb channel had migrated to the extreme south end of the inlet and was against the South Beach shoreline in the 20 May 1995 photographs (Figure 15). A second ebb channel was beginning to form around 1,000 ft (304.8 m) north of the initial breach. The ebb shoal was divided into three parts with a smaller north swash platform, central ebb platform, and a southern ebb platform. The terminal lobe of the ebb channel was south of the north end of South Beach as the shoal took on an extreme asymmetrical shape to the south. The South Beach continued to migrate landward, but did not move further to the

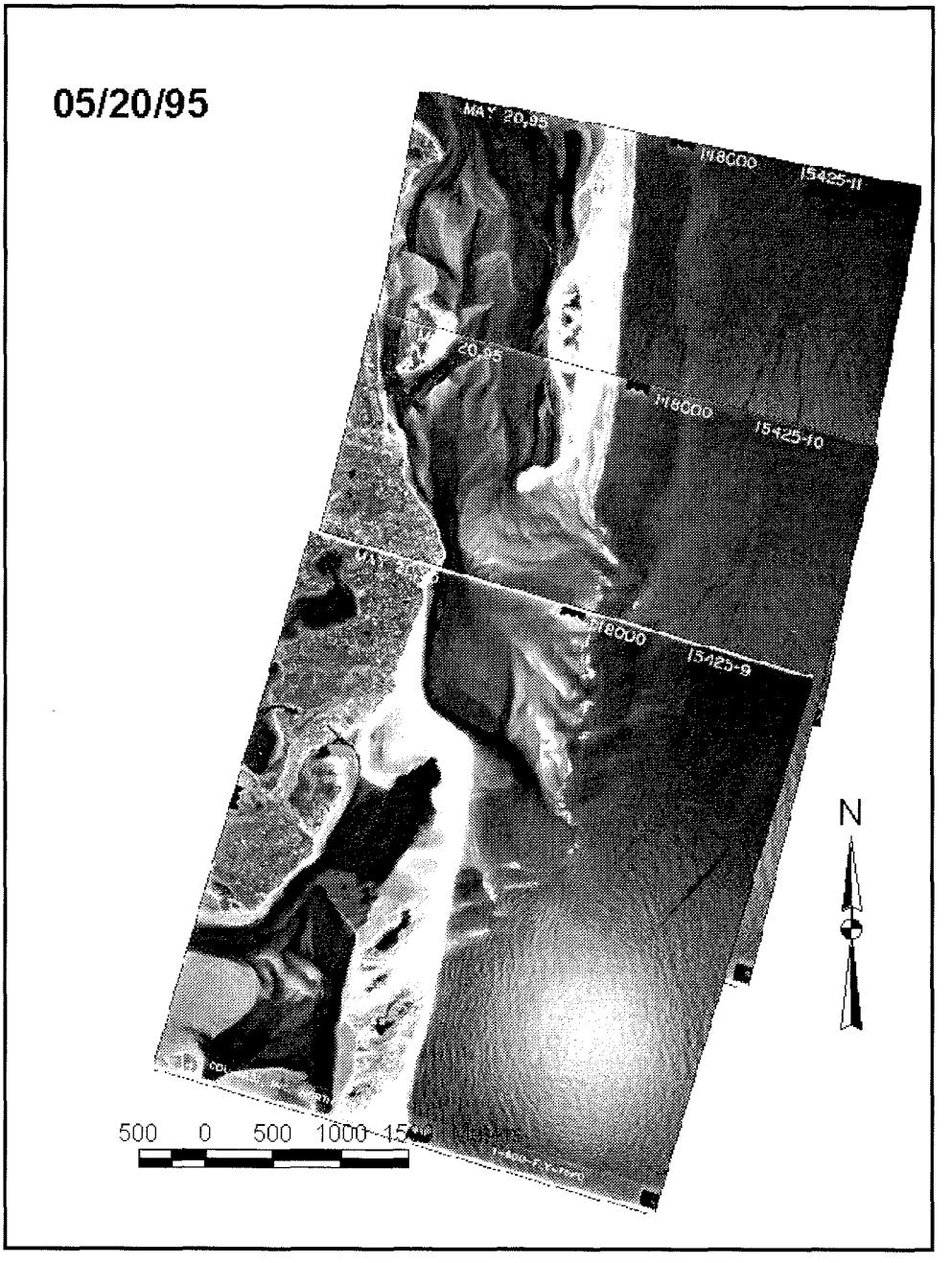


Figure 15. Morphology of Chatham Harbor, 20 May 1995, with two ebb channels

south. The flood shoal continued to widen and the ebb spits closed both the east and west channels into the northern part of Chatham Harbor. The main channel was now on the flood ramp in the middle of the flood shoal. Dredging through the western edge of the flood shoal's ebb shield was required to re-establish the Tern Island channel to the Fish Pier. This dredged channel can be seen in Figure 15 in the process of being dredged. Several spillover lobes can be seen trying to cut through the ebb shield to naturally re-establish a channel northward into Pleasant Bay.

By 27 March 1996, the second northern ebb channel had established in a east-west orientation some 1,400 ft (427 m) north of the original breach (Figure 16). The South Beach continued to migrate to the north as the Nauset Spit continued to migrate back toward the south. The ebb shoal continued to migrate into Chatham Harbor and expanded its asymmetrical shape to the south, attaching to South Beach some 5,000 ft (1,524 m) south of the northern tip. With the funneling of flood flow between the swash platform and mainland point, the flood shoal expanded in area and its shape was elongated to the north. The west channel was the access directly to Fish Pier, but shoaling in the channel adjacent to the distal end of the western ebb spit hampered navigation. With the expansion of the flood shoal, the east channel was shifted well to east, next to Nauset Spit. The flood ramp had widened and deepened and was directly adjacent to the main channel leading to the two ebb channels.

Ten years after the initial opening, the South Beach continued to migrate westward by overwash processes as the southern main ebb channel remained fixed against the attached mainland-South Beach shoreline. The 27 June 1997 photographs showed the increased deposition on the ebb shoal with exposed linear sand shoals on the central and southern portions during low tide (Figure 17). This deposition along the ebb shoal made navigation across the southern ebb channel difficult. The northern ebb channel was becoming more well defined, oriented almost due east-west, through the ebb shoal and pushing the northern terminal lobe further seaward. The northern swash platform gained sand, while a new spit feature formed at the end of Nauset Spit. The flood shoal was becoming more asymmetric as the flood flow moved the feature northward past Tern Island. A narrowing west channel separated the island from the flood shoal. Tern Island was also migrating up the estuary, with erosion on the south end and deposition of sand flats on the north end. Significant sand flats had also formed in the area to the north of Tern Island. The south Tern Island shoal, that had defined the southern side of the Tern Island channel, had completely eroded away by this time. Navigation into the Fish Pier was direct from the west channel, but shoaling was still a problem at the southern end of the western ebb spit of the flood shoal. The main flood flow was over the flood ramp, with extensive shoaling occurring in the east channel also.

The southward movement of the ebb shoal continued, with extensive overwash of the northern end of South Beach. Navigation was difficult at the distal end of the southern main ebb channel, as of 2 July 1998 (Figure 18). The location of this channel had become fixed against the shoreline of the attached South Beach, which hampered further southern migration of the channel. The northern channel was attempting to establish itself as the main channel, but formation of a channel margin linear shoal bisected the channel into two channel orientations. The ebb shoal in general continued to grow into the bay, along with a large growth in Nauset Spit. The confluence of the landward migrating northern channel/swash platform/Nauset Spit complex, mainland point and southern terminus of the flood shoal restricted the tidal flow to create the deep scour hole detected on the SHOALS bathymetric survey, in the navigation channel. The large expanse of the flood shoal filled almost the entire bay area. The westward movement of the shoal caused the western ebb shield to again close off access to the Fish Pier. A channel was dredged by the Town of Chatham through this spit to

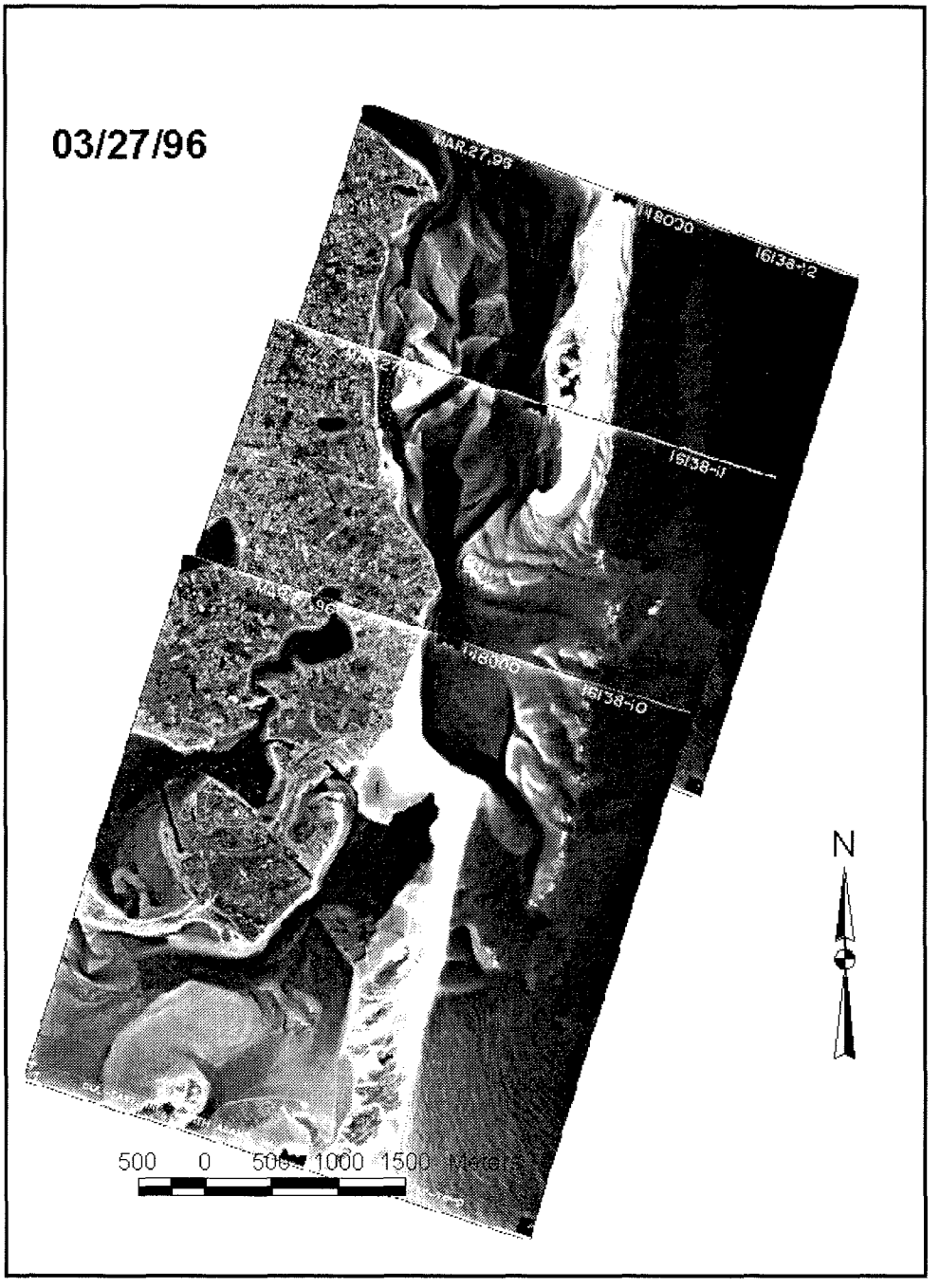


Figure 16. Morphology of Chatham Harbor, 27 March 1996

provide access from Aunt Lydia's Cove to the southern end of the flood ramp. The eastern channel had naturally re-established a navigable passage along the eastern side of Chatham Harbor to Pleasant Bay. The large ebb shield at the northern end of the flood shoal was restricting the flow up the estuary, and a large ebb-orientated spillover lobe formed at about the same location as the former west channel prior to the breach.

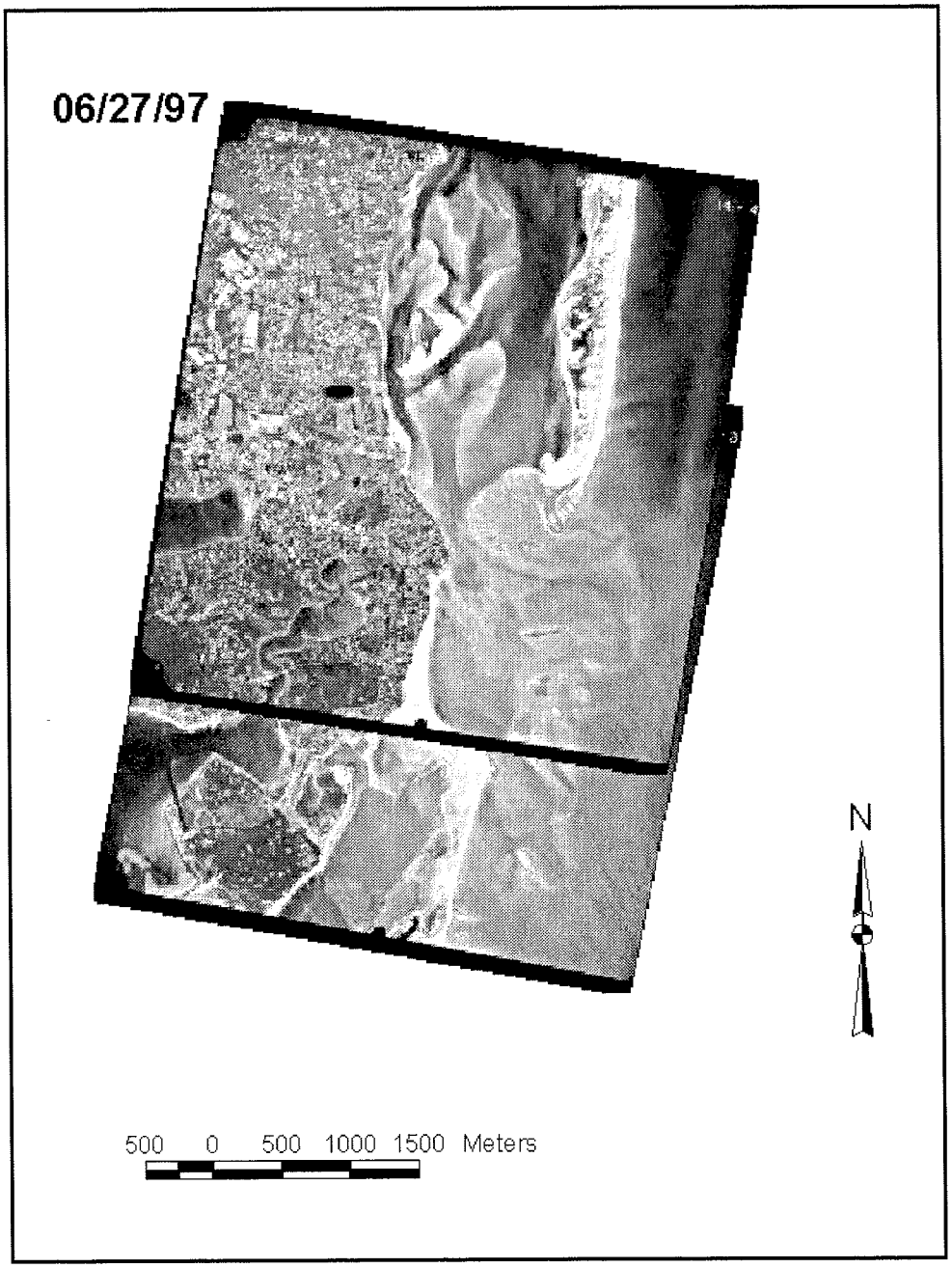


Figure 17. Morphology of Chatham Harbor, 27 June 1997

Twelve years after the initial breach, Chatham Inlet has still retained a highly dynamic morphology. Figure 19 shows the inlet as of 15 July 1999. The linear shoals continue to gain sand on the expanding ebb shoal. With the increasing dominance of the meandering northern ebb channel, the ebb shoal is expanding seaward on the north end. At the same time it is migrating further to the south, creating substantial shoals and making navigation through the southern ebb channel a challenge. A new ebb-orientated spit has formed at the tip of South Beach. The south channel has been pushed against the mainland shore as the ebb

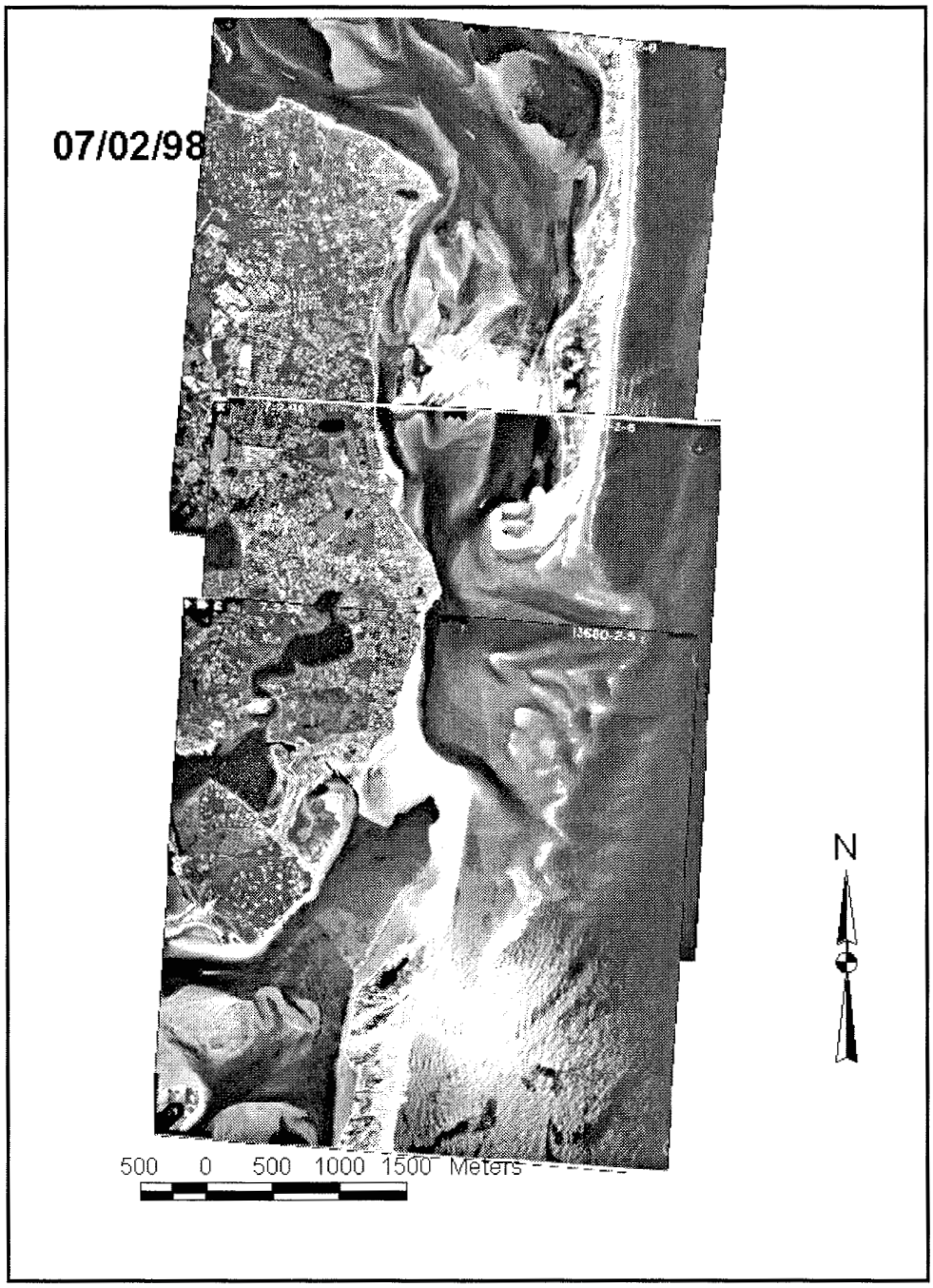


Figure 18. Morphology of Chatham Harbor, 2 July 1998

shoal continues to migrate landward into the bay. Beginning in 1976, Nauset Spit gained sand and migrated more to the south, narrowing the inlet throat. The spit has formed a series of three recurves since 1998. The flood shoal continues to expand northward and westward, causing Tern Island to migrate to the north also. The west channel between the island and flood shoal has closed as the spillover lobe has become the dominate feature. This ebb-orientated feature is trying to break through the flood shoal and re-establish the former west channel.

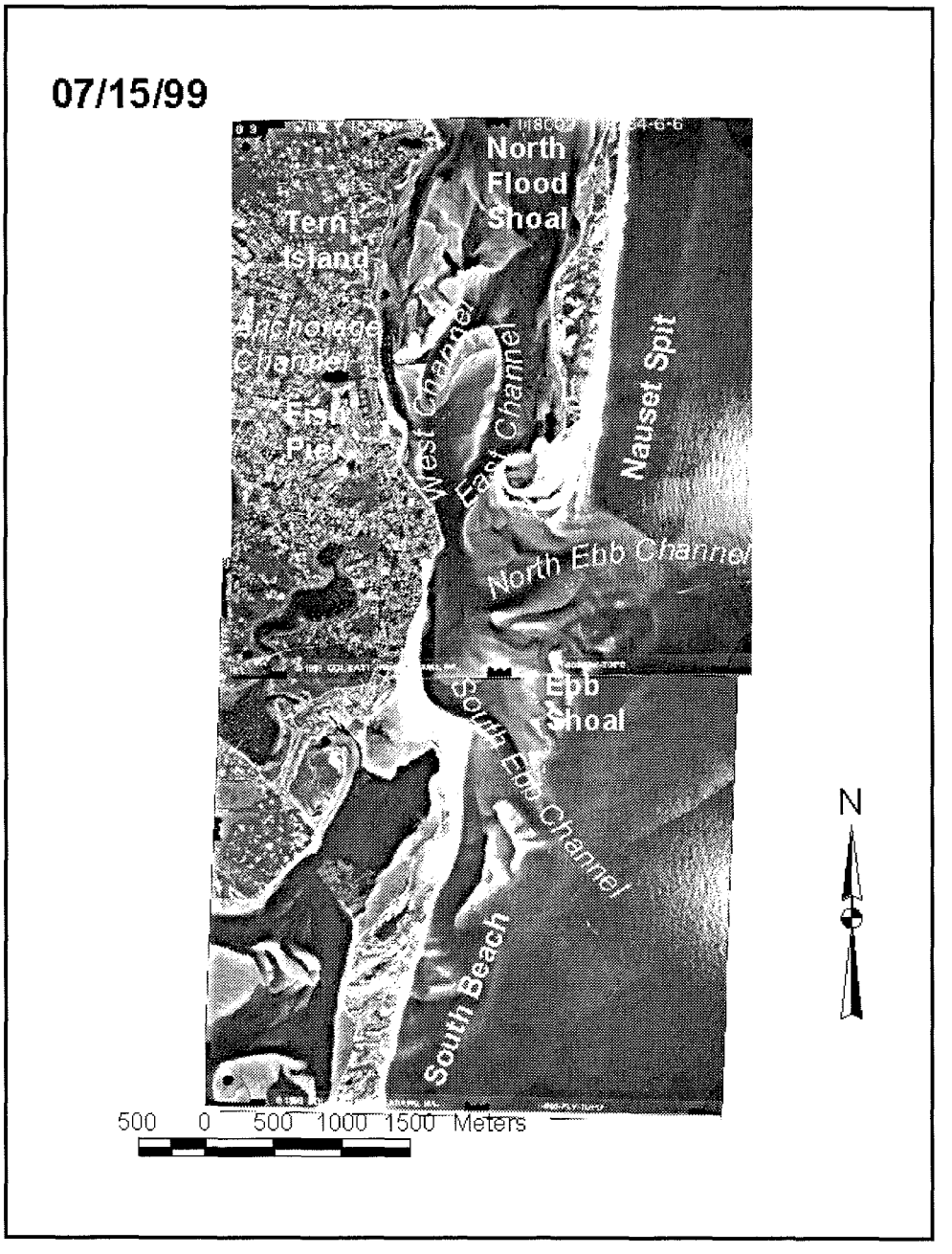


Figure 19. Morphology of Chatham Harbor, 15 July 1999

Navigation into the Fish Pier is still difficult as the western ebb spit of the flood shoal continues to clog off the navigation channel. Frequent dredging is required to maintain the opening from Aunt Lydia's Cove to the deepening flood shoal's flood ramp.

The two main issues with the evolution of Chatham Inlet have been maintaining a viable navigation channel for boating interests and protecting upland structures from erosion. The dynamic nature of natural inlet evolution has been well demonstrated with this inlet. The key events in the dynamic evolution of

Chatham Inlet and Harbor are listed in Table 2. While the inlet quickly formed a symmetrical ebb shoal with a central east/west oriented ebb channel, the flood shoal was split into a separate north and south flood shoal, expanding around two remnant Chatham Harbor shoals. The main ebb channel migrated to the south, with the ebb shoal forming an asymmetric form to the south as the ebb shoal expanded. The north swash platform also expanded to the south. The Nauset Spit end recurved north and west into Chatham Harbor until 1994, when it reversed direction and moved more to the south and west and enlarged. The South Beach spit recurved south and west into Chatham Harbor until the south flood shoal and south remnant sand flat combined with the spit to close off navigational access to southern Chatham Harbor. The welding of the south spit to the mainland beach in 1992 changed the circulation into north Chatham Harbor and Pleasant Bay. The remaining north flood shoal migrated and expanded northward. Tern Island and its associated south shoal evolved as the east and west channels changed course around the expanding north flood shoal. This expanding flood shoal restricted navigation into Aunt Lydia's Cove with shoaling of the west channel, requiring dredging to maintain access to the pier.

Table 2
Key Events in Morphology Evolution

Date	Event
01/02/87	Breach forms during northeaster.
05/87	North and south flood shoals incorporate existing remnant shoals in Chatham Harbor. Symmetric ebb shoal forms with single ebb channel and north swash platform.
05/89	South flood shoal overtakes south remnant sand flat.
08/90	Construction completed on mainland shoreline rock revetment.
05/92	South Beach spit attached to mainland beach.
03/94	Nauset Spit ends recurved migration to north, but continues to expand westward into Chatham Harbor in a series of recurved spits.
05/95	North ebb channel forms through ebb shoal creating a two-ebb channel system.
06/97	South Tern Island shoal removed as navigation channel reorients to a north-south direction adjacent to mainland shore.

Channel and Inlet Throat Changes

Changes to the throat section between the adjacent beaches and the position of the ebb channels was quantified by measuring the distance along a common line drawn along the axis of Nauset Spit between the edge of the north and south spits off of each yearly photo set. The width of the ebb channels was also measured where each side of the channel crosses this reference line. A zero point was taken at the site of the original breach. Figure 20 plots the inlet-throat width and channel positions, which were updated from Liu et al. (1993). The distance between the

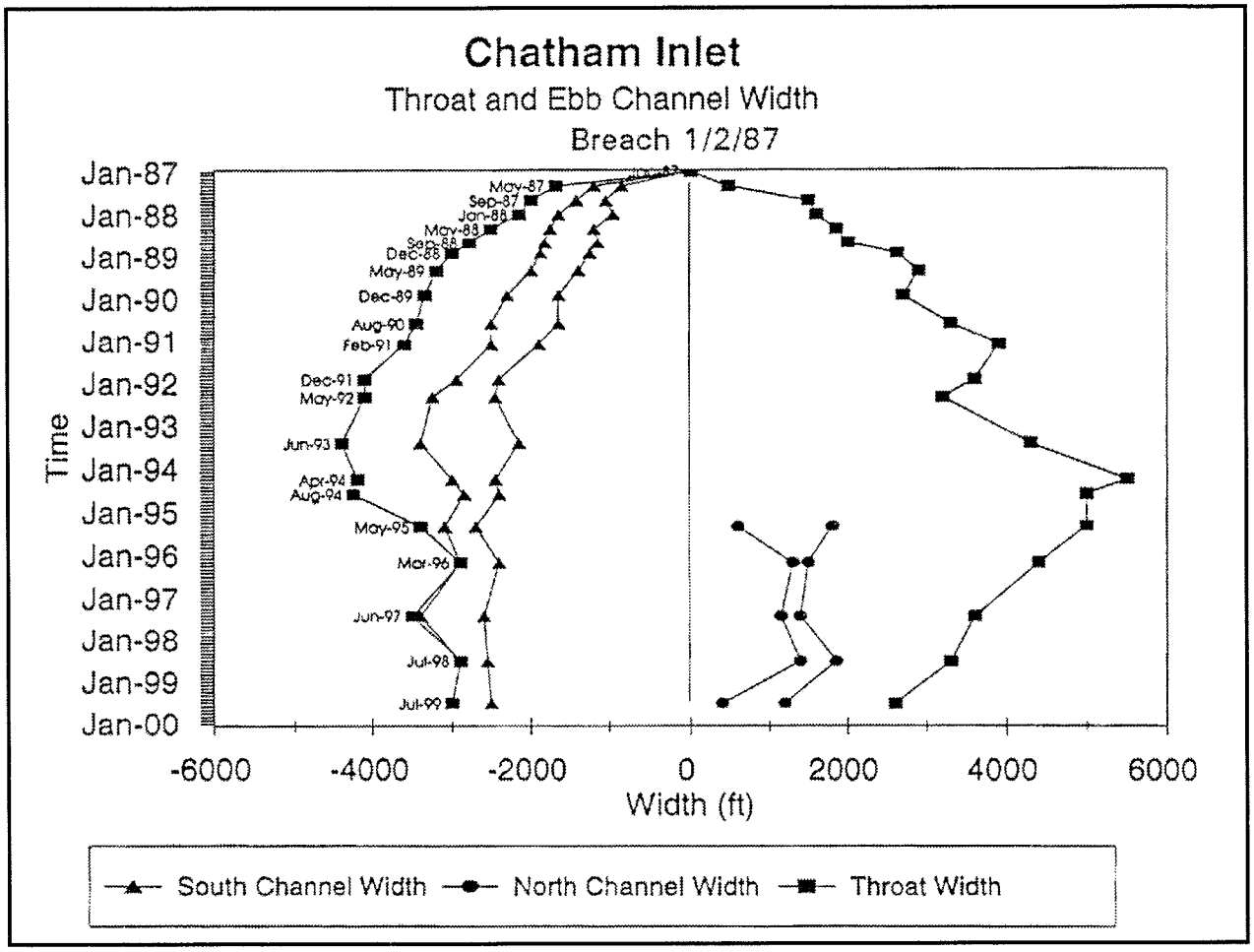


Figure 20. Temporal change in inlet throat width and position of ebb channels with repsect to original beach location

adjacent barriers rapidly expanded in the first five months to a width of 2,200 ft (670 m), with a single ebb channel of 350 ft (107 m) that had migrated 850 ft (259 m) south of the original breach. The inlet steadily widened as both the north and south spits recurved back and away from the inlet into Chatham Harbor. The throat reached its widest point in April 1994, measuring approximately 9,700 ft (2,957 m).

