



**US Army Corps  
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*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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# **Impacts of Navigation Channel Maintenance Dredging on the Coastal Processes of Chatham, Massachusetts**

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Final report

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# Preface

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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

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

| <b>Multiply</b>      | <b>By</b> | <b>To Obtain</b>       |
|----------------------|-----------|------------------------|
| 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)<sup>1</sup> 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

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<sup>1</sup> 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

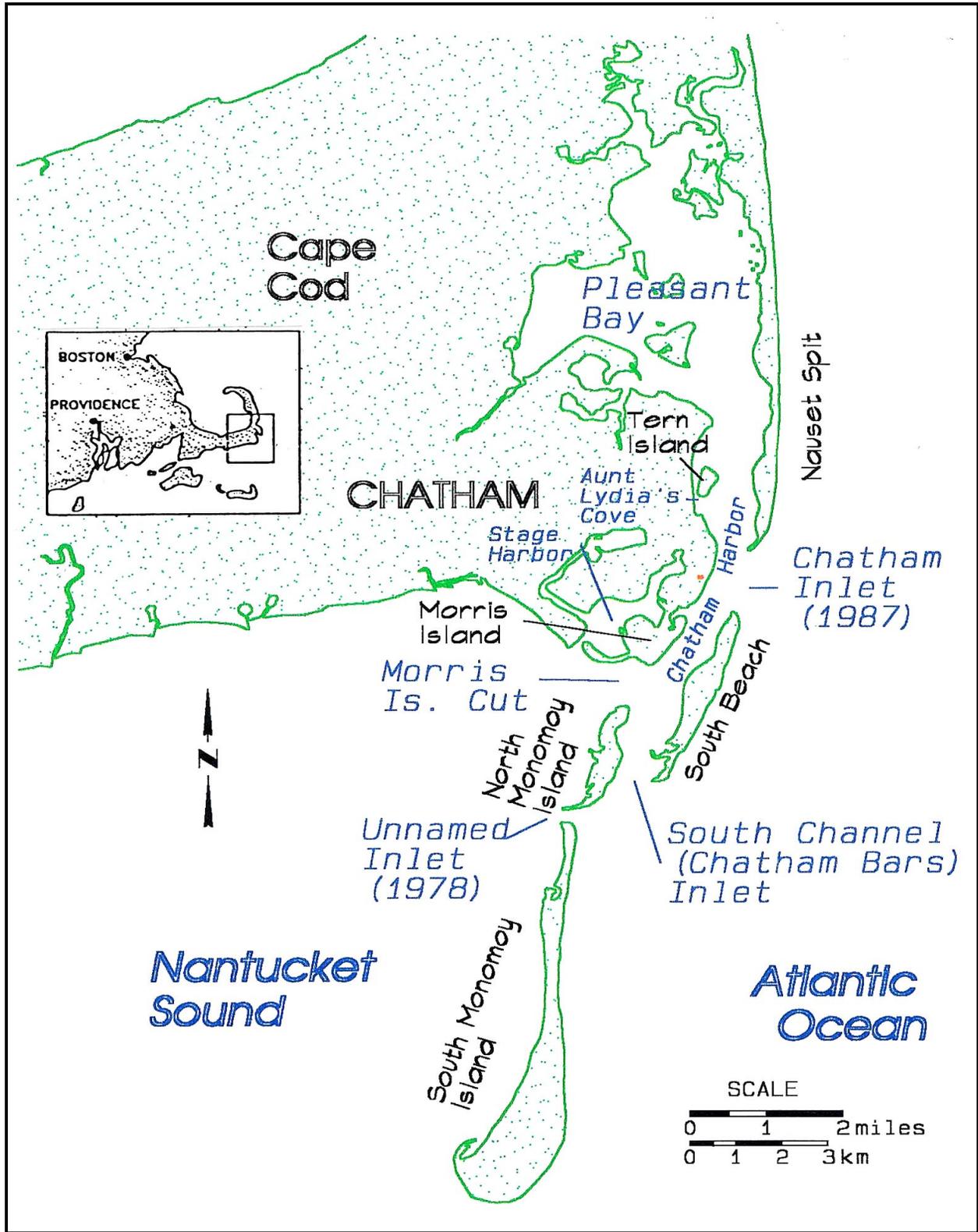


Figure 1. Location map showing main geographic features of Chatham area

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  $4.7 \times 10^5$  cu yd/year ( $3.6 \times 10^5$  m<sup>3</sup>/year) (Weishar, Stauble, and Gingerich 1989) and  $6.5 \times 10^5$  cu yd/year ( $5 \times 10^5$  m<sup>3</sup>/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.

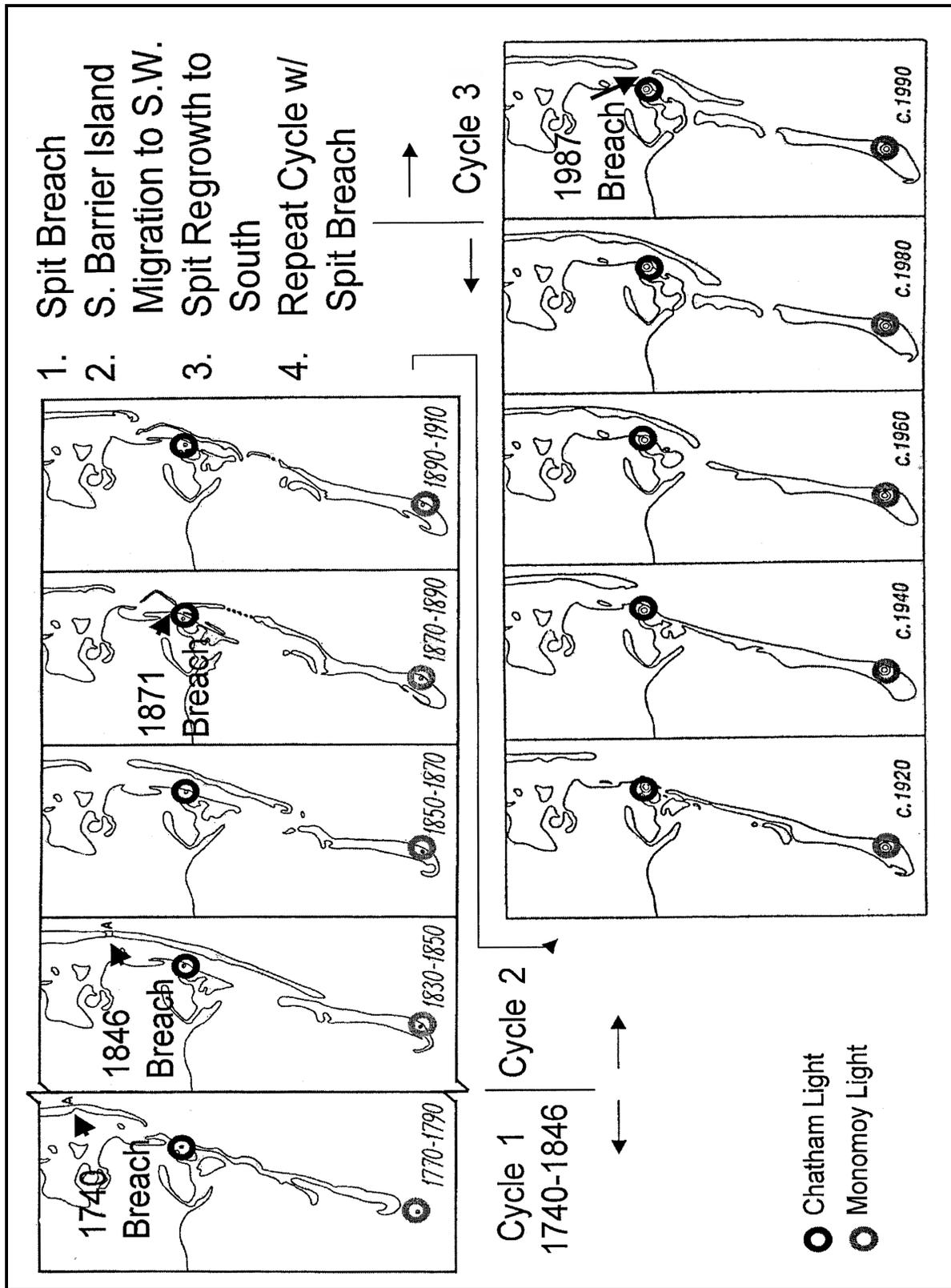


Figure 2. Cyclic change in Chatham shoreline since 1770s (after Giese 1988)

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 1991 are 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  $9 \times 9$  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.

| <b>Table 1<br/>Aerial Photographs of Chatham Inlet and Harbor</b>  |              |             |                                    |   |  |   |
|--|--------------|-------------|------------------------------------|---|--|---|
| <b>Date</b>  | <b>Scale</b> | <b>Type</b> | <b>Original Source<sup>1</sup></b> | <b>Location of Prints<sup>2</sup></b>                                   | <b>Remarks</b>                               | <b>Air Photo Frame</b>                                      |
| 11/20/82 <sup>3,4</sup>  | 1:18000      | Color       | Col-East                           | CHL   | Preinlet                                     | 9538A-1A-11, 12, 13   |
| <b>01/02/87 Inlet Formed</b>   |              |             |                                    |   |  |   |
| 05/07/87 <sup>3,4</sup>  | 1:9000       | B/W         | Col-East                           | CHL   | First postinlet partial coverage of mainland | 10970-7, 9, 11, 13  |
| 09/16/87 <sup>3</sup>  | 1:8000       | B/W         | ACT/AEM                            | CHL   | Partial coverage of mainland                 | AS779 2-5, 2-7, 2-9, 2-11                                   |
| 01/11/88 <sup>3</sup>  | 1:9000       | B/W         | Col-East                           | CHL-prints of flight line 2<br>Chat- fit line 1 scanned WHG             | 11:55 EST<br>Partial coverage of mainland    | 11257-2-7, 2-9, 2-11, 2-13 CHL<br>11257-1-9,1-11,1-13 - WHG |
| 05/05/88 <sup>3,4</sup>  | 1:18000      | B/W         | Col-East                           | CHL   | 11:55 EST                                    | 11466-9, 10, 11   |
| 09/01/88 <sup>3</sup>  | 1:18000      | B/W         | Col-East                           | CHL   | 10:10 EST                                    | 11588-11, 12, 13  |
| 12/29/88 <sup>3</sup>  | 1:18000      | B/W         | Col-East                           | CHL   | 11:04 EST                                    | 11687-2-4A, 5A, 6A  |
| 05/23/89 <sup>3,4</sup>  | 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 <sup>4</sup>  | 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 <sup>4</sup>  | 1:18000      | Color       | Col-East                           | CHL   |  | 13309-1-11, 12, 13  |
| 05/22/92 <sup>4</sup>  | 1:18000      | B/W         | ECM                                | Chat/scanned by WHG   | 11:20 EST                                    | ECM P00819 11-7,11-8,11-9                                   |
| 06/25/93 <sup>4</sup>  | 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 <sup>4</sup>  | 1:18000      | Color       | James Sewall                       | CHL   | 14:20 EST                                    | 153.545 1-5,1-6,1-7   |
| 09/12/94   | 1: 38000     | Color       | NOAA                               | <a href="http://mapindex.nos.noaa.gov">http://mapindex.nos.noaa.gov</a> | 15:13 GMT                                    | 5WKV4769  |
| 05/20/95 <sup>4</sup>  | 1:18000      | B/W         | Col-East                           | Chat/scanned by WHG   |  | 15425-9, 10, 11   |
| 03/27/96 <sup>4</sup>  | 1:18000      | B/W         | Col-East                           | Chat/scanned by WHG   | 11:55 EST                                    | 16138-10, 11, 12  |
| 6/27/97 <sup>4</sup>   | 1:18000      | B/W         | Aero Tech                          | Chat/scanned by WHG   | 12:30 EST                                    | 9704004 14-3, 4, 5  |
| 07/02/98 <sup>4</sup>  | 1:18000      | B/W         | James Sewall                       | Chat/scanned by WHG   |  | 13680-2-5, 6, 8   |
| 07/15/99 <sup>4</sup>  | 1:18000      | B/W         | Col-East                           | Chat/scanned by WHG   | 08:40 EST                                    | 19264-6-4, 5, 6   |
| <sup>1</sup> Col-East, P.O. Box 347, Harriman-West Airport, North Adams, MA 01247<br>ACT/AEM Co. 14 Cedar Swamp Road, Smithfield, R.I. 02917<br>James Sewall Company, Old Town, ME, 04468<br>ECM = East Coast Mapping, 9 Constitution Drive, Bedford, NH 03110<br>Aero Tech Co.<br><sup>2</sup> CHL = U.S. Army Engineer Research and Development Center, Vicksburg, MS (Coastal and Hydraulics Lab).<br>Chat = Town of Chatham/photos scanned by WHG = Woods Hole Group, Falmouth, MA.<br><sup>3</sup> Photo set used in Weishar, Stauble, and Gingerich (1989).<br><sup>4</sup> 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

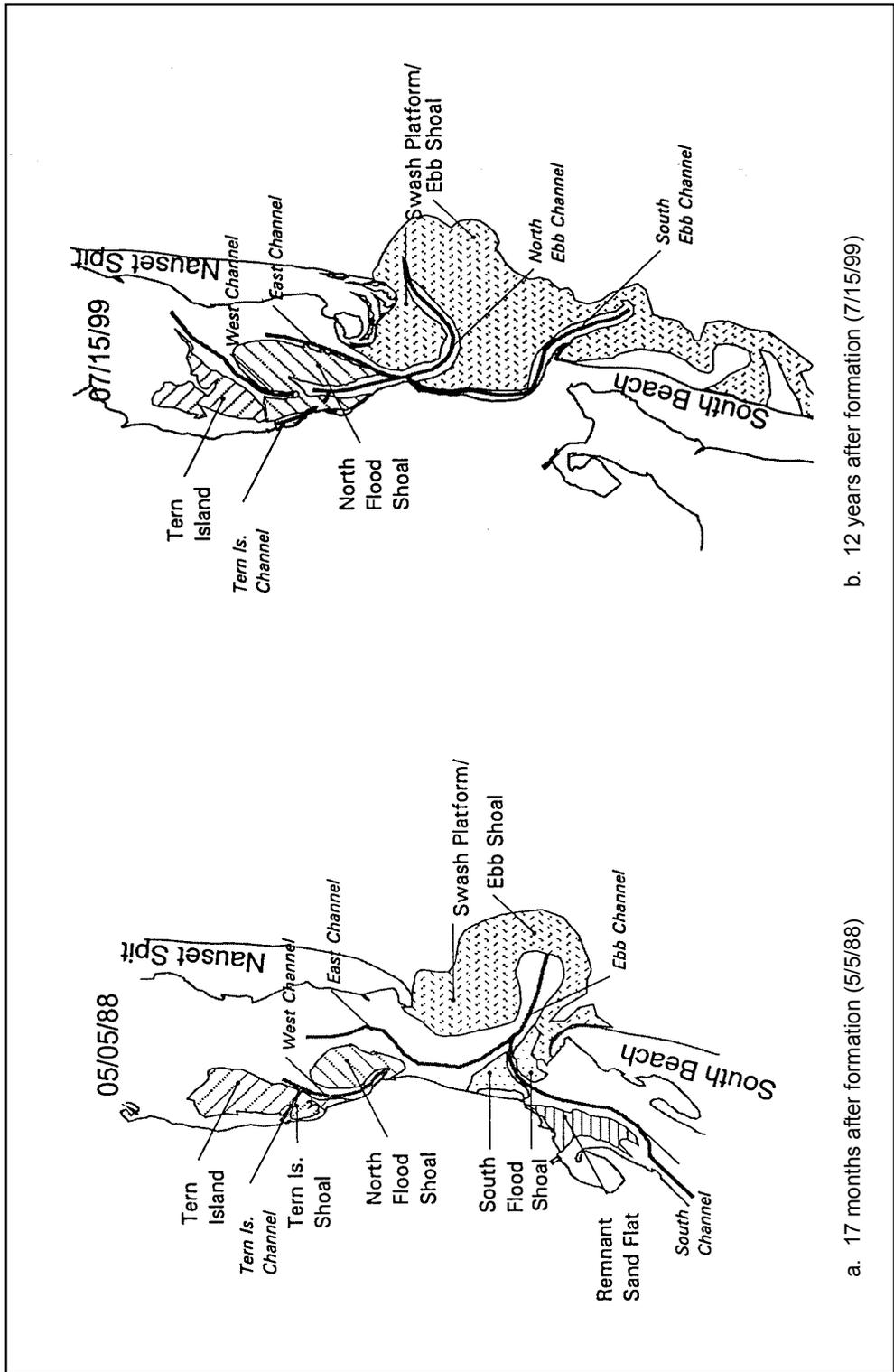
Maps have been produced of the north Nauset Spit and South Beach ocean and bay shoreline, and the Chatham mainland shoreline. The shoreline was defined visually on the aerial mosaic as the wet/dry line on the beach, based on the variation in color between the lighter gray tones of the dry beach and the 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 runoff, 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



b. 12 years after formation (7/15/99)

a. 17 months after formation (5/5/88)

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

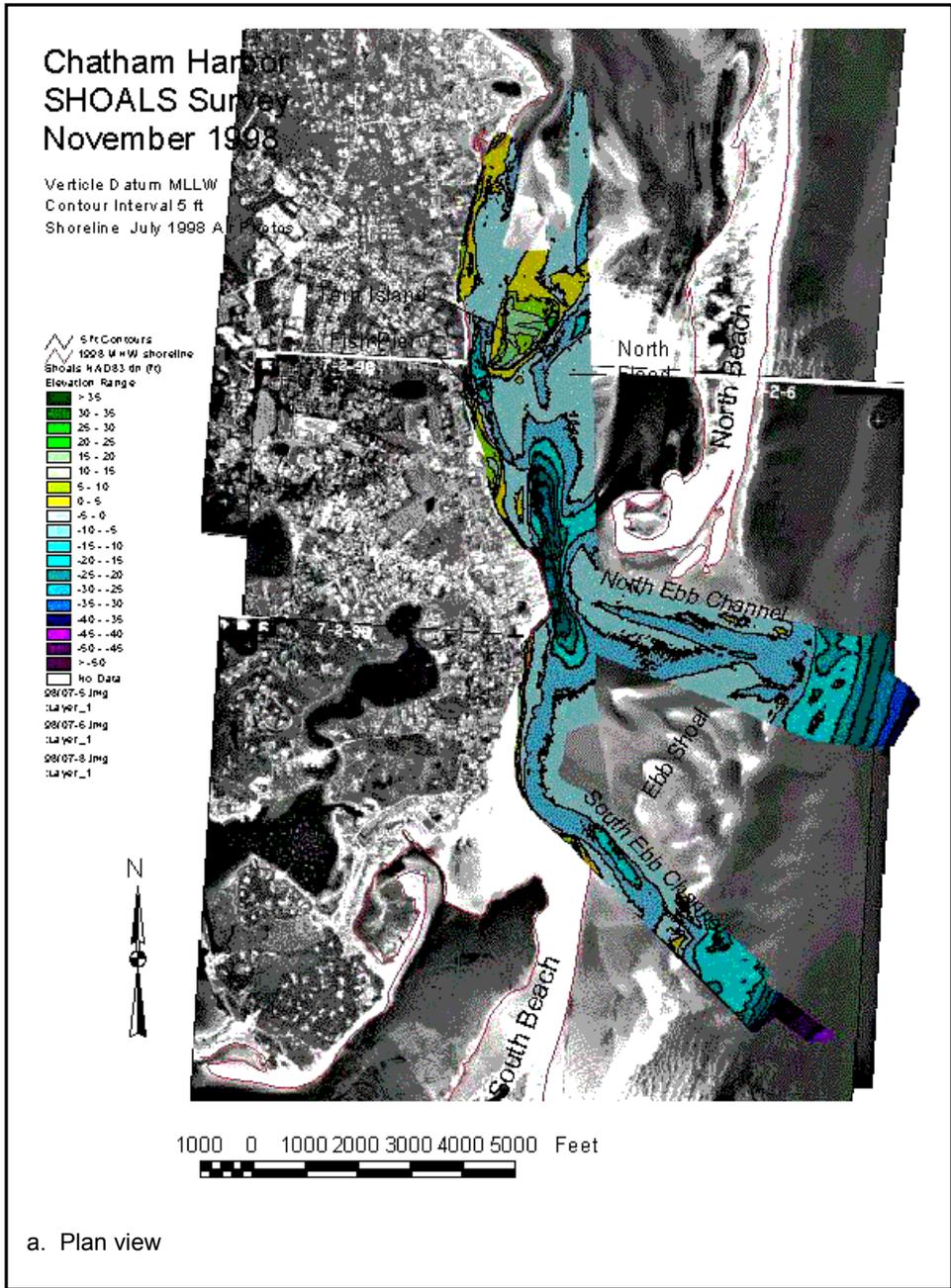


Figure 4. Bathymetry of portions of Chatham Inlet collected in November, 1987 by the SHOALS survey system (Continued)

