

ASSESSING THE PERFORMANCE OF THREE CONSECUTIVE CYCLES OF BEACH NOURISHMENT ON TWO WEST-CENTRAL FLORIDA BARRIER ISLANDS

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Abstract: Three cycles of beach nourishment at two barrier islands: Sand Key and Treasure Island, were studied over 17 years. Seventy-four and 17 beach profiles spaced ~300 m apart were surveyed bimonthly to quarterly on Sand Key and Treasure Island, respectively. Six beach sections were distinguished based on beach dynamics, including 2 erosional hotspots, 1 gap in the nourishment and 3 typical erosive beaches. At most locations, the shoreline (defined at +1 m contour) returned to a similar location at the end of each cycle, indicating the nourishment successfully maintained the target beach width. The Treasure Island erosion hotspot experienced increased beach loss over time, suggesting that the current nourishment design may not be adequate. The gap in the nourishment did not experience significant sand gain on the dry beach. A mechanism to impound sand on the dry beach is necessary. The current nourishment successfully compensated the sand deficit. The mechanism causing sand deficit was not eliminated at all the sites, suggesting that the current nourishment design serves as a long-term maintenance strategy.

Introduction

Beach Nourishment is a dominant shore protection strategy in the United States (Elko et al., 2021). This method has largely replaced the use of traditional hard engineering structures, like breakwaters and groin fields. From a sediment budget point of view, beach erosion is a result of a sand deficit (Wang and Beck, 2022). Beach nourishment is the only approach that addresses the sand deficit issue directly by replacing the sand in the littoral system and allows natural forces to continue adjusting (NRC, 1995). Beach nourishment is often considered sacrificial; in that it must be conducted repeatedly at a certain time interval that is controlled by erosion rates at the specific site (Dean, 2002). Along beaches with high erosion rates, aka erosional hotspots, two options can be applied: more frequent nourishment or constructing a wider beach during each nourishment.

The Pinellas County coast, located in west-central Florida, includes three heavily developed barrier islands: Sand Key, Treasure Island and Long Key, with regularly nourished beaches. Sand Key is a 22-km long barrier island extending across a broad headland in the middle (Fig. 1). The beach nourishment was mostly conducted in the middle stretch of the island. Treasure Island is 5.4 km long with

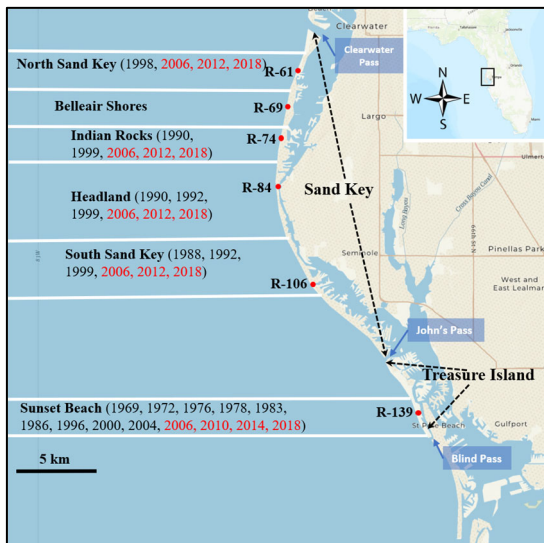


Fig. 1. Sand Key and Treasure Island, Florida, USA. Analyzed beach sections are shown with the dates of all nourishment projects and projects included in this study (red).

beach nourishment focused on the northern and southern ends. Long Key is 6.5 km long with nourishment also focused along the northern and southern ends.

Only the beach nourishment projects on two islands, Sand Key and Treasure Island, are analyzed in this paper. Beach profiles spaced at 300-m apart were surveyed bi-monthly to quarterly from 2006 to 2022 to quantify beach changes in association with the 3 nourishment cycles. Each beach profile extended from the dune field or seawall to about -3 m (NAVD88), or the short-term depth of closure in this area (Wang and Davis, 1999). Based on the extensive 17-year beach profile data, this study aims at answering the following questions: 1) Can beach nourishment eventually amend the sand deficit? 2) Can adjacent un-nourished beaches benefit from repeated beach nourishment and how? Or 3) Is beach nourishment mostly a long-term maintenance strategy?

