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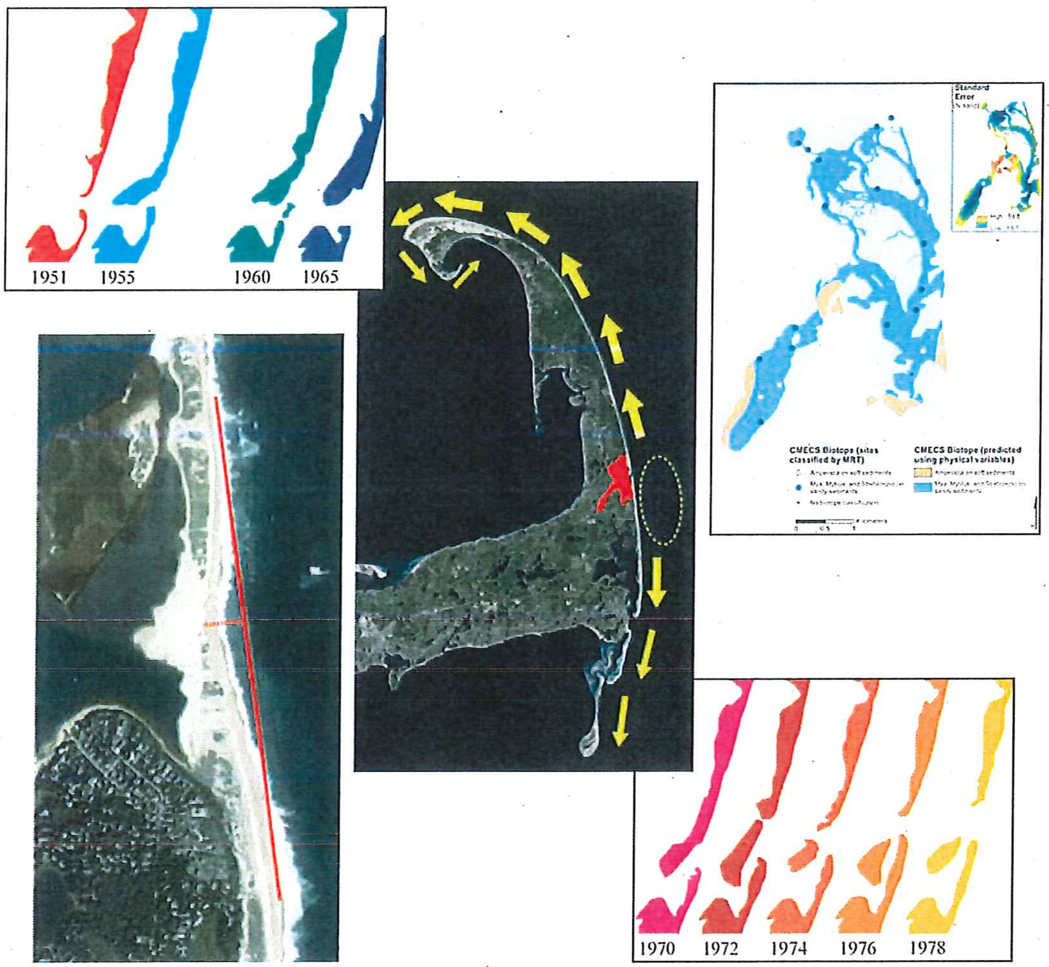
Potential Impacts to the Nauset Barrier from the Proposed Dredging and Disposal in Nauset Harbor

A Technical Report prepared for the Town of Eastham, Massachusetts



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EXECUTIVE SUMMARY

The Center for Coastal Studies has undertaken, for the Town of Eastham, an analysis of the potential impacts on coastal processes and barrier geomorphology that could be expected to result from the project as described within the '*Nauset Estuary Dredging Feasibility Assessment*' prepared by the Woods Hole Group for the Town of Orleans. The results of our analysis indicate two aspects of the project that should be considered as areas of concern. The first relates to the impact to be expected from the proposed placement of dredged material on the barrier beach immediately to the north of Nauset Heights. The site chosen for this deposition may be the most hydraulically efficient position for a tidal inlet in the barrier system, and it is the location that the inlet occupied for several centuries prior to the late 1940s. The effect of the proposed sediment deposition would likely be to prevent, or move further into the future, the formation of a tidal inlet in this hydraulically favorable location. The second area of concern is the proposed location of the backbarrier channel immediately behind the barrier beach where it is more likely to interfere with the landward migration of the barrier. This interference could be minimized by the channel placement farther westward within the proposed dredge zone. Our results indicate that the remainder of the project will have no major impact to the barrier system.

Lastly, based on our analysis it is our belief that the northward migration of the inlet is a result of downdrift migration of the inlet and not the commonly held notion of updrift migration. This is due to the nodal point shifting southward and as a result, this inlet will likely continue to migrate northward to the extent possible. The area immediately north of Nauset Heights is the most hydraulically efficient location for the inlet, where the most benefit and least manipulation would be required, however, due to the southerly shifting nodal point, the inlet will very likely continue to migrate northward.

INTRODUCTION

The Town of Eastham requested a geomorphic analysis of potential impacts of the proposed project to dredge in Nauset Harbor. The intended and potential unintended consequences to the barrier system discussed herein are based on the proposed project detailed in the document entitled, '*Nauset Estuary Dredging Feasibility Assessment*' prepared by the Woods Hole Group for the Town of Orleans dated February 2016.

