EXPLORING CENTENNIAL BARRIER-INLET EVOLUTION: INSIGHTS FROM UNDEVELOPED AND DEVELOPED PHASES AT BARNEGAT INLET, NEW JERSEY

SHANE NICHOLS-O'NEILL[1], JORGE LORENZO-TRUEBA[1], DANIEL J. CIARLETTA[2] AND JENNIFER L. MISELIS[2]

1. *Department of Earth and Environmental Studies, Montclair State University, 1 Normal Ave., Montclair, NJ 07043, USA. nicholsones1@montclair.edu, lorenzotruej@montclair.edu*
2. *U.S. Geological Survey, St. Petersburg Coastal and Marine Science Center, 600 4th St S, St. Petersburg, FL 33701, USA. dciarletta@usgs.gov, jmiselis@usgs.gov*

Abstract: Increasing costs of maintaining highly developed barrier islands can motivate changes in coastal management policies. A quantitative understanding of barrier island response to natural processes vs. coastal engineering can help guide new coastal management strategies. We analyze historical alongshore evolution and track coastal engineering efforts at the Island Beach–Barnegat Inlet–Long Beach Island, NJ barrier-inlet system, which has transitioned from natural to highly developed over the past 180 years. We build a quantitative mass-balance framework that tracks sediment reservoir volumes and transport fluxes within the barrier-inlet system to describe both the natural and developed alongshore evolution of this system. We find that minor coastal engineering efforts, including the construction of small-scale wood and stone jetties, not only shift sediment transport locally, but also shift system-wide sediment transport based on inlet-barrier island interactions and sediment partitioning.

Introduction

Societal benefits and ecosystem services provided by barrier islands are at risk as these dynamic landforms experience an increasing rate of sea-level rise (SLR) and changing storm patterns. Barrier morphologic response, which is the result of both natural processes and human activities, is difficult to quantify and presents challenges to future management (Hapke et al., 2013; Miselis and Lorenzo-Trueba, 2017). To further our understanding on the effects of natural processes and human development on decadal- to centennial-scale barrier island evolution, we investigate a mixed natural and developed coast comprising the alongshore-connected system of Island Beach (IB), Barnegat Inlet (BI), and Long Beach Island (LBI) in New Jersey (Figure 1a).

BI separates IB and LBI along New Jersey's southeastern shoreline. The region is characterized as a semidiurnal micro-tidal environment with southward alongshore sediment transport and significant wave height. Over the 20th century, substantial development has occurred at LBI and northern IB as these locations have emerged as major vacation destinations and tourist attractions. Conversely, southern IB has remained undeveloped as a protected space for recreation and wildlife management (Figure 1a).

Nautical charts and T-sheets cover the study area from 1839-present and help document the alongshore and cross-shore evolution as the system transitioned from natural to developed (Tenebruso et al., 2022). Within the chart record, the natural or undeveloped state is captured along with the more recent developed state of the barrier, allowing comparison between the system's natural evolution and its response to human development and coastal engineering. Specifically, the installation of small-scale jetties, beginning in the 1860s proved to be a pivotal interruption in the natural evolution of the barrier island system. Here we focus on documenting change in barrier morphology between 1839 and 1941 using GIS techniques and linking those changes to sediment storage and mass balance within the barrier system.

This study aims to identify the natural processes and the subsequent responses to coastal engineering and development on the alongshore evolution of the IB-BI-LBI inlet-barrier system. The primary focus will be the quantification of barrier island and inlet sediment partitioning at decadal to centennial timescales, from 1839-1941.

