CYCLICAL BEHAVIOR OF THE TIDAL INLET AT NAUSET BEACH, CHATHAM, MASSACHUSETTS

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ABSTRACT

Study of historical data concerning shoreline forms and change on southeastern Cape Cod over the past 200 years revealed a cyclical pattern of change in the barrier beach system off Chatham, Massachusetts, with a period of approximately 150 years. Based on the observed patterns and deductions concerning the processes controlling those patterns, predictions of breaching of the barrier beach and new inlet formation were provided to local coastal resource managers, reducing the negative impacts accompanying the formation of the new inlet when it eventually occurred.

INTRODUCTION

The characteristics of tidal inlet migration on barrier beaches, and the physical processes associated with such migrations, have been studied and reported with increasing frequency in recent years (e.g, Mitchell, 1875; Goldsmith, 1972; Bruun, 1978; Boon and Byrne, 1981; Aubrey and Speer, 1984). In addition to their scientific value, such studies have important applications to coastal management. Changes in tidal characteristics and wave patterns that accompany inlet migration and initiation produce a suite of associated changes within the estuaries behind the barriers: estuaries which, with their surrounding wetlands and uplands, are among the most highly valued coastal resources. Navigation, shell-fisheries, private and public property, and recreational activities, as well as natural ecosystems, are all subject to impacts resulting directly or indirectly from altered tidal ranges, phases and currents, and altered wave energy flux.

As an example of the importance of inlet migration studies to coastal management, a study of coastal changes at Chatham, Massachusetts, is presented here. Chatham, occupying Cape Cod's extreme southeastern corner, lies at the end of two littoral drift systems: one directed easterly along the Cape's south coast and one directed southerly along the southern portion of the east coast (Figure 1). As a result, Chatham's upland shores, together with numerous estuaries and wetlands, are relatively well protected behind a shield of barrier beaches.

Chatham townspeople are alert to changes and potential changes in the barrier shield (e.g., Nickerson, 1931). In keeping with this tradition, and suspecting that a change was imminent in the long easterly barrier known as Nauset Beach (or North Beach), the Chatham Conservation Commission requested in 1976 a study (Giese, 1978) to determine,

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as accurately as possible, what changes to expect and what courses of action should be taken in light of the expected changes.

The present report presents a conceptual model, and like all models it differs from reality. A modeling approach to the Chatham barrier beach problem is used because of the complexity of the natural system. The purpose of the model is to exclude secondary causes and effects in order to present clearly the primary causes and effects of inlet change. Also, like all models, it is based on incomplete data. The greater the amount of information put into the model, the closer it approaches reality. As additional historical data are located, and as future data become available, the model should be adjusted appropriately.

However, it is not likely that the basic structure of this primary model will be altered by the additions. The basic processes involved in the development of the Chatham barrier beaches have been understood for a long time. Henry Mitchell (1874, 1875) a century ago, said much of what is said here. It is difficult, from the viewpoint of a specific "present time" to separate significant changes from insignificant ones, and therefore much care should be exercised in making large model corrections based on contemporary observations.

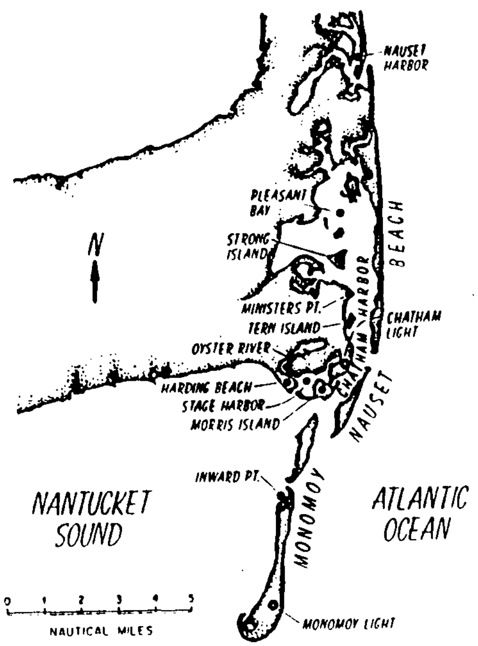

Figure 1. Chatham Harbor-Pleasant Bay estuary and Nauset Beach-Monomoy barrier system, <u>circa</u> 1980. The tidal inlet east of Chatham Light formed in January, 1987 and has been superimposed onto the earlier shoreline configuration.

