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Morphodynamic Evolution of a Newly Formed Tidal Inlet

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Abstract

A unique opportunity to document and understand the processes of tidal inlet evolution and morphodynamic interactions presented itself with the breach of Nauset Spit across from the town of Chatham, Massachusetts. In the first twenty-eight months since its formation, the morphological evolution of the new inlet can be characterized into four categories: 1) Inlet mouth widening, caused by the concurrent retreats of the north and south spits that flank the inlet mouth; 2) Cyclical spit elongation, breaching, and terminal detachment; 3) The southward migration of the thalweg of the main channel and its associated shoals; and 4) Shoal growth. Six major shoals both seaward and landward of the inlet mouth developed between inlet formation and 1991. The growth of shoals and spit elongation indicate the trapping of littoral sediments within the inlet mouth area and the influx of ocean sediments entering the lagoon through the new inlet. The southward movement of the inlet channel is driven by its own channel configuration. As a result of the formation of this inlet, Chatham Harbor has evolved into two separate systems, each having its own hydrodynamic and morphological characteristics.

Formation and Evolution of Multiple Tidal Inlets
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Introduction

Inlet formation by breaching of a narrow section in a barrier shoreline is common in the historical record of coastal areas. Initial inlet formation usually develops during storm conditions, when the storm surge raises the water level on either the oceanside or the bayside of the barrier. The increased water levels allow the storm-induced waves and swash processes to erode into the beach backshore and dunes. On narrow barrier shorelines, particularly where dunes are low and discontinuous, the swash often will breach between the dunes and overwash the barrier carrying water and sediment to the lagoonside of the barrier. If the storm duration is sufficiently long enough to allow repeated overwashing, particularly around high tide, storm waves can cut a breach of sufficient magnitude to create a channel. Once there is an opening to the back-barrier bay/lagoon, and if there is sufficient tidal forces to create ebb and flood flows through the breach, it may be sustained after the storm surge subsides. The interaction of the tidal and wave forces may subsequently maintain and modify the opening to create a persistent tidal inlet (see Friedrichs et al., this volume).

Once a tidal inlet comes into existence, it interrupts the wave-induced longshore sediment transport (FitzGerald, 1989), causing not only shoreline changes in the vicinity of the inlet, but also formation of shoals within the inlet mouth and on both landward and seaward sides of the inlet. The newly formed inlet acts as a conduit for sediment and water exchanges between the bay/lagoon and the ocean.

In the initial stage of inlet development following its formation, the tidal sand transport through the inlet has not obtained equilibrium with the littoral drift. Subsequently, the inlet is expected to show rapid changes in its adjacent shoreline configuration and shoal morphology as it interacts to the changing hydrodynamic conditions. These changes, however, lead the inlet towards an equilibrium state. This sequence of change reveals mechanisms by which the entire inlet/barrier-bay system responds to the formation of the tidal inlet.

On occasions when a new inlet forms in close proximity to another existing inlet and shares the same tidal prism, complex interactions among wave, tidal and littoral forces establish a new set of equilibrium conditions. Most literature regarding tidal inlet changes have focused on single inlets that have been in existence for a period of time, and have obtained some consistency in their configuration and shoal morphology. There has been little documentation on tidal inlet changes during the initial stage of their development. The present study provides a unique opportunity to examine the morphological changes of an evolving tidal inlet in the first 28 months following its formation.

Study Area

The study site, Chatham Harbor, is a bar-built estuary/lagoon located on the southeastern corner of Cape Code, Massachusetts (Fig. 1). The estuary is an elongate, coast-parallel body of well-mixed water, approximately 6 km long, 1 km wide, having a maximum depth of 7 m. The northern reach of the lagoon consists of the wider and shallow Pleasant Bay.

Before January 2, 1987, Chatham Harbor was sheltered from the Atlantic Ocean by a barrier spit called Nauset Beach. The opening of this estuary into the Atlantic Ocean was located at the southern tip of the spit through Chatham Bars Inlet (now referred to as South Channel, Fig. 2). Since the breach, the southern portion of the barrier spit has been cut off, forming a barrier island called South Beach. Monomoy Island was originally a 12.9 km long barrier island to the south and west of South Beach. During historic times, this island migrated westward toward Nantucket Sound (Giese et al., 1989) and is now bisected by a small unnamed inlet separating North and South Monomoy Islands (Fig. 2). An opening between Morris Island and North Monomoy Island, called West Channel, leads to Nantucket Sound.

Prevalent deepwater waves approach Nauset Beach from the E-NE quadrants (Wright and Brenninkmeyer, 1979). Wave observations immediately north of Nauset Beach indicate a wave climate having an equivalent significant wave height of 3 m observed in January and February (Aubrey et al., 1982). During the same period, southward mean flows having an average velocity of 6 cm/sec were also observed (Aubrey et al., 1982). As a result of the prevailing wave field, a net southward longshore sediment transport rate is estimated to be 5 x 10^5cubic meters/year for the northern part of Nauset Beach

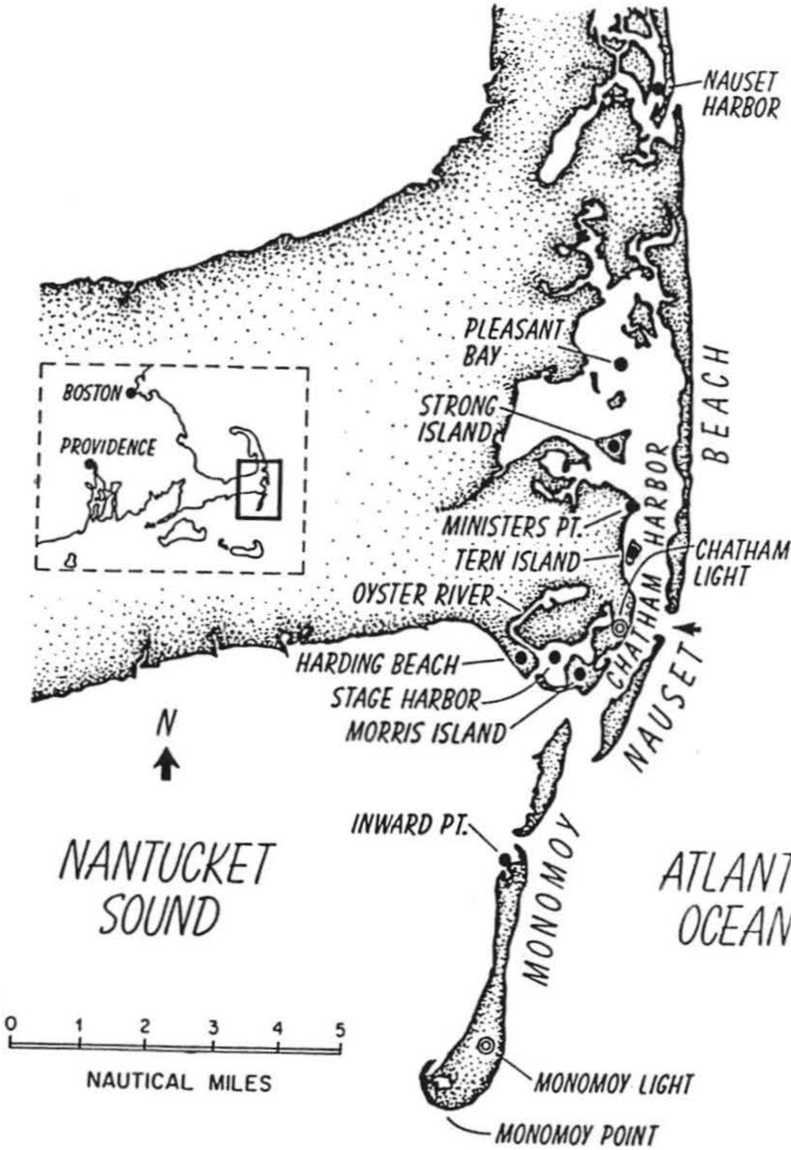


Figure 1. Index map of Chatham Harbor and the new inlet (marked by the arrow) formed on January 2, 1987. The shoreline drawn on this map (except the newly formed tidal inlet) was based on a map of 1980. The insert map shows the location of Chatham in Cape Cod, Massachusetts.

