SEDIMENTATION CONCERNS ASSOCIATED WITH THE PROPOSED RESTORATION OF HERRING RIVER MARSH, WELLFLEET, MASSACHUSETTS

Prepared for Cape Cod National Seashore, The Town of Wellfleet and The Association for Women Geoscientists, as part of a Geologist in-the-park project performed during the fall-winter of 2003-2004

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EXECUTIVE SUMMARY

INTRODUCTION

In 1909 construction of a dike was completed across the Herring River in Wellfleet, Massachusetts. Since that time the restriction of tidal flow has resulted in major water quality problems, fish kills, and the general degradation of a once productive 1100-acre salt marsh system. Multiple studies, conducted to determine ways of restoring habitat quality in and adjacent to the Herring River, have found that water quality can be improved and estuarine habitats restored by returning tidal flow to the area above the dike. However, the proposed opening of the dike, necessary to performing such a restoration, has raised concerns among local shellfishermen. The most recent question, and the impetus for this study, is whether increased tidal flow will change sedimentation below the dike. Town officials and resources managers are particularly interested in how changing the tidal regime in the river might affect sedimentation on shellfish beds. Therefore, the purpose of this study is to address sedimentation concerns related to the possible restoration of the Herring River and to assess the effect, if any, of altering the tidal system on oyster and hard clam culture in Wellfleet Harbor.

In order to address sedimentological concerns associated with increasing tidal flow to the Herring River, questions were solicited from local fishermen and Town officials concerning the proposed restoration, with special emphasis on the effects of dike opening on shellfish grants. Two major questions emerged:

1) Does opening the Herring River Dike affect the stability of The Gut?

2) Does opening the Herring River Dike affect sedimentation below (seaward of) the dike?

This report answers these two questions by synthesizing pertinent information from previous investigations augmented with new data and analyses specifically for the Herring River.

STABILITY OF THE GUT

The stability of The Gut has, for at least the past several hundred years, been controlled by forces along the Cape Cod Bay shoreline, and not by tidal flow in and out of Herring River. In order to truly understand the relationship between Herring River and The Gut, one must first comprehend The Gut's formation and geologic history. All of Cape Cod is made up of sediment deposited by glaciers about 18,000 years ago. As the glaciers retreated, sea-level began to rise as the ice melt returned water to the ocean basins. The rising sea inundated the Cape and waves began to erode the glacial sediments that compose it. The sediment removed from the cliffs of the Outer Cape was transported and redeposited by wind, waves and currents to form the Provincelands, Nauset Beach, Monomoy Island and The Gut. In such cases as Nauset Beach and The Gut to Jeremy, a strip of sand built a peninsula off of the mainland forming protected bays such as Pleasant Bay and Wellfleet Harbor, respectively.

Wellfleet Harbor occupies a part of a large depression that formed where glacial ice once existed and thus prevented the deposition of outwash sands. As the ice melted and sea-level rose the depression was flooded forming Cape Cod Bay. Islands such as Griffin Island, Great Island and Great Beach Hill formed from sands that filled holes or depressions in the melting ice sheet and became stranded and surrounded by water. On the ocean side, sea-level caused erosion along the glacial uplands. The removal of these sands, and subsequent movement northward, left behind the sea cliffs of Wellfleet and Truro. Once the sand reached the north end of the glacial outwash, at present Pilgrim Heights, it began to accumulate forming the Provincelands. The formation of the Provincelands prevented sand from the east from reaching the bay side beaches, leaving only the sediment eroding from the bay side uplands as a source. This sand, supplied from the north by long shore drift, formed the barrier beaches that today connect the bayside islands, Bound Brook I., Griffin I., Great I., and Great Beach Hill. Together these intermittent barrier beaches, spanning down to Jeremy Point, provide protection from waves and form the sheltered environment of Wellfleet Harbor.

Historically, the Herring River most likely emptied directly into the bay by flowing through the area that The Gut now occupies. However, as sand built south across this opening, forming The Gut, the Herring River was deflected to the south. This deflection indicates that river flow alone was not strong enough to maintain a tidal inlet. Bearing in mind that this change in flow direction occurred before the river was diked, it is a reasonable to conclude that small changes in tidal flow through the present dike would have no effect on The Gut. It also seems reasonable that even complete removal of the dike would not cause The Gut to breach; historical data demonstrate that the flow of an unaltered Herring River is simply too weak to maintain a tidal opening.

The existence of a broad tidal flat behind The Gut's fringing marsh is a testament to these low flow velocities. The accumulation of fine sand proves that there is not enough energy in the ebbing tide to transport it out to sea. Moreover, there is not even enough energy to scour the edge of this mudflat along the low tide channel. This lack of scour is documented by historic aerial photographs and topographic maps, which show the same channel configuration prior to the dike's construction as today. This continuity proves that even with the maximum ebbing flow, i.e. with no tide-restricting dike, there will be no scouring of the mudflat. Further evidence of the lack of any downstream effect of the dike is the fact that tidal conditions, such a tidal range, below the dike have not been affected by its installation. As intended, the construction of the dike has altered the river above it, with little change to the area below it.

The continued stability of The Gut, like its original formation, is primarily dependent on sand supplied from movement along Cape Cod Bay beaches and wind transport of finer grains to make and maintain the dune system. Erosion of The Gut is likely to occur as a result of storms. However, the wide salt marshes that back this beach and dune system provide a formidable resistance to erosion. It is highly unlikely that a channel would be cut through the thick cohesive marsh peats; therefore, there is little chance of a permanent inlet forming from a breach in The Gut.

It is more probable that in the case of a high-energy storm an overwash from the bay would occur through a low in the dunes. An overwash is a fan shaped deposit of sand that is washed from the beach through a break in the dunes and deposited on the

adjacent salt marsh surface. An overwash occurred on Ballston Beach during both the Blizzard of 2003 and the Halloween Storm of 1991. If this were to occur along The Gut, which is less likely because storm waves are smaller and less frequent on the bay side than the open ocean, natural post-storm processes would heal the beach. As seen on Ballston, smaller waves, which occur under normal/non-storm conditions, move the sand back onshore and rebuild the beach and dunes filling in the topographic low. Furthermore, even if a temporary overwash were to occur along The Gut, it is unlikely that there would be significant changes in water characteristics in Wellfleet Harbor, which would still receive most of its tidal volume from the south.

Both sea-level rise and a deficit of sand supplied to this system are the main natural forces of erosion along The Gut; however, human impacts exacerbate this erosion. Foot paths over the dune crest remobilizes sand and causes downward erosion. The resulting low-lying area is ideal for a washover to occur during a storm. The Town of Wellfleet and Cape Cod National Seashore are working to lessen this human impact.

SEDIMENTATION IN THE LOWER HERRING RIVER

To address questions pertaining to sedimentation below the Herring River dike, previous studies were researched and augmented by conducting a new study. An exhaustive literature search yielded only one pertinent study, also for Herring River, entitled *"Hydrodynamic and Salinity, Modeling for Estuarine Habitat Restoration at Herring River, Wellfleet, Massachusetts"* by Malcolm L. Spaulding and Annette Grilli completed in 2001. This study showed that the dike has reduced the tidal range above the structure by greater than 4.5 times, resulting in an asymmetry between the flood and ebb flow velocities of the lower portion of the river. This asymmetry increases the naturally flood dominant transport of sediment, resulting in a large deposit of sand just upstream of the dike. This deposit is referred to as a flood-tidal delta. A small ebb-tidal delta formed below the dike during its construction, but unlike the flood-tidal delta, modern sedimentation here is nil, allowing shellfish to colonize.

Spaulding and Grilli's (2001) hydrodynamic study addressed whether any of these sediments accumulating upstream of the dike would be resuspended and carried downstream if the Herring River were to undergo restoration. They modeled peak velocities in the river with all three tidal gates open on the dike and found that the flow would be less than 10 cm/sec. This predicted flow is half the standard 20 cm/sec necessary to resuspend any sand within the river. In addition, the 2001 study reported that any downstream movement of the flood-tidal delta sediments, or the fine–grain deposit just upstream of it, would most likely be a result of a rainstorm. However, seaward transport of sediment through the dike with all gates open would be the same as today, because all three flapper gates allow water to move in a seaward direction. Therefore it is likely that the resulting sediment transport patterns with the dike open would be identical to those during past rainstorms with the gates in their current configuration. During these events the larger sand size particles will likely settle just below the dike, near the present ebb-tidal delta, while the smaller silt-and clay-sized grains will widely disperse and deposit in the fringing marshes of The Gut or offshore. In

researching this study and talking to local shellfisherman, there no reports of siltation on shellfish beds after rainstorms.

To address this subject of sediment transport below the dike, Dr. Spaulding used existing field data to assess the potential for velocities to reach the necessary 20 cm/sec. Using the equation *velocity = volume of water per unit time / unit area*, Dr. Spaulding calculated peak flow with all gates open to be less than 6 cm/sec below the dike. Thus, this hydrodynamic study predicts no sediment will be resuspended in the event that all three gates of the Herring River dike are opened.

In order to test this prediction this study focused specifically on past changes in sedimentation in the lower portion of the Herring River. The theory behind this approach is that by measuring the changes in sedimentation after flow was constricted, it will be possible to predict the response of reverse conditions. Coastal topographic maps and aerial photographs, spanning the last century and a half, were used to map the intertidal region below the Herring River dike. Aerial photography revealed that a split s-shaped geometry, expressed in the low tide channel today, is the same as it was back when the first air photo was taken in 1938. This geomorphic consistency indicates that little to no sediment movement occurred over the past 65 years; this period includes any changes in flow from the breach and subsequent repair of the dike in 1968 and 1975, respectively. Since no real changes appear to have occurred since the installation of the dike, the 1974 USGS topographic map correctly represents the post-dike shape of the intertidal region in this area. In comparing this 1974 topographic map to one from 1848 prior to the dike construction, the only difference was the absence of the ebb-and flood-tidal deltas. Conversely, then it is logical to predict that any future adjustment to the dike's configuration, including complete removal, would affect sedimentation very little and only close to the dike itself.

The 2001 Spaulding and Grilli study showed that opening all the tide gates would not result in any movement of any sediment. In addition, the present study indicates that if the whole dike were to be removed, the only change in sediment patterns would be proximal to the dike. Therefore, with respect to the shellfish grants on Egg Island, they are simply too far away to be affected by any alteration of flow through the dike. Real-world evidence to support this fact was provided in 1968 with the rusting out of a sluice gate allowing tidal exchange for the next six years. There is no evidence that areas of high shellfish production such as Egg Island experienced increased sedimentation during this time. On the contrary, the consensus was that shellfish actually colonized in the area around the dike and subsequently died after the dike was repaired. An explanation of the brief colonization is that increased flood currents caused by the deterioration of the tide gates moved the fine sediment coming from Cape Cod Bay past the dike and up into the marsh. Salinity behind the dike also increased, favoring estuarine bivalves. In contrast, rebuilding the dike structure once again restricted flow. As the velocities slowed near the dike, fine sediment that would have otherwise been carried into the far reaches of Herring River, were once again deposited directly above and below the dike, thus covering the shellfish that had recently colonized.

Data from the restoration of Hatches Harbor show increased landward transport of sediment. Since March of 1999 portions of the Hatches Harbor flood plain diked in 1930 have been undergoing incremental restoration of tidal exchange. The amount of

sedimentation within the system was studied from 1997 to present using Sediment Elevation Tables or SETs. Data from these SETs show that sediment in the marsh below and just above the dike are accumulating at about 3 mm/year, which is the norm to compensate for local sea-level rise. However, accumulation rates of over 10 mm/year are recorded at SETs located farthest upstream from the dike, exactly what would be expected from the restoration of tidal flow and dominant upstream sediment transport..

Three SETs are already located in the Herring River marsh: 1) The Gut salt marsh, 2) the Phragmites marsh below High Toss and 3) the drained marsh above High Toss. These locations have been measured once a year to determine sediment accretion and/or loss, since 2000. In addition to the continued monitoring of these SETs, new monitoring of sediment grain size and organic content is proposed specifically to address the concerns of sedimentation on shellfish beds.

CONCLUSIONS

The Stability of the Gut and Its Relationship to the Herring River

- The continued stability of The Gut is dependent on the same two factors that governed its formation: 1) sand supply and 2) sea-level rise.
- The Gut influences the Herring River rather than vice versa as evidenced by:
- The large meander or bend in the river that occurred as a result of The Gut's formation, that forced water to flow south through the harbor.
- The existence of a wide mudflat on either side of the main ebb channel even before the dike was constructed, indicative of low ebb-flow velocities from the river.
- It is unlikely that The Gut would breach and form a permanent inlet due to the extensive marsh backing this barrier beach. If a large storm were to cause erosion along The Gut, a temporary washover may occur; however, natural post-storm rebuilding processes would quickly close it.
- Foot traffic across the dune system has worsened erosion and increased the possibility of a blowout. The Town of Wellfleet, Cape Cod National Seashore and volunteers are taking action to repair and limit this damage.

Sedimentation in the Lower Herring River

- Hydrodynamic models by Spaulding and Grilli in 2001 indicate that velocities above the dike, with all gates open, would be half that required to resuspend sediment.
- Calculations show that maximum flow velocities below the dike, with all gates open, will be just over a quarter (6 cm/sec) of the 20 cm/sec necessary to resuspend sediment.
- Geomorphic analysis of the intertidal area below the Herring River Dike shows almost no change over the past 155 years, with the exception of the formation of a small ebb- and larger flood-tidal delta. Otherwise, channel morphology below the

present dike was the same before dike construction in 1909 as it is today; the dike has had little effect on downstream sedimentation.

- The predicted change in sedimentation, as a result of restoring tidal flow to the Herring River, would be minimal and proximal to the dike.
- Data from both the 1960s breach and from Hatches Harbor sedimentation not only support this prediction, but also indicate that the resulting changes around the dike will improve sedimentary conditions for shellfish repopulation.

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INTRODUCTION

Background

Since 1909 the Herring River in Wellfleet, Massachusetts has been tidally restricted by a dike (Figure 1.1 & 1.2). The original 100-meter-wide channel is blocked by a causeway (Figure 1.2), with the exception of three two-meter-wide box culverts in the middle. The southern culvert is fitted with an adjustable sluice gate, whereas the other two contain flapper gates that allow flow only in a seaward direction. The purpose of diking (Figure 1.3), and subsequent draining (Figure 1.4), of this salt marsh system was to facilitate mosquito control and to provide additional land for development. Other than the extension of Chequesset Neck Road, the construction of two dwellings and a portion of a golf course within the river valley, no other land has been developed and mosquitoes remain a problem (Soukup and Portnoy, 1986).

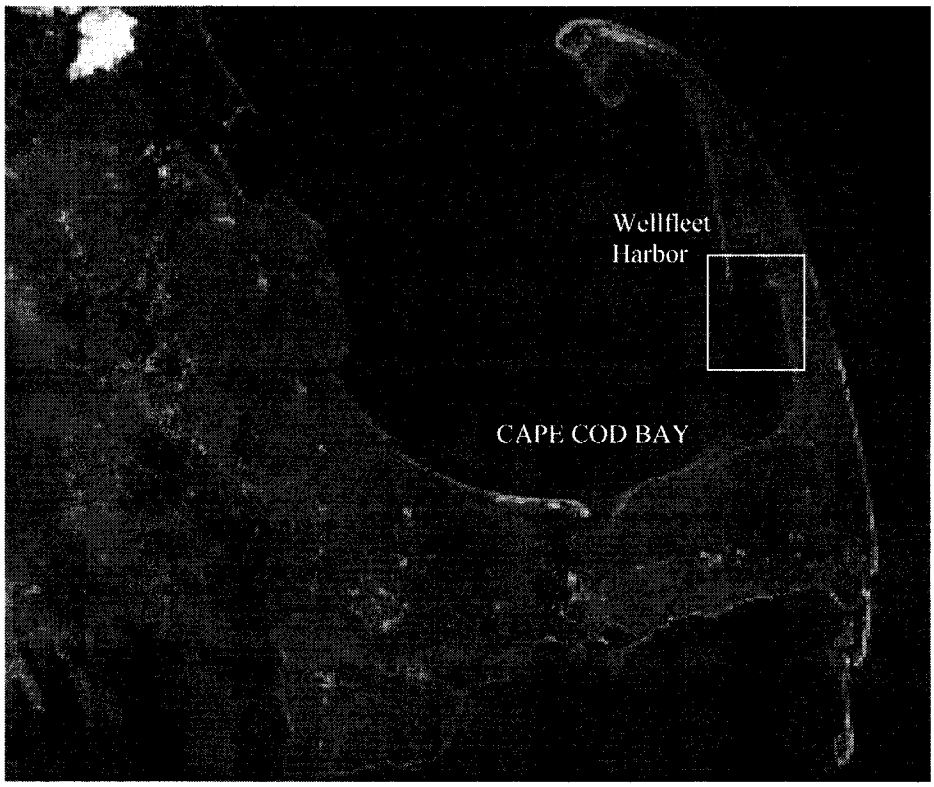


Figure 1.1: Satellite image of Cape Cod showing the location of the Wellfleet Harbor.

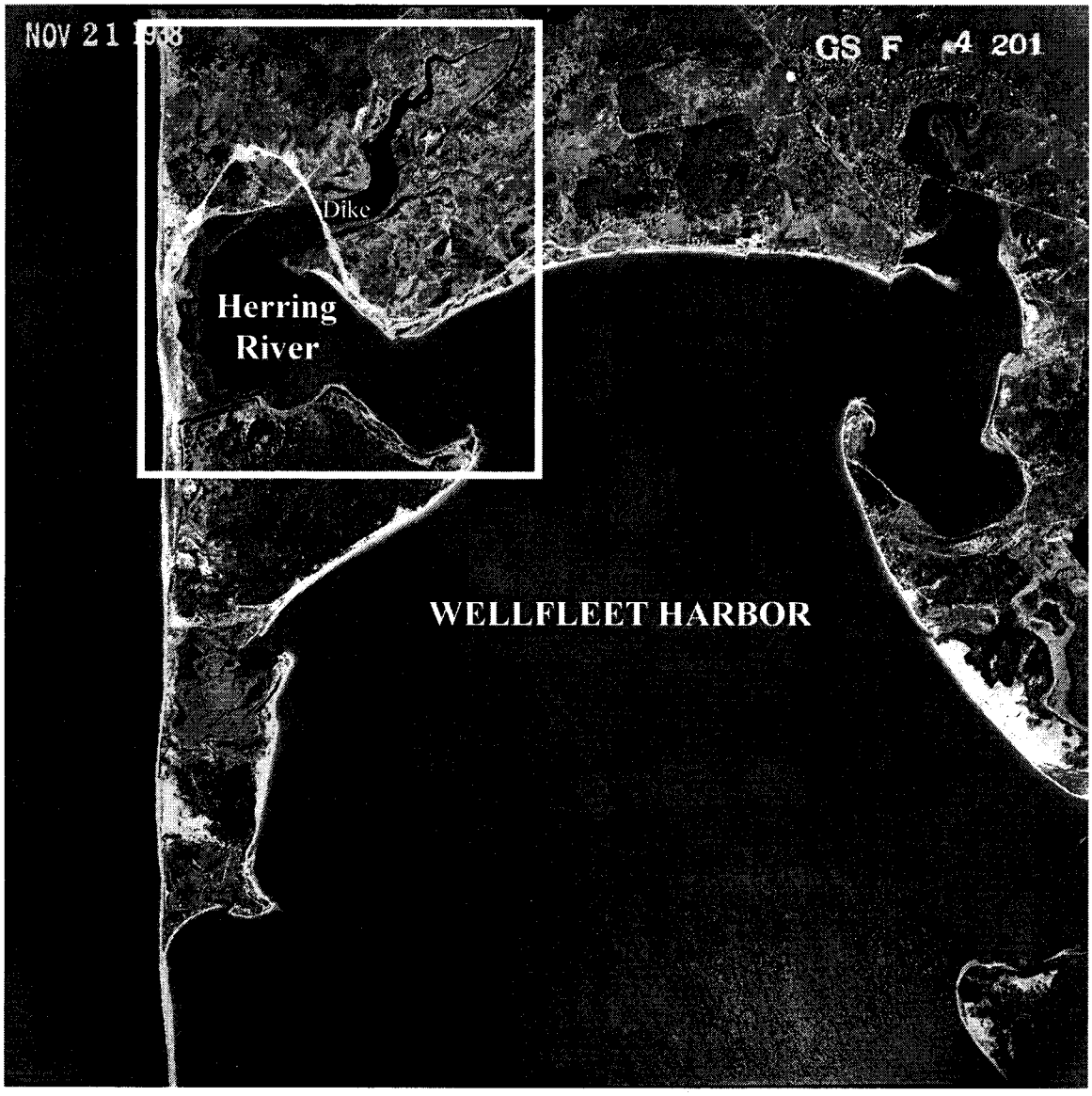


Figure 1.2: Location of Herring River with respect to the Wellfleet Harbor.

In the past the Herring River was the site of a major herring run. In addition to providing a nursery for fin and shellfish the Herring River maintained a productive 1100-acre salt marsh system, but that is not the case today. The tidal restriction on this system has resulted in major water quality problems including hypoxia, acidic waters (pH <4) and the formation of acid sulfate soils (Portnoy, 1991). Poor water quality has caused fish kills (Portnoy et al., 1987), and peat drainage has resulted in subsidence of the marsh surface of up to 80 centimeters (Portnoy 1997). With respect to coastal geology, marsh subsidence removes much of the protection that the coastal wetland normally provides in buffering high-energy storm waves. Ecologically, the freshening and drainage of the original salt marsh has allowed the invasion of exotic plants.

A series of scientific studies has been conducted by the Cape Cod National Seashore to determine ways to improve habitat quality in the vicinity of the Herring River. Results indicate that the environmental problems could be corrected by restoring tidal flow to the area above the dike (Portnoy and Reynolds, 1997). However, the proposal to increase tidal flow through the dike structure has raised concerns among local shellfishermen. To address how increased tide heights, salinity and sedimentation would be affected by restored tidal flow, hydrodynamic modeling was completed in 2001 (Spaulding and Grilli, 2001). Research has also been conducted to address the effects of flooding on the adjacent groundwater supply (Martin 2004).

Figure 1.3: 1908 T-sheet detailing the plan to install a dike across the Herring River.

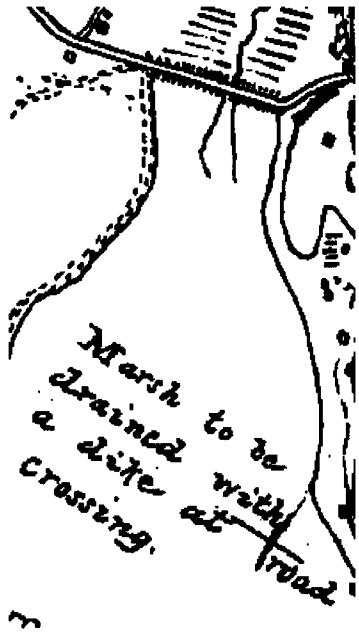


Figure 1.4: 1909 T-sheet indicating that the marsh above the Herring River Dike is to be drained.

Purpose

Town officials and resources managers are particularly interested in the issue of how changing the tidal regime in the river might affect sedimentation on shellfish beds seaward of the structure. Therefore, the purpose of this study is to address sedimentation concerns related to the possible restoration of the Herring River and to determine the effect of altering the tidal system on tidal flats used for oyster and hard clam culture in Wellfleet Harbor.

Plan/Methods

This study used a two-step approach to address sedimentation concerns associated with increasing tidal flow to the Herring River:

1) Solicitation of specific sedimentation questions concerning the restoration of the Herring River, with special emphasis on the effects on shellfish grants.

2) Response to these questions using pertinent information from previous investigations augmented with new, site specific data and analyses.

Results of Interviews

The first step, aside from background and previous studies research, was to amass a list of questions and concerns from shellfishermen with respect to sedimentation along the Herring River. A list of contact names was generated by speaking with various people in the Town of Wellfleet and Cape Cod National Seashore. Over the course of a two-week period several attempts to call every person on the list were made (Appendix A). After a standard introduction and statement of purpose for the phone call, the person was asked if he/she was willing to discuss their feelings on the issue. The following was the standard introduction:

> "Hi my name is Amy Dougherty and I am a geologist working with the Association of Women Geoscientists and Cape Cod National Seashore. I am performing a study related to sedimentation concerns associated with the potential restoration of the Herring River. Would you mind sparing a moment to talk?"

Several fishermen started their response by saying that they do not have any concerns related directly to sedimentation, but then went on to pose other concerns related to the restoration project. Since these questions are outside the investigator's area of expertise, and thus outside the scope of this study, they are not directly addressed in this report. However, due to the prevalence of these lingering concerns a list was compiled of the most prominent and recurring questions. This list, along with a log of detailed notes typed after every conversation, can be found in Appendix A.

From the various conversations it became evident that two major questions pertaining to sedimentation existed:

1) Does opening the Herring River Dike affect the stability of The Gut?
2) Does opening the Herring River Dike affect sedimentation below (seaward of) the dike?

Of the shellfishermen who expressed sedimentation concerns during the interviews, every one voiced both of these questions; therefore, they are the focus of this study. The following Chapter II will discuss the relationship between the stability of The Gut and the Herring River. Chapter III will detail a study performed specifically on sedimentation below the Herring River Dike. Chapter IV summarizes the conclusions found in previous chapters.