All of the landforms of Chatham consist of materials emplaced by one or the other of two distinct process-systems: deposition of materials released by melting during the retreat of the Pleistocene continental ice sheet, or deposition of materials eroded from these glacial deposits by wave action and carried to their present location by waves, currents and winds. The glacial deposits, which make up the "uplands" of Chatham, have been in place for some 16,000 years (Stone and Borns, 1986), during which time sea level has risen over 100 meters. It is the submergence of these Pleistocene glacial deposits by the rising sea that has produced most of the "inner" coastline of Chatham as it exists today.

In contrast, the "outer" coastline is formed by wave, current and wind transported materials that have been deposited within the recent past. The eastern outer coast of Chatham - Nauset Beach and Monomoy - comprises the southern part of a series of barrier beaches, islands and spits that are formed of sediments eroded by wave action from the sea cliffs of Eastham and Wellfleet and carried southward by littoral drifting. The southern outer coast of Chatham - Forest Beach, Ridgevale Beach and Harding Beach - is similarly made up of barrier beaches, islands and spits that consist of materials eroded and carried eastward from the exposed glacial deposits of the Nantucket Sound coast west of Chatham.

Altogether, the barrier beaches form a protective envelope around the uplands of Chatham. They provide the town her abundant sheltered harbors, tidal flats, and salt marshes, and they provide protection from erosion and therefore relative stability for the town's inner coastline. However, the barriers are not stable forms but rather constantly adjust to changing conditions. As the barriers change, the degree and type of shelter provided by them changes and, as a result, the harbors, flats, marshes and inner coastline also change.

It has been observed that the changes undergone by many barrier beaches, including those at Chatham (Goldsmith, 1972), follow cyclical patterns. During the past 200 years, a large amount of information has been gathered concerning the form and changes in form of the Chatham barrier beaches. The objectives of the present study are: first, to determine, by the analysis of this existing information, the patterns of change undergone by the Chatham barrier beaches over the past 200 years; second, to deduce the controlling processes from the observed patterns; and third, to predict, based on these patterns and processes and the engineering changes that have been imposed on the system, the patterns of changes that may be expected in the future.

METHODS

The underlying rationale of this study is that the large amount of existing professional and specialized information concerning the Chatham barrier beaches should be collected, analyzed and interpreted so as to make it available and useful to those individuals and groups responsible for making decisions concerning the management of the coastal resources of Chatham. Much of this information represents the work of geologists, hydrographers and engineers whose reports are generally unavailable to, and sometimes unintelligible to, the general public. Additional information necessary for this study was derived from charts and maps which, while generally available, are seldom found together in one place at one time.

The study covers a time period of 200 years, beginning with the remarkably accurate 1772 chart of Des Barres, and ending in 1972 with a doctoral dissertation by V. Goldsmith (1972) that describes in detail much of the history and controlling processes of the study area. Although there exists a considerable body of information concerning Chatham shoreline changes prior to 1772 (e.g., Goldsmith, 1972; Nickerson, 1931; and Mitchell, 1874), the detail and continuity through time of the early descriptions are insufficient for the purposes of this study.

Once the primary data sources (reports, historical accounts, studies, maps and charts) for the 200-year study period had been collected, pertinent information was divided chronologically into 20-year periods. For each 20-year period a generalized diagram was prepared representing the major (and omitting the minor) shoreline features of that time period. It should be emphasized that each diagram represents a composite of all data available for that time period, and therefore each necessarily differs from the coastal form at any one time during that period.

Based in part on the patterns of shoreline development revealed by the 20-year diagrams, in part on available tidal and hydraulic data (U.S. Department of Commerce, 1977; U.S. Army Corps of Engineers, 1957, 1968), and in part on previous work by the author and others (especially Mitchell, 1874, and Goldsmith, 1972) the processes controlling the observed shoreline changes were deduced.