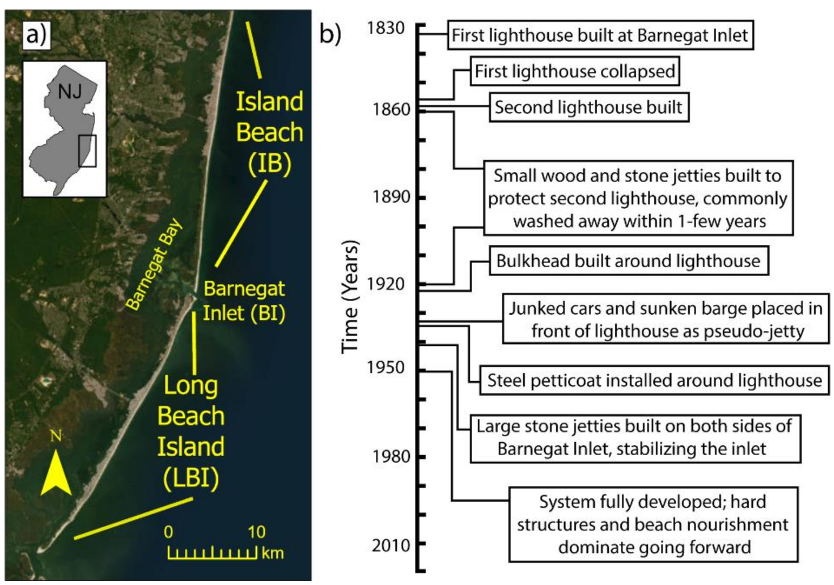

Fig. 1. (a) The IB-BI-LBI barrier-inlet system is located in southeastern New Jersey. (b) Coastal engineering timeline for northern LBI (James and Gifford, 2015). Base map image is the property of Esri and is used herein under license.

Background

Previous work quantified the morphologic response of LBI from 1839-present and identified two distinct phases of LBI evolution based on anthropogenic effects (Tenbruso et al., 2022). During the natural phase, from 1839-1934, the barrier-backbarrier system migrated landward under the influence of storm-driven overwash and SLR. During the developed phase, from 1934-present, anthropogenic effects changed the morphological response, including a reversal in the direction of ocean shoreline migration. This study focuses on quantifying alongshore morphologic variability and local-scale drivers of change. To this end, we study the natural to developed transition period in greater detail by combining a coastal engineering timeline with a map analysis of alongshore evolution.

Through the 19th century, BI's proximity to New York harbor made it important for ship navigation. A lighthouse was completed at the northern tip of LBI in 1835 to guide ships to BI. This lighthouse was destroyed in 1857 because of spit progradation processes. A second lighthouse was completed further south in 1859 and was soon at risk as BI continued to migrate south (Figure 2a). Beginning in the mid-1860s and through 1920, small-scale wooden and stone jetties were built to protect the second lighthouse. These structures were commonly destroyed within a few years. As LBI retreated putting the lighthouse at risk, coastal engineering efforts ramped up with concrete retaining walls built in 1908, installation of a steel petticoat around the lighthouse in 1934, and construction of large-scale stone jetties in 1940 (James and Gifford, 2015). We study the alongshore variability of coastal evolution during this natural to developed transition period to understand potential causes of the shift in LBI evolution .