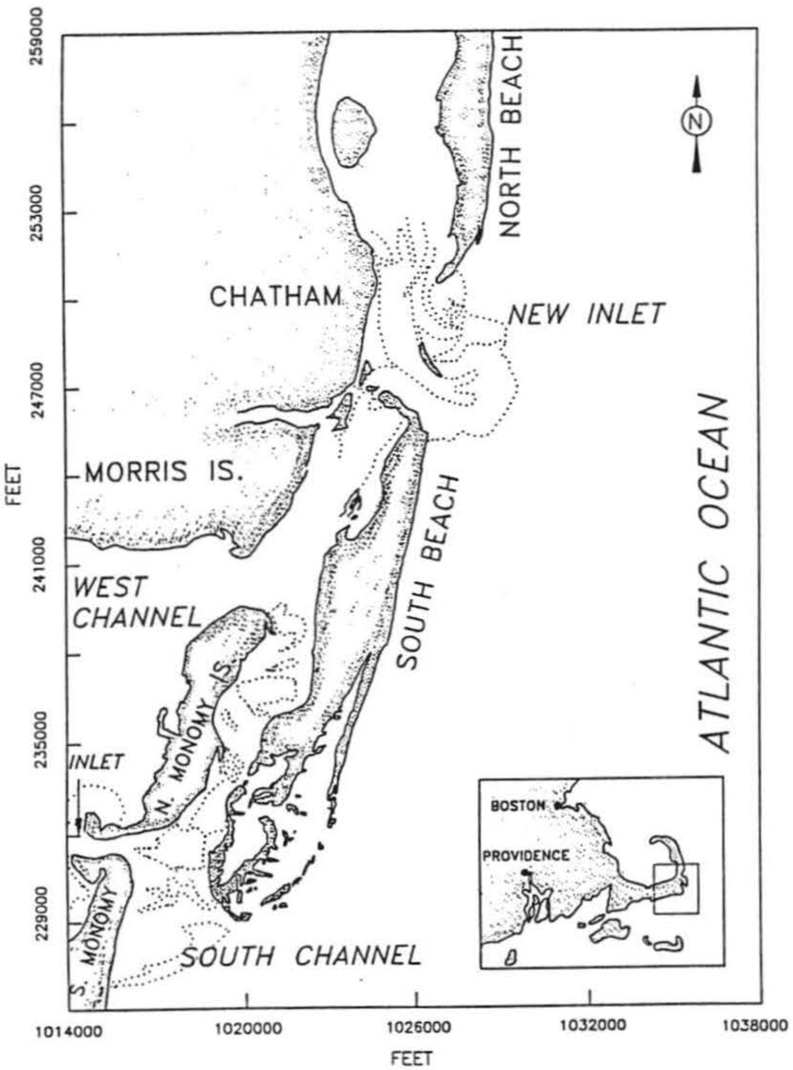


Figure 2. Updated map of Chatham Harbor estuary, with North Beach (spit), South Beach (barrier island) and North and South Monomoy Islands (reproduced from aerial photographs taken in September, 1988, and plotted on Massachusetts Grid). Along with the new inlet, the three previously existing inlets leading to the Atlantic Ocean and Nantucket Sound are now called South Channel, West Channel, and an unnamed inlet between N and S Monomoy Island.

(Cornillon, 1979). Due to their frequency and intensity, storms also play an important role in shaping the morphology of barrier spits in this area (Leatherman, 1979; McClennen, 1979; Aubrey and Speer, 1984).

On January 2, 1987, Nauset Beach was breached during a severe northeaster storm coinciding with a perigean high spring tide (Giese et al., this volume). The break-through first appeared as extensive washovers across the barrier beach when storm surge caused breaking waves to inundate the beach. When the storm subsided the next day, a meandering surge channel (approximately 5.5 m wide and 0.3 m deep) had been formed in the center of a washover fan in which the water continued to flow at both high and low tides. Aerial photographs taken a few days after the initial cut on Nauset Beach indicated that the transport of water had been predominantly bayward across the beach at high tides. In January and February 1987, Chatham experienced two more northeasters. By March, the breach had become 520 m wide.

The formation of the new inlet improved the efficiency of water exchange between the lagoon and ocean as indicated by the increased tidal range in Chatham Harbor after the breach. In April, 1988, near-bed measurements of the tidal current speed and tidal height within the channel throat of the new inlet showed that the average tidal range was 1.6 m. The maximum flood current speed exceeded 100 cm/sec, and the maximum ebb current speed exceeded 140 cm/sec (Fig. 3). On average, the maximum flood speed preceded the high water by about two hours, and the maximum ebb speed preceded the low water by about one hour and 45 min. This relationship indicates that the tide through the new inlet displayed mixed characteristics of both a progressive wave and a standing wave. The objective of this study is to provide initial, qualitative documentation on the morphological as well as bathymetric evolution of the newly formed inlet in Chatham.

Methods

This study included an analysis of a series of aerial photographs taken in a sequence starting shortly after the formation of the new inlet, to assess changes in shoreline and shoal morphology. A select set of sediment samples was collected and analyzed to characterize sediment grain-size distributions

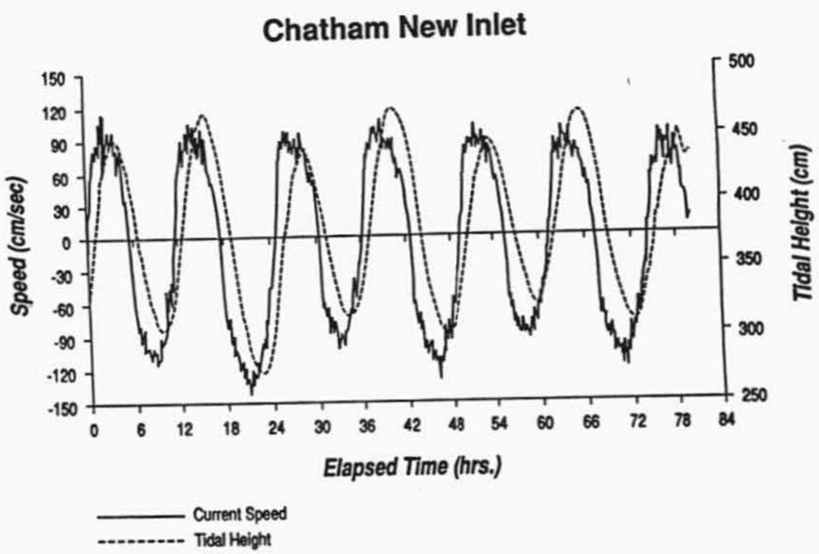


Figure 3. Tidal current speed and tidal height measured within the channel throat of the new inlet.

on a rapidly shoaling and evolving flood-tidal delta. Bathymetric survey were done of the evolving channels and shoals around the new inlet mouth Changes in shoreline position and inlet morphology were used to identify the processes of inlet formation, morphodynamics and sediment transport path ways active at the new inlet.

Aerial Photographs

Vertical aerial photographs of Nauset Beach and Chatham Harbor were taken at 4-month intervals beginning in May, 1987, through May, 1989. Except for the September 1987 set which was contracted by the National Park Service for another purpose, the time and altitude at which the photographs were taken were pre-determined to obtain maximum exposure of the intertidal shorelines and inter-to-subtidal shoals. A time sequence of 7 sets of aerial photographs has been obtained since the inlet formed (Table 1), along with a 1982 set of pre-breach conditions. Since several scales of photography were used in this analysis, a base map (1" = 1455') was constructed from a 1:24,000 USGS topographic map of Chatham. A Zoom Transfer scope was used to rectify and bring the various scales of the aerial photography to a common map scale. The shoreline shown on each set was digitized along the approximate low-tide waterline. In addition, the outlines of the inter- and subtidal shoals associated with the new inlet, such as the ebb-tidal delta, channel-margin bars and flood-tidal delta, were also digitized. The digitized photographs were then plotted on the Massachusetts Grid System (in feet) for further analysis. The reproduced maps were also carefully checked against one another for accuracy and precision, and were determined satisfactory for the qualitative purpose of this study.

Sediment Grain-Size Analysis

In September, 1988, eight surficial sediment samples were collected by hand near the time of low water from locations along a transect across the flood-tide delta (shoals) linking the spit on the South Beach to the inner shore of Chatham immediately south of the new inlet. These sediment samples represent recent depositional conditions of the previous falling tide. They were analyzed at the sediment laboratory of the Coastal Engineering Research Center of the Army Corps of Engineers, using a sonic sifter at quarter-phi sieve intervals. Grain-size frequency distributions and statistical data were then calculated using the Interactive Sediment Analysis Program (ISAP). Mean, sorting, skewness, and kurtosis were calculated using the method of moments.

Table 1. Time sequence of aerial photographs of Chatham Harbor.