Next, using knowledge of the controlling processes and the past shoreline behavior, predictions were made of future shoreline development (Figure 2). It should be recognized that while specific time periods and specific forms were designated for each future stage of development, this was done to suggest the time frames and type of coastal forms that might be expected.

RESULTS AND DISCUSSION

Summary of Coastal Changes

A survey of the forms of Chatham barrier beaches over the past 200 years (Fig. 2) reveals some distinct characteristics:

On the south coast, the barrier beach (Harding Beach) which joins the mainland at west Chatham and extends southeastward, forcing a 90° bend in the Oyster River, has maintained a fairly constant form. It has not been breached by natural causes. It has increased slowly in width and in length. In 1965, a controlled inlet was cut through this barrier beach and it was joined to Morris Island by a sand dike constructed by the U.S. Army Corps of Engineers.

On the east coast, the barrier beach from Nauset Harbor to Strong Island (i.e., the northern portion of Nauset Beach), has maintained a fairly constant form, without permanent breaks. However, a comparison of shoreline locations over the 200-year period indicates that this "stable" segment of barrier beach has migrated landward at a relatively uniform rate of between 1.5 and 3 m per year.

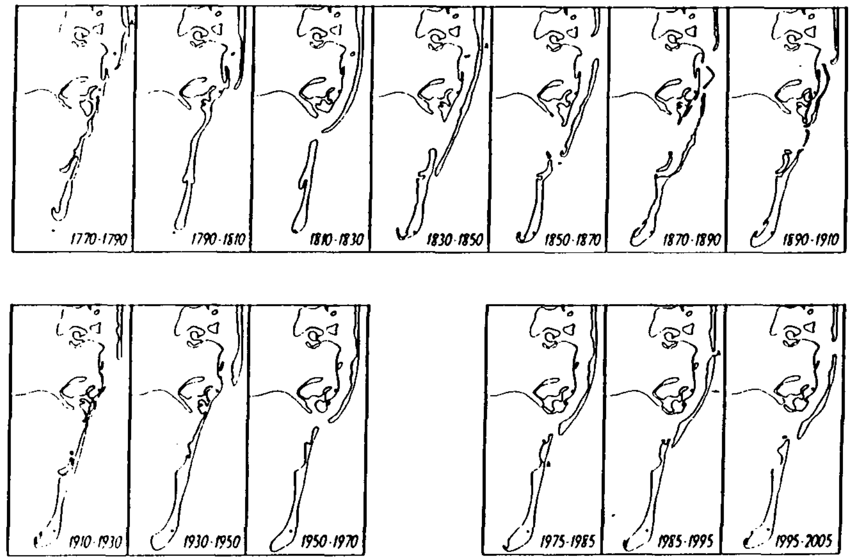

Figure 2. Historical changes in the Nauset Beach-Monomoy barrier system illustrated by generalized 20-year diagrams from 1770-1790 to 1950-1970 and predicted future changes illustrated by 10-year diagram from 1975-1985 to 1995-2005 as they were presented to the Chatham Conservation Commission in 1978. Note the approximately 140-year historical repetition of forms apparent in the first three diagrams in the bottom row. The letter "A" marks, in the 1770-1790 diagram, the approximate inlet location in 1740; in the 1830-1850 diagram, the inlet that formed in 1846; in the 1975-1985 diagram, the breach that formed in 1978; and in the 1985-1995 diagram, the predicted location of a future inlet. The actual location of the inlet that formed in January, 1987, is indicated by the arrow.

On the east coast, the barrier beach south of Inward Point to the southern extremity of the system (Monomoy Point), has been stable over the entire period. The northern end of this section has narrowed somewhat due to erosion along the eastern coast, while the southern end widened by growing southeastward approximately one-half mile between 1887 and 1964 (Oldale et al.,1971). However, there has been a marked decrease in the lengthening of the barrier during the past 200 years. While Mitchell (1886) reported that "the dry land of Monomoy has extended southward 2 miles during the past century," Oldale et al. (1971) show virtually no lengthening (as opposed to widening) since 1887.