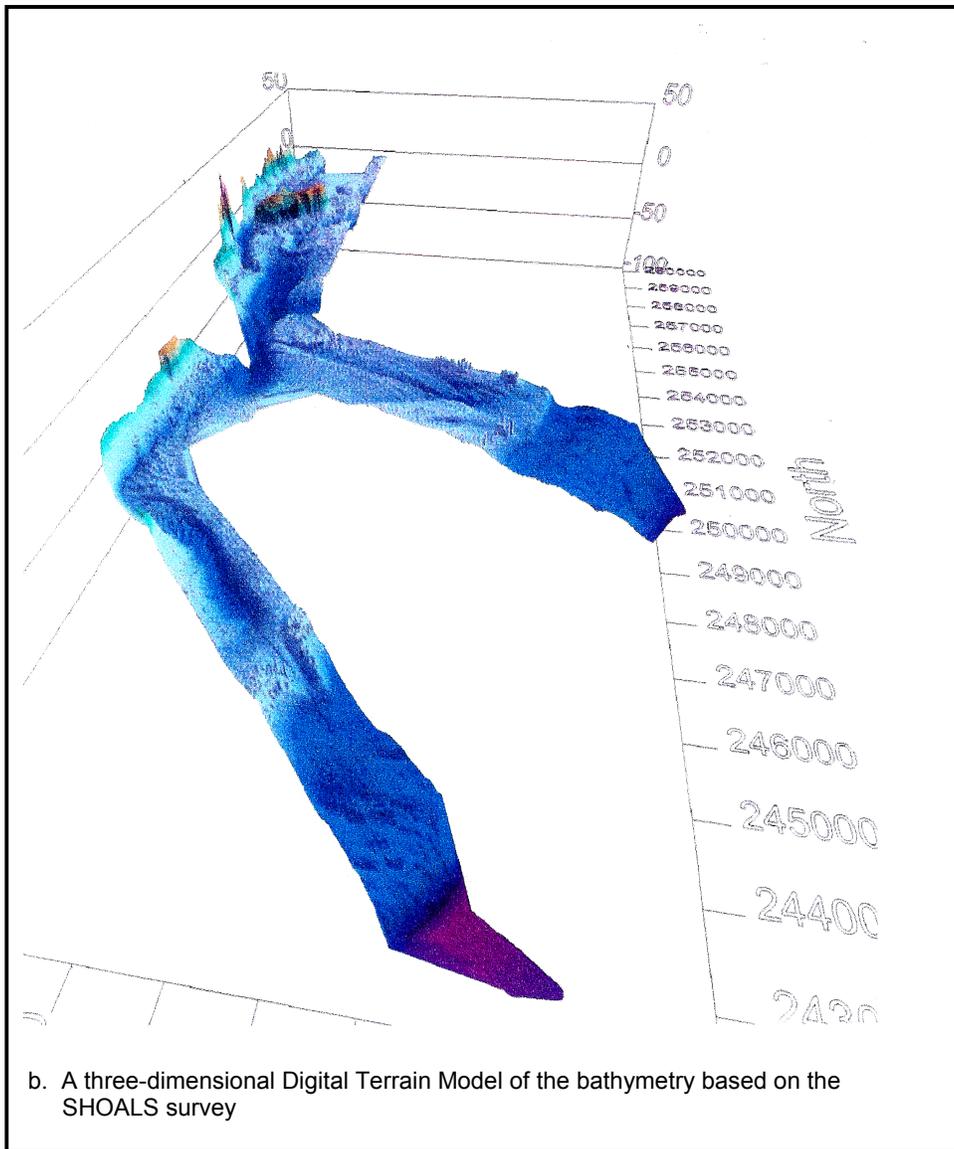


Figure 4. (Concluded)

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

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## 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

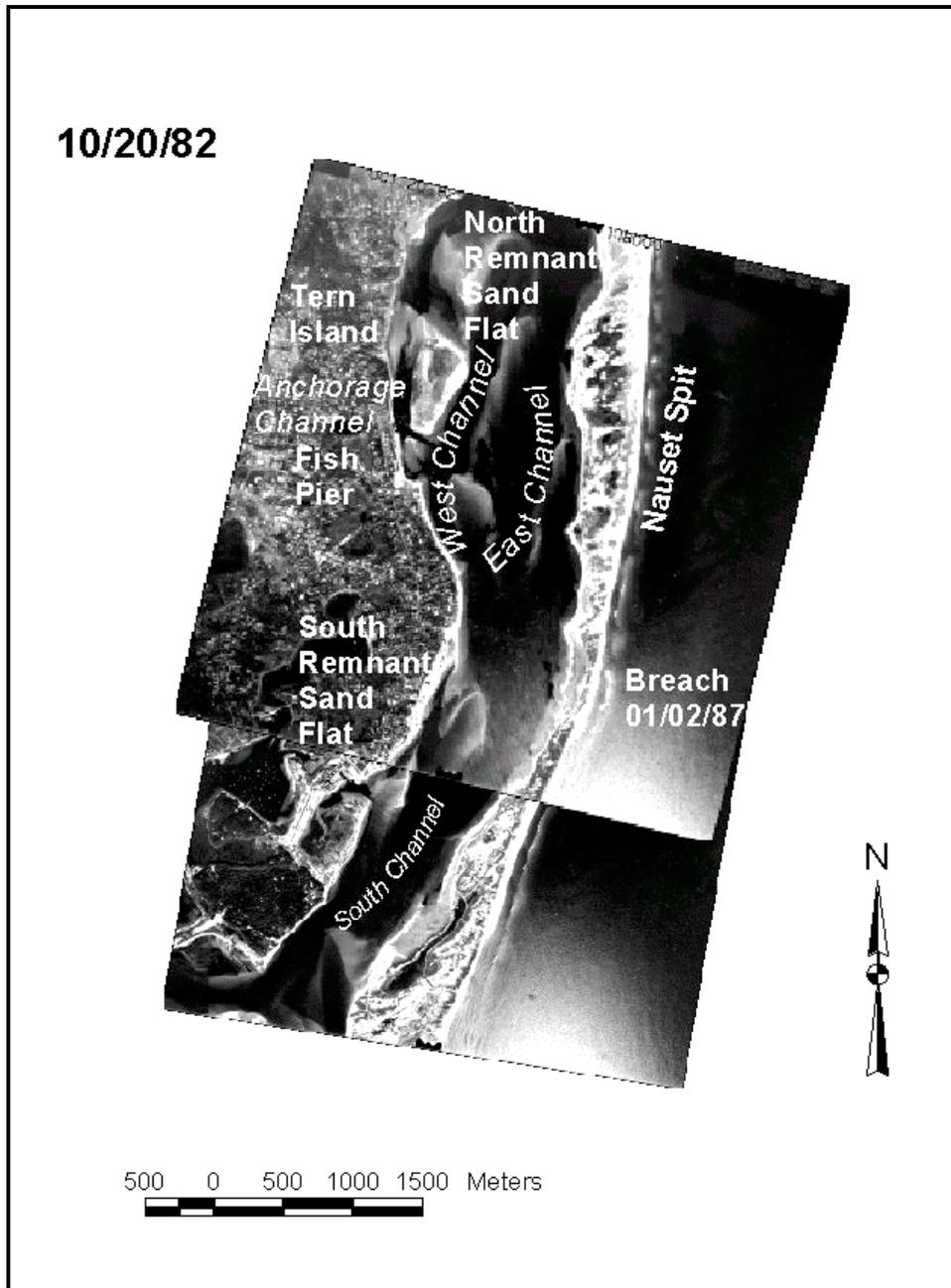
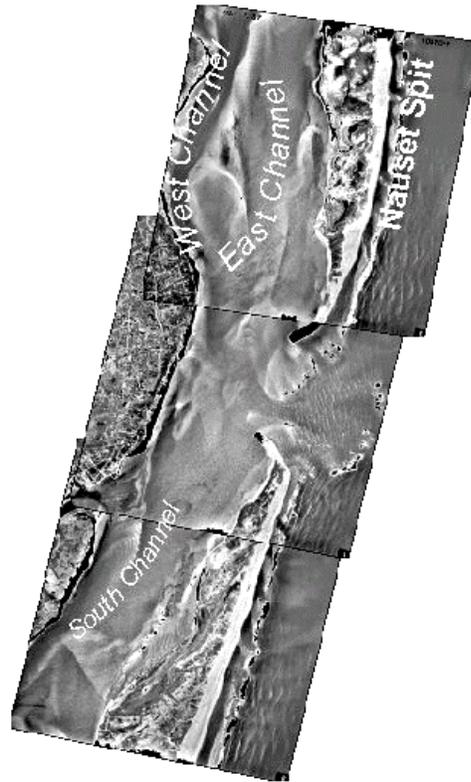


Figure 5. Preinlet morphology of Chatham Harbor, 20 October 1982

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).

05/07/87



500 0 500 1000 1500 Meters

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.

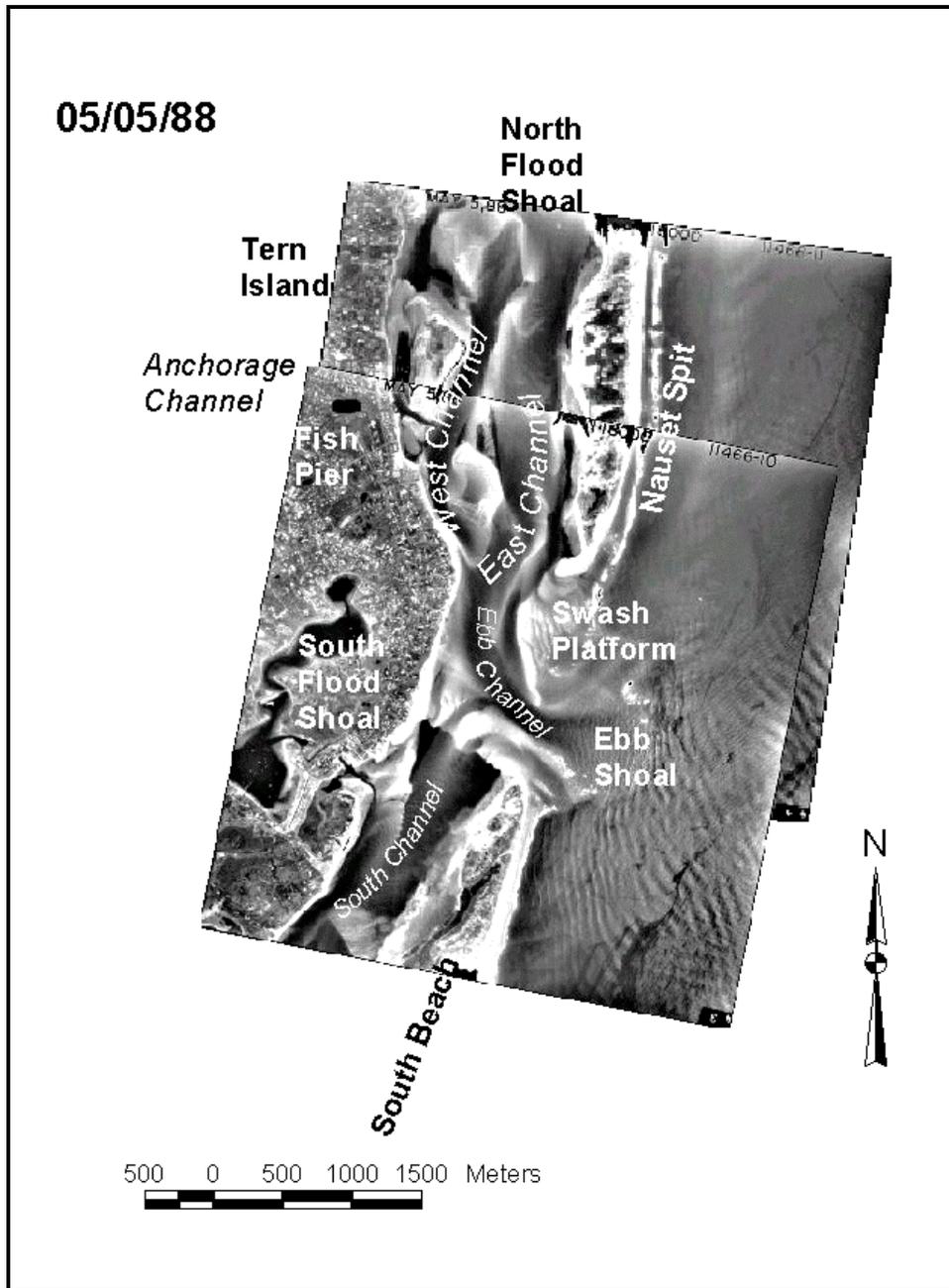


Figure 7. Morphology of Chatham Harbor, 5 May 1988

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.