Time	Scale	Remarks
October 1982	1:18000	Including portions of Monomoy Islands
May 1987	1:9000	
September 1987	1:8000	Excluding portions of inner shore of Chatham
January 1988	1:9000	
May 1988	1:18000	Including Monomoy Islands
September 1988	1:18000	Including Monomoy Islands
December 1988	1:18000	Including Monomoy Islands
May 1989	1:18000	Including Monomoy Islands

Bathymetric Survey

A bathymetric survey was conducted in April, 1988. A Del Norte microwave radar navigation system was used for positioning. Depth was measured using an Odom Echotrac fathometer on board a 19-foot Boston Whaler. The data were logged into a shipboard computer simultaneously with the position information using automated, integrated navigation software. The depths were later corrected for tidal elevations at the time of the survey. The survey covered the seaward edge of the terminal lobe of the ebb-tidal delta of the new inlet, part of the main channel around the throat of the new inlet, and channels of the two previously existing inlets.

Morphological Evolution of the New Inlet

Since the initial breach in January 1987, the new inlet has continued to grow and develop distinctive geomorphology. The interactions between tidal and wave forces during the 28-month study period have resulted in the evolution and migration of the newly formed tidal inlet, its associated shoals and channels, and adjacent shorelines. Specific details of the continued widening of the inlet and resulting complex changes in the shorelines of the north and south spits adjacent to the inlet are examined. Common inlet-associated shoals have formed and the evolution of these flood and ebb-tidal shoals are described.

Inlet-Mouth Widening and Spit Retreat

Maps of the low-tide shoreline (solid lines) and outlines of inter- to subtidal shoals and channels (dotted lines) around the new inlet (Figs. 4a-h) were produced from the aerial photo sets. The distance between the spit on North Beach and that on South Beach continued to increase between May, 1987, and May, 1989, allowing greater influence of ocean waves to impinge upon the interior of the estuary. This widening was accomplished by the southward retreat of the north end of South Beach (the south spit), and the contemporaneous northward retreat of the south end of North Beach (the north spit, Fig. 5). The shoreline changes along the axis of Nauset Beach were quantified by measuring the distances from the tips of the north and south spits, and from the north and south edge of the main channel at the throat, to the location where the breach first appeared (Fig. 6).

Within the trends of the progressive movements of the north and south spits, both spits showed short-term fluctuations in their orientations and lengths (Fig. 5). Casual observations indicated that the north spit retreated in a stepwise fashion that included southward lengthening followed by severe overwashing and subsequent detachment of the tip of the spit. The detached remnant spit soon became a subtidal shoal and disappeared. At times, after a shortening episode of terminal detachment, the tip of the north spit would grow southward, passing the previous position as exemplified by the positions of the north spit terminus in January, 1988 relative to September, 1987; September, 1988 relative to May, 1988; and May, 1989 relative to December, 1988 (Fig. 5). No seasonal pattern for the retreat of the north spit was established due to inadequate temporal coverage of the aerial photographs. However, the pattern of alternate spit truncation and elongation was evident.

Simultaneous with the progressive southward retreat of the north end of South Beach, the south spit also displayed cyclical elongation followed by breaching and terminal detachment. The detached terminus then became an intertidal island. Subsequently, a chain of the NW-SE oriented intertidal islands and flats has formed landward of the south spit as a result of the combination of both the cyclical E-W movements of the south spit and the progressive southward retreat of the north end of South Beach. Three such cycles during 1987 and 1988 have been observed, each having a period of approximately four months. Within each cycle, distinctive morphological stages of the spit were recognized (Ebert and Weidman 1989).

Although the frequency of aerial photographs of this study is out of phase with the spit cycle, different stages from different spit cycles were recorded. The south spit in September, 1987 (Fig. 4c) represents the initiating stage of a new cycle preceded by a breach. In May, 1988, the spit was probably in the middle-stage of rapid growth (Fig. 4e). September, 1988 (Fig. 4f) represents the late stage at which a breach is about to occur. The repetitive elongation of the south spit in its growth-and-breach cycles indicates a constant influx of littoral sediments into Chatham Harbor.

Shoal Development and Evolution

As the new inlet formed, a series of shoals became readily identifiable from the aerial photography. Six areas of shoals have been identified based on shoal configurations and previous inlet investigations (see for example Hayes, 1980, Boothroyd, 1985). The new inlet has developed many of the shoal morphologies commonly associated with tidal inlets. Figure 7 shows the generalized inter- to sub-tidal sand bodies labeled 1 through 8. Shoal features associated with the inlet mouth are the ebb-tidal delta (1) and flood-tidal deltas (5 and 6). The specific morphology of the flood-tidal deltas is

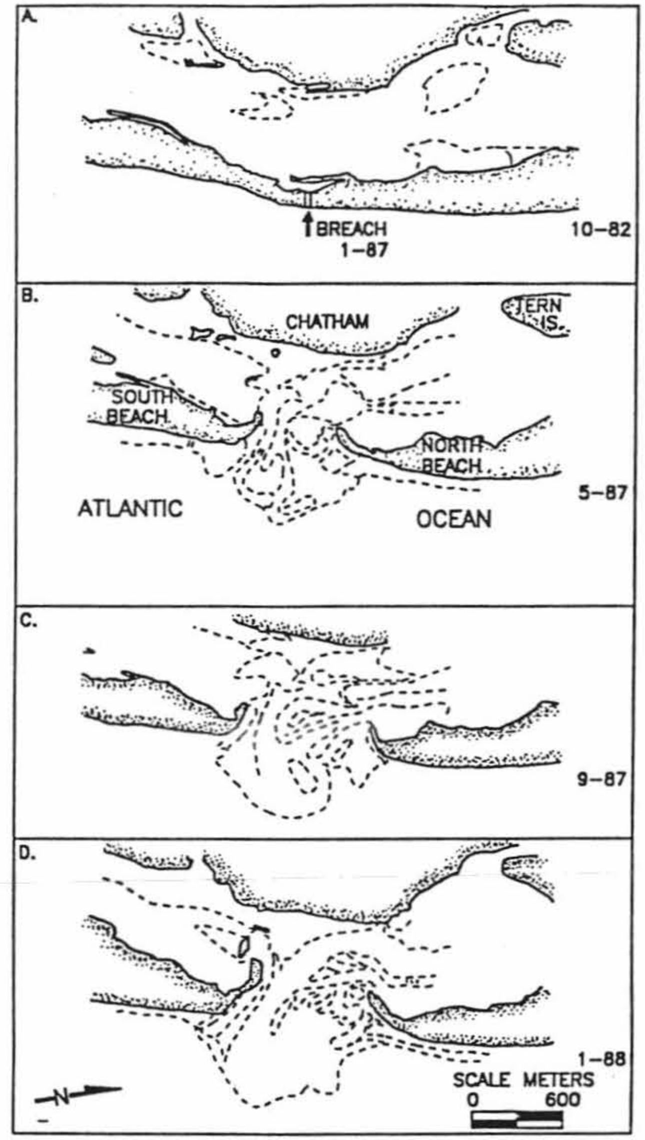
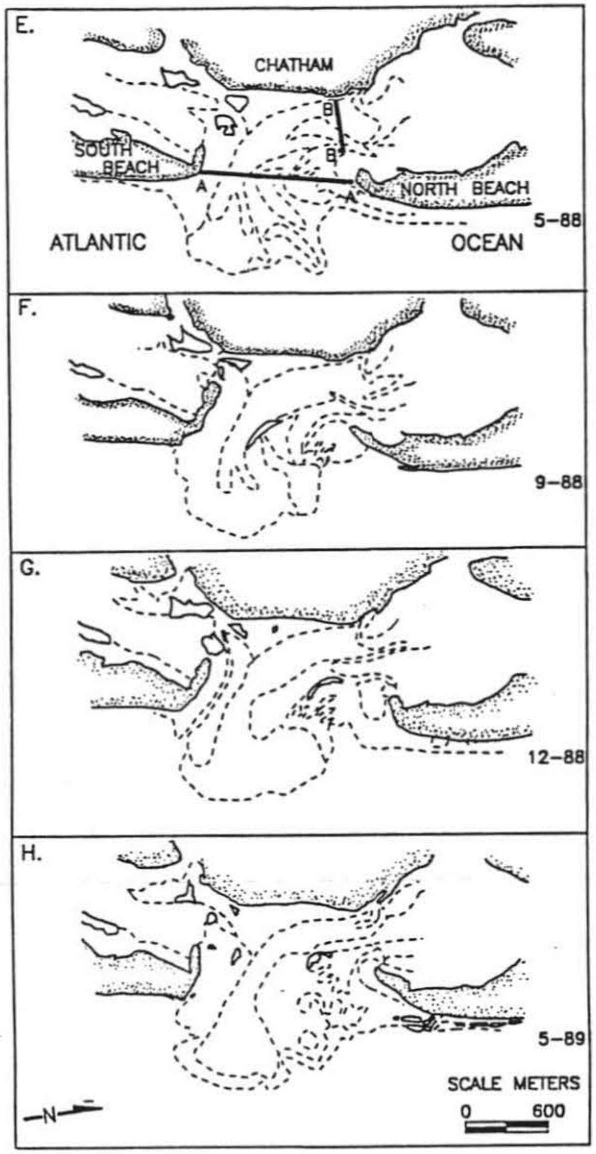


Figure 4. Development of shorelines (solid lines) and shoals (dotted lines) of the new inlet from aerial photography in: a) October, 1982; b) May, 1987; c) September, 1987; d) January, 1988; e) May, 1988; f) September, 1988; g) December, 1988; and h) May, 1989.