Fundamental to any decision will be the clear delineation of what the priorities are with regards to this project and potential impacts to the system. The priorities of Cape Cod National Seashore are outlined in their enabling legislation and include preserving natural environments and process for future generations. In many respects towns are faced with a greater range of concerns and responsibilities to best serve the community in the short- medium- and long-term. Therefore, the foundation of making any ecosystem-based decision must be set within a solid understanding of that system, particularly a dynamic, open-ocean, barrier system. Including: how that system has evolved through time; what stage of evolution is the system currently in; what are the parameters for future system evolution given expected natural perturbations, (storms, sea level rise, etc.) and human-induced alterations (dredging, structures, development, etc)?

This report will begin with a cursory review of basic coastal processes related to tidal inlets, barrier spits and islands, and coastal sediment transport. This will be followed by recent changes to the system (the last few centuries), with a particular focus on the last 70-80 years, which reveals a fundamental shift, not widely known, about the recent evolution of the system. This information is not included in the project design document, but should be central to any project design, proposed alteration or, in fact, scientific study done in Nauset Harbor. Some recent and ongoing studies by the Center are briefly discussed (tidal studies and benthic habitats) to provide some basic system information. Finally, within this context the report presents our thoughts on the geomorphic implications of the proposed project.

LONGSHORE SEDIMENT TRANSPORT AND INLET MIGRATION

In order to better understand tidal inlet migration, it is important to have a fundamental understanding of the basic processes of coastal sediment transport. There are two primary ways sediment moves in the coastal zone, alongshore and across-shore (on and offshore). As waves approach the beach at an angle, sediment is picked up and deposited *downdrift*. The terms *updrift* and *downdrift* refer to the net direction of sediment transport, similar to upstream or downstream in a river setting.

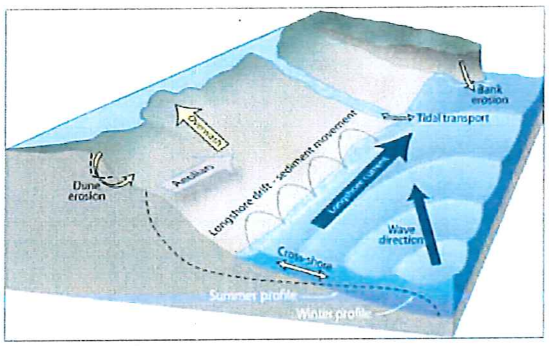

Figure 1. Longshore Sediment Transport, taken from Berman (2011).

On any given day depending on the wind and waves sediment can be moving in either direction, however over the course of a year, for example, there is a net direction of longshore sediment transport. Depending on where you are on the outer beach that direction is north, towards Provincetown, or south, towards Monomoy.

This introduces the concept of a *nodal point* or where the net direction of longshore sediment transport diverges. If both Provincetown and Monomoy are both receiving sediment from longshore transport, then somewhere on the outer beach that direction of sediment transport must diverge. It is important to remember that while it is called a nodal point in the literature it is not an exact location that can be shown on a map or a place on the beach where you can see the sand traveling in opposite directions. Similar to rates of shoreline change, the net direction of longshore sediment transport must be understood within the context of a larger set of processes in this case net vs gross annual volume of sediment transport.

The idea of the net annual volume of sediment transport is a straightforward one and is best illustrated via an example. If a nor'easter is occurring for three days, it can be safely assumed that most, if not all, of the sand being transported along a given stretch of Nauset Beach is traveling to the south. However, during other times sand will be traveling northward. Therefore, to continue the hypothetical, if 500,000 yd^3 of sediment moved southward during a given year but 600,000 yd^3 moved northward, then you would have 100,000 yd^3 of net annual volume sediment transport to the north. In this example, and in many cases, more sand is moving southward (500,000 yd^3) than the net annual sediment transport volume (100,000 yd^3) but for management purposes it is the net annual volume and direction of sediment transport that is the key to understanding ongoing system evolution.

Typically, tidal inlets migrate in the direction of net longshore sediment transport. Tidal currents flowing in and out twice daily work to keep the inlet open, as waves move sediment down the coast that transported sand can 'clog' up the inlet. Though an oversimplification, it can be viewed a 'battle' between waves and tidal currents. This relationship between tidal currents and waves characterizes tidal inlets and often determines management needs, dredging, marking navigation channels, etc. Some tidal inlets, like Barnstable Harbor, need very little management, the channel does not vary greatly and does not require dredging to keep it open. Inlets along the outer beach in Pleasant Bay and Nauset Harbor do have troubles with shoaling and/or rapid channel shifting. We mentioned an oversimplification above, in truth there are many factors at play in determining inlet position, migration and natural stability including storm activity, tidal prism, barrier width, barrier height, hydraulic efficiency with regards to inlet position and migration, new inlet formation, etc., which can effect tidal currents and wave active at the main inlet channel.

Another concept that is important to understand is that of the *littoral cell.* A littoral cell is a coastal compartment that contains all of the sources, transport pathways and sinks of sediment for a given stretch of coast. The outer Cape beach from Provincetown to Monomoy is a complete littoral cell. All the material eroded from the outer beach/bluffs (source) is transported to either Provincetown to the north or Monomoy to the south (sinks), though a small portion is lost to the offshore and onshore system. A foundational principle for informed coastal management is the awareness of the coastal resource (e.g. beach, dune, tidal inlet) and its location within the relevant littoral cell.

