CYCLICAL SHORELINE EROSION: THE IMPACT OF A JETTIED RIVER MOUTH ON THE DOWNDRIFT BARRIER ISLAND

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Abstract: Beaches and inlets throughout the U.S. have been stabilized for purposes of navigation, erosion mitigation, and economic resilience, commonly leading to changes in shoreline dynamics and downdrift erosion/accretion patterns. The developed beach of Plum Island, Massachusetts is highly dynamic, experiencing regular complex erosion / accretion patterns along much of the shoreline. We analyzed > 100 years of high-water line positions derived from satellite imagery, t-sheets, historical maps, and aerial photography. Unlike most beaches, the river-proximal sections of Plum Island are not uniformly retreating. Rather, the beach undergoes short-term erosion, followed by periods of accretion and return to a long-term mean stable shoreline position. These cycles occur over different timeframes and in different segments of the beach, creating an ephemeral erosion 'hotspot' lasting as briefly as one year. The highly dynamic and spatially diverse nature of erosion along Plum Island provides insight into the complex nature of coupled inlet-beach dynamics over multiple timescales.

Introduction

Coastlines throughout the world have been highly developed, creating high risk areas due to the dynamic nature of beaches, tidal inlets and barrier islands. To mitigate risk, communities utilize inlet, dune and shoreline stabilization structures, altering natural processes and occasionally leading to localized exacerbated erosion. Plum Island, a barrier island located in northeast Massachusetts, is largely unique among US East Coast barriers in that it is neither heavily nourished nor undergoing landward migration. Its shoreline is highly stable: over the last 150 years, the island has experienced long-term erosion at the statistically insignificant rate of only 0.09 ± 0.6 m/yr (Thieler et al. 2013). Located in a mixed-energy, tide dominated setting at the mouth of the Merrimack River in the western Gulf of Maine, Plum Island is one of a series of five barrier islands, totaling 34 km and fronting the largest marsh system north of Long Island (the *Great Marsh*). This barrier complex was formed in a setting which experienced rapid, isostatically driven changes in relative sea level (RSL) following the retreat of the Laurentide ice sheet at 16–17 ka (Borns et al. 2004). Upon slowing of RSL rise 6–7 kyr B.P., sediments derived from abundant quartzose sources in the granitic plutons of the White Mountains were reworked to form a proto-barrier system (Rhodes 1973; McIntire and Morgan 1963; Hein et al. 2014) which gradually migrated landward during a period of relatively rapid RSL rise. Plum Island stabilized in its current position between 4 and 3 ka, and has been largely stable to progradational since (Hein et al. 2012).