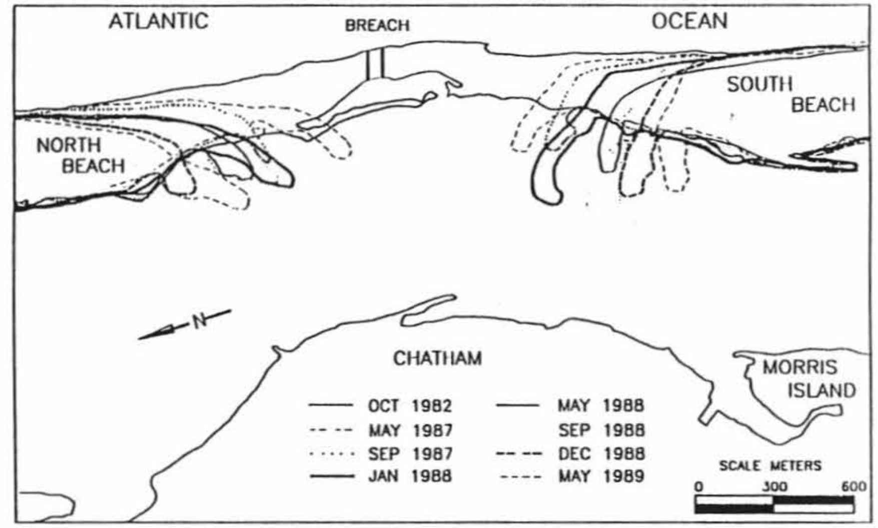


Figure 5. Sequential shoreline changes of the two spits flanking the new inlet, from May, 1987 to May, 1989. The pre-breach shoreline of October, 1982 is also plotted for comparison.

influenced by the long narrow estuary shape and close proximity of the Chatham mainland shore.

The ebb-tidal delta at the new inlet is the most prominent feature seaward of the inlet mouth. A large channel-margin swash platform (2) also developed on the updrift (north) side of the inlet channel throat. Landward of the inlet mouth, the flood-tidal shoal complexes are somewhat different from the classical inlet flood shoal development. The narrow, elongate, and coast-parallel Chatham Harbor constricts expansive flood shoal configuration. In addition, the presence of remnant shoals that predate the opening of the inlet also influence present shoal locations (Fig. 4a). Each of the north and south flood-tidal deltas is associated with remnant shoals (Fig. 7).

Two other remnant lagoon shoals also interact with the inlet morphodynamics. A linear shoal (7) trending parallel with Nauset Beach is visible on the

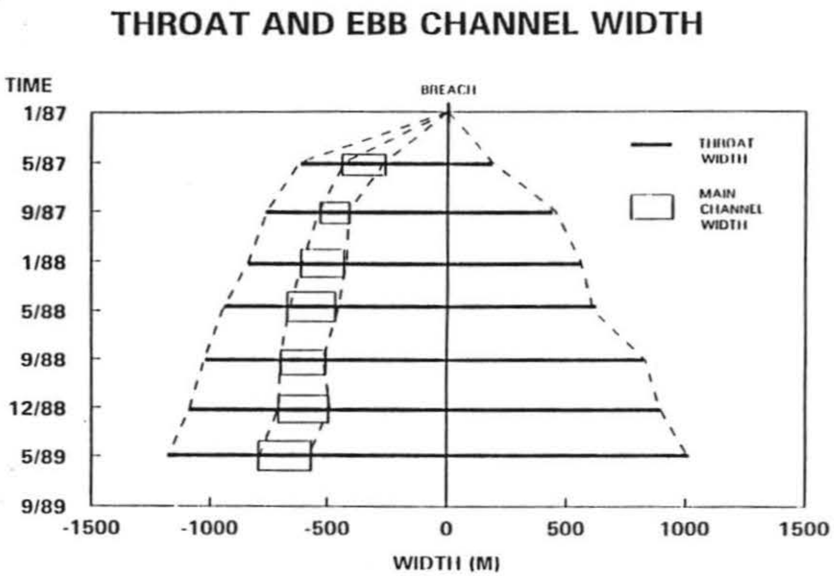


Figure 6. Temporal changes of the width of the new inlet mouth between north and south spits (solid lines) and the width and position of the main channel throat (rectangles) with respect to the location of the initial breach (the origin on the horizontal axis). The positive distance indicates the north side of the initial breach.

1982 aerial photography. This shoal seems to be related to tidal flow along the axis of the estuary and has been modified as the inlet develops. A sand flat (8) in front of the small boat harbor between Toms Neck and Morris Island is also present on the 1982 aerial photography and remains after the inlet opened.

As the new inlet continues to evolve both the ebb- and flood-tidal deltas grew in size. Table 2 gives the area of the shoals measured from the aerial photography. Numbers preceding each shoal or spit indicate the location on Figures 8a and 8b, which summarize these areal changes. Since subaqueous boundaries of each shoal were determined visually, this type of analysis is only indicative of sediment depositional changes that were visible from the aerial photography. No detailed bathymetry corresponding to the dates of aerial photography was available.

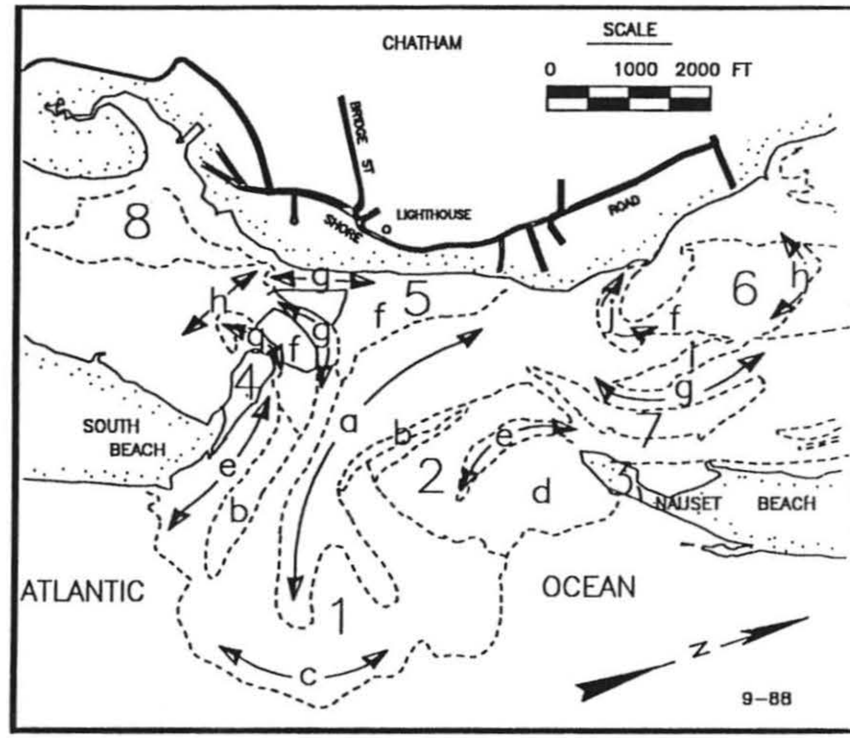


Figure 7. Shoal development of the new inlet (plotted on September, 1988 aerial photograhs). The arrows indicate the inferred sediment transport pathways associated with the shoals. 1 = Ebb Tidal Delta; 2 = Swash Platform with: a = ebb channel; b = channel marginal bars; c = terminal lobe; d = swash bars; e = flood channels; 3 = North Spit; 4 = South Spit; 5 = South Flood-Tidal Delta; 6 = North Flood-Tidal Delta with: f = flood ramp; g = flood channel; h = ebb shield; i = ebb spit; j = spillover lobe; 7 = Remnant Linear Shoal; 8 = Remnant Sand Flat.

The areal changes of the ebb-tidal delta(1) indicate a persistent growth of the shoal into the ocean with a southward shift corresponding to the southward shift in the main channel. The channel-margin swash platform (2) increased rapidly between May and September 1987, and the rate of increase slowed between September, 1987 and September, 1989. The platform area again exhibited a rapid increase to a maximum in May, 1989 (Fig. 8a).