PRESENT CONDITIONS AND RECENT STUDIES

Shoreline change rates

The United States Geological Survey (USGS) and the Massachusetts Office of Coastal Zone Management (MCZM) routinely measure rates of shoreline change along the coast of Massachusetts. The rates are generated by looking at shorelines from historical charts, aerial photographs and most recently lidar data. The most recent study yields long term erosion rates in the Nauset Harbor area from 3-5 ft yr (Figure 2) and the methods used are described in the report (Thieler et al., 2013).

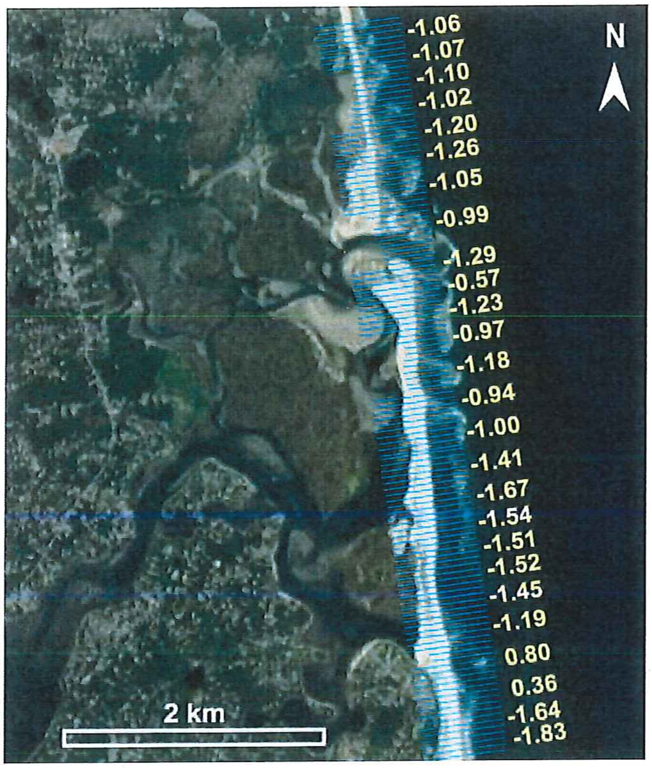

Figure 2. Shoreline change rates in meters taken from the Massachusetts Shoreline Change project (Thieler, et al. 2013).

Although it may seem counterintuitive, rates of shoreline change, while valuable, cannot be used to predict future shoreline position for short-term management purpose because storms are the primary driver of coastal change. These rates are the documented changes in shoreline position over the years of the study. A basic statistical analysis is performed, and an annual rate of shoreline change is developed. These data are very useful to guide understanding of the general dynamics of a system, but it is critical to understand that the annual rates are not linear. In other words, if the rate of erosion is 1 ft/yr the beach does erode 1 inch per month. While this is obvious, there is a tendency to forget this for management questions related to decadal scale shoreline position. Although the long-term rate in the area is ~3-5 ft/yr it is not uncommon for areas to lose 30-40 ft in one winter or even one storm event. It is important to remember that shoreline change rates are periodic (average erosion/year) and the primary drivers of shoreline position are episodic (storms).

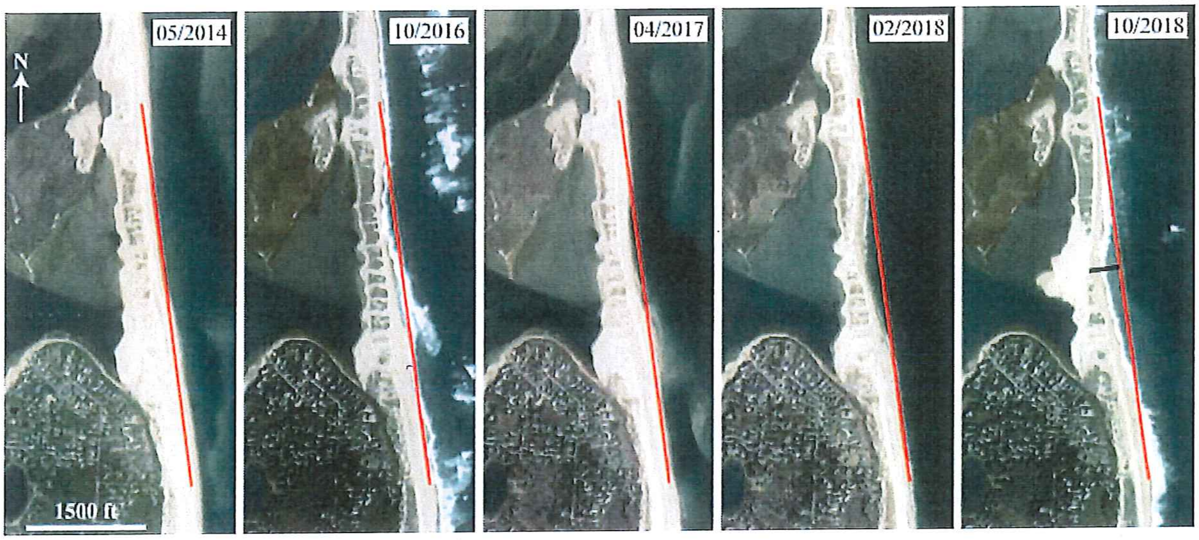

Figure 3. Shoreline change north of Nauset Heights. The red line is in the same geographic location for each photo. The shoreline has moved more than 400 ft landward in some places from 2015 through 2018, or >140 ft/yr. The black line in 10/2018 photo shows area of greatest change. All photographs taken from Google Earth.