On the east coast, between Strong Island and Inward Point, the barrier beach has undergone a regular series of changes. Two hundred years ago, the barrier beach extending southward from Nauset Inlet was a barrier spit which ended approximately opposite the present location of Tern Island. The Chatham coast southward from this point was not protected. The barrier beach began again at Morris Island and continued without interruption to Monomoy Point. The northern barrier gradually grew southward, until, by 1820, it reached south of Morris Island and overlapped the southern barrier, which then separated from Morris Island. Following the separation, the south end of the northern barrier continued to grow southward and the north end of the southern barrier continued to retreat southward.

Finally, in 1846, a new inlet formed through the northern barrier opposite Ministers Point (Allen Point). The inlet rapidly grew wider and as it did so, the barrier beach south of it gradually disintegrated, and its remnants were driven westward onto the Chatham mainland.

Gradually, the barrier beach north of the inlet grew southward once more and the barrier beach south of Morris Island regained a continuous form and reattached to Morris Island, so that by about 1940, the general form of 1800 had returned. After 1940, the post-1800 pattern was repeated - continued southward growth of the northern barrier until it reached south of Morris Island; separation of the southern barrier from Morris Island; continued southward growth of the northern barrier and southward retreat of the north end of the southern barrier. The southern barrier was breached (as had been predicted by Oldale et al., 1971) in 1978 just north of Inward Point (marked "A" on the diagram for 1975-1985 in Figure 2).

Processes

There are three general processes responsible for the shoreline forms and changes that have been described. First in importance is coastal submergence - that is, a rise in the level of the sea surface relative to the land surface. It is this process that determined the primary form of the coast coupled with the morphology of the glacial drift surface. The general outline of the inner shoreline of Chatham is the result of submergence. Second in importance is wave action. Wave action is responsible for the general outline of the outer shoreline of Chatham - for the barrier beaches them-selves - as well as for the specific,

secondary forms of the inner shoreline. Third in importance is tidal action. This is the process responsible for the secondary features of the barrier beaches, especially the inlets. Each of these processes will be discussed separately.

Coastal submergence. Zeigler et al. (1965) have presented a general view of the development of the shoreline form of southeastern Massachusetts due to submergence between 15,000 and 6,500 years ago. Fifteen thousand years ago, "present day" Cape Cod, Martha's Vineyard, Nantucket, and Georges Bank were all part of a single land form which extended some 320 km east of the present eastern limit of the land. By 10,000 years ago, Georges Bank was reduced to an island about 80 km long, and by 6,500 years ago that island was disappearing. Even at that time, however, Cape Cod, Martha's Vineyard, and Nantucket were joined still and the ever-shrinking land mass which they formed included much of the "present day" Nantucket Shoals.

Relative sea-level has risen along the Massachusetts coast over the past 40 years at a rate ranging between 2 and 3 mm. per year (Aubrey and Emery, 1983), about one-third of which is due to global sea-level rise and the remainder to subsidence (Braatz and Aubrey, in press). By applying this rate of sea-level rise to the areal distribution of upland in Chatham, Giese and Aubrey (1987) have calculated that the town loses a minimum of 0.4 hectares (1 acre) per year of upland due to the passive submergence. The inner shoreline of Chatham owes its general form in part to this passive submergence of the glacial deposits, and in part to erosional and depositional processes associated with changes in the barrier beaches.

Wave action. The Chatham outer coast is formed of barrier beaches that consist of sediment transported southward by littoral drifting due to wave action. The source of this sediment is the eroding cliffs in Eastham and Wellfleet. The original map by Des Barres of 1772 shows the barrier beach as outside of, and unattached to, the Orleans upland, and a note on the map indicates that the end of the barrier off Chatham Harbor had grown approximately 3 miles southward (from the point designated "A" on the 1770-1790 diagram in Figure 2) in 30 years. During the first half of the 19th century, there was much discussion of the rate of southward growth of this barrier beach as well as of Monomoy (see, for example, Hitchcock, 1837).