05/23/89

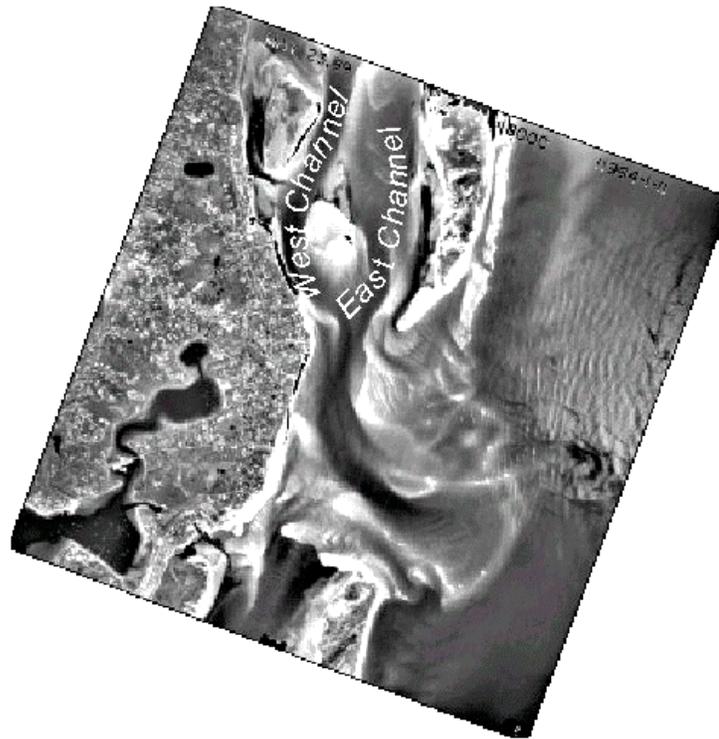


Figure 8. Morphology of Chatham Harbor, 23 May 1989

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

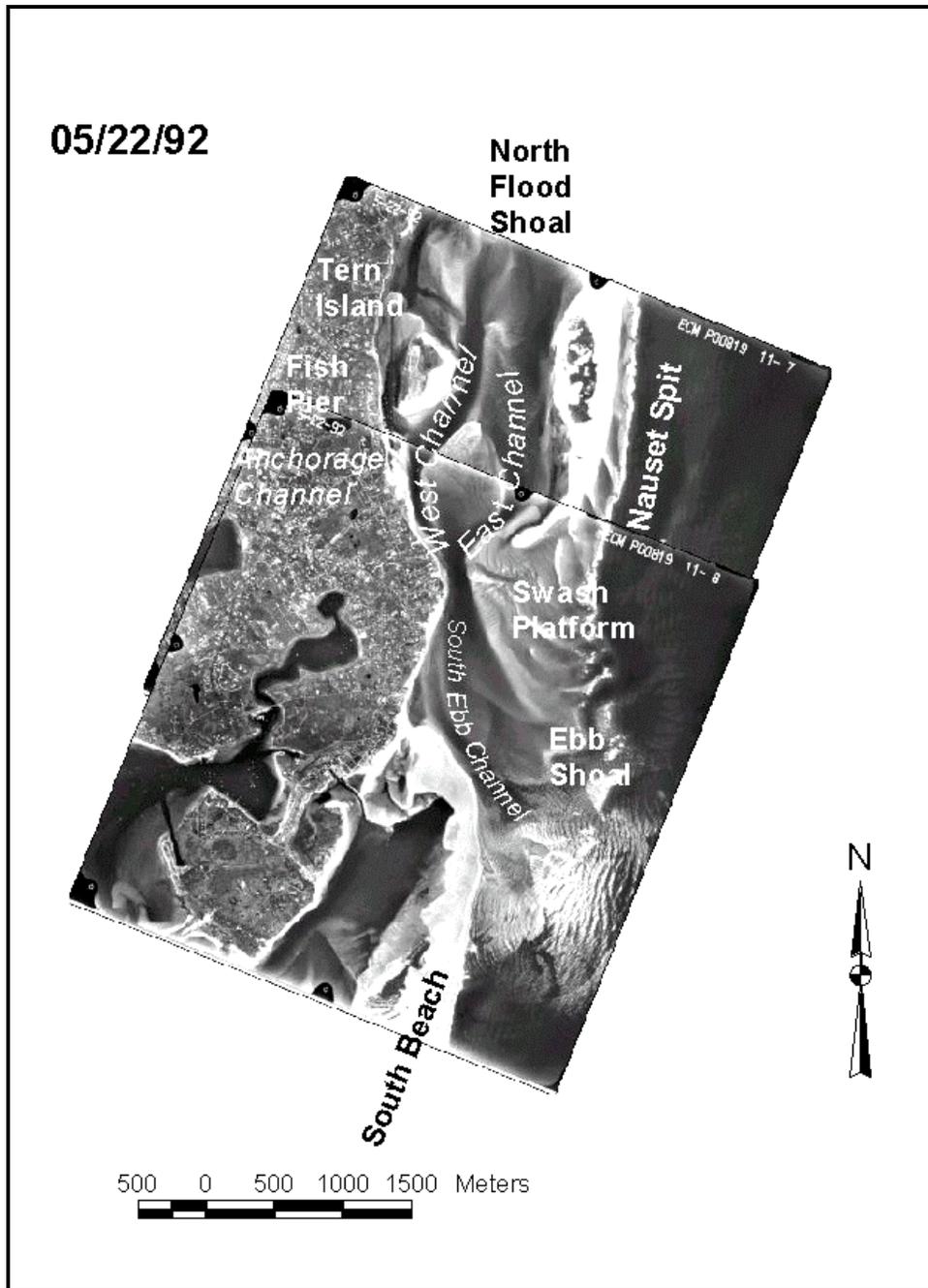


Figure 10. Morphology of Chatham Harbor, 31 December 1991

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

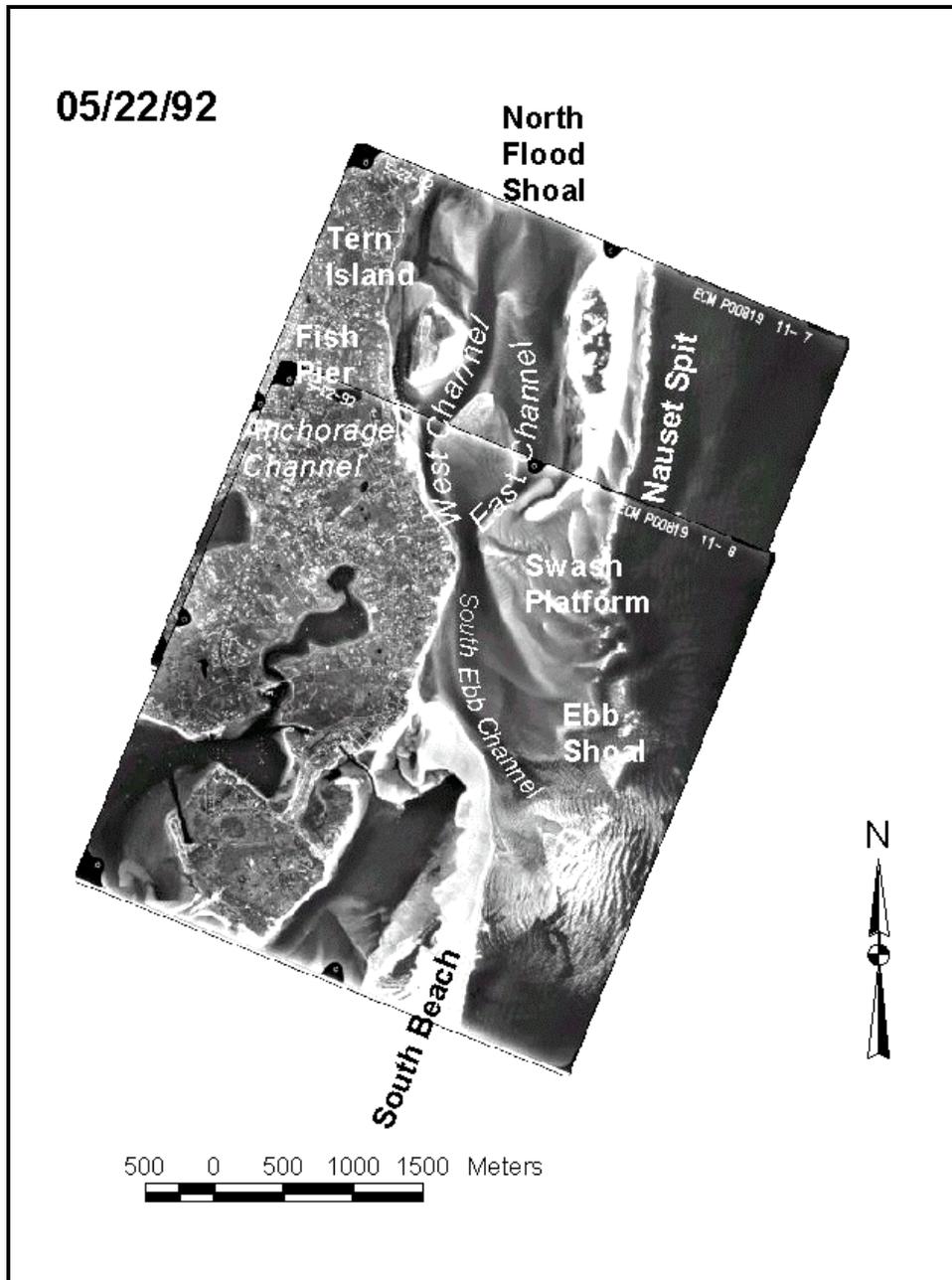


Figure 11. Morphology of Chatham Harbor, 22 May 1992, with south spit attachment to mainland beach

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

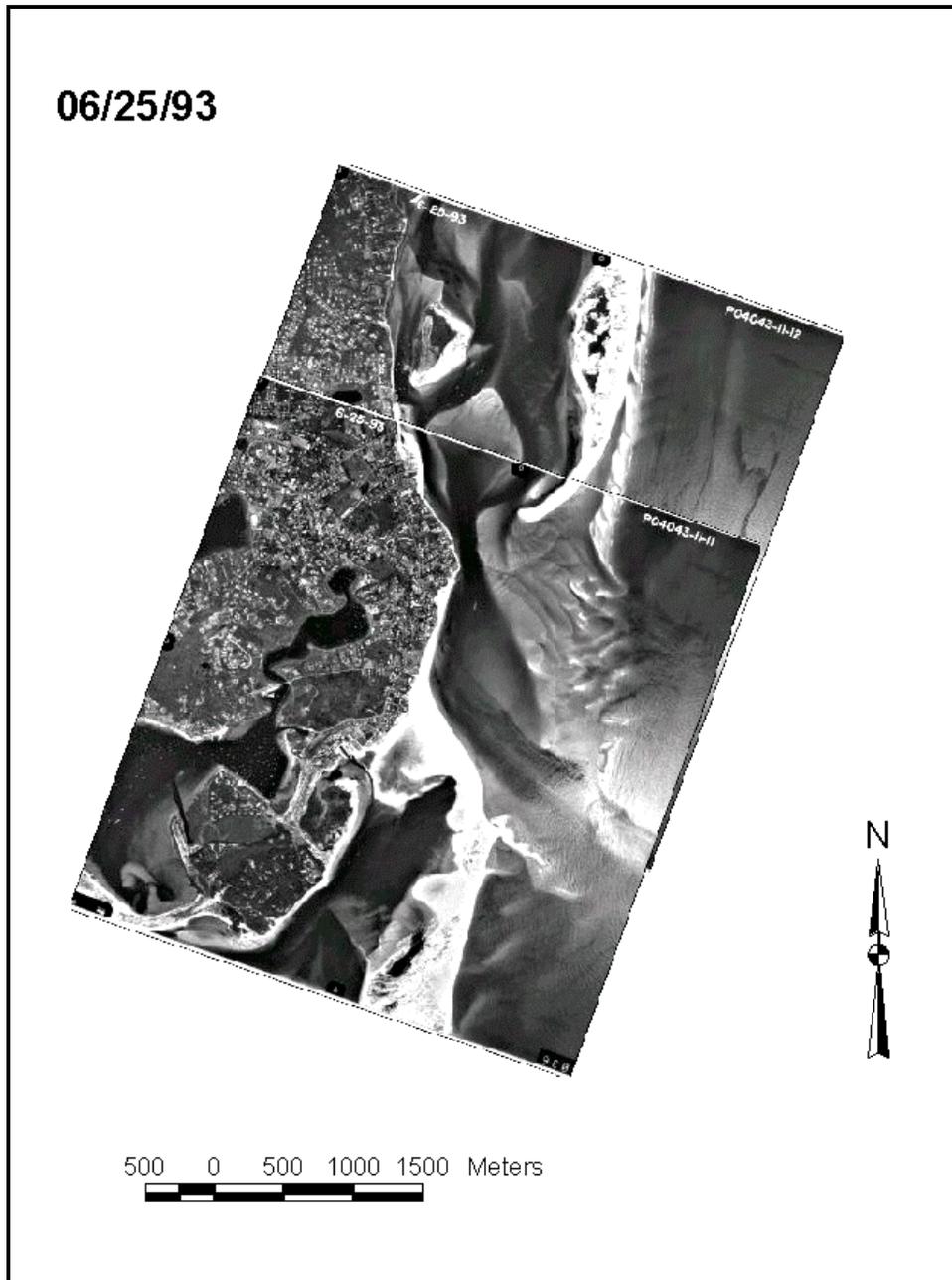


Figure 12. Morphology of Chatham Harbor, 25 June 1993

(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

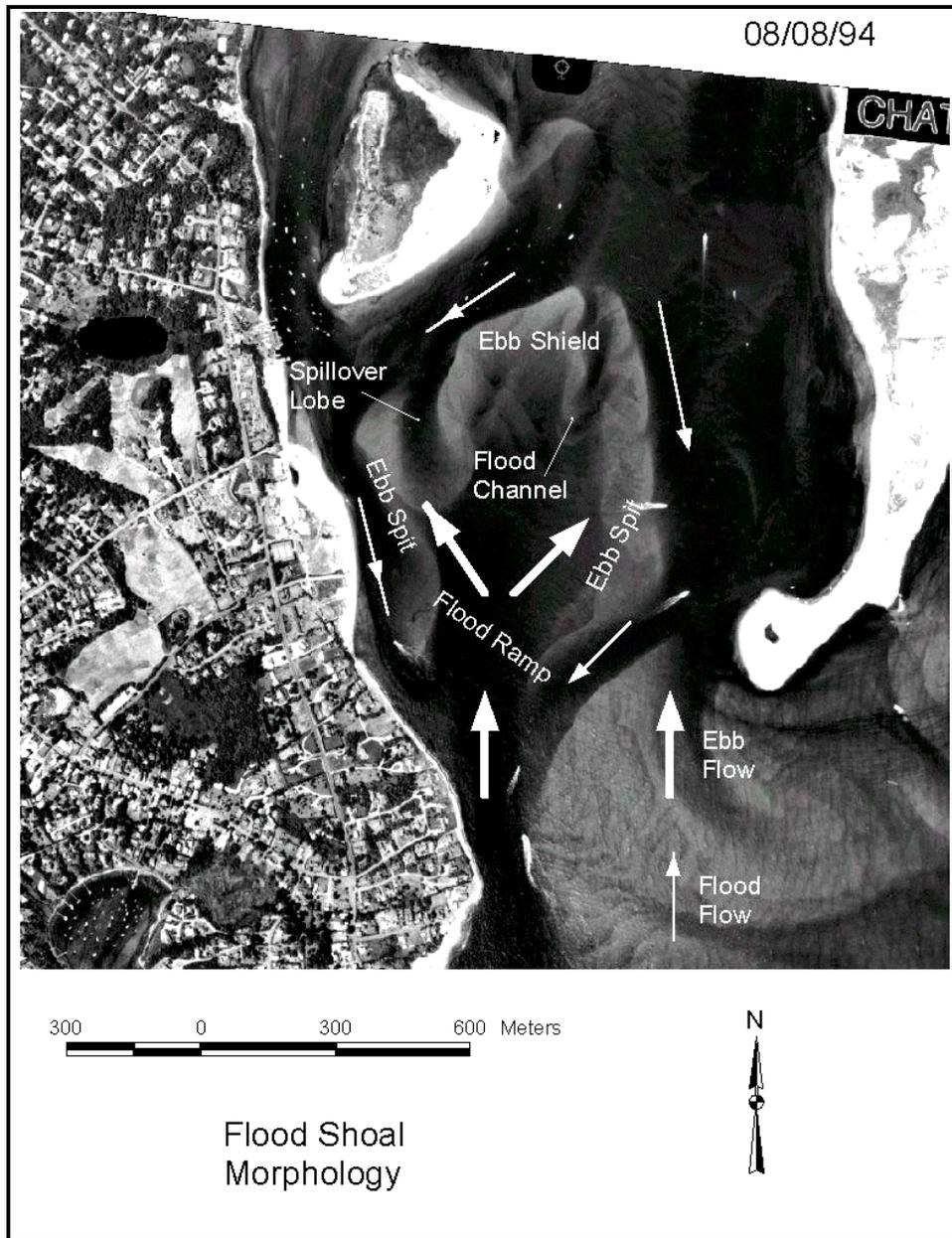


Figure 13. Morphology of the Chatham north flood shoal based on a model of Hayes (1975)

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.

08/08/94



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

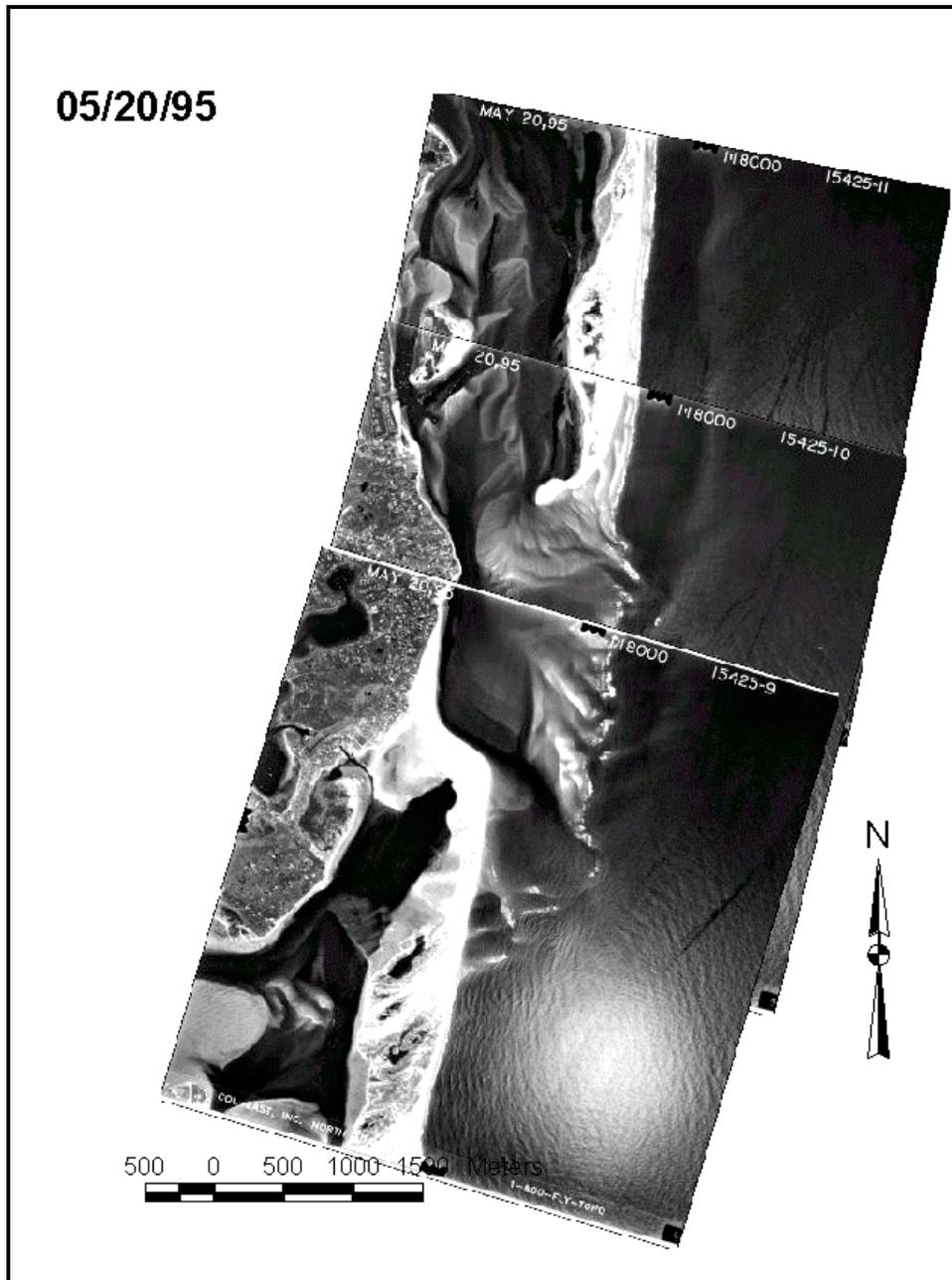


Figure 15. Morphology of Chatham Harbor, 20 May 1995, with two ebb channels

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

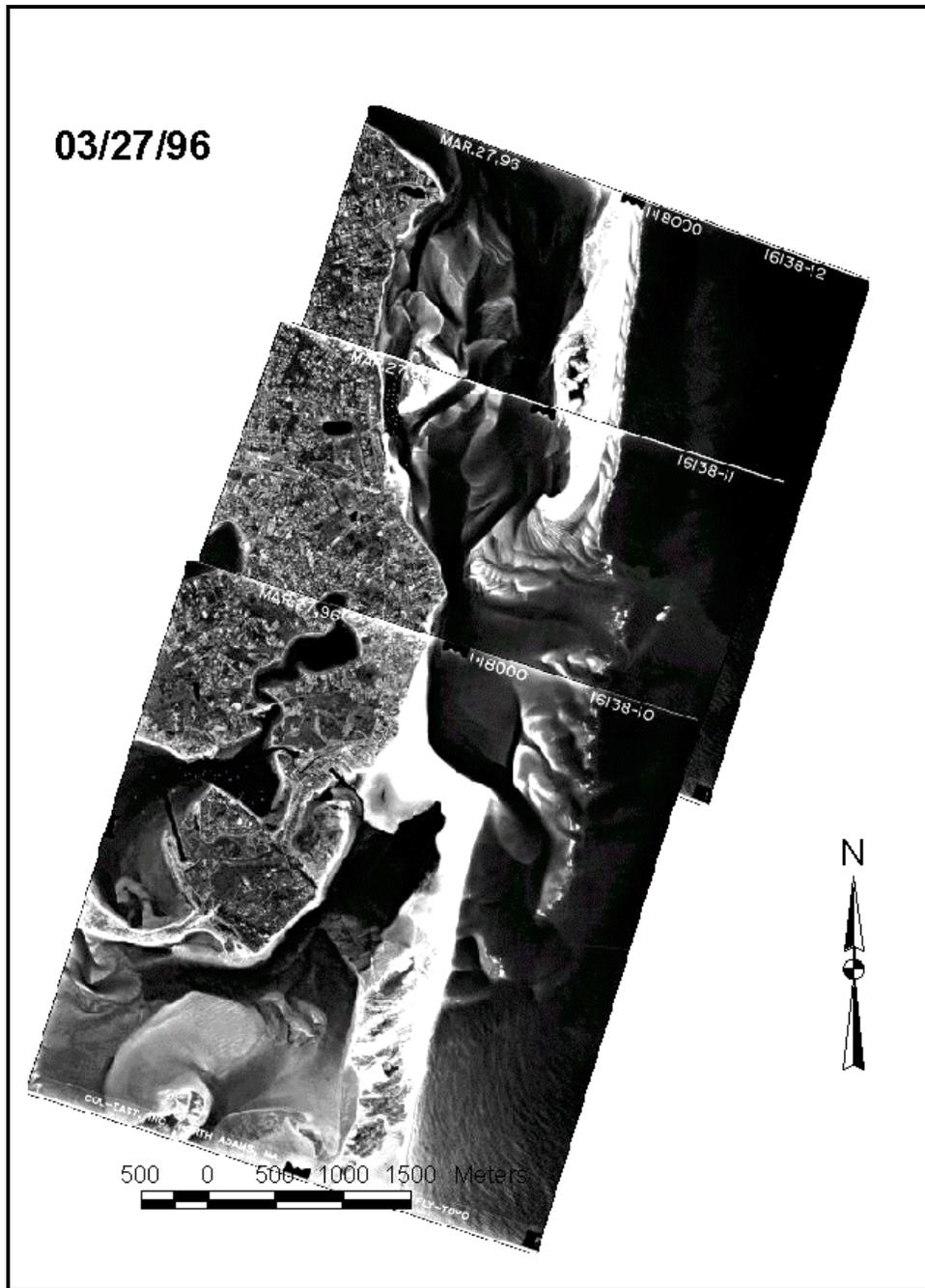


Figure 16. Morphology of Chatham Harbor, 27 March 1996

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.