The southern ebb channel which was the only ebb channel at the time, migrated southward to a maximum of 3,400 ft (1,036 m) south of the original breach in June 1993. The channel was also at one of its widest points at that time at 1,250 ft (381 m). This averages out to a southerly migration rate of 567 ft/year (173 m/year) over the six-year period. The South Beach spit welded to the mainland beach one year earlier in 1992. The attachment and growth of the sand bridge restricted further southerly migration of the south channel after June 1993. After that time, the South Beach grew back to the north, maintaining a position around 3,000 ft (914 m) south of the original breach from March 1996 through 1999. The Nauset Beach spit also reversed direction growing back to the south after June

1993 as the spit straightened and gained sand. As of 1999, the width of the inlet was 5,600 ft (1,707 m).

A northern ebb channel formed in early 1995 some 1,000 ft (305 m) north of the original breach. That northern channel meandered to the north and as of 1999 was 800 ft (244 m) wide. With two ebb channels, and a complex system of shoals at the mouth of the south ebb channel, the south ebb channel narrowed to approximately 500 ft (152 m) in July 1999. It is now positioned against the South Beach shore and presumably will lose its dominance to the north channel. As a single south ebb channel, it was approximately 600 ft (183 m) wide.

A plot of the channel center lines through time shows the southern migration of the south ebb channel, with the position becoming fixed in 1994 after the South Beach became permanently attached to the mainland (Figure 21). The north channel meandered around after its formation in 1995, but has remained north of the original breach. Chatham Inlet has evolved into a two-ebb channel system and the channels have continued to change position within the inlet throat, with the north channel now taking a more dominant role as the preferred channel.

Mainland Shoreline Segments

With the opening of the inlet, the mainland shoreline went from a low energy, tidally dominated estuarine condition to an open ocean wave and tide dominated system. These processes had a profound influence on the morphologic evolution of the mainland shore, with the beach responding to both cross-shore and longshore currents. To describe the highly variable change in the mainland shoreline, it has been divided into four segments, based on morphology and position relative to the inlet throat.

Aunt Lydia's Cove

Part of segment 1, north of the Fish Pier extending from Cow Yard Landing to the Fish Pier has been protected from waves and tidal currents by Tern Island and the extensive shoals on the north end of Tern Island. This mainland shoreline in Aunt Lydia's Cove, behind Tern Island has changed little throughout the study period (Figure 22). The shore is composed of a narrow width of sand and some marsh. In contrast, south of the Fish Pier the shoreline reach extending to Claflin Landing has undergone extensive change. This area of the Cove's shoreline has been influenced by the changes in the south Tern Island shoal and later by changes in the navigation channel and western ebb spit of the north flood shoal. South of Claflin Landing, the shoreline experienced erosion and flood tidal currents have transported some of that sand northward. A spit formed at the southern point of Aunt Lydia's Cove in 1990 as the sand deposit started to grow north. This spit progressed to the north in yearly increments until 1996 when the accretion formed a wide beach in that area. Since 1996 the shoreline has remained in that position as the Tern Island shoal eroded and the main channel has occupied the area just off the beach. The town has nourished the beach at Claflin Landing with an approximate total of 8,000 cu yd (6,117 m^3) in May 1998 and May 2000.

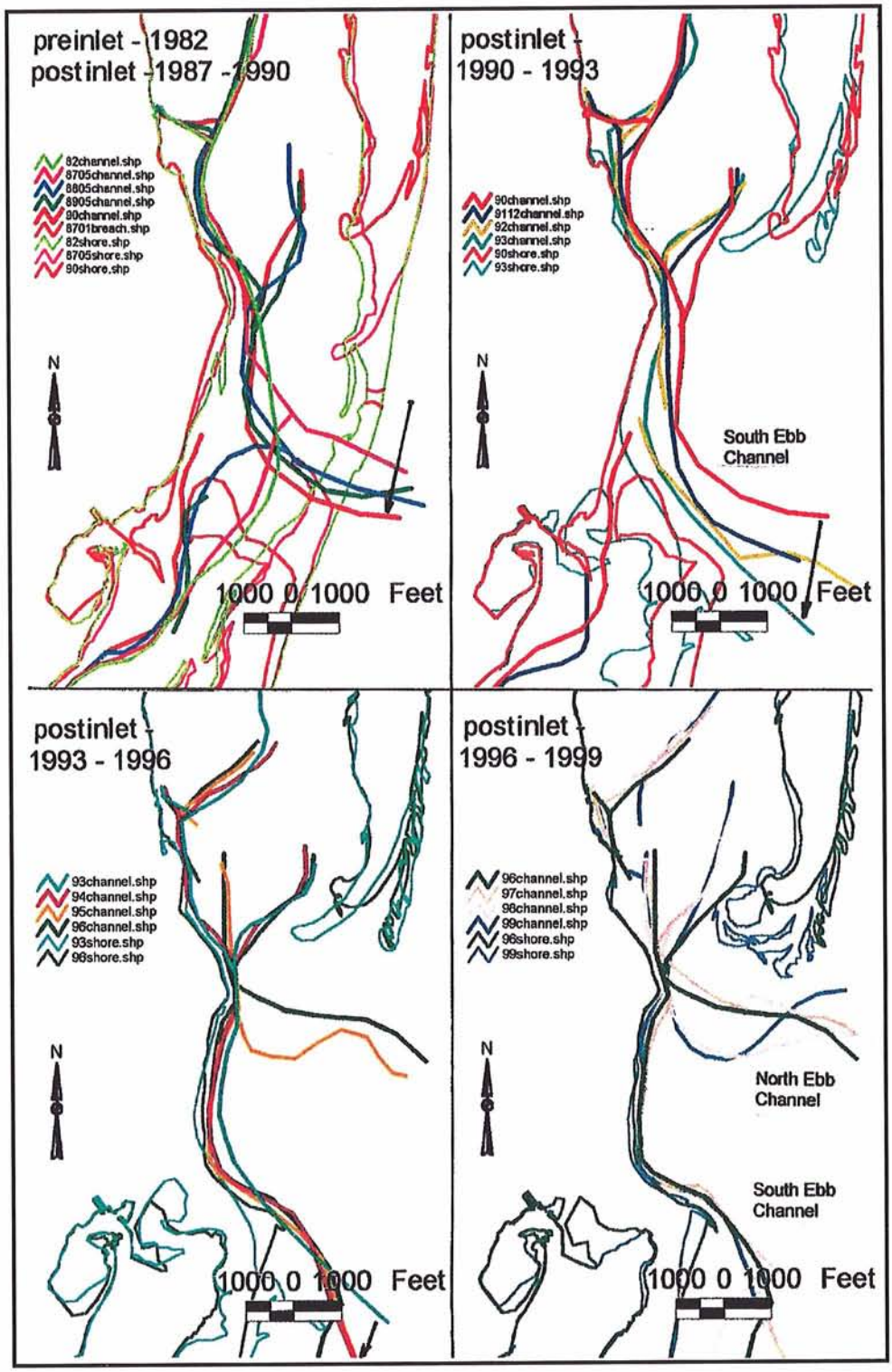


Figure 21. Change map of ebb channel center lines

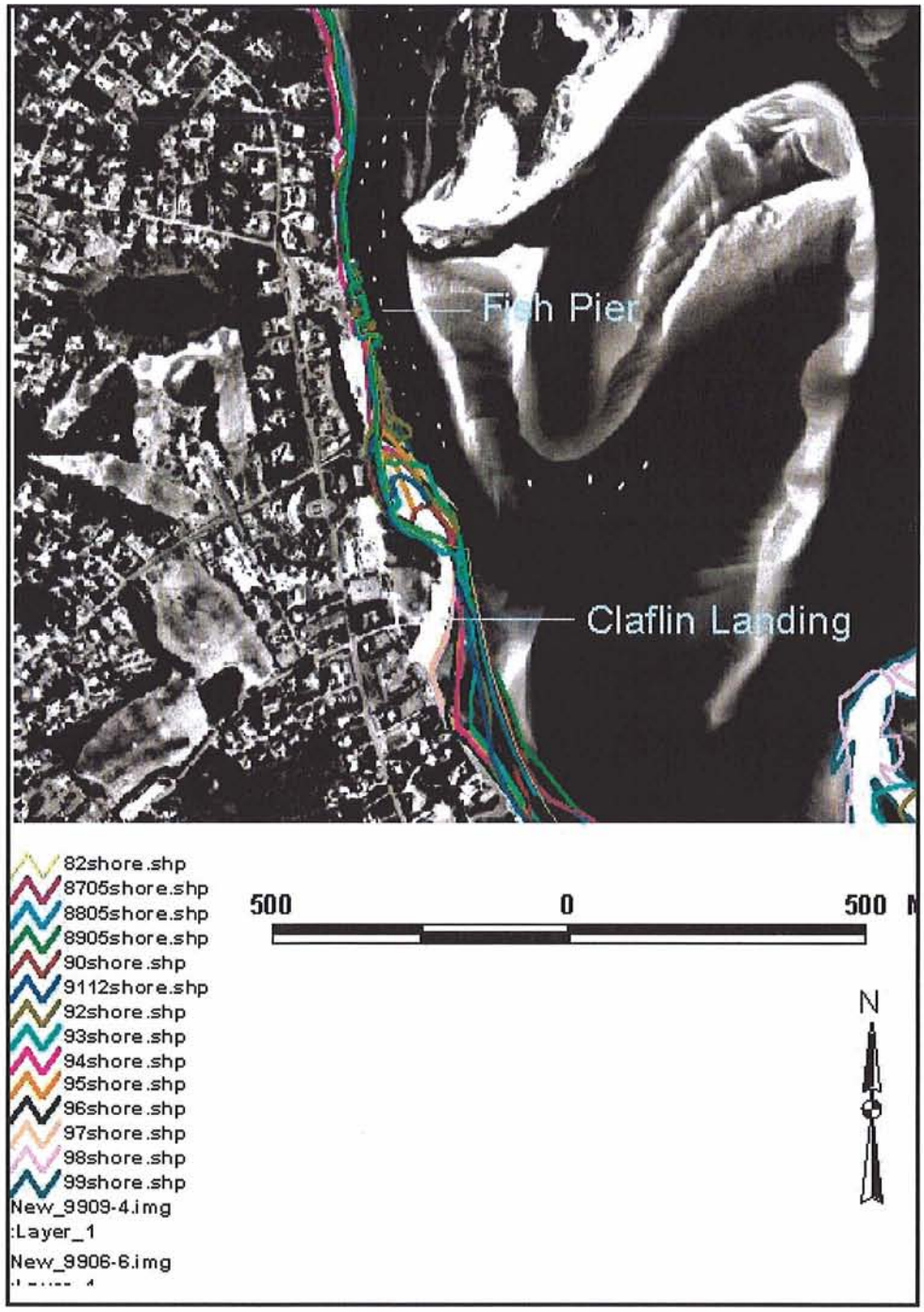


Figure 22. Mainland shoreline change in Aunt Lydia's Cove (Cow Yard Landing to Claflin Landing)

Seawall

Segment 2 extends from Claflin Landing to Holway Street and includes the area that has experienced the most erosion and damage to upland structures. Figure 23 shows the mainland shoreline change from preinlet 1982, where the shoreline was from 100 to 300 ft (30.5 to 91.4 m) further seaward. As the inlet

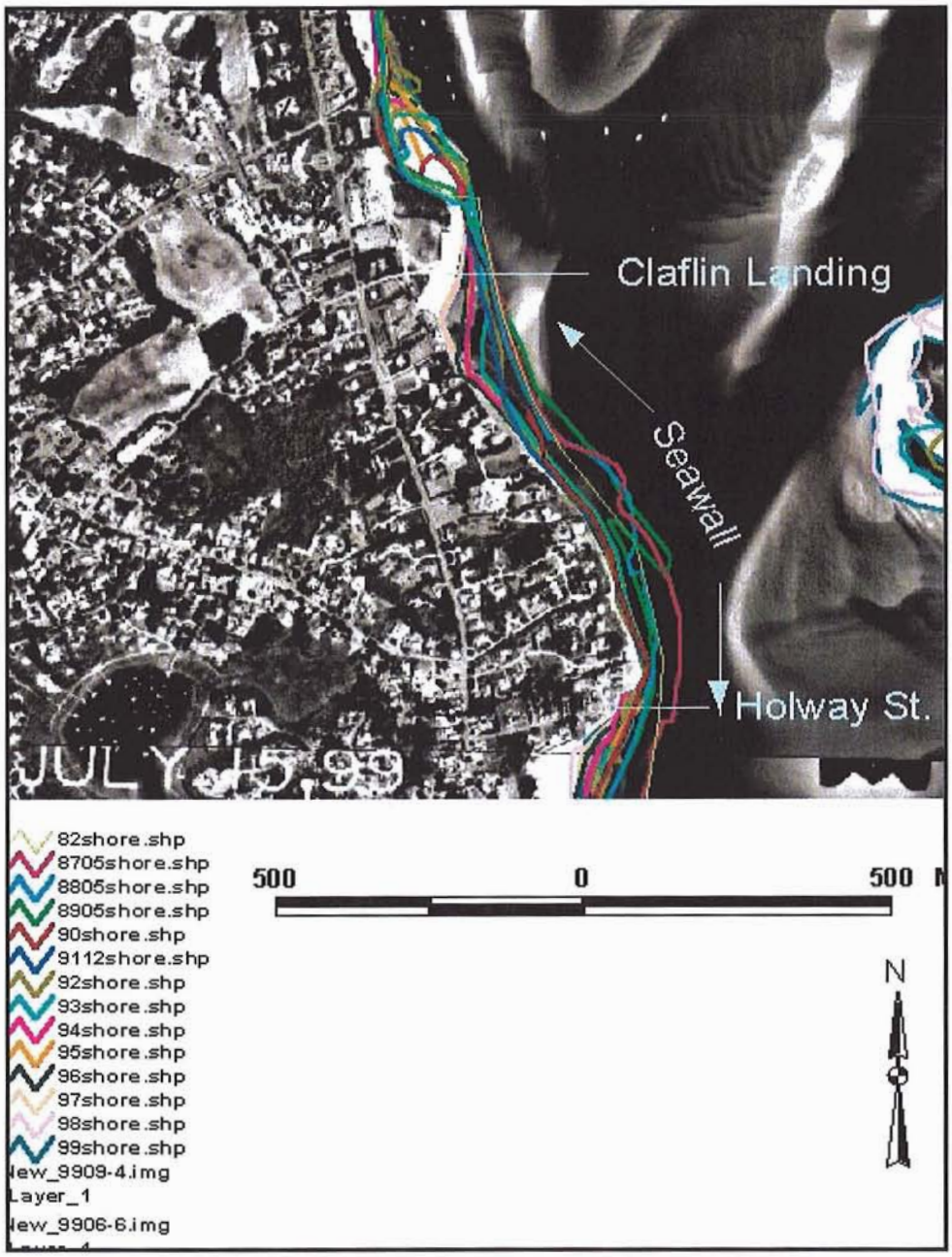


Figure 23. Mainland shoreline change in seawall area (Claflin Landing to Holway Street)

was opening, after 1987, the shoreline maintained a wide low tide beach along this stretch of shore that formed a point into Chatham Harbor through 1989. As Nauset Spit moved north and west the inlet throat expanded and allowed waves and stronger tidal currents to directly encroach upon this shoreline. A stone revetment was constructed during the winter of 1987-1988 to protect the upland property as the shoreline began to erode almost immediately after the inlet opened and some houses were damaged or completely destroyed. Erosion in front of the structure continued through 1989, and the revetment was enlarged and strengthened between 1989 to 1990 after being overtopped by storm waves. By 1990 the beach

had eroded back to the seawall and the toe of the revetment became the fixed shoreline position. The beach immediately north of seawall construction exhibited up to a 300-ft (92-m) retreat from 1989 to 1997. A tennis court adjacent to Claflin Landing had been undermined by erosion and its former location is now the present beach.

Chatham Lighthouse

Preinlet conditions along the beach in front of Chatham Lighthouse from Holway Street to past the lighthouse included a 200-ft (61-m) wide beach with an ebb-orientated ebb spit. This segment 3 shoreline also began to erode immediately after the inlet opened, with the loss of some homes at the foot of Andrew Hardings Lane. A rock revetment was constructed at the foot of Water Street in the winter of 1987/1988. As the inlet opened, this beach segment continued to erode moving the shoreline landward to the base of the cliff until 1992, when the South Beach spit attached to the mainland (Figure 24). Then the shoreline on the southern end of the segment began to grow seaward again as sand was deposited on the beach as the South Beach attachment became larger. As of 1999 the shoreline had moved seaward some 300 ft (92 m) relative to the 1992 maximum retreat position. The north end of the segment from the south end of the large seawall at Holway Street to the smaller rock revetment has experienced a landward retreat to a maximum landward position in 1998. Around 25,000 cu yd (19,115 m^3) of sand was placed on this beach from the navigation channel dredging into Aunt Lydia's Cove by the Town of Chatham in October 1998, May 1999 and October 1999. This nourishment has moved the shoreline seaward again around 50 ft (15 m). A rotational nodal point has developed in this segment around the small seawall at the foot of Water Street, with the north end moving landward and the south end moving seaward.

South Beach

The most significant change in shoreline position has occurred in the fourth segment between Windmill Terrace and the dike to Morris Island. Preinlet conditions had a narrow shoreline curving back to a small marina (Figure 25). As the inlet opened up, some sand eroded from the mainland beach to the north was transported to this area and the shoreline moved seaward. As the spit recurved back from South Beach, sand detached from the spit and was added to the south flood shoal, with some sand making it to the mainland shore in this area. As the south flood shoal expanded in area and the South Beach spit grew, the tidal flow into south Chatham Harbor became restricted to two channels and finally one channel adjacent to the mainland. The south remnant shoal became attached to the south flood shoal and the mainland shore as a spit in 1989. As a result the shoreline moved seaward. The biggest change occurred when the South Beach spit attached to the mainland in early 1992, effectively cutting off tidal flow to south Chatham Harbor. The resulting land bridge joined the mainland shoreline to the South Beach ocean shore. Overwash of this area resulted in expansion of this land bridge, infilling the former south flood shoal with sediment. The South Beach attachment to the mainland still has limited elevation, with some well established

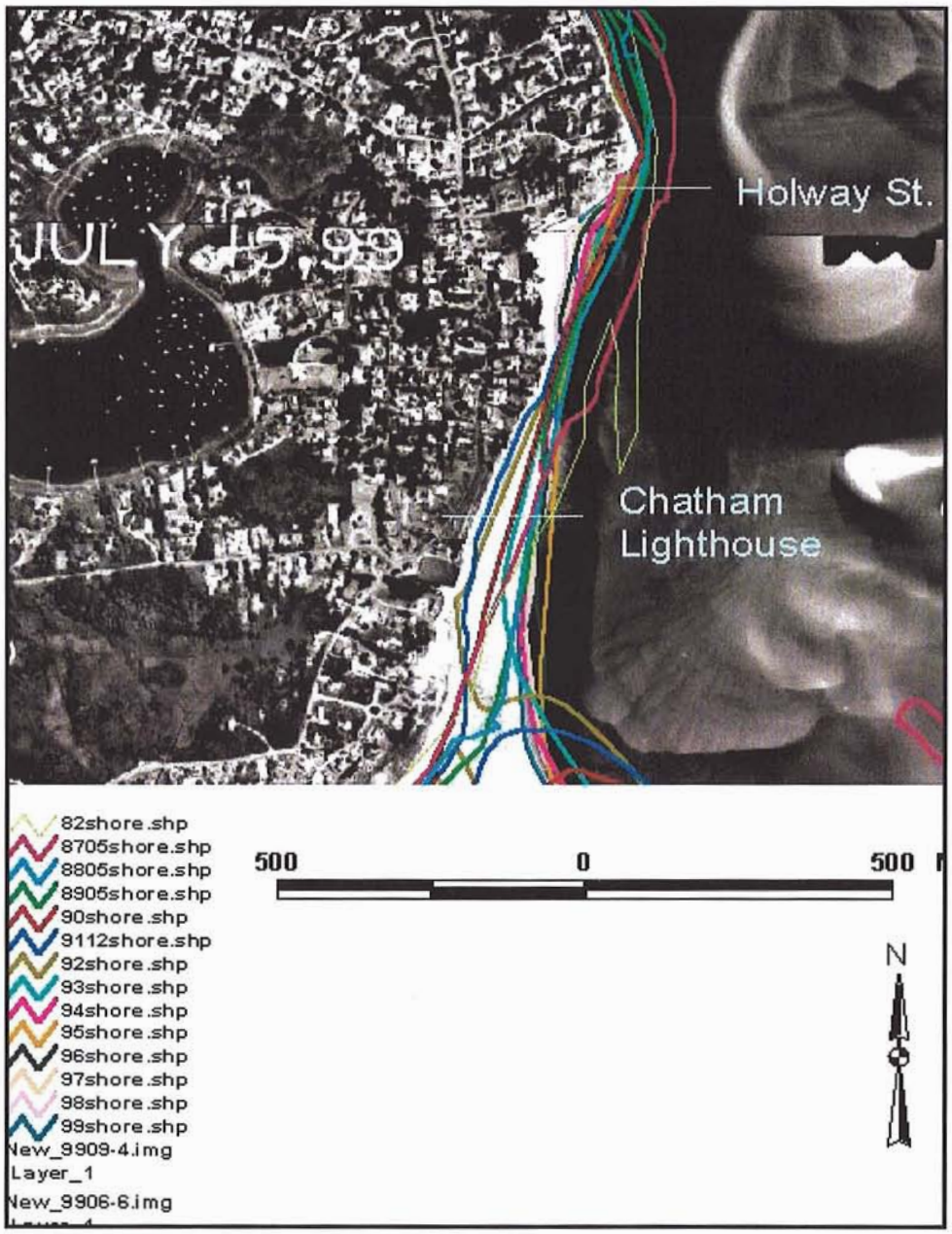


Figure 24. Mainland/South Beach shoreline change along the Chatham Lighthouse area (Holway Street to Chatham Lighthouse)

dunes and large areas of tidal flats on the inside. The area has expanded over the 1992-1999 time period and now is dry except for overwash at the elbow of South Beach during the highest storm tide levels. The outer shoreline of the north end of South Beach has moved landward some 1,300 ft (396 m) as the island, turned spit, migrates toward the mainland.

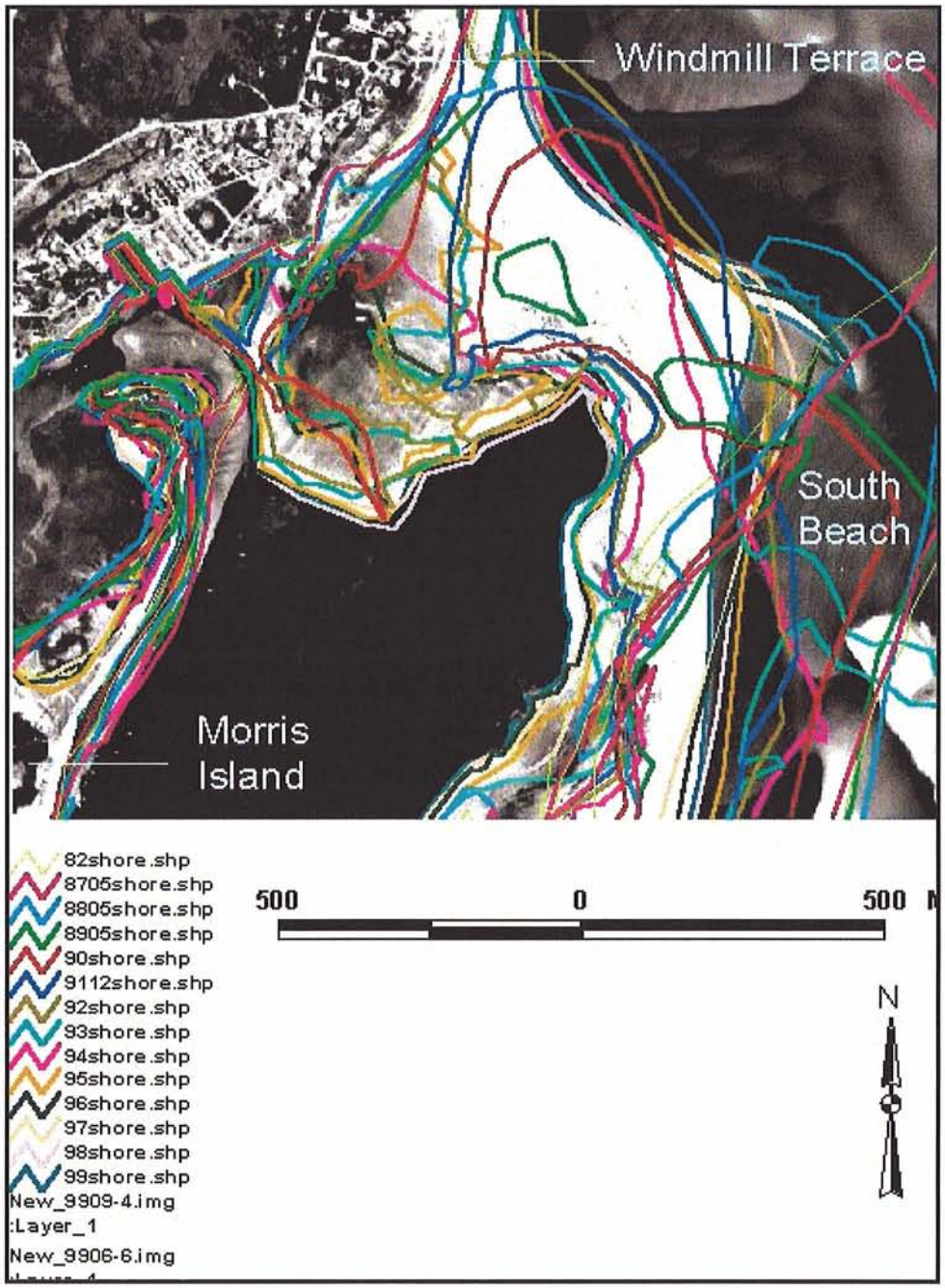


Figure 25. Mainland/South Beach shoreline change along Toms Neck (Chatham Lighthouse to Morris Island)

4 Ebb and Flood Shoal Evolution

A second task was to categorize ebb and flood shoal development and evolution patterns. Identification of change in area and an estimate of volume in the six identified shoals/adjacent shores from the previous study (Weishar, Stauble, and Gingerich 1989) has been updated to the new configurations of today. Six areas of inter- and subtidal shoals and the two spits were identified based on typical inlet morphology (Hayes 1980; Boothroyd 1985). As the new inlet developed, the basic inlet shoal morphologies formed. The eight shoals and adjacent spits of the inlet in 1989 were as follows:

a. Oceanside.