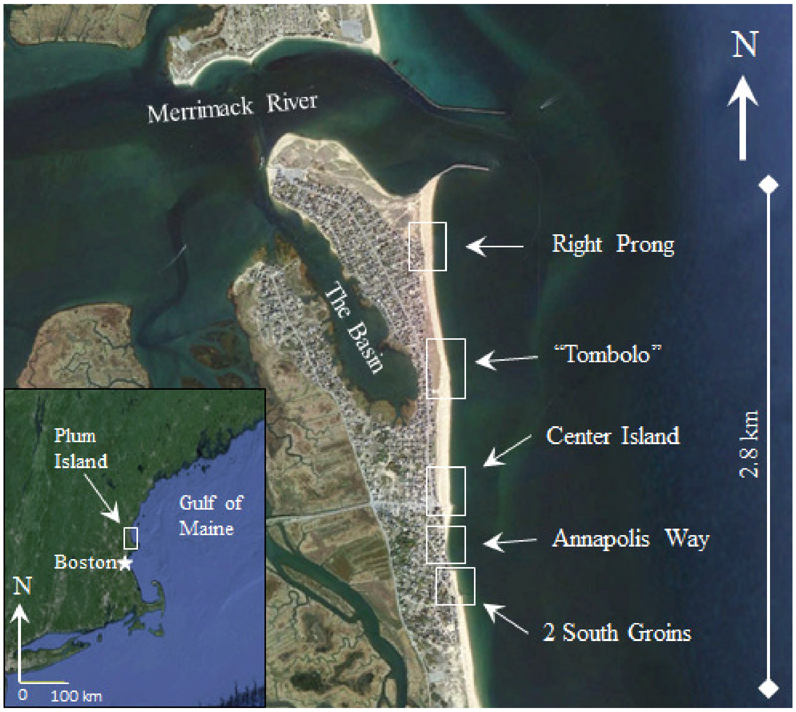

Fig 1 Plum Island, Massachusetts in the Gulf of Maine with survey area and four highlighted subareas along the shoreline

Human Settlement and Inlet Stabilization

Plum Island and the surrounding area were initially settled by Europeans in the late 1600s, and by the 1800s the town of Newburyport, just upriver on the

Merrimack, had become a commercially viable port (Labaree 1962). At the mouth of the Merrimack River is a highly dynamic tidal inlet. Over historic time this inlet, along with the proximal beach / barrier system, has undergone periods of river-mouth migration, spit elongation, ebb-tidal delta breaching, elongate bar attachment, and periods of offshore bar formation and migration (Fig. 1; FitzGerald 1993). These processes created a serious navigational challenge for the thriving port upstream. Most notably, a large-scale, natural reorientation of the river mouth occurred between 1827 and 1851. During this period, the river breached its ebb-tidal delta and shifted from a hydraulically inefficient southeast orientation to its current positon, roughly due east (Nichols 1942; FitzGerald 1993). Shoreline attachment of a landward-migrating sand bar after collapse of the former ebb delta formed the northeast fork of Plum Island; the former river channel became the shallow "Basin" located between the eastern and western prongs of the island (Fig. 1; FitzGerald 1993).

In response to these navigational challenges, construction began on a pair of jetties to stabilize the Merrimack River mouth in 1881. The South Jetty was completed in 1905 with a total length of 745 m, while the North Jetty was completed in 1914 to a final length of 1250 m (USACE, 1917). Since this time, the inlet has undergone a program of routine dredging, on average once every 3.2 years, which has removed more than two million cubic meters of sediment from the Merrimack Inlet since 1937 (E. O'Donnell, USACE, personal communication).

Following jetty construction, the northern portion of the island has experienced successive cycles of much smaller-scale erosion and accretion. Recent periods of intense, localized erosion have prompted federal, state, and local governments, as well as private homeowners, to employ a variety of mitigation strategies to protect public and private property. This includes the construction of a series of four shore-perpendicular groins along a 500 m stretch of the beach in the 1970s (Table 1), and more recent (2008 – 2014) dune stabilization measures such as coir bags and rip-rap revetments (Fig. 3). These have shown varying degrees of success: more than a dozen houses have been lost to erosion over the past seven years.