TIDAL CYCLES IN NAUSET HARBOR

Water level data were collected in Nauset Harbor at a station in Town Cove, Orleans, between April 2016 and December 2018 (Figure 4) in part for a project funded by Cape Cod National Seashore (Legare et al., 2018). Water level data were also collected at three secondary locations (Salt Pond, Upper Nauset Marsh and Lower Nauset Marsh) for a minimum of 30 days during the summer of 2016. All water level data were collected at six-minute intervals using HOBO Water Level Titanium U20-TI pressure sensors from ONSET®. Pressure loggers for primary stations were affixed to stationary pilings at Goose Hummock on Town Cove in Orleans, MA. The loggers were inserted into a PVC pipe for protection and holes were drilled to allow the free flow of water. Pressure loggers for secondary stations were attached to 75 cm sand screws within a PVC case attached by two hose clamps. Data from the stations were corrected for the effects of atmospheric pressure using data from adjacent atmospheric pressure recorders (located in Orleans). The water

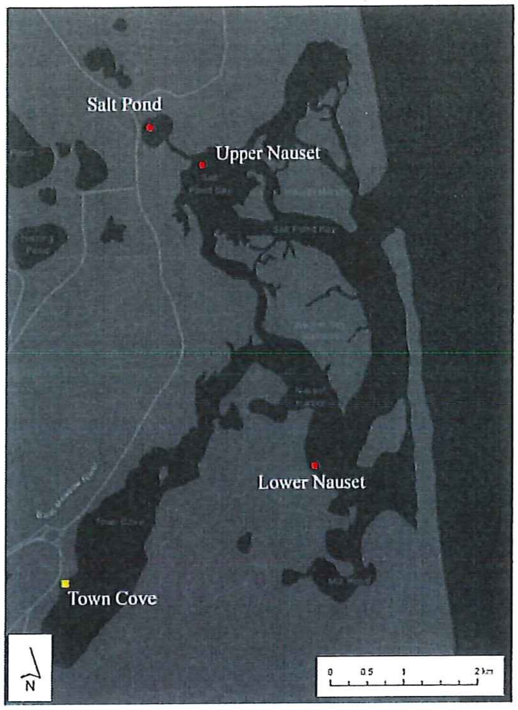

Figure 4. Station locations for the primary station in Town Cove (Yellow) and the Secondary stations in Red.

level data were corrected relative to NAVD88 (m), by means of precision RTK-GPS surveys. An accuracy assessment was created for data collected at in Town Cove by comparing the calculated (corrected pressure sensor) readings to measured water levels on an adjacent tide staff. The readings were graphed and a linear regression was performed with an R^2= 0.99.

Monthly tidal statistics were calculated for all stations and include Mean Sea Level (MSL), Mean High Water (MHW) Mean Low Water (MLW) and Mean Tide Range (MTR) (Table 1). For the primary station in Town Cove, long-term water level elevations (April 2016 to October 2018) were used to create a datum referenced tidal profiles (table 1). The tidal datums represent average tidal elevations computed for the 1983 to 2001 National Tidal Datum Epoch (NTDE). The tidal profiles used the NOAA tide station #8443970 (tidesandcurrents.noaa.gov/stationhome.html?id=8443970) as a reference. Summary tidal statistics were compared to Boston and Town Cove for the month they were deployed.

Table 1. Summary data from Primary (Pr) and Secondary (Se) tide recorders in the Nauset Harbor study area in June 2016 (Hemmingway) and July 2016 (Salt Pond and Upper Nauset). Town Cove in June –July 2016 is provided as a comparison. Mean Sea Level (MSL), Mean High Water (MHW), and Mean Low Water (MLW) are given in NAVD88 (meters). Tide Range (MTR) is given in feet.

Sites	Year	Month	MSL	MHW	MLW	MTR
Town Cove (Pr)	**2016**	**6**	1.02	2.82	-0.30	3.12
Lower Nauset (Se)	2016	6	1.21	2.89	-0.10	2.99
Town Cove (Pr)	**2016**	**7**	0.98	2.79	-0.33	3.12
Salt Pond (Se)	2016	7	1.02	2.82	-0.46	3.28
Upper Nauset (Se)	2016	7	1.12	2.89	-0.36	3.25

BENTHIC HABITATS IN NAUSET HARBOR

The Center for Coastal Studies worked on a large project for the National Park Service to develop methods to produce benthic habitat maps in four embayments throughout Cape Cod National Seashore (Borrelli et al., 2019). Data were collected in Nauset Harbor in 2014 and the findings are presented here briefly to introduce the town to the study within the Harbor and demonstrate the biodiversity and abundance of macro-invertebrates in the Harbor.