Despite of the periodic changes in its orientation through time, the areal size of the north spit showed little fluctuation except for September, 1987 when

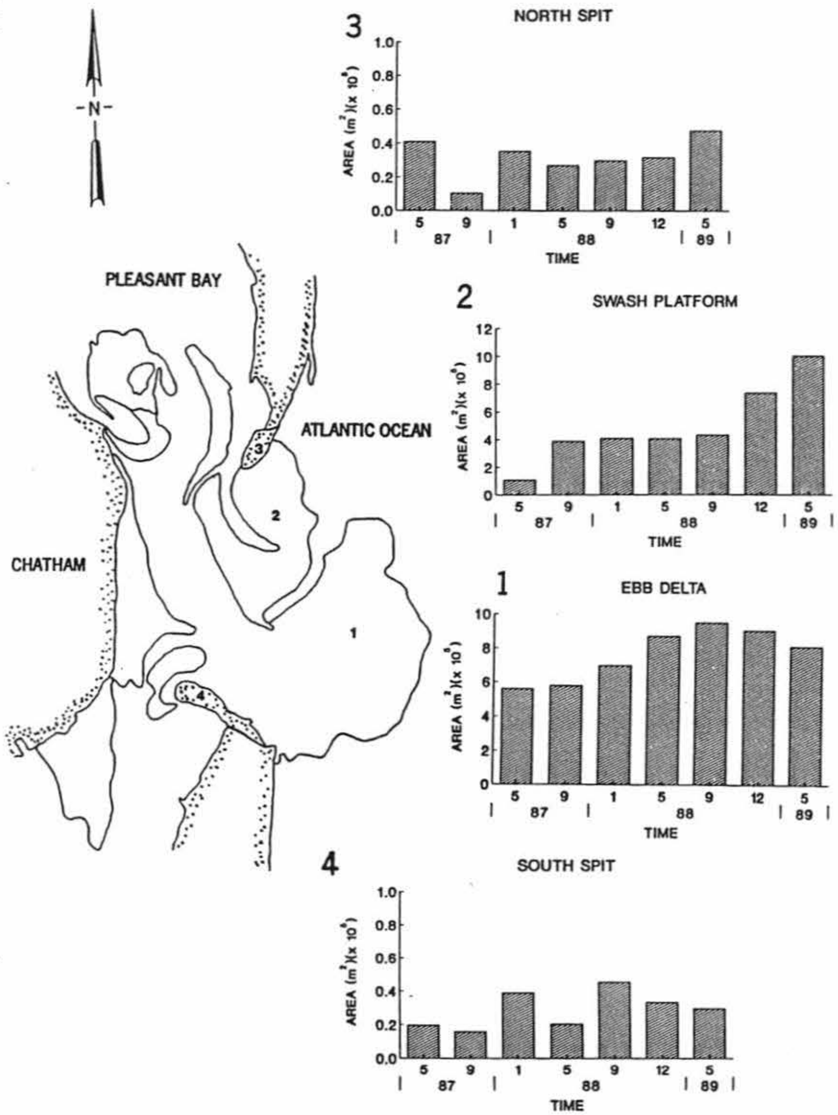


Figure 8a. Post-breach shoal and spit area changes on oceanside of the new inlet (note area scale

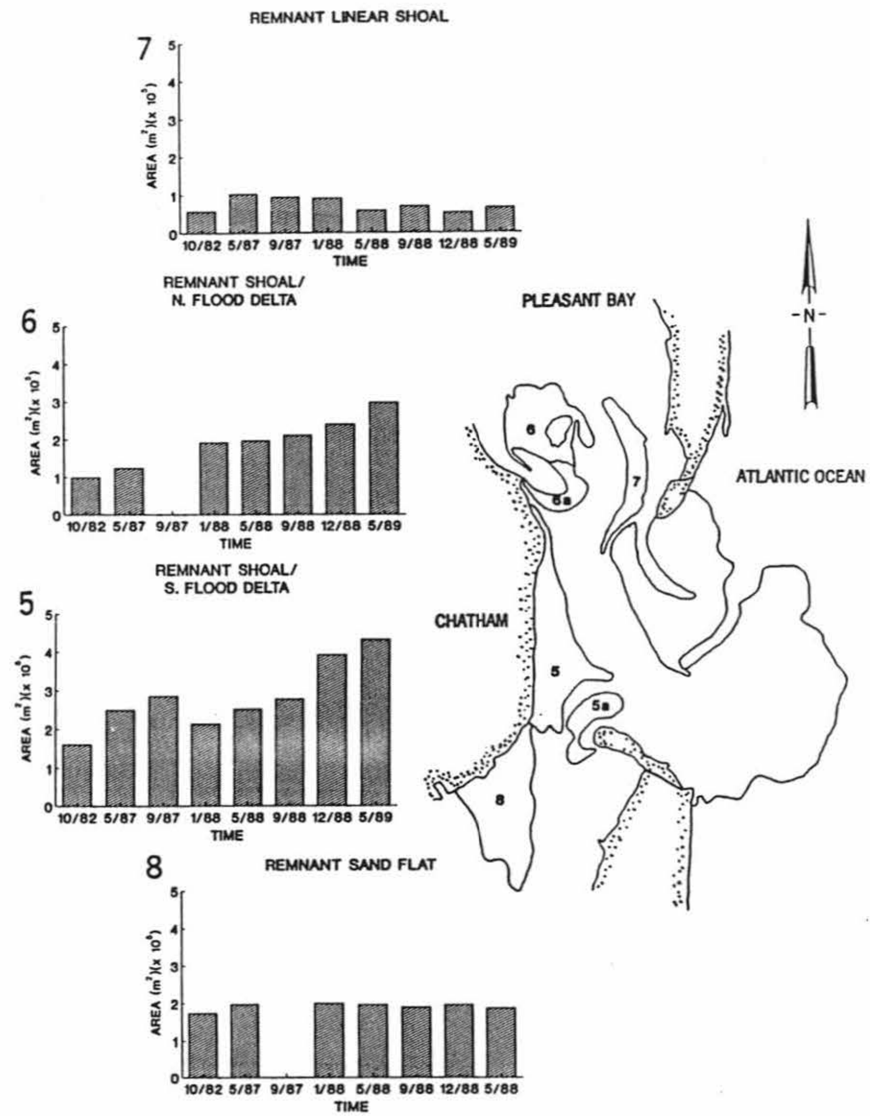


Figure 8b. Post-breach shoal area changes on the landward side of the new inlet.

Table 2. Area change in New Inlet shoals and spits.

DATE: SHOAL/SPIT SHOAL #	10/82	5/87	9/87	1/88	5/88	9/88	12/88	5/89	TYPE
	AREA ($x10^5$ m^2)								
1	-	5.60	5.80	7.00	8.74	9.54	9.09	8.24	EBB DELTA
2	-	1.07	3.87	4.08	4.07	4.33	7.41	10.03	SWASH PLATFORM
3	-	0.41	0.10	0.35	0.27	0.30	0.31	0.47	NORTH SPIT
4	-	0.20	0.16	0.39	0.20	0.46	0.33	0.30	SOUTH SPIT
5	1.60	2.47	2.85	2.06	2.90	2.04	1.93	2.57	REMNANT
5a	-	0.03	-	0.07	0.62	0.73	1.99	1.75	SHOALS/S.
Total (5)	1.60	2.50	2.85	2.13	2.52	2.77	3.92	4.32	FLOOD DELTA
6	0.99	1.07	N/A	1.74	1.69	1.64	1.85	2.76	REMNANT
6a	-	0.18	-	0.18	0.28	0.46	0.55	0.27	SHOAL/N.
Total (6)	0.99	1.25	-	1.92	1.97	2.10	2.40	3.03	FLOOD DELTA
7	0.58	1.03	0.94	0.91	0.59	0.70	0.52	0.65	REMNANT LINEAR SHOAL
8	1.74	1.97	N/A	1.99	1.96	1.89	1.96	1.87	REMNANT SAND FLAT

the area of the north spit was reduced to about half of its average size. Between May, 1987 and May, 1989, there was a small net decrease in area of the north spits. The area of the south spit fluctuated as a result of the cyclical growth and periodic separation of the distal end of the spit. However, a net gain of $0.1x10^5$ m^2 was measured on the south spit during the length of the study.