(1) Ebb tidal delta - was the most prominent feature on the ocean side of the inlet. It formed as a symmetrical feature with one main ebb channel and progressively became more asymmetric in shape as the prevailing coastal processes caused the shoal and main ebb channel to migrate southward.

(2) Swash platform - was a large sand body that developed on the north side of the southward migrating main ebb channel and expanded with multiple swash bars.

(3) North spit - the spit at the distal end of Nauset Beach began to migrate north and west into Chatham Harbor as the inlet throat expanded.

(4) South spit - the spit at the northern end of the South Beach barrier island migrated landward and south into Chatham Harbor as the inlet throat expanded.

b. Bayside.

(1) South remnant shoal/flood tidal delta - this preinlet sand shoal was incorporated into the southern part of the flood shoal as the inlet opened.

(2) North remnant shoal/flood tidal delta - a preinlet sand shoal that evolved into the north flood shoal as the inlet established.

(3) North remnant linear shoal - was present before the inlet formed just behind Nauset Spit that became part of the north spit as it migrated into the harbor.

(4) South remnant sand flat - present before the inlet opened and is now incorporated into the land bridge to South Beach.

As the inlet has evolved over the past 13 years, the eight inlet sand features have undergone an extensive modification. Area change has been updated from the first study, based on a analysis of this continuing morphologic evolution since the inlet breach formed. The eight shoal and adjacent spit areas of the original study have been modified to reflect the evolutionary processes that have occurred to the sand features. The present major morphologic features and channel orientations are different from the initial inlet and are identified as follows:

a. Oceanside.

(1) Ebb tidal shoal/swash platform complex - now evolved into a southward asymmetric multiple sand body separated by two ebb channels. A smaller north swash platform is reforming north of the new north ebb channel. A central swash platform is located between the two channels and contains multiple swash bars. The southern part of the ebb shoal now extends south of South Beach and contains a complex pattern of swash bars.

(2) North spit on Nauset Spit - has now migrated westward into Chatham Harbor and recently moved back to the south after initial northward movement. The spit has grown in area and has several recurved parts extending into Chatham Harbor.

(3) South spit/South Beach land bridge - spit has now welded to the mainland beach, closing off southern Chatham Harbor and presenting a low, overwash dominated land bridge to the north tip of the South Beach barrier island.

b. Bayside.

(1) South flood shoal - the south flood shoal evolved as the south spit recurved back into southern Chatham Harbor. As the spit grew, it gradually overtook the south flood shoal and is now incorporated in the South Beach land bridge.

(2) Remnant south sand flat - as the southern flood shoal progressed south into Chatham Harbor it overtook the remnant sand flat which is now incorporated into the South Beach land bridge.

(3) Tern Island - existed before the inlet and has eroded from the south and sand flats accreted on the north as the inlet has evolved. Other sand flats north of Tern Island have also expanded greatly as sand moves up from the south.

(4) Tern Island south shoal - originally an intertidal shoal on the south side of the entrance channel to the Fish Pier, has now been eroded away as the north flood shoal and west flood channel/new entrance channel have evolved.

(5) North flood shoal - has grown in area and migrated north expanding from a circular shoal into a more typical flood shoal shape, with a flood ramp, east and west flood channels, ebb shield, ebb spits, and spillover lobes.

Analysis Methods

All of these areas have undergone major morphologic change from the preinlet conditions to their present form. Table 3 gives the area of the shoals and adjacent spits measured from the areal photography. The visible edge of the shoal was digitized in ArcView from the rectified and georeferenced aerial photography. The shoal edge was identified by the change in gray tones from the light gray of the shoal to the dark gray of the deeper water. In most cases the annual aerial photography was quite clear and the shoal boundary was distinct. The digitized outline of the shoal for each year was entered onto a separate layer and the area was calculated by ArcView. From the one and only bathymetric survey of the inlet collected by the SHOALS lidar system in November 1998, the approximate depth range of the visible shoal edge on the July 1998 aerial photography was determined to be between 5 and 10 ft (1.5 and 3 m) mllw. The water clarity and tone quality appeared to be consistent on all yearly photo sets, so it is assumed that this depth range was digitized on each of the shoal edges. This depth range was assumed for the ebb shoal/swash platform, north and south flood shoal, south remnant shoal, Tern Island and south Tern Island shoal boundaries.

The shoreline position was determined from all of the aerial photography as a line digitized along the consistently visible gray tone line separating the wet/dry line or approximate water table line on the inlet adjacent spit beaches and the mainland shoreline. Based on a few photographic sets, where a high tide debris line was visible, this water table line is just below the high tide line.

The volume measurements were computed based on the area of each feature on a given data multiplied by a constant depth based on the 1987 bathymetry. The depths of the shoals were estimated to be conservatively 5 ft (1.5 m) thick. The seaward edge of the ebb shoal was measured at the end of the north and south ebb channel as around 54 ft (16.5 m) mllw and the deepest scour hole in Chatham Harbor was around 29 ft (8.8 m) adjacent to the rock revetment along the mainland shoreline. The actual thickness of the ebb shoal mass can be estimated at much more than 5 ft (1.5 m) but with only one bathymetry survey and the highly variable morphology over the study period, a conservative measure of 5-ft (1.5-m) thickness was used. The flood shoals (both north and south), Tern Island south shoal, and south remnant shoal were also estimated at a 5-ft (1.5-m) thickness given that the depth of the channels around the north flood shoal in 1998 were around 10 to 15 ft (3 to 4.5 m) mllw.

Again, lack of historic yearly bathymetry and high variability in harbor morphology over the study makes it difficult to be more accurate in shoal thickness.

Table 3
Change in Area of Inlet Shoals and Adjacent Spits

Date	Ebb Shoal/ Swash Platform	North Spit/Beach	South Spit/Beach	Tern Island	Tern Island South Shoal	North Flood Shoal	South Flood Shoal	South Remnant Shoal	Total
yr	sq ft	sq ft	sq ft	sq ft	sq ft	sq ft	sq ft	sq ft	sq ft
1982	0	6224684	5601611	3308848	450710	1664693	2090386	1625886	20966818
1983									
1984									
1985									
1986									
1987	8473313	4337110	3579652	3507770	487424	3596588	2387466	2440074	28809397
1988	14348273	4047831	3351176	3603971	656516	2534508	2097385	2315147	32954807
1989	24192647	3199360	2702626	3276882	720241	3427389	3461444	0	40980589
1990	23453238	2542673	3361460	3779306	559539	3454325	3702389	0	40852930
1991	29069362	1952920	3680238	3483419	358818	3484629	2331860	0	44361246
1992	28167007	2756824	5071030	3002239	271558	4111015	0	0	43379673
1993	27042967	2455487	5197459	3011699	224933	4122713	0	0	42055258
1994	34557692	1568692	4393436	2634461	210410	4092786	0	0	47457477
1995	27395115	1977288	5527297	2879412	99431	4190647	0	0	42069190
1996	37100720	2256268	5766248	2679286	200582	4332657	0	0	52335761
1997	31449904	2295702	6561062	3012764	0	4243118	0	0	47562550
1998	33117311	3721063	6547137	3399847	0	5350739	0	0	52136097
1999	33097490	4195798	6334234	3472525	0	5868891	0	0	52968938

The north and south spit areas and Tern Island itself were estimated at a 10-ft (3-m) thickness based on a topographic survey of Tern Island done by the New England District in 1994. Average elevation was 10 ft (3 m) above mlw or 8 ft (2.4 m) above mllw. From stereo pairs it was estimated that the average elevation on both the north and south spits were around 3 to 5 ft (1 to 1.5 m) above mllw relative to the elevation of 8 to10 ft (2.4 to 3 m) on Tern Island. Elevations were highly variable through time as the spits were subject to frequent overwash and dune erosion. Tern Island's area included the shoals adjacent to the north of the island. A thickness of 5 ft (1.5 m) above mllw and 5 ft (1.5 m) below mllw were estimated to cover the volume of these subaerial features. This accounted for the intertidal volumes adjacent to the shorelines of these features that were outside the measurements of the wet/dry line indicator of shoreline area on the spits and the highly variable shoals adjacent to the north end of Tern Island. Shoal and spit volume estimates are shown in Table 4.

Ebb Shoal/Swash Platform Complex

The largest area feature at Chatham Inlet was the ebb shoal and swash platform complex. This feature did not exist prior to the inlet formation, but quickly established itself within the first four months after the breach. The areal changes in the ebb shoal and swash platform complex indicate a persistent growth of the shoal into the ocean with a southward migration of the swash platform corresponding to the southward migration of the main ebb channel (Figure 26). When the new north ebb channel established itself in 1995, the ebb shoal again emerged into the ocean on the north end, as the southern end of the shoal complex continued to elongate to the south adjacent to South Beach.

Figure 27 shows the rapid growth in area of the swash platform/ebb shoal within the first 3 years. Figure 28 mirrors the area change with the estimate of volume change assuming a 5-ft (1.5-m) thickness in the shoal. Peaks in area and volume were measured in 1989, 1991, 1994 and reached a maximum in 1996. The area and volume have been constant from 1998 to 1999.

North Spit

The north spit rapidly moved to the north and west within the first 2 years as the inlet throat expanded. The spit continued to recurve to the north but at a slower rate and finally stabilized and is now moving to the west into Chatham Harbor. The area of the spit was measured to a constant point on North Beach shown by the line on Figure 29. The preinlet area (Figure 30) and volume (Figure 31) of the barrier island was measured from the 1982 aerials from the 1987 breach position to the northern area limit. This north spit has decreased in area and estimated volume from the initial breach to a minimum in 1994. Since 1994 the spit has moved south again and to the west and has gained back almost all of the area and volume it had after the initial breach as the spit has formed several complex recurves from sand being transported to the south along Nauset Spit.

Table 4
Estimated Volume Change of Inlet Shoals and Adjacent Spits

Date	Ebb Shoal/ Swash Platform	North Spit/Beach	South Spit/Beach	Tern Island	Tern Island South Shoal	North Flood Shoal	South Flood Shoal	South Remnant Shoal	Total
yr	cu yds	cu yds	cu yds	cu yds	cu yds	cu yds	cu yds	cu yds	cu yds
1982	0	2305623	2074837	1225597	83471	308301	387139	301114	6686083
1983									
1984									
1985									
1986									
1987	1569258	1606466	1325903	1299278	90271	666088	442159	451902	7451324
1988	2657300	1499317	1241276	1334911	121587	469391	388436	428765	8140982
1989	4480478	1185043	1001053	1213757	133389	634752	641059	0	9289531
1990	4343540	941806	1245085	1399855	103627	639741	685682	0	9359336
1991	5383646	723362	1363160	1290258	66453	645353	431860	0	9904093
1992	5216530	1021128	1878310	1112029	50293	761360	0	0	10039649
1993	5008357	909512	1925139	1115533	41658	763526	0	0	9763726
1994	6400085	581044	1627329	975804	38968	757984	0	0	10381213
1995	5073575	732387	2047311	1066534	18415	776108	0	0	9714330
1996	6871053	835722	2135818	992408	37148	802408	0	0	11674557
1997	5824522	850328	2430217	1115928	0	785825	0	0	11006821
1998	6133326	1378282	2425060	1259303	0	990957	0	0	12186927
1999	6129655	1554124	2346200	1286223	0	1086919	0	0	12403121

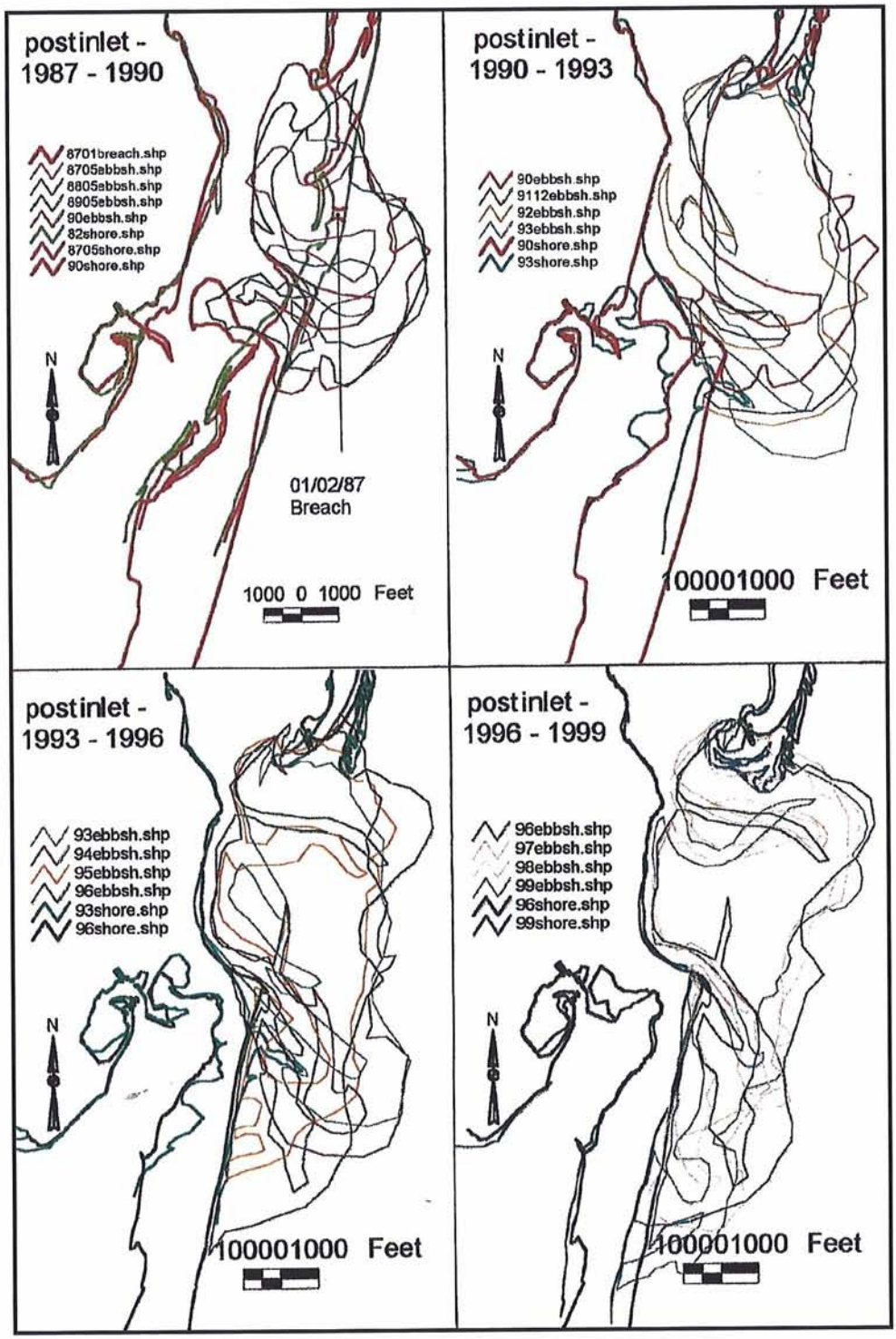


Figure 26. Map of growth in area of ebb shoal/swash platform

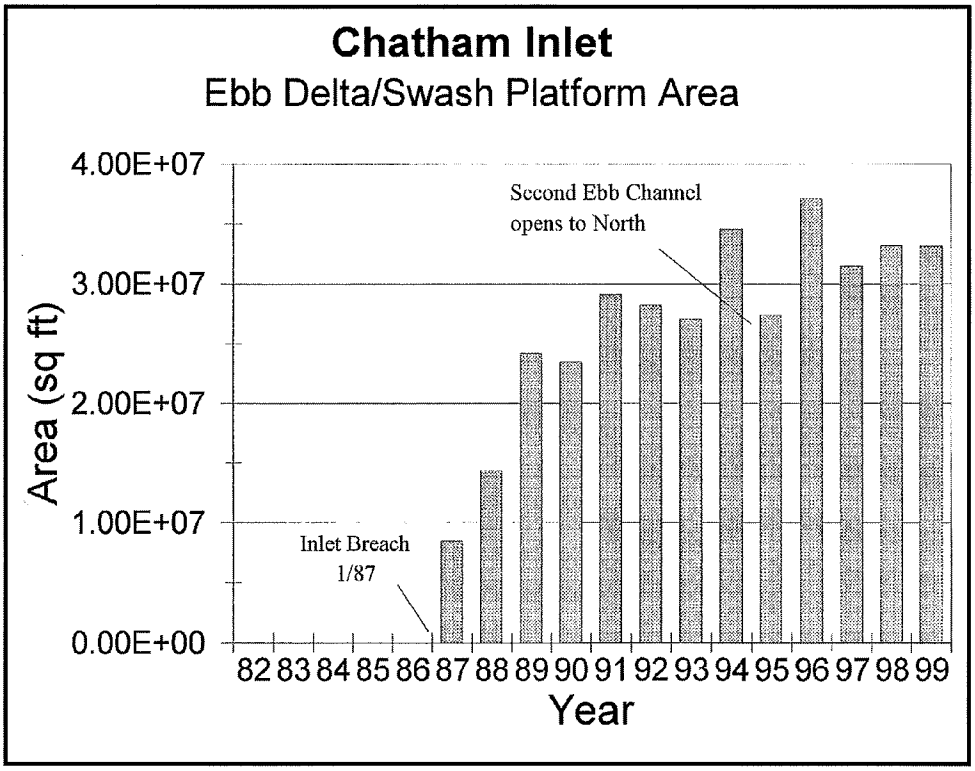


Figure 27. Postbreach area changes to ebb shoal/swash platform

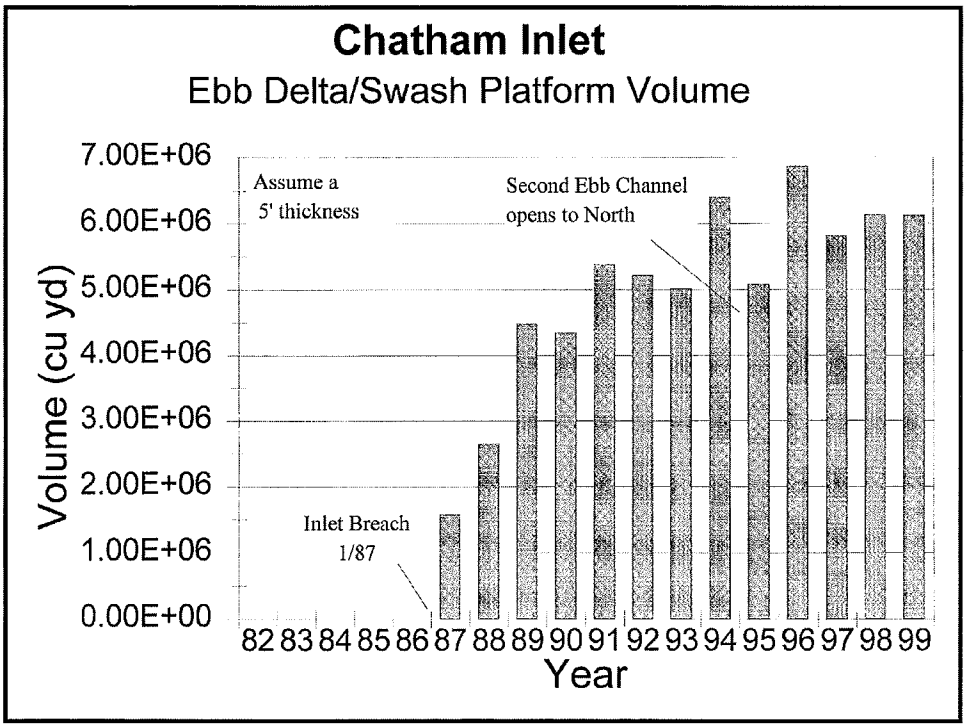


Figure 28. Estimate of volume change in ebb shoal/swash platform

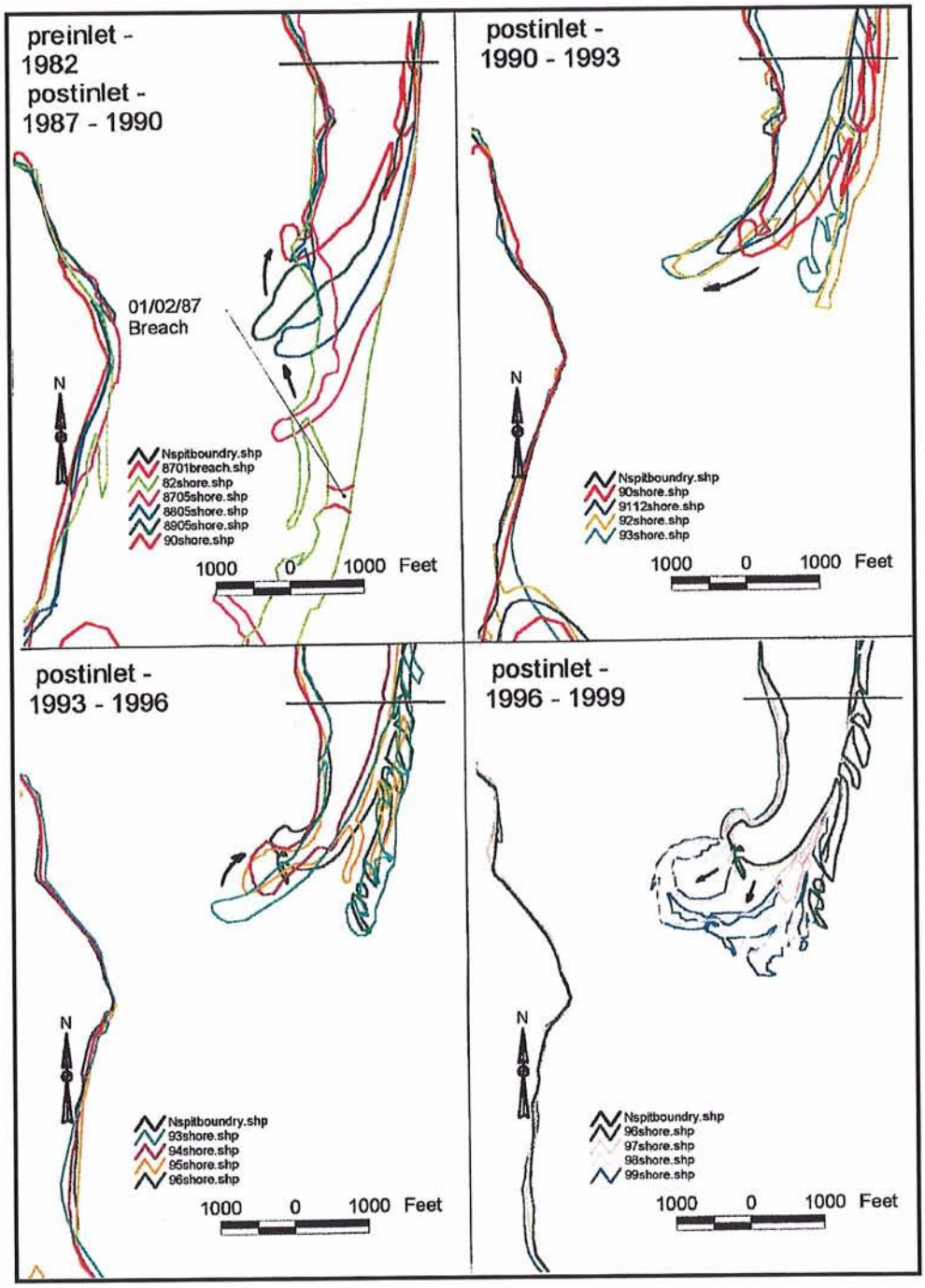


Figure 29. Map of area change to north spit. Line identifies common northern limit of area measurement

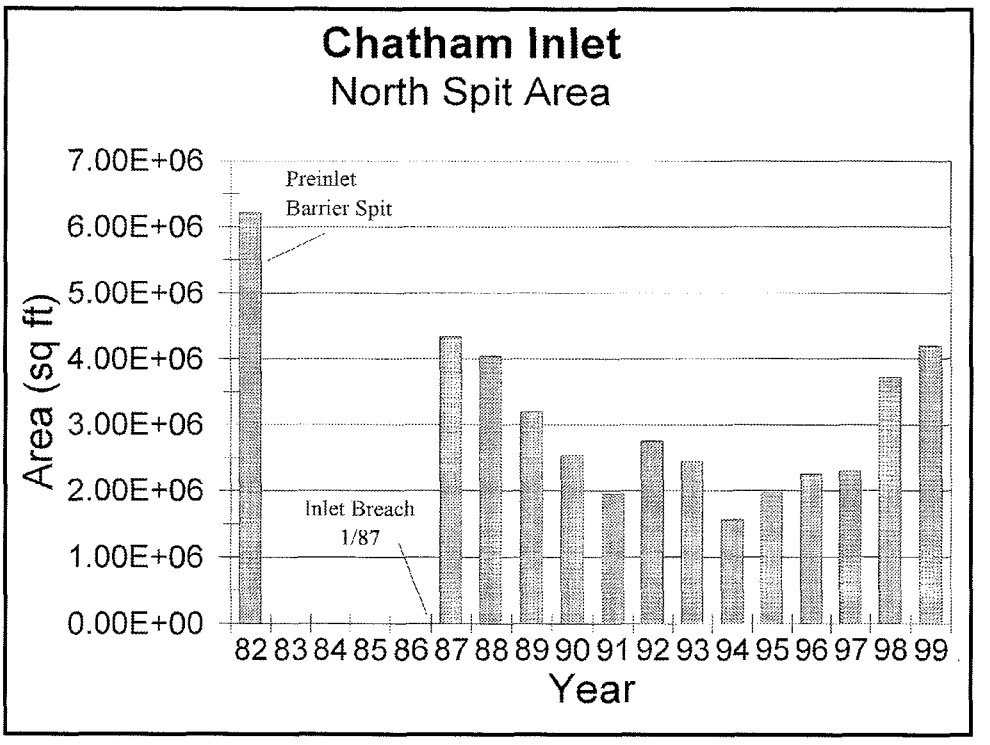


Figure 30. Area change from prebreach to 1999 of north spit

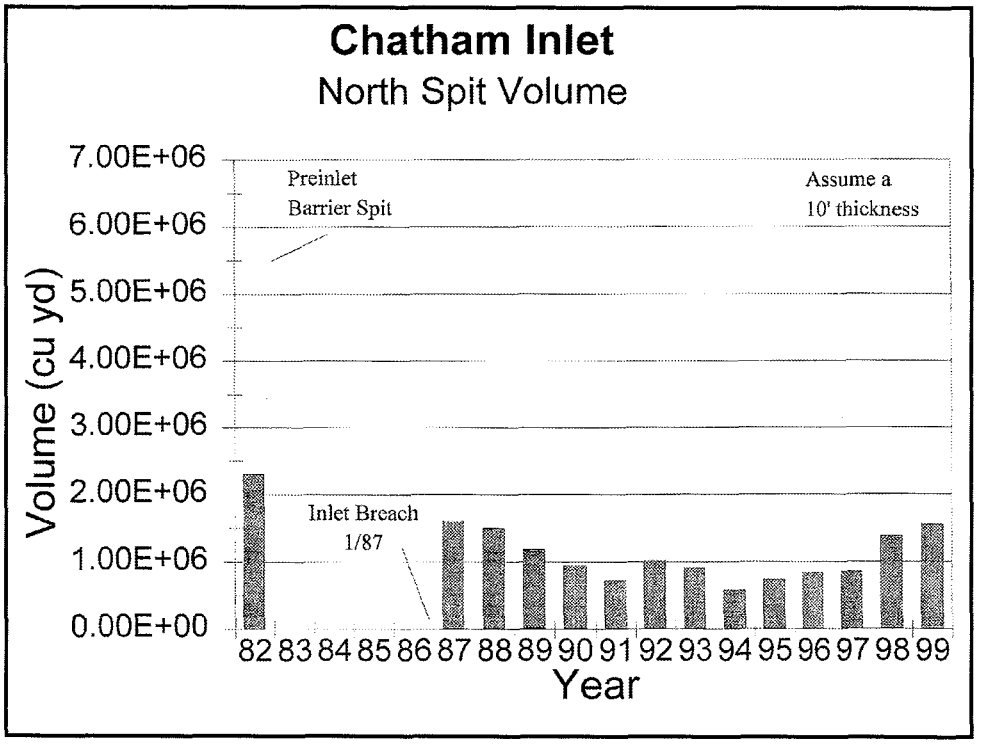


Figure 31. Estimate of volume change in north spit

South Spit/South Beach

Figure 32 illustrates the complex changes to the south spit as it first migrated south and west into south Chatham Harbor and then overtook the south flood shoal and south remnant sand flat to form the land bridge between the mainland and South Beach. The area was measured to a constant point on South Beach as shown by the line on Figure 32. The South Beach barrier island shoreline has also retreated landward almost one island width as the inlet has evolved. Again the preinlet area of the then Nauset Spit barrier was measured from the 1987 breach to the limit line on the 1982 preinlet photo set. Figure 33 shows the measured change in area and Figure 34 shows the change in estimated volume of the south spit. The area and volume of this south spit reached a minimum in 1989 as the spit moved rapidly south and west.