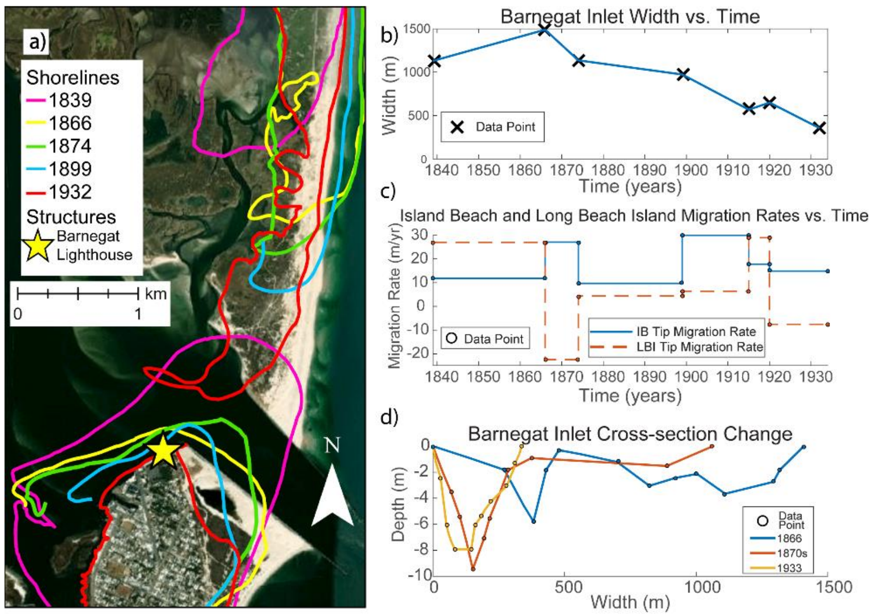

Fig. 2. (a) Map of Barnegat Inlet shorelines 1839-1932. (b) Barnegat Inlet width change over time. (c) Island Beach and Long Beach Island migration rates. (d) Barnegat Inlet cross-section change over time. Base map image is the property of Esri and is used herein under license. Copyright © 2022 and its licensors. All rights reserved.

Map Analysis

Historic maps of the study region, covering 1839-1941, were compiled, digitized and overlain to study alongshore evolution (NOAA OCS, 2004). Changes in system behavior were identified both temporally and spatially. Distinct shifts in alongshore evolution took place around 1875 and 1934. From 1839-1875 LBI and IB evolved rotationally as ocean shorelines for both barrier islands shifted landward near BI while ocean shorelines for both barrier islands shifted seaward distally from BI (Figure 3). Rotational evolution of the barrier islands ended by 1875 when ocean shorelines at northern IB and southern LBI also began to retreat, yielding an overall transgressive system (Figure 3). System behavior shifted again around 1930 when shorelines either stabilized or began to expand seaward. The 1930 shift in overall system behavior aligns with findings by Tenebruso et al. (2022), marking the effects of large-scale coastal engineering efforts at LBI.

Throughout both periods, magnitudes of cross-shore ocean shoreline movement were greatest near inlets. IB and LBI shoreline positions immediately adjacent to BI varied significantly more than stable island centers. The southern tip of IB (herein S IB) and northern tip of LBI (herein N LBI) migrated south at different rates until large-scale stone jetties were completed in 1941(Figure 2c). From 1839-1866 BI widened as N LBI migrated south at 27 m/yr., faster than S IB at 12 m/yr. From 1866-1941 migration of N LBI slowed to 1 m/yr. while S IB migrated at a relatively consistent rate of 18 m/yr., causing BI to narrow. BI narrowing accelerated over time until inlet stabilization. Depth data from nautical charts indicate BI deepened as it narrowed, from a maximum depth of 6 m in 1866 to 8 m in 1933 (NOAA OCS, 2004). BI's flood tidal delta continually grew from 1839-1957, throughout inlet widening, narrowing, migration and stabilization (Figure 4). Ebb tidal delta analysis was not performed due to limited availability of historic ebb tidal delta data. S LBI consistently elongated southward from 1840-1920 and narrowed from 1875 to 1920 (Figure 5).