The evolution of the flood-tidal deltas is dated back to shoals that existed in the lagoon prior to the breach. As the inlet evolved, these shoals took on more characteristics of inlet-related configurations. In 1982, a large sand flat (Fig. 4a) approximately of $1.6x10^5$ m^2 in area existed off the Chatham lighthouse on the mainland shore. After the breach, it has been modified by waves and tidal currents and became incorporated into the south flood-tidal shoal complex (5 & 5a, Fig. 8b). This shoal complex continued to grow to a

maximum size by May, 1989. The interaction of this shoal with the growth of the south spit caused the area of the shoal to fluctuate. The shoal complex has essentially prevented effective water exchange between the northern and southern parts of the lagoon. A net gain of approximately $2.71x10^5$ m^2 was measured from October, 1982 to May, 1989, as this south flood-tidal shoal continued to evolve and migrated southward.

A large shoal (6) having the area of $1.0x10^5$ m^2 also existed in mid-lagoon in 1982, which caused the main channel to bifurcate on its way to Pleasant Bay (Fig. 4a). After the breach, this shoal has been modified to become the north flood-tidal delta complex (6 & 6a, Fig. 8b). There has been steady growth in the area of this shoal with time (Fig 8b.). No area was measured from the September, 1987 photographs since the entire shoal was not visible on the lower altitude photo set. A net gain of approximately 1.99x105 m2 was measured from October, 1982 to May, 1989. The growth of an ebb spillover lobe (6a) extending into the original channel may become a hazard for navigation as this shoal complex continues to develop.

The linear sand shoal (7) gained approximately $0.5x10^5$ m^2 of area after the breach and has increased slightly by $0.07x10^5$ m^2 over the twenty-four month period since May, 1987 (Fig 8b). The other remnant sand flat area (8) increased slightly in area immediately after the breach and has remained essentially constant during the study period. The transport of sediment southward along the mainland shoreline, and the slow movement of the south flood-tidal delta into the southern part of the lagoon, indicate that more sand will probably reach this shoal in the near future.

Southward Migration of the Main Inlet Channel

Aerial photographs show that a main channel between the north and south spit (not well-defined on May, 1987 photographs, Fig. 4b) has formed, which bends seaward from shore-subparallel to shore-perpendicular through the new inlet mouth. The changes of the channel orientation suggest the capture of the tidal prism by the newly formed inlet. The water exchange between the estuary and ocean is now more efficient through the new inlet than through South Channel, due to less friction (shorter route).

South of the main channel bend is the area of an extensive subtidal shoal complex. These shoals formed a platform on which the detached remnants of the south spit underwent transformation to become flood tidal-delta-like shoals. Interspersed between these intertidal islands that extended across the estuary are small flood-dominated secondary channels connecting the two parts of the estuary (Fig. 4e-h). These channels are only effective during the late stage of the flood tide and early stage of the ebb tide when the water elevation is high.

The existence of the broad and shallow inter- to subtidal channel-margin swash platform on the updrift side of the main channel in the throat area resulted in an asymmetric configuration shown by the cross-sectional profile (marked by A-A' in Fig. 4e) of the inlet mouth (Fig. 9). The position of the southernmost edge of this platform showed southward advancement from May, 1987 to May, 1989 (represented by the position of the northern bank of the main channel throat, Fig. 6). Because of the net northward retreat of the north spit, the length of this platform actually increased.

As the edge of the channel-margin swash platform progressively advanced southward, the position of the mid-point of the main channel in the inlet throat also shifted southward. This southward movement has an average migration rate of 12 m per month between May, 1987, and September, 1988 (Fig. 6), and a slower rate of 9 m per month from September, 1988 to May, 1989.

From May, 1987, to May, 1988, the width of the channel in the throat section increased from approximately 110 m to 192 m, and remained about the same thereafter. Since the width of the channel is proportional to the size of the channel (Bruun et al., 1978), the asymptotic trend of the channel width increase may suggest that the expansion of the channel in the inlet throat has stopped between May and September, 1988. In other words, the main channel is no longer in the scouring stage, characteristic of the initial stage of inlet development (Bruun et al., 1978). However, the channel, while maintaining a constant width through the throat area, is still migrating southward with the ebb-tidal delta, causing the south spit to retreat southward.

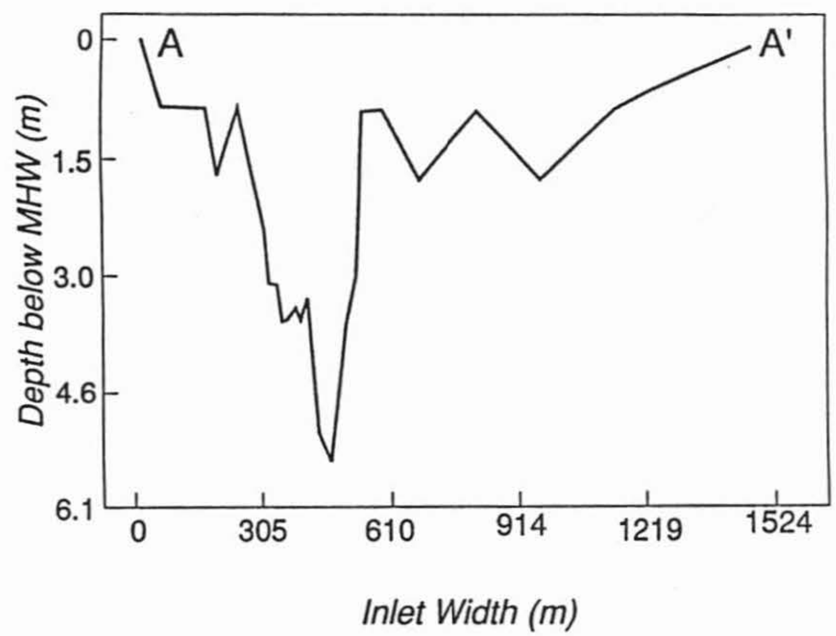


Figure 9. Cross-sectional profile across the inlet mouth (see Fig. 4e for position).

Sediment Patterns along the Shoals South of the Main Channel Bend

Eight surficial sediment samples were collected in a transect across the south spit and flood tidal shoal/channel complex (Fig. 10, Table 3). The flood-tidal delta sediments all group in the well sorted and medium mean grain size category. Within this grouping, the sub-environments of the overwash (#1) and tidal flat samples (#5, 7) are distinguished by slightly better sorting and slightly coarser means than the flood channel samples (#4, 6, and 8). The overwash throat on the spit was probably influenced by waves and tidal currents from the mid to high portion of the tidal cycle. The two tidal flat areas

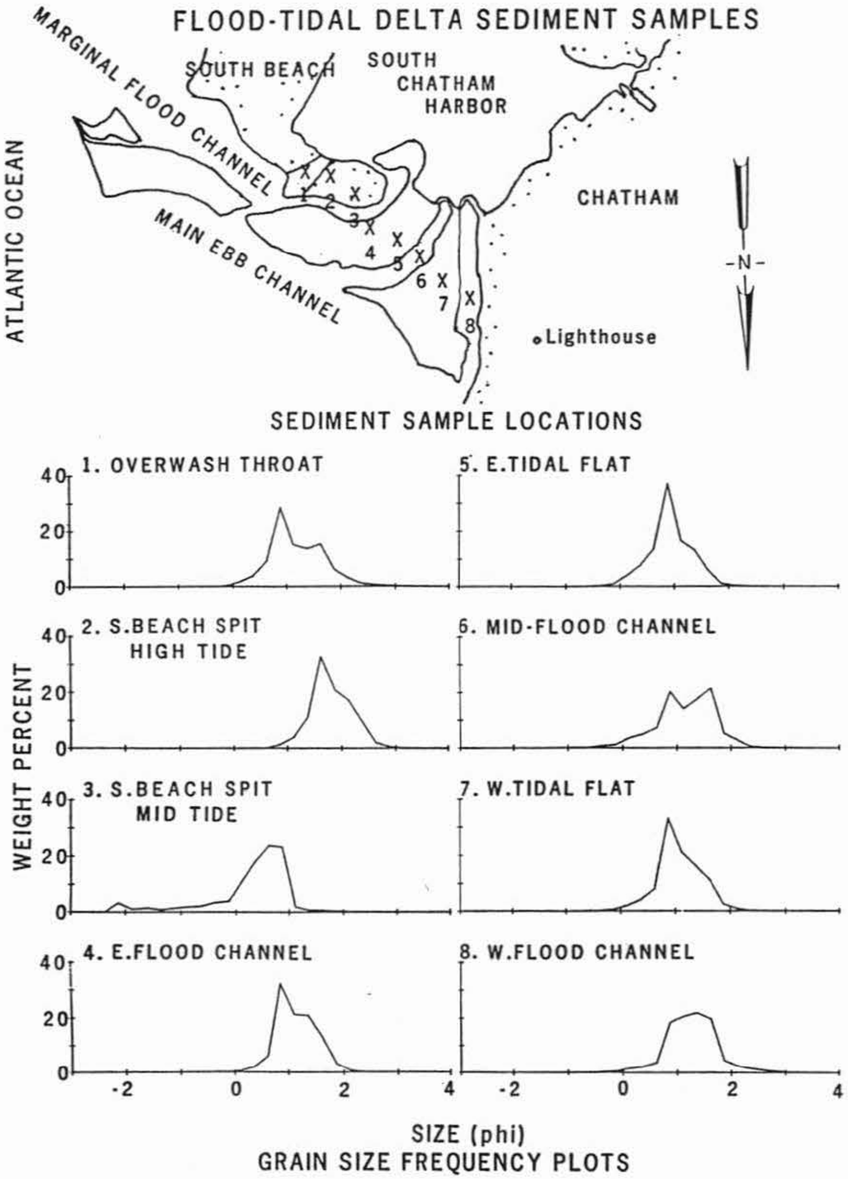


Figure 10. Sediment grain-size frequency distributions and their corresponding locations across the shoals between the south spit and the inner shoreline at low water in September, 1988.