CHAPTER 2

STABILITY OF THE GUT AND ITS RELATIONSHIP TO THE HERRING RIVER

Introduction

People frequently ask whether opening the Herring River Dike would threaten the stability of The Gut or cause it to breach. This is of great concern because this strip of land channels the Herring River outflow into Wellfleet Harbor rather than directly into Cape Cod Bay (Figure 2.1). It is commonly thought that a breach might threaten shellfish resources in and around Wellfleet Harbor from an influx of bay water changing salinity, temperature and nutrients within the shellfish-rich inner basin.

This chapter explains how flow through the Herring River, even when unrestricted by a dike, is not a strong enough forcing mechanism to influence The Gut. In order to determine the relationship between Herring River and The Gut, one must first understand its formation in the context of the geologic history of the Cape.

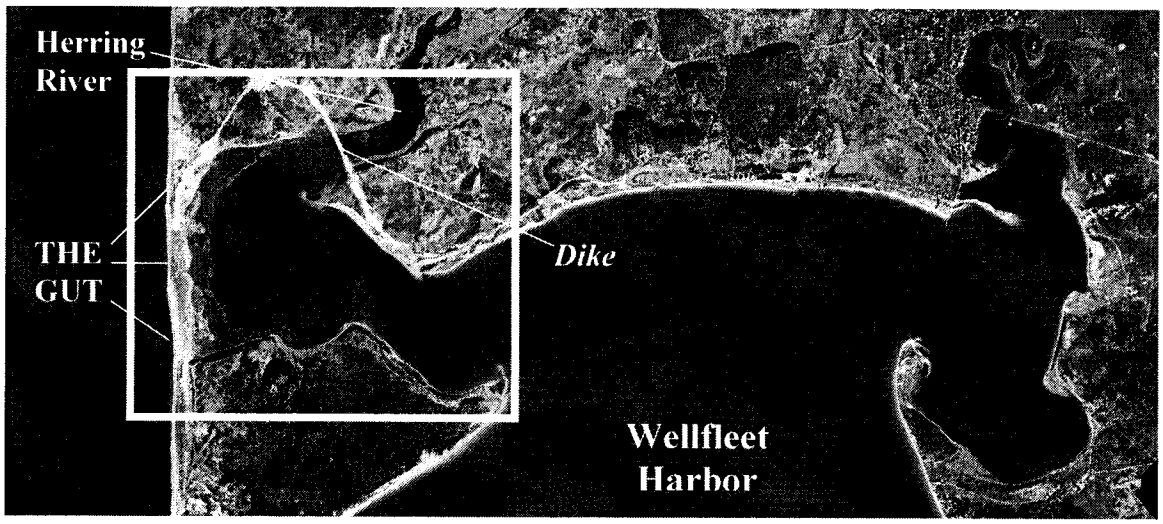


Figure 2.1: Location of The Gut in relation to the Herring River & Wellfleet Harbor

Brief Geologic Background

About 1.5 million years ago, global climate change caused glaciers to advance into the temperate regions of North America. These advances were followed by periods of warming and retreating ice. This cycle of glacial and interglacial periods occurred many times. The most recent glacial advance started about 50-70 thousand years ago. In the north, the ice that existed over Hudson Bay spread in all directions, and extended to cover all of New England. As the glaciers grew in size they incorporated a great deal of water evaporated from the sea causing sea level to drop considerably, estimated as much as 120 meters. The area where Cape Cod now exists was above sea level during the last glaciation. (Odale, 2001)

As glaciers move they scour the land underneath them and accumulate sediment within the ice. When a glacier stops and begins to retreat it leaves behind a large deposit of sediment, known as a moraine. The northern portions of Martha's Vineyard, Nantucket and Long Island are all moraines, known as terminal moraines, because they mark the southernmost extent of ice in the northeast region. As the ice retreated during the last glacial period, it either readvanced and/or stagnated just north of its farthest extent (Figure 2.2) forming a recessional moraine and outwash plains that now comprise Cape Cod (Figure 2.3). Further retreat and melting of this continental ice sheet returned water to the ocean basins causing global sea level to rise. Eventually the rising sea encroached upon the glacial deposits left behind by the ice. Around 9,500 years ago, rising sea level reached exposed Cape and wave erosion of the glacial deposits began. At first, uplands composed of glacial drift began to erode as waves attacked the fragile land forming sea cliffs. The eroded sand was then transported and redeposited by waves and currents to form bays, like Pleasant Bay and Wellfleet Harbor, protected from the open ocean by barrier spits and islands (Figure 2.3) (Uchupi et al., 1996).

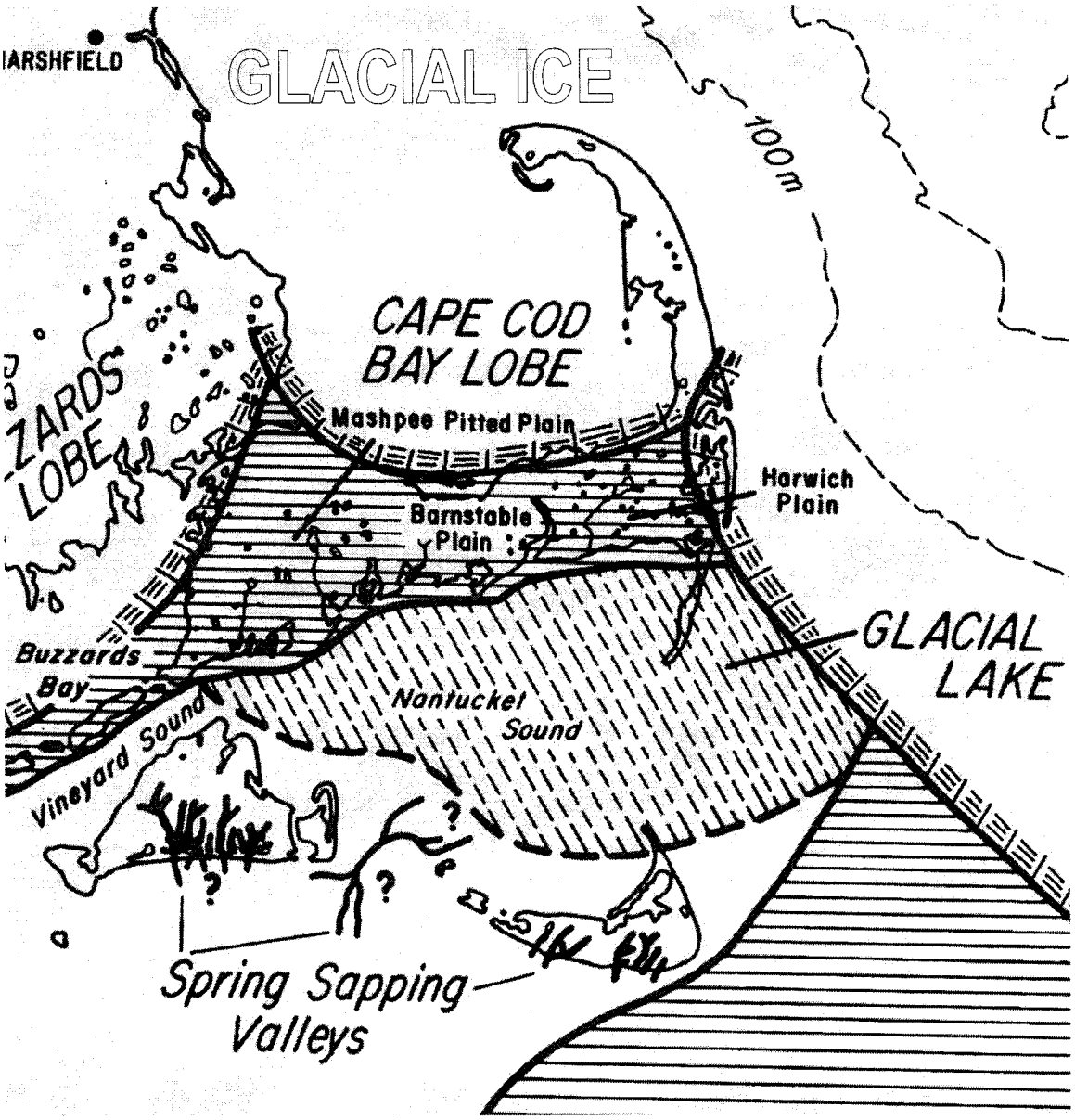


Figure 2.2: Map of southeastern Massachusetts as it looked prior to 18,000 years ago. Note the position of the ice lobe that occupied present-day Cape Cod Bay. (Uchupi et al., 1996)

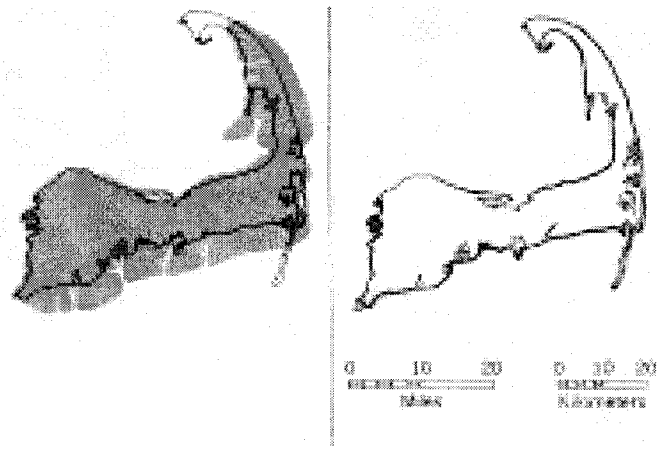


Figure 2.3: On the left in green/gray is the hypothetical configuration of the Cape about 6,000 years ago, before extensive wave erosion of these glacial deposits formed the current shape outlined in black. The right is a map showing the present pattern of erosion, with red (black) indicating shorelines experiencing erosion and green (gray) displaying areas undergoing deposition. (Odale, 2001)

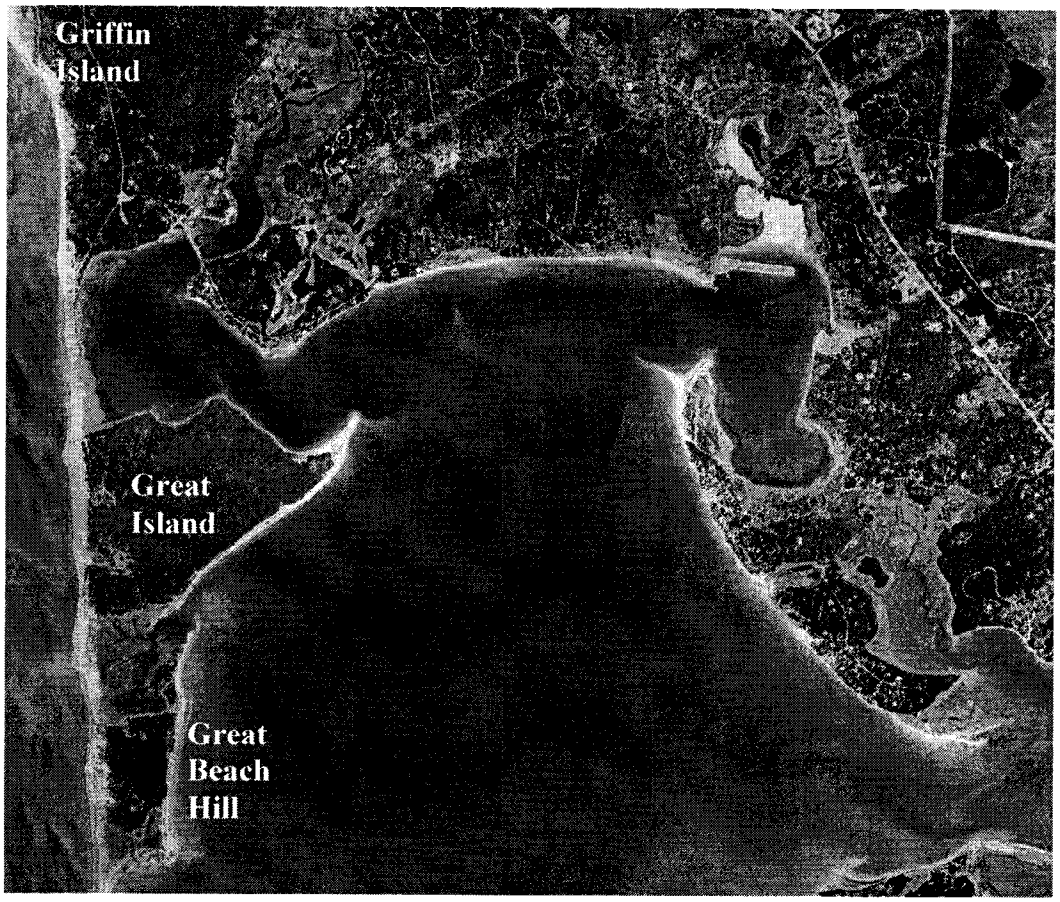


Figure 2.4: This 2001 air photo of Wellfleet Harbor shows the present day connected nature of the Wellfleet Harbor Islands.

Formation of The Gut

Wellfleet Harbor occupies a part of a large depression that formed due to the existence of the glacial ice that prevented the deposition of outwash sands (Figure 2.2). As the ice melted and sea level rose the depression filled with water forming Cape Cod Bay. Islands such as Griffin Island, Great Island and Great Beach Hill formed from sands that filled holes or depressions in the ice; as ice melted and sea level rose, they became surrounded by water. Despite their names, one would not consider these features to be islands today due to their connections to each other and the mainland (Figure 2.4). However, in the 1720s many people lived on these islands, which protected deep and useful anchorages at the time (Wood, 1973). A sketched map of the Cape by Henry David Thoreau depicts these islands as such, isolated by water (Figure 2.5).

On the ocean side of the outer Cape, continued sea-level rise and persistent erosion took sand from the glacial sea cliffs and transported it north (Figure 2.6) to form the Provincetown Spit (Figure 2.7). A spit is a peninsula-like accumulation of sand that extends off the mainland, sometimes curving at the end to form a recurved spit. The formation of the Provincelands prevented sediment transport to the Cape Cod bay beaches form the Atlantic (Figure 2.6). However, sediment from the eroding bay-side uplands continued to supply sand to the bay side beaches by long shore drift. The sand moving south formed a spit of land off of the Wellfleet mainland. Eventually this spit connected to the northernmost island and then each successive island to the south (Figure 2.8). This accumulation of sand that ties two landmasses together is known as a tombolo. Once these tombolos were in place, they provided protection from waves and formed the sheltered environment of Wellfleet Harbor. As a result of this quiet environment, marshes formed behind these tombolos (Figure 2.8). The newly formed marshes became so extensive north of The Gut that they actually filled in Duck Harbor landlocking Merrick Island (Figure 2.10).

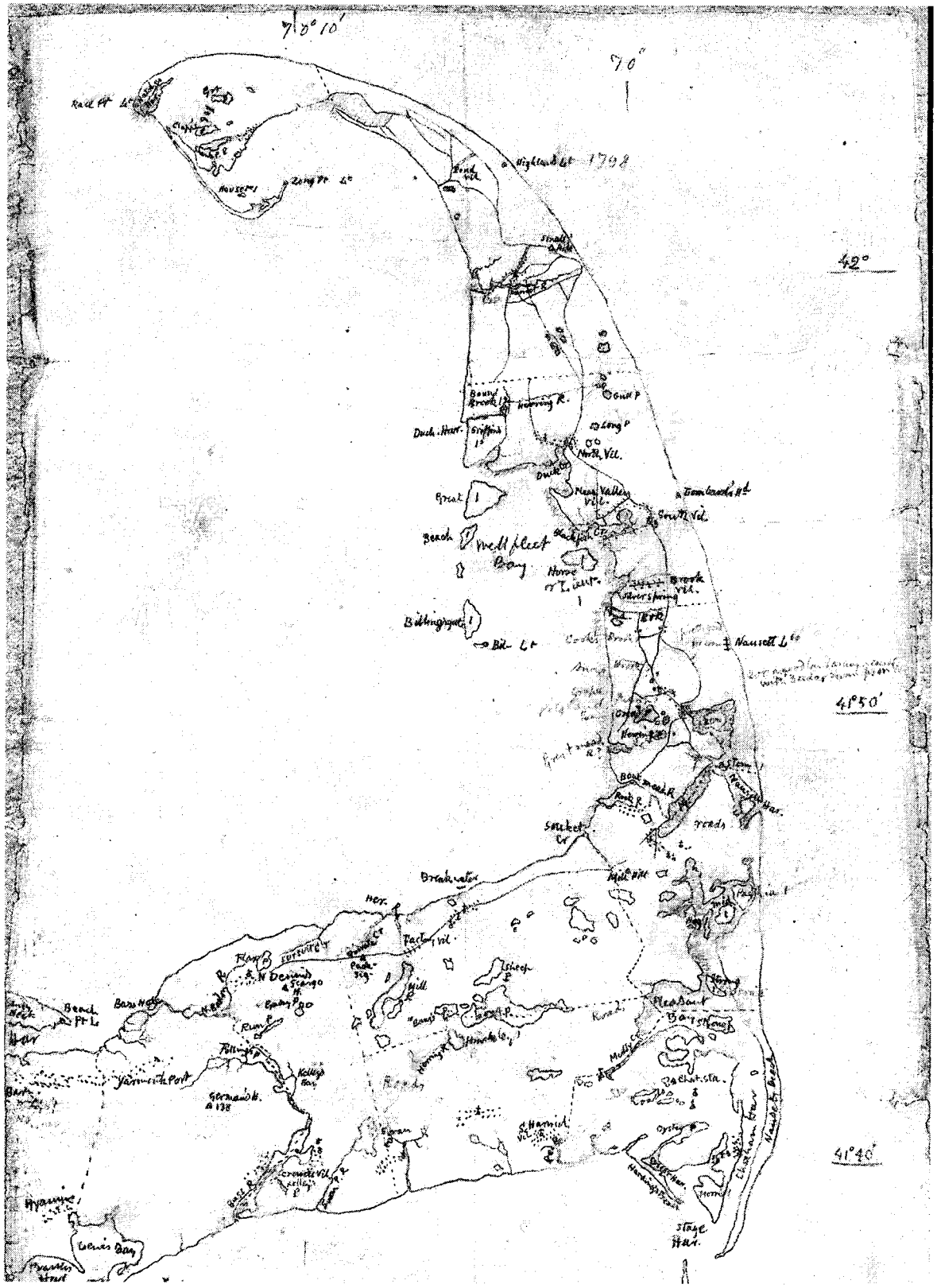


Figure 2.5: This map is a portion of a sketch of the Cape drawn by Henry David Thoreau. Note the depiction of the Wellfleet Harbor Islands as unattached.

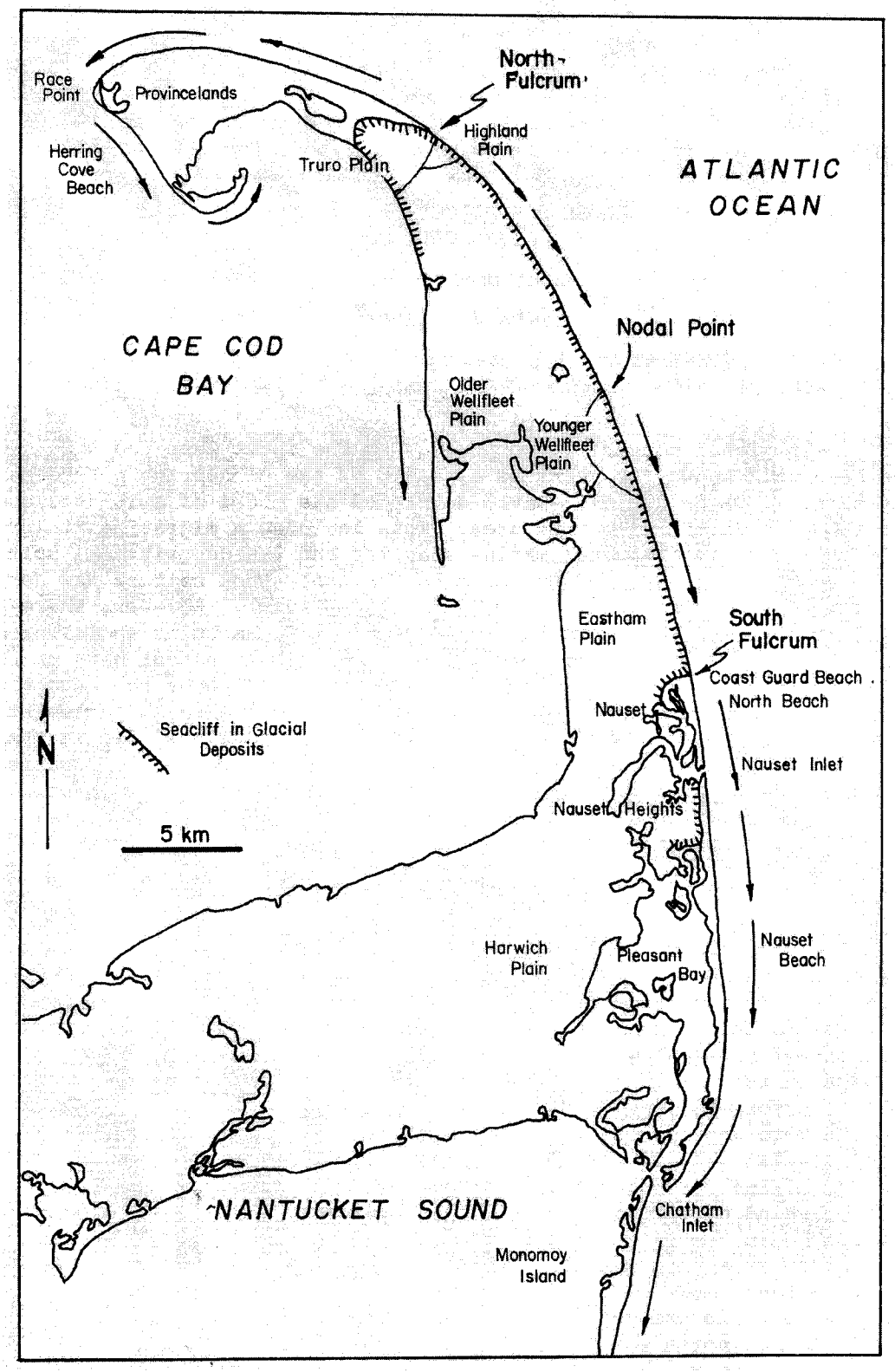


Figure 2.6: Sediment transport map of outer Cape Cod showing the southward transport of sands eroded from the adjacent Wellfleet bay side beaches. (Fisher, 1979)

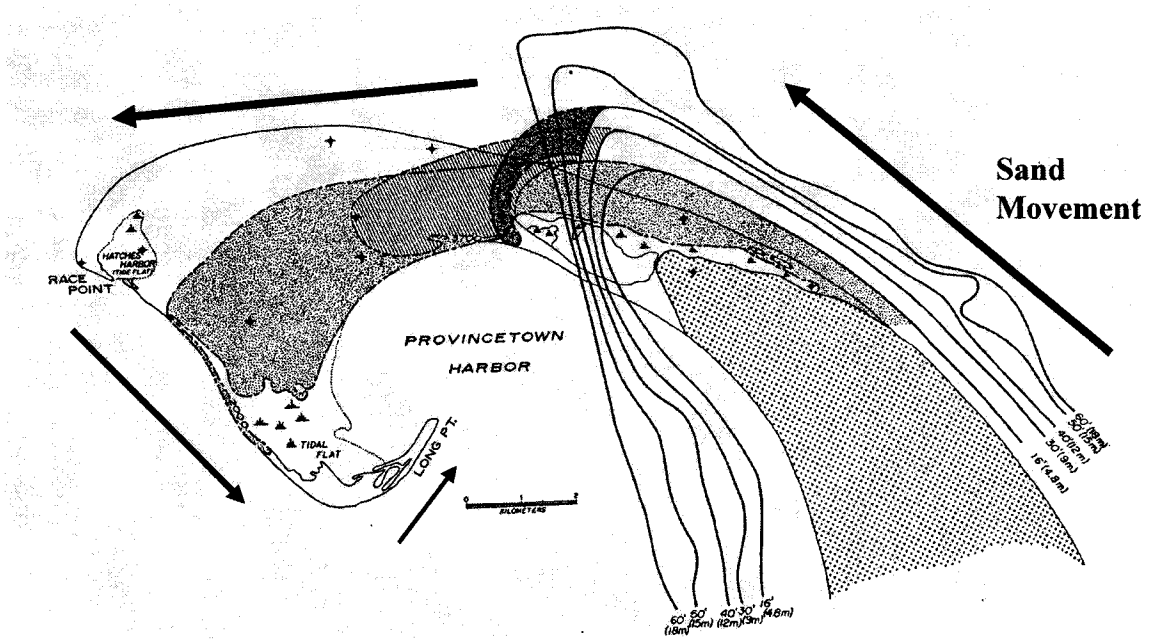


Figure 2.7: Sediment transport map showing the evolution of the Provincetown Spit. Note that each successive black line from right to left is the former configuration of the Provincetown Spit. The spit was initially building to the northwest and then begins to recurve due west, southeast and then due east. This shape is a result of open-ocean waves interacting with Cape Cod Bay tidal forces. (Zeigler et al. 1965)

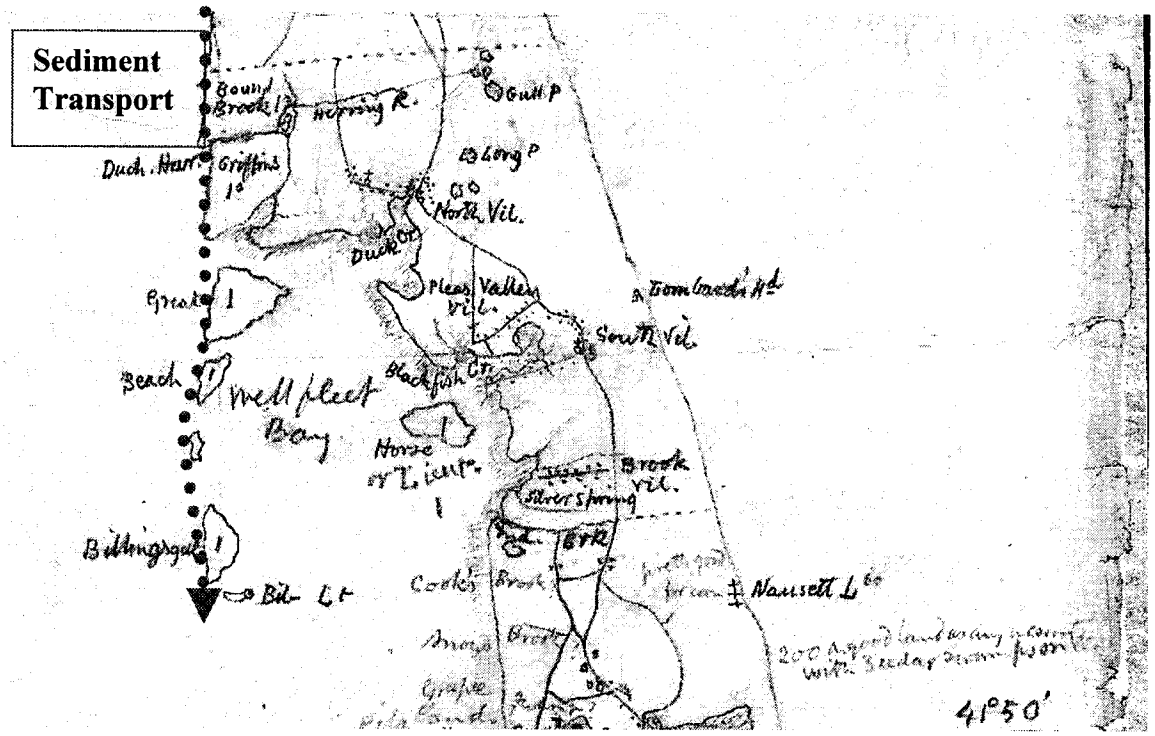


Figure 2.8: Map of sediment transport superimposed on Thoreau's sketch showing the formation of tombolos that connect the islands.