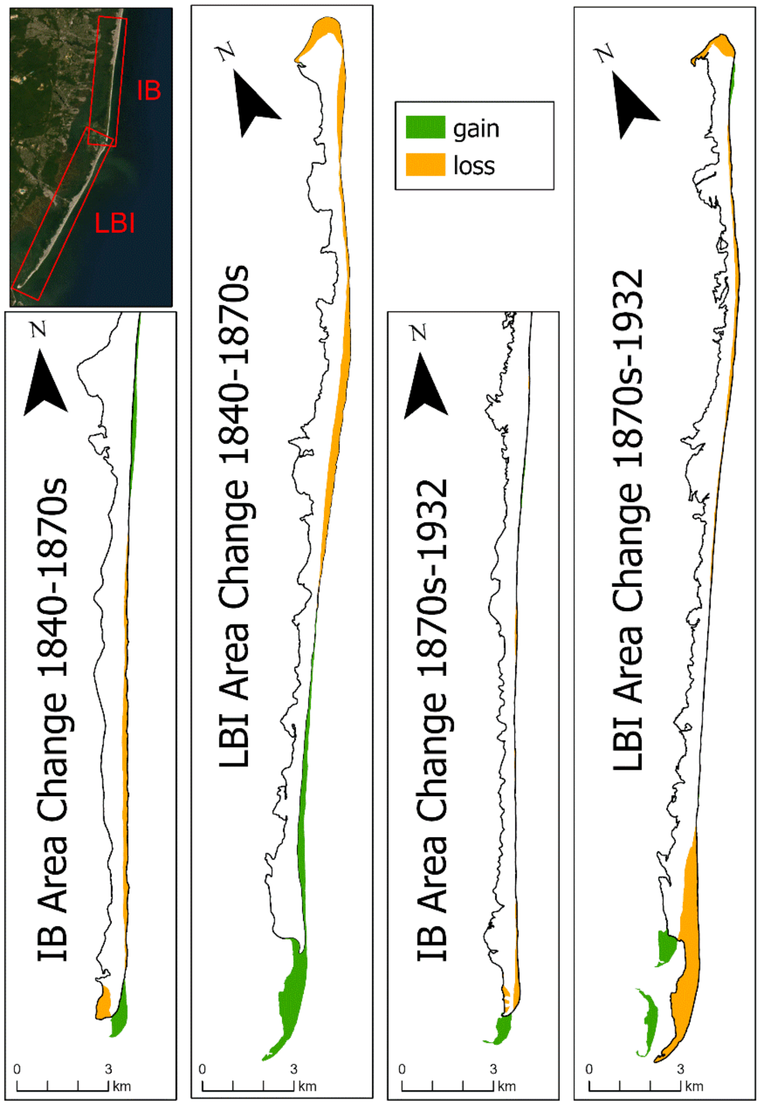

Fig. 3. Island Beach and Long Beach Island area change from 1840-1870s and 1870s-1932. Base map image is the property of Esri and is used herein under license. Copyright © 2022 and its licensors. All rights reserved.

A major shift in system behavior occurs around 1875 and is coincident with early coastal engineering efforts related to lighthouse protection. Therefore, we subdivide the natural phase defined by Tenebruso et al. (2022) into two sub-phases. First, the natural phase, from 1839-1875 and second, the transition phase, from 1875-1934. The change in system behavior is evidenced by the transition from barrier island rotation to transgression, the transition from inlet widening to inlet narrowing, and the decrease in N LBI's erosion. Analysis by Tenebruso et al., (2022) was unable to identify this system behavior shift as it did not include alongshore analysis nor BI evolution. The following will describe the natural and transition phase evolution from a mass-balance perspective, identifying changing sediment fluxes and reservoir volumes within the IB-BI-LBI barrier-inlet system.

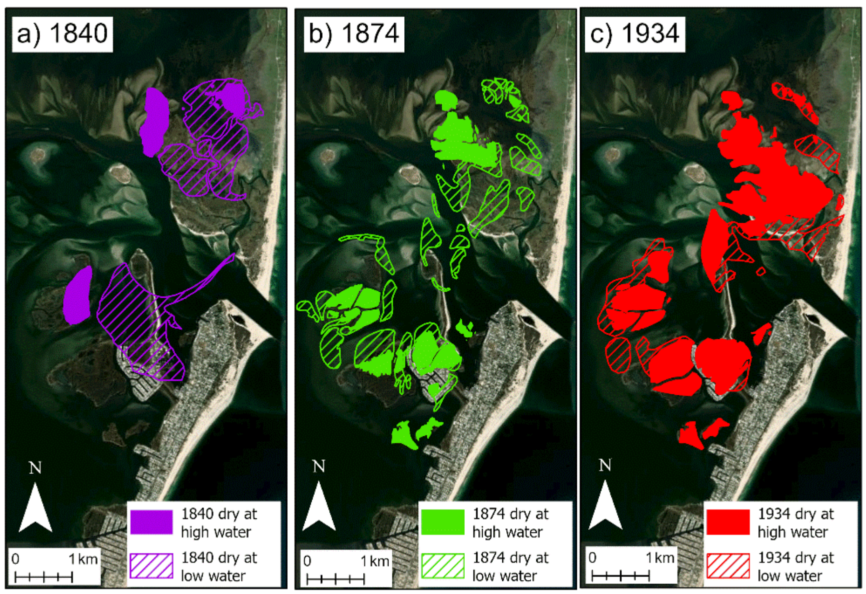

Fig. 4. Barnegat Inlet flood tidal delta evolution 1840-1934. Base map image is the property of Esri and is used herein under license. Copyright © 2022 and its licensors. All rights reserved.