In 1990, the southward movement slowed and a more westward movement began. With the welding of the spit to the mainland in 1992, the area and volume has grown as sand has been deposited to the land bridge. The initial east-west orientation of the land bridge has changed to a more northwest-southeast orientation as sand has accreted to the spit and the south ebb channel has migrated up against this beach. This landform reached its maximum area and estimated volume in 1997/98 and is now slightly decreasing in area and volume as the beach continues to experience overwash into the bay and landward retreat of the shoreline.

South Flood Shoal

Prior to inlet formation, several shoals existed in Chatham Harbor. One of these shoals, the south remnant shoal, was in front of the Chatham Lighthouse and was oblong in shape (Figure 35). After the inlet breached the barrier spit, this shoal became incorporated into the south flood shoal. Modified by tidal currents and waves entering the bay through the inlet, this shoal migrated to the south and was at times composed of from one to two segments separated by channels into south Chatham Harbor. The south and westward migrating south spit finally overtook the south shoal in 1991. The measured area (Figure 36) and estimated volume (Figure 37) of the shoal remained constant until 1989 when the size increased as sand was added to the shoal as it overtook the south remnant sand flat to the south. The maximum volume was reached in 1990 as the shoal migrated south between the mainland beach and south spit. Most of the south shoal was incorporated into the south spit in 1991 and finally the spit welded with the mainland and incorporated the south shoal into the continuous sand bridge connecting the mainland with South Beach by early 1992.

Remnant South Sand Flat

Another preinlet shoal was located south of Chatham Lighthouse near a marina entrance and the spit to Morris Island. Figure 38 shows the location of the remnant south sand flat relative to the south remnant shoal/south flood shoal

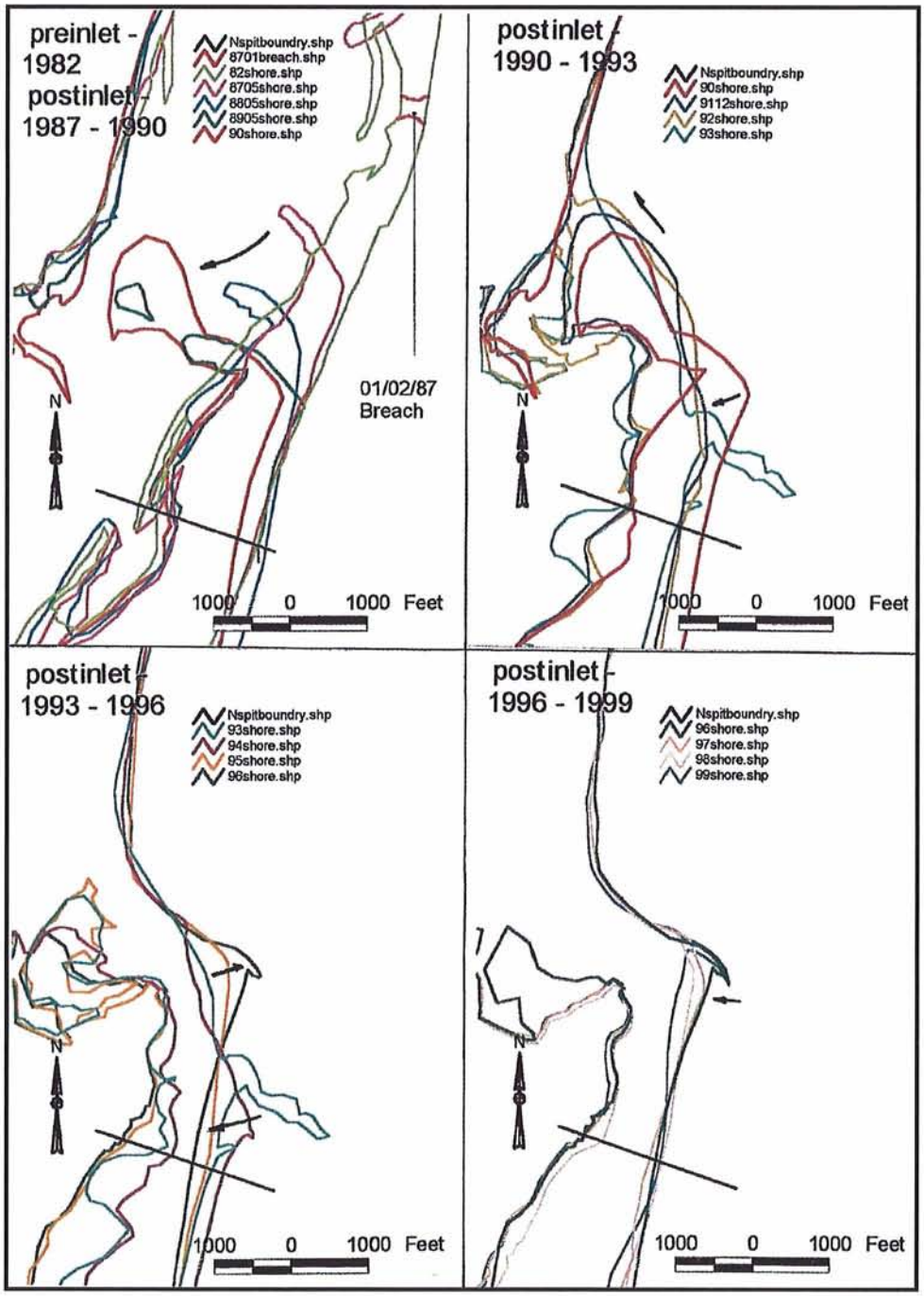


Figure 32. Map of area change to initial recurving south spit and final South Beach land bridge. Line identifies common southern limit of area measurement. Common mainland area boundary used was the 1982 dune/cliff/vegetation line

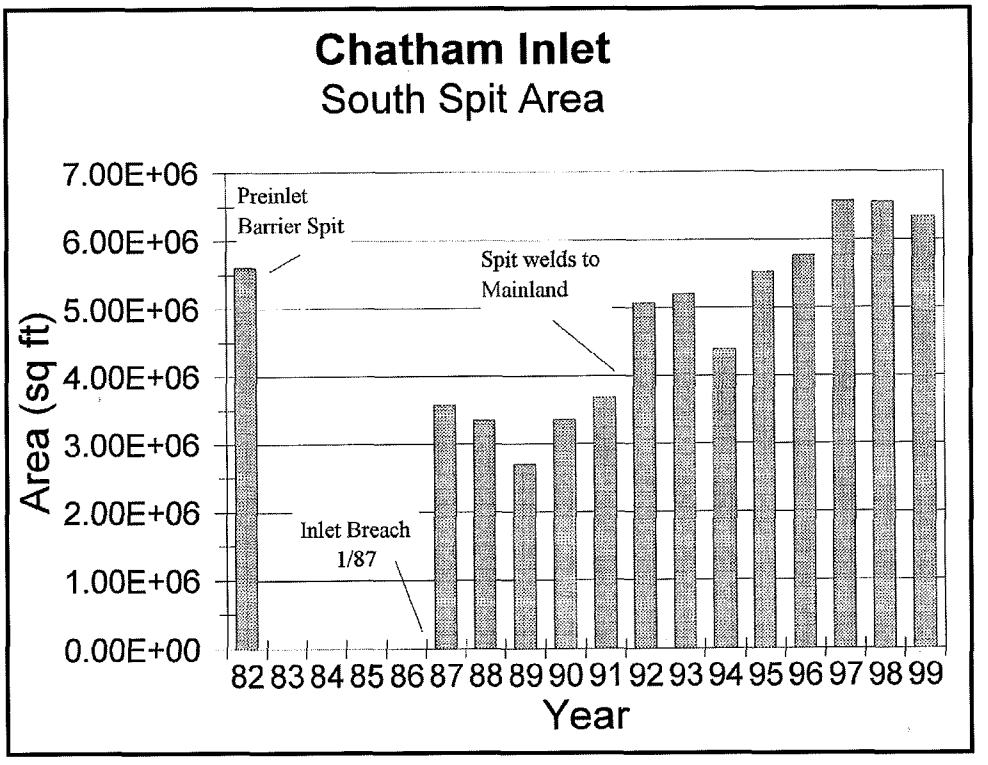


Figure 33. Area change from prebreach to 1999 of south spit/South Beach

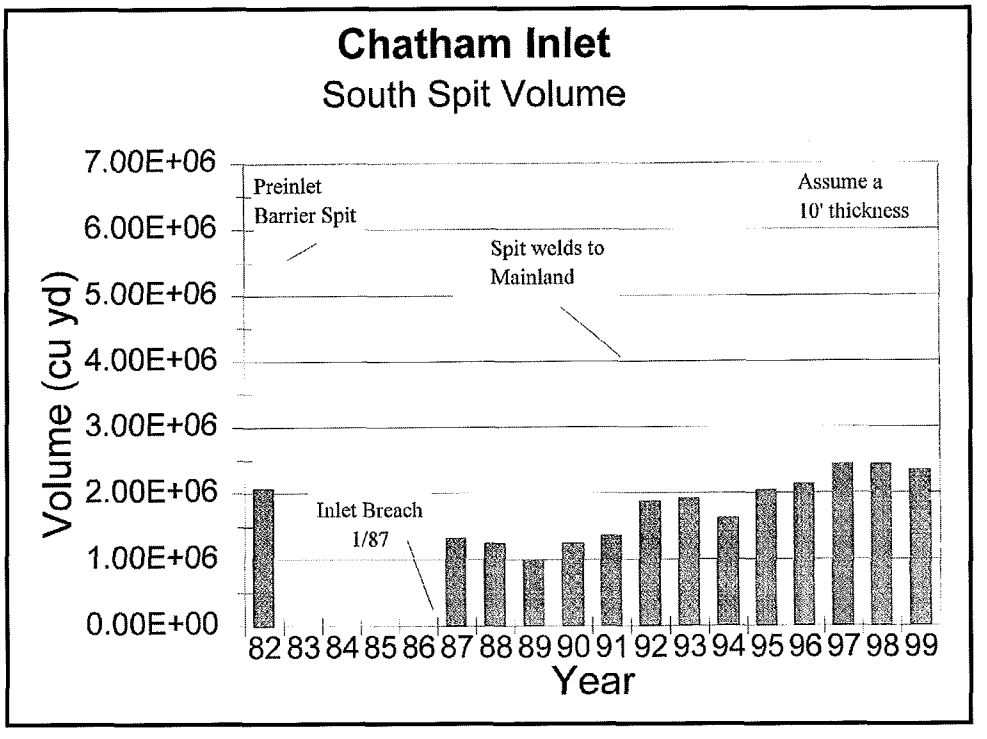


Figure 34. Estimate of volume change of south spit/South Beach

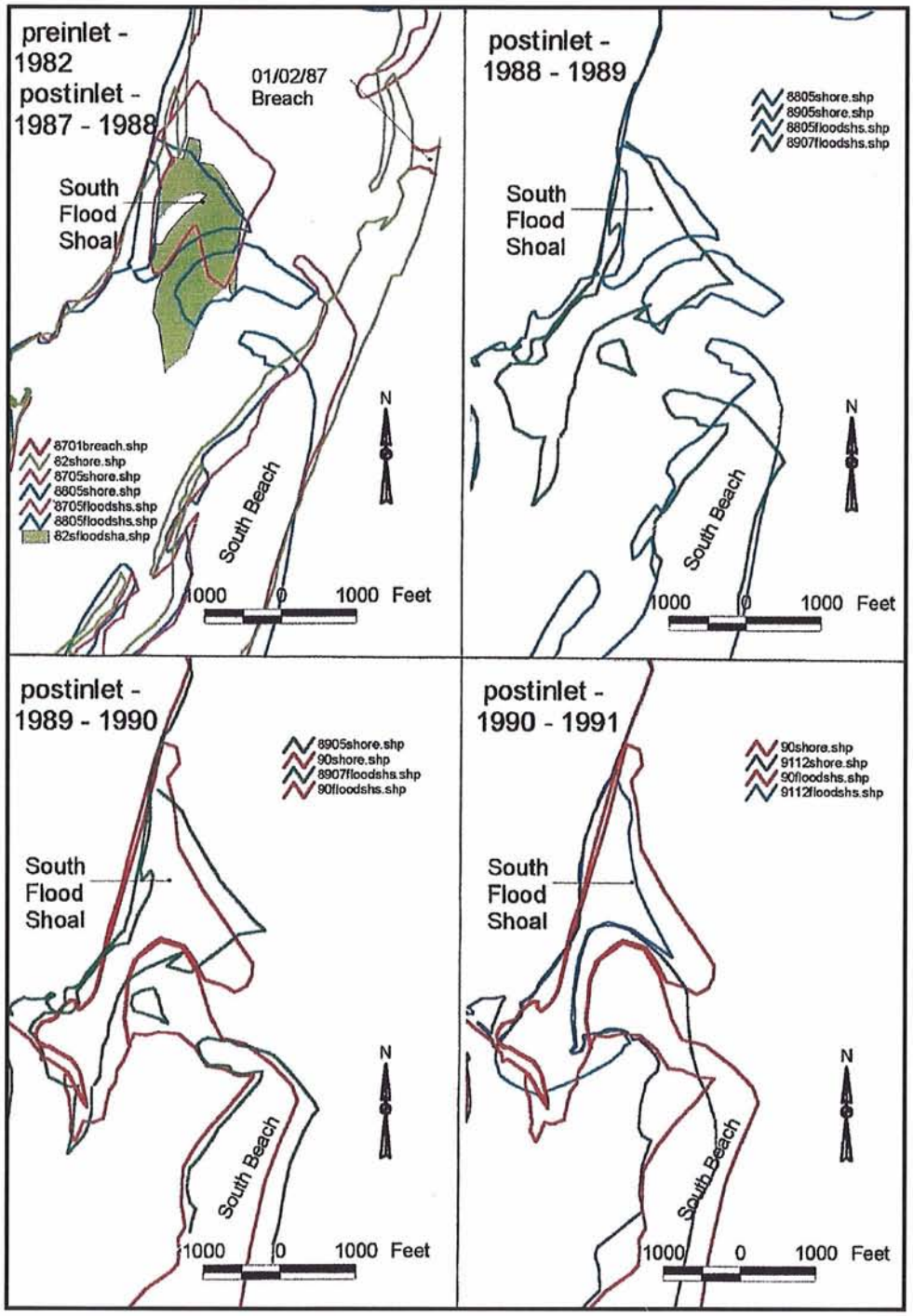


Figure 35. Map of area change to south flood shoal. Solid area shows preinlet remnant shoal that was incorporated into the south flood shoal

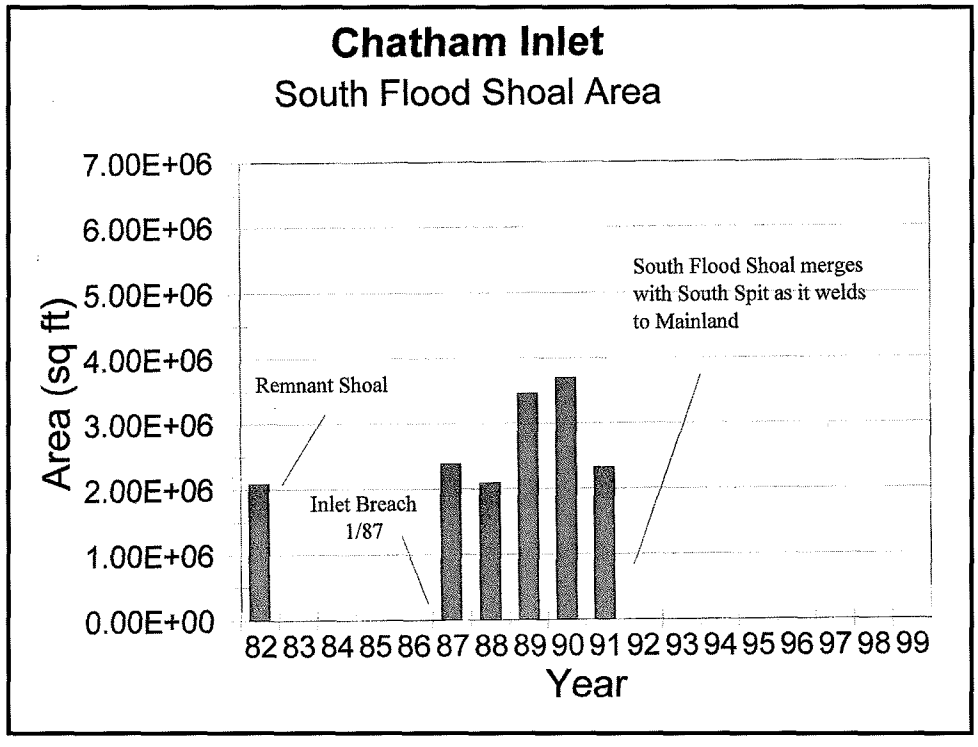


Figure 36. Area change from prebreach shoal to 1999 south flood shoal

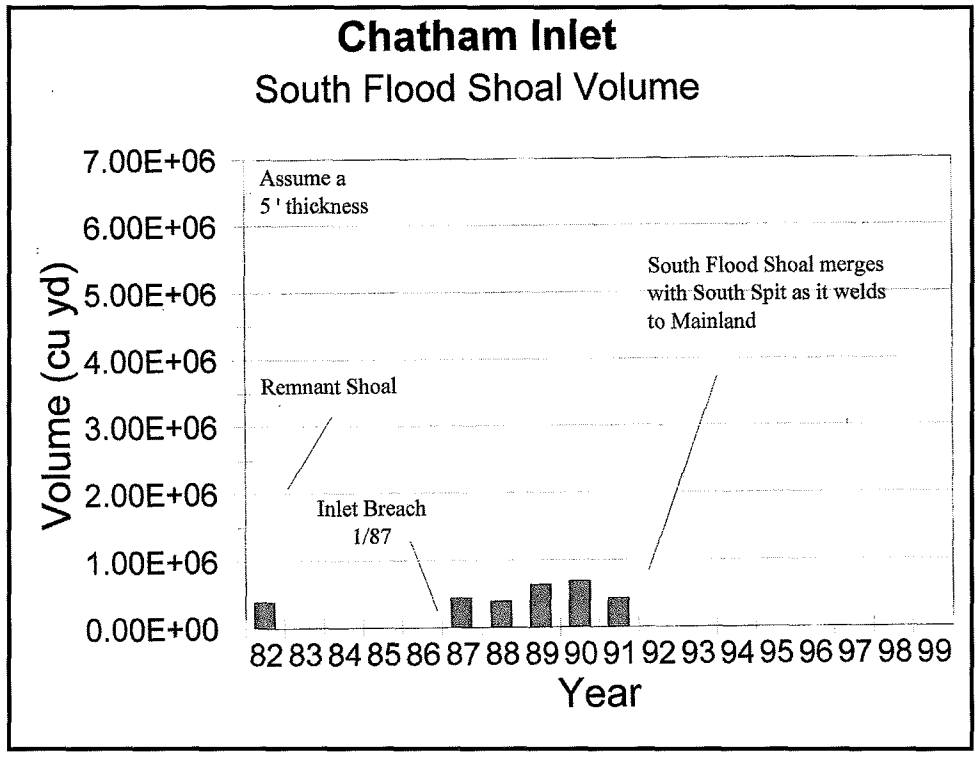


Figure 37. Estimate of volume change in south flood shoal

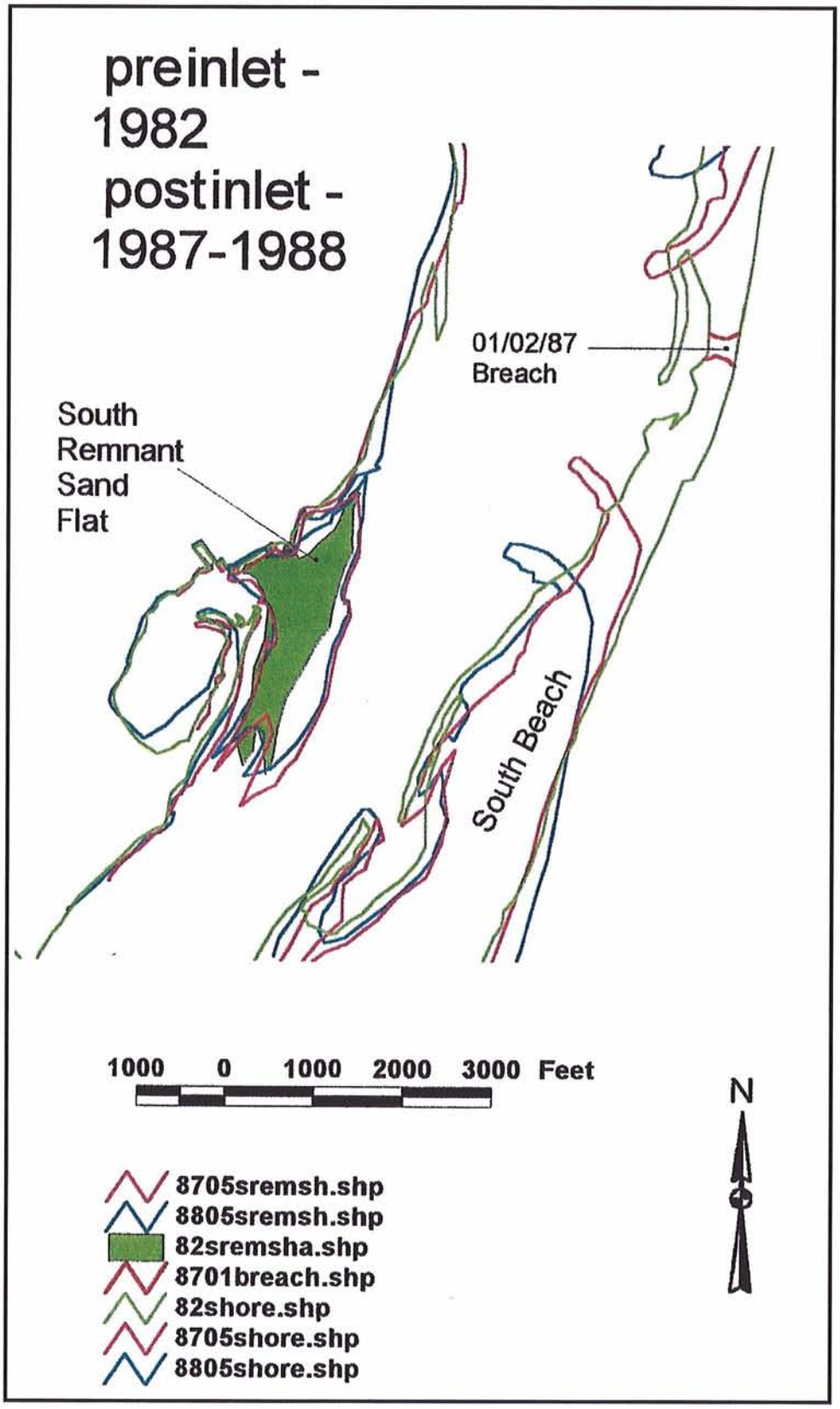


Figure 38. Map of area change in remnant south sand flat. Solid area shows pre-inlet remnant shoal incorporated into the remnant south sand flat

complex. This shoal existed for only two years after the breach until the south flood shoal migrated south and incorporated this remnant sand flat into it. Figure 39 shows the measured area and Figure 40 shows the estimated volume of the remnant south sand flat. While short lived after the inlet opened, this shoal gained sand as tidal currents flowed into south Chatham Harbor in 1987 and 1988. With the complicated multichannel configuration and shoaling associated with the loss of tidal current velocity, the south remnant sand flat became the distal end of the south flood shoal and finally the landward side of the land bridge.

Tern Island and Tern Island South Shoal

Another preexisting sand body in Chatham Harbor was Tern Island. Tern Island was the outer boundary of Aunt Lydia's Cove and the anchorage around the Chatham Fish Pier commercial harbor. Tern Island has historically been used as a disposal site for sporadic prebreach maintenance dredging. Prior to the 1987 inlet, the channel to the Fish Pier was oriented southeast-northwest and was between Tern Island and a shoal called south Tern Island shoal (Figure 41). After the inlet opened, there was little change in Tern Island, its south shoal and Aunt Lydia's Cove entrance channel, until 1990. The measured area and estimated volume of Tern Island remained relatively constant gaining slightly from before the inlet opened (Figures 42a and 43a). At that time, the north flood shoal began to migrate north, causing the channel to reorient and caused Tern Island to migrate to the north. Changes in the orientation of the west flood channel around the north flood shoal also caused the Tern Island south shoal to lose area and volume (Figures 42b and 43b).

The change in the west flood channel and reorientation of the Aunt Lydia's Cove entrance channel slowly eroded and finally removed the entire Tern Island south shoal by 1997. Tern Island remained relatively constant in area and estimated volume over the study period, with a minimum area/volume in 1994 and 1996. The island has been used as a disposal site for the initial dredging of the entrance channel into Aunt Lydia's Cove by the New England District, with a placement of about 100,000 cu yd (76,460 m^3) in 1995. This additional fill volume has not been included in the estimated volume calculation for 1995. Sand has eroded on the south end and is migrating to the sand flats on the north. The present area and estimated volume is close to the preinlet conditions.