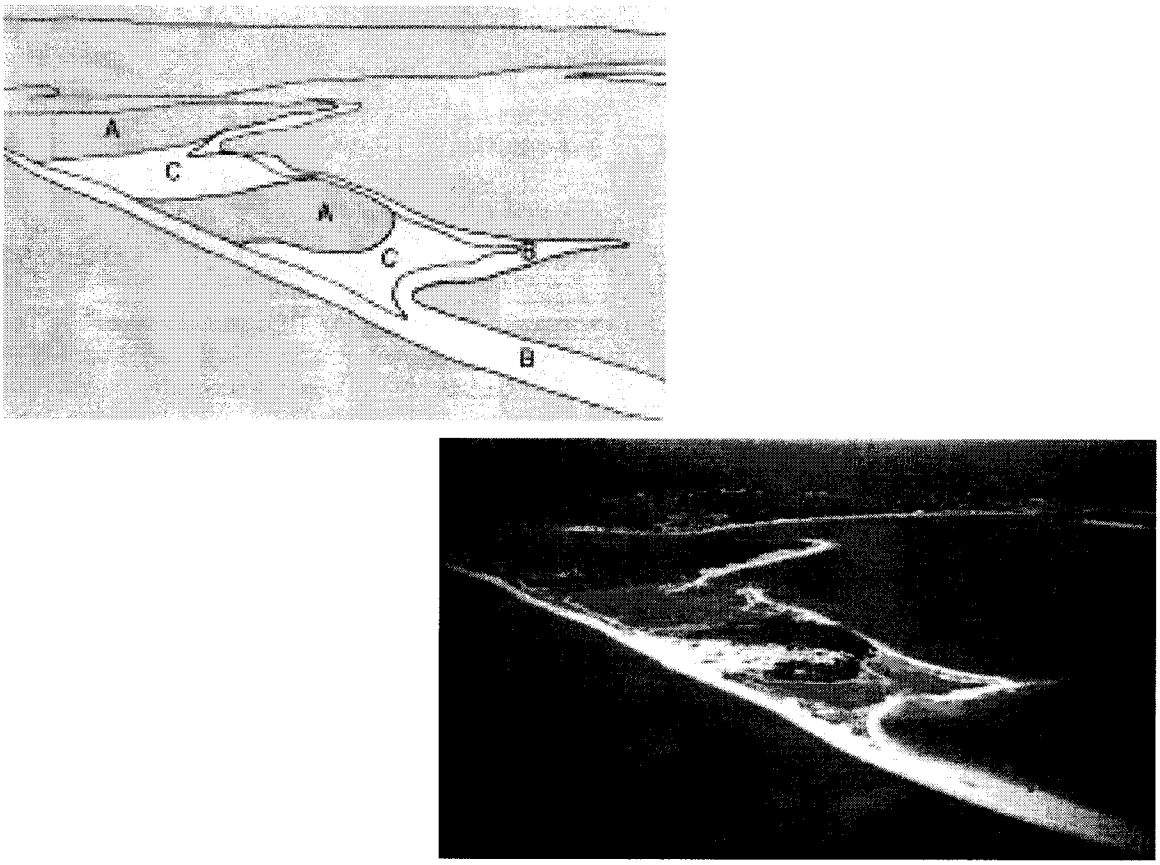


Figure 2.9: Top left is a cartoon schematic showing the evolution of the area directly south of The Gut, which is how it would have formed without the existence of the Herring River. First the islands are created by glacial deposits (A) then sand transported southward forms tombolos connecting them B) and as a result of the quiet water environment behind the spits and tombolos a thick marsh forms (C). The bottom right image is a photograph of the area illustrated above. (Oldale, 2001)

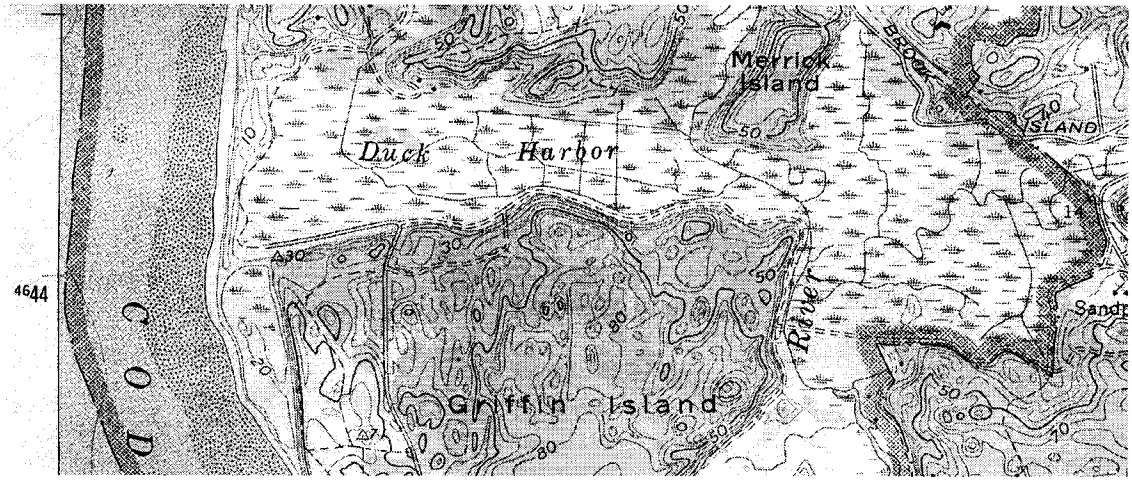


Figure 2.10: 1974 coastal chart showing the presence of marsh where Duck Harbor once existed.

Relationship of the Herring River to The Gut

Historically, the Herring River most likely emptied directly into the bay through the area that The Gut now occupies. However, during the elongation of the spit, which formed the tombolo that is The Gut, the Herring River was deflected to the south. This deflection shows that the river (i.e. prior to any dikes and thus unrestricted) was not strong enough to maintain an inlet through The Gut. This change in the course of the river occurred naturally well before the Chequesset Neck Dike was built. Thus, the altered course was under the maximum flow condition afforded by an open tidal river system. Therefore, it is reasonable to conclude that small changes in the tidal flow through the dike would have no effect on The Gut. Furthermore, based on the above historical evidence, it seems safe to assume that even complete removal of the dike would not cause The Gut to breach. Maintenance of an open inlet requires there to be a large hydraulic gradient, i.e. difference in water levels, between two water bodies during the normal tidal cycle. Because of the large opening for tidal waters between Jeremy Point and Wellfleet mainland, no such gradient can develop. Water follows the path of least resistance: in this case it is much more efficient hydraulically for the Herring River to empty into open Wellfleet Harbor and out past Jeremy Point than through The Gut.

A testament to these low flow velocities is the existence of a broad mudflat of fine-grained riverine sediments behind The Gut's barrier system (Figure 2.11). This accumulation of fine sand proves that there is not enough energy in the ebbing tide to transport this sediment. There is not even enough energy to scour the edge of this mudflat along the main ebb channel. This lack of scour is evident in all available aerial photographs and charts dating back to before dike construction; the intertidal morphology below the dike has not changed despite radical human alterations to river flow (Figure 2.12). Thus, even with dike removal and maximum ebb flows, there should be no scouring of the mudflat.

Given that The Gut influences the Herring River rather than the converse, what factor controls the stability of The Gut? The continued stability of The Gut, like its formation, is primarily dependent on longshore sediment transport on the Cape Cod Bay beaches and aeolian (wind) transport of finer sand to make and maintain the barrier's dune system. Erosion of The Gut is most likely to occur as a result of a storm; however, the wide salt marsh that backs this beach and dune system provides formidable resistance to erosion. It is highly unlikely that a channel would be cut through these thick and cohesive marsh peats; therefore, there is little chance of a permanent inlet forming from a breach in The Gut. It is more probable that in the case of a high-energy storm, an overwash from the bay would occur through a low in the dunes. An overwash transports sand from the Bay beach through a breach in the dune system to form a fan-shaped sand deposit on the back-barrier salt marsh surface (Figure 2.13). Natural post-storm processes that bring sand back onshore and rebuild dunes (Figure 2.14) to subsequently heal the breach.

Importantly, even if a temporary overwash were to occur, it is unlikely that there would be significant changes in water characteristics in The Gut's basin. Hydrodynamically, tidal exchange associated with an overwash through The Gut would be only a fraction of the tidal exchange that presently occurs around the south end of Jeremy Point; thus salinity and temperature changes would be minor. (Argow, 2000)

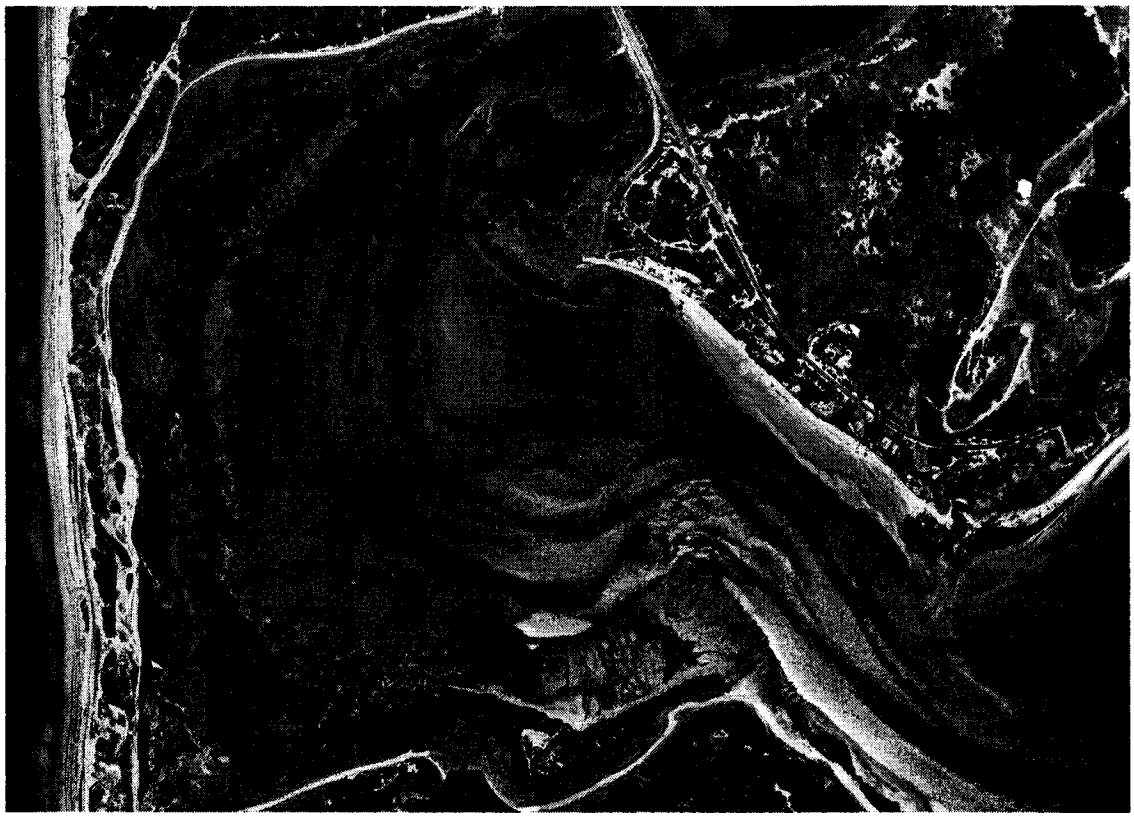


Figure 2.11: Air photo taken at low tide reveals broad mudflats flanking either side of the main ebb channel of the Herring River. This shows that flow velocities are not strong enough to even scour the channel banks, much less breach The Gut.

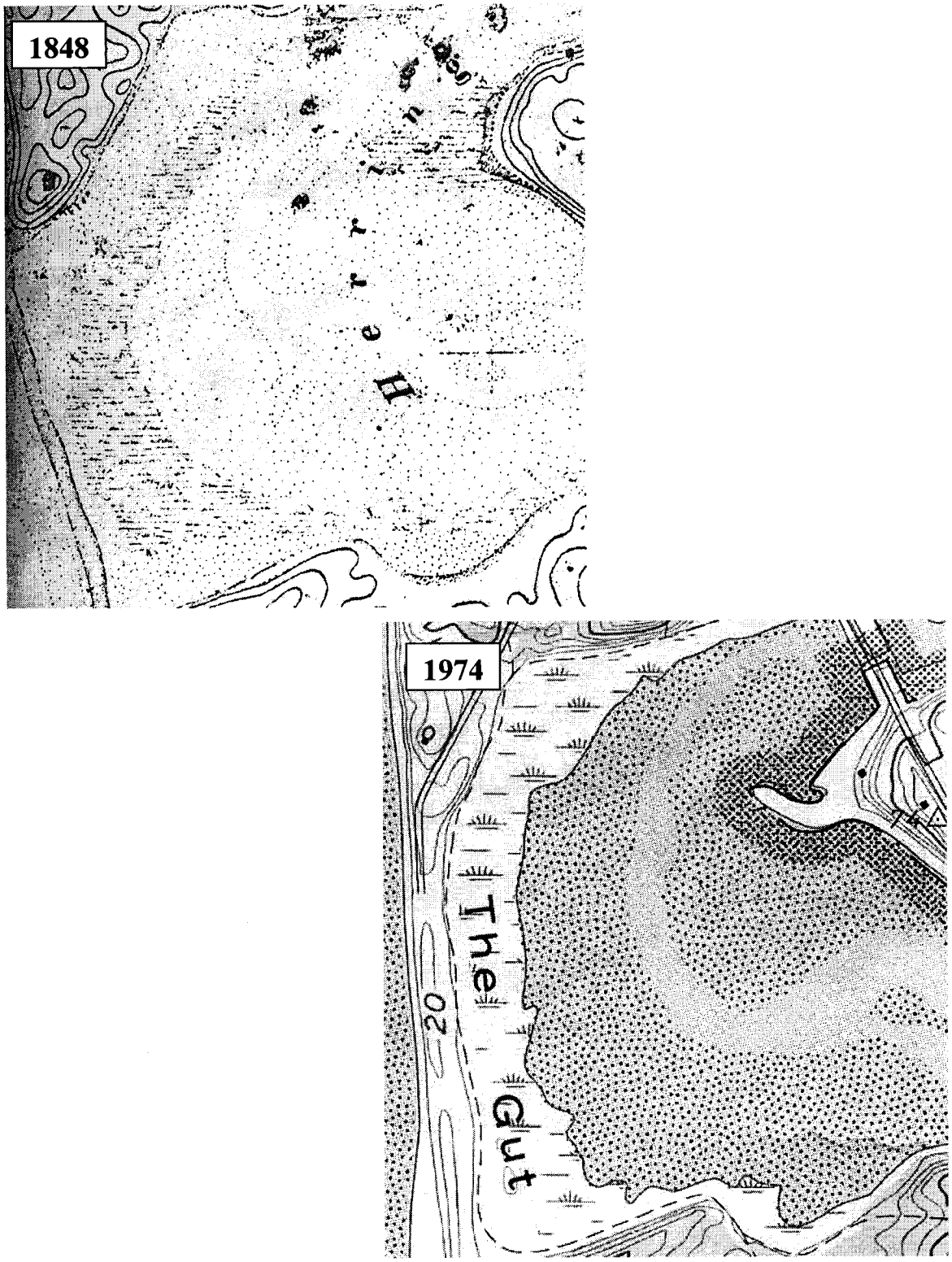


Figure 2.12: Comparison of coastal charts from 1884 and 1974 show that the main ebb channel has not moved throughout the last 100 years and thus was the same prior to the construction of the dike in 1909. Therefore, the position of the ebb channel is not expected to change if the dike were opened.

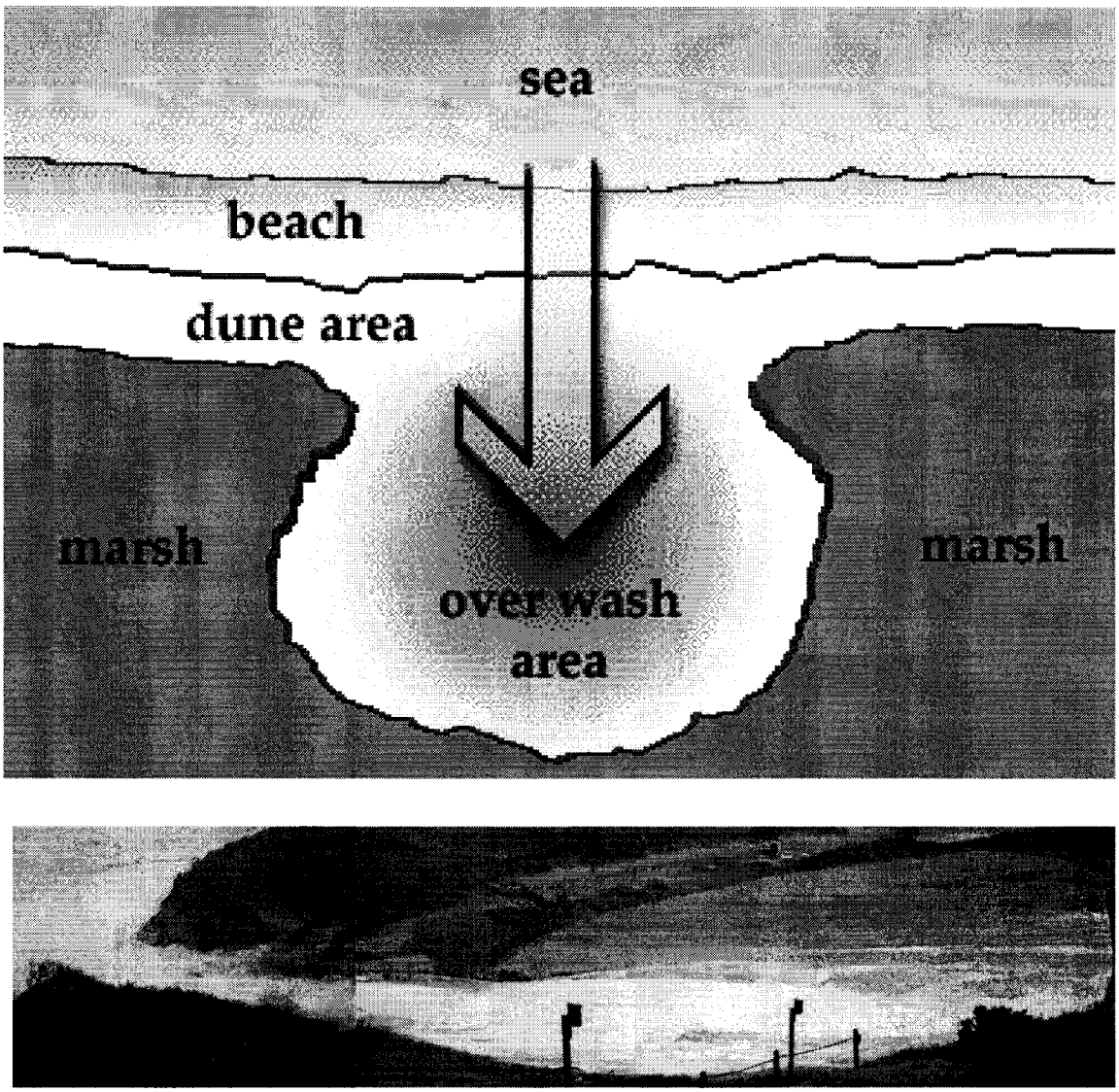
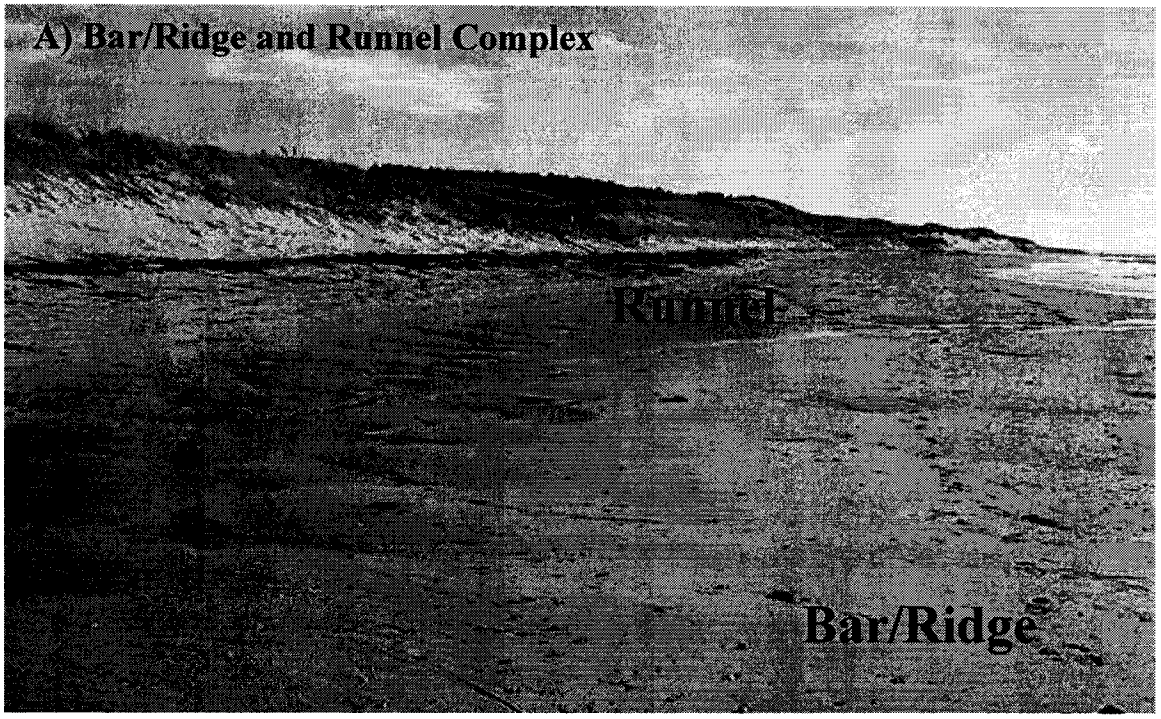


Figure 2.13: Above is a cartoon showing the aerial view of a washover forming on a barrier. Below is a photo taken at Ballston Beach during an overwash in 1991. Even this large overwash on the highly dynamic Atlantic shore did not result in a permanent inlet.