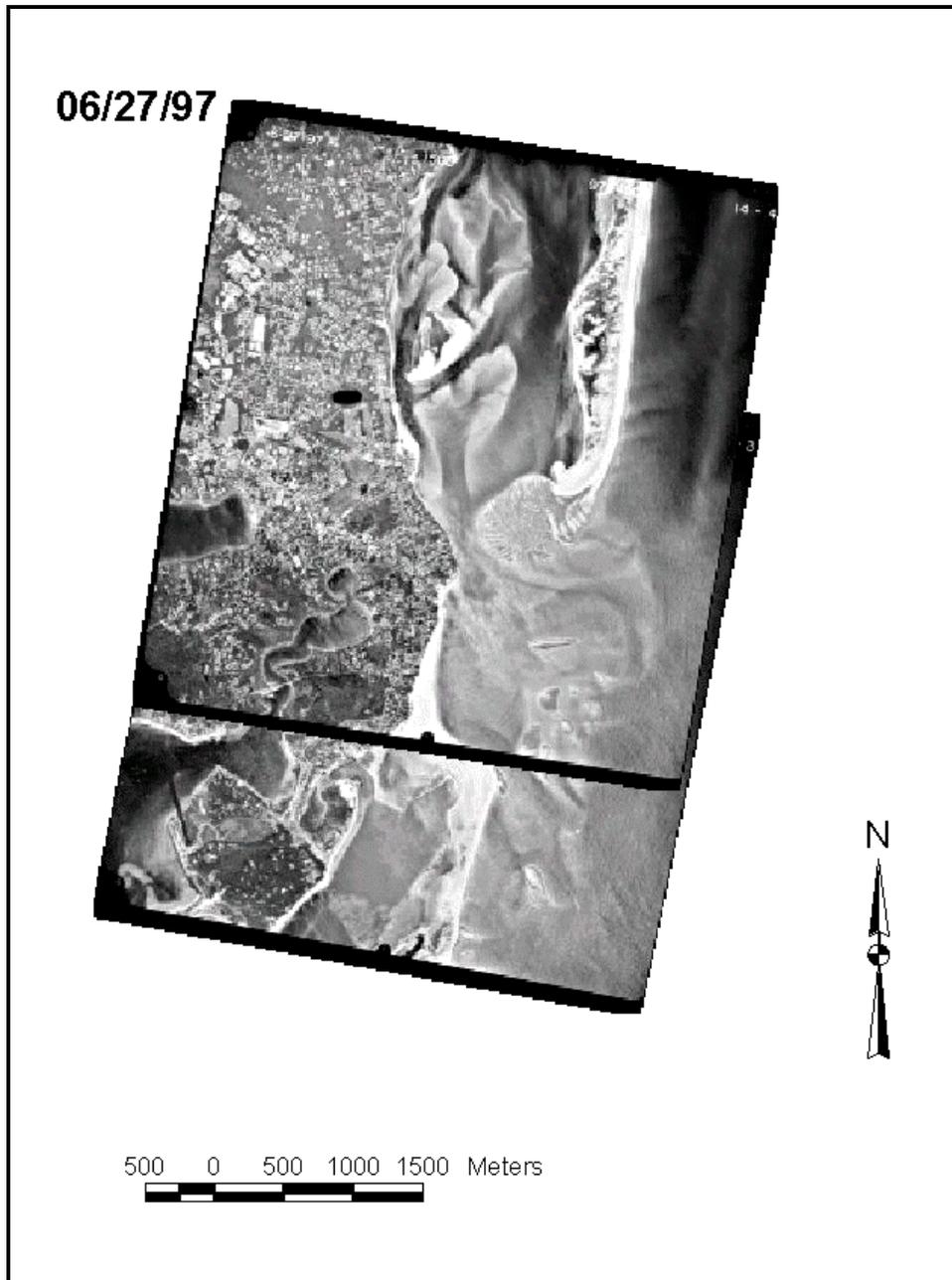


Figure 17. Morphology of Chatham Harbor, 27 June 1997

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

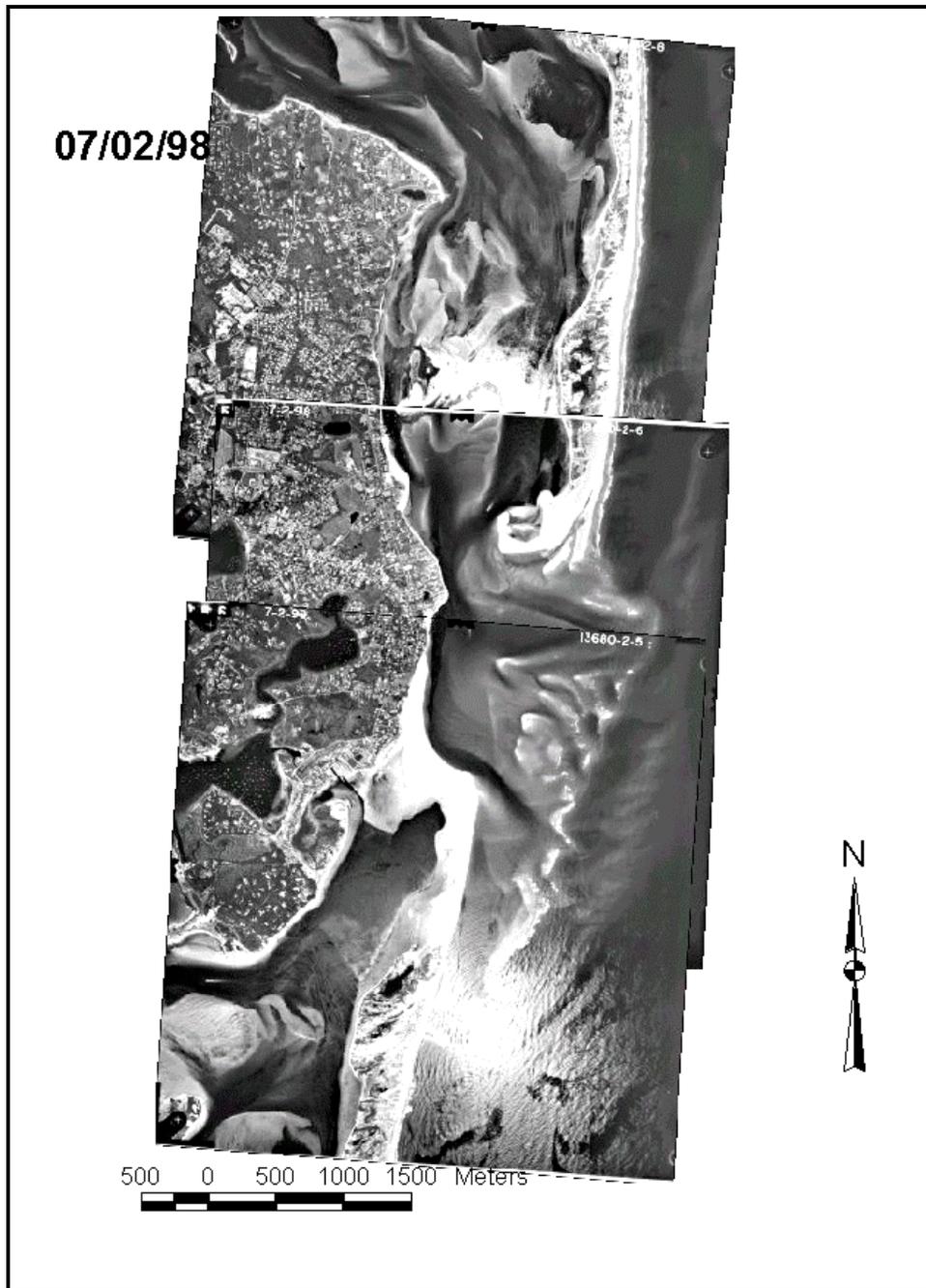


Figure 18. Morphology of Chatham Harbor, 2 July 1998

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.

07/15/99



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.

| <b>Table 2<br/>Key Events in Morphology Evolution</b> |   |
|---|---|
| <b>Date</b>   | <b>Event</b>  |
| 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

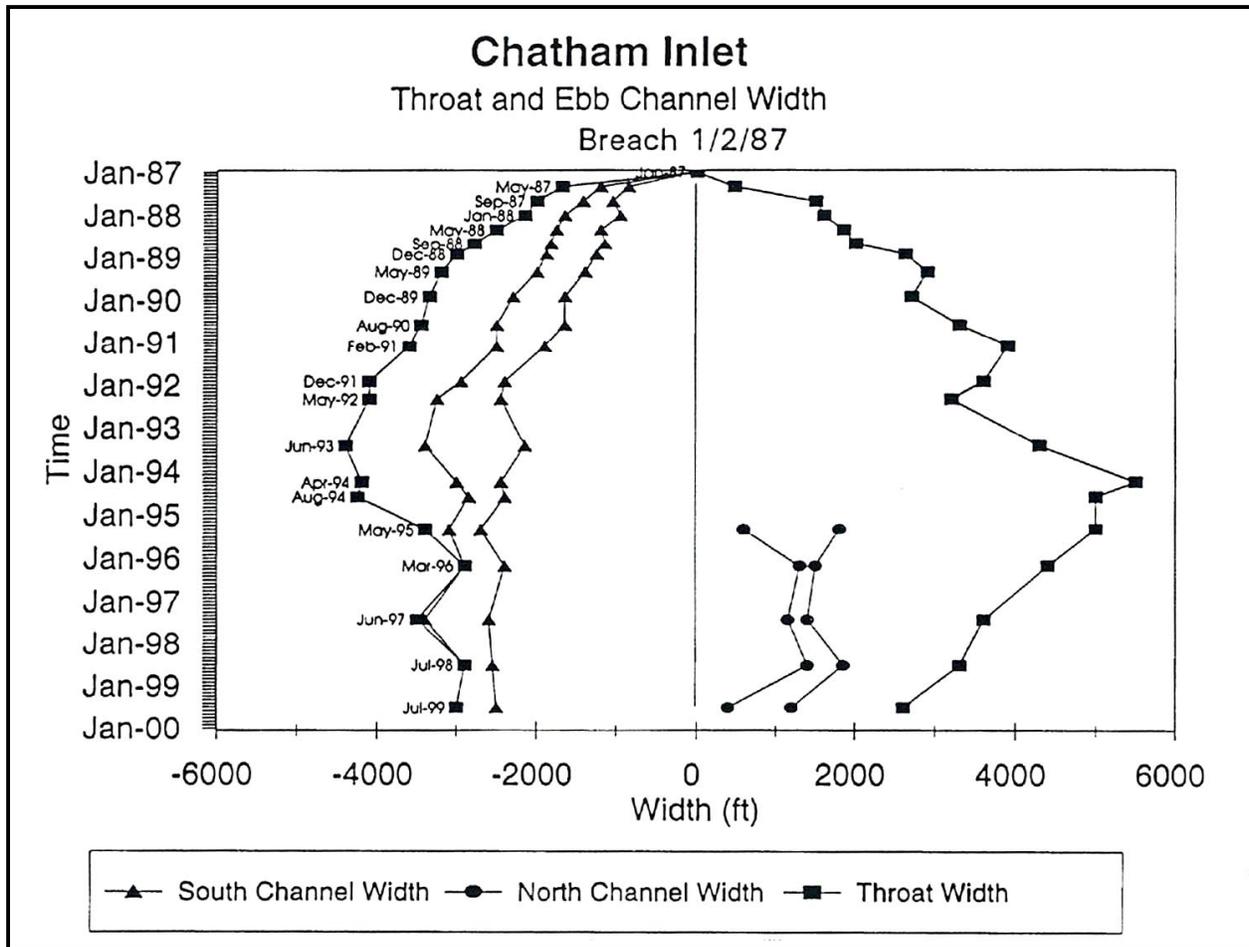


Figure 20. Temporal change in inlet throat width and position of ebb channels with respect to original beach location

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 recurred 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 long-shore 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<sup>3</sup>) in May 1998 and May 2000.

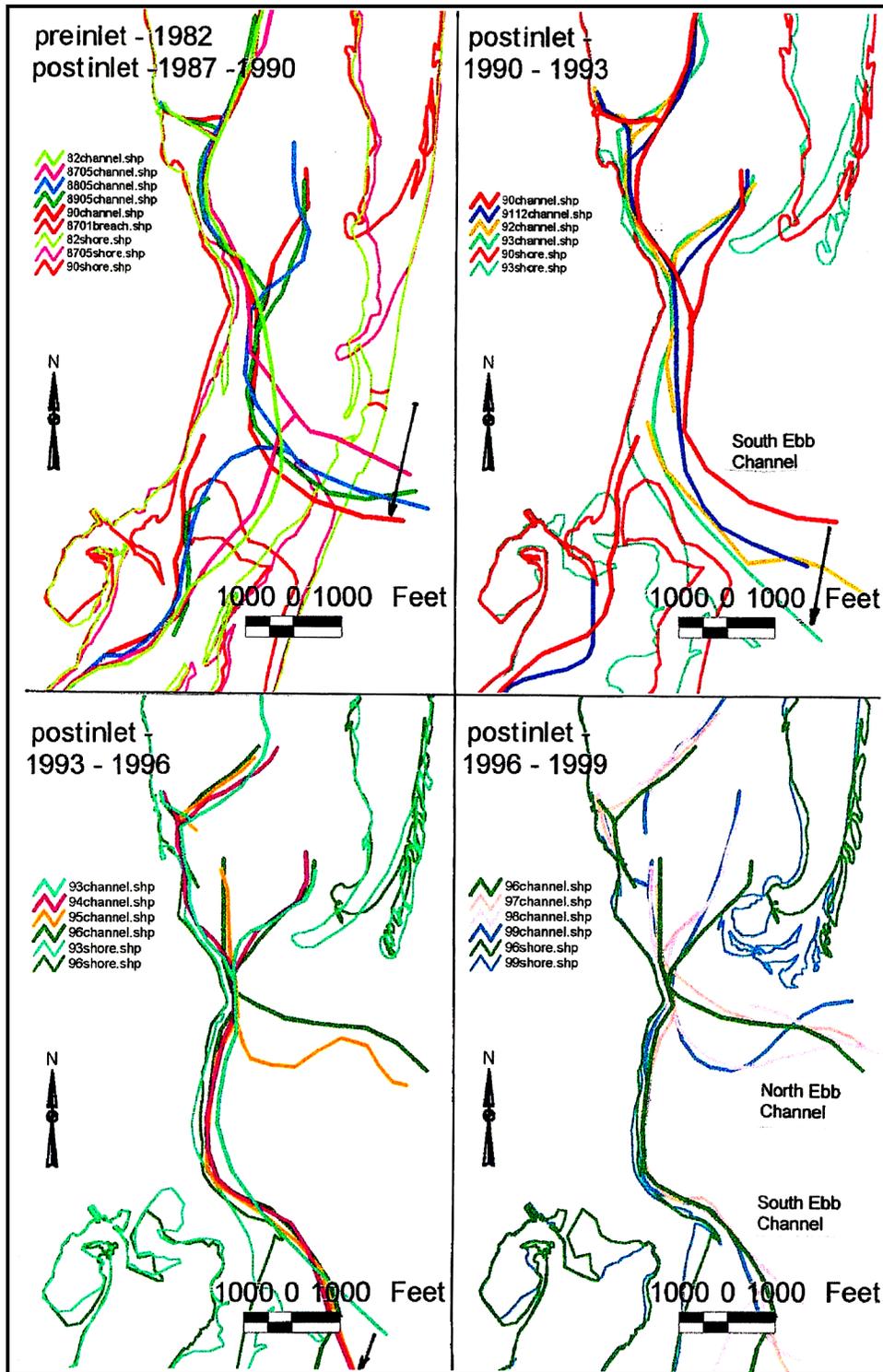


Figure 21. Change map of ebb channel center lines

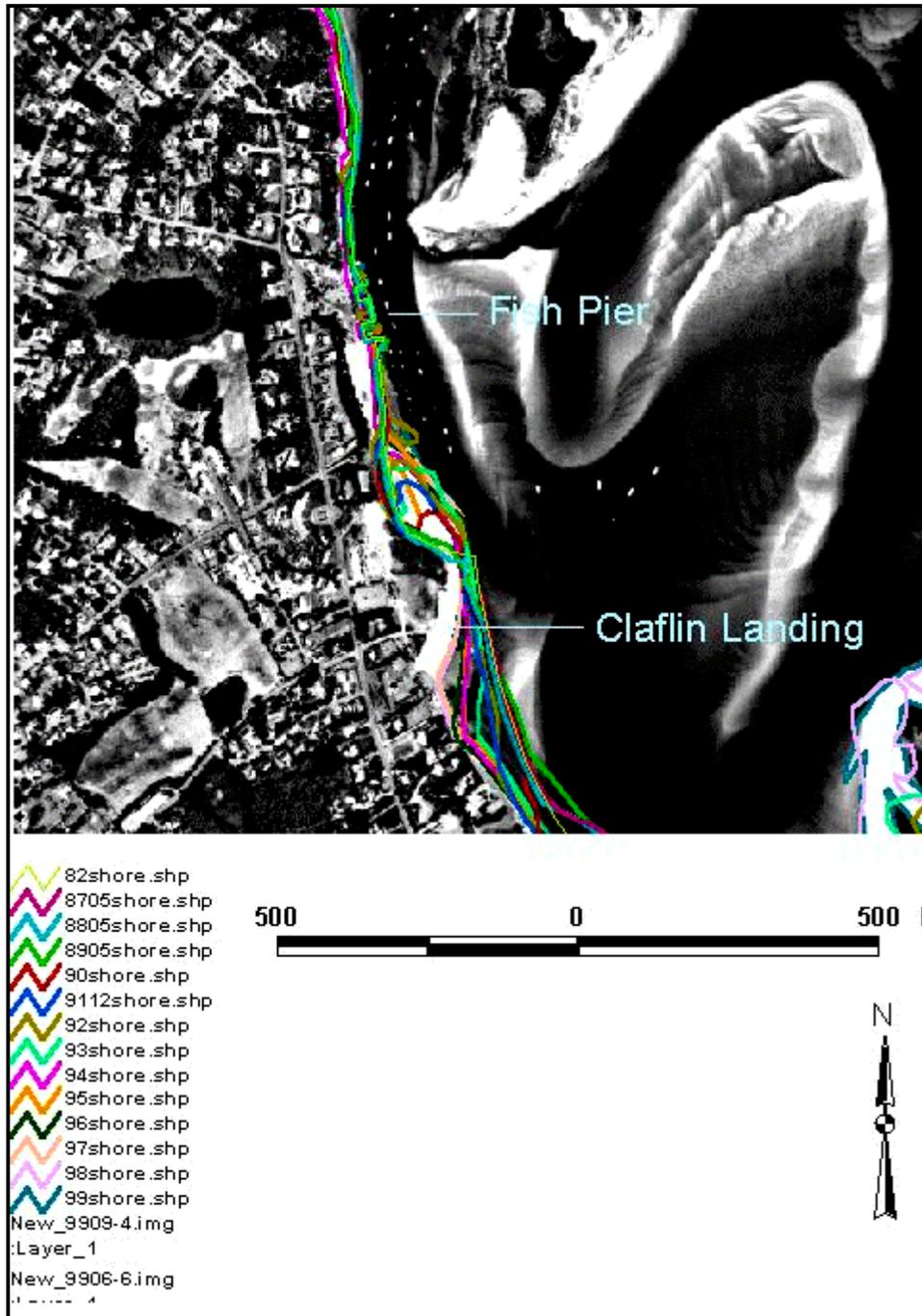


Figure 22. Mainland shoreline change in Aunt Lydia's Cove (Cow Yard Landing to Clafin Landing)

### Seawall

Segment 2 extends from Clafin 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