Table 3. Sediment sample location and grain size statistics

Location	Moment Mean (Φ)	mm	Moment Sorting (Φ)	Moment Skewness (Φ)	Moment Kurtosis (Φ)
Overwash	1.13	0.46	0.36	0.00	3.47
High Tide on Spit	1.80	0.29	0.37	0.12	3.16
Mid Tide on Spit	0.29	0.82	0.76	-1.60	5.59
East Flood Channel	1.18	0.44	0.51	0.33	3.78
East Tidal Flat	0.92	0.53	0.40	-0.17	3.67
Mid Flood Channel	1.15	0.45	0.53	-0.59	3.42
West Tidal Flat	1.07	0.49	0.41	-0.01	4.04
West Flood Channel	1.27	0.42	0.49	-0.01	4.9

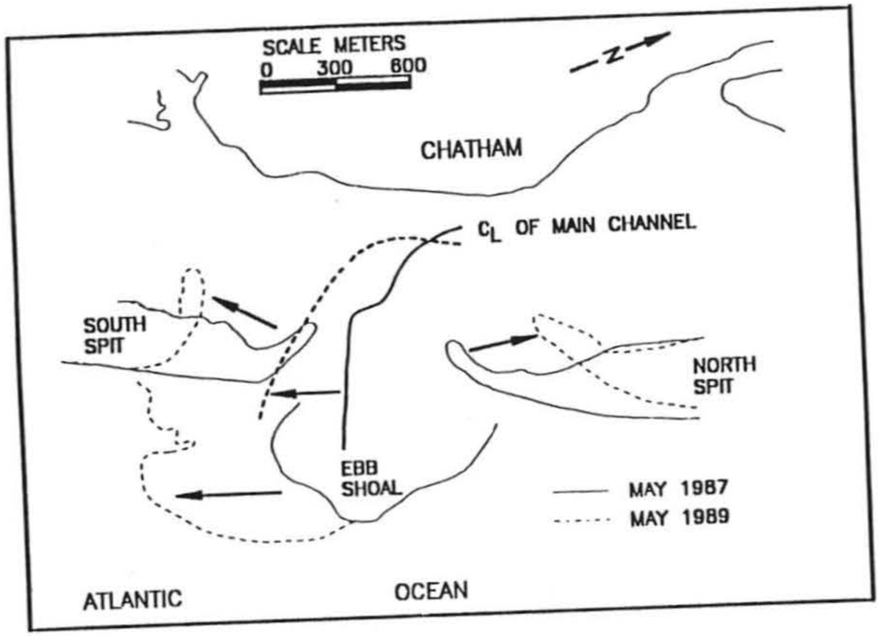


Figure 11 Net changes in north and south spit shorelines, ebb-tidal delta, and thalweg (C_L) of main channel from May, 1987 to May, 1989.

are under the influence of tidal currents around high tides and are exposed during low tides. Each channel sample exhibited slightly bimodal distributions, perhaps suggesting the unequal influence of bi-directional tidal currents.

Processes

Based on the evolution of the inlet and shoal morphology and sediment distribution and channel bathymetry, processes driving this system can be inferred. Morphological changes in the development of the new inlet from May, 1987, to May, 1989, are summarized in Figure 11, which highlights

spatial changes and direction of movements observed in the two barrier spits, ebb-tidal delta, and main channel.

The tip of the north spit moved approximately 700 m northward and slightly landward while the south spit moved about some 580 m southward and appreciably landward due to the shore-normal re-orientation. The ebb-tidal delta has grown seaward and moved to the south while a large channel-margin swash platform on the north and a marginal linear bar on the south of the main channel throat have developed within the inlet mouth. The main channel thalweg also shifted position some 400 m to the south. The south spit/south flood-tidal delta complex has virtually filled in the N-S oriented channel that existed in May, 1987, as the delta moves farther southward into the estuary. The remnant shoal/north flood-tidal delta complex has developed and seems to cause shoaling in the adjacent navigation channel.

The Influence of Waves and Tidal Currents

Seasonal wave climate and longshore drift patterns may play a role in the fluctuations of both the north and south spit development. The southwesterly waves and northward drift in summer caused the north spit to retreat farther to the north, whereas in winter the predominantly stronger northeasterly waves and southward drift erode the south spit into the lagoon. Wave refraction around the growing ebb-tidal delta is also likely to play a role in forming a localized northward drift aiding in the south spit elongation into the lagoon.

The apparent downdrift migration of the main channel and inlet throat, the edge of the updrift channel-margin platform, and the downdrift retreat of the south spit (north end of South Beach) all indicate sediment accumulation on the updrift side of the main channel thalweg and concurrent sediment removal on the downdrift side. This depositional pattern suggests trapping of littoral sand within the area of the new inlet mouth and resulting insufficient sand bypassing (Oertel, 1988).

In addition, sediments from the littoral drift are partially diverted seaward and landward by tidal flows through the main channel to form the flood and ebb-tidal deltas. The influx of littoral sediments into the lagoon is probably aided by waves and is evident from the accretion on the inner shore south of the main channel bend (Giese et al., 1989), from the cyclical elongation of the south spit, and from the extensive growth on the north and south flood-tidal delta complexes. The depositional processes along the shoals between the south spit and the mainland shore south of the main channel bend are influenced both by ocean waves and tidal currents. Sediment grain size characteristics along these shoals indicate strong wave influence on the landward-accreting south spit, and moderate wave influence on the tidal flats. Among the secondary channels that connect the main channel and South Chatham Harbor, the landward- and seaward-most secondary channels are probably dominated by flood-tidal currents. The mid-secondary channel is probably more affected by ebb tidal currents that flow from South Chatham Harbor into the main channel of the new inlet. Despite of the influx of ocean sediments and the prevalent depositional patterns inside the estuary, the small erosional segment on the inner shore (Giese et al., 1989), however, is a localized phenomenon, which is caused by the proximity of the main channel to the shore as shown by the cross-sectional profile of the channel (marked B-B' in Fig. 4e) in Figure 12.

Morphodynamics of the Main Channel of the New Inlet

Although a hydrodynamic equilibrium is attained at the inlet throat, the continuing southward migration of the main channel and the ebb-tidal delta suggests that the position of the inlet has not yet reached a state of morphodynamic equilibrium in the entire inlet/barrier-bay system. The correspondence between the accretional trend of the edge of the channel-margin platform and the erosional trend of the south spit (Fig. 6) indicates that these two features are both related to the southward-advancing main channel throat that separates the two. Aubrey and Speer (1984) suggested that a bending inlet channel configuration can be responsible for lateral inlet migration, creating a steep outer (southern, in the case of this study) channel bank, and an accreting point bar on the inner (northern) bank. This mechanism is likely operational in the new inlet of Chatham due to its morphological similarities to a bending channel. However, because of the effects of littoral drift and shoaling waves, the point bar equivalent in the Chatham case is the broad updrift channel-margin swash platform. Subsequently, this channel bending mechanism is the dominant factor in causing the southward migration of the main channel