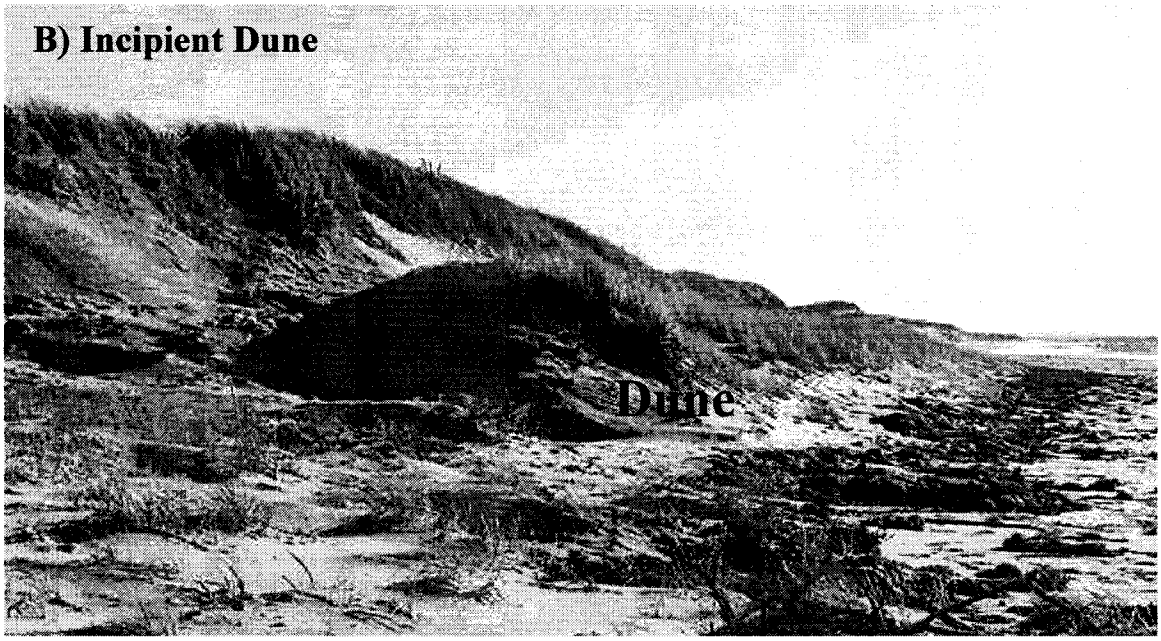


Figure 2.14: Present day pictures along The Gut showing barrier recovery mechanisms that occur after a storm to rebuild the beach. A) Shows a bar or ridge of sand that is reworking back onshore after being eroded by waves from a high-energy storm event. The topographic low landward of the ridge is known as a runnel, where water tends to pool after a high tide. B) Is a picture of a new dune that is forming from fine-grained particles of sand that are moved by wind.

Threats to The Gut

Both sea-level rise and a deficit in the sand supplied to this system are the main natural forces of erosion along The Gut. However, anthropogenic factors such as pedestrian traffic are exacerbating this erosion. The mere act of walking over the dunes to gain beach access results in the trampling of vegetation that is vital in stabilizing the dune sand (Figure 2.15). Loss of vegetation remobilizes sand and, where a path may form from cross-dune traffic (Figure 2.16), the wind is focused and causes downward erosion (Figure 2.17). These low-lying devegetated areas are ideal sites for blowout formation (Figure 2.18) and subsequent washovers during storms.

Figure 2.15: Vegetation loss on the dune due to pedestrian traffic.

Figure 2.16: Established path has caused complete elimination of vegetation.

Figure 2.17: Severe erosion, outlined in red (black), which can develop over an established path.

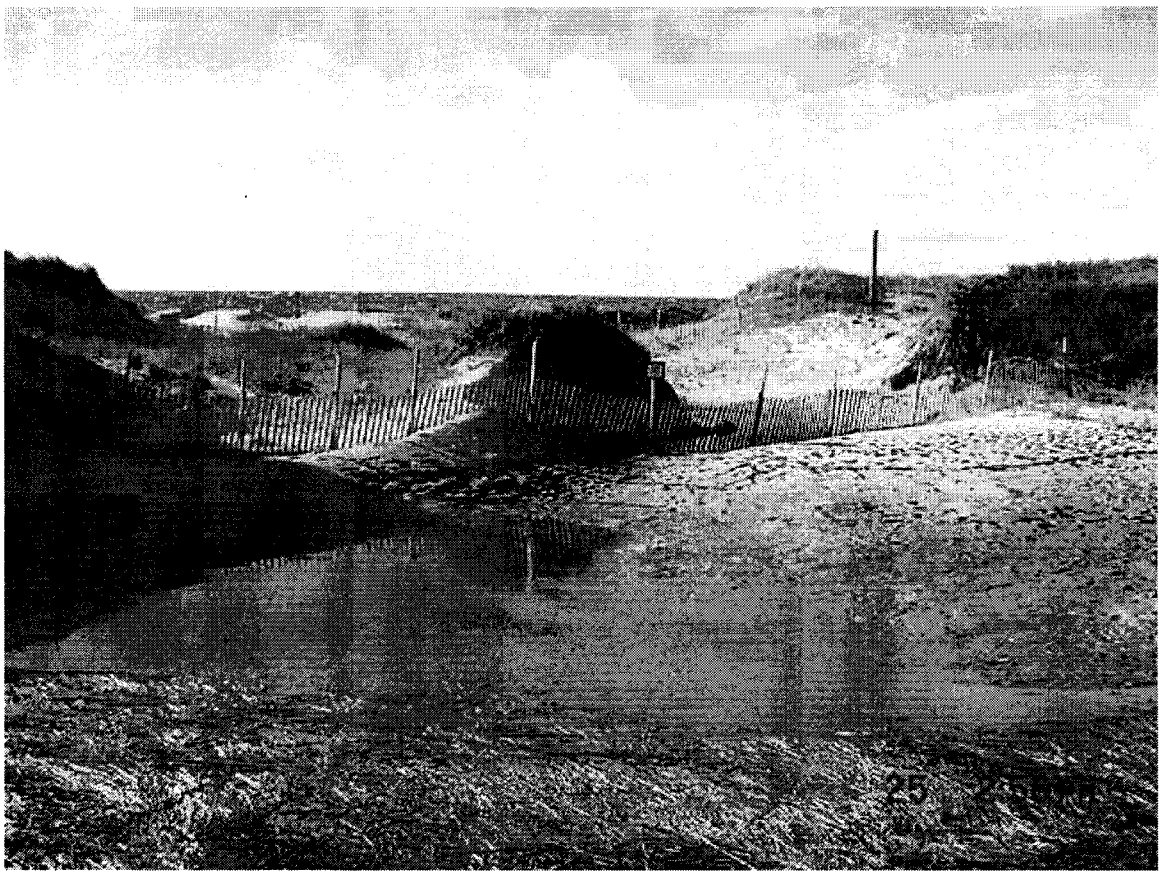


Figure 2.18: Dune blowout on the southern end of The Gut. These blowouts form as wind is funneled through topographic lows between dunes as a result of erosion.

With currently increasing sea level, it is common for barrier beaches to migrate landward; the process is known as barrier rollover. This transference of sand from the front to the back of the barrier is essential in maintaining the width of the barrier beach. On the river side of The Gut this natural process interrupted by a road (Figure 2.19). The maintenance of this road constrains barrier rollover by preventing sand accumulation. If the landward movement of sand is obstructed, the barrier becomes stationary and sand will simply be eroded and lost to the system. This erosion will result in an overall thinning of the barrier beach. The thinner the barrier, the more likely it is to be overwashed.

Figure 2.19: Wooden fence that leads to path/road behind the barrier.

Measures being taken to minimize erosion of The Gut

In reaction to the degradation of the dune system by pedestrian traffic, steps have been taken by the Town of Wellfleet and Cape Cod National Seashore to monitor this erosion and lessen the anthropogenic impact. Mitigation projects include road and path crossover closures utilizing signage and fences. As a result of the serious problem of blowouts related to foot travel, dune cross-overs for beach access will be limited to only two locations. These formalized crossovers are marked with signs (Figure 2.20) and string to provide "symbolic" fencing (Figure 2.21) making the accepted routes more obvious to encourage their use. The Town of Wellfleet established the northern route (Figure 2.20), located just south of the old Gut parking lot, many years ago. A second crossover was recently selected at the south end of the tombolo (Figure 2.21). The placement of these walkways at the ends of the Gut is not only convenient, i.e. closest to the parking area and to Great Island, but also environmentally optimal, i.e. adjacent to the widest expanses of storm-resistant salt marshes (Figure 2.22). In addition, the paths have a meander or zigzag pattern that should minimize erosion by wind and water (Figure 2.23).

Figure 2.20: Northern beach access on The Gut as indicated in posted sign.

Figure 2.21: Southern beach access marked by signs and symbolic fencing.

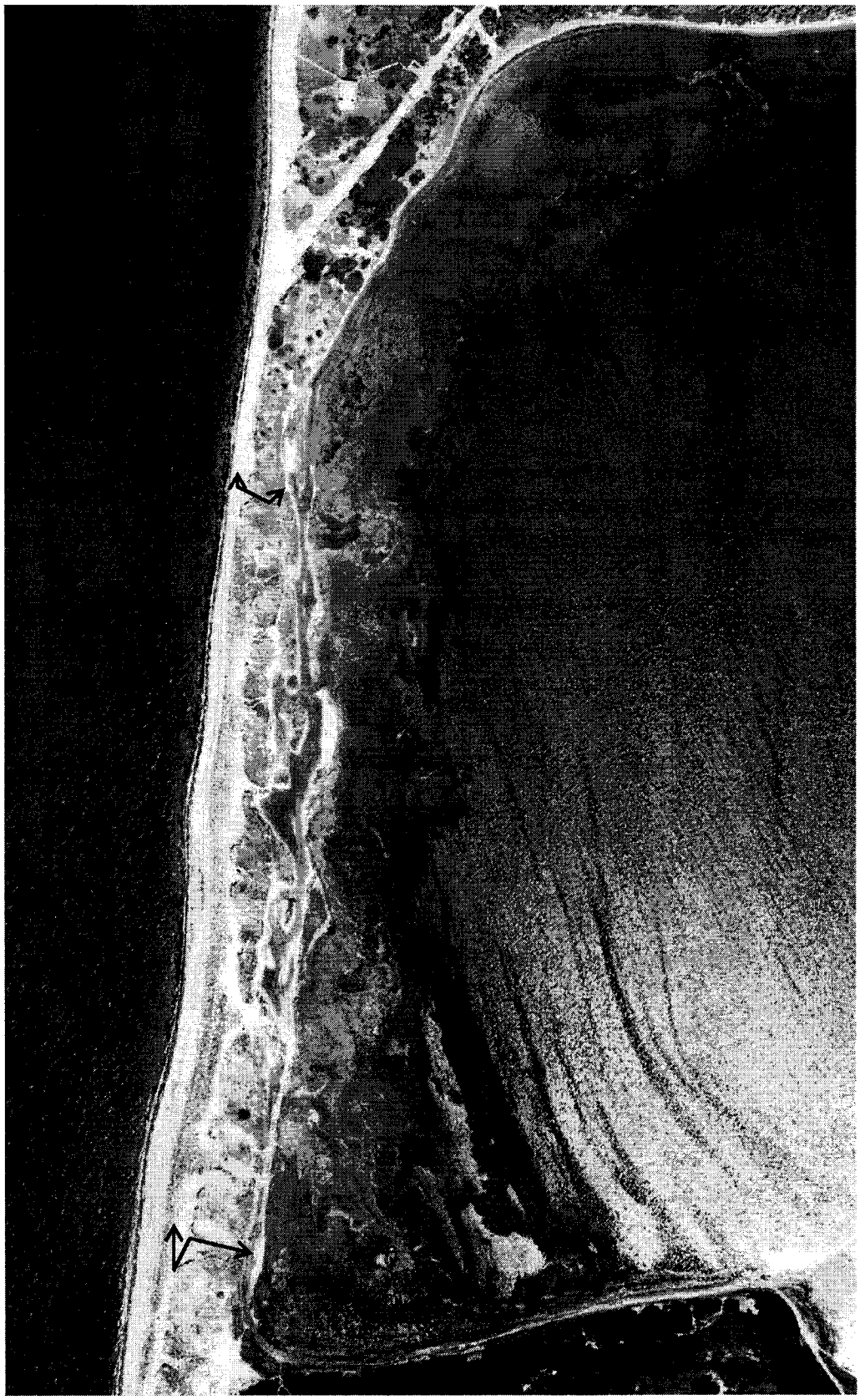


Figure 2.22: Location of north and south crossovers established along The Gut.

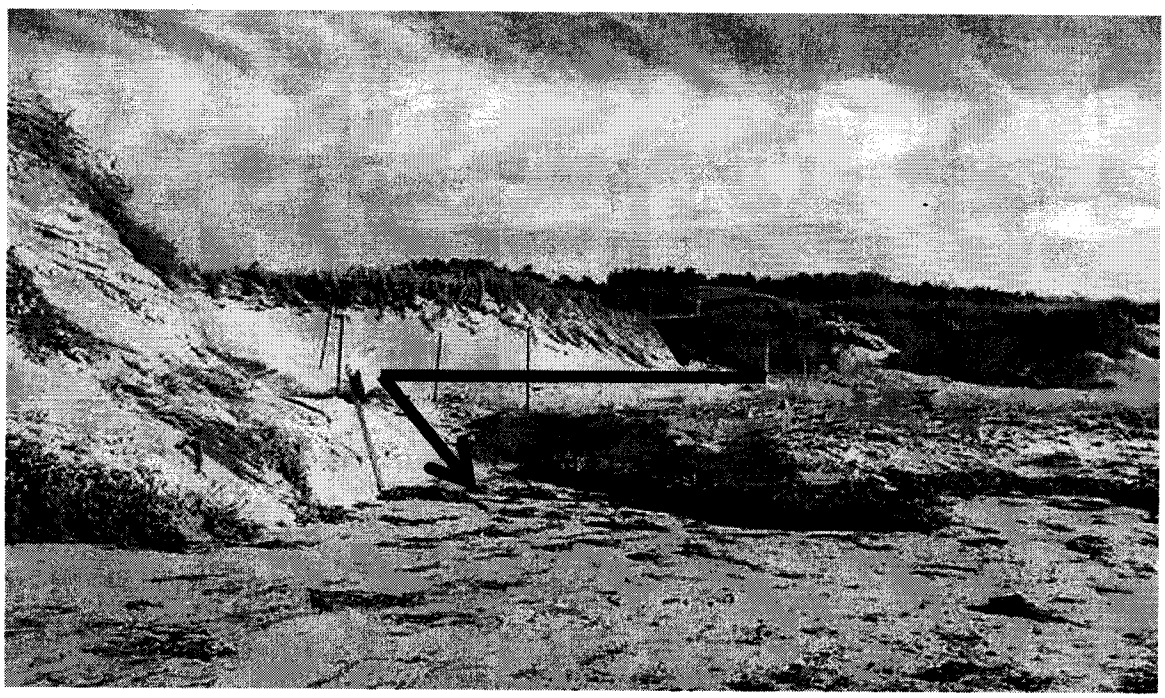


Figure 2.23: Photograph looking east of the southern beach access on the Gut. Note the meander or zigzag pattern of the path, highlighted in red.

In areas that have formed paths or blowouts in the more vulnerable central portion of The Gut, restoration projects were undertaken. The largest blowout, located on the southern portion of The Gut, has been sectioned off with dune/snow fencing to both block traffic and capture sand (Figure 2.18). In addition to posting signs (Figure 2.24), dune grass was planted to promote sand accumulation and stabilize the dunes (Figure 2.25). These management practices should minimize erosion due to pedestrian traffic on The Gut.

Figure 2.24: Signs successfully deter pedestrians and promote natural revegetation.

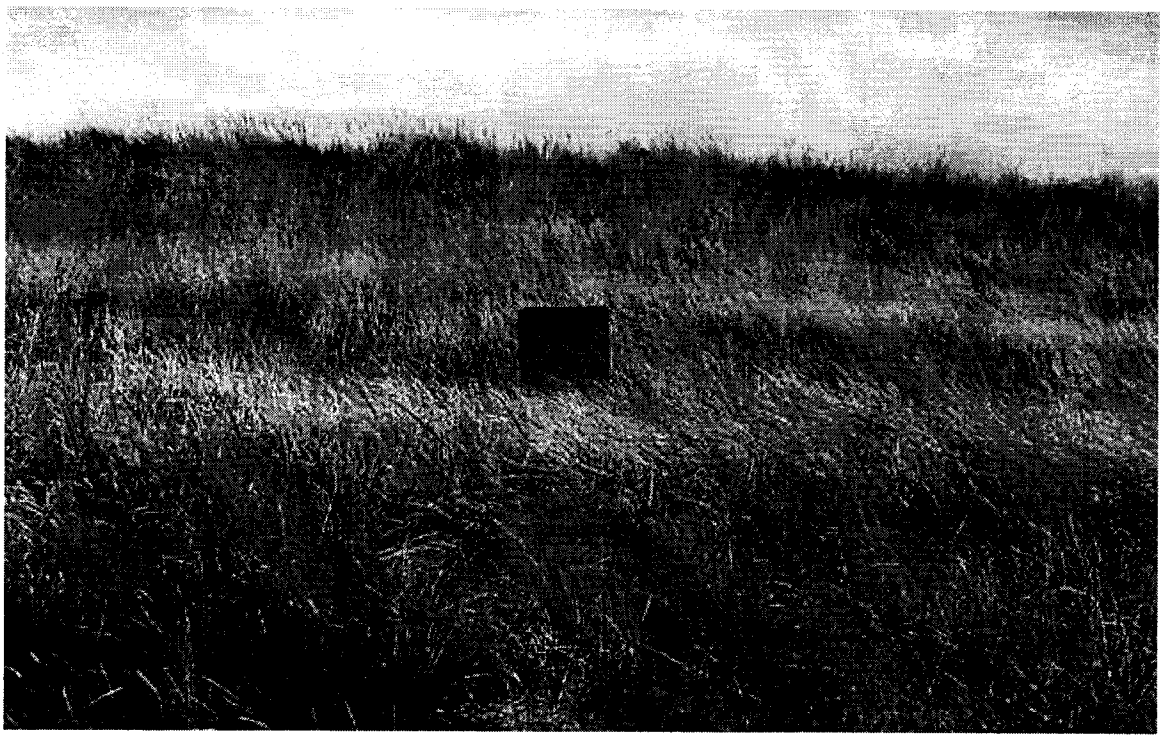


Figure 2.25: A dune stabilized through signage and revegetation programs.

Conclusions

- The continued stability of The Gut is dependent on the same two factors that governed its formation: 1) sand supply and 2) sea-level rise.
- The Gut influences the Herring River rather than vice versa as evidenced by:
- The large meander or bend in the river that occurred as a result of The Gut's formation, that forced water to flow south through the harbor.
- The existence of wide mudflat on either side of the main ebb channel present even before the dike was constructed, indicative of low ebb-flow velocities from the river.
- It is unlikely that The Gut would breach and form a permanent inlet due to the extensive marsh backing this barrier beach. If a large storm were to cause erosion along The Gut, a temporary washover may occur; however, natural post-storm rebuilding processes would quickly close it.
- Foot traffic across the dune system has worsened erosion and increased the possibility of a blowout. The Town of Wellfleet, Cape Cod National Seashore and volunteers are taking action to repair and limit this damage.

CHAPTER 3

SEDIMENTATION IN THE LOWER HERRING RIVER

Introduction

The question most frequently asked, and apparently of greatest concern, was whether opening the Herring River Dike would affect sedimentation on shellfish beds below the structure. A sample of these questions is provided below:

- What is the expected sedimentation and reconfiguration of Egg Island once the dike is opened?
- What are the short-term effects of opening the dike before the system reaches a new equilibrium?
- What is going to happen (with respect to sediment) below the dike?

Strategy

The above questions regarding sedimentation below the Herring River Dike were addressed by:

1) Synthesis of existing scientific research on Herring River and on diked salt marshes in general.
2) A new study designed specifically to address the sedimentation concerns below the Herring River Dike. The approach of this study is described in the methods section below.

Literature Review

In order to acquire as much information as possible, an extensive literature review was conducted. In addition to regular access to the North Atlantic Coastal Laboratory Library, multiple trips were taken to Marine Biological Laboratory Library (Woods Hole) and Boston University's Science and Engineering Library. Several geology database search engines were used such as GeoRef and Geobase. Despite this intense effort, no other studies were found with respect to sedimentation associated with restoration of a diked salt marsh. In contrast, many studies on the Herring River were found; however, only one addressed the issue of sedimentation. This study performed by Malcolm L. Spaulding and Annette Grilli in 2001 entitled *"Hydrodynamic and Salinity, Modeling for Estuarine Habitat Restoration at Herring River, Wellfleet, Massachusetts"*, was extremely useful as a base for the new investigation and will be referenced frequently throughout the remainder of this report.

Synthesis of the 2001 Hydrodynamic Study

Effects of Dike Construction

The dike across the mouth of the Herring River has reduced the tidal range above the structure by greater than 4.5 times (Figure 3.1). The difference in tidal range from 2.53 meters below the dike to 0.56 meters above the dike, causes an asymmetry between the flood and ebb flow velocities in the lower portion of the river. The faster flood currents, particularly during very high and storm tides, result in a dominant transport of sediments in an upstream direction. Once sediment-laden water enters the sluice gate the constriction of flow causes the water to speed up, much like putting your finger over a garden hose causes the water to spray out. With this increased flow, sediment is rapidly transported through the dike and into the relatively unconfined, large portion of the lower river. The entrance into this comparatively quiet water causes the flow to disperse, much like the jet stream of a Jacuzzi dissipates with distance, and forms what is known as a plume (Figure 3.1). As the plume velocities and turbulence decrease away from the sluice opening, to suspended sediment settles. The larger grains settle first and are deposited just landward of the dike in a fan or triangular shape bedform, similar to a delta at the base of a river. The finer grains are carried farther and deposited just upstream of the delta. This system is more analogous to a tidal inlet than a river mouth because of the confined bi-directional flow created by the tides. In sticking with the model of a tidal inlet, this sedimentary deposit above the dike will be called the flood-tidal delta (Figure 3.1 & 3.2).

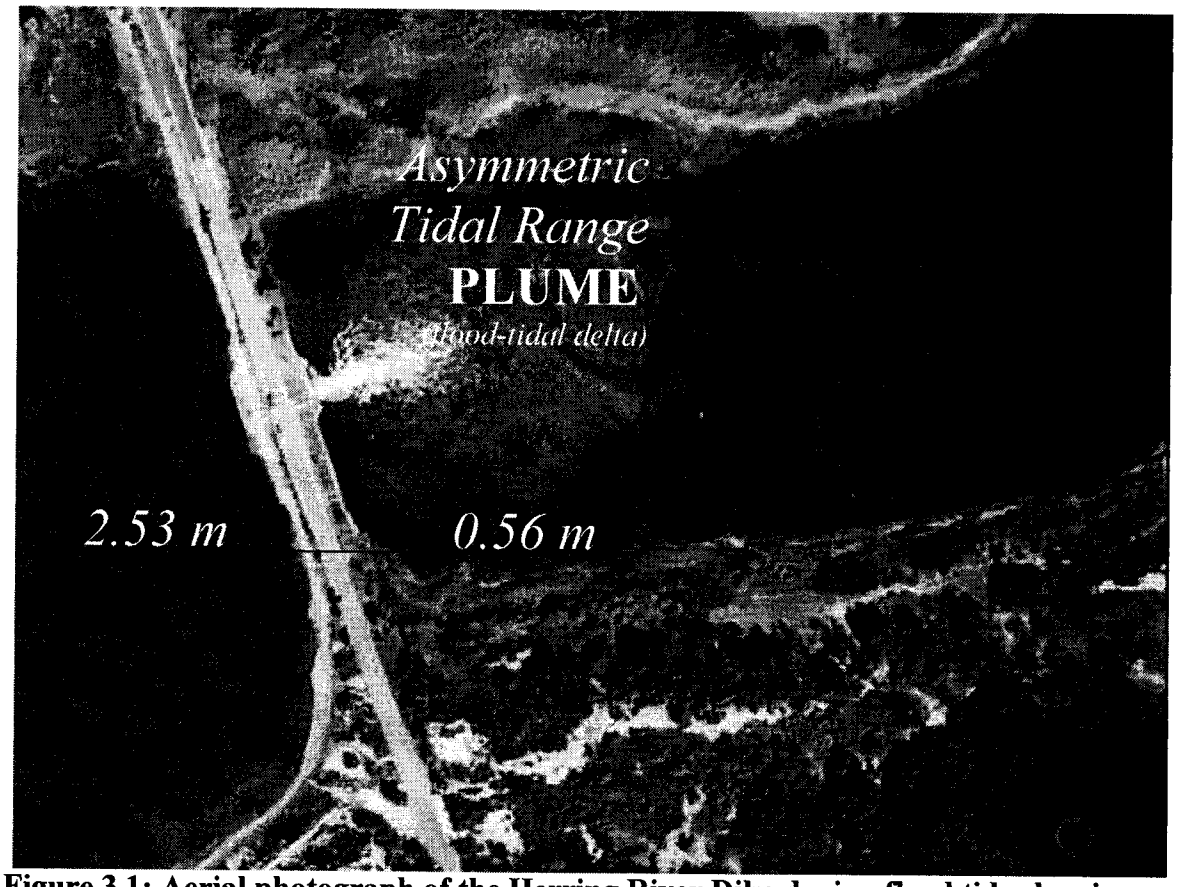


Figure 3.1: Aerial photograph of the Herring River Dike during flood tide showing the flood-tidal delta. Sediment accumulates above, rather than below, the dike because flood-tide velocities are higher and thereby transport more sediment than ebb tides (Figure 3.2).