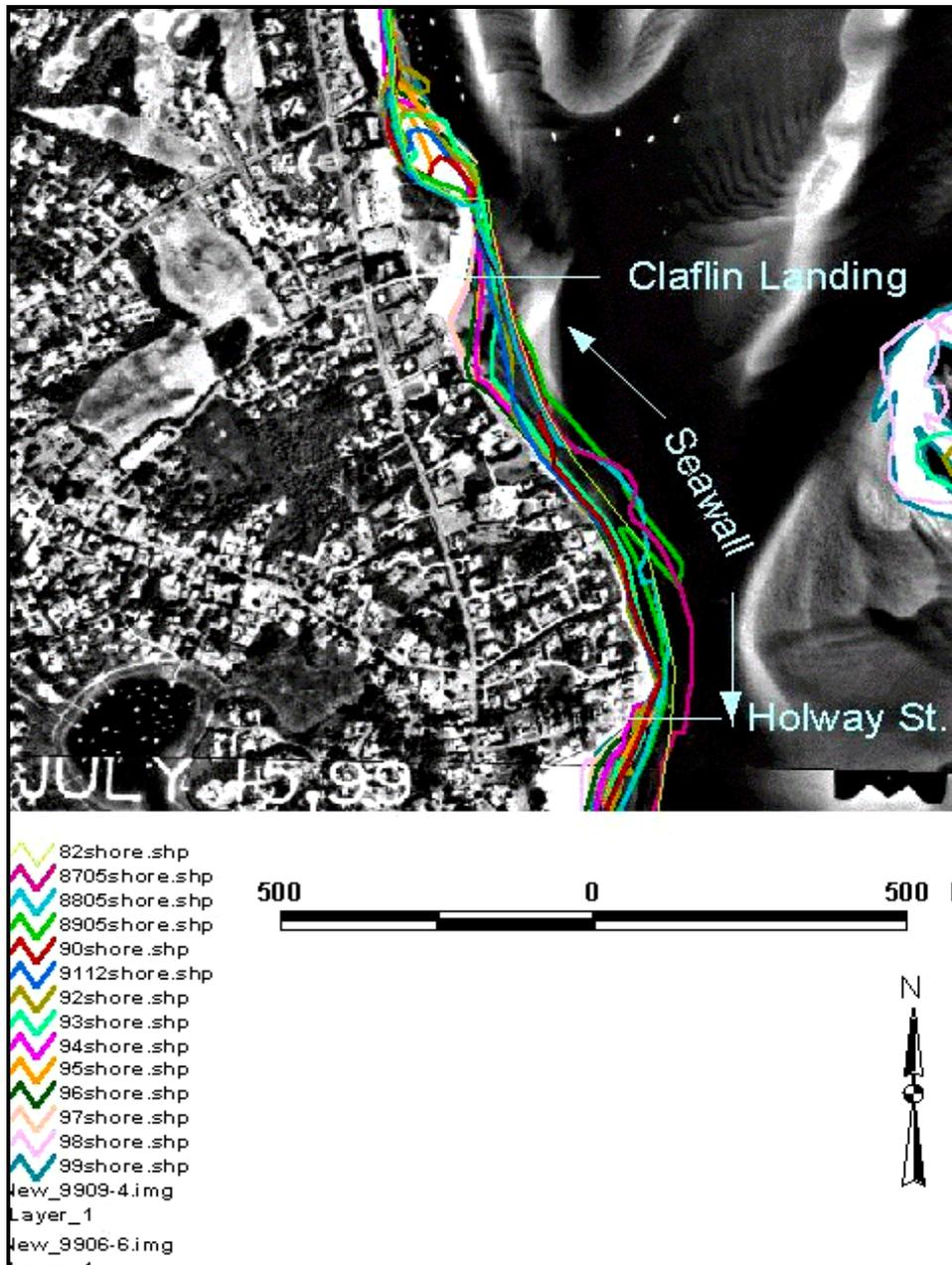


Figure 23. Mainland shoreline change in seawall area (Clafin Landing to Holway Street)

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<sup>3</sup>) 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

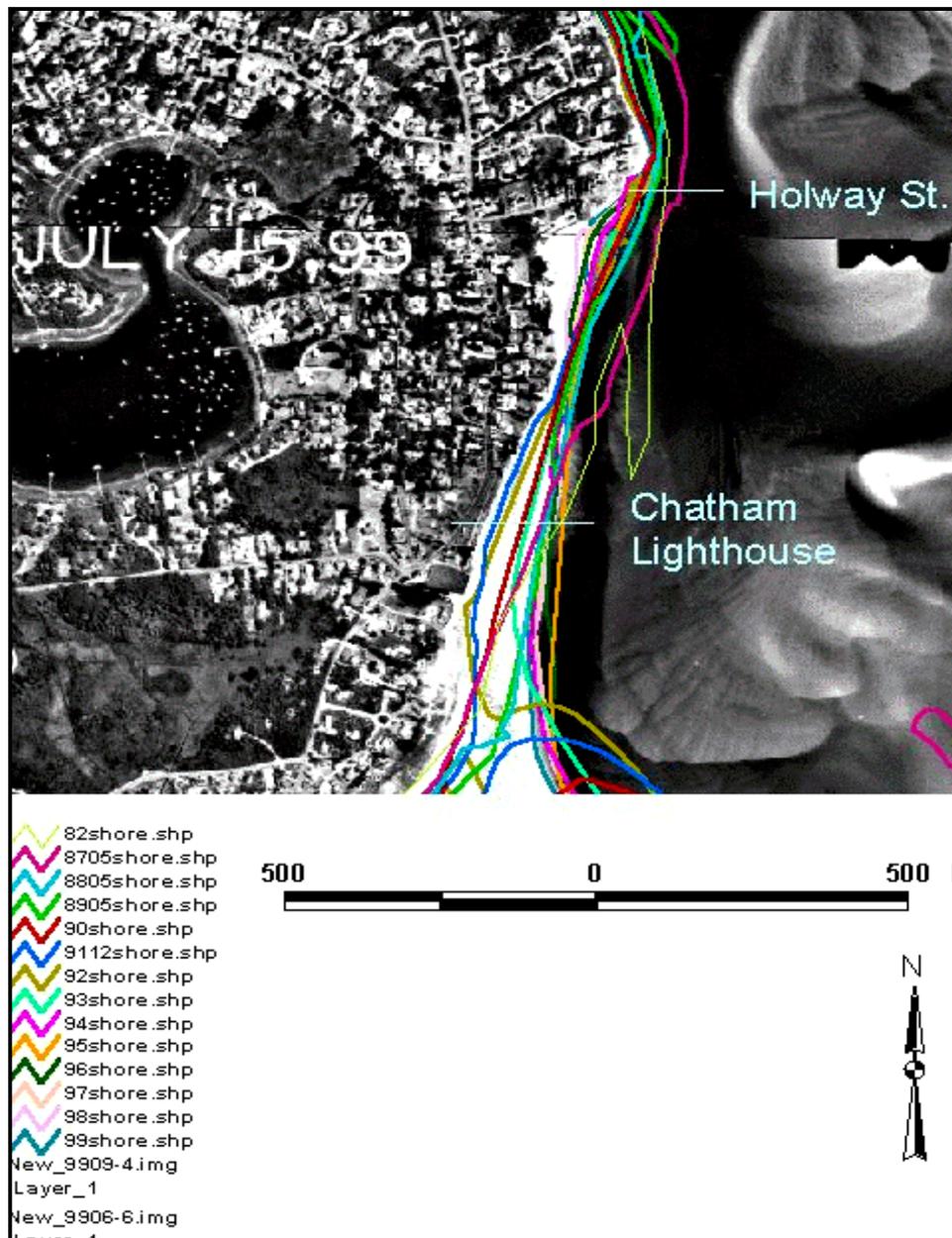


Figure 24. Mainland/South Beach shoreline change along the Chatham Lighthouse area (Holway Street to Chatham Lighthouse)

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.

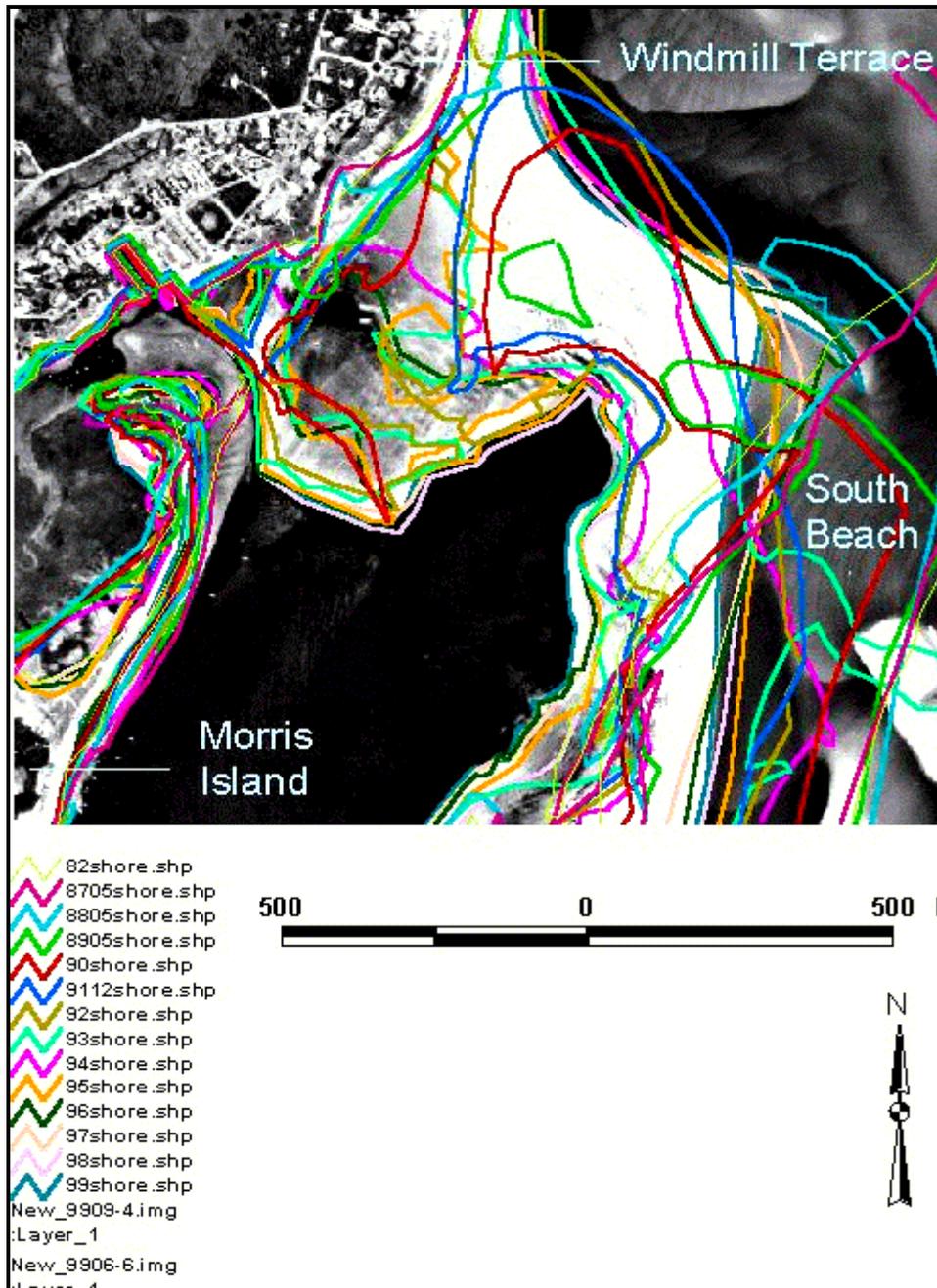


Figure 25. Mainland/South Beach shoreline change along Toms Neck (Chatham Lighthouse to Morris Island)

## 4 Ebb and Flood Shoal Evolution

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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<br>Change in Area of Inlet Shoals and Adjacent Spits |                                 |                     |                     |             |                            |                      |                      |                           |          |
|--|---------------------------------|---------------------|---------------------|-------------|----------------------------|----------------------|----------------------|---------------------------|----------|
| Date   | Ebb Shoal/<br>Swash<br>Platform | North<br>Spit/Beach | South<br>Spit/Beach | Tern Island | Tern Island<br>South Shoal | North Flood<br>Shoal | South Flood<br>Shoal | South<br>Remnant<br>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 mllw 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 to 10 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/<br>Swash<br>Platform | North<br>Spit/Beach | South<br>Spit/Beach | Tern Island | Tern Island<br>South Shoal | North Flood<br>Shoal | South Flood<br>Shoal | South<br>Remnant<br>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             | 973804      | 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 |