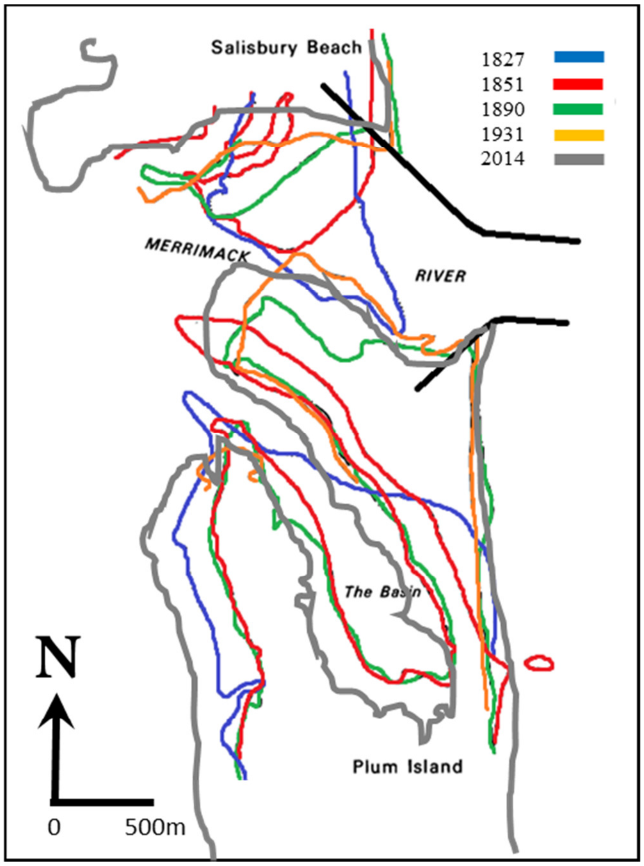

Figure 2 Long-term shoreline changes along the sections of Salisbury Beach (north) and Plum Island (south) proximal to the Merrimack River inlet (modified from FitzGerald 1993)

Methods

We used Geographic Information Systems (GIS) digital mapping to assess changes in the shoreline position of the northern 2.8 km of Plum Island over the last 100 years. This section of coast is the most proximal to the Merrimack River Inlet and is the only developed section of beach on the island.

Table 1. Periods of significant erosion experinced along the Plum Island shoreline, along with associated mitigation responses.

Shoreline Year	Highest Erosion Location (Fig. 1)	Erosion distance to steady state shoreline (shore perpendicular)	Mitigation response
1912	200 m north of tombolo	110 m	unknown
1928	Tombolo	100 m	unknown
1953	Right Prong	115 m	Beach Nourishment 425,000 m^3, Construction of 4 Groins
1978-79	Center Island south to 2 South Groins	95 m	Intermittent rip rap revetments
2008-2014	Center Island south to Annapolis Way	110 m	Coir bags, rip rap revetments along the entire 500 m section of beach

We used historical shoreline data covering the period following installation of the inlet jetties. A total of 14 paleo-shorelines were mapped. These data were derived from a variety of sources, each with its own degree of accuracy and precision. The most recent data source is georeferenced satellite imagery available from Google Earth via Massachusetts Coastal Zone Management. This imagery is available from 1994 to 2014. Additionally, abundant aerial photographs from the USACE over the last 50-60 years provide high-resolution imagery from 1962 to 2010. The earliest shorelines (1912, 1928 and 1953) are mapped from historical maps and nautical charts, notably National Oceanic and Atmospheric Association (NOAA) T-sheets dating to the early 1990s. All of these maps and charts were georeferenced in ArcGIS to the base imagery of the georeferenced 2013 and 2014 satellite imagery.

Our collection of mapped shorelines is skewed towards more recent dates due to the ready availability of satellite imagery and aerial footage. Abundant data are also available from the 1960s and 1970s due to regular fly-overs by the USACE. Prior to this time, available imagery and map data are much sparser, available only from infrequent mapping by NOAA. Furthermore, these shorelines, mapped at 1:10,000scale, are the least precise data source available. Nonetheless, mapped shorelines from this period are crucial to our ability to analyze the evolution of Plum Island's shoreline during the early period of residential and commercial development in the early 1900s.

Each HWL was mapped from the South Jetty at the northern end of Plum Island, south 2.8 km to the northern border of the Parker River National Wildlife refuge; this represents the entire oceanfront of the developed section of the island. The 14 HWLs were all mapped at 1:1000, regardless of the initial source material. The only exception was for the earliest shorelines (1912, 1928, 1953), which were mapped at the scale available from the T-sheets (1:10,000) This was done to provide the most precise and consistent assessment of shoreline variations from year to year. This enables cohesive comparison in ArcGIS of all HWLs (Fig. 4) or select years of interest (Figs. 5 & 6).