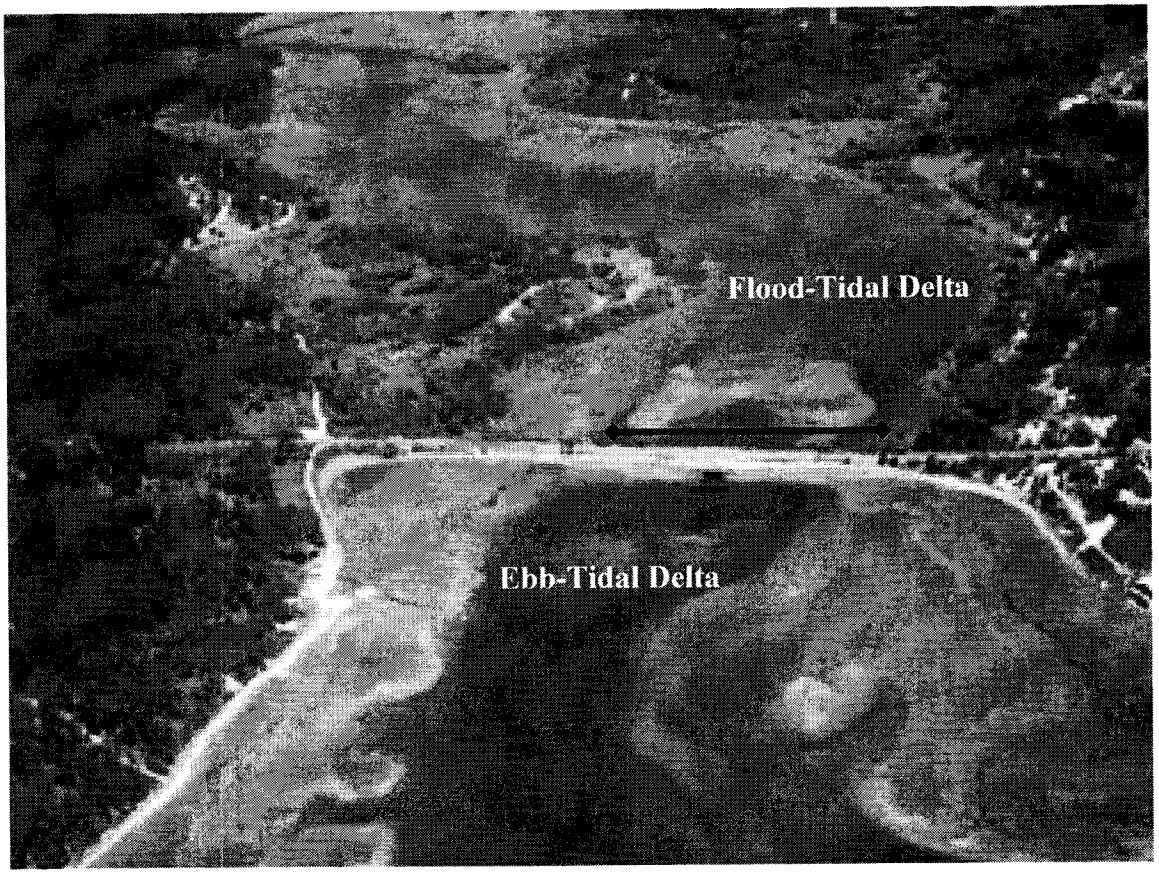


Figure 3.2: Air photograph showing the location of the flood-and ebb-tidal deltas, as well as the reduction in width of the river (black line with diamond end points located above the road) to the small opening of the dike (black line below the road).

The same process occurs during an ebb tide, but to a lesser extent because the flow is weaker. While the force of the rising tide in Cape Cod Bay pushes floodwaters, the ebb is driven only by gravity. The dike restricts the amount of water entering the river during the flood; this results in less hydraulic head forcing the water back out on the return tide. These low ebb velocities transport little sediment in a seaward direction, as evidenced by the smaller size of the ebb-tide delta (Figure 3.2).

This lack of sediment moving in a downstream direction prompts the question of why an ebb-tidal delta exists at all. It is thought that both deltas initially formed when the dike was built and flow was constricted to one small area (Figure 3.2). Erosion caused by the focused flows scoured a channel proximal to the culverts and perpendicular to the dike. The scoured material was then deposited at the upstream and downstream ends of the channel, forming the flood-and ebb-tidal deltas respectively. Once the channel became established and the area reached equilibrium, little additional sediment was added to the ebb-tidal delta allowing oysters to colonize it (Figure 3.3). In contrast, the flood-tidal delta continues to grow by the constant addition of sediment brought in from the ocean, preventing colonization by oysters.

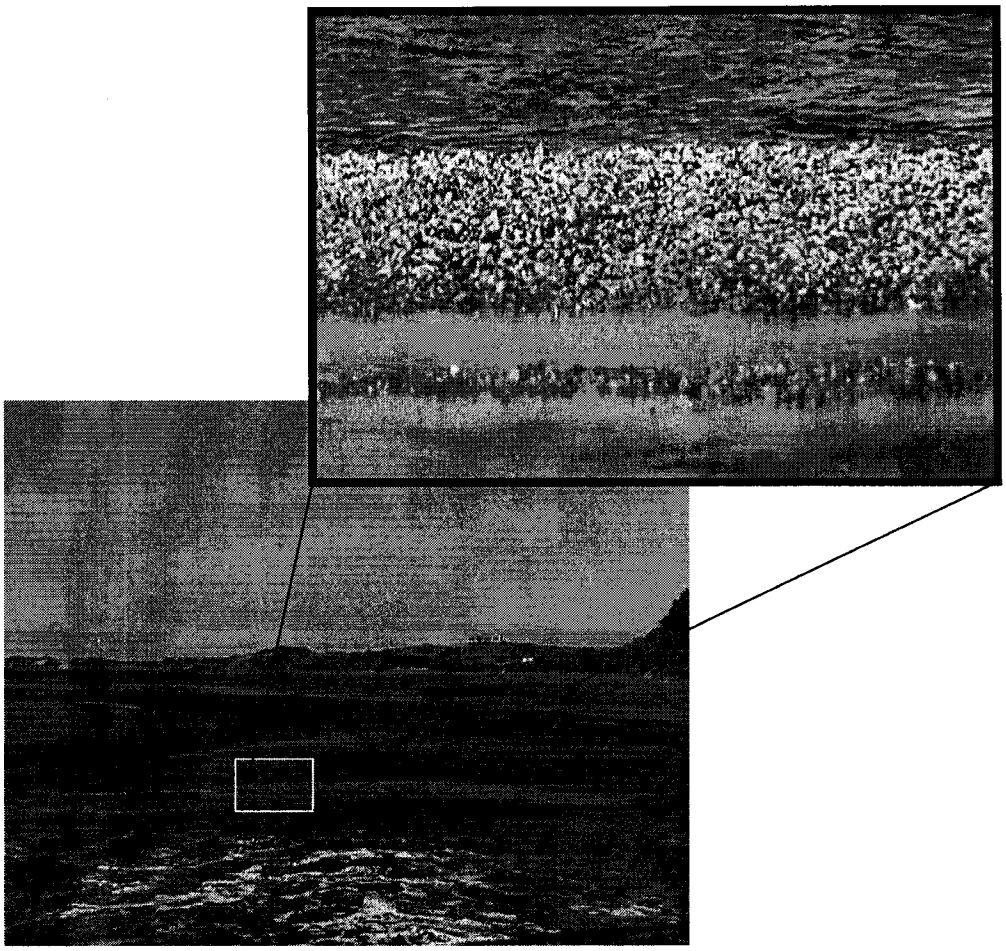


Figure 3.3: Digital photo of ebb-tidal delta armored with shellfish.

Above the Dike

Spaulding and Grilli's (2001) extensive hydrodynamic study measured the velocities of the ebbing tides proximal to the flood-tidal delta and found them to be insufficient to resuspend the sediment within the delta or the fine-grained material just upstream of it. These currents will be reduced even more if the dike is opened to allow more water to flow through the structure. In keeping with the above hose analogy, the situation is likened to taking your thumb off of the nozzle, thus increasing the opening and causing the water to stop spraying and to return to a slower flow. Although increased sluice gate openings will cause water velocities through the dike itself to decrease, both tidal range and current velocities will increase in the river upstream of the dike; however, flows will still be far too slow to resuspend sediment. Spaulding and Grilli's study determined peak velocities in the river with all three dike gates open to be less than 10 cm/sec, which is half the 20 cm/sec necessary to resuspend sand within the river (Figure 3.4).

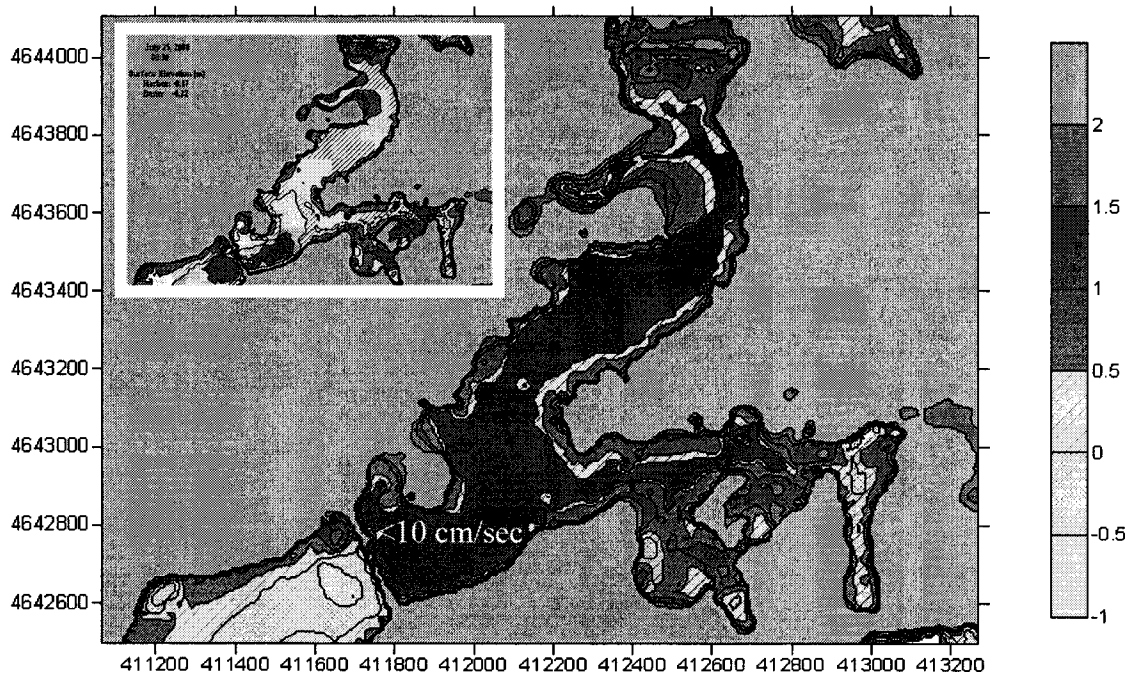


Figure 3.4: Snapshot of Spaulding and Grilli's hydrodynamic model that predicted maximum velocities above the dike, with all gates open, to be less than 10 cm/sec.

Spaulding and Grilli also estimated that the flood-tidal delta will undergo minor changes during storm events, but for the most part it is likely to remain much as it is at present. Under these storm conditions the delta and riverine sands would probably undergo very slow erosion and dispersal within the river. The finer-grained sediment such as silt and clays, which would be resuspended under normal tidal forcing, would be transported both up-and downstream during storms. However, keeping in mind that the stronger flows are associated with the flood tide, the dominant transport direction would remain upstream. Therefore the fine-grained material that is usually deposited in the channel above the flood-tidal delta, due to lack of flow energy, would then be moved farther upstream and deposited in the marsh. In the case of a large rain event, Spaulding and Grilli report that the ebb tides may transport sediment in a seaward direction. The rain is an independent driving mechanism responsible for the re-suspension of the sediment and its movement out of the drainage basin. Once this sediment is suspended it would be carried seaward through the dike in the same manner as is the case today, regardless of the dike's configuration, because all three flapper gates allow water to move in a seaward direction. Therefore, it is likely that the resulting sediment transport patterns with the dike open would be identical to those during past rainstorms with the gates in their current configuration. During these events the larger sand size particles will likely settle just below the dike, near the present ebb-tidal delta, while the tiny silt-and clay-sized grains will widely disperse and deposit in the fringing marshes of The Gut or offshore.

In speaking with people, the fine-grained material that has been deposited above the flood-tidal delta was of particular concern. While discussing this material with Dr. Spaulding he explained that these fines are deposited mainly in the channel, instead of on the marsh surface as typically expected, because the flow above the dike is hindered by the structure. Under natural conditions, the flow within the channel would be too fast to allow fine sediment to be deposited. Instead it would be transported farther upstream and dispersed into the marsh where the grass disturbs and slows the flow. Thus, before the dike, these fine sediments were carried through the channel and settled on the upstream marshes. However, with the existing dike, even with three gates open, the flow is not strong enough to resuspend most sediment during a normal tidal cycle. During a rainstorm and subsequent runoff events, silt and clay may be suspended according to Spaulding and Grilli (2001), but they will behave much like the fine sediment from the delta. To reiterate, these fine-grained particles will likely be deposited in the fringing marshes or offshore where flows are low and the water is calm enough to let the small particles settle. It is unlikely, even during a rainstorm, that these fines will settle on sand flats because the flow environment is too fast. In researching this study and talking to local shellfisherman, no one reported of siltation on shellfish beds after rainstorms.

Below the Dike

The Spaulding and Grilli study predicted that velocities would not exceed the threshold necessary to resuspend sediment above the dike. However, the study did not directly model flows below the dike. To address this subject of sediment transport below the dike, Dr. Spaulding used existing field data to assess the potential for velocities to reach the necessary 20 cm/sec. The flow velocity is determined by taking the peak volume of water per unit time that is passing through a unit area. This basically means, to figure out how fast the water can possibly flow below the dike, divide the greatest amount of water per second by the cross-sectional area of the river. Below the dike the peak flow under present conditions was measured to be 5-8 m^3 /sec; which was rounded to 10 m^3 /sec. Since the cross-sectional area is smallest just below the dike (measured in the field to be 500 m^2), this area was used because the velocities are fastest there (Figure 3.5).

So if: **Velocity = volume of water per unit time / unit area**

Then: **Velocity = (10 m^3 /sec) / 500 m^2**

Or: **Velocity = 0.02 m/sec (*2 cm/sec*)**

This calculation shows that peak velocities below the dike are a 10th of the 20 cm/s necessary to resuspend sediment. Spaulding and Grilli also point out that even during spring tides where 30% stronger velocities are expected, the threshold for resuspension will still not be approached. Even with all sluice gates open, which results

in a volume increase by a factor of three (2 cm/sec X 3), the velocities would still be just over a quarter of the 20 cm/sec needed (6 cm/sec). Keeping in mind that this is the maximum velocity, because it was calculated using the smallest channel cross-sectional area, velocities will decrease with distance and enlarging channel cross-sectional area, below the dike, reducing even further the possibility of moving any sediment. Thus, the hydrographic model predicts no re-suspension of sediment above the dike, while the above calculations show no sediment movement below it. Changes in sedimentation patterns, as a result of opening the dike, will be minimal and very near the structure. In order to further test this conclusion, a new study was performed focusing specifically on the portion of the Herring River below the dike.

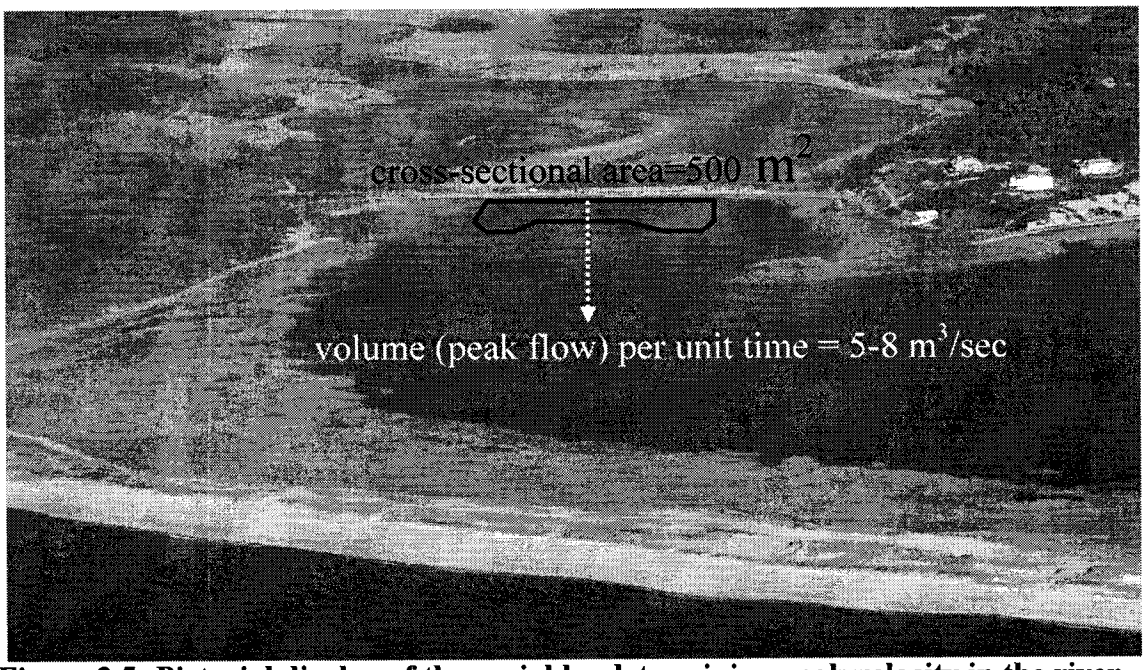


Figure 3.5: Pictorial display of the variables determining peak velocity in the river channel below the dike.

Methods

The approach was to map sedimentation patterns over time using historical data. The theory behind this approach is that by measuring the changes in sedimentation after construction of the dike, and during subsequent alterations to its configuration, it is possible to predict the response under similar or converse conditions. This is based on one of the major principles of geology: the present is the key to the past and the past is the key to the future.

Initially, historic aerial photos and coastal charts of the Herring River were acquired and scanned into digital form. When necessary these images were entered into a Geographical Information System (GIS) database and rectified. Once all of the images were geo-referenced or scaled, prevalent bedforms or channels were identified and mapped throughout time. From the changes in these large-scale features, long-term

transport trends were extrapolated. Upon completion of the remote sensing component, field data were collected to ground-truth the results. Detailed field data were collected on present day bedforms and grain-sizes exposed at low tide, as well as flow directions during tidal cycles. Whenever possible these observations were documented using digital photographs (Appendix C).

Data Analysis

The investigation of long-term sediment transport patterns utilized historic t-sheets, coastal topographic maps and air photos spanning the last century and a half. The data consist of a series of images displaying the intertidal bathymetry of the same lower portion of the Herring River proximal to the dike. In accordance with the change in the intertidal geomorphology, the years selected straddle major events in the dike operation and are indicated as such in the figure captions. This section is separated into two parts: aerial photography and coastal topographic maps.

Aerial Photography

In each of these sections an untouched digital image is shown as raw data and below is a blow up of the area analyzed for comparison. The shape of the main ebb channel has been interpreted and mapped as white or yellow dots on the analyzed sections.

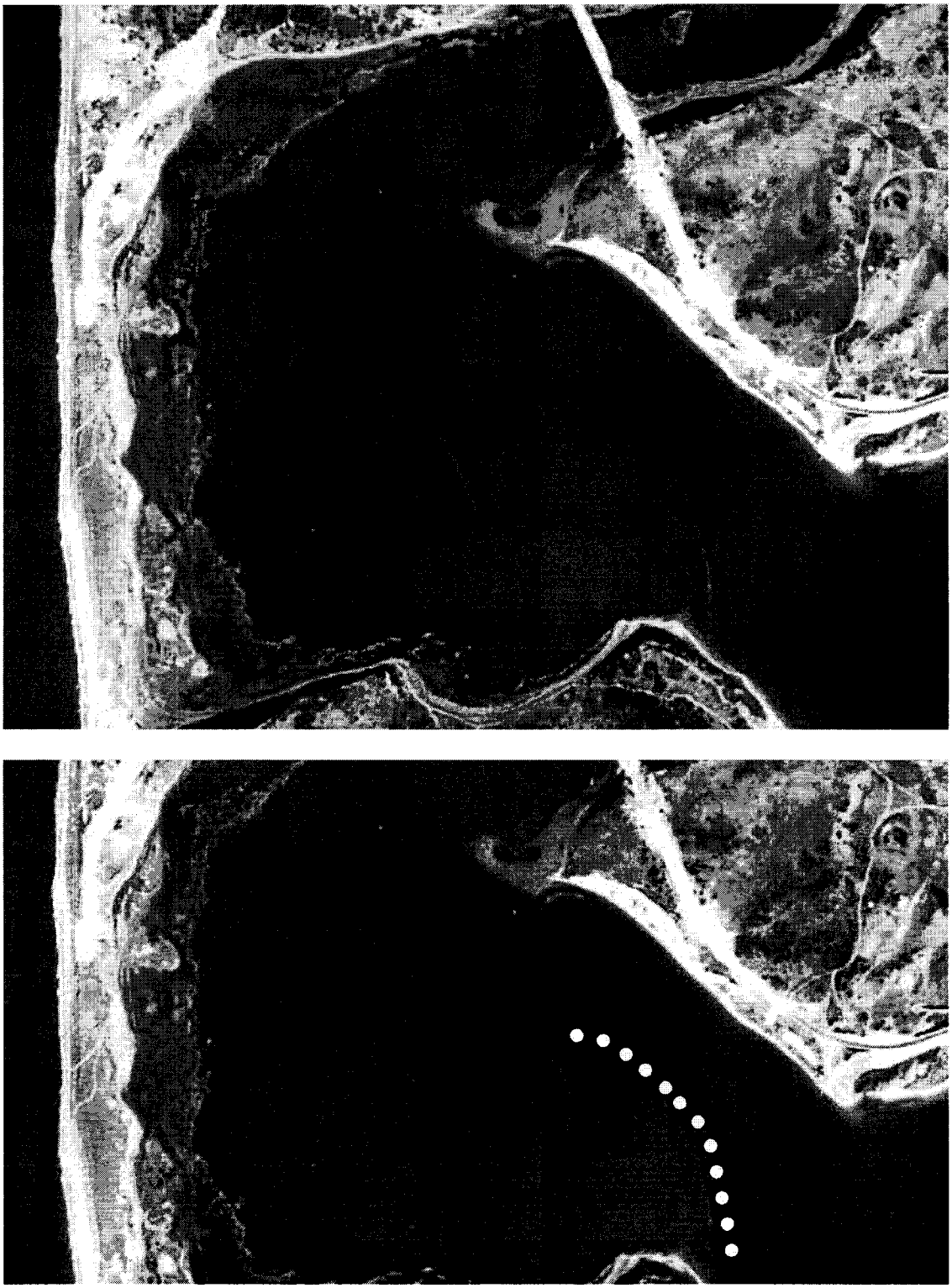


Figure 3.6: This is the first air photograph of Herring River taken in 1938, 30 years after the dike was constructed. It is hard to see what the configuration of the intertidal area is due to it being high tide, but you can make out what seems to be part of the main ebb channel marked by white (or yellow) dots.