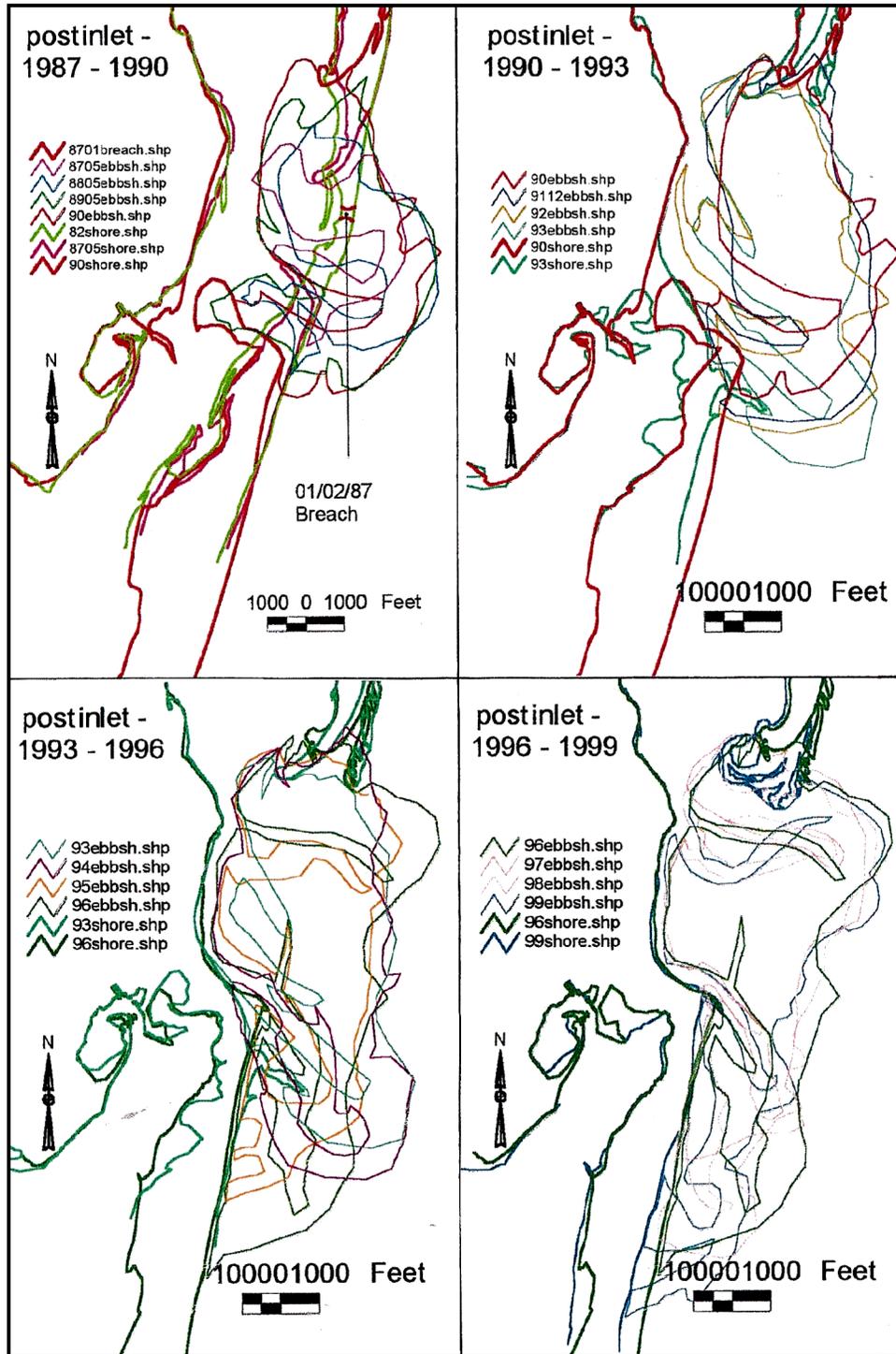


Figure 26. Map of growth in area of ebb shoal/swash platform

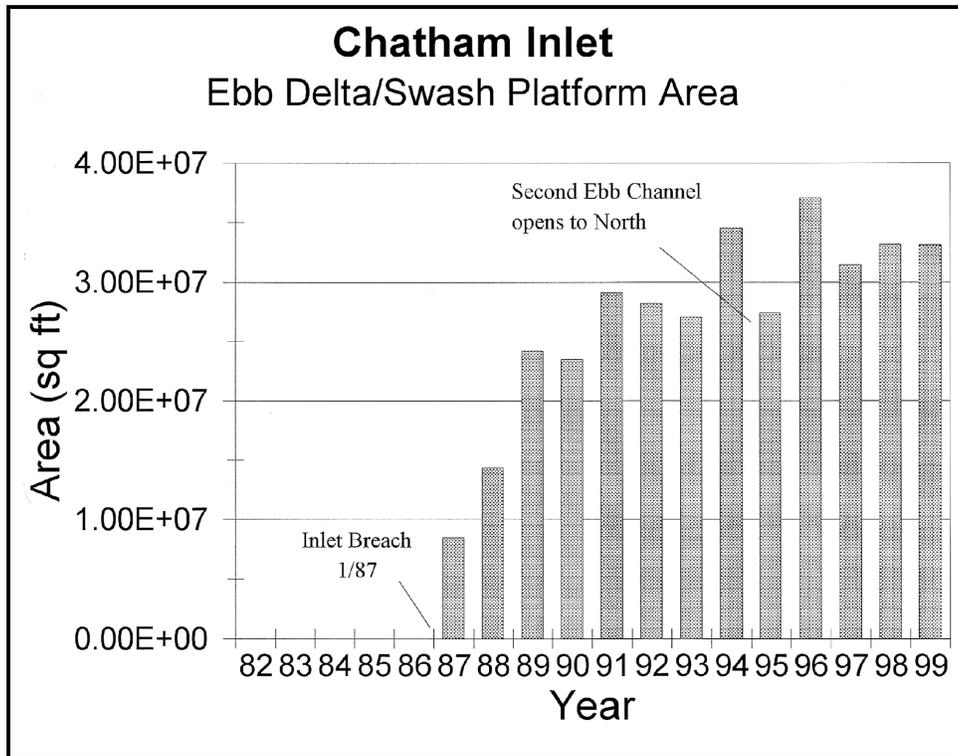


Figure 27. Postbreach area changes to ebb shoal/swash platform

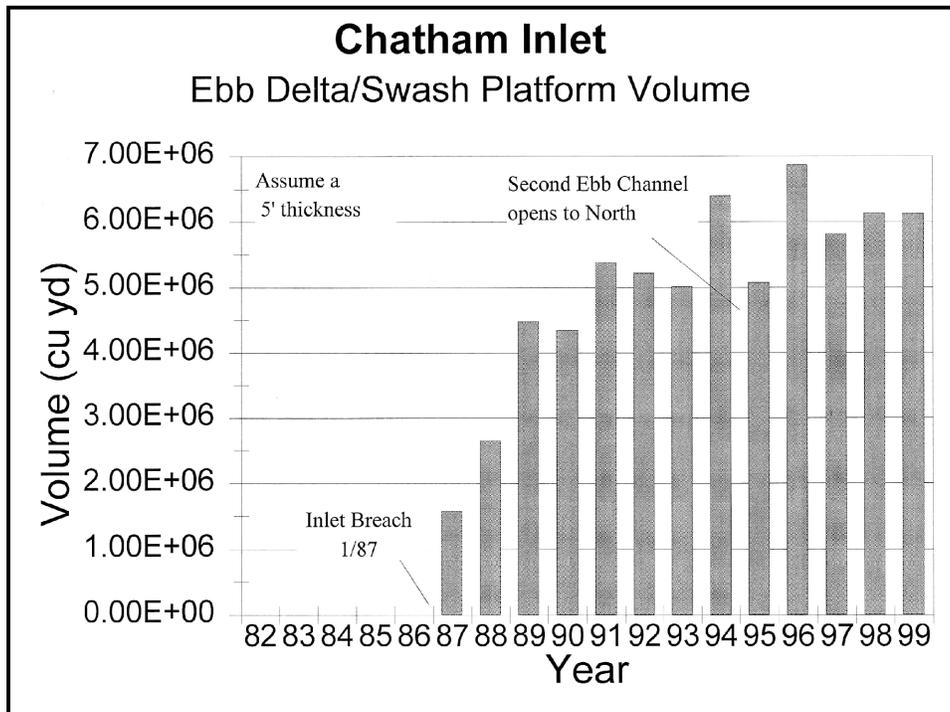


Figure 28. Estimate of volume change in ebb shoal/swash platform

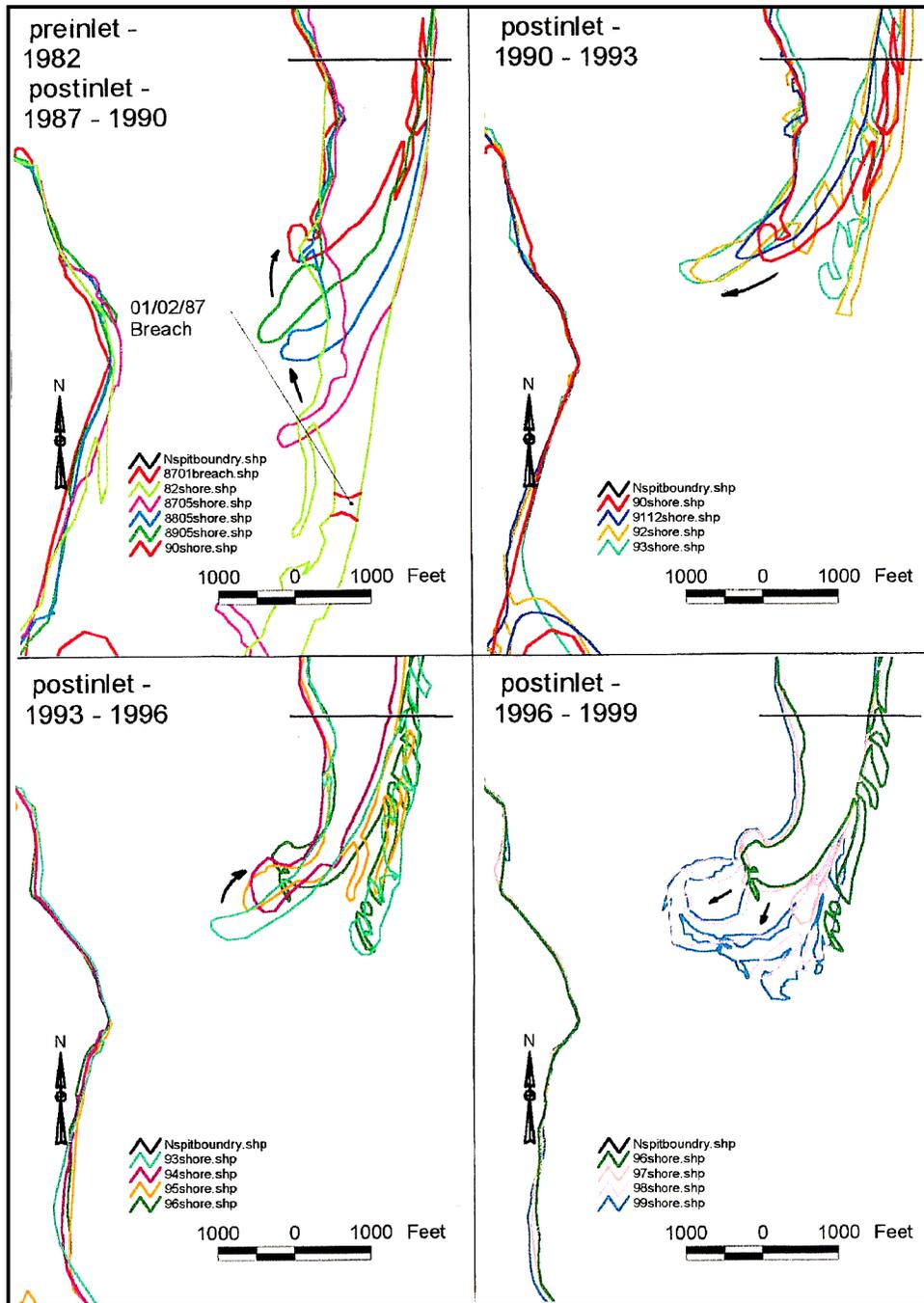


Figure 29. Map of area change to north spit. Line identifies common northern limit of area measurement

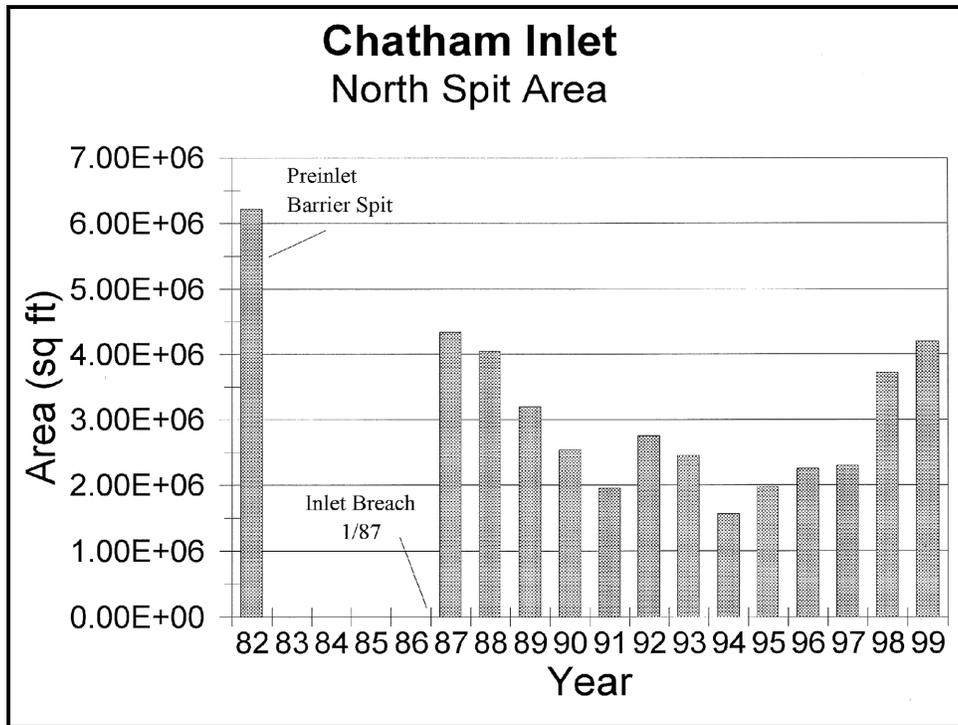


Figure 30. Area change from prebreach to 1999 of north spit

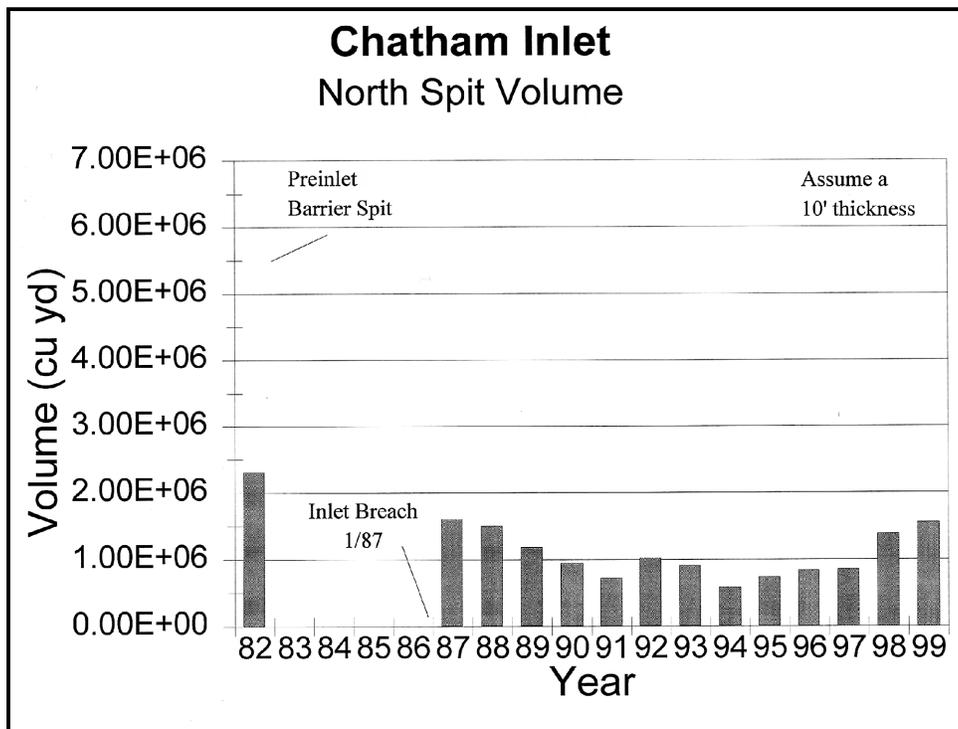


Figure 31. Estimate of volume change in north spit

## 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

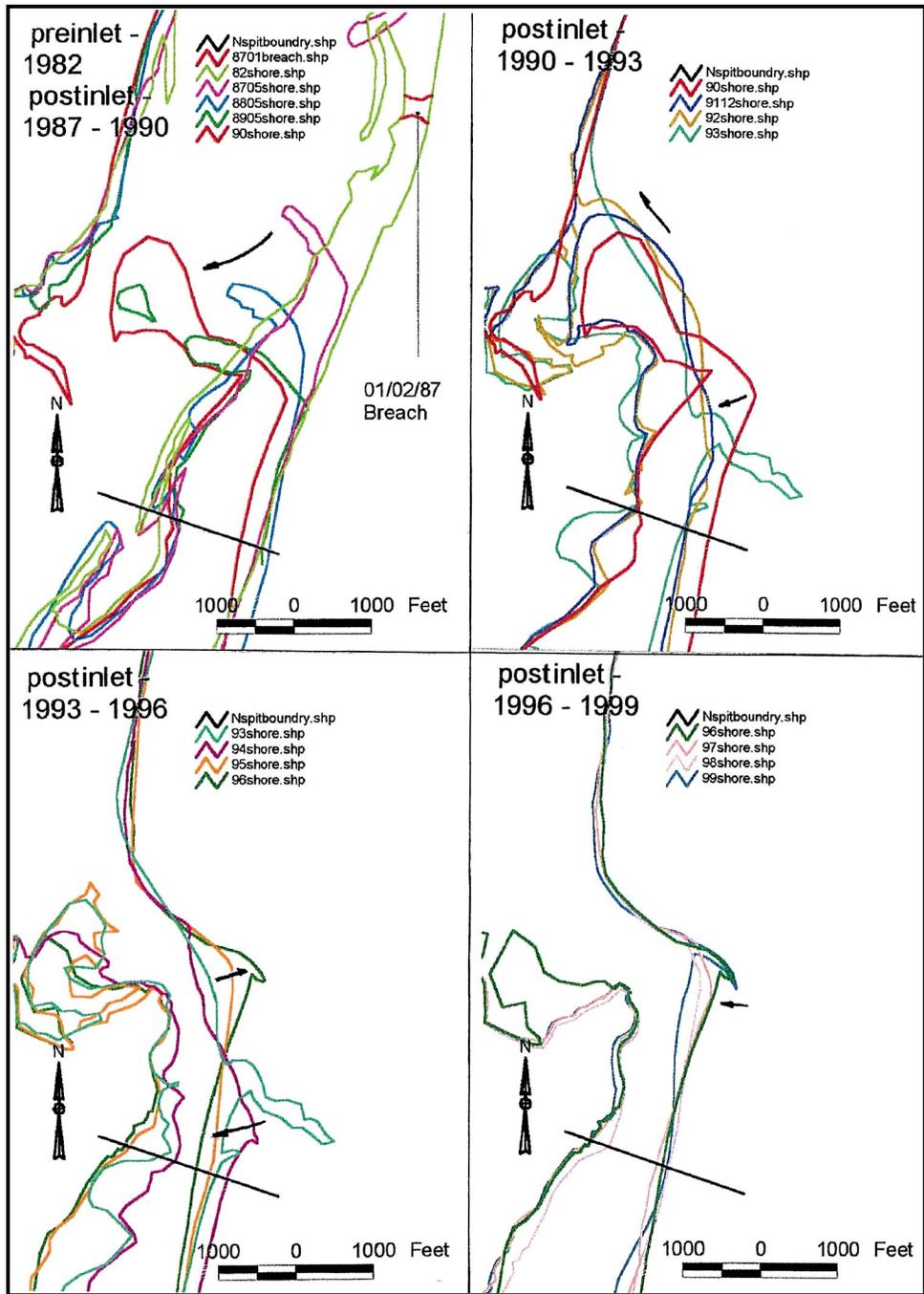


Figure 32. Map of area change to initial recurring south spit and final South Beach land bridge. Line identifies common southern limit of area measurement. Common mainland area boundary used was the 1982 dune/cliff/vegetation line

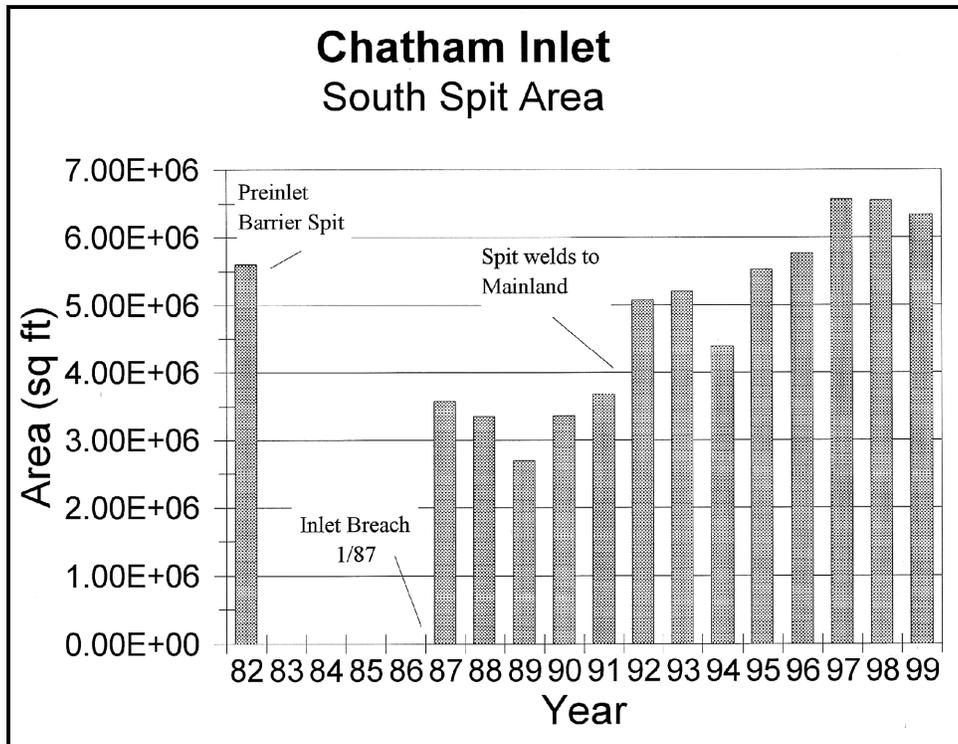


Figure 33. Area change from prebreach to 1999 of south spit/South Beach

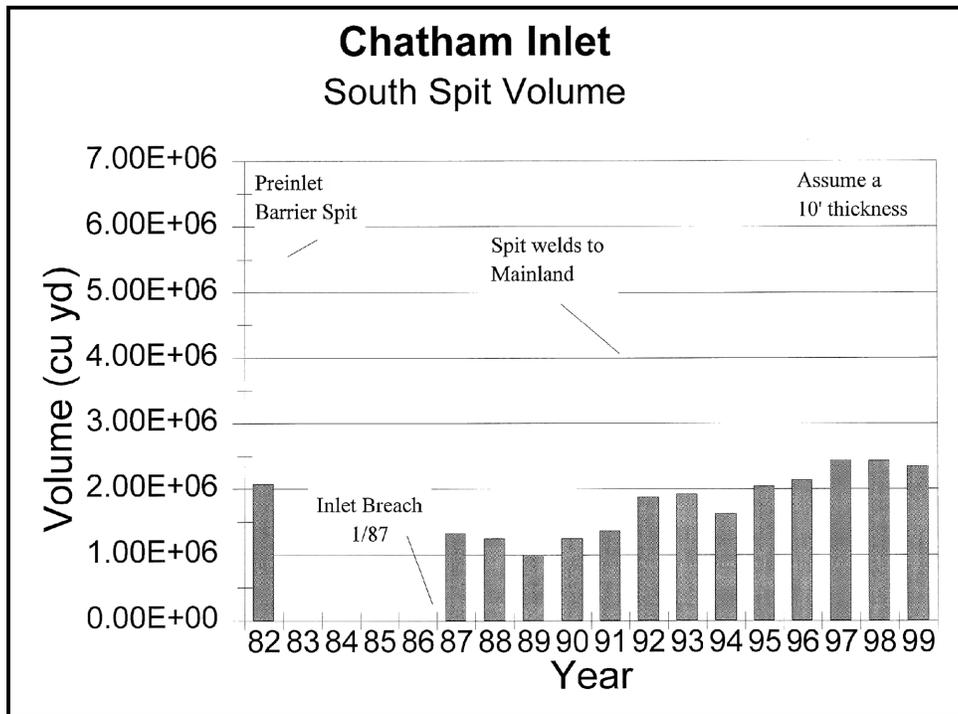


Figure 34. Estimate of volume change of south spit/South Beach

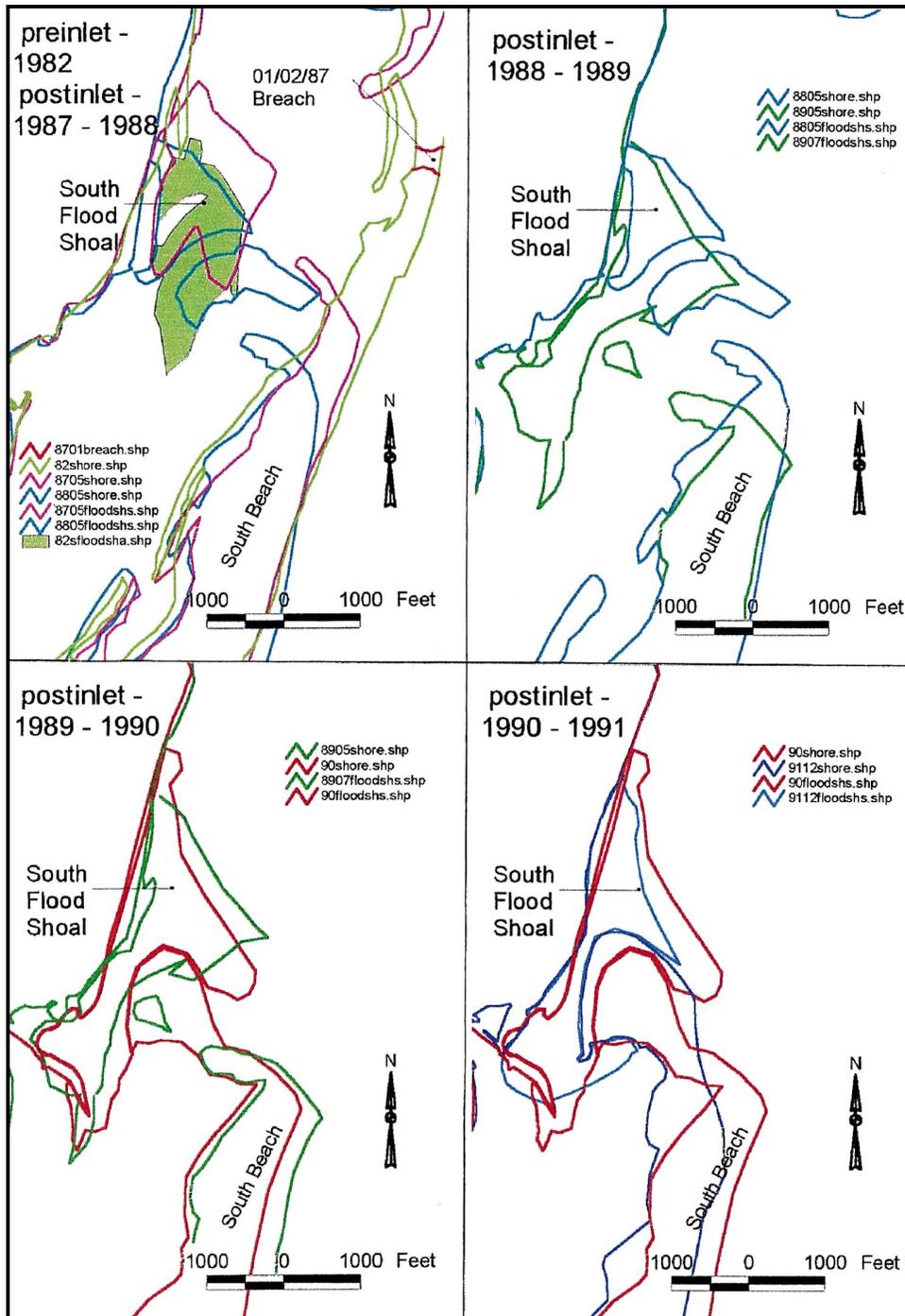


Figure 35. Map of area change to south flood shoal. Solid area shows preinlet remnant shoal that was incorporated into the south flood shoal