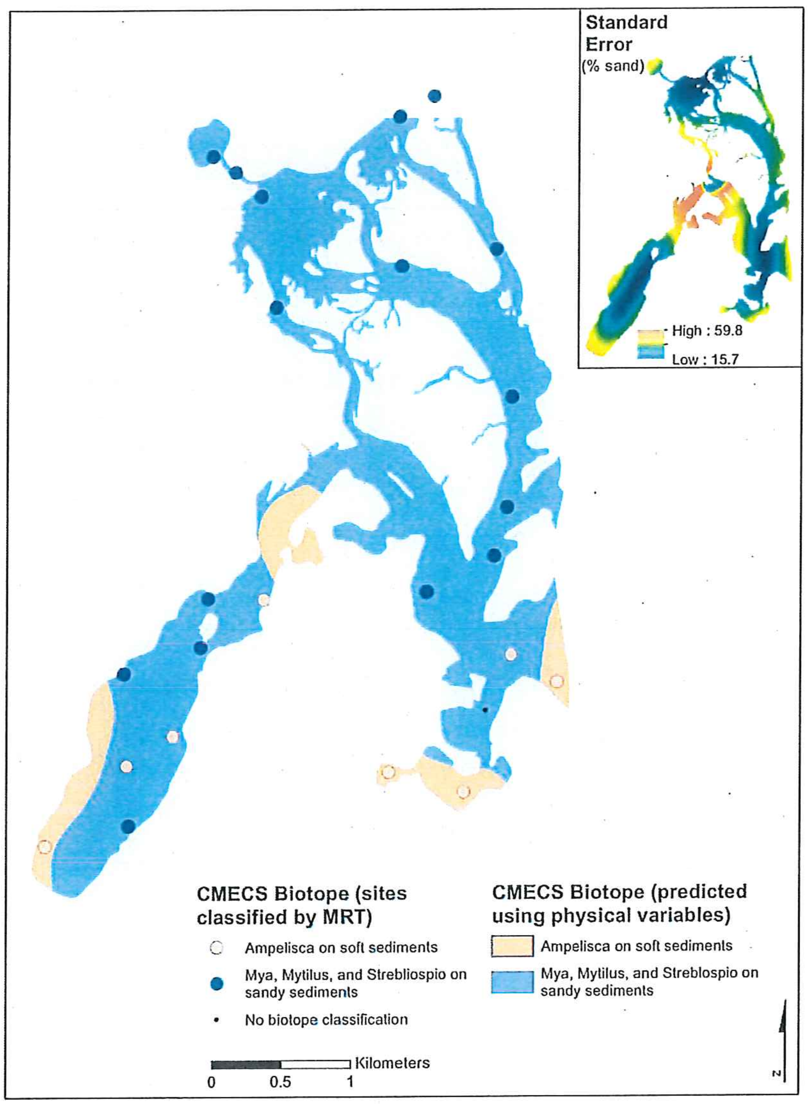

Figure 5. Biotopes for Nauset Harbor taken from Borrelli et al. (2019), see report for details.

Coastal ecosystems are subject to environmental and human-induced stressors and managing these areas can be challenging. Monitoring them and creating benthic habitat maps are important first steps to maintain and manage these ecosystems as well as reliably evaluate the effects of climate change, nutrient pollution, dredging activities and aquaculture on coastal ecosystems. Benthic habitats are defined by their biological and physical components and recognizing their importance and relative contributions are essential.

By using the Coastal Marine Ecological Classification Standard we connected the physical characteristics

(Geoform and Substrate Component) with the biological characteristics (Biotic Component) of Nauset Harbor. CMECS was designed to classify coastal and marine habitats throughout U.S. waters, and its ability to offer classification precision at local, ecologically-relevant scales is still evolving. In other words, the data collection and analysis methods used for any study may be robust and designed to capture the environmental and biological variability at a particular location, but classifying those data using CMECS may obscure important habitat patterns. Regardless, as a national standard, CMECS has significant value as a common language for the inventory and/or comparison of habitat data collected by disparate and varied investigators within U.S. regions, coasts, and the nation as a whole.

The 25 stations sampled, yielded a total of 38,242 individuals belonging to 75 species (Figure 5). The highest species diversity was observed at station 6, south of Hopkins Island and highest abundances at station 11, just northwest of it. The most abundant species in Nauset Harbor were *Corophium sp.* and *Ampelisca sp.*, both amphipods or side swimmers, that are bottom dwelling and build tubes out of fine grained sediments. Amphipods are an integral part of the food web, providing a food source for many fish and birds. Although Massachusetts does not release an official list of invasive species, a literature research showed that *Microdeutopus gryllotalpa* (a species of side swimmer) is an established invader of New England waters and indeed Nauset Harbor (https://invasions.si.edu/nemesis/calnemo/SpeciesSummary.jsp?TSN=93477). *Lepidonotus squamatus, Microdeutopus anomalus and Polycirrus* were also found; these species are considered to be cryptogenic in New England, meaning their origin (native vs introduced) is uncertain.

Based on abiotic factors such as grain size metrics and organic matter content of the sediment, we could explain 15.6% of species distribution in Nauset Harbor. This number is low in comparison to previously published studies conducted around New England, which achieved 21-68.9% explanation. Water column factors such as dissolved oxygen, pH and salinity also play an important part in species distribution, however, these factors are subject to change by seasons, tides, anthropogenic input and weather events and have to be monitored across seasons and years before potential inclusion as an explanatory factor. Indeed, CMECS' fourth component (Water column component) incorporates chemical features of the area and could result in higher percentages when analyzing the driving factors behind species distribution.

GEOMORPHOLOGICAL CONSIDERATIONS

It is our belief that the most important concept discussed in this report, central to the management of Nauset Harbor, is whether the inlet is migrating updrift (against the direction of net longshore sediment transport) or downdrift (with the direction of net longshore sediment transport). Another way of stating this: Where is Nauset Inlet within the Outer Cape Littoral Cell?.

The inlet has been migrating northward since the early 1950's after a prolonged period of little to no migration from the 1770s (Aubrey et al., 1982). This distinction, updrift vs downdrift inlet migration, is critical to the understanding of current system state and barrier evolution, but more importantly to future migration and evolution patterns and trends.

There is a long-held belief, locally and in the peer-reviewed literature that the 'nodal point' or the area where the direction of net sediment transport diverges on the outer beach is to the north of Nauset Inlet, near Wellfleet (Figure 6). As mentioned above the nodal point is not a single point on the map but is more of a zone and as such an approximate location can provide the needed management guidance.