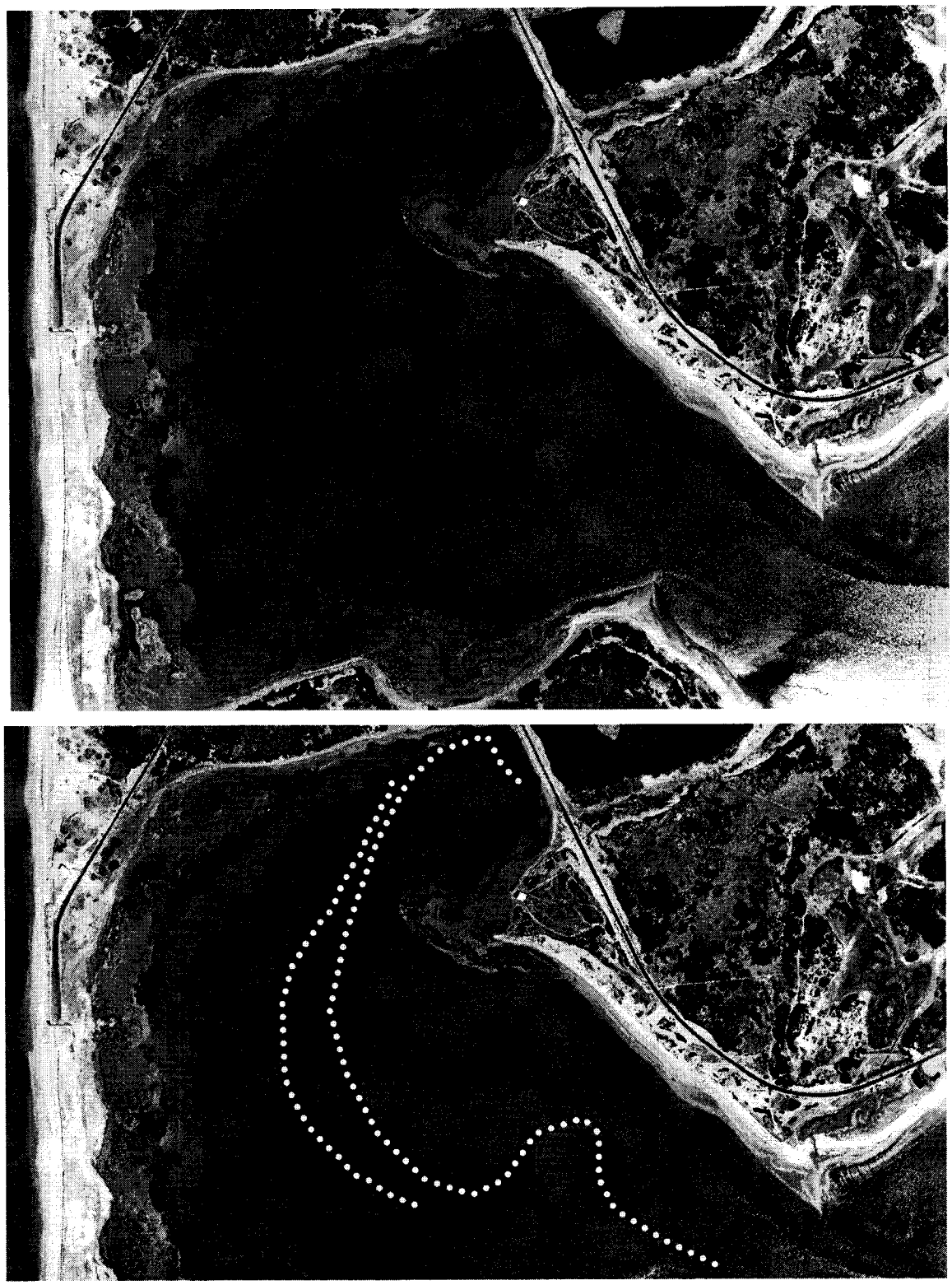


Figure 3.7: This 1960 air photo was taken at a slightly lower tide and you can start to see the whole length of the main ebb channel and the possibility of a second channel. For reference this is the last photo taken before the dike breach in 1968.

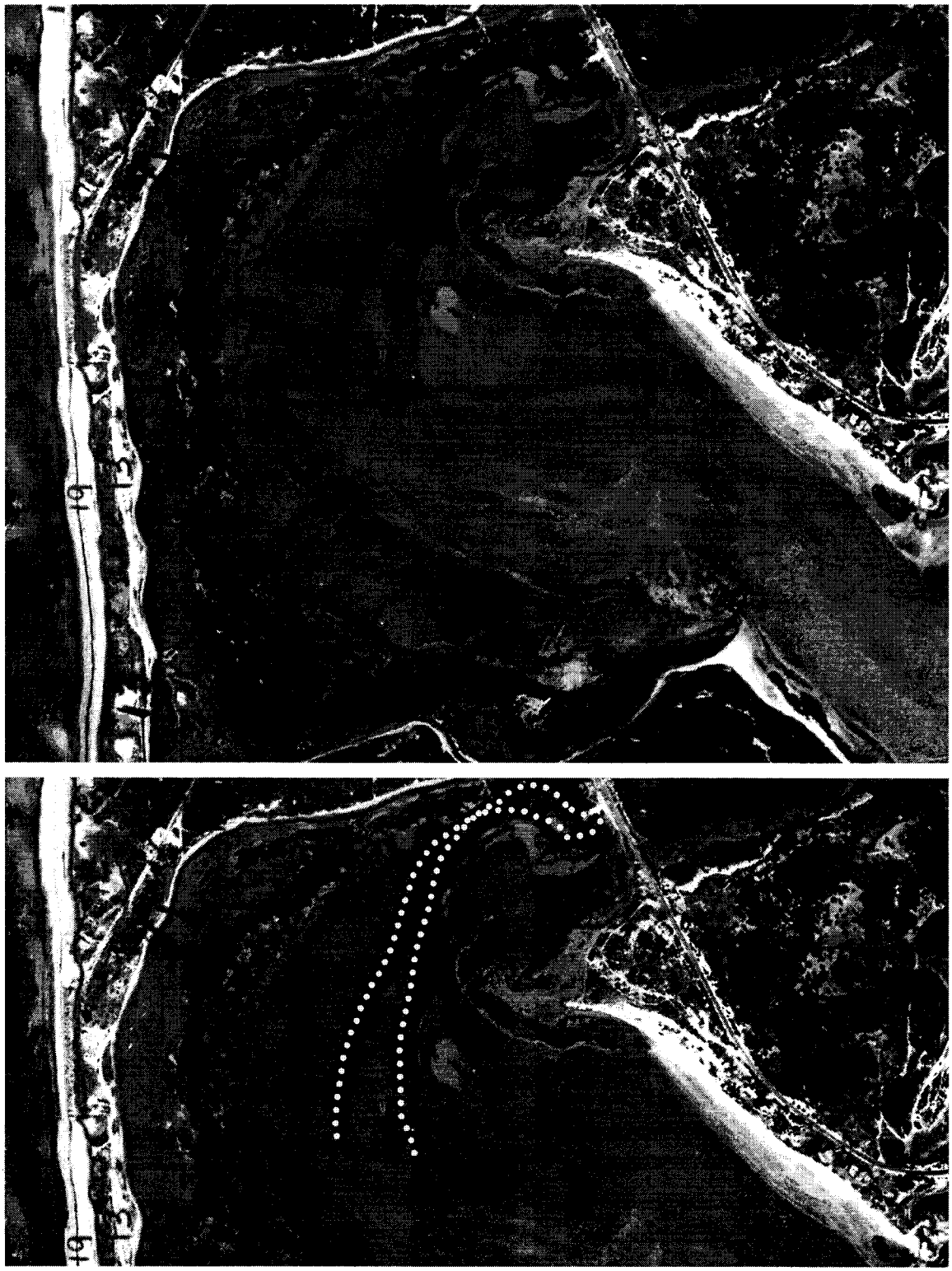


Figure 3.8: 1977 air photo taken just after the dike was rebuilt following the breach. This low-tide shot shows that the main ebb channel, while maintaining the same shape, actually splits in two just below the dike.

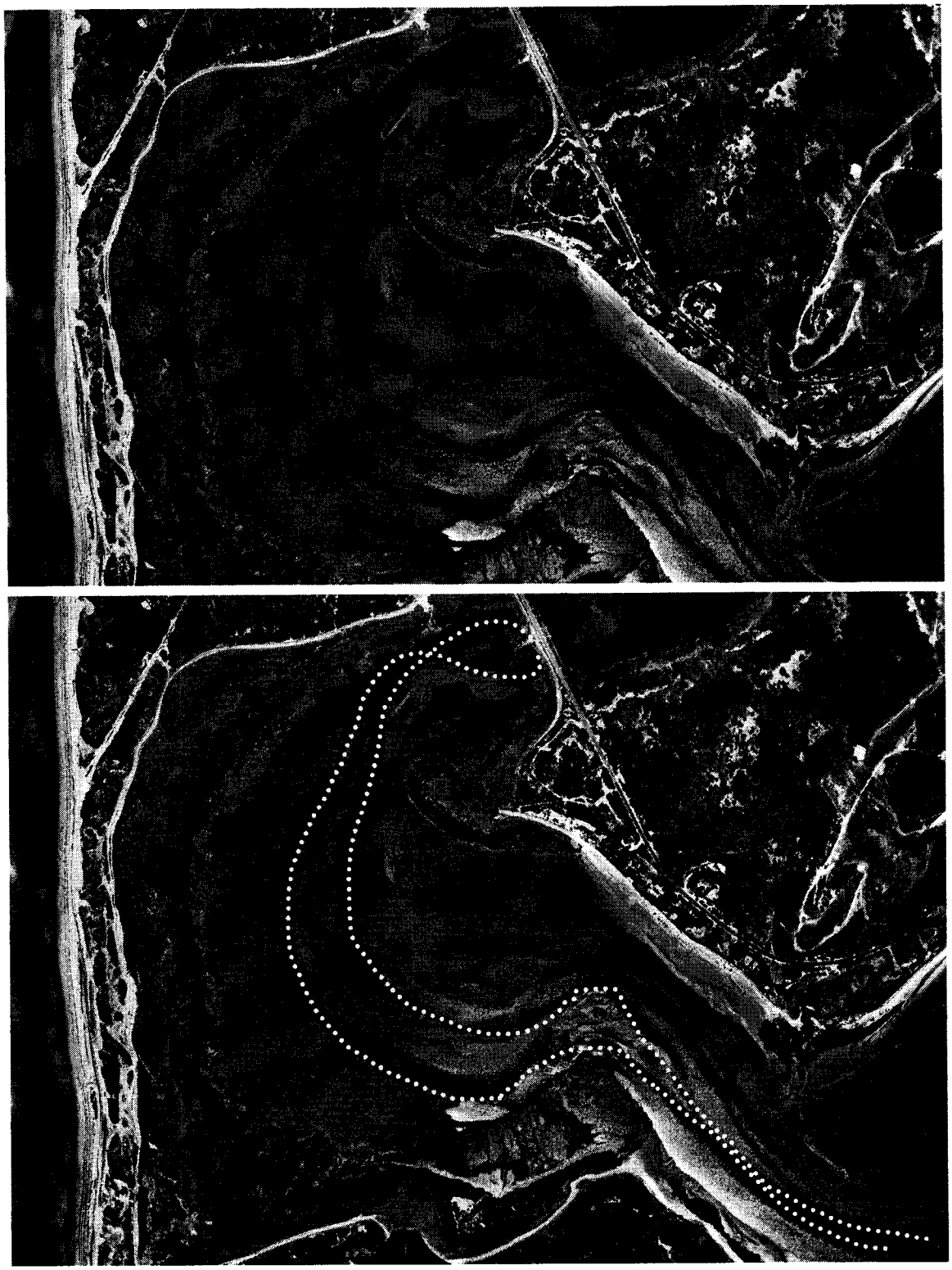


Figure 3.9: This 1987 air photograph, taken at the lowest tide in the series, shows the same main ebb channel morphology as the rest and also the split seen in 1977. This photo was taken over ten years after the dike was repaired following the breach.

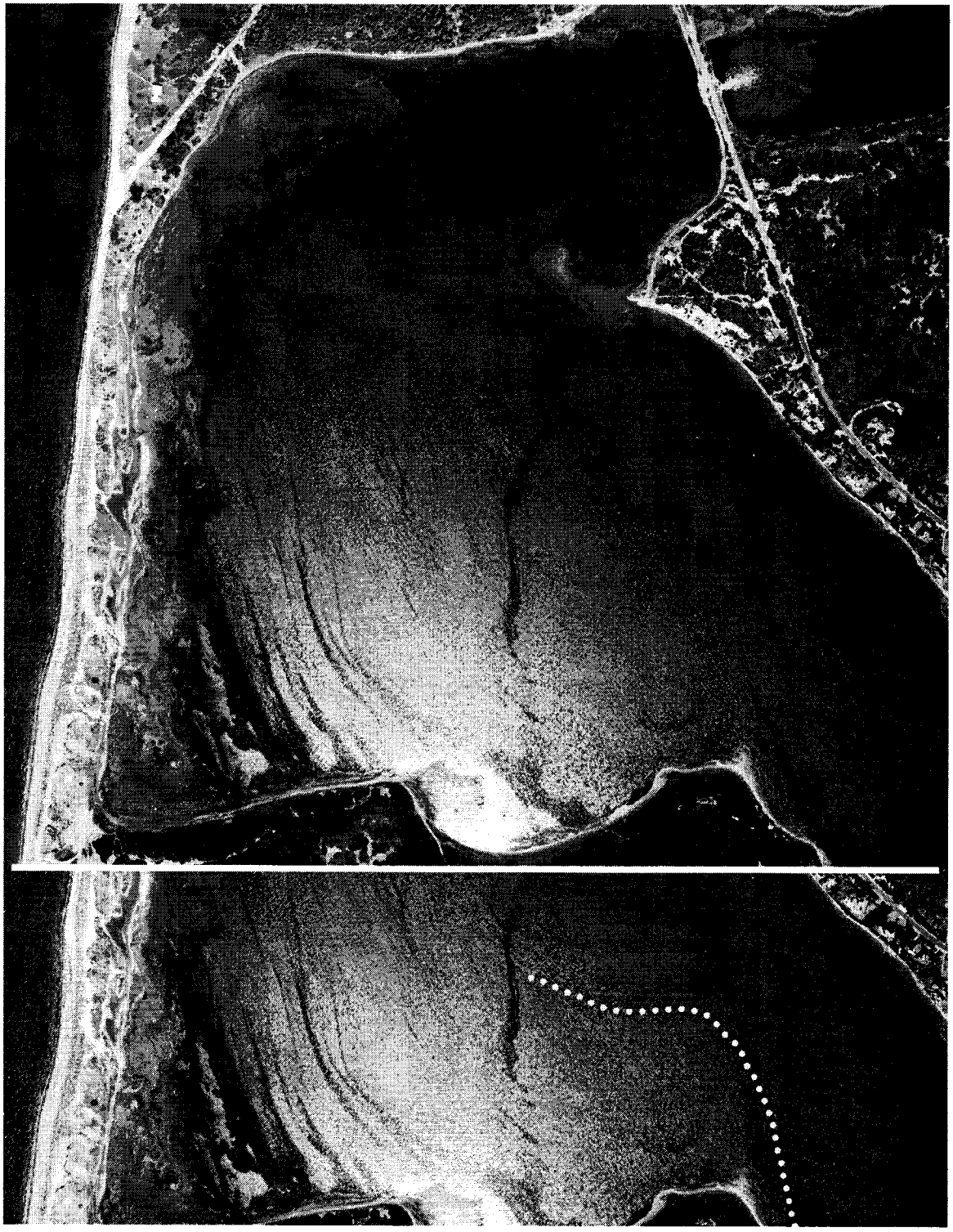


Figure 3.10: This 1991 air photo was taken at high tide, thus restricting the view of the intertidal morphology with the exception of possibly the lower channel like 1848 (Figure 3.13).

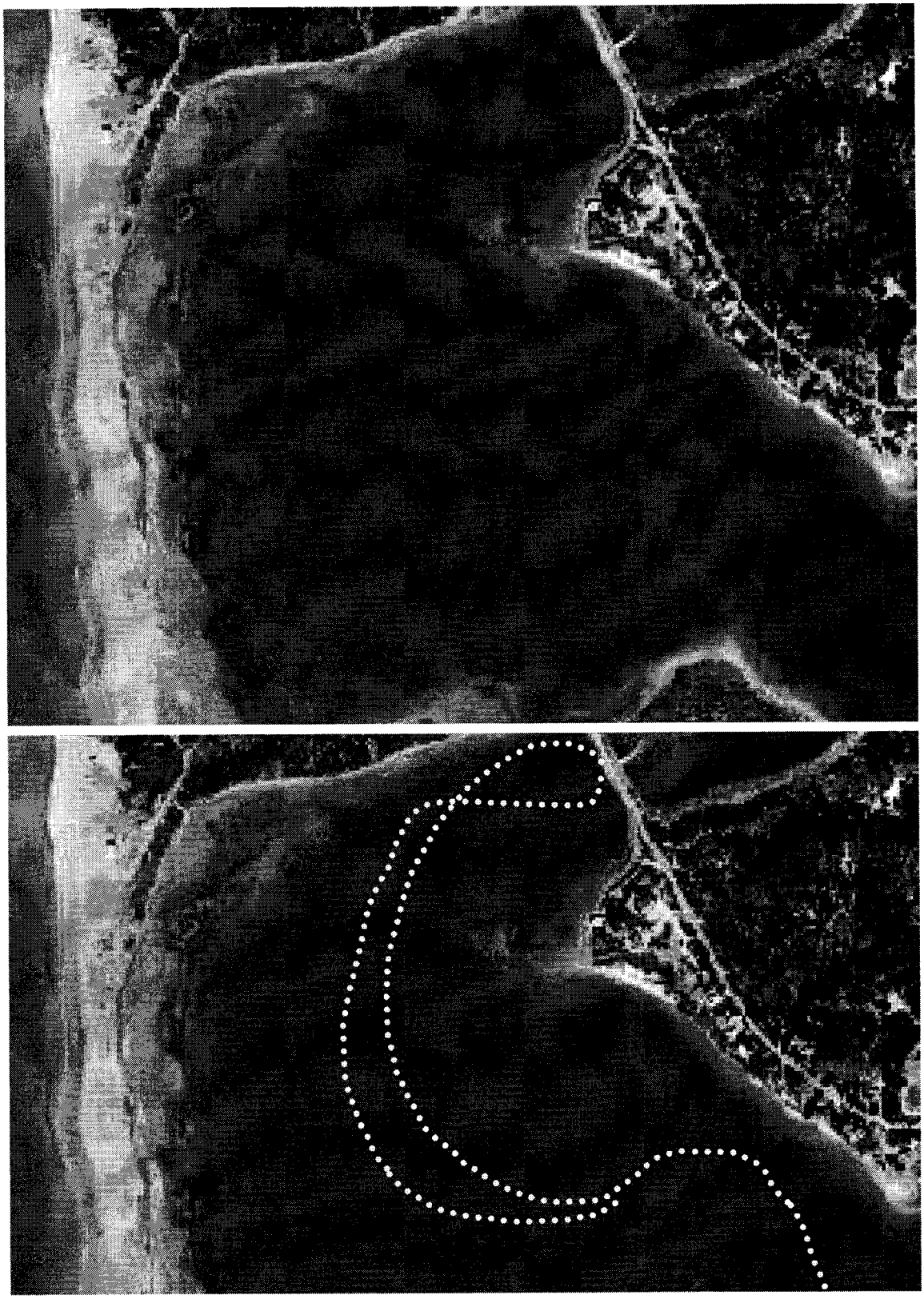


Figure 3.11: This 2001 air photo was taken at about mid-tide revealing the same configuration and faint impression of the duel channels as seen previously.

Coastal Topographic Maps (T-Sheets)

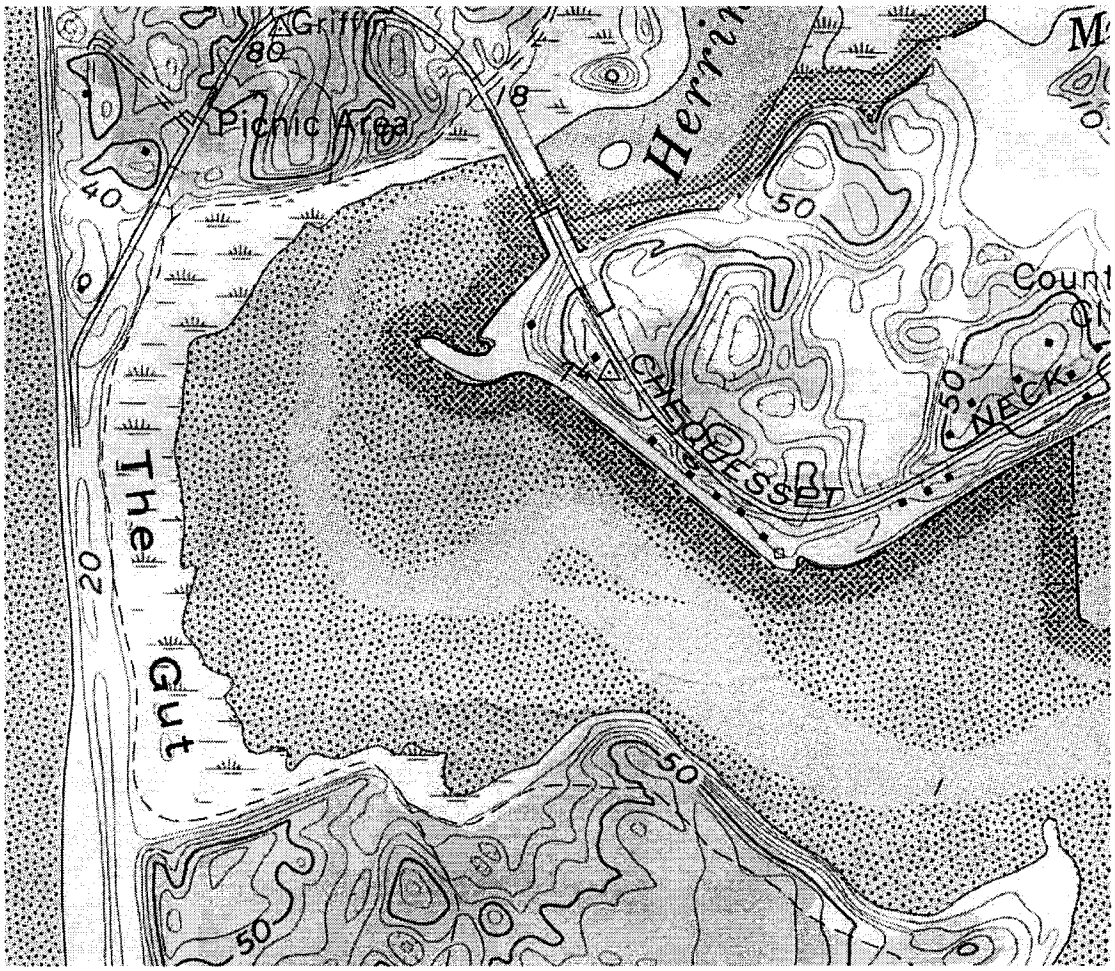


Figure 3.12: 1974 USGS topographic map showing the configuration of the intertidal bedforms in the stipple pattern. This depiction reveals the same main ebb channel geometry that was evident in the air photographs.

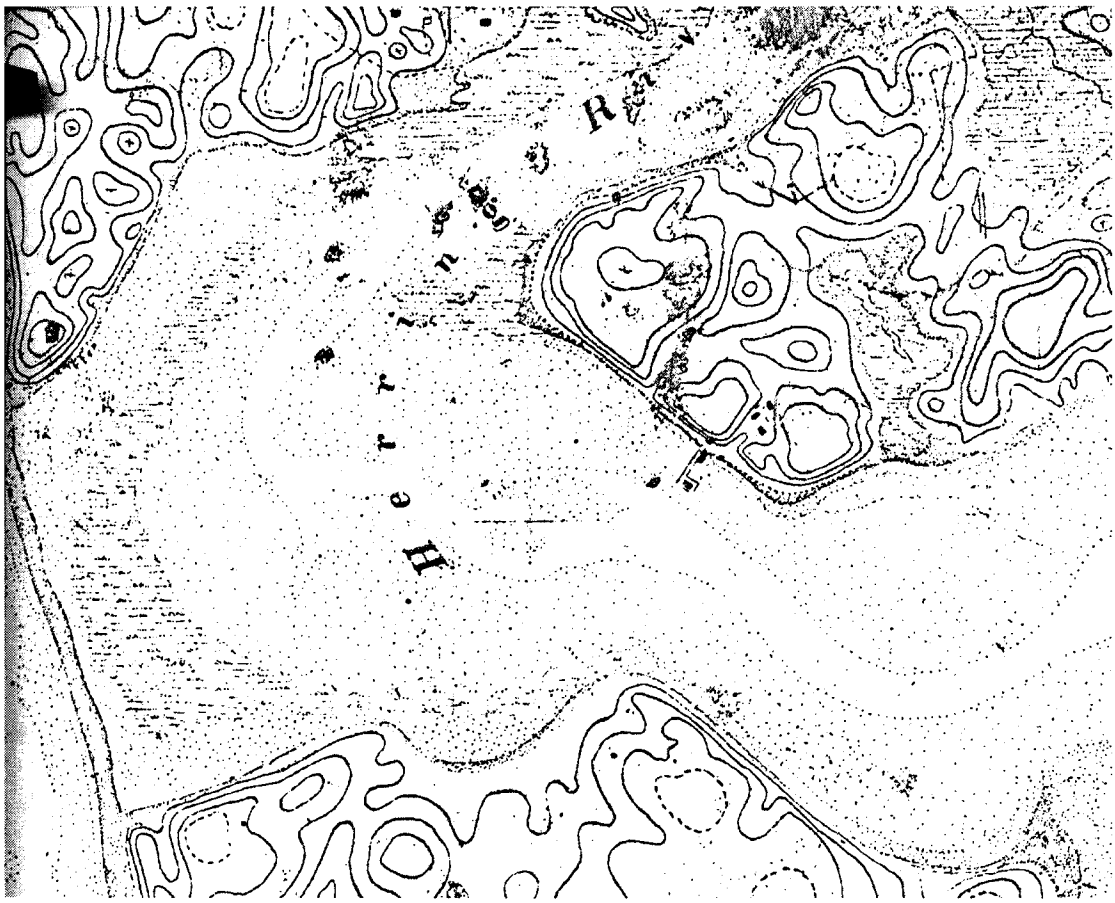


Figure 3.13: This t-sheet (coastal topographic map) from 1848 shows the intertidal morphology that existed prior to the dike's construction in 1908-1909. The configuration of the main ebb channel has the same s-shape geometry as the post-diked scenario depicted in the 1974 coastal chart.