Study Area

This study examines beach nourishment projects along two heavily developed barrier islands in west-central Florida: Sand Key and Treasure Island (Fig. 1). Regional scale beach nourishment on Sand Key started in the late 1980s and early 1990s (Fig. 2). To account for spatial variations caused by the two tidal inlets at the end and the broad headland in the middle, the long Sand Key nourishment is divided into 5 sections by this study (Fig. 1). The North Sand Key stretch is

2.1 km long and is a persistent erosional hotspot (Roberts and Wang, 2012; Cheng and Wang, 2022). Typically, the dry beach is widened by ~ 76 m per nourishment along this stretch. The Belleair Shores stretch is 1.8 km long and has never been nourished due to issues associated with land ownership. Indian Rocks stretch is 2.4 km long and located along the northern flank of the headland. Typically, the dry beach is widened by ~ 27 m. The Headland stretch is 3.9 km long and typically widened by ~ 27 m. South Sand Key is 3.3 km long and located along the southern flank of the headland and widened typically by ~ 27 m as well.

Beach nourishment on Treasure Island began in the late 1960s, being one of the earliest nourishments along the Gulf coast of Florida. Beach nourishment was conducted at the northern and southern ends, adjacent to the tidal inlets. The nourishment at the northern end is a short project of less than 0.5 km long and not included in this analysis. Sunset Beach at the southern end is 1.2 km long and is typically widened ~ 30 m per nourishment cycle. Sunset Beach is a persistent erosional hotspot (Roberts and Wang, 2012). Along Treasure Island, beach erosion and subsequent nourishment occur at both ends related to beach-inlet interaction, typical of Florida barrier islands (Dean, 1988; Wang and Beck, 2022). However, along Sand Key, the two ends are relatively stable due to long jetties at both tidal inlets and a groin field at the southern end of the island.

The total sand volume placed during each nourishment event and volume placed per year are illustrated in Fig. 2. The total volume of sand as well as volume per year placed in Sand Key and Treasure Island did not show a clear increasing or decreasing trend with time. Sand Key nourishment cycle ranged from 6 to 10 years. For the 3 studied cycles, the total amount of sand as well as the volume per year remained relatively constant, with slightly less sand used in the 2012 nourishment. For Treasure Island, four nourishment cycles were studied, at every 4 years. The amount of sand used in the nourishment increased from 2006 to 2018 nourishment. This beach is not expected to be nourished until 2024. That is the reason for the decreased volume per year for the 2018 cycle.

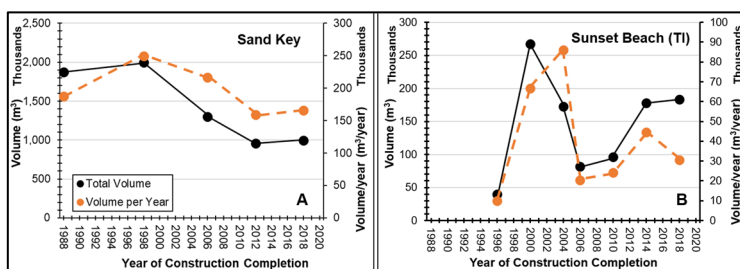


Fig. 2. Time-series total sand volume and volume per year at each nourishment event.

In summary, the six study sites (Fig. 1) represent a large range of beach conditions. North Sand Key represents an aggressive erosional hotspot. Sunset Beach represents a moderate erosional hotspot. Indian Rocks, Headland and South Sand Key represent roughly average conditions of a chronically eroding beach in the west-central Florida area. Belleair Shores represents a gap between two nourishment projects. These provide an opportunity to study long-term performances of beach nourishment projects.

Methods

Beach profiles, spaced ~300 m alongshore, were collected bimonthly to quarterly along the two islands since 2006, shortly after the nourishment that year. A total of 74 beach profiles on Sand Key and 17 on Treasure Island were surveyed over 17 years. The beach profile monitoring encompassed the entire islands including both nourished and un-nourished sections. In addition to regular monitoring, surveys immediately after storm impact were also conducted. Directly relevant to this study, Hurricane Hermine impacted the studied barrier islands in 2016 near the end of the 2012 nourishment cycle.