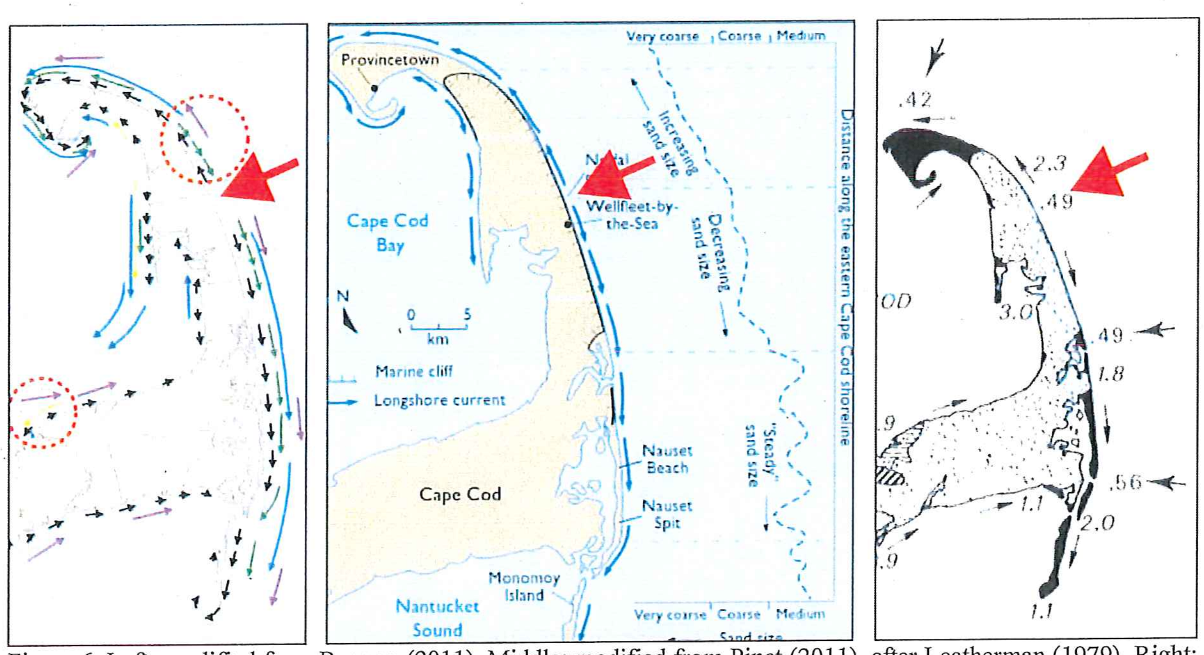

Figure 6. Left: modified from Berman (2011). Middle: modified from Pinet (2011), after Leatherman (1979). Right: Fitzgerald (1993). Short red arrows added here, indicate location of nodal point as drawn by respective author.

Aubrey and Speer (1984) published a journal article stating their updrift migration hypothesis and it is referenced in the Woods Hole Group report.

> *The history of northerly inlet migration at Nauset Estuary, in a direction opposite the dominant longshore sediment transport, is contrary to patterns of migration at most other natural inlets. Aubrey and Speer (1984) analyzed historical charts, aerial photos, and storm histories from the area to develop a conceptual model that explains the inlet migration patterns.*

The evidence for our hypothesis refuting the idea of a decades-long cycle of updrift inlet migration is based on multiple studies and analyses. The first is a series of papers and reports that looked at century-scale onshore/offshore profiles which were collected in the late 1880s by Henri L. Marindin along the outer beach from Chatham to Provincetown (Marindin, 1890). Starting in the early 2000s investigators at the Center and Cape Cod National Seashore began to re-survey those profiles, that started on land and went out to ~30 ft of water depth. Their studies yielded information on the orientation of the outer beach, which indicated that it has rotated clockwise since the 1880s (Giese and Adams, 2007). They hypothesized that this change in orientation was a result of relative sea level rise over George's Bank and the resulting increase in wave energy from the southeast. Using these data and applying the concept of littoral cells, (i.e. nodal points, sinks, sources, sediment transport pathways) it was demonstrated that the nodal point had moved southward toward the vicinity of Nauset Harbor (Giese et al., 2011).

The second piece of evidence is the geomorphological analysis of historical charts and recent aerial photography. The earliest map of the area from 1779 shows the inlet just north of Nauset Heights, 167 years later the 1946 aerial photograph shows the inlet is the same place (Aubrey et al., 1982). With at least 8 separate maps/photographs of the area between those dates (1810, 1844, 1856, 1872, 1887, 1893, 1910, 1938) it is very unlikely that the inlet had any significant episodes of migration. Therefore, the inlet was positioned in the southernmost part of Nauset Harbor since, at least, the late 1700s, which was very likely the most hydraulically efficient position given the existing conditions.

Tidal inlets are very dynamic coastal features that are constantly changing with each tidal cycle. As mentioned above the twice daily tidal currents work to keep the inlet open and the wave-driven longshore sediment transport moves sediment along the shore that can redirect tidal currents, shoal or even close the inlet.

In a geomorphic analysis of the inlet from 1946 to the present, trends and patterns begin to emerge. From as late are the 1770s to 1946 Nauset Barrier spit extended from the north, to Nauset Heights, which was in keeping with a north-to-south direction of net sediment transport (Figure 7). A *spit* is a coastal landform that is connected to the mainland on one end and extends into open water at the other end. Sometime between 1946 and 1951 a southern spit formed and began to grow northward while the northern spit shortened, perhaps signaling a shift in the net direction of sediment transport. The growth of the southern spit continued until at least 1955. The southern tip of the northern spit became wider and grew at an angle toward the harbor.