Discussion

Despite difficulties in mapping sediment bedforms on some of the photos that were taken at high tide, historic photos are more than adequate to show the main ebb channel through time. The channel exists between intertidal flats; thus, mapping this channel through time is the same as mapping the extent of the intertidal flats. The aerial photographic time series shows that the visible parts, if not all, of the channel maintain a similar s-shaped geometry. At mid to low tide a split is evident around the ebb-tidal delta and then crosses and splits again just downstream of it. This geomorphic consistency indicates that no significant change in channel morphology has occurred since 1938. This period includes any changes in flow caused by the breach and subsequent repair of the dike in 1968 and 1975, respectively.

Coastal bathymetric surveys, referred to in earlier time as t-sheets, were used in order to study the shape of the actual intertidal flats themselves. These bedforms have been consistently mapped at low tide by the United States Geologic Survey. The most

recent of these maps was made in 1974 (Figure 3.12). By comparing the 1974 map to the aerial photograph closest to that time (1977) (Figure 3.9), it can be seen that the main ebb channels are identical in shape. Since the main ebb channel in 1977 appears to be the same in all the rest of the air photographs, the 1974 coastal chart is representative of the post-dike morphology in the intertidal region of the lower Herring River.

Even though no real change appears to have occurred after the installation of the dike, the question still remains as to whether original dike construction in 1909 affected sedimentation downstream. To address this question, an 1848 t-sheet / coastal topographic map was acquired (Figure 3.13) and compared to the 1974 map (Figure 3.12). This comparison revealed that despite the establishment of ebb-and flood-tidal deltas proximal to the dike, sedimentation did not change because of dike installation. Conversely, it is logical to predict that any future adjustment to the dike's configuration, including complete removal, would affect sedimentation very little and only very near to the dike itself. This lack of change in channel morphology and sedimentation below the dike is reasonable considering that the harbor's hydrodynamic regime (e.g. tidal range) was hardly affected by the emplacement of the Herring River Dike. In other words, any changes that have taken place below the dike have been minimal and are most likely a result of harbor dynamics that occur regardless of the dike's existence.

Real World Support for Discussion

Testimony about 1968 Breach in the Herring River Dike

In 1968 the sluice gate rusted out allowing an instantaneous, non-incremental, influx of salt water into the area just above the dike. This tidal flow continued for the following six years until the dike was repaired in 1975. During this period, there is no record of increased sedimentation onto areas of high shellfish production such as Egg Island. As part of this study, phone interviews were conducted with shellfisherman that were around during this time; they had no recollection of adverse sedimentation resulting from this breach. On the contrary, there were multiple reports of shellfish colonizing and thriving in the area around the dike with the increased tidal flow. A biologist for Coastal Zone Management, Gary Clayton, conducted a survey for the Commonwealth of Massachusetts that documented people's observations after the breach. The consensus was that the shellfish grew in the area around the dike and subsequently died after the dike was repaired (Figure 3.14 & 3.15).

This breach represents an opportunity to test the effects of opening the dike. With this perspective, it is logical to predict that if a sudden and large change in the tidal flow did not cause sedimentation on shellfish grants in 1975, then small and incremental changes would not initiate movement. These data support the conclusions of both this study and that of Spaulding and Grilli (2001). Additionally, the opening of this dike would initiate the return of the shellfish around the dike, and possibly even extend favorable habitat farther upstream.

With respect to concerns about sedimentation on Egg Island, the reality is that it is simply located too far away form the Herring River Dike to experience any change

associated with the restoration (Figure 3.16). Shellfisherman that worked Egg Island during the dike breach in 1968 report no change in sedimentation. That is not to say that sediment is not accumulating on Egg Island, but any change in the tidal flats is a result of tidal dynamics in the Harbor and Cape Cod Bay rather than any influence of the Herring River. Indeed, if we compare the configuration of Egg Island from 1848 to 1974 (Figure 3.17), it appears that little has changed. By virtue of the fact that sea level is rising on an average of 2.5 mm/year in this area, sediment must be accumulating on these intertidal flats to keep then from becoming subtidal. Thinking back to sediment movement along the Cape, which was discussed in the previous chapter, sand is moving southward along Wellfleet's Cape Cod Bay beaches. The sand that is not incorporated into the barrier beaches connecting the Wellfleet Harbor islands is carried either into the harbor or the bay. Looking at a sediment transport map (Figure 3.18), large bedforms, known as sand waves, indicate the direction that sand is moving. This movement is indicated on the map with arrows sized to represent the sizes of the bedforms. All of these arrows show that the net landward movement of sand is coming along Cape Cod Bay beaches and into the harbor. Close study of these bedforms suggests that over time these sand waves have been stationary, indicating that the harbor has reached an equilibrium in which the sediment transported into the harbor is simply keeping up, or building vertically (aggrading), with sea-level rise. It is the tidal forcing of bay and harbor, and not the Herring River, that shapes Egg Island and the rest of the intertidal flats in Wellfleet Harbor (Figure 3.19).

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DEPARTMENT OF THE ATTORNEY GENERAL
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DIVISION
Tel: (617) 727-2265

MEMORANDUM

TO: Gary Clayton, Biologist CZM

FROM: Bev Tangvik, Investigator Public Protection Bureau

DATE: March 20, 1979

RE: Herring River, Wellfleet

The following is a summary of telephone interviews with people who live and/or work near the Herring River in Wellfleet. The interviews were conducted to document personal observations and experiences of environmental alterations in the saltmarsh, shellfish and alewifes which they feel are attributable to the new tidal gate in the Herring River Dike.

1. Alton Atwood - Oysterman and member of the Shellfish Advisory Committee. He has lived and worked near the Herring River all his life. Since the new tidal gate was contructed he has observed that the oyster beds have been covered with mud on the Bay side. Before the dike was built the mud was washed away.

2. Steven Kozelka - Chairman of the Shellfish Advisory Committee. He has lived near the Herring River for four years. His observations describe the changes in the shellfish. There are no longer shellfish west of the dike and the area down toward the bay. He attributes this to silting on both sides of the dike. He has seen a reduction in growth rate of the oysters due to less feed coming down river. He believes the dike is detrimental to shellfish in the harbor as well, due to the reduction in feed.

Figure 3.14: Page #1 of interviews conducted by the Commonwealth of Massachusetts that clearly state that shellfish, which colonized after the dike breached, were subsequently silted over when the dike was repaired.

3. Russell Swart - Shell fisherman and member of the Shellfish Advisory Committee. He has lived and worked near the Herring River since 1972. He has observed changes in the shellfish during this time. When the gate was in need of repair in the early 1970's shellfishing was great with lots of shellfish on both sides of the dike. After the dike was fixed all the oysters and steamers died. The river is silting in on the salt water side.

He doesn't believe there were many herring this year.

4. Michael Parlenti - Shellfisherman and member of the Shellfish Advisory Committee. He has lived and worked near the Herring River all his life. His observations are focused on the changes in the shellfish in the area. Before the dike was repaired there were a lot of shellfish on both sides of the dike, but there has been a decline in the shellfish since the reparation of the dike. Since the dike was repaired there has been a reduction in tidal flow causing a decline in food on the salt side. When the dike went under repair sand was placed around the dike and this sand killed the shellfish. Is this my or rebuilt?

He believes the herring in the river are about the same, maybe a little less.

5. Wilber Rockwell - Member of the Conservation Commission. He was Selectman for five years, retired Spring 1978. He believes there has been no detrimental effects to the alewifes with the new dike relative to the old dike and the time when the dike was in need of repair. He observed during the time the dike was in need of repair that trees were killed in the surrounding area due to the two foot difference in water elevation.

Figure 3.15: Page #2 of interviews conducted by the Commonwealth of Massachusetts that clearly state that shellfish, which colonized after the dike breached, were subsequently silted over when the dike was repaired.

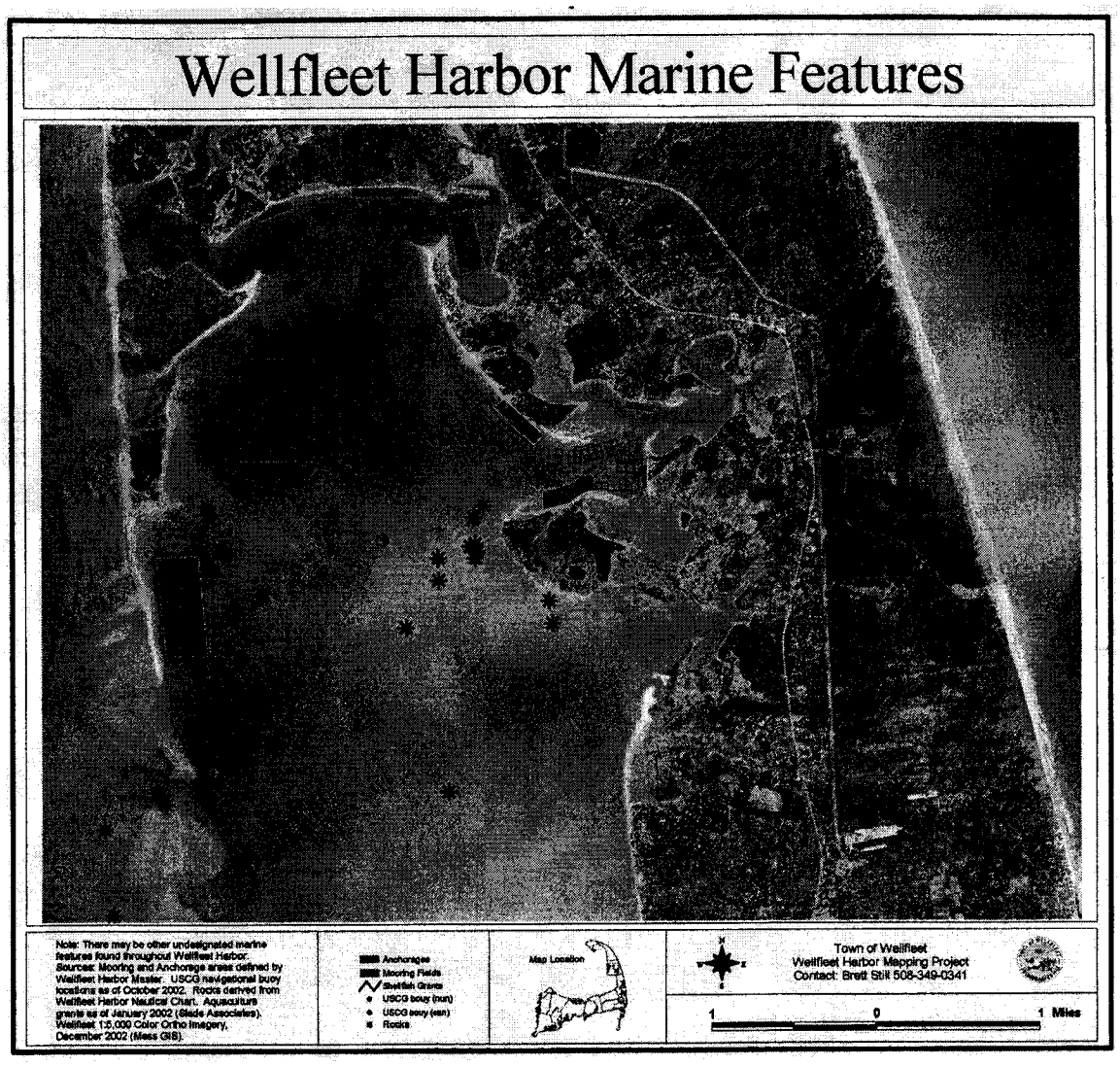

Figure 3.16: Location map of Wellfleet Harbor marine structures showing that the closest shellfish grant is over a mile away from the Herring River Dike.

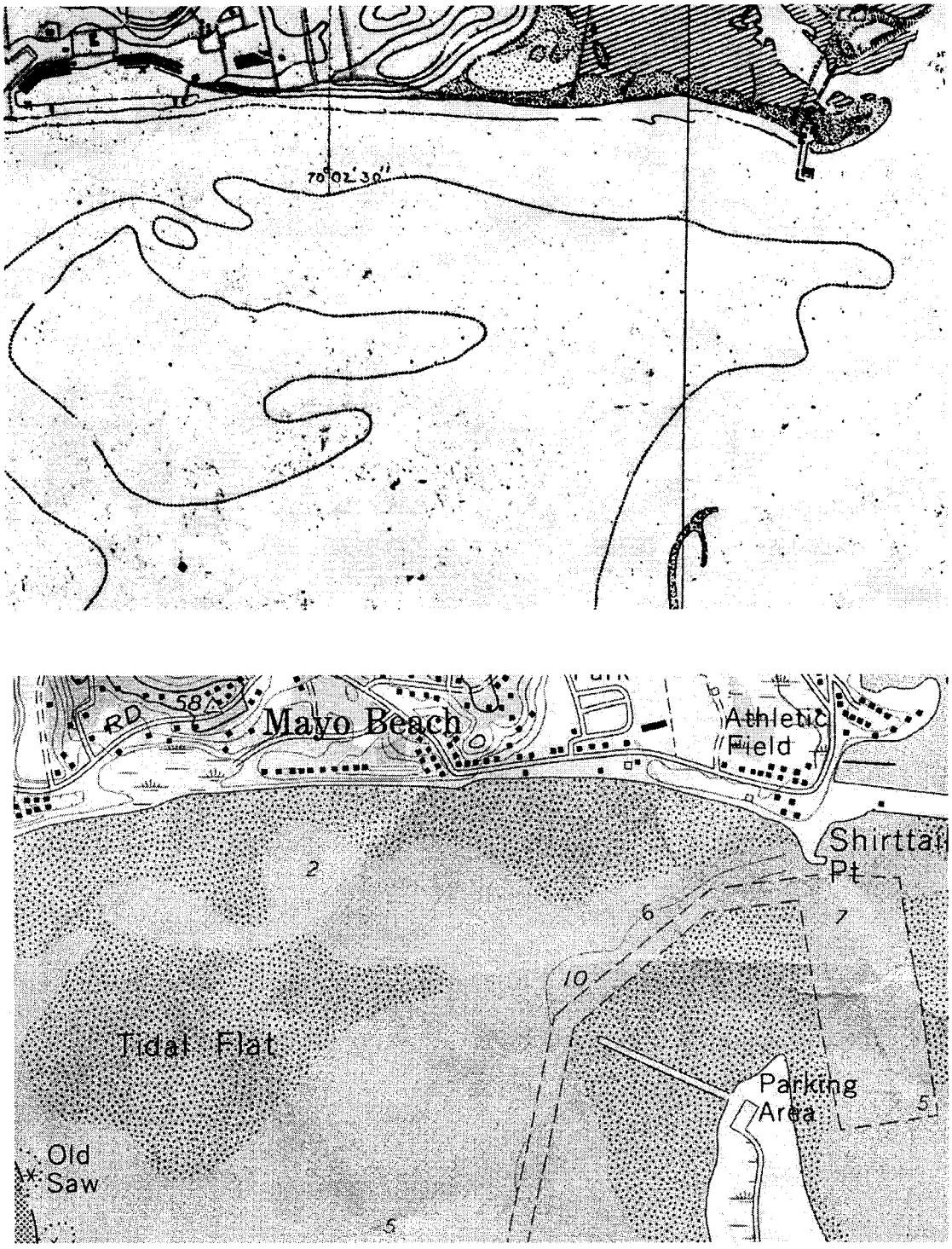

Figure 3.17: Comparison of maps from 1848 and 1974 in the area of Egg Island and the northeast part of Wellfleet Harbor reveals similar intertidal morphologies.

Figure 3.18: Sediment transport map of Wellfleet Harbor that shows the dominant direction of transport is from Cape Cod Bay up into the Harbor and Herring River.

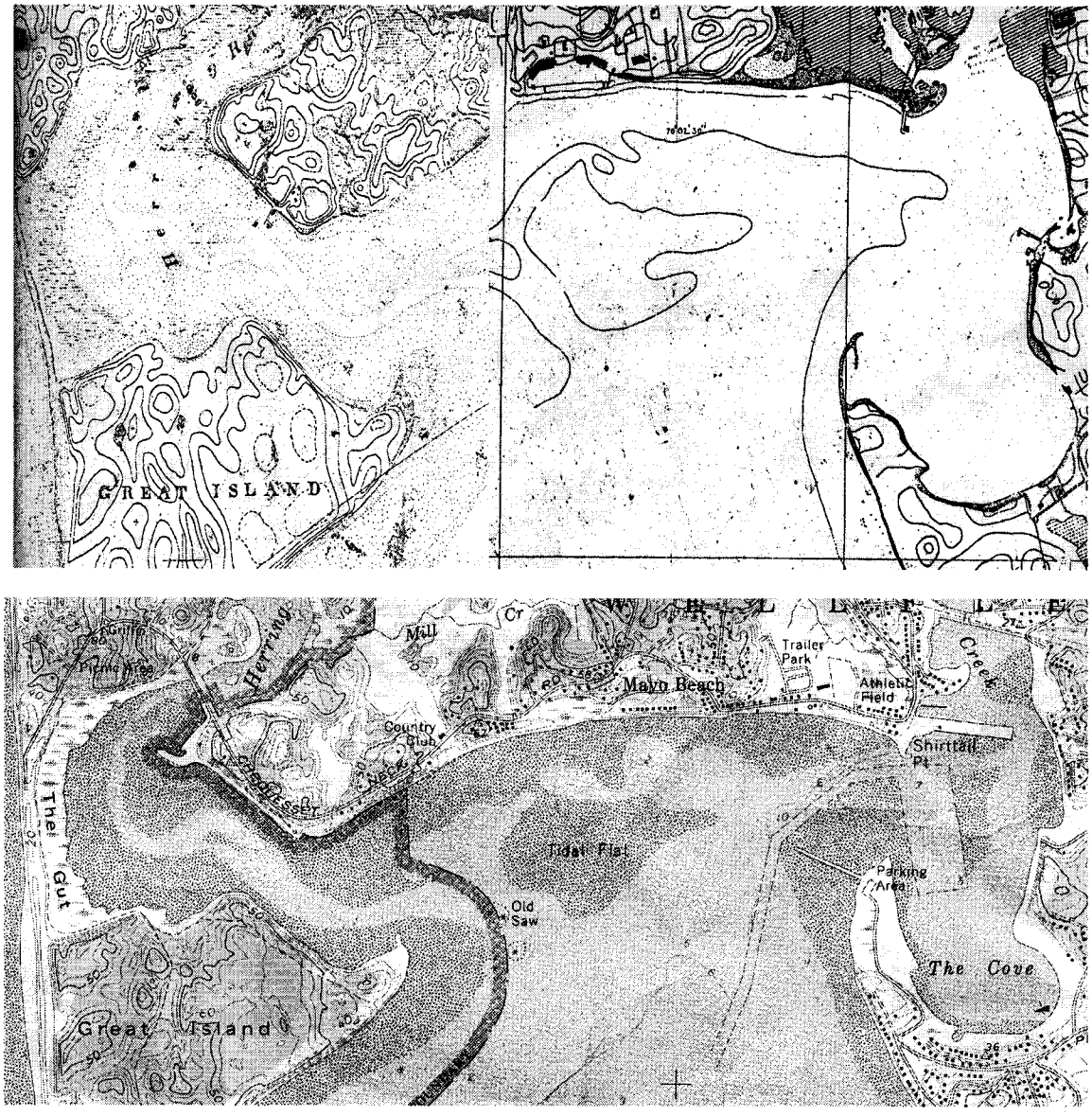

Figure 3.19: Comparison of coastal topographic maps of Wellfleet Harbor from 1848 and 1974 shows similar intertidal morphology over the past 155 years.

Sedimentation Study of Hatches Harbor Restoration

Since March of 1999 portions of the Hatches Harbor flood plain, diked in 1930, have been undergoing incremental restoration of tidal exchange. As part of a large scale monitoring program associated with the restoration, sedimentation within the system was studied from 1997 to present, with the most recent data collection occurring in 2003 (Portnoy et al., 2004).

In order to measure sediment accumulation, nine Sediment Elevation Tables (SETs) were used. SETs allow accurate and repeated measurements of both sediment accretion and/or loss on the marsh surface. Three of these SETs are located below the

dike in the unrestricted marsh, whereas six are above the dike in the restricted marsh (Figure 3.20). Of the six located above the dike, three are near the dike structure and three are located farther away. Looking at a graph of the data for the unrestricted marsh (Figure 3.21), there is a 3 mm/year accumulation of sediment within the marsh, compensating for the local rate of sea-level rise. However, the graph of all the data from the restricted marsh shows considerably more sediment accumulation above the dike (Figure 3.22). This increased upstream accumulation is a result of the dominance of landward sediment transport, just what is predicted for Herring River in the event that it undergoes restoration.

Focusing on sedimentation within the restricted area, the accumulation of sediment near the dike is similar to that of the unrestricted marsh (Figure 3.23), whereas highest sedimentation is occurring in the far reaches of the restricted system (Figure 3.24). The dynamics are similar to the Herring River during its breach. The water flowing through the dike is confined and moving too quickly to allow any sediment to be deposited. However, when the water reaches the upper portion of the stream and slows, fine-grained sediment can settle out of the water column. Indeed this is what happened when the Herring River dike breached in the late 1960s and explains the colonization by shellfish and their subsequent death following the dike's repair. Increased flood currents, caused by the deterioration of the tide gates, moved the fine-grained sediment coming from Cape Cod Bay past the dike and up into the marsh. In rebuilding the dike structure, tidal flow was again restricted and the fine grains that would have been carried into the far reaches of Herring River were deposited directly above and below the dike, thus covering the shellfish that had colonized since the breach. The Hatches Harbor SET data support the idea that increased tidal exchange at Herring River will shift sediment deposition from the vicinity of the dike to farther upstream, to the benefit of recolonizing shellfish.

Figure 3.20: Location of Sediment Elevation Tables (SETs) located within Hatches Harbor (Portnoy, Gwilliam & Smith, 2004).

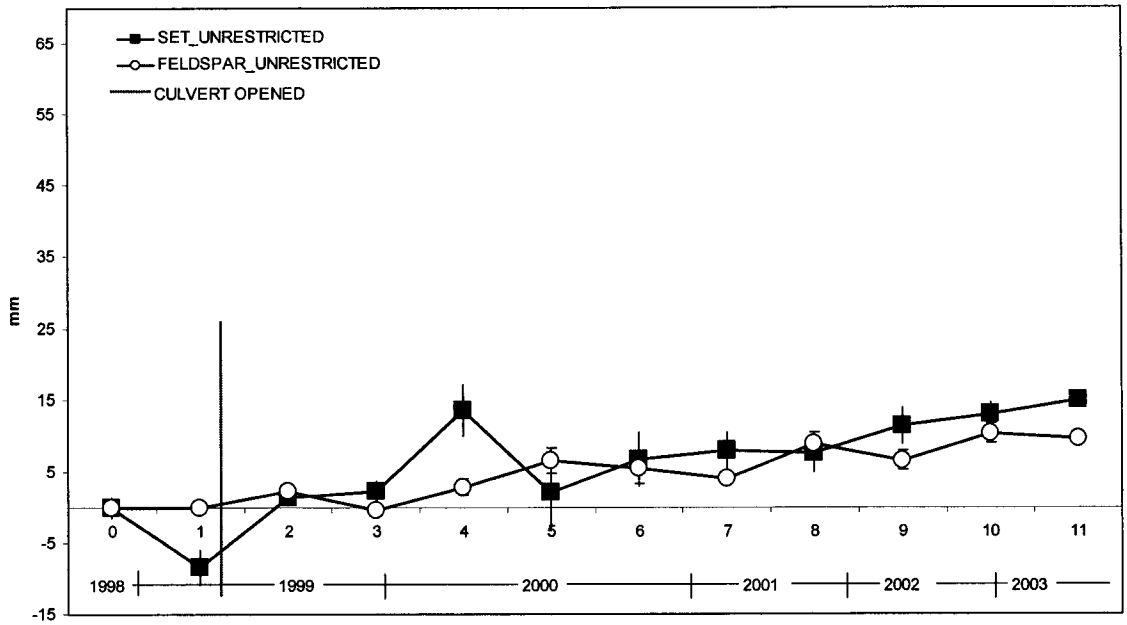

Figure 3.21: Trends in sedimentation as measured by sediment elevation tables (SETs) and feldspar horizons at Hatches Harbor in the unrestricted marsh below the dike. This shows a small increase in sediment deposited within the marsh, commensurate with sea-level rise. (Portnoy et al., 2004)

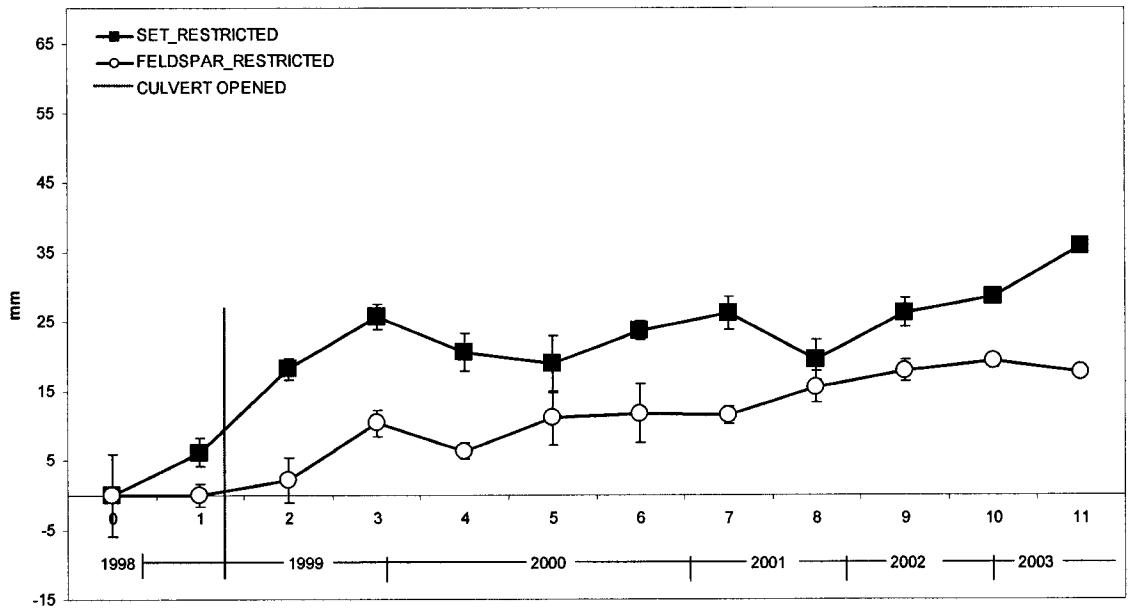

Figure 3.22: Trends in sedimentation as measured by sediment elevation tables (SETs) and feldspar horizons at Hatches Harbor in the restricted marsh above the dike. With tidal restoration, sedimentation above the dike has exceeded that measured in the unrestricted marsh downstream (Portnoy et al., 2004).