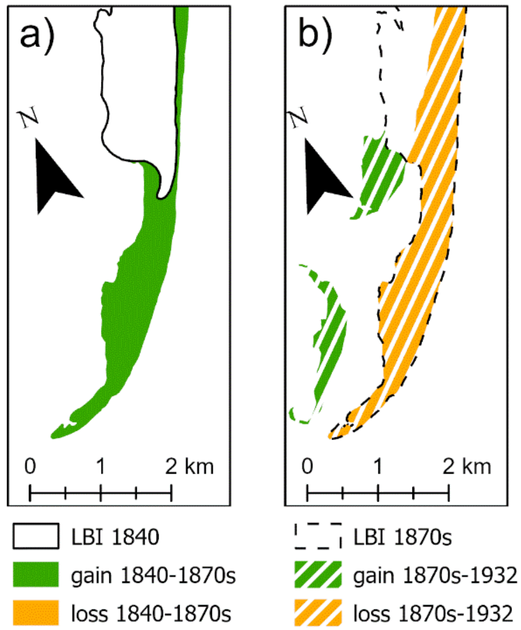

Fig. 5. (a) Southern LBI accretion 1840-1932.

Barrier-Inlet Mass-Balance Framework

We introduce an idealized geometry for a barrier-inlet-barrier system to quantify process-based changes in reservoir volumes (m^3) over time, including the updrift barrier, V_{ub}, flood tidal delta, V_{ftd}, downdrift barrier northern tip, $V_{dbnt,}$ and downdrift barrier, V_{db}, over decadal timescales (yrs.) (Figure 6). We identify 6 sediment transport fluxes (m^3/yr) that connect these reservoirs and move sediment through the system including sediment transport to the updrift barrier, Q_1; sediment transport leaving the updrift barrier, Q_2; sediment transport to the flood tidal delta, Q_3; sediment bypass, Q_4; sediment transport leaving the northern tip of the downdrift barrier, Q_5; and sediment leaving the downdrift barrier, Q_6. In this framework, the sum of flood tidal delta sediment transport flux and sediment bypass flux equal the sediment transport flux leaving the updrift barrier. Changes in these sediment transport fluxes alter system evolution and can explain major shifts in the IB-BI-LBI system.

Sediment volume change was estimated for each reservoir by assigning characteristic sediment depths to reservoir change areas measured in the map analysis. The flood tidal delta (FTD) sediment thickness (Z_{ftd}) was set to 1.5 m based on lagoon depth (D_L) Barrier thickness (Z_{ub} and Z_{db}) was set to 12 m based on shoreface depth (DT) (Figure 6). Reservoir volume changes per year are displayed in figure 7 for the natural and transition phases.