Fig 3 A. Coir bags at Center Island, 2010 B. homeowner stabilizing porch post storm, 2010 C. Revetment construction, two south groins, 2014 D. Groins & rip rap revetment, Annapolis Way, 2014

Shoreline mapping based on older, non-photographic sources (*e.g.,* maps, t-sheets) proved the most challenging. Although many of these sources simply reproduce mapped HWLs, they commonly do not contain detailed information regarding the nature of what section of the beach (*e.g.,* wrack lines, berms, etc.)

was mapped to produce a given shoreline. Plum Island experiences tides with a range of 2.7 m. A combination of two techniques was used to consistently identify the high-water line (HWL) on both satellite and aerial imagery. First, where possible, the division between dark and light sands on the beach was mapped. This line is assumed to indicate the highest wave run-up of the day the imagery was captured. In the cases where the sand division was either not apparent or the imagery resolution was too poor, the HWL was mapped as the seaward edge of the wrack line, as per Thieler et al. (2013). This feature is easily mappable even in lower-quality imagery because of the color contrast between the dark wrack against the light sand. Unfortunately, wrack lines tend to be discontinuous along the length of the beach. In such cases, the HWL was interpolated between changes in elevation (*e.g.,* berm, beach cusps) and sections with a visible wrack line.

There is some uncertainty in HWL mapping due to variations in wave and tide action. For example, a recent spring tide or high storm waves would produce a higher, more landward HWL than the longer-term mean HWL for that time period. This uncertainty has been addressed in previous shoreline mapping efforts of Plum Island (Hapke et al. 2011; Thieler et al. 2013) through incorporation into a mapping uncertainty which also accounts for mapping resolution, historical uncertainty, and, if applicable, rectification image uncertainty. These are treated as a compilation for each shoreline, thereby creating a single numeric uncertainty for each paleo-shoreline position.

Results

The shorelines analyzed represent 102 years of change along northern Plum Island. Despite gaps as large as 20 years in the available data, we are able to identify several short and long term shoreline trends.

The HWL position along northern Plum Island has shifted at least 70 m at any given location. The largest shift, 115 m, is seen between 1953 and 1974 in the northern-most section of the right prong (Table 1, Fig 1). However, such shifts are not unidirectional; rather, periods of erosion are followed by accretion and growth of the beach. Thus, even over this 100-year time period, Plum Island does not follow a pattern of continuous erosion as is common for most eroding and retrograding barriers (Oertel 1985).

Moreover, HWL fluctuations are not consistent along the shoreline. Rather, some sections of the coast experience up to 100 m of erosion at a given time while others maintain a relatively wide beach. For example, erosion in 1912 was the most severe to date along on the southern portion of the island, but the beach proximal to the jetty was its widest on record during this same time. By contrast, the HWL from 1994 was relatively straight along the coast, experiencing neither hotspots of erosion nor accretion.