North Flood Shoal

A large shoal was also present in the northern part of Chatham Harbor in mid-lagoon in 1982 that caused the main channel to split into an east and west channel on its way to Pleasant Bay. This shoal was oblong and after the breach, this remnant shoal became the north flood shoal (Figure 44a). This remnant shoal was located just to the north of the expanding inlet throat and quickly took on the characteristics of the northern side of the flood shoal. Just four months after formation, this shoal almost doubled in measured area (Figure 45) and estimated volume (Figure 46). The shape became more teardrop as sediment deposited on the shoal as the tidal flow slowed as it made the turn to the north. Briefly in 1988,

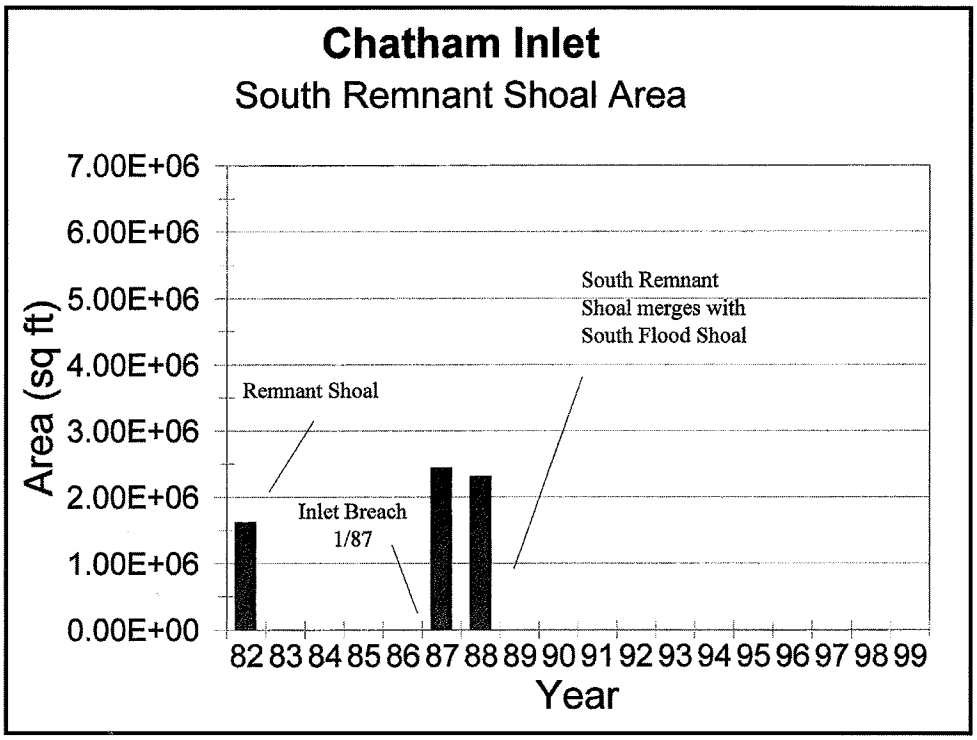


Figure 39. Area change from prebreach to 1999 to remnant south sand flat

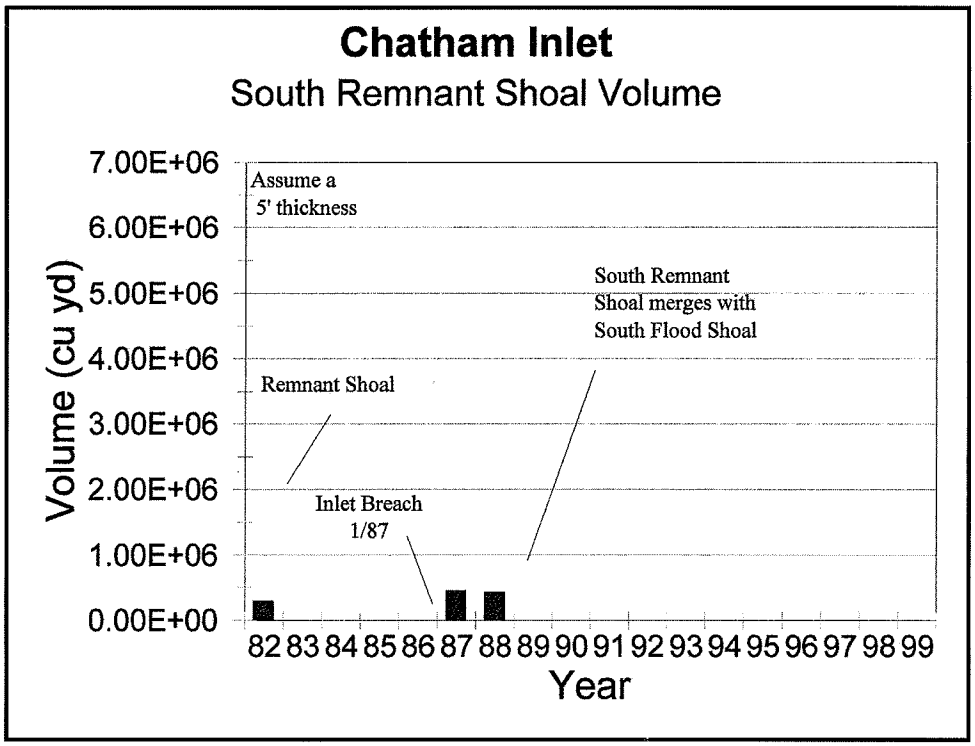


Figure 40. Estimate of volume change in remnant south sand flat

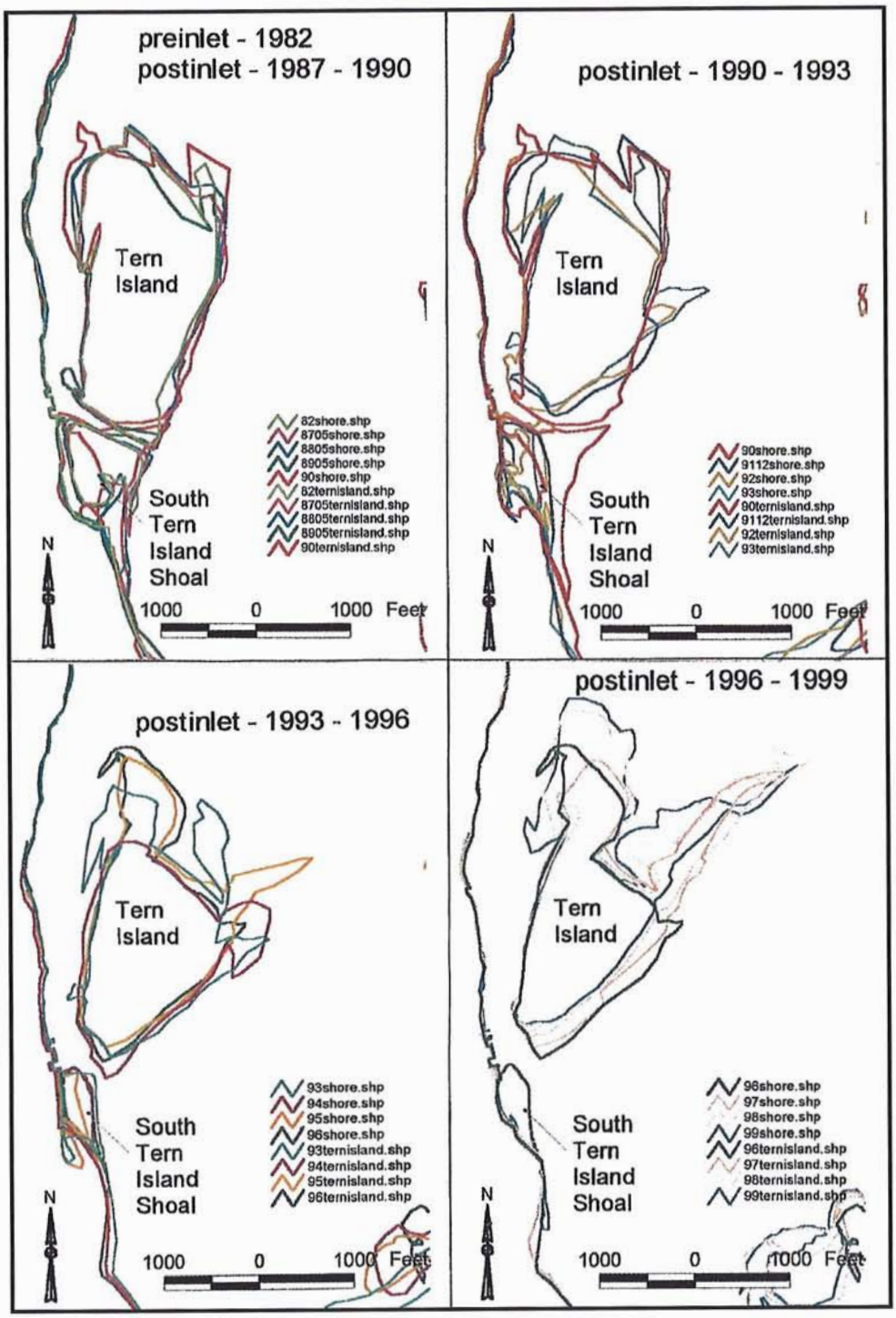
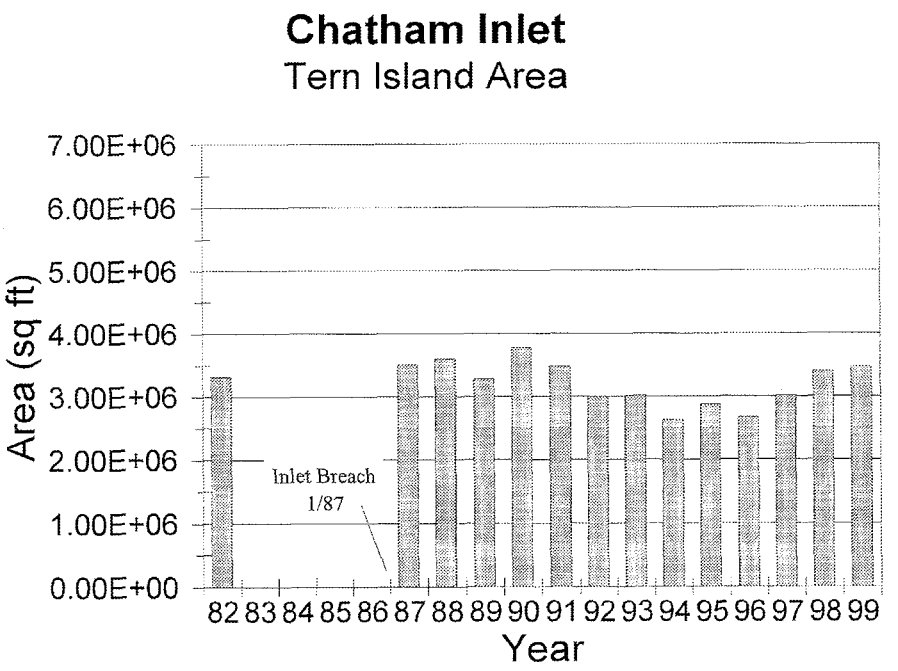
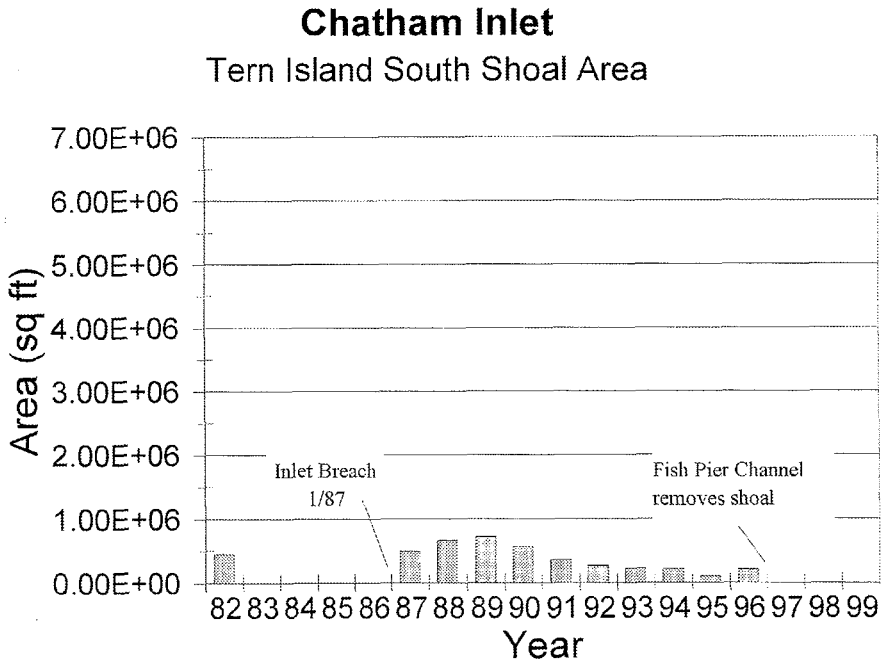


Figure 41. Map of area change to Tern Island and Tern Island south shoal

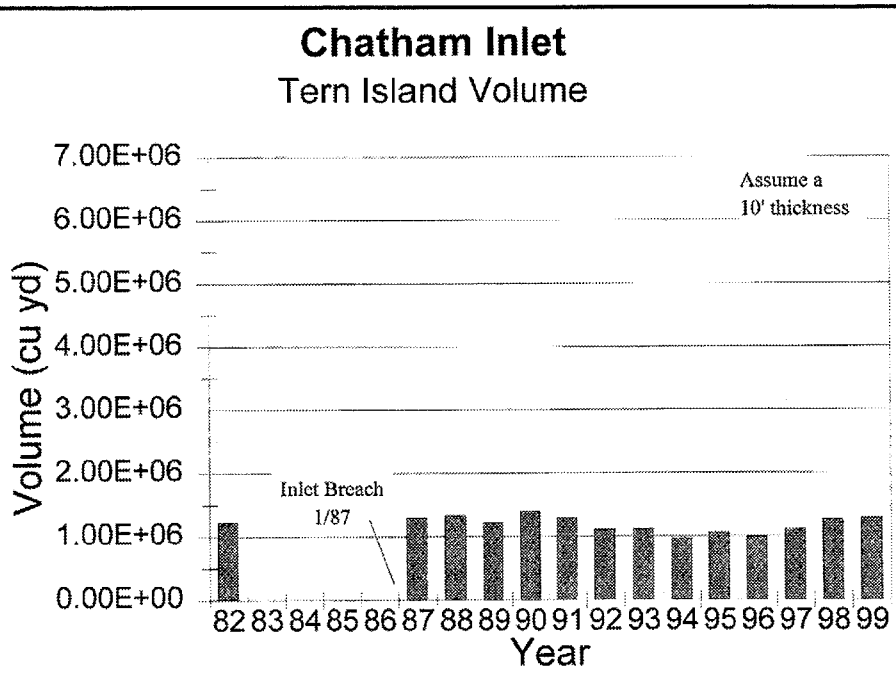


a. Tern Island

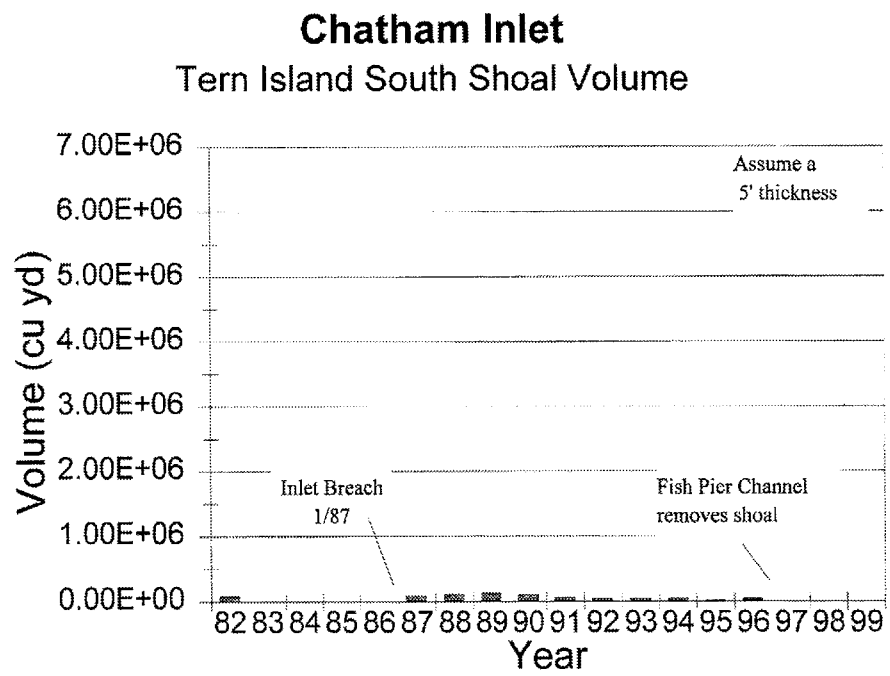


b. Tern Island south shoal

Figure 42. Area change from prebreach to end of study



a. Tern Island



b. Tern Island south shoal

Figure 43. Estimate of volume change

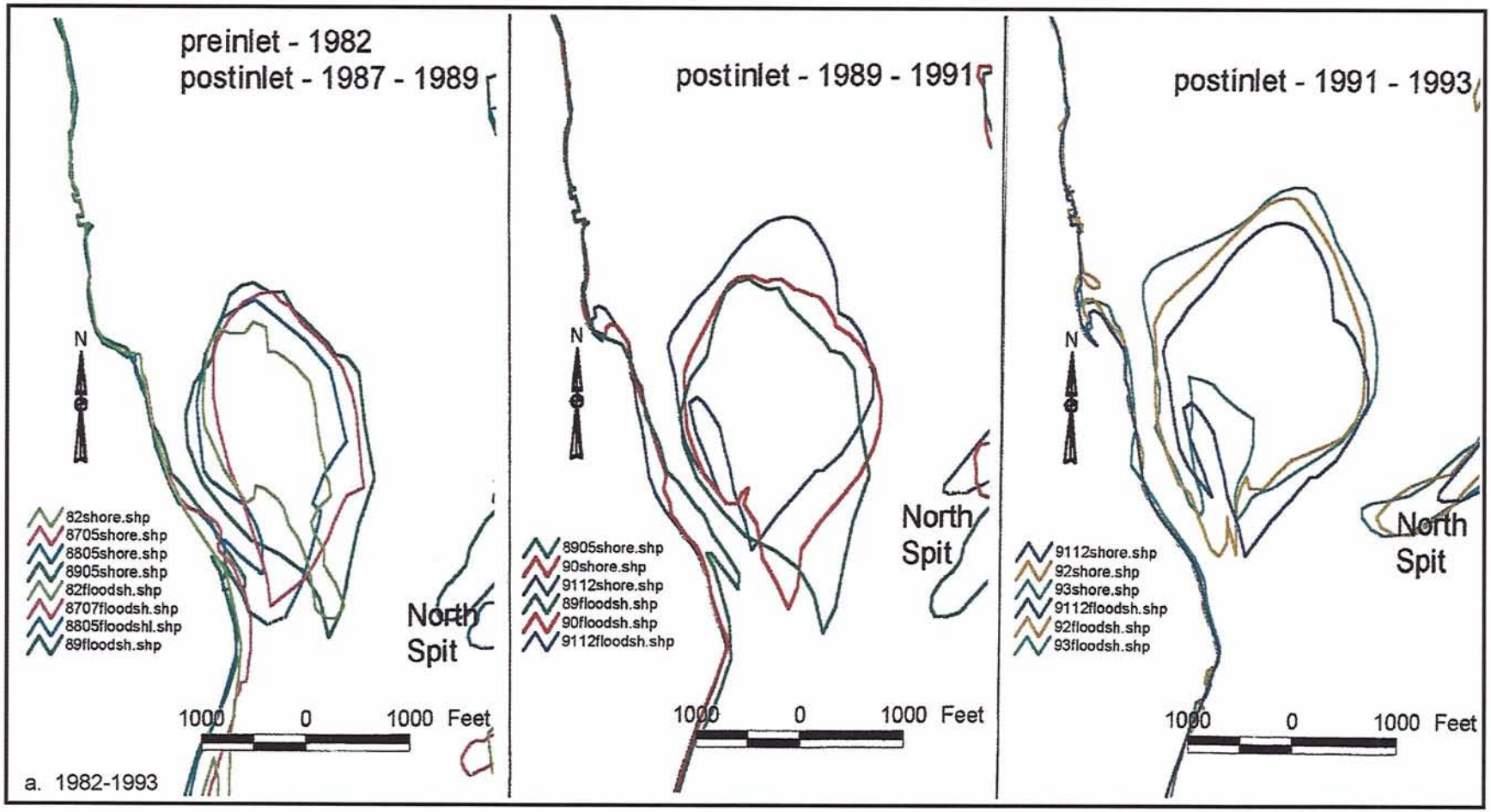


Figure 44. Map of change in north flood shoal (Continued)

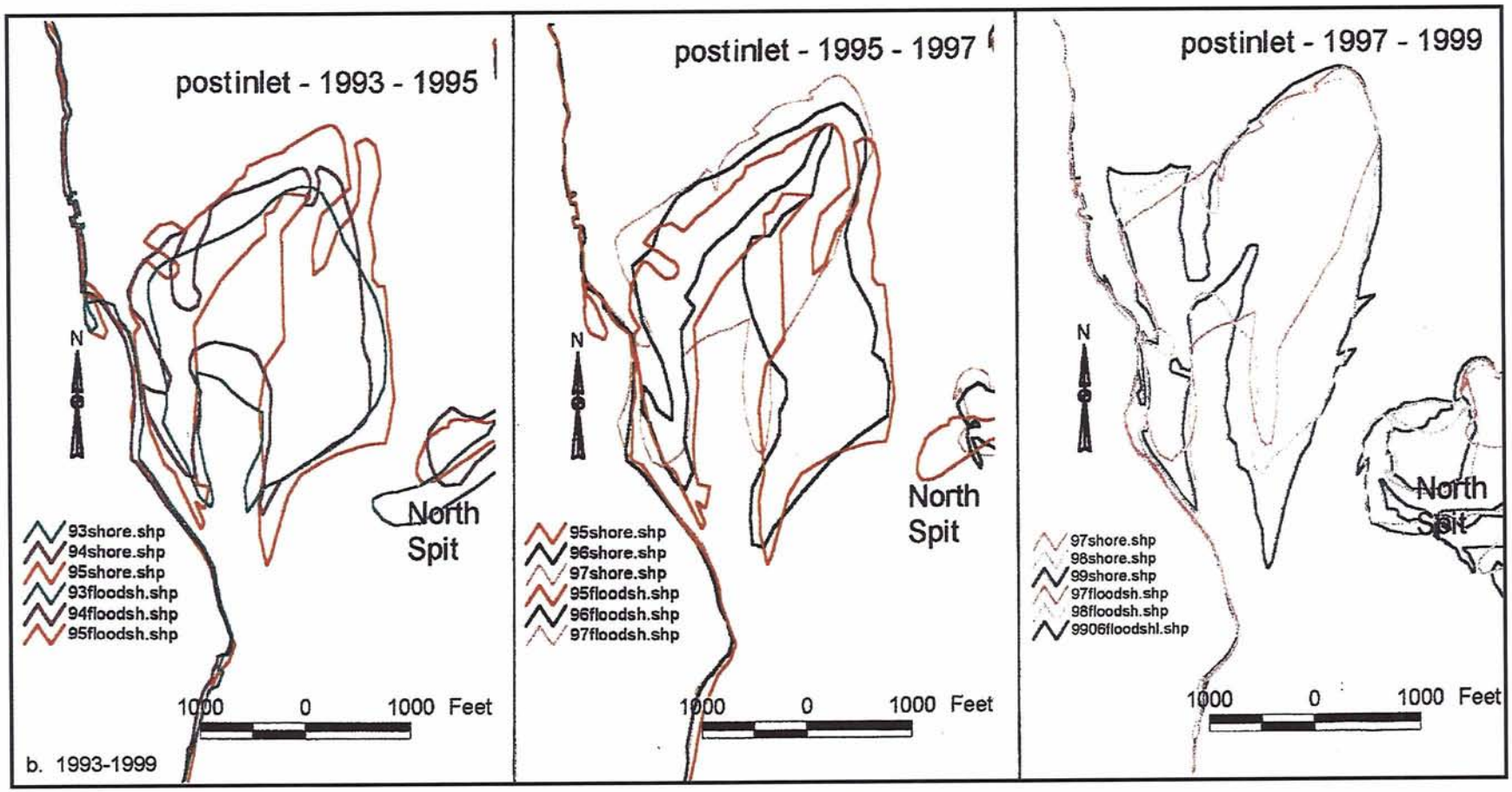


Figure 44. (Concluded)

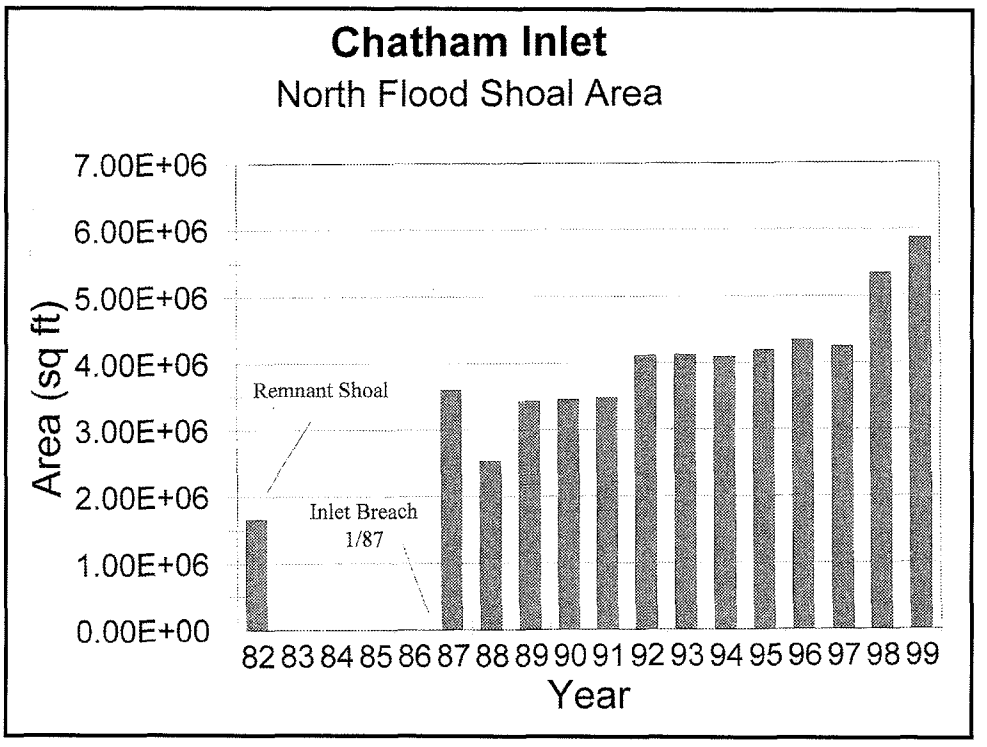


Figure 45. Area change from prebreach to 1999 in north flood shoal

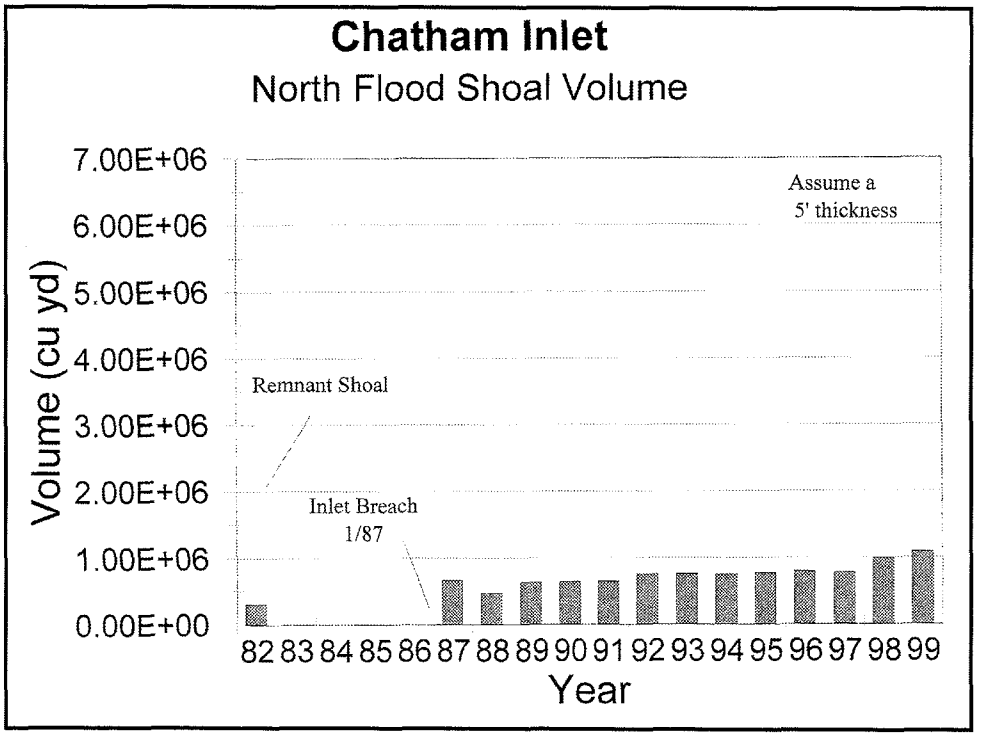


Figure 46. Estimate of volume change in north flood shoal

the shoal lost area and volume and became somewhat attached to the mainland beach, shoaling the west flood channel. By 1989, the west channel opened again as the shoal continued to gain sand and expand laterally on both the east and west sides. While maintaining a teardrop shape and near constant area, the shoal began to migrate up-estuary between 1989 and 1991.

In 1991, a flood ramp started to form on the western side of the shoal closest to the inlet and expanded northward almost bisecting the shoal by 1995 (Figure 44b). This ramp formation corresponded with the closing off of the south Chatham Harbor by the welding of the South Beach to the mainland. All the tidal flow was now directed north into Chatham Harbor and Pleasant Bay. In 1994, the west ebb spit had migrated close to the mainland shore, with growth of the ebb shield on the north side. This process had restricted the flow through the west channel and shoaling resulted in the channel. The first spillover lobe formed on the ebb shield as the west channel tried to re-establish. This growth and shoaling make navigation difficult into Aunt Lydia's Cove. It necessitated the dredging of the entrance channel in 1995, which can be seen partially completed through the west ebb spit. The flood ramp grew to the north in 1996, again almost cutting the flood shoal in two, in an attempt to naturally re-establish the west channel. This channel had became narrowed and was forced by the ebb shield to occupy the remnants of the east-west entrance channel as it flowed around the large ebb shield and down the west side of the west ebb spit. In 1988, the flood shoal again expanded in area and volume, after several years (1992-1997) of near constant area and volume. The north flood shoal has expanded in width and length as it almost fills the entire north Chatham Harbor. Its shape has changed as it took on more characteristic flood shoal features over time.

A new spillover lobe began forming by ebb currents trying to cut the shoal in half, to re-establish the main west flood channel in 1997. This lobe was located on the western side of the ebb shield, close to the preinlet west channel center line. This spillover lobe has grown in 1998 and 1999 to become a major feature on the north side of the flood shoal and has almost divided the shoal in half by 1999. The flood shoal continues to increase in area and volume with growth northeastward up-estuary. The east-west entrance channel to the Fish Pier anchorage has been pushed toward Tern Island and finally almost shoaled in. The west side of the shoal has migrated west and is almost attached to the mainland beach. To maintain access, a new channel has been cut in a northwest-southeast orientation on the lower west ebb spit just off Claflin Landing by the county through the thinnest part of this west ebb spit.

5 Sediment Pathways

A third task was to review the past studies on identification of sediment transport pathways at Chatham Inlet and to identify present pathways based on developments in inlet morphology. The processes driving the system can be inferred based on the evolution of the inlet and shoal morphology. Spatial changes and directions of movement observed in the inlet features identify the predominant sediment transport directions.

Initial Inlet Development (1987-1991)

For the first three years of inlet evolution, the trend was for the throat to expand and the shoal features to form and establish typical inlet features. This can be illustrated by summarizing the movement of the main ebb channel, the ebb shoal, and adjacent spits (Figure 47). The ebb shoal has grown seaward and the edge migrated 2,500 ft (762 m) to the south while a large channel-margin swash platform has formed on the north and a marginal linear bar has formed on the south. From 1987 to 1991 the main ebb channel center line has moved some 1,800 ft (549 m) southward. The South Beach spit initially moved south 1,400 ft (427 m) then westward incorporating the south flood shoal and virtually closing off the south Chatham Harbor by 1991. Nauset Spit has migrated 2,000 ft (610 m) north and west into Chatham Harbor. The growth of the north flood shoal in both width and length up-estuary caused the west flood channel to move westward, while the eastern channel experienced shoaling.