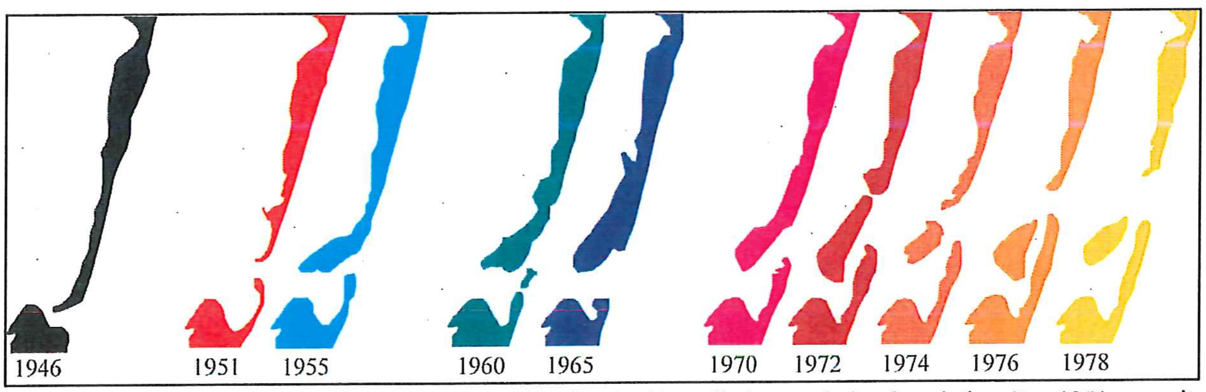

Figure 7. Historical geomorphology of Nauset Harbor barrier. Four distinct periods of evolution. Pre-1951: no spit growth from Nauset Heights. 1951 – 1955: Initiation of southern spit elongation. 1960 – 1965: Southern spit breakup, northern spit widening. 1970 – 1978: Southern spit growth, northward inlet migration.

In the next time series (1960 – 1965) the southern spit was seen to be breaking up, while the northern spit widened, a sign of the reversal of net sediment transport direction from northward back to southward. Then, starting in 1970, a sustained period of southern spit growth and northern spit shortening as the inlet migrated to the north.

Based on these two separate, unrelated lines of evidence it is hypothesized that the nodal point has shifted to the south and is in close proximity to Nauset Inlet. This would mean that the northerly migration of Nauset Inlet since the 1950s is in fact downdrift which is counter to the common understanding but has major implications for management.