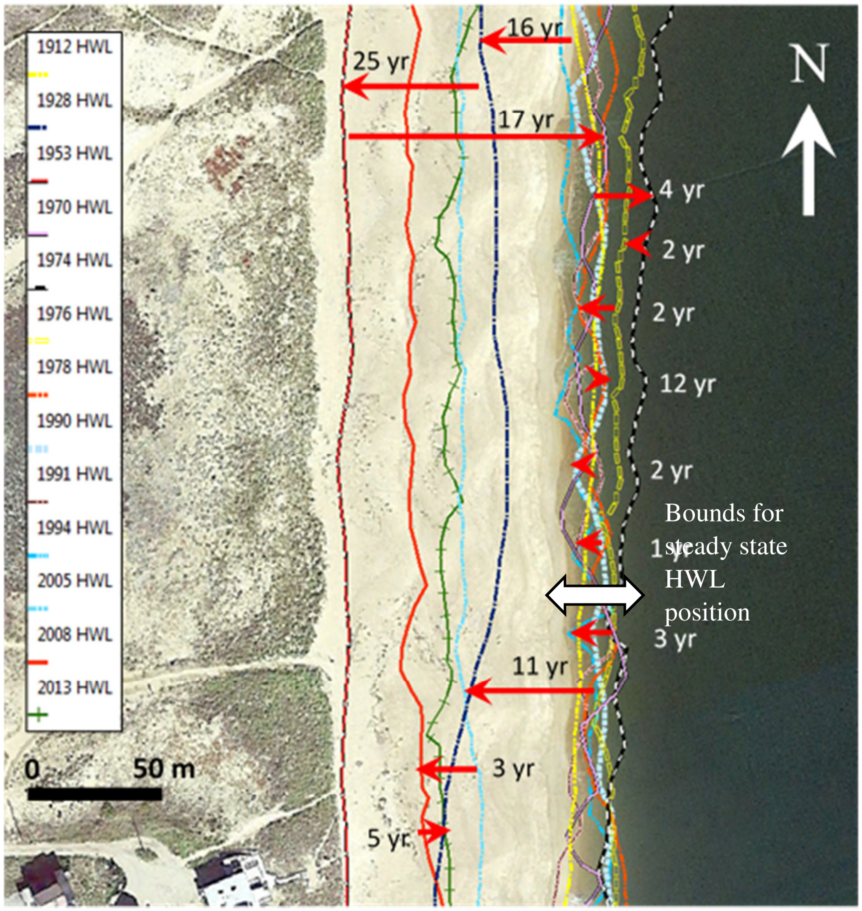

Figure 4: Fourteen mapped high-water lines. Arrows indicate direction of shoreline change from year to year, with time period between mapped HWLs noted.

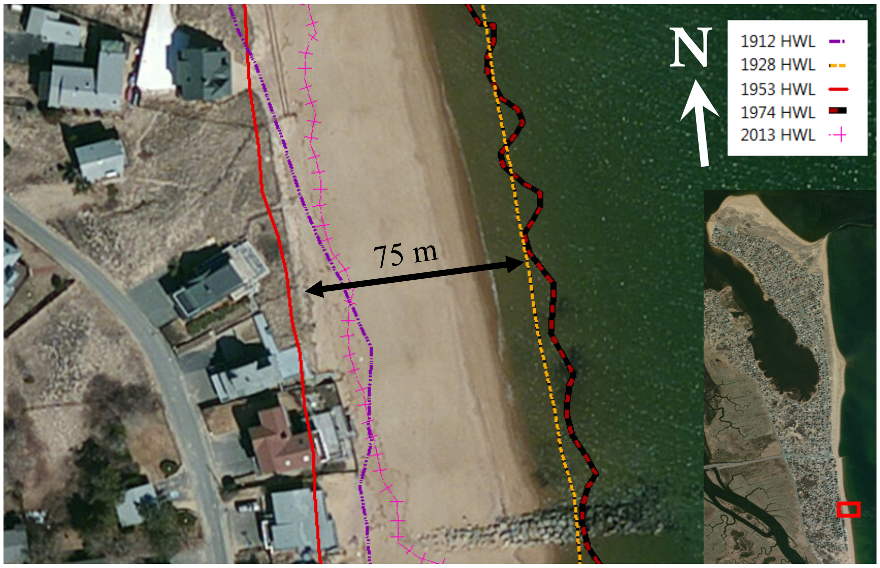

Figure 5: 50–60 year shoreline fluctuation from highly eroded landward position to long-term steady-state seaward position.

Discussion

Analysis of 102 years of HWL positions illustrates the complex erosional patterns of northern Plum Island. Most notably, there is no long-term trend of erosion and/or barrier retrogradation along this coast. Rather, this 2.8-km long section of beach experiences bi-directional fluctuations in HWLs across a 100-m wide shore-normal swath. These take the form of three superimposed trends: (1) a long-term fluctuation to and from a steady state HWL position (Fig. 4); (2) a 50-year cycle of erosion and accretion along the southern section of beach (Fig. 5); and (3) the migration of a 'hot spot' of erosion along the central and southern sections of the beach (Fig. 6).

There are numerous erosion mitigation structures that certainly contribute to the high variability of regional erosion. The jetty at the northern end of the island acts to fully stabilize the northernmost section of the beach. This, combined with abundant sediment supplied by a local reversal of southerly longshore transport due to wave refraction around the ebb-tidal delta, results in a consistently wide, healthy beach immediately south of the jetty. Moving further south along the island, a series of shore perpendicular groins have been installed. Four of these are visible today, however several others have been buried by beach and dune growth. Lastly, coir sand bags were used as dune stabilizers along the tombolo and center island after the period of erosion in 2008 (Fig. 1 & Fig. 3).