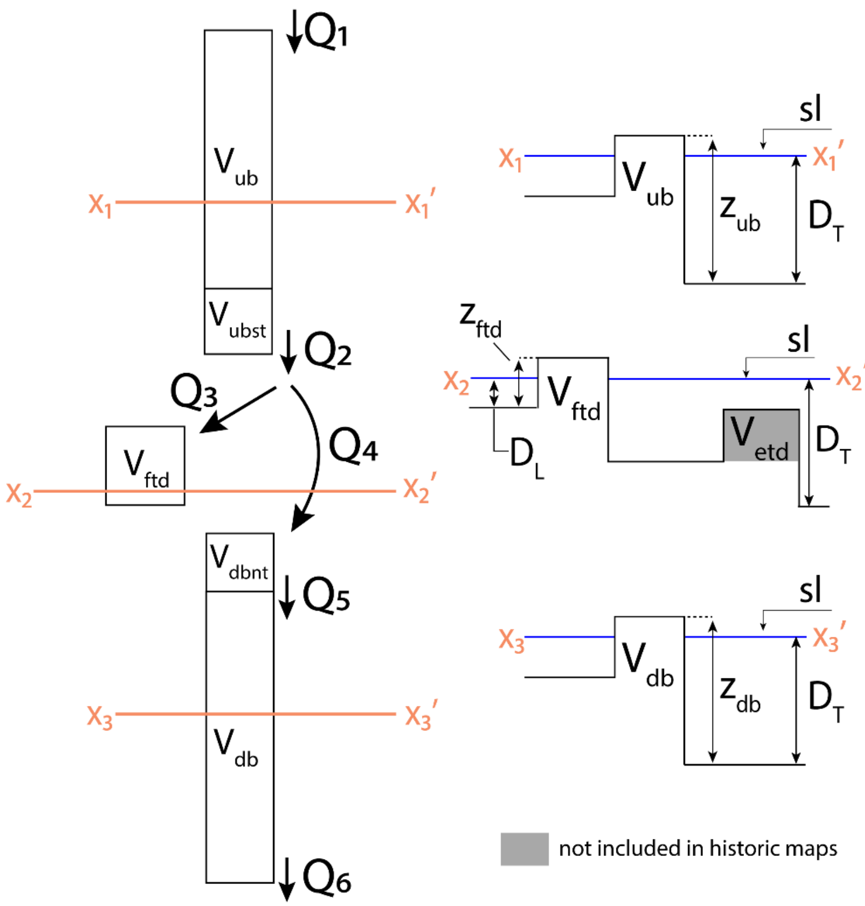

Fig. 6. Barrier-inlet system idealized geometry including sediment fluxes and sediment reservoirs in plan-view and cross-section.

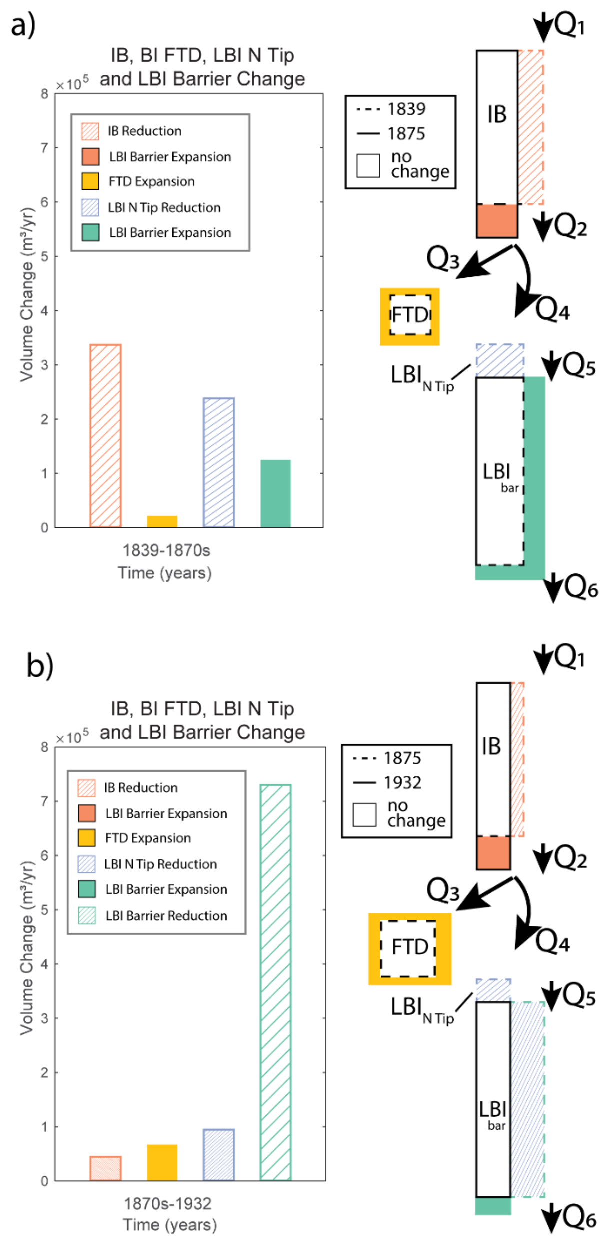

Fig. 7. Barrier-inlet system reservoir changer per year results. (a) Natural phase, 1839-1875. (b) Transition phase, 1875-1932.