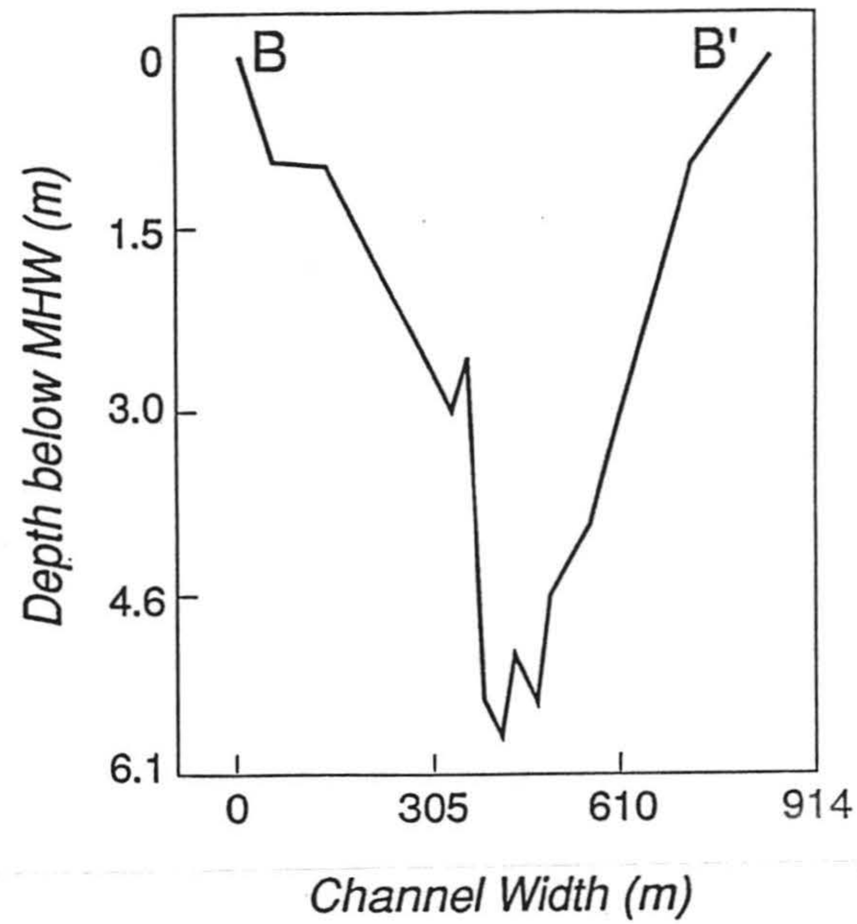


Figure 12. Cross-sectional profile across the main channel between mainland beach and north spit (see Fig. 4e for position).

throat. In other words, the southward movement of the channel throat is largely controlled and sustained by the configuration of the channel thalweg. This process can probably continue without interference from the littoral drift system as long as the channel geometry remains unchanged.

The northward trend for the tip of the north spit suggests that the movement of the north spit is unrelated to the movement of the main channel throat. Since the south end of North Beach is on average about 1 km from the channel throat section and is separated by a channel-margin platform, it is conceivable that processes causing southward movement of the throat and the lengthening of the channel-margin swash platform are not directly affecting the north spit. It is likely that the net shoreline retreat on the south end of North Beach is caused by the seaward re-orientation and displacement of the nearshore bar, which is a littoral sediment conduit, to join the distal end of the ebb-tidal delta off the south end of North Beach (Fig. 4). Consequently, the south end of North Beach is experiencing a net sediment deficit, which is occasionally offset by the change in the position of the nearshore bar and the nearshore wave field. The northward retreat of the north spit will gradually stop when the inlet throat is far enough from the spit so that the effect of the ebb-tidal delta on the nearshore bar system no longer affects the south end of North Beach.

Sediment Transport Pathways

Based on the developments ebb- and flood-tidal shoals, a hypothetical sediment transport pathway map has been constructed (Fig. 13). Sand enters the inlet from the north in the longshore transport system along the shoreline and nearshore bar of Nauset Beach. Some sand is transported into the inlet across the channel-margin swash platform via swash bar migration, wave transport, and in the associated marginal channels around the north spit. Some sand is moved into the main channel where it is transported both landward and seaward. Localized northward transport adjacent to the South Beach shoreline moves sand into the lagoon in the south marginal flood channel along the south spit. Some material may be by-passed around the ebb-tidal delta and transported along South Beach towards the shoals and spit associated with South Channel to the south.

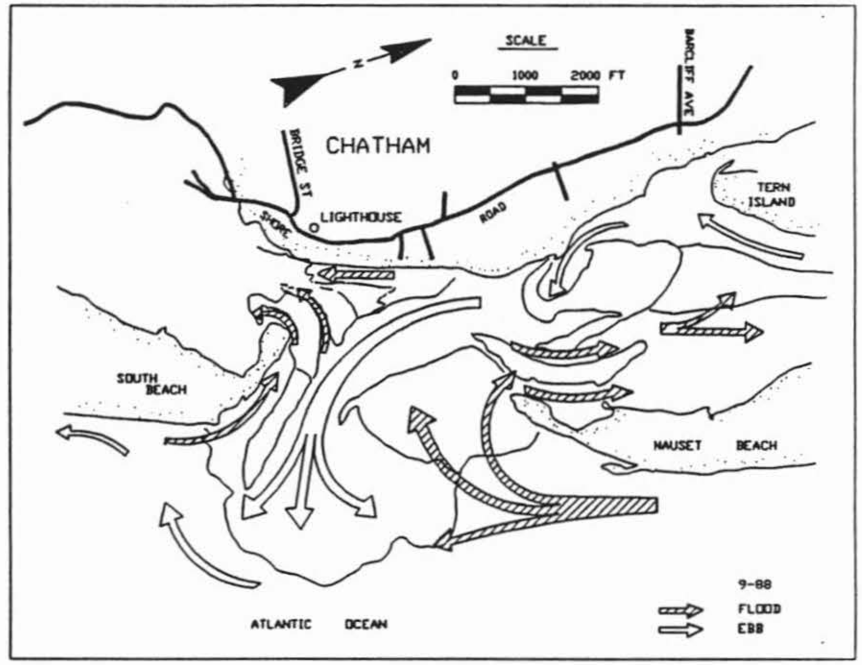


Figure 13. Hypothetical sediment transport pathways at the new inlet based on morphology from September, 1988 shoal configuration.

Inside the inlet mouth, the sediment entering from the north side of the main channel flows northward along the linear shoal and across the north flood-tidal delta towards Pleasant Bay. The sand entering from the main channel and south marginal flood channel built the south flood-tidal delta, which continues to grow and move southward into South Chatham Harbor. The ebb shields developing on the southern end of the three secondary channels on the south flood-tidal delta complex will progressively block northward ebb flow during the latter portion of the ebb cycle from flowing back into the main channel.

Conclusions

A new tidal inlet has been created by breaching of a barrier spit during a storm. The presence of this inlet interrupts the old barrier/lagoon system. As result, adjacent shorelines of the newly formed inlet have responded to the new hydrodynamic conditions. Since its formation, the mouth of the new inlet has been widening through time. This widening is contributed by the concurrent retreats of the two spits that flank the new inlet. Along with the progressive retreat, the north spit displayed fluctuations in its length and orientation. The south spit on the other hand, although maintaining a shore-normal orientation, has shown cyclical elongation followed by periodic breaching and terminal detachment.

As the new inlet evolved, ebb- and flood-tidal shoal complexes have formed. Six shoal areas have been identified. Seaward of the new inlet mouth, there is a well developed ebb-tidal delta. Within the inlet mouth, a large channel-margin swash platform is largely located on the updrift side of the channel throat of the new inlet. Both features have grown in size as the inlet evolved. As the main channel migrated to the south, the ebb-tidal delta has grown both seaward and southward.

Four other shoal features have been identified to be flood-tidal delta complexes of the new inlet. A linear shoal and northern flood-tidal delta located on the northern side of the new inlet evolved from remnant features now modified by the new hydrodynamic conditions since the breach. The south flood-tidal delta is growing in area and also moving into the southern portion of Chatham Harbor. The south flood-tidal delta effectively prevented the water exchange between the northern and southern parts of the estuary. The growth of shoals landward of the inlet mouth and the cyclical elongation of the south spit suggest the influx of ocean sediments entering the lagoon through the new inlet.

As a result of the shorter exchange route and the capture of the most of the tidal prism, the shore-parallel main channel thalweg turned seaward at a right angle to form a bend through the new inlet mouth. This new channel configuration is likely responsible for the southward migration of the channel throat and partially for the formation of the shallow channel-margin swash platform on

the updrift side of the channel throat. The continuing southward migration of the new inlet channel and associated shoals suggests the morphodynamics of the new inlet have not reached equilibrium with the entire barrier/lagoon system. Furthermore, the northward movement of the north spit indicated the north spit is not influenced by the same processes that caused the rest of the new inlet system to move southward.

Morphological changes following the formation of the new inlet suggest that Chatham Harbor has developed into two separate parts. The northern part of the lagoon is actively interacting with the littoral system and increasing in length as the channel throat advances southward at the expense of the southern part of the estuary. The mouth of the new inlet effectively traps sediments from the littoral system, and less sediment is likely to by-pass the new inlet in the immediate future.

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