Over the period of study, the HWL of the developed section of Plum Island tends to revert to a long-term mean *steady state* position. The dominant trend along the island is a cycle of shifts between this steady state position and an erosive position located 20–100 m landward of the long-term average HWL (Fig. 4). The timing of this periodic retreat of the beach to this erosional position is not consistent along the beach. Rather, retreat occurs as a 200–1000 m long "hotspot" of erosion that forms in one location and migrates over a period of years along the island, before disappearing as the entire beach accretes. This indicates that there are localized factors controlling erosional patterns, which are superimposed upon a regional trend. Furthermore, these shifts do not occur with any regularity, nor are they of the same magnitude each time. This is particularly true in northern sections of the beach (for example, note the shorelines in 1928, 1953, 2005, and 2013 in Fig. 4). This indicates that the presence of erosional shorelines is likely due to a pattern of controlled events localized in a small area, and not necessarily caused by a large storm event, which would be more likely to cause coastline-wide change, or successive years of barrier-wide erosion driven by upstream sediment supply changes, inlet dredging, etc.

Mapping of the southern extent of our study area also captured a trend of shoreline variability spanning approximately 50 years (Fig. 5). Proximal to the two southern-most groins, a clear pattern exists of shoreline erosion to a maximum position approximately aligned with the 2014 dune toe (Fig. 3), followed by return to the steady-state position. The erosive position is located *ca.* 75 m landward of the long-term steady-state position (Fig. 5).

Investigation of the most recent period, for which we have the most frequent data and ground observations, provides for a high-resolution exploration of short-term HWL changes. Specifically, the region between Center Island and Annapolis Way (Fig. 6) has experienced alongshore heterogeneity in erosion over the past ten years. At Center Island, a period of gradual erosion is observed from 1994 until the point of maximum erosion in 2008; several houses along this section of beach were lost during winter storms in 2008. By 2014, however, the beach had completely healed, with the HWL returning to its steady state position. This cycle is also seen on the south end of Annapolis Way, which experienced gradual erosion from 1994 until 2014, at which time the beach was completely submerged at mid tide, leaving waves crashing along a rip-rap revetment emplaced in 2013. Together, these observations indicate that erosional patterns are not uniform along the beach, but are highly localized in an erosion "hot spot". Erosional shorelines develop gradually over several years, followed by very rapid (< 5 years) recovery and a return to the steady state shoreline position. The migration of this 'hot spot' demonstrates the dynamic nature of this beach, and the significant variability in beach width over just a few hundred meters.