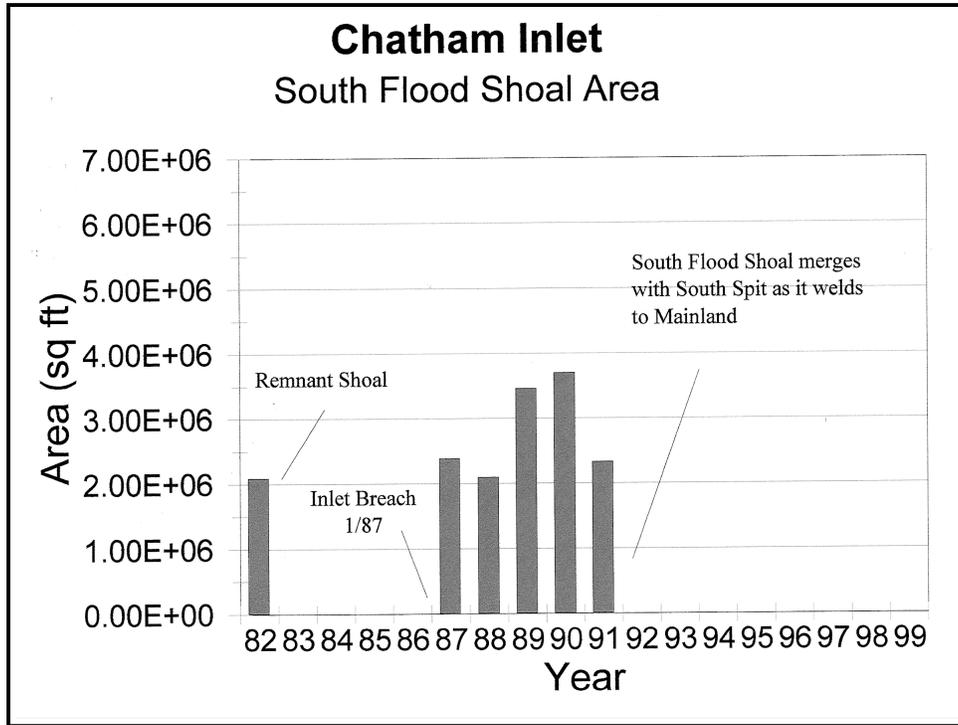


Figure 36. Area change from prebreach shoal to 1999 south flood shoal

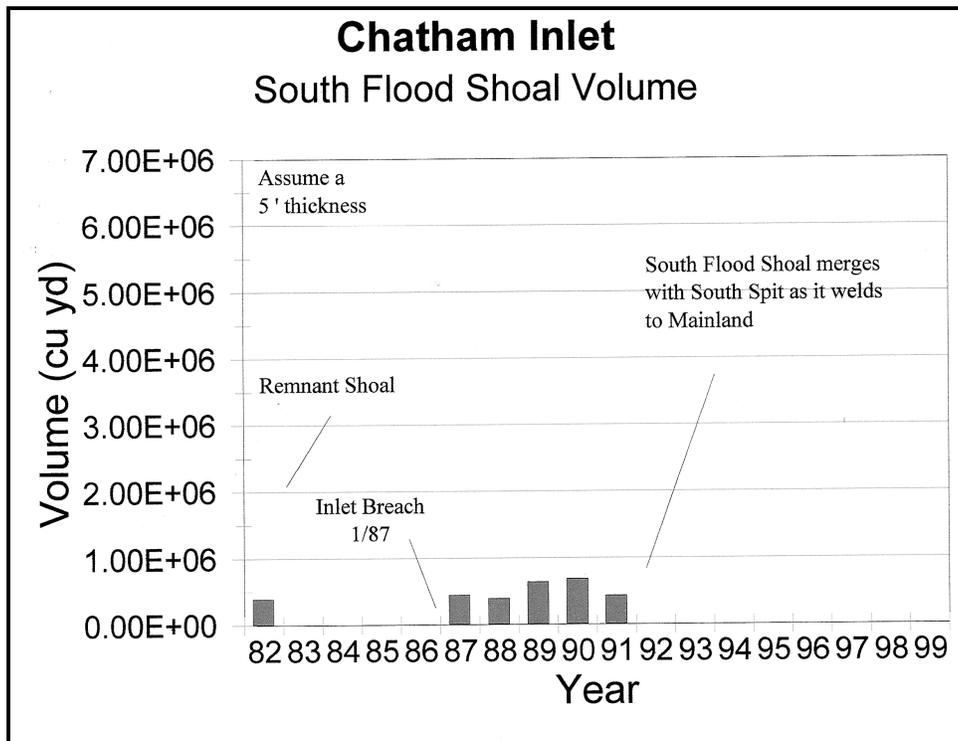


Figure 37. Estimate of volume change in south flood shoal

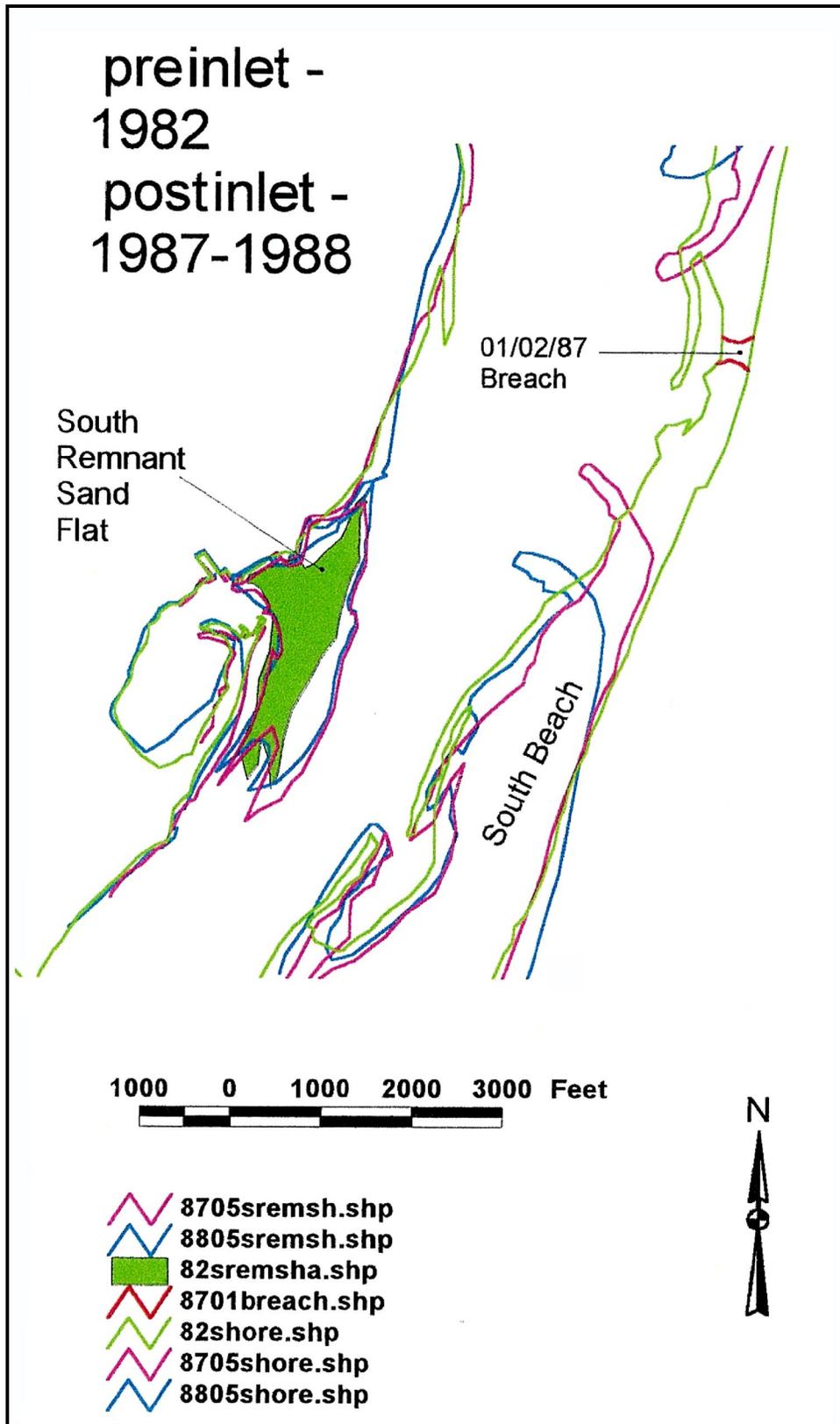


Figure 38. Map of area change in remnant south sand flat. Solid area shows pre-inlet remnant shoal incorporated into the remnant south sand flat

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<sup>3</sup>) 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,