Sediment transport to the updrift barrier (Q_1), between the natural and transition phases, is negligible, demonstrated by the limited shoreline change within the region directly updrift of the area of interest (Figure 3). The stability of the updrift shoreline is related to its position within the New Jersey coastal region's nodal zone (Figure 1; Ashley et al., 1986). The relatively constant system input over the period of interest enables the comparison of downdrift evolution between the natural and transition phases. Therefore, IB barrier volume change was controlled by the relative amount of sediment leaving IB (Q_2). The slowing of IB's area loss in the transition phase indicates a decrease in downdrift sediment transfer (Q2), which likely reduced the amount of sediment moving through and bypassing BI to LBI. Even though sediment input to the flood tidal delta (Q_2) decreased, the flood tidal delta growth accelerated from the natural to transition phase (Figure 7). This growth could be explained by a shift in sediment partitioning where Q_3 increased at the cost of Q_4, once again reducing the amount of sediment moving downdrift from the natural to transition phase.

N LBI is defined as a separate reservoir volume from the rest of the LBI barrier as it is the only location where coastal engineering structures were built prior to 1920. The small-scale jetties of the 19th century may not have completely halted N LBI's migration but did affect N LBI during the transition phase as the erosion of N LBI declined (Figures 4c and 8). The decline in N LBI's erosion reduced the volume of sediment leaving N LBI (Q5) which further starved the downdrift portion of the system. Reductions in multiple sediment fluxes due to slowdowns in updrift reservoir volume loss (Q_2 and Q_5) or a deviation in partitioning (Q_4) led to the major shift in LBI barrier evolution from overall gain, to major loss between the natural and transition phases (Figure 7). The shift in Q_4 and Q_5, two changes that helped to transform LBI into a transgressive system, coincide with the earliest coastal engineering structures at N LBI spatially and temporally. Therefore, we provide a mechanistic explanation for the processes that connect the construction of early coastal engineering structures to the shift in system behavior between the natural and transition phase.

Coastal Engineering and LBI Sediment Starvation

A decline in the growth of BI's flood tidal delta would be expected following the decline of sediment leaving IB (Q_2) in the transition phase. Instead, the rate of growth for BI's flood tidal delta tripled suggesting additional sediment was partitioned to the flood tidal delta (Q_3) at the expense of sediment bypass (Q_4). The shift in sediment partitioning coincides with the shift in inlet geometry between the natural and transition phases and could explain the consistent growth of the BI flood tidal delta despite inlet narrowing. To maintain a large enough cross-sectional area for BI's tidal prism, BI deepened as it narrowed during the transition phase. We suspect that the deeper and narrower inlet concentrated tidal flow, increased tidal flow velocity, and increased alongshore sediment capture from S IB (Q_3) (Hoan et al., 2011). Increased velocity also led to further inlet deepening, producing a positive-feedback cycle which accelerated sediment accumulation in the flood tidal delta (Q_3).

The additional partitioning of sediment to the flood tidal delta decreased sediment bypass to LBI, Q_4, reducing LBI sediment input and leading to the ultimate shift from rotational to regressive evolution during the transition phase. Although not included in this study due to a lack of historical map data, we expect the ebb tidal delta to grow along with the flood tidal and act as an additional sediment sink that also contributes to downdrift losses to LBI. Though, unlike IB, LBI shifted from overall sediment gain to overall sediment loss (Figure 7). The opposite is true for N LBI where sediment loss decreased from natural phase to transition phase (Figures 4 and 8). This local effect, likely the result of northern LBI jetty construction beginning in the 1860's, suggests even small-scale coastal engineering played a role in LBI alongshore evolution. Tenebruso et al. (2022) was unable to identify this local effect because cross-shore evolution was averaged over the entire island, missing alongshore variability.