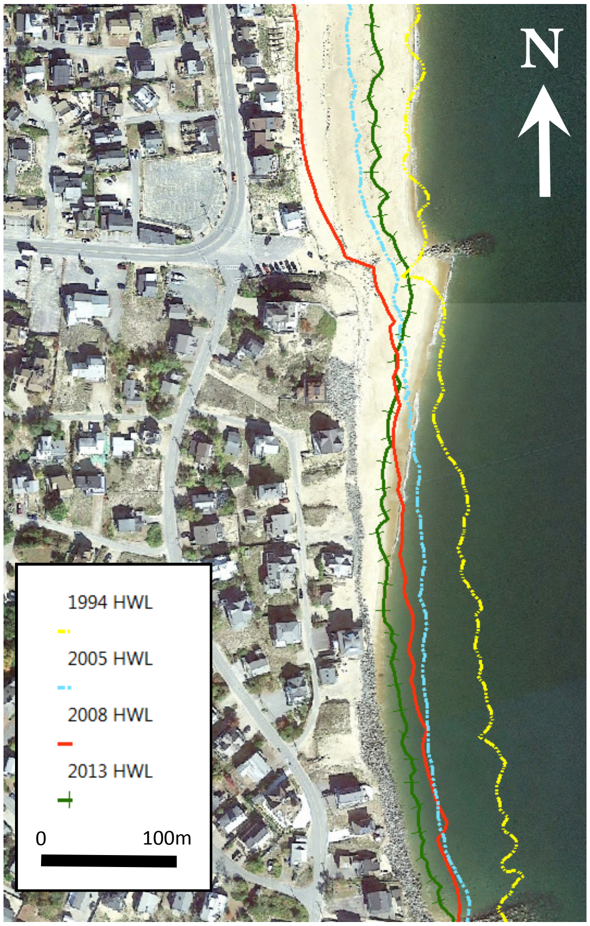

Fig 6: Short term shoreline fluctuations, illustrating the ephemeral 'hotspot' of erosion as is migrates from the Center Island groin south along Annapolis Way.

Hypothesized Mechanisms

It is hypothesized that periods of shoreline erosion are related to the temporary trapping of sediments in an expanded ebb-tidal delta offshore of the Merrimack River Inlet. This proposed mechanism is similar to that described for the jettied inlet system at Ocean City Inlet, MD, in which accretionary sand pulses on the downdrift Assateague Island were determined to have been caused by bypassing through the ebb-tidal delta (Kraus, 2000). Under these conditions on Plum Island, not only does growth of the ebb-delta and delta-attached bars starve the beach of sand, but wave refraction about the southern end of this delta bar focuses wave energy along narrow sections of the beach, driving the formation of the erosion hotspot. Elongation of this bar over time shifts the focus of wave energy, driving the hotspot further to the south.

Short-term erosion and hotspot migration are hypothesized to be further influenced by the erosion-mitigation structures emplaced along Plum Island (Fig. 3). This is most evident in observations of the recent formation and migration of an erosional hotspot between Center Island and Annapolis Way. Here, the hotspot migrated alongshore from Center Island in 2008 to 2014 on Annapolis Way (Fig. 6). At any given time the most severe erosion is focused on the north side of the adjacent groin. Scour and erosion on one side of a groin indicates downdrift transport, although dominant transport along Plum Island is to the south, driven by northeast storms. Thus, the pattern of erosion and deposition around the groins is evidence for reversal of longshore transport along northern Plum Island. Moreover, erosion on the downdrift (north) side of the groins is hypothesized to be amplified during winter storms. Storm waves produce channelized scour due to the flattening of the bathymetric profile along downdrift groins, thus creating short term (1–3 year) hot spots. Similar erosion patterns were seen at Fort Pierce, FL (Bruun 1995) where hurricane waves struck the downdrift side of jetties and groins, eroding the shoreline.

Conclusions

Mapping and analysis of HWLs from 1912 to 2014 along the developed beach at Plum Island, MA provide insight to the dynamics of the erosion at this beach drowndrift of the jettied Merrimack River Inlet. This system is highly dynamic, mimicking natural inlet-beach systems in which sediment delivery to the downdrift beach is largely controlled by dynamic inlet processes such as ebb-delta breaching. However, whereas cycles of ebb-delta breaching at natural inlets tend to operate on timescales of 4–8 years (FitzGerald 1982), shoreline erosion-accretion cycles on Plum Island occur at roughly 25–50 year intervals. The HWL along this beach has a long-term clear steady state position to which the shoreline consistently returns to after periods of erosion (Fig. 4). These erosional / accretional patterns are spatially non-uniform, with some sections of beach undergoing erosion at any given point in time, while others are stable in the long-term mean position. Moreover, certain sections of this beach experience longer term (~50-60 years) fluctuations, in which the shoreline position varies from the steady state location to the eroded position proximal to the oceanfront row of houses (Fig. 5). Finally, erosion is typically highly localized, commonly along as little as 100 m stretch of beach. These focused areas of erosion, or 'hotspots', are ephemeral features that migrate along the beach over periods of months to years.