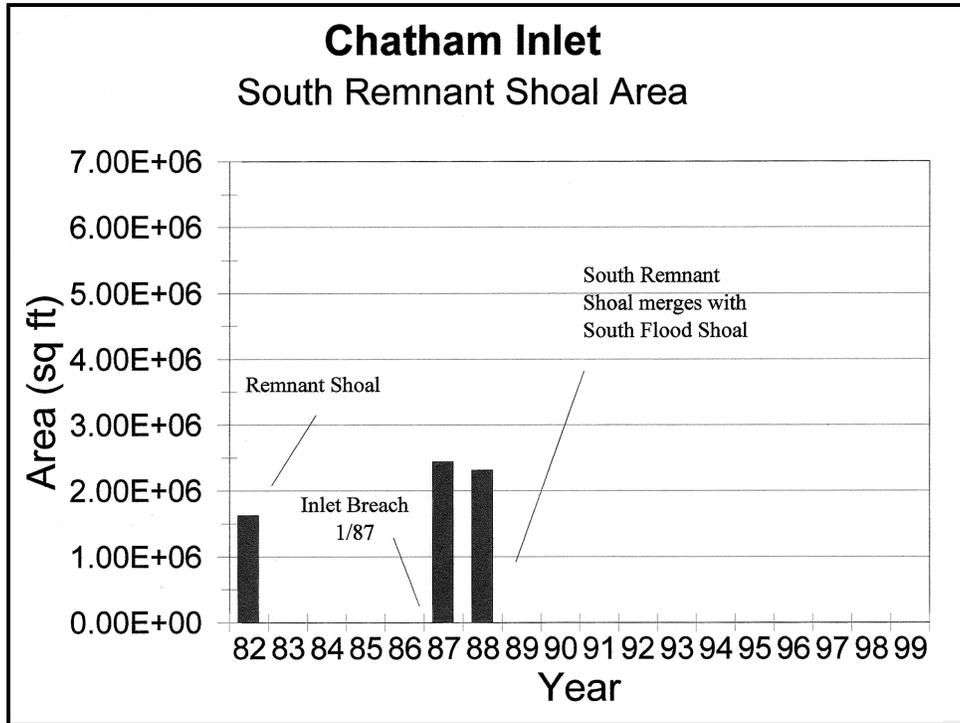


Figure 39. Area change from prebreach to 1999 to remnant south sand flat

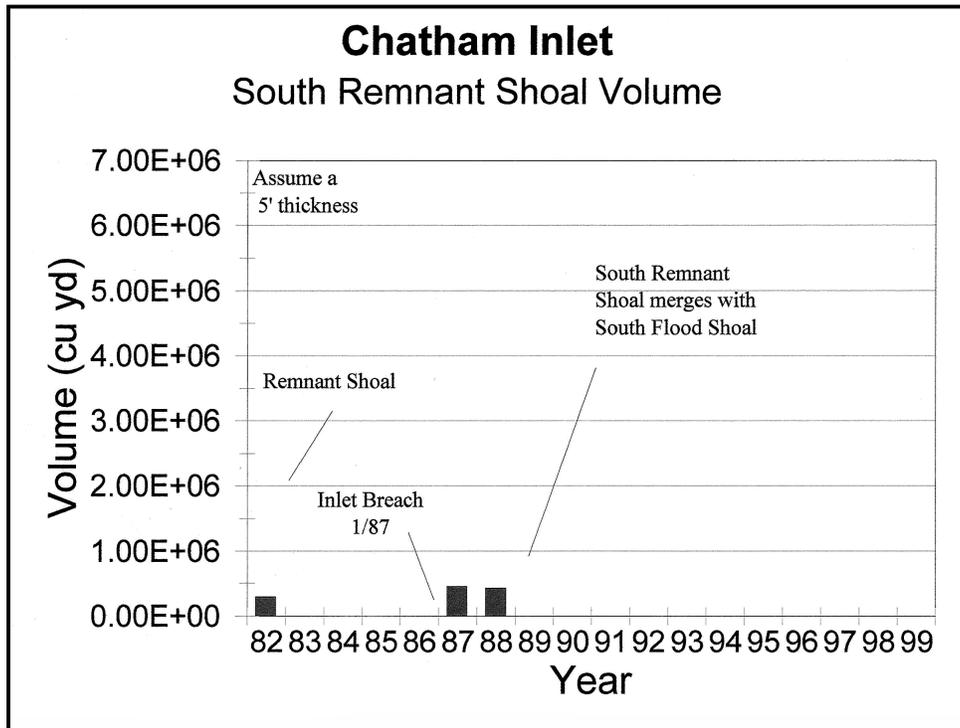


Figure 40. Estimate of volume change in remnant south sand flat

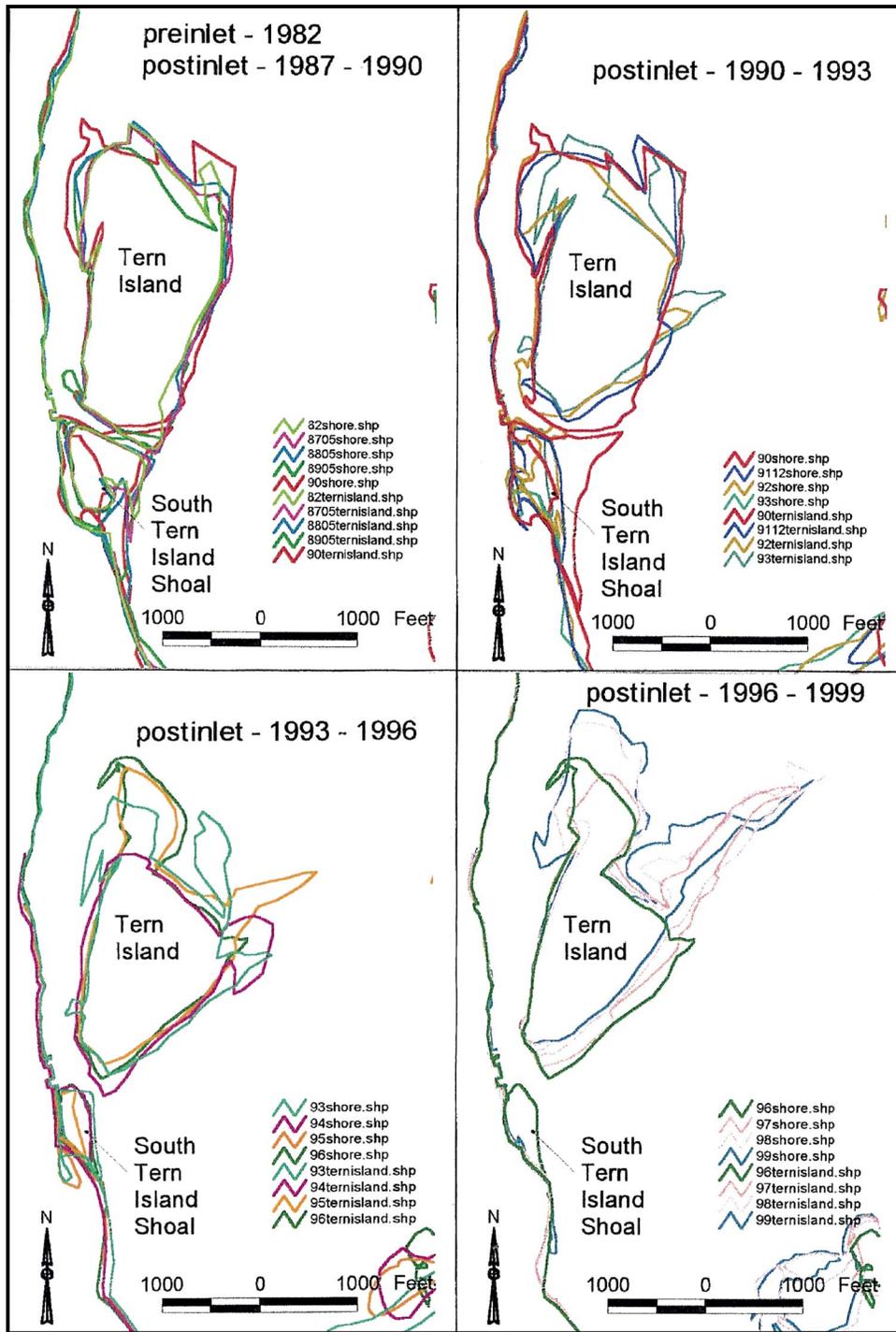


Figure 41. Map of area change to Tern Island and Tern Island south shoal

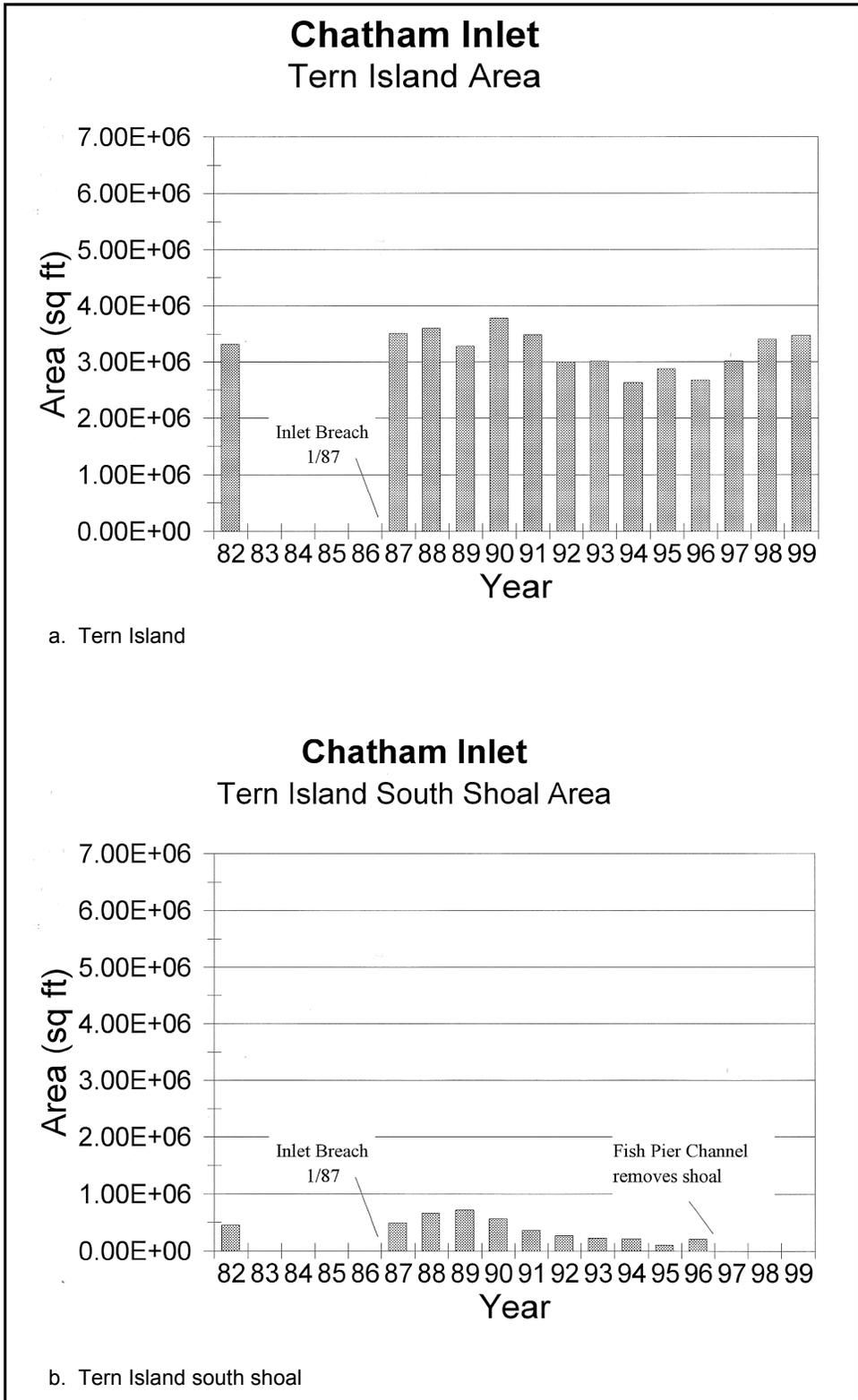


Figure 42. Area change from prebreach to end of study

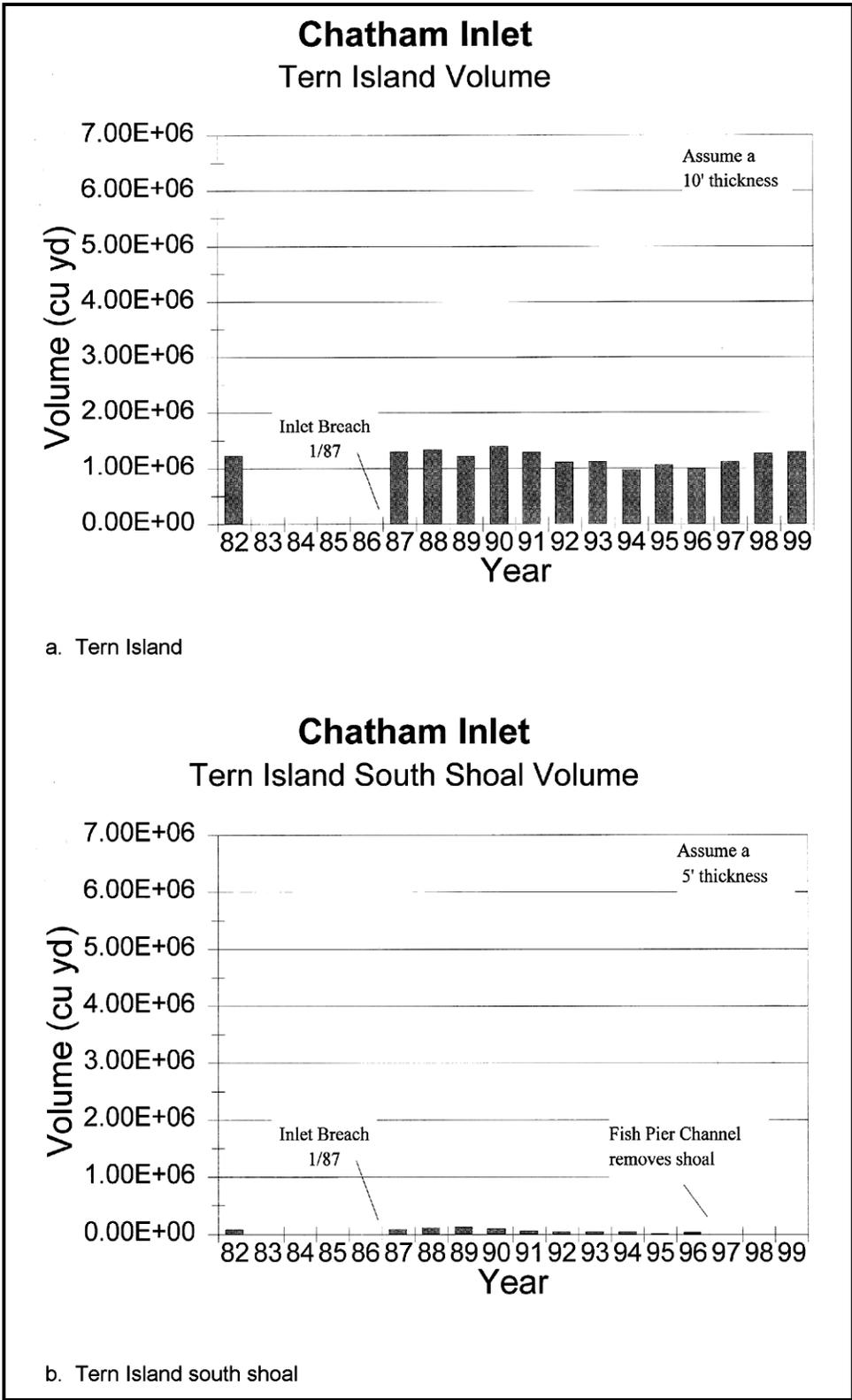


Figure 43. Estimate of volume change

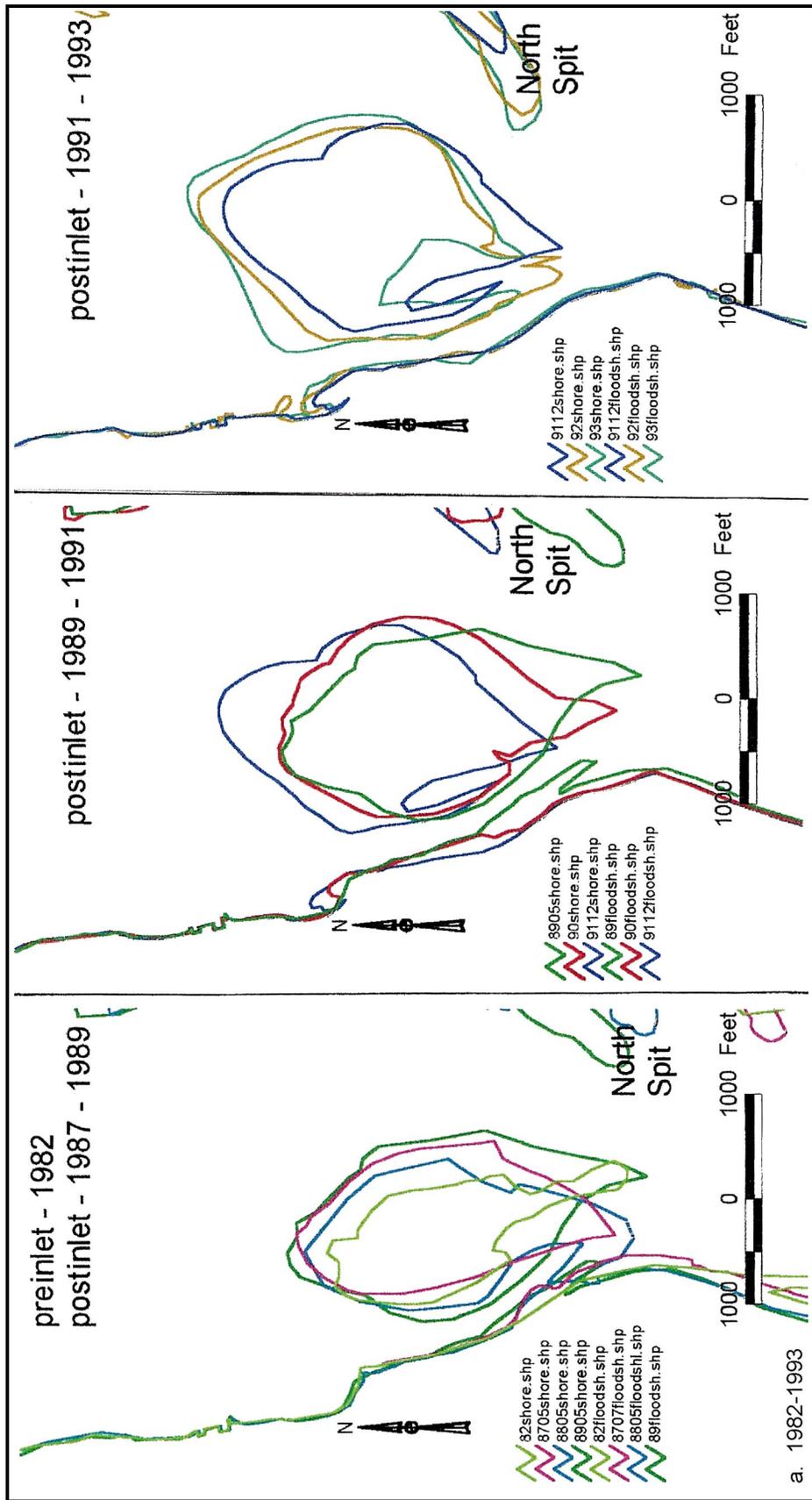
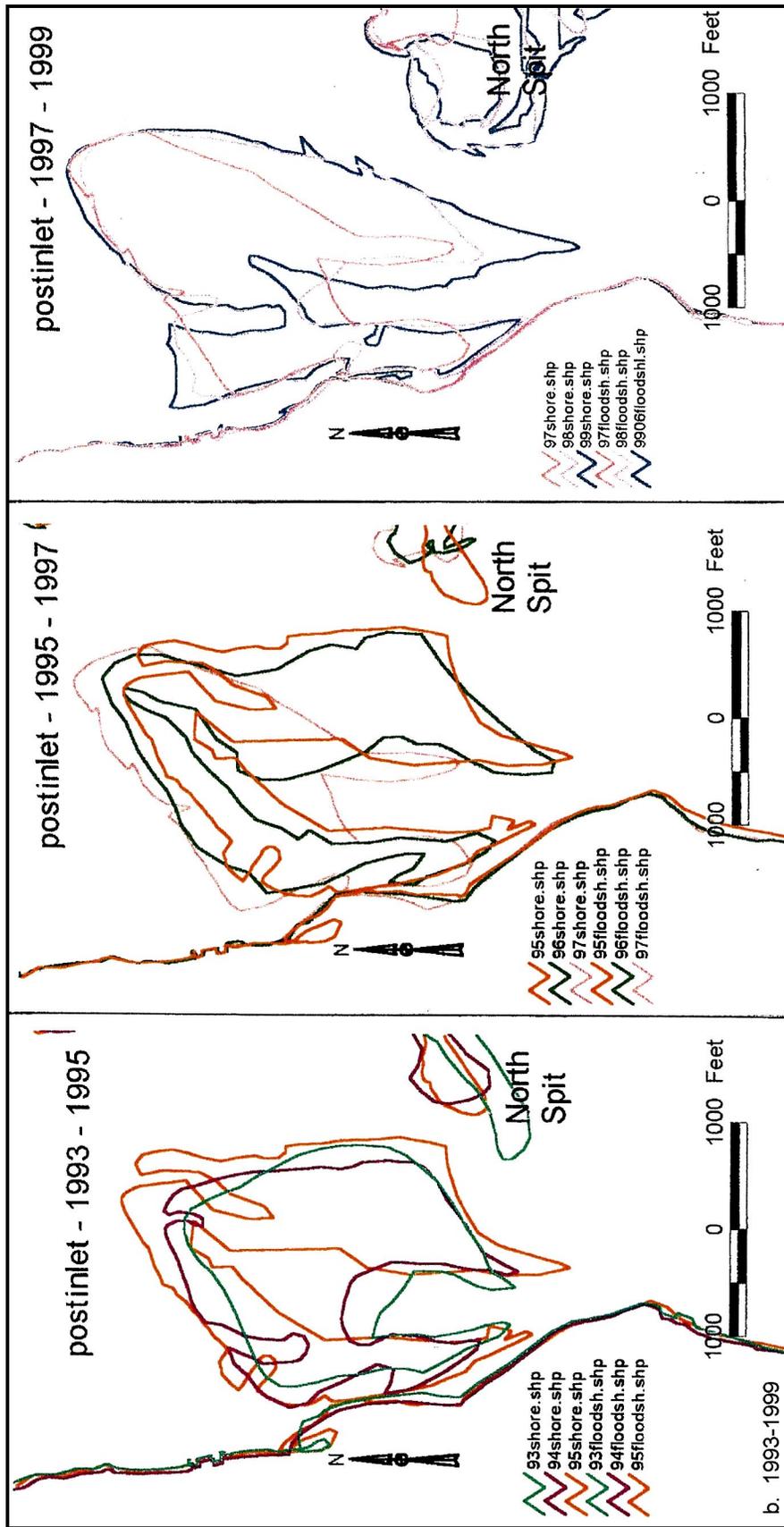


Figure 44. Map of change in north flood shoal (Continued)



b. 1993-1999

Figure 44. (Concluded)

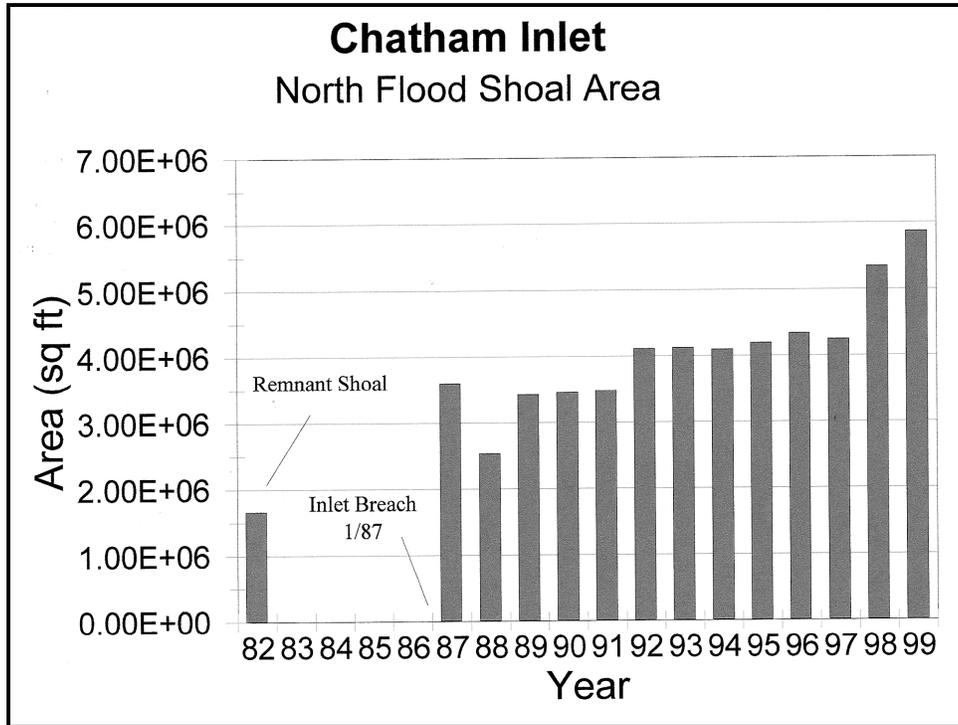


Figure 45. Area change from prebreach to 1999 in north flood shoal

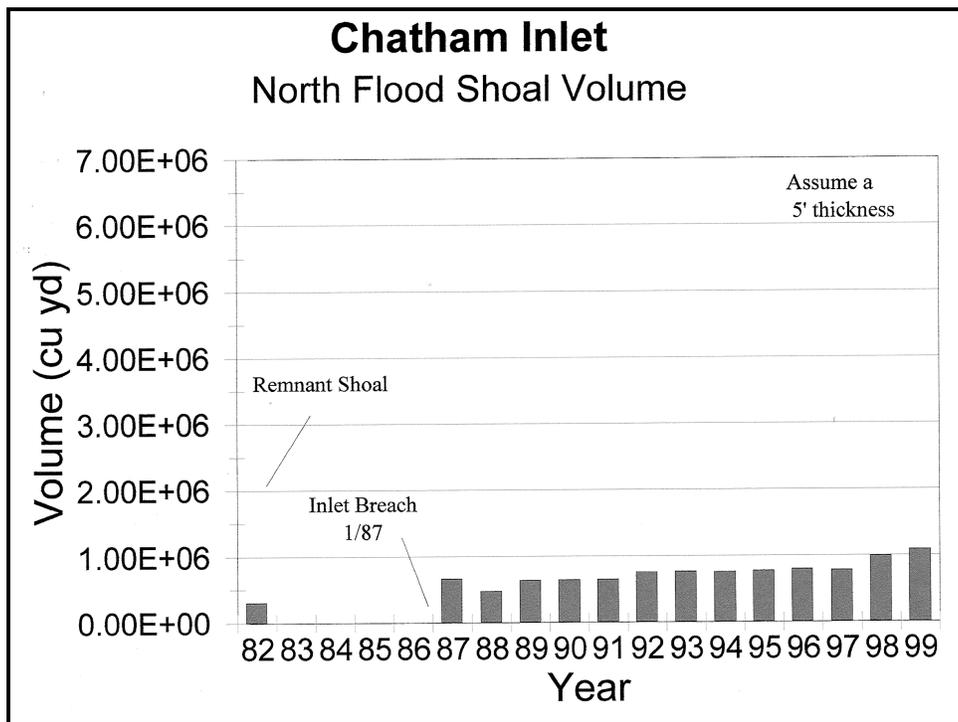


Figure 46. Estimate of volume change in north flood shoal

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 become 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.