Seasonal wave climate and longshore drift patterns have played a role in the evolution of the adjacent spits and ebb shoal (Liu et al. 1993). Summer seasonal wave approach from the southwest and northward drift influence the northward movement of the north spit. The more energetic winter wave climate dominated by northeasters with the dominant northeast wave approach and southward longshore drift cause the southward migration of the ebb shoal/swash platform, ebb shoal and South Beach spit. The retreat of the South Beach shoreline indicates that the inlet is acting as a littoral block and insufficient sand is bypassing the inlet. Most of the southward sediment transport is being incorporated into the growing ebb and flood shoals.

Ebb dominance of the tidal currents was established based on measurements in this early phase of inlet development (Liu et al. 1993; FitzGerald and Montello 1993). FitzGerald and Montello (1993) found that the maximum flood currents

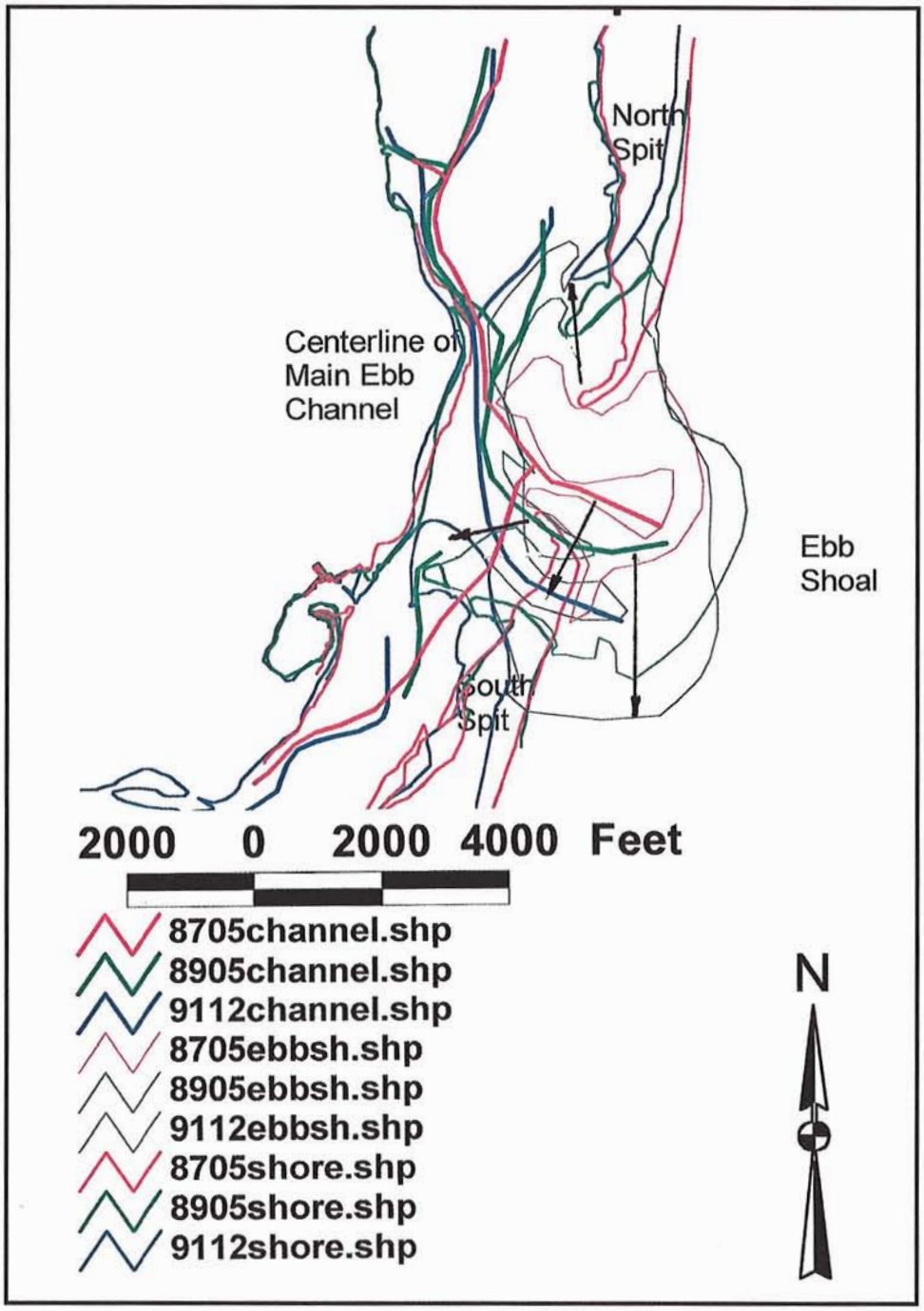


Figure 47. Net changes in main ebb channel, ebb shoal edge, and north and south spits from 1987 to 1991

occur close to high water, allowing flood-driven transport to flow over the shallow northern swash platform. The maximum ebb flow occurs close to low water, when the flow is confined to the main ebb channel, which results in a strong ebb-dominated main inlet channel.

Sediment transport pathways at Chatham Inlet, based on morphology from September 1988, were presented in Liu et al. (1993) and shown in Figure 48. The southward moving net longshore transport is diverted into the inlet, particularly on the flood tide. Sand is transported into the inlet by flood flow over the swash platform, in the main channel and next to the South Beach spit. At that time, the south flood shoal was composed of two shoals with three channels allowing flood flow into south Chatham Harbor. Flood flow also moved into north Chatham Harbor around the north flood shoal. Ebb flow, more confined to the deeper channels, flowed south around the north flood shoal and out the main ebb channel over the ebb shoal and continued south along South Beach. Ebb flow was somewhat blocked from flow out of south Chatham Harbor due to the shallowness of the south flood shoal. A more detailed sediment transport pathway pattern developed by Fitzgerald and Montello (1993) and based on the August 1990 aerial photographs, current measurements, bed form interpretation, and sediment data from the summer of 1990, is shown in Figure 49.

A similar pattern of flood flow over the swash platform transports sand into the northern Chatham Harbor. Sand is transported onto the flood tidal shoal, and up the east and west flood channels. Ebb tidal currents move sand out of the harbor, basically, in the east and west tidal channels into the main ebb channel and out onto the ebb shoal. At this time the South Beach spit had almost attached to the mainland beach with predominantly flood flow through the gap and prevented much tidal flow and sediment transport interchange with south Chatham Harbor.

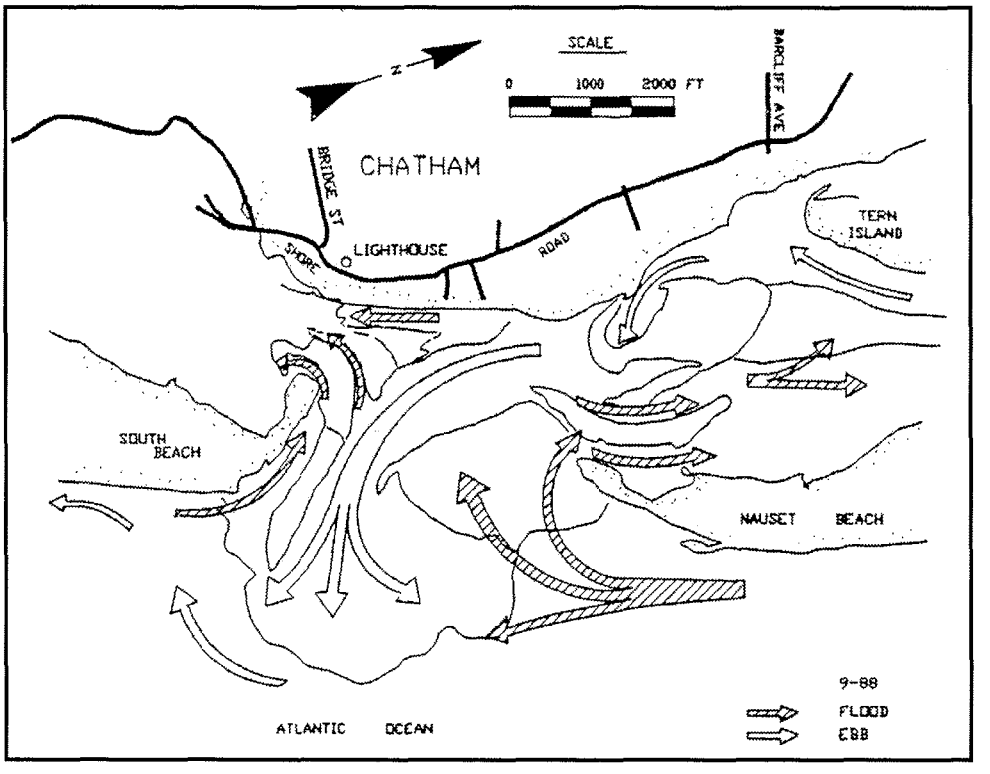


Figure 48. Sediment transport pathways at Chatham Inlet based on morphology from September 1988 (Liu et al. 1993)

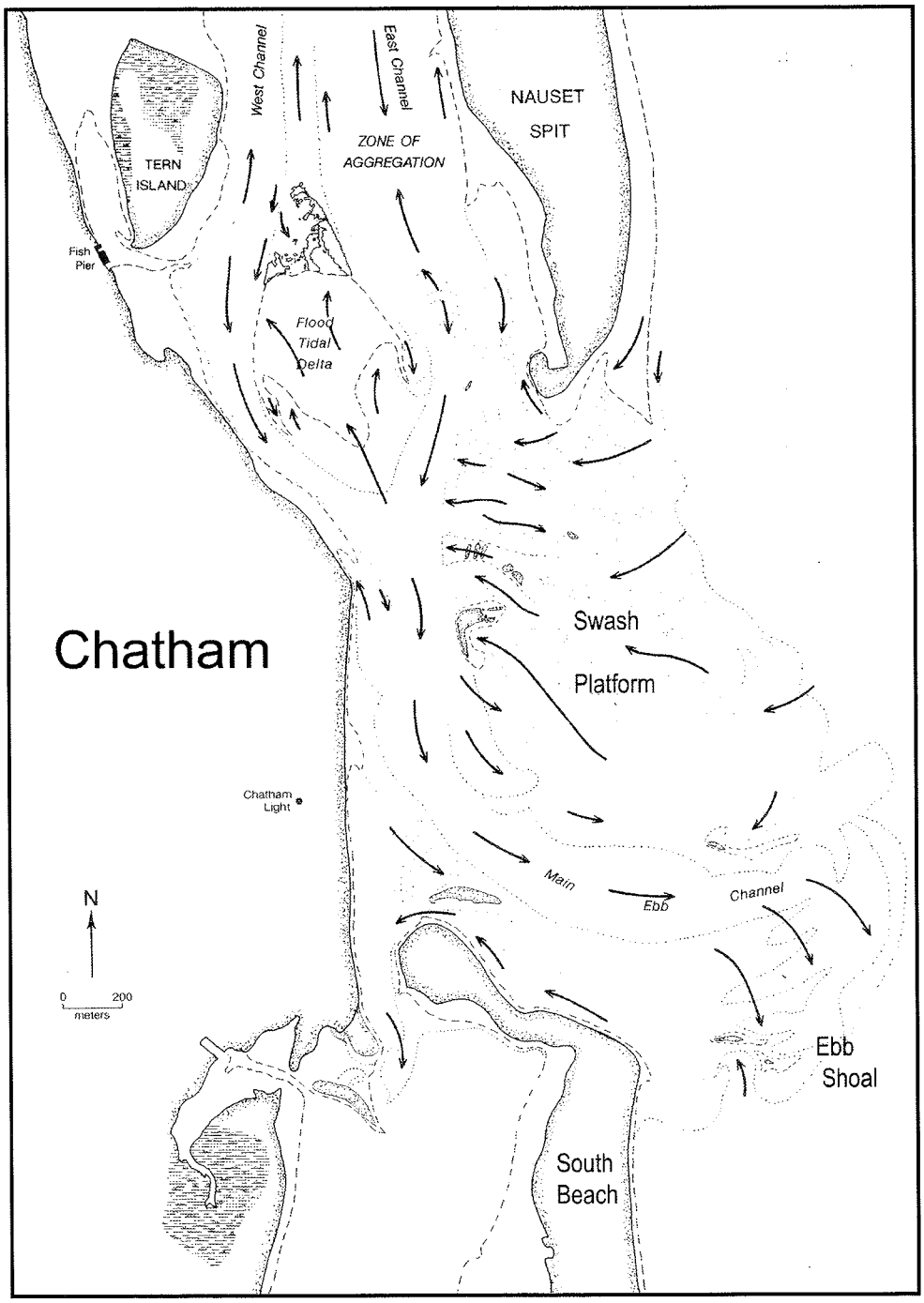


Figure 49. Detailed sediment transport pathways from summer 1990 (after Fitzgerald and Montello 1993)

Inlet Development (1991-1995)

With the welding of South Beach to the mainland in 1992, the circulation and predominant sediment transport was restricted to north Chatham Harbor and Pleasant Bay. Net changes in the main ebb channel, ebb shoal edge, and north and south spits from 1991 to 1995 are summarized in Figure 50. The ebb shoal

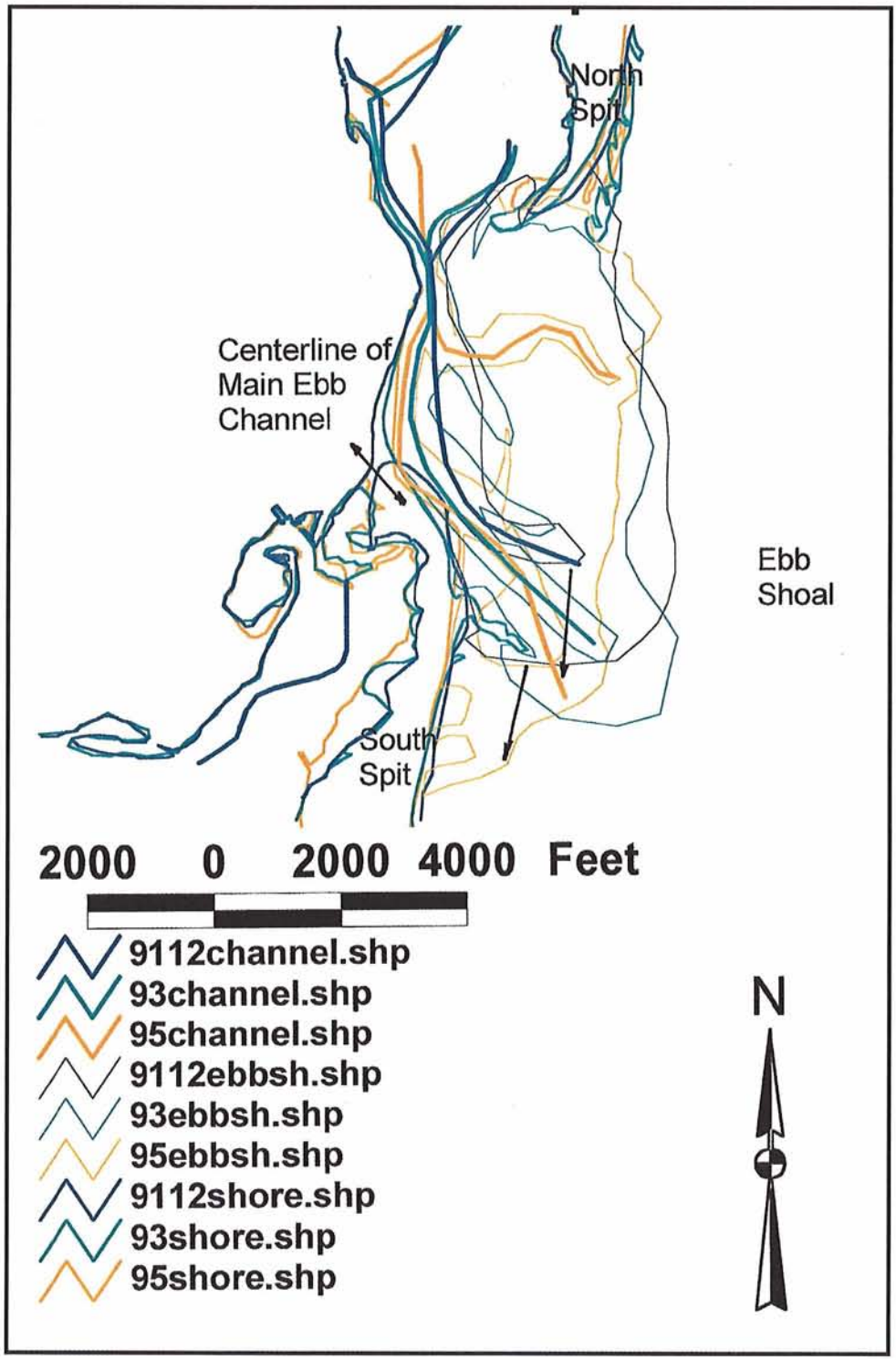


Figure 50. Net changes in main ebb channel, ebb shoal edge, and north and south spits from 1991 to 1995

continued to grow and migrate southward moving south another 2,000 ft (610 m). Ebb shoal sediments were now off the northern end of South Beach. The main ebb channel continued to move south but at a slower rate than earlier. The main ebb channel was restricted in its southern movement by the land bridge and only the distal end over the ebb shoal moved some 2,000 ft (610 m) further south. The ebb shoal/swash platform complex also expanded into the bay.

The North Beach spit became more stationary as the main ebb channel moved further to the south. The northward retreat has stopped as predicted by Liu et al. (1993) based on the fact that the inlet throat had reached far enough south so that the ebb tidal shoal no longer affects the spit or the nearshore bar system off the end of Nauset Beach. The center line of the main ebb channel was approximately 5,500 ft (1,676 m) south of the north spit during this time period and the main driving mechanism for north spit movement is related to the seaward reorientation and displacement of the north beach nearshore bar system.

With the enlargement of the ebb shoal into the bay, the main ebb channel was forced closer to the mainland beach. By 1995, a new north ebb channel had established itself on an east-west orientation some 1,500 ft (457 m) south of the north spit. It is suspected that the long narrow main ebb channel to the south had become too restricted to carry the ebb flow out of the estuary and a new shorter, more efficient, channel established itself closer to the main body of the estuary. With the welding of the south spit to the mainland and the filling of the ebb shoal across the throat of the inlet, the circulation patterns of the inlet underwent a drastic change over these 3 years. The establishment of a northern ebb channel bisected the swash platform and shortened the northern portion of the platform. The central swash platform was large and had numerous swash bars and small channels. Sediment transport pathways based on morphology from May 1995 are shown in Figure 51. The flood flow into the inlet was accomplished both on the north and central swash platforms. The flood shoal by this time developed a large flood ramp and the main west flood channel was in the center of the ramp. The expanding ebb shield deflected the return ebb flow from the upper parts of Chatham Harbor and Pleasant Bay around both sides of the flood shoal. Since the west channel was forced close to the mainland beach, tidal flow became restricted through that channel. Two spillover lobes trying to form through the ebb shield suggest that the ebb flow was having difficulties navigating the flood shoal and was trying to establish a straighter route to the inlet throat.

Inlet Development (1995-1999)

With the closure of south Chatham Harbor and the establishment of the second north ebb channel, Chatham Inlet continues to evolve toward a dynamic equilibrium with the prevailing coastal processes. Net changes in the main ebb channel, ebb shoal edge, north spit and South Beach land bridge for the third period from 1995 to 1999 are shown in Figure 52. With the southern main ebb channel extending some 6,000 ft (1,829 m) in length and being forced against the mainland beach by the ever expanding ebb shoal, the flow through this channel is much more restricted than before. Over this last 3-year period, the position and orientation of this channel has remained relatively stable. The newer north

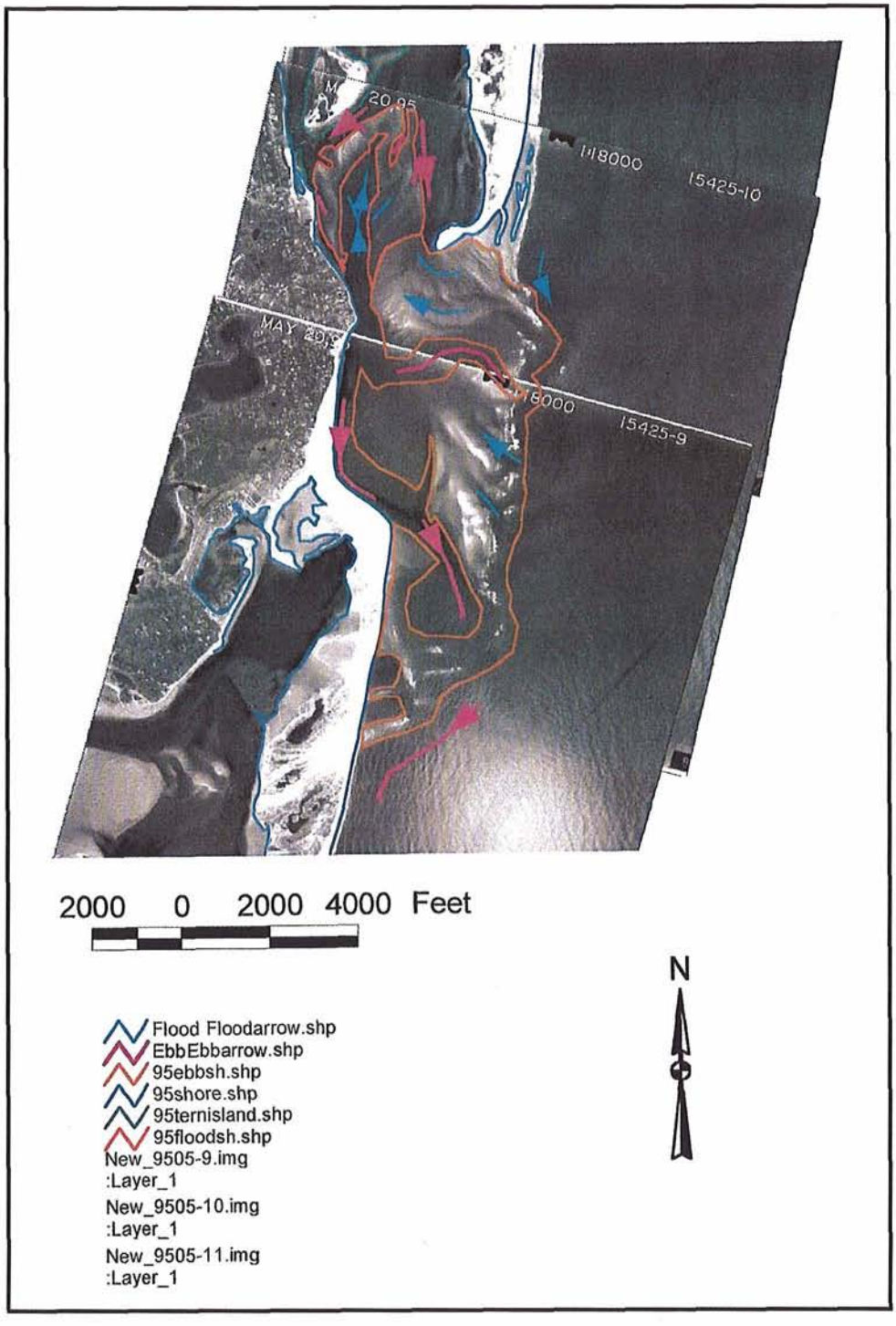


Figure 51. Sediment transport pathways based on morphology from May 1995

channel has exhibited more fluctuation in position and orientation. In 1995, the north channel had the curved bend reminiscent of the original single ebb channel soon after inlet formation. By 1997, this north channel had straightened to a more southeast orientation, but by 1999 the channel had reorientated back to the 1995 position. The outer end of this channel has migrated 1,000 ft (305 m) toward the

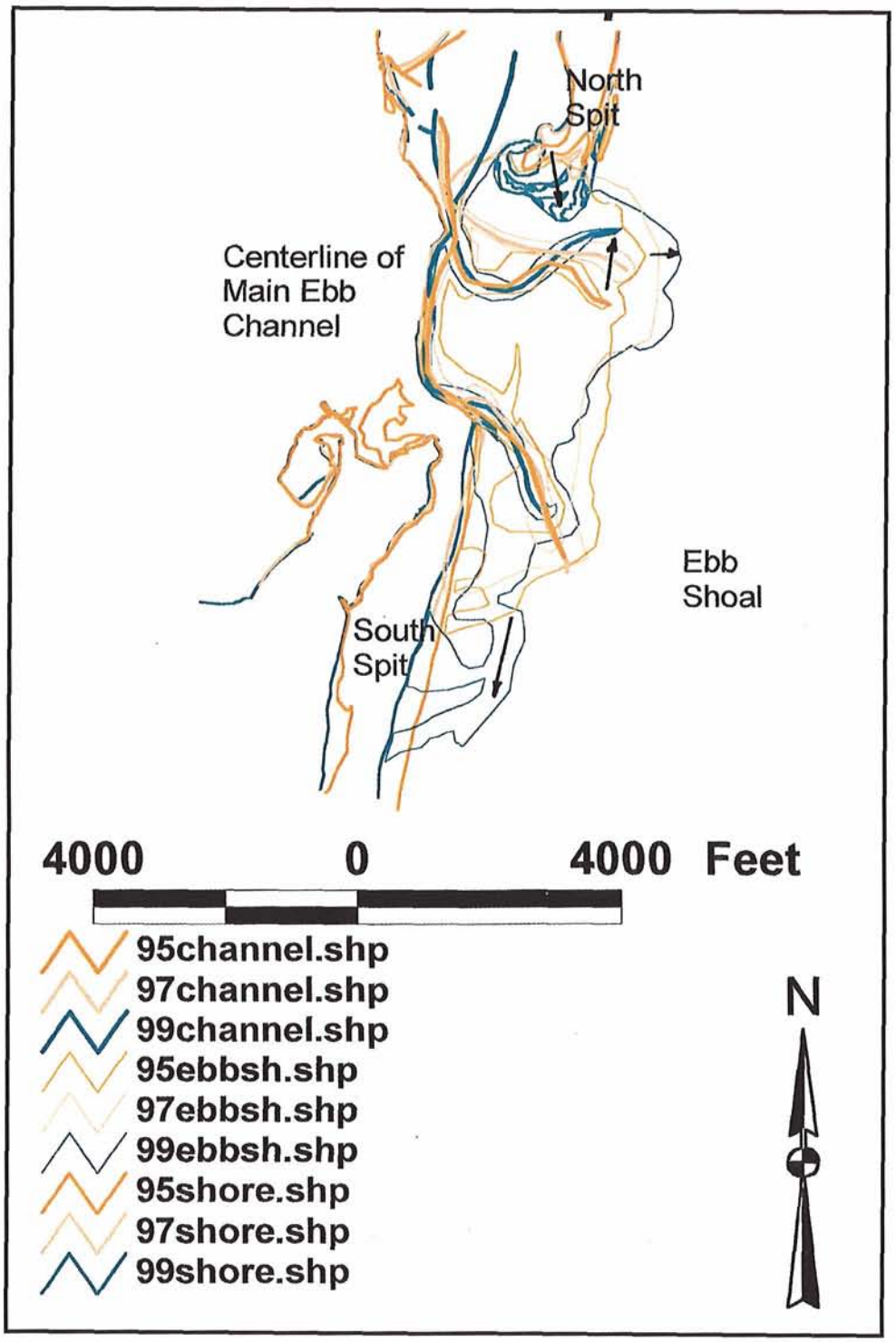


Figure 52. Net changes in main ebb channel, ebb shoal edge, and north and south spits from 1995 to 1999

north, against the prevailing southward drift. This channel is not as pronounced as the south channel and has had several areas of shoaling over these 3 years. Navigation through this channel and the outer end of the south channel has been difficult due to the shifting ebb shoal terminal lobes. The harbor master at

Chatham Harbor first began formally marking the north channel in 1998 for the fishing fleet.[1] Controlling depths have been approximately 4.0 to 6.0 ft (1.2 to 1.8 m) mllw in spot areas at the terminal lobe. With the northward movement of the north channel, the north swash platform has reduced its area and the north spit has changed from a stable feature to one that has grown south and has become larger, with the formation of several recurved spits and bars since 1997. As of the summer of 2000, the south channel has been essentially abandoned for navigation.

Sediment discharge through the north ebb channel has caused the northern third of the ebb shoal to expand seaward 500 ft (153 m) in a crescent shape, reminiscent of the initial ebb shoal formation in 1987/88. The southern ebb channel tip has retreated landward slightly (300 ft or 92 m) over the same period. It appears that the northern ebb channel will become the dominant channel in the future. Southward transport of the ebb shoal is still evident in the growth of the shoal 2,500 ft (762 m) further to the south along the South Beach shoreline. This southern portion of the ebb shoal has complex channel margin shoal features. The shoreline along the land bridge and northern 3,000 ft (914 m) of South Beach has remained relatively stable, somewhat protected with this nearshore shoal complex. Some of these shoal features are beginning to migrate onto the South Beach as of the summer of 2000.[1] South of this area the shoreline is still retreating.