C. H. Davis (1849) recognized that the barriers were built of sediment supplied by the eroding cliffs to the north. He postulated that the sediment was transported by tidal currents which, he believed, divided at a point near Nauset Light - north of that point the resultant tidal flow was northward; south of it, the resultant was southward. Accordingly, Davis believed, northward growing spits developed in Truro and Provincetown, and southward growing spits in Chatham.

However, during the second half of the 19th century, the role of waves as the primary agent causing littoral drifting became clear, and in 1875 H. Mitchell wrote:

> "One may easily see how the Nauset beach composed of alluvia swept down the outside coast by the sea from the northeast, has extended itself along the resultant between the ocean waves on the one hand and the outflow of Pleasant Bay on the other. In this way, it has gone on till the too confined waters of Pleasant Bay have forced a more direct outlet again, and the march of the beach from above has recommenced. The early history of these movements is in no wise peculiar; the same may be observed at many other places upon our sandy coast. But this familiar history seems to be closed."

This paragraph describes, as well as any could, the basic processes controlling the development of Nauset Beach. Only the last sentence should be changed - while "this familiar history" appeared to Mitchell to be closed, it most certainly was not, as events during the century between his writing and the present time have shown.

The second major mode of change of the barrier beaches of Chatham - their steady landward (westward) migration - also was observed, measured and discussed during the second half of the 19th century. The fact of this migration was demonstrated strikingly by the discovery, in 1863, of the wreck of the ship, Sparrow-Hawk, on the outer side of Nauset beach (Anon., 1865). The Sparrow-Hawk had been wrecked in 1626, on the inner side of Nauset Beach and therefore her discovery 237 years later on the outside proved that the barrier had moved westward a distance equal to its width during that time period.

Precise measurements of the westward barrier migration were obtained first by H. Marindin of the U.S. Coast and Geodetic Survey for a 10-km length of shoreline beginning about 1.5 km north of the inlet into Pleasant Bay in 1887 and continuing northward to Nauset Inlet (Marindin, 1889). He compared his survey of this coastline undertaken in 1887-1888 with a survey made in 1868, and determined that the "crestline" of the beach showed a mean recession of 2.4 m per year averaged over the 10-km length.

The landward migration of the barriers is accomplished in part by the erosion of the beach and in part by sand transport across the barrier, from east to west. This important crossbarrier transport is accomplished by three mechanisms: dune migration, storm wave overwash, and deposition on the inside of tidal inlets in the form of flood tidal deltas (Leatherman and Zaremba, 1986).

In summary, the effect of wave action is, first, to transport sand southward along the barrier beaches; and second, to cause the barriers to migrate westward. The annual volume of sand moved southward by wave action has been calculated (Zeigler et al., 1965) to be about 230,000 m^3.

Tidal action. While wave action is responsible for the existence of the barrier beaches that form Chatham's outer shoreline, tidal flow is the factor that, together with wave action, controls the inlets through the barriers, and therefore, to a large extent, the form of barriers. The tidal hydraulics and inlet dynamics of the Chatham barrier beach system did not receive detailed study until the second half of the 20th century. The Army Corps of Engineers (1968) installed tide gauges and current meters in Chatham Harbor and Pleasant Bay, and used the results and Keulegan's (1951) model to calculate the hydraulic friction of the system. The effect of the tidal inlets on the southerly-directed littoral drifting and thereby on the barrier beach south of the inlets has been discussed by Goldsmith (1972). A detailed description of the "Chatham Bars" inlet and its associated shoals was published by Hine (1975).

Briefly, the system works as follows: The existence of, and the changes of, a tidal inlet through a barrier beach are controlled by the balance between two opposing forces: the volume rate of tidal flow of water through the inlet which acts to keep it open, and the volume rate of littoral drifting of sediment along the outside shoreline of the barrier which acts to close it. The rate of littoral drifting is controlled by the characteristics of the waves that reach the shoreline. The rate of tidal flow is determined by the tidal range and the surface area of the body of water inside the barrier. An increase in the rate of littoral drifting tends to narrow the inlet which results in an increase in the speed of tidal flow and therefore in channel scour. By this means balance is maintained (e.g., O'Brien, 1931; Bruun, 1978).