Captured sediment by jetties at N LBI altered multiple sediment fluxes leading to downdrift starvation of LBI (Figure 7). First, they directly reduced the amount of sediment that left N LBI, Q5. Second, they contributed to the narrowing of BI which shifted inlet geometry, ultimately leading to increased sediment transport through the inlet (Q_3) at the cost of sediment bypass (Q_4), further starving LBI. Therefore, the cascading effects related to the construction of small-scale jetties at N LBI in the 1860's likely played a major role in the significant shift from accretion and elongation to erosion and retraction at LBI between the natural and transition phases.

Conclusion and Future Work

Our historical analysis provides insight into the major shift in drivers of morphological change at the IB-BI-LBI barrier system. Prior to the 1870s, natural processes led to a complex barrier-inlet interplay that involved inlet widening, slow flood tidal delta growth, and barrier island rotation. A major shift in system behavior took place in the 1870s when the inlet began to narrow, flood tidal delta growth accelerated, and barrier island rotation ended. The shift between these two periods coincided with the initial construction of small-scale coastal engineering structures at N LBI. These jetties slowed erosion of N LBI which not only directly starved the rest of LBI of sediment but also started a chain of processes that led to a shift in sediment partitioning, increasing sediment transport to the flood tidal delta and reducing sediment bypass, further starving LBI of sediment. Additional work is required to determine how quickly and to what degree sediment transport fluxes and reservoir volumes respond to individual natural processes and anthropogenic effects within the system.

Moving forward we hope to develop a numerical model to implement this mass-balance framework with the results from the map analysis, improve reservoir volume calculations with higher resolution map analysis, and examine empirical relationships that relate sediment fluxes to inlet geometry and tidal prism to further quantify the role coastal engineering plays compared to natural effects. Better understanding these different modes of past evolution can help to guide coastal management strategies as beach nourishment increases in cost, sea level-rise accelerates, and extreme storm patterns change.

Acknowledgements

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This work was supported by the U.S. Geological Survey Coastal and Marine Hazards and Resource Program. Additionally, federal funds as part of the Megalopolitan Coastal Transformation Hub under NSF award ICER-2103754.

References

Ashley, G. M., Halsey, S. D., and Buteux, C. B. (1986). New Jersey's longshore current pattern. *Journal of Coastal Research*, 453-463.

Hapke, C. J., Kratzmann, M. G., and Himmelstoss, E. A. (2013). Geomorphic and human influence on large-scale coastal change. *Geomorphology*, 199, 160-170. doi: https://doi.org/10.1016/j.geomorph.2012.11.025

Hoan, H., Hanson, H., Larson, M., and Kato, S. (2011). A mathematical model of spit growth and barrier elongation: Application to Fire Island Inlet (USA) and Badreveln Spit (Sweden). *Estuarine, Coastal and Shelf Science*, *93*(4), 468-477.

James, S. and Gifford, E. (2015). Cultural resources investigation data recovery for Barnegat Inlet north jetty unanticipated discovery Barnegat Inlet, New Jersey (Report number 34164.MAR). Panamerican Consultants Inc. URL: https://www.nap.usace.army.mil/Portals/39/docs/Civil/34164.m-Barnegat%20Shpwrk.pdf

Miselis, J. L., and Lorenzo-Trueba, J. (2017). Natural and human-induced variability in barrier-island response to sea level rise. *Geophysical Research Letters*, 44(23), 11-922. doi: https://doi.org/10.1002/2017GL074811

NOAA OCS. (2004). Office of Coast Survey's Historical Map & Chart Collection [Scanned Maps]. National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey (OCS). URL: https://historicalcharts.noaa.gov/ (Accessed April 2022)

Tenebruso, C., Nichols-O'Neill, S., Lorenzo-Trueba, J., Ciarletta, D. J., and Miselis, J. L. (2022). Undeveloped and developed phases in the centennial evolution of a barrier-marsh-lagoon system: The case of Long Beach Island, New Jersey. *Frontiers in Marine Science*, *9*.