Figure 53 illustrates the sediment transport pathways based on morphology from July 1999. There are numerous ebb and flood dominated channels interspersed with swash bars on the ebb shoal. The main ebb flow is shared with the north and south ebb channels. A complex flow pattern is also evident around the expanding flood shoal, with the east flood channel being more dominant at this time. With the expansion of the ebb shield around the north end of the flood shoal, the west flood channel has been blocked in since 1997. The west flood channel has tried to break through the ebb shield in several spillover lobes in the past 3 years, and it now appears that it is trying to re-establish a channel with a large spillover lobe through the ebb shield, just about in the same position and with a similar orientation to the original west flood channel of the 1987/89 time period. Deposition on the west ebb spit of the flood shoal has further restricted the southern portion of the west flood channel, which has flowed into the center of the flood ramp area since 1995. It is hypothesized that the west flood channel will re-establish itself through the existing flood shoal with the breakthrough of the spillover lobe. The western flood shoal will become detached and form a new Tern Island south shoal.

[1] Personal Communication, 2000, T. Keon, Dept. of Coastal Resources, Town of Chatham, MA.

Figure 53. Sediment transport pathways based on morphology from July 1999

6 Dredging Plan Recommendations

The highly dynamic nature of Chatham Inlet has presented a challenge in maintaining safe navigation through shifting shoals and channels. Although the inlet evolutionary processes are still not completely understood, this study has undertaken to examine development of the major shoreline and shoal morphology and identify patterns of change in a seemingly chaotic growth over 13 years since inlet formation.

There were two areas of difficult navigation due to shoaling and shifting channels. The first area was in the north and south main ebb channels, particularly where they cross the terminal lobe of the ebb shoal. The changes in the swash bars on the swash platform near the shifting channels also have presented hazards to navigating a safe passage into the Atlantic Ocean.

A second problem area was in maintaining a reliable navigation channel in the vicinity of the west flood channel and entrance channel for the Town of Chatham's commercial fishing fleet and U.S. Coast Guard vessels anchored in Aunt Lydia's Cove. Shoaling associated with the growth and evolution of the north flood shoal, Tern Island, and Tern Island south shoal resulted in large changes in the depth and orientation of these two channels.

Dredging History

Ten separate channel dredging operations have been done since 1989 to maintain access to the Fish Pier anchorage (Table 5). The first four were done by local interests through a private contractor, but were not well documented. Subsequent operations dredged either the entrance channel between Tern Island and Tern Island south shoal, parts of the anchorage in Aunt Lydia's Cove and later the west ebb spit of the north flood shoal to connect the anchorage to the west flood channel. The U.S. Army Corps of Engineers first received authorization for the Aunt Lydia's Cove Project on 31 August 1994 under authority of Public Law 86-645, Section 107, as amended. This existing project provides for dredging of an entrance channel 8 ft (2.4 m) deep and 100 ft (30.5 m) wide for a length of 900 ft (274 m), and a 9.5 acre (38,446.5 m^2) anchorage also to a depth of 8 ft (2.4 m). Figure 54 shows the boundaries in blue of the 1994/95 dredging operation, completed in June 1995. More than 100,000 cu yd (76,460 m^3) of sand were

Table 5
Aunt Lydia's Cove – Dredging and Disposal Area Summary 1989-1999

Date	Dredge Agency	Dredging Location	Quantity (cu yd)	Disposal Area
1989	private contractor	entrance ch.[1]	unknown	unknown (Tern Island?)
1991	private contractor	anchorage/ entrance ch.[1]	unknown	unknown (Tern Island?)
1992	private contractor	unknown	unknown	unknown (Tern Island?)
1993	private contractor	anchorage/ entrance ch.	~35,000	unknown (Tern Island?)
1994/95	USACE	anchorage/ entrance ch. (near Tern Is.)	100,000+	Tern Island
March 1998	private contractor emergency dredging	entrance channel to improve flushing	~1,000	Tern Island
May 1998	Barnstable County	entrance ch. (off Claflin Ln)	9,239	~5,000 at Claflin Ln. ~4,000 at various Town landings
May 1998	Barnstable County	anchorage (spot shoal)	1,511	Town Landing -Cockle Cove (truck hall from CBI beach at Fish Pier)
Oct/Nov 1998	Barnstable County	entrance ch. (off Claflin Ln)	8,961	Andrew Harding's Lane beach
May 1999	Barnstable County	entrance ch. (off Claflin Ln)	9,820	Andrew Harding's Lane beach
Oct 1999	Barnstable County	entrance ch. (off Claflin Ln)	6,022	Andrew Harding's Lane beach

Source: Town of Chatham, Department of Coastal Resources and County of Barnstable, Department of Dredging.
[1] Dredge location from aerial photography.

removed during this initial construction. The originally authorized dredged entrance channel was in approximately the same position as where the 1987/89 natural channel had been between Tern Island and south Tern Island shoal. Dredging operations can be seen in progress in Figure 15, where the dredge is cutting through the western portion of the north flood shoal's ebb shield.

Until May 1998, the natural channel between Tern Island and the north flood shoal was the primary all-tide access to the anchorage and Fish Pier.[1] After the spring of 1998, the flood shoal northward migration closed off this channel, restricting tidal flushing. The channel was essentially shoaled in after this time and access to the Fish Pier during most phases of the tide were effectively closed. The Town of Chatham decided to abandon this channel and re-establish a channel on the western marginal ebb spit. Smaller quantities of sand were dredged to maintain the entrance channel through this growing west ebb spit of the north flood shoal by Barnstable County in 1998 and 1999. Controlling depth had shoaled to around 2 ft (0.6 m) mllw over this spit. Sand from the last three

[1] Personal Communication, 2000, T. Keon, Dept. of Coastal Resources, Town of Chatham, MA.

dredging events totaling some 24,803 cu yd (18,964 m^3) was placed on the eroding beach just south of the mainland beach rock revetment at Andrew Harding's Lane. This placement is seen in Figure 24 as the white area on the beach just south of Holway Street.

A proposed new channel orientation is also shown in magenta in Figure 54 for dredging by the New England District in 2000. This channel is within the dredge area maintained by Barnstable County (in yellow). This new channel orientation is based on the recent evolution of the west ebb spit of the north flood shoal, where the narrowest point to cut through the spit is in the orientation shown. This channel location is the same one used by the county, which has only had to dredge the outer end to maintain access. With the possible breach of the flood shoal spillover lobe and re-establishment of the west flood channel in its prebreach position and possible detachment of the entire west side of the flood shoal, the most likely path of a stable navigation channel for the next few years is on a northwest-southeast orientation, through the western ebb spit area.

Dredged Volumes Relative to Inlet Volumes

Records of volumes of material dredged from the Aunt Lydia's Cove entrance channel and anchorage in front of the Fish Pier are available since 1993. A comparison of the volume estimated to be contained in the north flood shoal was compared with the volume of material dredged from the entrance channel and anchorage over the study period (Figure 55a,b). For 1993, about 4.5 percent of the material contained in the flood shoal at that time was dredged. The 1994/95 dredging by the New England District removed about 13.2 percent of the estimated volume of the flood shoal that year. The three dredging operations of 1993 removed some 2.0 percent of the estimated volume of the 1993 flood shoal. In 1999, about 1.5 percent of the estimated flood shoal sand volume was removed. From Table 5 a total of 170,553 cu yd (130,405 m^3) have been documented to have been dredged from the cove since 1993.

To assess what impacts the dredging may have had on the entire inlet system, a compilation of the total estimated volume from all of the inlet morphologic features was done over time. Figure 56 shows the cumulative total estimated volume of each separate inlet feature through time. Comparison of the dredged volumes with the total estimated volume of sand in each inlet feature indicates that the 1993 dredging quantities were 0.36 percent of the inlet sediment volume. The 1994/95 dredge quantity was 0.96 percent of the inlets volume of sand located in the measured inlet features in 1995. The combined dredging in 1998 was 0.16 percent of the total inlet sand volume that year. The two dredging events in 1999 accounted for 0.13 percent of the total inlet sand volume in 1999.

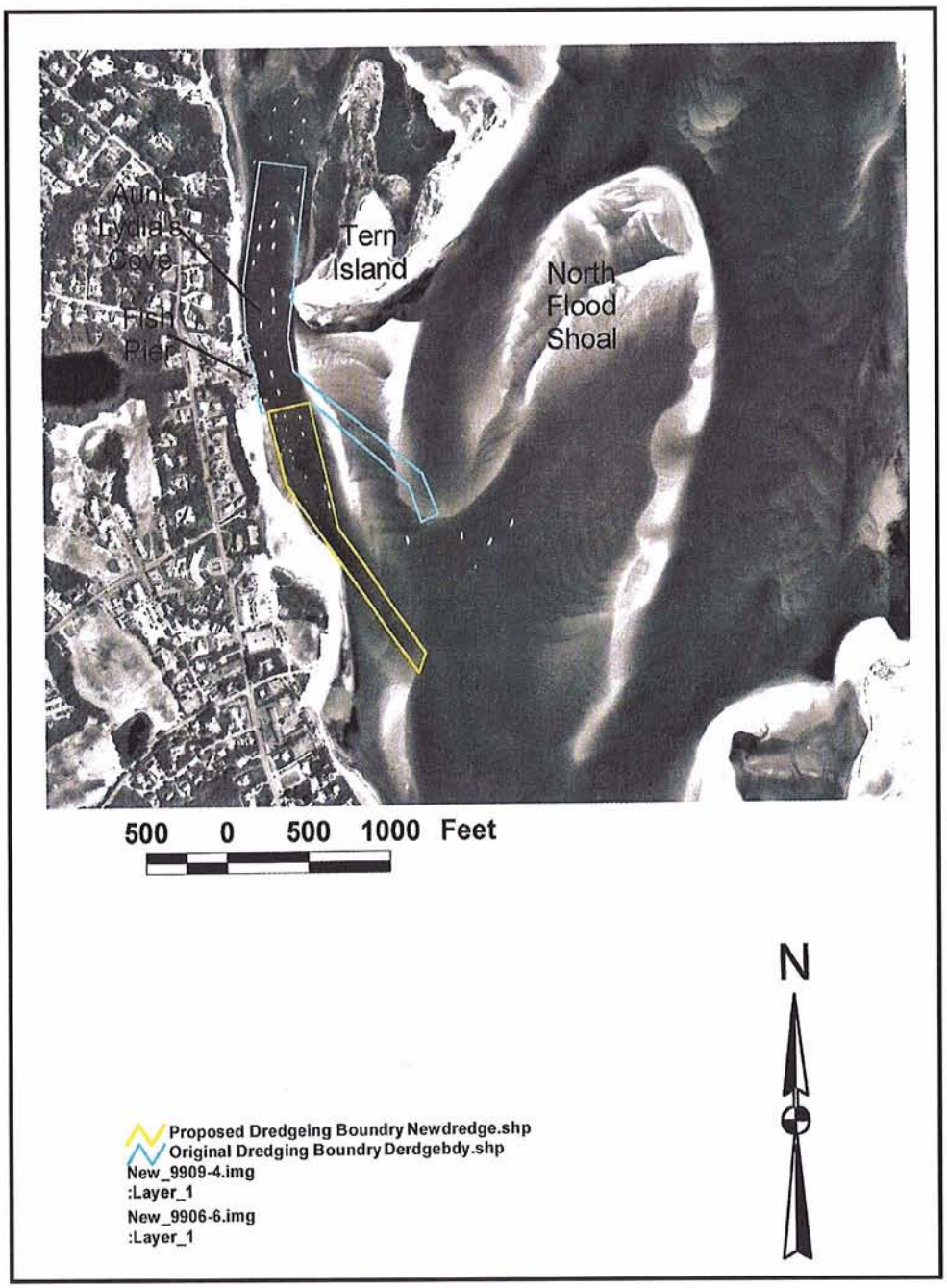
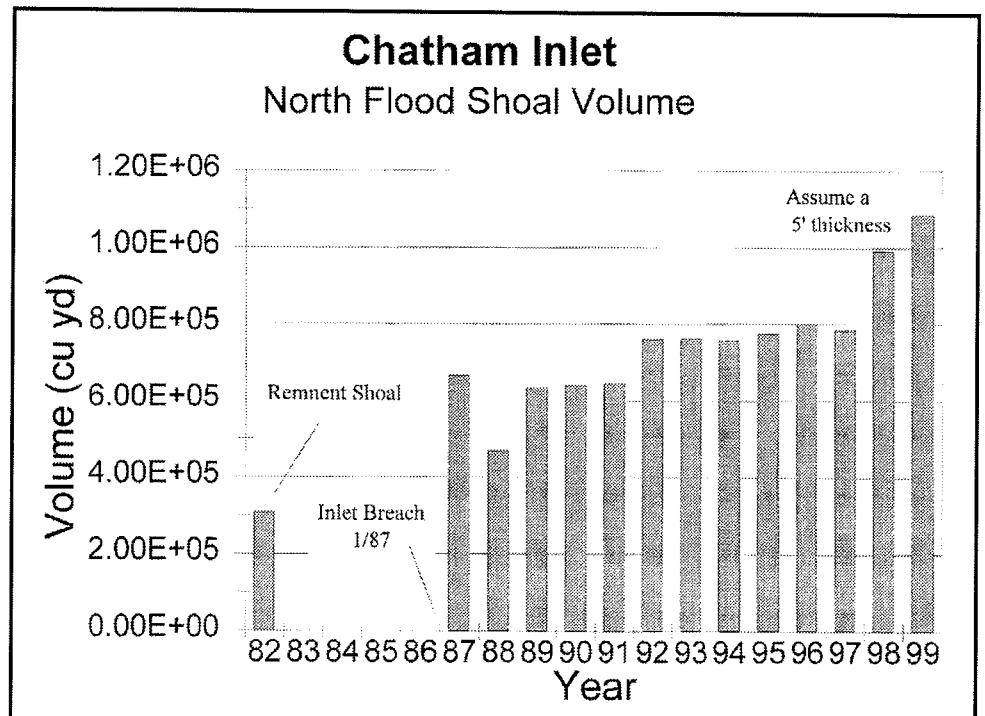
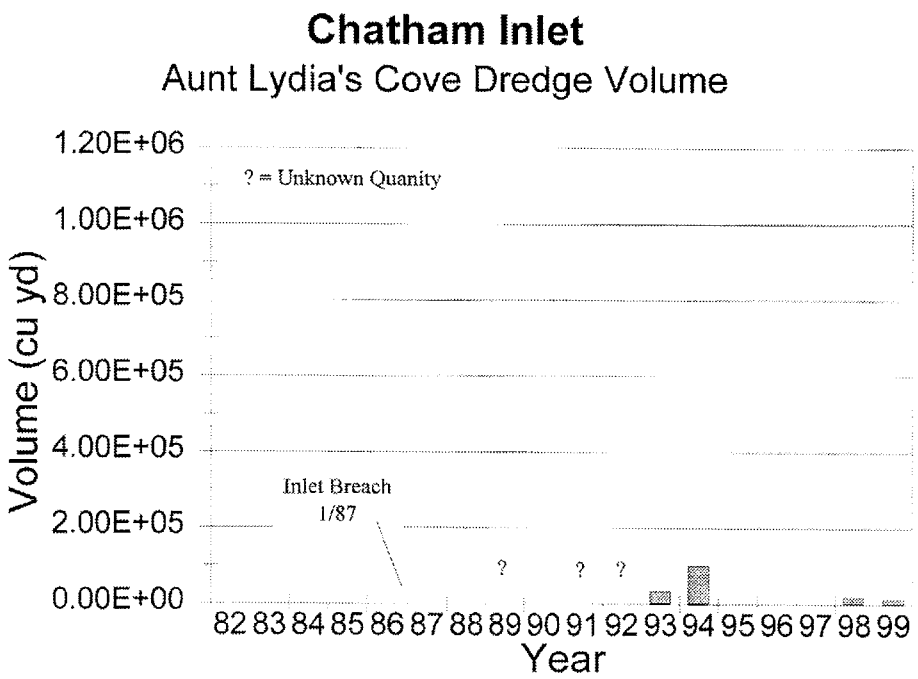


Figure 54. Previous boundaries from 1994/95 dredging and proposed new orientation of dredging boundaries based on current morphodynamics



a. North flood shoal volume change



b. Aunt Lydia's Cove dredge volume

Figure 55. Comparison of north flood shoal volume change with volume of dredged material from Aunt Lydia's Cove (entrance channel and anchorage)

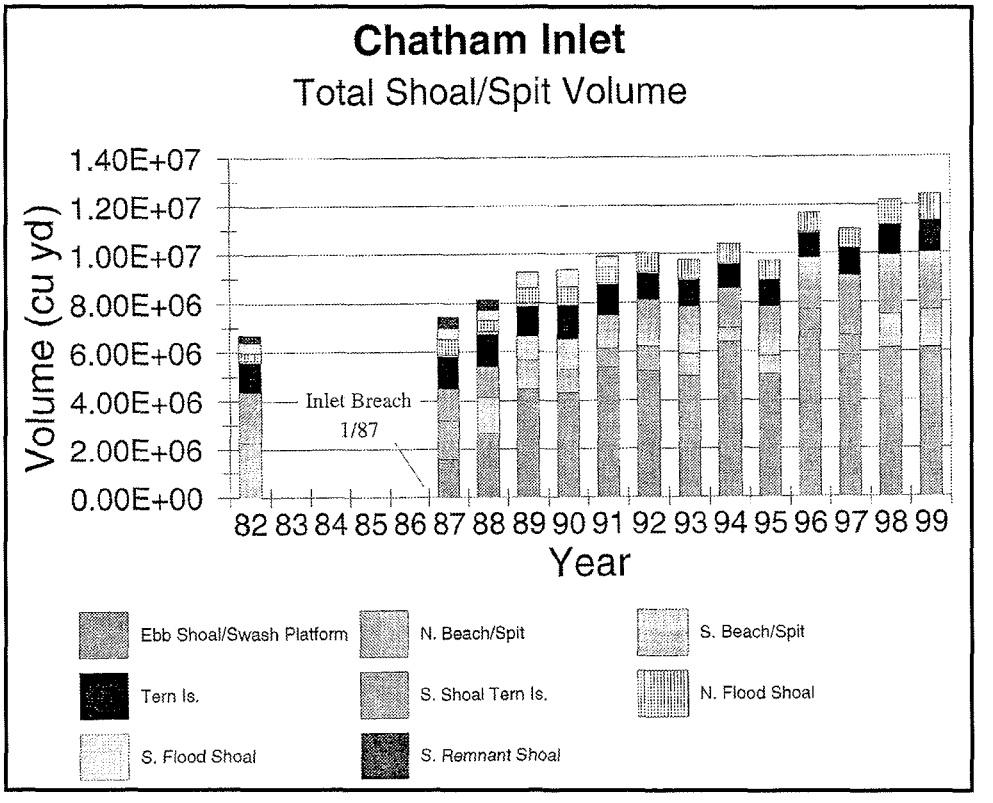


Figure 56. Total estimated volume of sediment in various morphologic units at Chatham Inlet from preinlet to 1999

Dredged Material Disposal

The dredged material placement locations are unknown for 1989, 1991, 1992, and 1993, but are most likely on Tern Island.[1] Material from some infrequent dredging before the breach to maintain the entrance channel was also placed on Tern Island. The 1994/95 dredged material from the entrance channel and anchorage was placed in a disposal mound on Tern Island. Three separate dredging operations during 1998 placed material at various beaches on the mainland shore of the Town of Chatham either in Pleasant Bay, Chatham Harbor, or Nantucket Sound. The two 1999 dredging events placed sand on the beach at the end of Andrew Hardings Lane. Of the quantity of sand removed from the entrance channel and anchorage, 45,514 cu yd (34,800 m^3) can be documented as having been placed back into the Chatham Inlet system on its mainland beaches. Some of the remaining material was placed on Tern Island (100,000 cu yd or 76,460 m^3) and approximately 5,511 cu yd (4,214 m^3) was placed on town beaches outside the inlet influence.

Future disposal sites to consider would be the land bridge area between the mainland and South Beach, which is low and narrow. The shore has been retreating landward at the north tip of South Beach and is subject to frequent overwash during storms. A new breach could form along the land bridge or somewhere on

[1] Personal Communication, 2000, T. Keon, Dept. of Coastal Resources, Town of Chatham, MA.

the north end of South Beach and possibly threaten the mainland shoreline in the vicinity of and to the south of the lighthouse. If the 140-year cycle continues, this South Beach will eventually retreat west and south and weld to the Morris Island and North Monomoy Island shore. This would leave the Town of Chatham mainland shore open to wave and tidal forces until Chatham Inlet and Nauset Spit migrate south and reform the barrier spit. The use of some alternate disposal sites may require non-Federal coast sharing. The continued placement of sand on the beach at Andrew Hardings Lane and the beach in front of the Chatham Lighthouse is also recommended to protect the upland property in this area as the mainland beach evolves in response to the inlet migration. Additional disposal of material on the seaward edge of the ebb shoal (in around 10 ft (3.1 m) of water depth) is also possible. This nearshore disposal site will keep material in the littoral zone and allow sand bypassing to continue to the South Beach area.

It is difficult to predict accurately the evolution of the shoreline and inlet over the next 50 years, but by examining the patterns of shoreline adjustment from the past cycle, a general idea of the change can be achieved. A review of historic shoreline evolution from the 1850s to the 1920s (Weishar, Stauble, and Gingerich 1989) indicated that the last breach occurred in 1846 approximately 2 miles (3.2 km) to the north of the present inlet (just off Allen Point at the southern end of Pleasant Bay). For some 20 to 30 years the ebb and flood shoals of this new inlet developed. The South Beach barrier island was deprived of this normally uninterrupted southerly sand transport and experienced accelerated erosion, and decreased island width in the vicinity of the Town of Chatham (Figure 57). In November 1871, a new second breach cut through this low barrier just opposite the then twin Chatham Lights (almost in the same position as the 1987 breach). The 1873 shoreline has distinct similarities to the present inlet configuration of the early 1990s. By the early 1880s, this sand-starved island had breached in numerous places. The town was unprotected from the ocean waves and currents and suffered severe erosion to the mainland shorefront, including the loss of the two lighthouses. Street ends were lost and several houses had to be moved inland. Between 1886 and 1893 a smaller South Beach barrier island had formed closer to the mainland. By 1920 (a little less than 50 years after the 1871 breach) the barrier island finally welded to the mainland in the vicinity of Morris Island. Monomoy Island and Morris Island were now part of a continuous spit attached to the south end of Chatham's mainland. The mainland beach was wide at this time, with no offshore barrier spit or island. Nauset Spit reformed and migrated south so that by 1950 (99 years after the breach), the new spit had again formed a protective barrier to the mainland.

With the former cycle, the inlet dynamics were slightly different in that the 1846 larger northern inlet and 1871 southern inlet coexisted and were for the most part connected through north Chatham Harbor for some 10 years. Chatham Harbor was also open to the south until the 1880s. The present configuration with one inlet carrying the prism for the estuary system presents a different evolutionary twist. It is hypothesized that the sand starved South Beach will still repeat the cycle of erosion through overwash, island breaching, and landward migration. Since Tern Island is privately owned and has reached its capacity, this site may not be available for future dredge material placement. Future placement may be

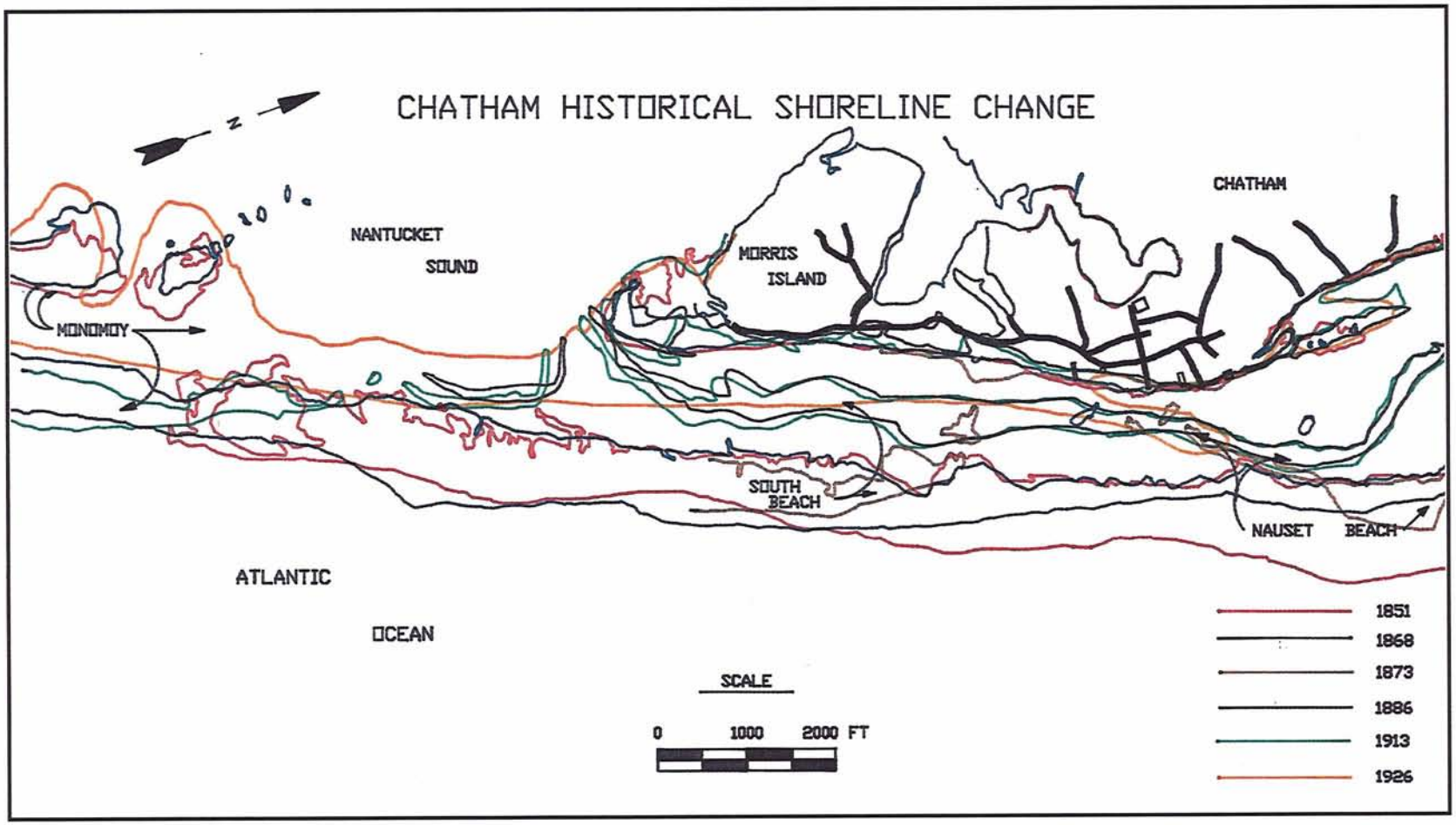


Figure 57. Historic shoreline change from last inlet breach cycle (1851-1926)

needed on the land bridge to slow any possible catastrophic breakup of South Beach, although at present, the area is a nesting ground for Piping Plover.

At the present time, the quantities being dredged from the entrance channel and anchorage at Aunt Lydia's Cove to maintain navigation to the Fish Pier are small relative to the inlet as a whole. The volume of material removed has been less than 1 percent of the entire inlet sand volume and appears not to have affected the evolutionary pattern of the inlet shoals or adjacent shorelines. Placement of 76 percent of the dredged material has been within the inlet system with 26.7 percent being placed on eroding mainland beaches near the inlet opening to stabilize landward retreat of the shoreline. The location of dredging on the west side of the flood shoal is off to the side of the main tidal circulation within Chatham Harbor. Continued dredging in the locations currently proposed for the newest dredging operation and any additional near future dredging are only enhancing the natural channel patterns to keep open navigation to the Fish Pier.

Current regulatory approvals allow for up to 100,000 cu yd (76,460 m^3) to be dredged within the area of the entrance to Aunt Lydia's Cove within any single year, with a cap of 350,000 cu yd (267,610 m^3) in a 5-year period. To date, dredging volumes have been well below this annual volume, except in 1994/95. The present volume of the north flood shoal is estimated to be near 1.1 million cu yd (0.84 million m^3), so the maximum allowable dredging volume per year is about nine percent of the total shoal volume. If this maximum amount of sand were to be removed in any year, there still would be minimal impact on the growth of the north flood shoal.