Without tides, a continuous barrier beach could extend from Eastham to Monomoy Point. Even with tides, such a continuous barrier could exist, provided that the barrier were everywhere separated sufficiently from the mainland that tidal flow could occur freely from Pleasant Bay through Chatham Harbor to Nantucket Sound. When tides are added to both sides of such a continuous barrier, the potential for an inlet through the barrier is added also: the difference in tidal range between the open ocean (about 2.0 m) and Nantucket Sound (about 1.2 m) would result in a hydraulic head across the barrier, and this, in turn, would produce a pressure gradient across any storm-produced breach that might occur, forcing a tidal current through it. Whether or not the resulting incipient inlet would reach a critical size (Escoffier, 1940; van de Kreeke, 1985) and remain open, would depend upon the volume rate of the littoral drift attempting to close it.

In fact, however, tidal flow in Chatham Harbor is restricted, and becomes more so as the barrier beach lengthens and migrates westward. As the degree of restriction increases, the range of the Chatham Harbor-Pleasant Bay tide decreases and its phase lag (relative to the outside tide) increases. Both effects increase the hydraulic head across the barrier and eventually the constriction becomes so great that when a breach occurs through the northern part of the barrier (a natural occurrence as described above), Chatham Harbor-

Pleasant Bay water is discharged through the breakthrough instead of through the inner channel, and the breach increases to critical size and becomes an inlet.

The southward moving sand supplied by littoral drifting is intercepted at the new inlet. Some sediment is carried in and added to the flood tidal delta and some is carried out and added to the ebb tidal delta. Because of the reduction in the volume of sand supplied to it, the barrier south of the new inlet is "starved." It gradually breaks down and is moved landward.

Eventually, the inlet is no longer an inlet but rather marks the southern end of the barrier spit which grows southward with the addition of sediment supplied by littoral drifting. The previous barrier, south of the "new" spit, moves onto the Chatham mainland, forming the "peninsula" of Monomoy. At this stage, the attachment of Monomoy to the southern Chatham mainland is secured by rapid littoral drifting along this shoreline resulting from its open exposure to waves.

When the "new" barrier spit grows far enough southward to overlap the southern barrier, and when this southern barrier becomes breached in the ordinary manner, the breach remains open because the littoral drifting required to close it is no longer available. Thus the northern end of the southern barrier retreats as the southern end of the northern barrier advances. The cycle is reinitiated when the northern barrier once again has become sufficiently long and close to the Chatham mainland to produce a hydraulic head across the barrier sufficient to enlarge a storm-produced breach to critical size.

The new inlet of 1987. A new cycle of inlet change was initiated by a severe northeasterly storm occurring together with a perigean spring tide on January 2,1987. The barrier beach was breached at a point almost directly east of Chatham Light House - a low, narrow reach that had been overwashed (but not breached) during previous spring tides. Chatham townspeople had noted the narrowing of the beach at that point over the previous few years, and the possibility of its breaching had been discussed widely.

The new inlet enlarged rapidly to 100 m wide by January 16, 500 m by February 3, and 1 km by April 15. Analysis of a 30-day tide record from Chatham Harbor taken during April revealed a mean tidal range of 1.4 m, as compared with a range of 1.1 m recorded approximately 20 years earlier (U.S. Army, 1968). The increased tidal range and wave energy produced a variety of coastal erosion and channel shoaling problems with strong impacts on the fishing and boating industries, and on private and public property and interests. Shoreline straightening processes have resulted in rapid erosion, and in some cases accretion, along the inner shoreline in the vicinity of the new inlet, and existing navigation channels have shoaled or disappeared entirely. At the same time, of course, new channels have formed, most importantly the new inlet itself, the use of which reduces by about an hour and a half the running time of commercial fishing vessels between Chatham Harbor and the Atlantic.