The factors responsible for these cycles are hypothesized to include a combination of wave energy channelization along groins, ebb-delta bar attachment to the shoreface, and wave refraction around the ebb-tidal delta. These processes are the focus of future study.

These findings demonstrate that cyclical shoreline migration patterns along northern Plum Island are driven by interactions with the jettied Merrimack River Inlet. Furthermore, they demonstrate the importance of analyses over multiple timescales to fully understand the nature of changes along this beach. Proper management of Plum Island and other engineered inlets/beachfronts requires similar analyses at both historical and modern timescales to fully understand beach dynamics and to mitigate future accelerated coastal change.

References

Borns, W.H. Jr., Doner, L.A., Dorion, C.C., Jacobson, G.L. Jr, Kaplan, M.R., Kreutz, Kreutz, K.J., Lowell, T.V., Thompson, W.B., and Weddle, T.K. (2004) "The deglaciation of Maine, USA," *Developments in Quaternary Sciences*, 2, p. 89-109

Bruun, P. (1995) "The Development of Downdrift Erosion," *Journal of Coastal Research*,11, No. 4, 1242-1257

Fitzgerald, D. M., (1982). "Sediment Bypassing at Mixed Energy Tidal Inlets," *Proceedings 18th Coastal Engineering Conference*, American Society of Civil Engineers, 1094-1118.

FitzGerald, D. M. (1993) “Origin and Stability of Tidal Inlets in Massachusetts, in Formation and Evolution of Multiple Tidal Inlets” (eds D. G. Aubrey and G. S. Giese), *American Geophysical Union*, Washington, D. C.

Hein, C. J., Fitzgerald, D. M., Carruthers, E. A., Stone, B. D., Barnhardt, W. A., Gontz, A. M. (2012). “Refining the model of barrier island formation along a paraglacial coast in the Gulf of Maine,” *Marine Geology*, 307-310, 40-57

Hein, C. J., Fitzgerald, D.M., Buynevich, I.V., Van Heteren, S., and Kelley, J.T. (2014) “Evolution of paraglacial coasts in response to changes in fluvial sediment supply,” *Geological Society, London, Special Publication*, 388, 247-280

Hapke, C.J., Himmelstoss, E.A, Kratzmann, M.G., List, J.H. and Thieler, E.R. (2011) “National Assessment of Shoreline Change: Historical Shoreline Change along the New England and Mid-Atlantic Coasts,” *Open-File Report 2010-1118*, United States Geological Survey, 1-66

Kraus, N. C. (2000) “Reservoir Model of Ebb-Tidal Shoal Evolution and Sand Bypassing,” *J. Waterway, Port, Coastal, Ocean Engineering*, Nov/Dec 126, 305-313

Labaree, B. W. (1962) “Patriots and Partisans: The Merchants of Newburyport,” *Cambridge: Harvard University Press*, 1764-1815

McIntire, W.G. and Morgan J.P. (1964) “Recent Geomorphic History of Plum Island, Massachusetts and Adjacent Coasts,” *Louisiana State University Press*, Baton Rouge, Louisiana State University Coastal Studies Series, 1-44

Nichols, R.L. (1942). “Shoreline Changes on Plum Island, Massachusetts,” *American Journal of Science*, 240, 349-355

Oertel, G. F. (1985) “The Barrier Island system,” *Marine Geology*, 63, 1-18

Rhodes, E. G. (1973). “Pleistocene-Holocene sediments interpreted by seismic refraction and wash-bore sampling, Plum Island – Castle Neck, Massachusetts,” *Coastal Engineering Research Center (U.S.)*, USACE, 1-57.

Thieler, R. E., Smith, T.L., Knisel, J.M. and Sampson, D.W. (2013) “Massachusetts Shoreline Change Mapping and Analysis Project, 2013 Update,” *Open-File Report 2012-1189*, United States Geological Survey, 1-16.

U.S. Army Corps of Engineers, *War Department Annual Reports,* 1917, Volume 2, Report of the Chief of Engineers, 1918, pp. 69-70.