The impact of this dredging in the vicinity of Aunt Lydia's Cove on the growth of the north flood shoal appears to be minimal. The small amount of sand removed to maintain the navigation channel opening through the west spit of the flood shoal is not changing the natural northward migration patterns of the flood shoal or the growth and redevelopment of the natural west channel in its preinlet orientation. Natural processes are much more dominant in the evolution of the inlet. Sand moves southward in the direction of dominant drift along the ocean side of Nauset Spit. The southward and westward growth of the spit resumed in 1998 after several years of westward movement of the spit into the bay (1990-1993) and northeastward recurving (1994-1997). The present natural change from the dominance of the south channel through the ebb shoal to the newly developed north channel will further affect this migration rate of the spit and growth of the swash platform. The north channel will probably develop into the dominant channel and proceed to migrate southward. As this happens, Nauset Spit and the north swash platform will most likely resume a more southward growth. From past cycles, the southward movement of the inlet could take several years (up to 50 years based on the last cycle) to move Nauset Spit past the present inlet position. The South Beach will probably break up through overwash events that will migrate the barrier island and the present ebb shoal westward until it welds onto the mainland. This south and westward migration of the South Beach and present ebb shoal will allow Nauset Spit and the inlet to migrate south also.

7 Conclusions

Weishar, Stauble, and Gingerich (1989) completed an initial reconnaissance study of the effects of a new breach through Nauset Spit which occurred due to an extratropical storm on 2 January 1987. The breach quickly formed a new inlet which has become the main inlet in a complex four-inlet system on the southeast ocean coast of Cape Cod at Chatham, MA. That study ended in 1989 and the need is now present to update the evolution of the inlet/barrier-bay system which has continued to evolve for the past 13 years. The inlet's geomorphic features are continuing to evolve and have not yet reached an equilibrium condition. Maintaining a navigation channel into Aunt Lydia's Cove is still a problem for the Town of Chatham commercial fishing fleet and the U.S. Coast Guard that maintains a rescue vessel at the Fish Pier at the harbor. This new study has evaluated the growth and change occurring over the past 13 years and provided guidance on inlet evolutionary trends, regional sand management, and navigational channel stability to assist the District in its navigation planning.

Historic Evolution - Areas of Concern

Although 13 years is a short time frame in the average 140-year cycle of Chatham Inlet, certain patterns have emerged in how the inlet is evolving with the prevailing coastal processes. The use of historic aerial photography allowed the mapping of morphology changes in the inlet's channels, shoals, and adjacent shorelines. By comparing the distinct migration patterns of each feature, trends in spatial and temporal evolution were shown. A complex interaction of morphodynamics was identified and distinct patterns in evolution were shown. As the inlet continues toward a dynamic equilibrium of forces and morphologies, several areas of concern have developed.

Aunt Lydia's Cove entrance channel and anchorage

As the inlet has evolved, the main navigation channel trouble spots have been the entrance channel into Aunt Lydia's Cove and the achorage at the Fish Pier. The orientation and depth of this channel has been controlled by the location and evolution of the north flood shoal, Tern Island, and the Tern Island south shoal. All three of these features existed in the preinlet state as remnant sand features. The initial channel orientation even before the 1987 inlet formation was in a general east-west direction, connecting a dominant west flood channel with the

anchorage. After the inlet opened, the north flood shoal began to trap sand as the tidal flow made the sharp bend to the north into north Chatham Harbor. The shoal expanded to the northeast as well as toward the east. The entrance channel moved to the north through 1990 above the expanding and northward migrating shoal (Figure 58). The west channel was deflected to the west around the widening flood shoal from 1990 to 1994 (Figure 59). As the west flood channel was moving west, the entrance channel changed from an east-west orientation in 1990 to a more north-south orientation beginning in 1991. As of 1994, the west flood channel was up against the mainland shore, north of Claflin Landing and the Tern Island south flood shoal was also deflating. This channel reorientation contributed to eroding the shoreline and bottom scour of the Tern Island south flood shoal's shallow tidal flat. With this change in orientation, the entrance channel became shorter in length through the west ebb spit.

As the north flood shoal expanded, the west flood channel was truncated by the expanding ebb shield and a flood ramp developed that occupied the southern portion of the channel position by 1995. The west ebb spit of the flood shoal expanded west, moving closer to the mainland shore. The growth in sand on the ebb shield area of the flood shoal actually bisected the west flood channel and the shoaling severely limited navigation to the northern Chatham Harbor and Pleasant Bay. The entrance channel (now in a north-south orientation and functioning as a marginal ebb channel) became a bypass around the shoal to gain access to both the anchorage and the north bay area. As the flood shoal encroached up the estuary, the ebb shield and west ebb spit all but closed off the west flood channel (Figure 60). In 1998 and 1999 dredging of this west ebb spit off Claflin Landing was required to maintain what had become the only viable path. The progression was for a more north-south entrance channel to be forced over against the mainland shore by the expanding flood shoal.

The anchorage area within Aunt Lydia's Cove began to have shoaling problems, particularly along the eastern Tern Island side, as the north flood shoal evolved. Tidal current velocities have increased in this area as the entrance channel orientation has moved to a more north-south orientation. Tidal flow that originally was in the west flood channel was now diverted somewhat into the anchorage area, around the growing ebb shield. Ebb-dominated shoal patterns developed to the north of the anchorage as the tidal flow was diverted through the anchorage by the growth of large sand flats north of Tern Island.

West flood channel

As of 1995 the west flood channel was for the most part closed off by the westward and northward growing flood shoal. What had been the predominant channel up to Pleasant Bay had been forced out of position by the flood shoal growth and eventually became shoaled in. Beginning in 1996, small spillover lobes had formed in the ebb shield as ebb currents from the upper bay tried to flow out to the inlet, but was restricted since no distinct channel was present. Beginning in 1997 and becoming more well established by 1999, a very large spillover lobe had formed in the historical position of the preinlet west flood channel and appears to be attempting to break through the flood shoal and

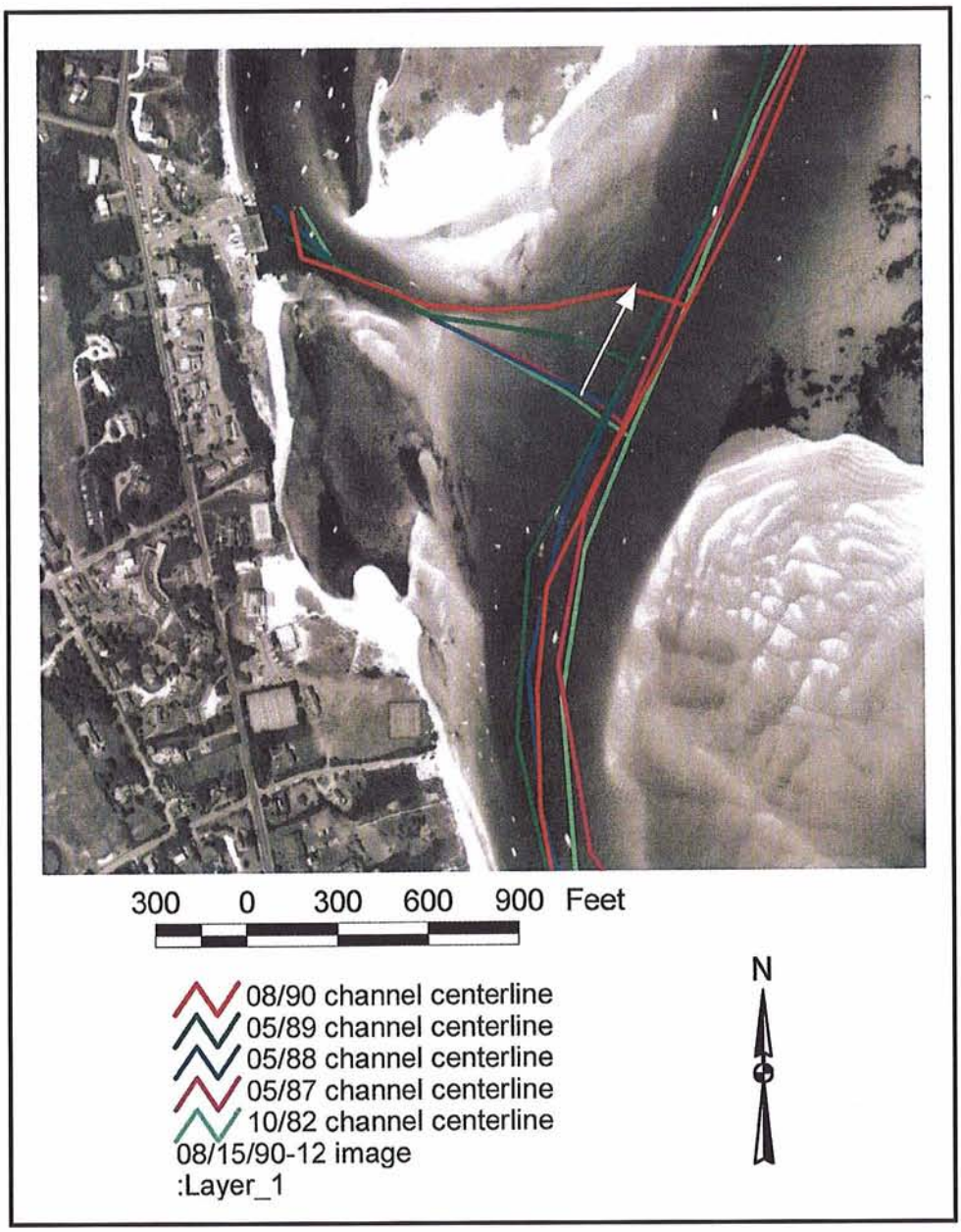


Figure 58. Evolution of Aunt Lydia's Cove entrance channel 1982-1990

re-establish a more permanent channel to Pleasant Bay (visible in Figure 60). If this channel is successful in cutting through the ebb shield, the western half of the flood shoal will be separated and re-establish the Tern Island south shoal. At that point, the location of the entrance channel will have to be re-evaluated in light of the stability of this shoal feature.

Chatham Harbor scour hole

As of the bathymetric survey collected by SHOALS in 1997, a large scour hole had formed with depths of around 29 ft (8.8 m) mllw at the confluence of the

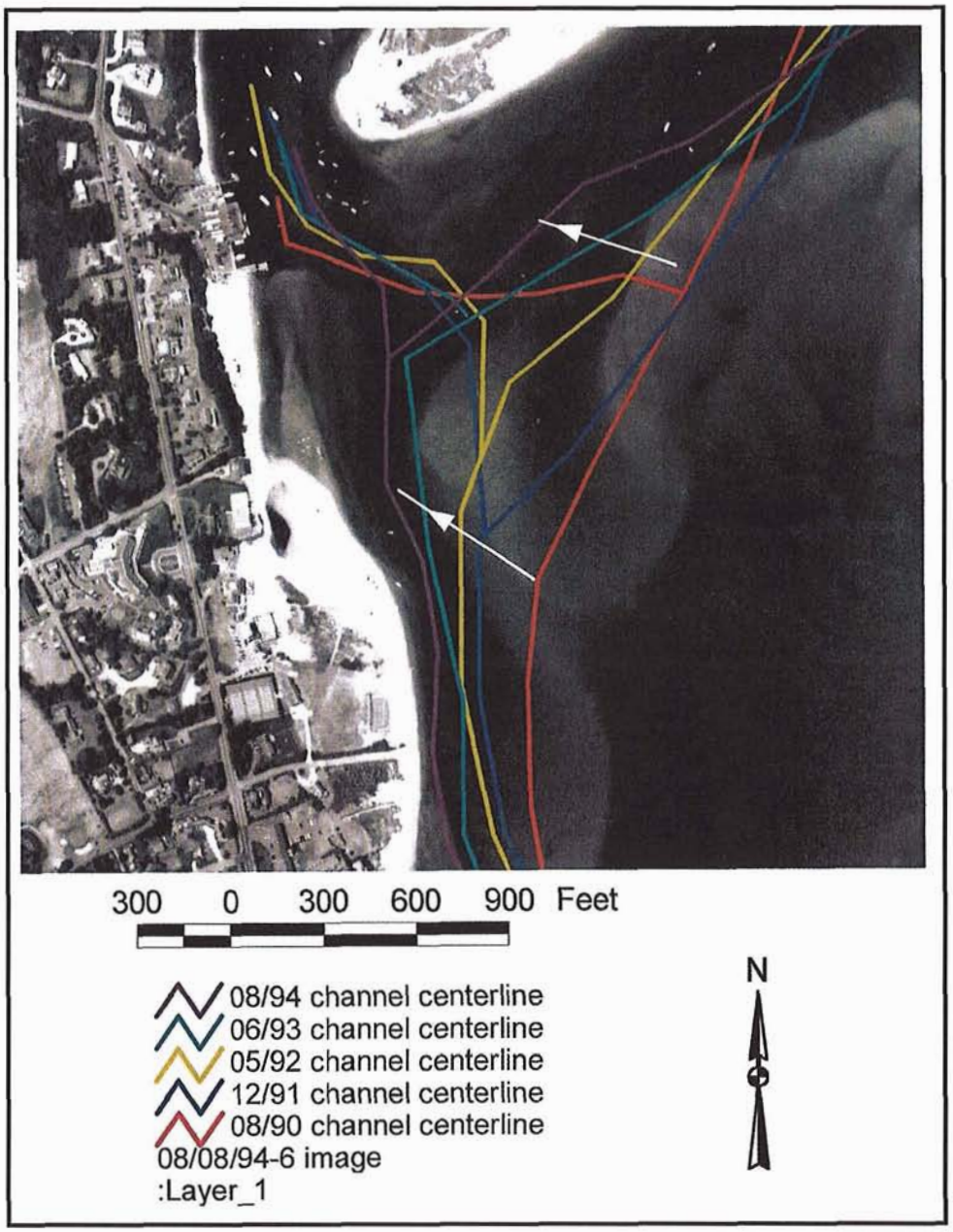


Figure 59. Evolution of Aunt Lydia's Cove entrance channel 1990-1994

landward end of the north ebb channel, the elongated south ebb channel and the east and west flood channels. This scour hole was present on a field survey in the summer of 1999 and was located immediately off the edge of the mainland shore rock revetment. The westward growth of the north beach spit has also narrowed Chatham Harbor in this area. The entire tidal prism for Pleasant Bay has been forced through this narrowing area, which has increased the tidal velocities. Tidal currents from all four channels meet in this area, along with waves entering the inlet throat, and most likely create a turbulent flow condition during parts of the tidal cycle. This scour hole needs to be monitored to assess any erosion of the bed

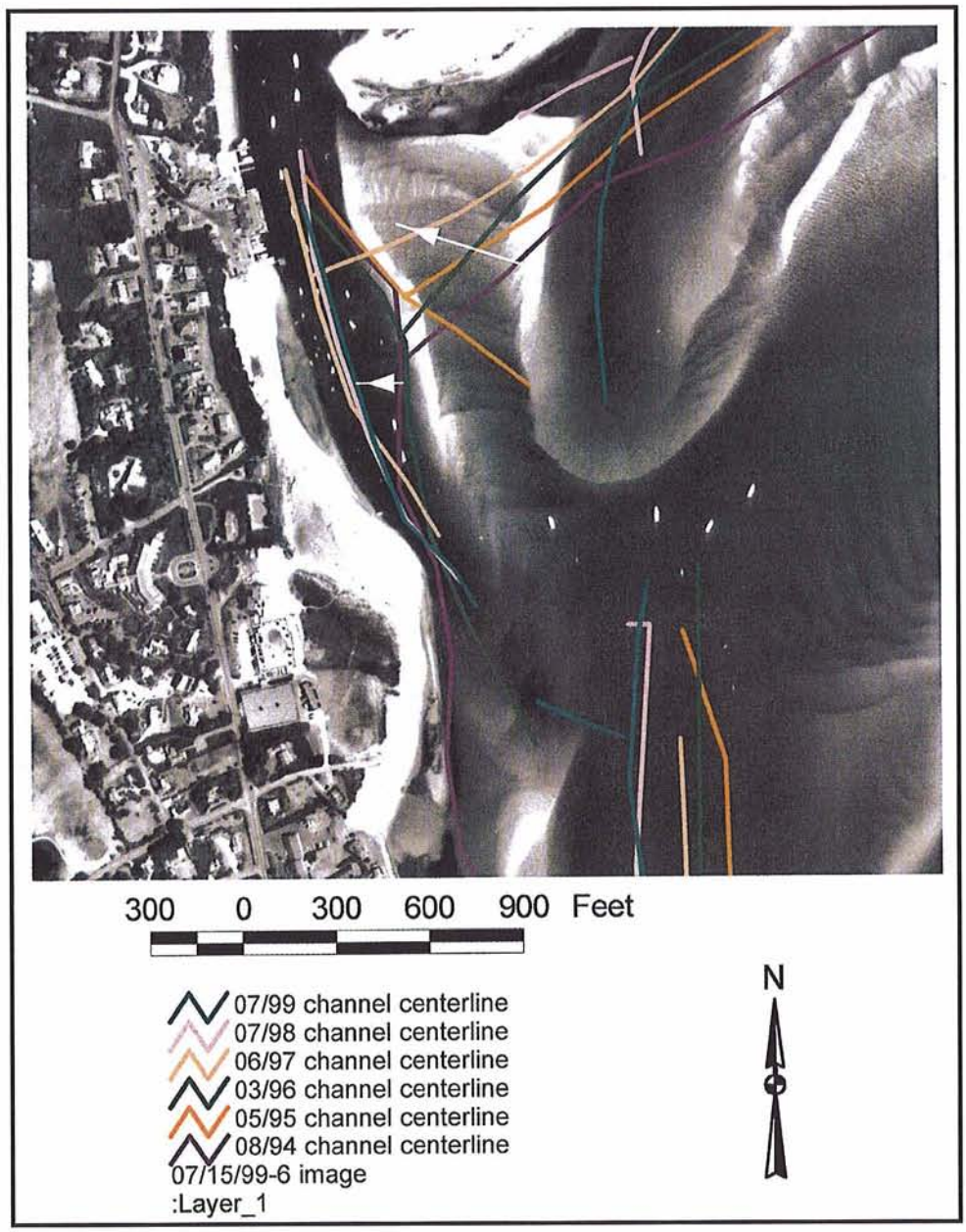


Figure 60. Evolution of Aunt Lydia's Cove entrance channel 1994-1999

at the base of the rock, which may result in undermining of the seawall built to protect the upland property between Claflin Landing and Holway Street.

Main ebb channels

Beginning in 1995, a north ebb channel formed at the northern end of the ebb shoal. For the past 5 years this channel has evolved and now appears to be establishing itself as the dominant ebb channel. The southern ebb channel has become so elongated that it has become hydraulically inefficient, basically being forced against the mainland shoreline and land bridge to South Beach by the expanding

ebb shoal swash platforms. The reduced area and extended length has caused this channel to narrow and shoal-in, therefore carrying less of the tidal prism of the inlet. While there are two channels, the flow has not been strong enough to establish a definite outlet and shoaling and shifting channels are common. This has presented difficult navigation conditions over the terminal lobe at the seaward end of both channels. Shoaling and poor navigation will continue, as the north channel becomes the dominant channel. This may take some time, given the size and complexity of the ebb shoal and its three swash platforms.

South Beach land bridge

As of 1992, the South Beach spit grew west and incorporated the south flood shoal and south remnant shoal as it welded to the mainland beach in front of the present Chatham Lighthouse. This event greatly changed the circulation pattern of the four inlet multiple system and made the new Chatham Inlet the single opening for north Chatham Harbor and Pleasant Bay. Since that time the northern tip of South Beach has undergone severe erosion and migrated landward. This sediment bridge is subject to beach scarping and overwash during high-water level events. As of now, the shoreline extending between South Beach and the mainland is in a relatively stable position. If the past inlet cycles are any indication of the future, South Beach will continue to lose sediment and migrate landward. In the most extreme case, the island will break apart with several breaching episodes in the future as the general island mass moves toward the mainland.

Mainland shore evolution

Since the opening of Chatham Inlet, the shoreline on the mainland directly in front of the inlet has undergone erosion and shoreline retreat. A rock revetment composed of a series of individual private and some public structures was completed by 1990 to protect the upland infrastructure along the shoreline most threatened. As the inlet evolved, an erosion wave moved both to the south and north of this severe erosion area. Further south and north, sand was accreting as spits along the beachfront. The welding of South Beach to the mainland in 1992 reversed the erosion trend to the beach in front of Chatham Lighthouse and to the South Beach area. What had been a retreating shoreline became an accretionary shoreline, with the accretion migrating north as the land bridge gained sand over time.

In the later years, erosion has occurred on the mainland beaches adjacent to the rock revetment. On the north end of the revetment, dredged material was placed on the beach at the foot of Claflin Landing . Adjacent to the south end of the revetment, sand was placed on the beach at Andrew Hardings Lane, in between this revetment and a smaller rock revetment to the south. This sand placement has slowed the shoreline retreat trend in this erosion-stressed area. At the present time the mainland beaches adjacent to the rock revetment are maintaining their position.

Inlet Evolutionary Trends

Flood shoal and Aunt Lydia's Cove navigation

In the short term, the recommended dredging of a channel orientated from northwest to southeast over the thinnest area of the west ebb spit of the flood shoal will provide a serviceable navigation channel, with the least amount of dredging. This dredged channel will connect the anchorage with the lower part of the west flood channel and out to the inlet. In the near future, the apparent re-establishment of the west flood channel through the spillover lob of the ebb shield of the flood shoal will change the tidal circulation, navigation channel orientation, and flood shoal growth. It appears that the west side of the present flood shoal will become detached as the channel cuts through the shoal. The sand in this western part of the present shoal will form a shoal similar to the former Tern Island south shoal. The position and orientation of the entrance channel to the anchorage may have to be re-evaluated as this shoal detachment takes place.

With the split of the flood shoal, the trend of shoal growth will probably be located more to the east side of Chatham Harbor. The northward movement may also continue until an equilibrium is established with the ebb and flood flow dynamics. The growth in the flood shoal in both measured area and calculated volume has continued since inlet formation and this influx of sand has interfered with both the east and west flood channel position and depth. The re-established west flood channel through the ebb shield area of the flood shoal may restore a more stable tidal circulation to the upper reaches of the estuary.

Ebb shoal navigation

With the development of the north ebb channel since 1995, the ebb shoal has undergone a switch from the once single main ebb channel that has migrated to the south to a two-channel system. The north ebb channel appears to have begun the process to become the dominant channel, and to abandon the south ebb channel. Southward and landward migration of the ebb shoal has all but pinched off the elongated and hydraulically inefficient south ebb channel.

Future development of the more efficient north ebb channel will establish a growth trend in the northern ebb shoal/swash platform, moving the north end seaward. The north ebb channel will begin to migrate more to the south and repeat the cycle of southward migration. The southern part of the ebb shoal and its large swash platform will migrate south and landward following the South Beach toward the mainland. Navigation over the ebb shoal will become more difficult, as the north channel becomes the main ebb flow route and the south channel loses its identity as the southern swash bars migrate randomly, bisecting the swash platform into several small ebb channels.

Shoreline evolution

There is evidence over the past two years (1998/99) that the north spit is beginning to migrate back to the south through a series of swash bars and recurved spit growth. It is unclear in the short term how the spit will react to the increased dominance of the north ebb shoal. Eventually, the north spit will again migrate southward prograding Nauset Spit to the south, once again following the 140-year cycle. The last cycle took around 100 years for the spit to grow past the town's mainland shore.

The South Beach and its land bridge to the mainland will most likely move southward and landward by overwash and breaching and weld to the mainland shore as it did in the late 1920s in the last cycle. This process will add large amounts of sand to the mainland shoreline and eventually the southern part of Chatham Harbor will disappear. In the distant future the spit will connect Morris Island with North Monomoy Island. In the meantime, the mainland shoreline may undergo periods of alternating accretion and erosion as the sand of the shoals and South Beach migrate in an uneven fashion toward it.

Regional Sand Management

The maintenance of navigation channels at Aunt Lydia's Cove will continue to be a challenge. It is recommended that in the short-term, dredging of the west ebb spit of the flood shoal be continued in its general location as shown in Figure 54. A re-examination of the orientation will be needed after the west flood channel re-establishes itself and the sand in the detached western part of the flood shoal takes on its own morphology.

Dredging of the ocean side of the ebb shoal in the vicinity of where the north ebb channel is located may be necessary in a few years as the ebb shoal and its two channels evolve. In this transitional period, when two ebb channels are present, currents may not be strong enough to maintain a clear channel through the terminal lobe of the ebb shoal. Eventually, one of the channels will become more dominant and the ebb flow will be able to maintain an open passageway to the ocean. Dredging was not necessary in this area when the inlet first opened since the single main ebb channel was sufficient to maintain a channel as it migrated to the south. The removal of small quantities of material to facilitate safe passage over the ebb shoal as the inlet evolves to a more dominant north channel may be necessary. There should be little adverse impacts if the dredged material is bypassed to the south, mimicking the natural processes.

A regional sand management plan needs to take into account the long-term cycle that has occurred at Chatham at least twice in its recorded history. Short-term remedial action should be based on the general trends that will most surely occur in this third cycle. Disposal of the dredged material should be in anticipation of future changes and needs. This cycle has started out slightly different from the past cycle in that only one inlet is now draining the Chatham Harbor and Pleasant Bay estuary system. The present inlet has formed at the site of the southern inlet of a two-inlet system of the past cycle. Each cycle will be driven by

the frequency and intensity of storms, but the general pattern will follow the prevailing coastal processes, which are unchanged from past cycles.

Dredging practices to date have centered around the navigation to the Fish Pier and have been limited to the Aunt Lydia's Cove area. A comparison of the average annual shoal dynamics (based on a measure of area change and estimated volume) to quantities of dredging showed that the amount of sand removed was on the order of less than 1 percent of the overall inlet sand volume. Most of that material was placed on Tern Island or on the mainland beaches that have experienced erosion due to the inlet evolution. Future dredged material disposal should be kept in the system and be placed in anticipation of erosion problems based on the general Chatham Inlet cycle. In-water disposal of material on the shallow seaward edge of the ebb shoal is possible and will allow sand to remain in the littoral system and bypass to the south. The main trend will be for South Beach to migrate south and west and finally weld onto the mainland opposite Morris Island. (This phase of the cycle took around 50 years on the last cycle.) For some time the mainland shoreline will be open to the ocean as the breakup and landward movement of South Beach occurs. Nauset Spit will over time migrate south and bypass the mainland shoreline again being lead by the southward migration of the throat of Chatham Inlet (a process that took 100 years on the last cycle).

The dredging currently authorized by regulatory approval, to maintain a navigable entrance channel to the anchorage in Aunt Lydia's Cove consists of removing less than 10 percent of the volume of the current north flood shoal in any given year and in practice has removed on the order of 1 percent of the volume of the existing flood shoal during the last several dredging operations. The location of the dredging area on the west ebb spit of the north flood shoal is somewhat removed from the main inlet geomorphology and sediment dynamics and should have negligible impacts on the evolution of the inlet. The main processes that affect the dredging area are ebb and flood tidal flow on the western edge of the flood shoal. A new re-establishment of the west flood channel by natural forces will have a significant effect on modifying the tidal circulation and morphodynamics of this north flood shoal area that has been expanding up-estuary and growing laterally since inlet formation.

The largest dynamics occur on the ebb shoal/swash platform area and this area is presently undergoing a large natural perturbation in the switch of the dominant ebb channel from the former south ebb channel to the recently formed north ebb channel. The North Beach spit has also undergone a shift from a general pattern of growth to the west into the bay with the development of several recurved spits, to a more southerly migration of the entire spit form over the past 2 years, as was common immediately after formation. This change to a dominant north ebb channel over the ebb shoal and a smaller north swash platform will play a more significant role in the migration and evolution of the north spit over the next few years than any dredging of small quantities on the western edge of the flood shoal.

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14. ABSTRACT

During an extratropical storm on 2 January 1987, a breach formed in a barrier spit opposite the Town of Chatham on the southeast corner of Cape Cod, MA. An inlet rapidly developed at the site of the breach from wave action and tidal currents. Typical inlet morphology developed at this new inlet, including a large ebb shoal and swash platform and a single main ebb channel on the ocean side. In the narrow elongate bay, a north and south flood tidal shoal developed over remnant sand shoals. Over time, the inlet throat widened as the adjacent barrier spits recurved back into the bay. Navigation through this quickly evolving inlet system became difficult with channel shoaling and migration. Dredging of parts of the navigation channel has been undertaken since 1989 to maintain an opening for commercial fishing and U.S. Coast Guard interests between the Atlantic Ocean and the Fish Pier. This dredging removed only a minimal volume of the material, and has had little impact on the large dynamic system. Inlet morphology evolution include the welding of the South Beach to the mainland beach, closing off south Chatham Harbor and returning the system to a single inlet system in 1992. By 1995, a north ebb channel had formed creating a two-ebb channel inlet. Major changes have occurred in the entrance channel and anchorage area of Aunt Lydia's Cove. The growth and migration of the north flood shoal has changed this channel configuration which has required several dredging events to maintain navigation to the Fish Pier. Based on the flood shoal area morphology evolution patterns, new dredging boundaries were

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recommended for maintaining the navigation channel in a rapidly evolving system. A review of the historic 140-year cycle of inlet formation and evolution at Chatham Inlet suggests that, while there are slight differences, the general trend in inlet change is following the two previous inlet formations. Based on the general historic evolution and the detailed 13-year present history, guidance for sand management and future navigation channel stability have been addressed.