CONCLUSIONS

1. The Chatham coast consists of two different types of land forms: a relatively stable inner coast formed chiefly by submergence of Pleistocene glacial deposits but modified in part by wave action; and an extremely dynamic outer coast consisting of barrier beaches formed by wave, tidal and wind action.

2. The barrier beaches are a valuable component of Chatham's coastal environment. By providing protection from large waves, they greatly reduce coastal erosion and storm and flood damage along the inner coast. By forming a sheltered estuarine environment between themselves and the inner coast, they provide for an extensive salt marsh, a productive fin and shellfishery, and a protected harbor for commercial and pleasure craft.

3. The Chatham barrier beaches owe their existence to, and change form in response to, a number of different natural forces and processes:

Coastal erosion west of Chatham provides sand for Chatham's south coast barrier beaches.

Coastal erosion north of Chatham provides sand for Chatham's east coast barrier beaches.

Eastward directed net wave energy is responsible for sand transport to the barriers along the south coast.

Southward directed net wave energy and an absence of obstacles to littoral drifting are responsible for sand transport to the barriers along the east coast.

Tidal flow maintains a channel from Stage Harbor to Nantucket Sound and from Pleasant Bay and Chatham Harbor to the Atlantic Ocean.

Easterly winds, storm waves and storm tides are responsible for sand transport westward across the east coast barrier beaches in the form of dune movement, overwash deposits, and breakthroughs and flood tidal deltas.

Tidal range and phase differences provide the hydraulic potential necessary to maintain a new inlet to Chatham Harbor when the east coast barrier has migrated too far westward toward the Chatham mainland.

4. The Chatham barrier beaches undergo changes in form that are adaptations and responses to the forces that act upon them and form them. Such changes in the form of the barriers make it possible for them to adjust to the changes in the imposed forces, some of which result from changes in the barriers themselves.

5. The major changes in form undergone by the Chatham east coast barriers over the past 200 years are cyclical. The period of the cycle is approximately 150 years. Assuming that the cyclical changes continue without interruption, the future form of the shoreline can be predicted. Shoreline predictions, made in 1978 for the Chatham Conservation Commission, for the periods 1975-1985, 1985-1995, and 1995-2005 are presented in Figure 2.

6. The 1978 report to the Chatham Conservation Commission (Giese, 1978) proved to be useful to the community by communicating to the general public information readily available to coastal scientists and engineers concerning the behavior of this barrier beach/estuary system. Its relative wide readership was achieved by careful packaging (e.g., the 20-year diagrams); concise, non-technical writing; and wide-spread distribution as a separate section inserted into the local weekly newspaper, the Chronicle. Because the community generally accepted the inevitability of barrier breaching and the shoreline changes that would accompany it, the Conservation Commission was able to enforce more stringent restrictions on coastal development than would have been possible otherwise, and thereby reduced the negative impacts accompanying the formation of a new tidal inlet.

7. Cycles of downdrift inlet migration and subsequent breaching updrift are characteristic of undisturbed barrier beaches (Mitchell, 1875), and while the cycle may be defined more clearly and better recorded at Nauset Beach than at many other locations, the methodology described in this report could be applied usefully elsewhere. As an alternative means of environmental management, communities may find that they are better able to preserve their coastal and estuarine resources by predicting and planning for tidal inlet changes than by attempting to prevent such changes.

8. The most critical requirement for improved tidal inlet predictions is the development of adequate mathematical models for such systems. However useful empirical techniques, such as those described above, may prove to be in particular situations, predictions based on site-specific observations alone do not lead to useful solutions to the general problem. Because of the wide variety and complex form of natural barrier beach/estuary systems, general solutions applicable to many individual systems must be sought through mathematical models derived from hydrodynamical principles. Analytical models such as that of van de Kreeke (1984) contribute significantly to our understanding of the roles and relative magnitudes of the controlling forces and require further development. But the greatest need for the purpose of practical inlet migration predictions is the development of numerical models adequate for application to a wide range of natural systems.

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