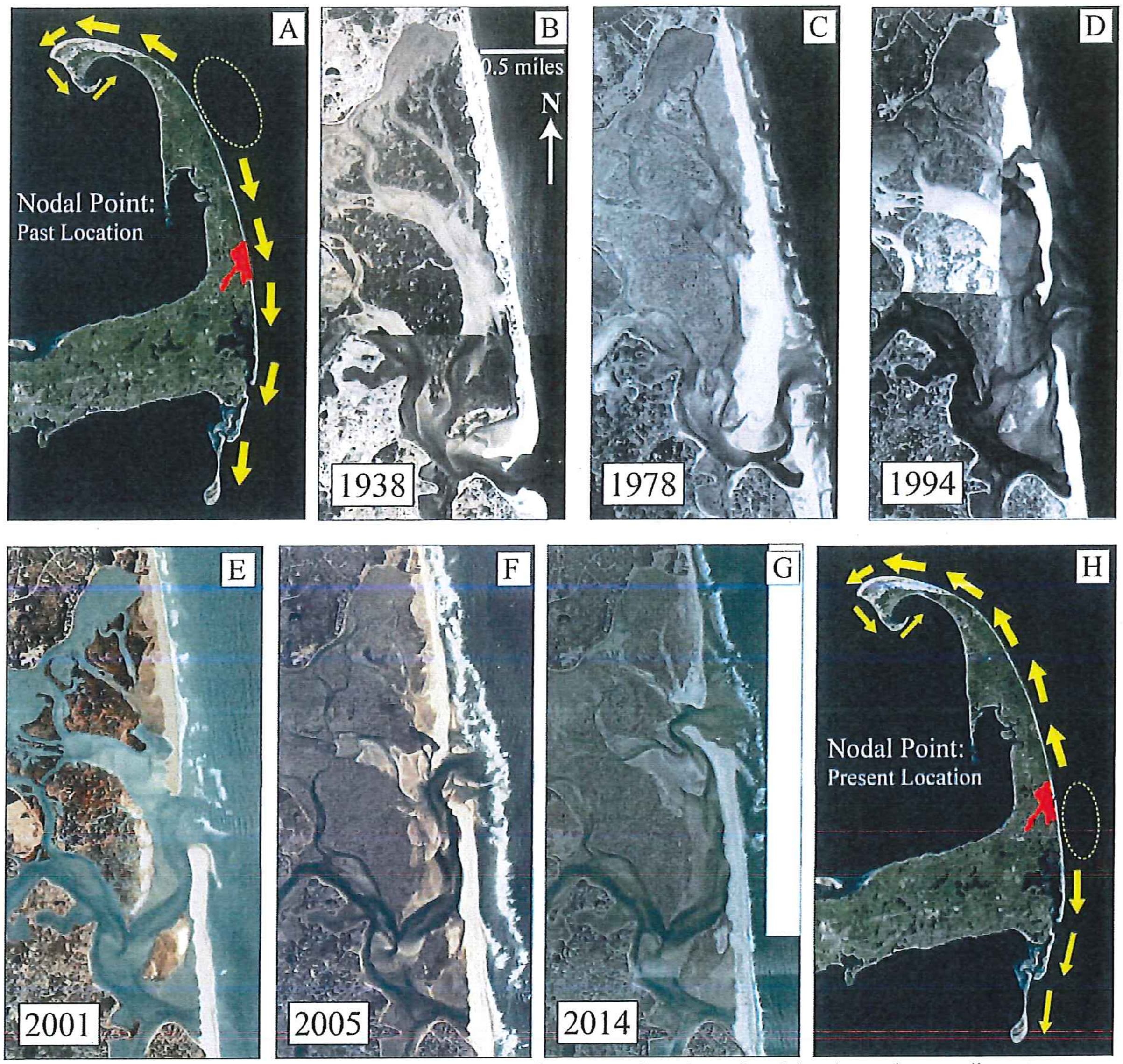

Figure 8. Hypothesized shift in nodal point. A: Approximate past location of nodal point and net sediment transport directions for outer cape. Red polygon is Nauset Harbor. Dotted oval is approximate location of nodal point. B-G: Aerial photographs of tidal inlet. H: Approximate present location of nodal point and net sediment transport directions for outer cape. Red polygon is Nauset Harbor. Dotted oval is approximate location of nodal point.

Primary among these is that the net annual volume of sediment moving along the shoreline has very likely decreased. When the nodal point was to the north close to the Wellfleet/Truro town line (Figure 8) large stretches of high coastal bluff were being eroded and that material was traveling past Nauset Inlet on its way to Monomoy. The area from the nodal point south to Nauset harbor was its 'source' and that sediment provided Nauset Barrier with sediment. When barriers overwash during storm events, as can be seen clearly in Figure 3, particularly between 02/2018 – 10/2018, that deposited material can increase the elevation of the barrier or widen it, either of which helps natural barriers keep pace with sea level rise. With the reduced sediment in the longshore transport system less material will be available for this natural process to occur, making it more difficult for the barrier to maintain itself within the ongoing cycle of sea level rise. With increasing rates of sea level rise projected for the future this problem will be further exacerbated.

CONCLUSIONS AND RECOMMENDATIONS

Coastal managers must always weigh potential impacts, both intended and unintended, to multiple resources and stakeholders of any action (or non-action) taken in these systems. Based on our analysis we provide the following conclusions with regards to the potential geomorphological impacts from the proposed dredging project to the barrier.

1. The placement of dredged material on the barrier starting at the northern tip of Nauset Heights in Figure 9 (site A) will alter the natural profile on the barrier. The intended consequence of this action is to prevent, or move further into the future, the formation on a tidal inlet in this location.

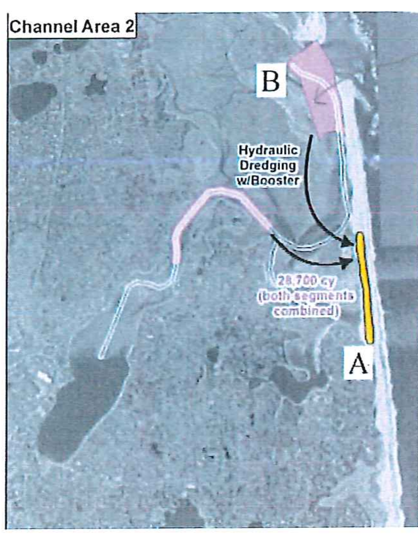

Figure 9. Taken from figure 23 of the Woods Hole Group Report. The letters 'A' and 'B' were added.

This location was the most hydraulically efficient position for the inlet through historical times up until the late 1940s and may well be the most hydraulically efficient position today, additional studies would be warranted to determine this. Further, the inlet in this position will maximize the natural benefits of tidal flow, improved water quality and increased tidal ranges, however slight, that can be attained in this system without manipulation thereby reducing the potential for unintended consequences from human-induced changes/

The possibility of negative consequences occurring were the inlet to reform in this area of course do exist, but by altering the barrier and backbarrier system by dredging and the placement of dredged material many more variables are brought into play. Were the inlet to form here it would likely begin to migrate north after a period of time, similar to other natural inlets under these conditions.

2. Dredging a channel immediately behind a barrier (Figure 9, Site B) that is overwashing and migrating landward could accelerate erosion during storm events by providing a deeper channel for sediment to be carried into. This would also reduce the barrier widening that occurs during overwash events. This widening is one of the ways in which barriers keep pace with sea level rise. These washover fans that are created can also be valuable habitat for many species of birds and support salt march growth.

3. The remainder of the proposed dredging with have little to no impact on the barrier/inlet configuration.

Our recommendations have to do with the clear establishment of a goal, or goals, with regards to the management of Nauset Harbor. The Center was charged with assessing the potential geomorphological consequences of the proposed to the Nauset Barrier. However, the question of what constitutes a negative impact is not always clear especially in dynamic, open ocean, multi-use, multi-stakeholder coastal ecosystems. If the town wants, and is able, to allow the inlet to naturally evolve to the extent practicable, then the placement of material in area 'A' shown in Figure 9 should not be allowed. Similarly, if the town wants, and is able, to allow the barrier near the inlet to migrate landward in response to storm events the channel should not be dredged immediately adjacent to the barrier, rather it should be dredged as far as away as is practical, though that may have implications for other resources in Nauset Harbor.

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