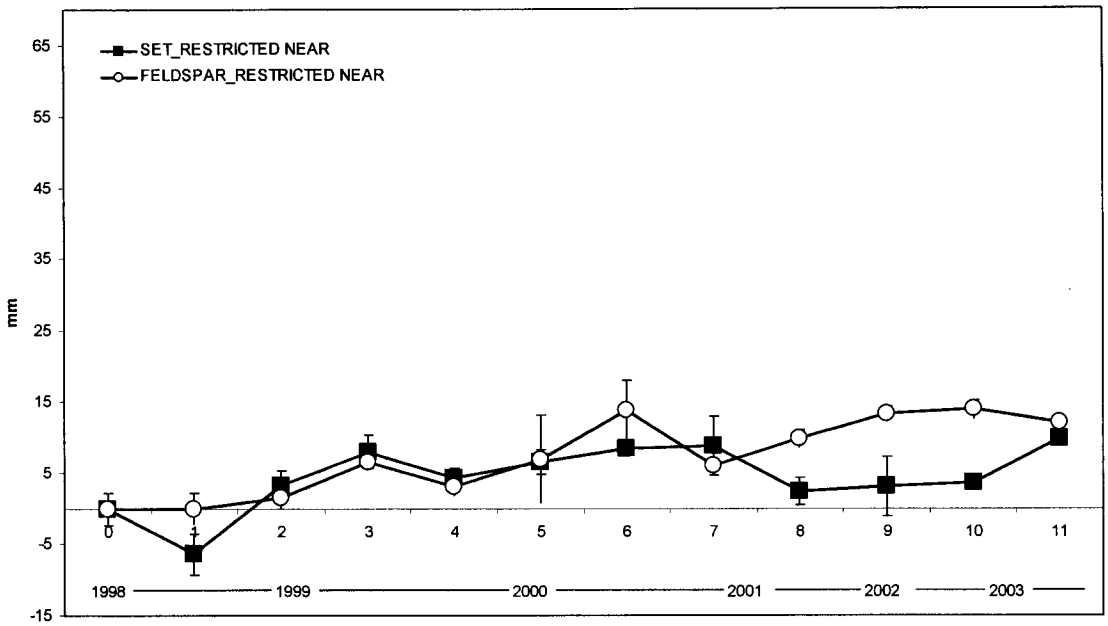

Figure 3.23: Trends in sedimentation as measured by sediment elevation tables (SETs) and feldspar horizons in the Hatches Harbor restricted marsh directly above the dike. These data show that accumulation rates just above the dike are similar to those just below. (Portnoy et al., 2004)

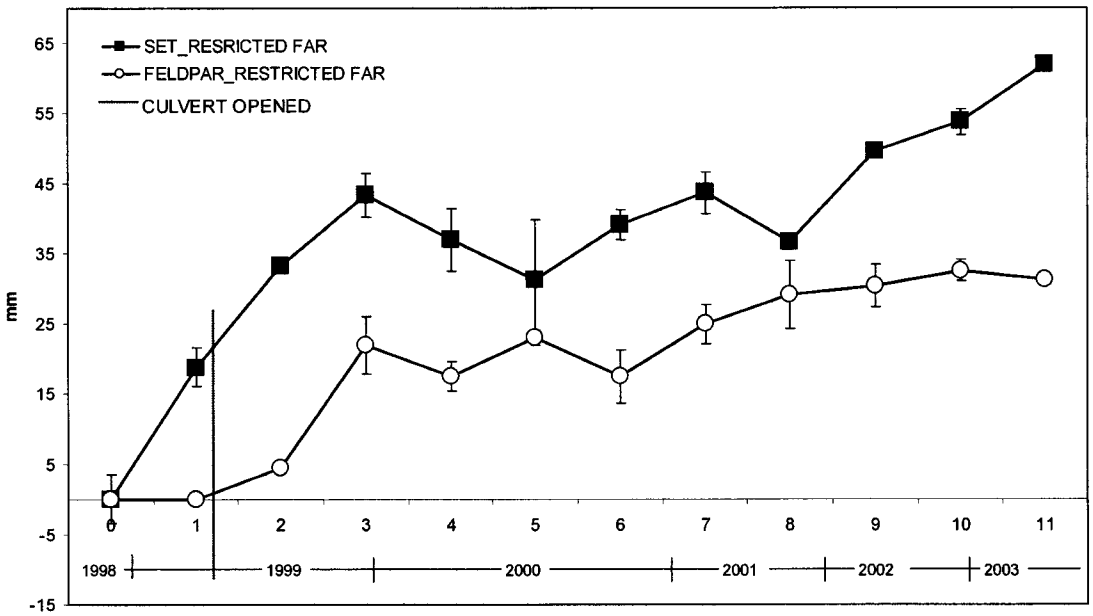

Figure 3.24: Trends in sedimentation as measured by sediment elevation tables (SETs) and feldspar horizons in the Hatches Harbor in the restricted marsh farther upstream of the dike. These data show that the majority of the sediment is being deposited farther upstream from the dike. (Portnoy et al., 2004)

Recommended Sediment Monitoring for Herring River

Current annual monitoring of sedimentation on the marsh surface (SETs, see above) below the dike at The Gut, in *Phragmites* below High Toss Road, and in the drained marsh above High Toss Road will continue as part a Park-wide program. Since these SETs focus solely on sedimentation within the marsh, monitoring of intertidal flats below the Herring River dike is proposed specifically to address concerns for sedimentation of shellfish beds. The objective of sedimentation monitoring on shellfish beds is to assess whether dike opening affects sediment quality on downstream intertidal flats used for shellfish culture. A suggested protocol follows:

1) Identify areas of concern to shellfishermen and Town resource managers. These will include shellfish beds closest to the river mouth, including the Town propagation area and Egg Island, but also should include reference (or control) sites. Reference sites, at sufficient distance from the Herring River Dike so as to be unaffected by river flow, are important to separate Harbor-wide sedimentation from river effects.

2) Randomly, i.e. without bias, establish sampling plots on the above-selected areas of concern, and use GPS to find them and to record their locations.

3) Prior to any dike openings and at least annually thereafter, collect the top 5 cm of sediment from each station (e.g. 3-inch diameter cores). Monitoring should ideally occur during the spring, winter and fall of each year, to account for seasonal differences.

4) Section the cores into 1-cm strata and analyze for grain size and organic content.

5) Compare sediment quality over time and among study sites, including reference areas.

Figure 3.25: Enlarged version of hard structure map (Figure 3.16), focusing on the location of shellfish grants.

Conclusions

- Hydrodynamic models by Spaulding and Grilli in 2001 indicate that velocities above the dike, with all gates open, would be half that required to resuspend sediment.

- Calculations show that maximum flow velocities below the dike, with all gates open, will be just over a quarter (6 cm/sec) of the 20 cm/sec necessary to resuspend sediment.

- Geomorphic analysis of the intertidal area below the Herring River Dike shows almost no change over the past 155 years, with the exception of the formation of a small ebb- and larger flood-tidal delta. Otherwise, channel morphology below the present dike was the same before dike construction in 1909 as it is today; the dike has had little effect on downstream sedimentation.

- The predicted change in sedimentation, as a result of restoring tidal flow to the Herring River, would be minimal and proximal to the dike.

- Data from both the 1960s breach and from Hatches Harbor sedimentation not only support this prediction, but also indicate that the resulting changes around the dike will improve sedimentary conditions shellfish repopulation.

Results of Interviews

The first step, aside from background and previous studies research, was to amass a list of questions and concerns from shellfishermen with respect to sedimentation along the Herring River. A list of contact names was generated by speaking with various people in the Town of Wellfleet and Cape Cod National Seashore. Over the course of a two-week period several attempts to call every person on the list were made (Appendix A). After a standard introduction and statement of purpose for the phone call, the person was asked if he/she was willing to discuss their feelings on the issue. The following was the standard introduction:

> "Hi my name is Amy Dougherty and I am a geologist working with the Association of Women Geoscientists and Cape Cod National Seashore. I am performing a study related to sedimentation concerns associated with the potential restoration of the Herring River. Would you mind sparing a moment to talk?"

Several fishermen started their response by saying that they do not have any concerns related directly to sedimentation, but then went on to pose other concerns related to the restoration project. Since these questions are outside the investigator's area of expertise, and thus outside the scope of this study, they are not directly addressed in this report. However, due to the prevalence of these lingering concerns a list was compiled of the most prominent and recurring questions. This list, along with a log of detailed notes typed after every conversation, can be found in Appendix A.

From the various conversations it became evident that two major questions pertaining to sedimentation existed:

1) Does opening the Herring River Dike affect the stability of The Gut?
2) Does opening the Herring River Dike affect sedimentation below (seaward of) the dike?

Of the shellfishermen who expressed sedimentation concerns during the interviews, every one voiced both of these questions; therefore, they are the focus of this study. The following Chapter II will discuss the relationship between the stability of The Gut and the Herring River. Chapter III will detail a study performed specifically on sedimentation below the Herring River Dike. Chapter IV summarizes the conclusions found in previous chapters.

Defining Local Concerns Regarding Sedimentation

After the survey for previous relevant studies, the next step was to define clearly the questions and concerns of Wellfleet officials and shellfishermen with respect to sedimentation along the Herring River. The author first generated a list of contacts among people who had extensive local knowledge of Wellfleet's shellfish resources and their harvest. In informal conversations with these people, two major questions emerged pertaining to sedimentation:

3) Does opening the Herring River Dike affect the stability of The Gut?

4) Does opening the Herring River Dike affect sedimentation below (seaward of) the dike?

Every shellfishermen who expressed sedimentation concerns voiced both of these questions; therefore, this study assesses both questions in depth. Chapter II discusses the relationship between the stability of The Gut and the Herring River. Chapter III details a study performed specifically on sedimentation below the Herring River Dike. Chapter IV summarizes all study findings.

CHAPTER 4

CONCLUSIONS

The Stability of the Gut and Its Relationship to the Herring River

- The continued stability of The Gut is dependent on the same two factors that governed its formation: 1) sand supply and 2) sea-level rise.
- The Gut influences the Herring River rather than vice versa as evidenced by:
- The large meander or bend in the river that occurred as a result of The Gut's formation, that forced water to flow south through the harbor.
- The existence of wide mudflat on either side of the main ebb channel present even before the dike was constructed, indicative of low ebb-flow velocities from the river.
- It is unlikely that The Gut would breach and form a permanent inlet due to the extensive marsh backing this barrier beach. If a large storm were to cause erosion along The Gut, a temporary washover may occur; however, natural post-storm rebuilding processes would quickly close it.
- Foot traffic across the dune system has worsened erosion and increased the possibility of a blowout. The Town of Wellfleet, Cape Cod National Seashore and volunteers are taking action to repair and limit this damage.

Sedimentation in the Lower Herring River

- Hydrodynamic models by Spaulding and Grilli in 2001 indicate that velocities above the dike, with all gates open, would be half that required to resuspend sediment.

- Calculations show that maximum flow velocities below the dike, with all gates open, will be just over a quarter (6 cm/sec) of the 20 cm/sec necessary to resuspend sediment.

- Geomorphic analysis of the intertidal area below the Herring River Dike shows almost no change over the past 155 years, with the exception of the formation of a small ebb- and larger flood-tidal delta. Otherwise, channel morphology below the present dike was the same before dike construction in 1909 as it is today; the dike has had little effect on downstream sedimentation.

- The predicted change in sedimentation, as a result of restoring tidal flow to the Herring River, would be minimal and proximal to the dike.

- Data from both the 1960s breach and from Hatches Harbor sedimentation not only support this prediction, but also indicate that the resulting changes around the dike will improve sedimentary conditions for shellfish repopulation.

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APPENDICES

APPENDIX A: Synopsis of Non-sedimentation Questions that Still Linger

List of Questions

Notes from Phone Conversations with Shellfisherman

APPENDIX B: Gut Photos

Mosaiced Panoramic

Mosaiced Pictures

Individual Photos

APPENDIX C: Herring River Photos

Fly Over Photos

Mosaiced Panoramic

Mosaiced Pictures

Individual Photos

APPENDIX D: Presentations and Articles

The State of the Wellfleet Harbor Conference Poster

Article in the Provincetown Banner

Article in the Cape Codder

Shellfish Advisory Board Power Point Presentation

Conservation Commission Meeting Power Point Presentation

Due to size and amount of information contained with in these appendices, they are located in digital form on the accompanying CD.

AMY JENNELLE DOUGHERTY

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Cape Cod National Seashore
99 Marconi Site Road
Wellfleet, MA, 02667

Permanent Address:
112 Villanova Road
Glassboro, NJ, 08028

EDUCATION

University of Auckland, Auckland, New Zealand
Accepted to Ph.D. program with a focus Coastal Geology
*Awarded University of Auckland International Doctoral Scholarship (2004-07)

Boston University, Boston, Massachusetts
Degree: Master of Arts, September 2002. GPA: 3.98/4.0
Concentration: Coastal Geology (Earth Sciences)

Union College, Schenectady, New York
Degree: Bachelor of Science, June 1997. GPA: 3.1/4.0
Major: Geology & *Minor:* Environmental Studies
*Gilligan Scholar: academic based athletic scholarship for basketball (1993-97)
*Dean's List (1996-97)

ACADEMIC ACCOMPLISHMENTS

Masters Thesis, 1998-2002
Title: Deciphering the Origin and Evolution of Castle Neck Barrier, Massachusetts

- Presented offshoot research from my thesis at the Coastal Sediments Meeting 2003, Clearwater FL.
- Presented part of research at the National Geological Society of America (GSA) Meeting 2001, Boston, MA.
- Presented part of research in a special section of the American Geophysical Union (AGU) Spring Meeting 2001, Boston, MA.
- Presented part of research at the Northeast Region Geological Society of America (GSA) Meeting 2000, New Brunswick, NJ.
- Awarded a research grant from Geochron's Kruger Labs, 2000.
- Awarded a research grant from the Geological Society of America, 2000.

Independent Research Project at M.I.T., 1997-1998

- As part of an ongoing study to better understand evolution of the Himalayan Orogen, I dated movement on the South Tibetan Detachment System using High precision $^{40}Ar/^{39}Ar$ geochronology on rocks from the Nyalam region, Southern Tibet.
- Presented research at the National Geological Society of America (GSA) meeting, Toronto, Canada.

Undergraduate Senior Project and Senior Thesis Presentations / Publications, 1997
Senior Environmental Seminar Project entitled: A Risk Assessment of PCB's in the Hudson River (with a special focus on the geochemistry of PCB's).
Senior Thesis in Geology entitled: A Geochemical Analysis of the Saratoga Mineral Springs, NY.

- Presented thesis at the Northeast Region Geological Society of America (GSA) meeting, Philadelphia, PA.
- Presented thesis at The National Conference for Undergraduate Research (NCUR), Austin, TX.

Teaching Assistantship through a Grant form NASA, 1995-1996

- Researched, developed and helped teach labs for an introductory geology course entitled "Earth System Science".
- Attended the Universities Space and Research Association/Goddard Lecture Series in Earth System Science, NASA/Goddard Space Flight Center, Seabrook, MD, 1996.
- Attended a workshop on Earth Systems Science Education by the University Space and Research Association/NASA, Santa Barbara, CA, 1995.

AMY JENNELLE DOUGHERTY

WORK EXPERIENCE

Coastal Geologist/ Private Consultant, Wellfleet Harbor, Wellfleet, MA, 1 – 3/2004
- Construct a management report, including a GIS based sediment transport map of Wellfleet Harbor and grain-size statistics, to determine if dredge spoil can be used for a harbor beach renourishment project.

Geologist-in-the-Park Coastal Sedimentologist, Cape Cod Island National Seashore, MA, 9/2003-3/2004
- Addressing sedimentation concerns associated with the opening of the Herring River Dike, Wellfleet, MA.

GeoCorps America Coastal Scientist, Cumberland Island National Seashore, GA, 5 - 8/2003
- Study back-barrier erosion and document its impact on archaeological and natural resources.

Adjunct Professor, Bentley College, Waltham, MA, 9/2001-5/2002
- Prepared and taught 3 sections of *Introduction to Geology* including both lecture and lab classes.

Coastal Sedimentologist/Consultant, Nantasket Beach, Hull, MA, 12/2001-2/2002 & 7/2002
- Analyzed 36 sediment samples from eroding Nantasket Beach and wrote a data report.
- Tested 5 sand samples and wrote a management report recommending sand for beach nourishment.

Coastal Research Scientist, Duxbury Beach, MA, 5/2001-3/2002
- Conducted independent research on threatened coastal birds in accordance with Audubon Society.
- Supervised 15 "Nest Monitors" that protected and studied individual families of Piping Plover.
- Designed new, in addition to performing ongoing, studies on coastal erosion and barrier ecology.
- Wrote two 300+page data reports and two management summary reports for the town of Duxbury.

Teaching Assistant, Boston University, MA, 9/1998-5/2002
- Taught 15 sections of introductory geology labs and 3 sections of sedimentology labs, 1998-2002.
- Asked by the Department Chair to teach two night courses and one summer class for Boston University, 2001-2002.
- Teaching Assistant for B.U.'s field camp in Ireland, Summer 1999 (invited back for 2000&2001).
- Honored by Boston University as the Earth Science Teaching Assistant of the year, 1998-1999.

Lab/ Research Assistant, M.I.T., Cambridge, MA, 9/1997-9/1998
- In addition to independent research, I preformed mineral separation, sample preparation, instrument analysis and data reduction on university and contract projects.

Assistant Team Leader, AmeriCorps/Maine Conservation Corps, Augusta, ME, 6/1997-9/1997
- Assisted in construction of a 40-mile hiking-trail loop off the Appalachian Trail near Mt. Katadin.
- Restored Park Service cabins to serve as functional housing for Americorp members.

Maintenance & Construction Worker, Rowan University, Glassboro, NJ, 6/1996-9/1996
- Helped demolish and rebuild art wing at Rowan University.

Grounds & Landscaper, Rowan University, Glassboro, NJ, 6/1995-9/1995
- Planted, seeded, trimmed, mulched and even laid cement around the campus.

Farm Hand, DiEugenio Orchards, Glassboro, NJ, 6/1993-9/1993 & 6/1994-9/1995
- Preformed various tasks in and around the peach orchards and produce packing house.

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PUBLICATIONS

Dougherty, Amy J., and Fry, John F., 2003, Back-barrier Erosion Threatens Archeological Sites on Cumberland Island National Seashore, Georgia; Geological Society of America, 115th Annual Meeting, Abstracts with Programs

Dougherty, Amy J., FitzGerald, Duncan M., Johnston, Shelley J., and Ferullo, Brian, 2003, Ground-Penetrating Radar Provides a Detailed View of the Complexities of Barrier Progradation, Castle Neck, Massachusetts, USA, Special Publication for the International Coastal Symposium in Clearwater, FL, May 25-25, 2003

Dougherty, Amy J., FitzGerald, Duncan M., Pendleton, and Buynevich, Ilya V., 2003, Evidence for Storm-Dominated early Progradation of Castle Neck Barrier, Massachusetts, USA: Marine Geology, In Press

Dougherty, Amy J., 2002, Deciphering the Origin and Evolution of a Paraglacial Barrier: Castle Neck Barrier, Massachusetts, Unpublished M.A. Thesis, Boston University, Boston, MA, p. 117 Submitted

Dougherty, Amy J., Rosen, P., FitzGerald, D., and Jahoda, J., 2002, Evaluation of Shorebird Habitats, Nesting Patterns and Beach Processes along Duxbury Beach, Massachusetts, Management Report submitted to the Town of Duxbury, MA, p.15

FitzGerald, D., **Dougherty,** Amy J., Rosen, P., and Jahoda, J., 2002, Beach profile summary report entitled: Morphological Changes along Duxbury Beach: 2002-2001 Survey Period, Management Report submitted to the Town of Duxbury, MA, p.17

Dougherty, Amy J., 2002, Duxbury Beach Profile and Wrack Analysis, Data Report submitted to the Town of Duxbury, MA, p.379

Dougherty, Amy J., 2002, Duxbury Beach Summer Report 2001, Data Report submitted to the Town of Duxbury, MA, p.363

Dougherty, Amy J., 2002, Grain Size Statistics on Potential Nourishment Sand from J.F. Price Company: Management Report submitted to the Town of Hull, MA, p.13

Dougherty, Amy J., 2001, Grain Size Distribution of Sediment Collected from Six Test Pits along Nantasket Beach, Massachusetts: Consulting Report Submitted to the Town of Hull, MA, p.13

Dougherty, Amy J., FitzGerald, Duncan M., Krol, Michael A., and Idleman, Bruce, 2001, Provenance Study of Barrier Sands using 40Ar/39Ar Laser-Probe Dating of Single Crystals Detrital Muscovites, Merrimack Embayment Barriers, New England; Geological Society of America, 113th Annual Meeting, Abstracts with Programs

Dougherty, Amy J., FitzGerald, Duncan M., Pendleton, Elizabeth A., and Buynevich, Ilya V., 2001, Styles of Barrier Evolution as a Function of Proximity to the Updrift Tidal Inlet, Castle Neck, Northern Massachusetts: American Geophysical Union, Spring Meeting Abstracts

Buynevich, Ilya V., FitzGerald, Duncan M., **Dougherty**, Amy J., and Smith, Lester B., 2001, Stratigraphic Evidence for the Historical Position of the East Cambridge Shoreline, Boston Harbor, Massachusetts, Journal of Coastal Research, Vol. 17, No. 3, p. 620

Dougherty, Amy J., FitzGerald, Duncan M., & Buynevich, Ilya V., 2000, Complex Holocene Origin and Development of Castle Neck Barrier, Northern Massachusetts: The Geological Society of America, Northeast Section, 35th Annual Meeting, Abstracts

PUBLICATIONS (Continued)

Krol, M.A., Sherwood, M., & **Dougherty**, A.J., 1999, Tertiary Denudation History of the Indian Plate, Naran, Pakistan: Constraints from $^{40}Ar/^{39}Ar$ Thermochronology: The Geological Society of America, Northeast Section, 34th Annual Meeting, Abstracts

Dougherty, A.J., Krol, M.A., & Hodges, K.V., 1998, Miocene Tectonic Unroofing and Cooling of the Greater Himalayan Sequence, Nyalam Region, Southern Tibet: The Geological Society of America, 111th Annual Meeting, Abstracts with Programs, v. 30; 1

Dougherty, A.J., 1997, A Geochemical Analysis of the Saratoga Mineral Springs, NY: Unpublished B.S. Thesis, Union College, Schenectady, NY

Dougherty, A.J., Naples, C., Lederer, R., & Hollocher, K., 1997, A Geochemical Analysis of the Saratoga Mineral Springs, NY: The Geological Society of America, Northeast Section, 32nd Annual Meeting, Abstracts with Programs, v. 29; 1

Dougherty, A., Naples, C., Lederer, R., & Hollocher, K., 1997, Chemical Variations of Surface Waters of Saratoga County and the Saratoga Mineral Springs and Wells, New York: NCUR (National Conference of Undergraduate Research) -97 Book of Abstracts