The beach profiles were surveyed following standard level-and-transit procedures using an electronic total survey station and a 4-m survey rod. All surveys were conducted using Florida State Plane West coordinate system in meters. The elevation was referred to NAVD88 which is 8.2 cm above mean sea level (MSL) in this area. The RMAP software, developed by the USACE, was used to analyze the beach profiles. RMAP allows extraction of contour locations and calculation of profile-volume changes. The -0.5 m contour was used to represent the seaward limit of the intertidal zone. The +1.0 m contour was used to represent the seaward limit of dry beach. Based on the characteristics of the beach profile and field observations, the seaward edge of the dunes was identified at each profile location. The distance between the dune edge and the +1.0 m contour represents the width of the dry beach. The difference between the dune edge and -0.5 m contour represents a maximum width of the beach extending to spring low tide. These two contours were used to examine the beach width after nourishment and near the end of the cycle, along with the temporal change. Beach profile volumes above +1.0 m and -0.5 m contour were calculated from the dune edge. The volume changes at the beginning and end of each nourishment cycle were used to evaluate the performance of the individual nourishment.

The 3 most recent Sand Key nourishments occurred in 2006, 2012, and 2018, or every 6 years. The end of nourishment was represented at approximately 4.2 years after the construction. This is because there is only 4.2 years of data for the 2018 nourishment. In addition, at some locations the beach was eroded to the seawall

after 4 years. The 4.2-year duration was used to maintain a consistent temporal scale of the different nourishment cycles. The nourishment interval at Treasure Island was shorter than that at Sand Key. Four nourishments were conducted in 2006, 2010, 2014, and 2018, with a cycle of 4 years, as used in this study. The long Sand Key project was divided into 4 sections based on background erosion rates, in addition to a gap in the nourishment (Fig. 1). The Sunset Beach nourishment on Treasure Island represents a modest erosional hotspot. The goal of distinguishing these sections is to quantify nourishment performance at a number of beaches with different morphodynamic conditions.

Results

North Sand Key is an aggressive and chronic erosional hotspot. Much more sand was placed along this section as compared to all the other sections (Fig. 3). The beach profile was shifted further seaward for the 2018 nourishment as compared to the 2012 and 2006 ones. However, at the end of the 3 nourishment cycles, all beach profiles retreated to a similar position (Fig. 3A). Hurricane Hermine impacted the study area near the end of the 2012 nourishment cycle and caused more erosion at the already depleted beach. There are modest longshore variations along the North Sand Key project (Fig. 4A). Profile R-61 represents an extreme example although other profiles show a similar trend but with a generally smaller magnitude. The dry beach width at the end of the nourishment shows less longshore variation (Fig. 4B) while the width of the dry and intertidal beach demonstrates greater variability (Fig. 4A). The dry beach width is a more consistent indicator than the dry-intertidal beach width, which is influenced by the foreshore slope that changes regularly with tidal fluctuation and wave condition changes (Roberts and Wang, 2012; Wang et al., 2020). Along this section, the dry beach width changes ranges from about 10 m to nearly 60 m at R-61 (Fig. 5A). The beach change during the 2nd nourishment cycle is greater than the other 2 cycles due to hurricane Hermine's impact at the end of the cycle. The average beach width loss, excluding R-58 and R-65A at the two ends, was 26 m, 49 m and 35 m in 2006, 2012 and 2018 respectively. As expected, the volume loss follows a similar spatial trend to the dry beach width change (Fig. 5B). The average volume loss is 12 m³/m, 16 m³/m and 11 m³/m for each cycle. Overall, the repeated beach nourishment did not result in a progressively wider dry beach. The beach retreated to similar locations at the end of each cycle.

Belleair Shores, located directly south of the North Sand Key represents a gap in the nourishment (Fig. 1). No sand was ever placed along this section. The sub-aerial portion of the beach profile showed little change (Fig. 3B). In contrast, significant change occurred along the sub-aqueous part of the profile with a generally accretionary trend. During the 3 nourishment cycles, the width of both

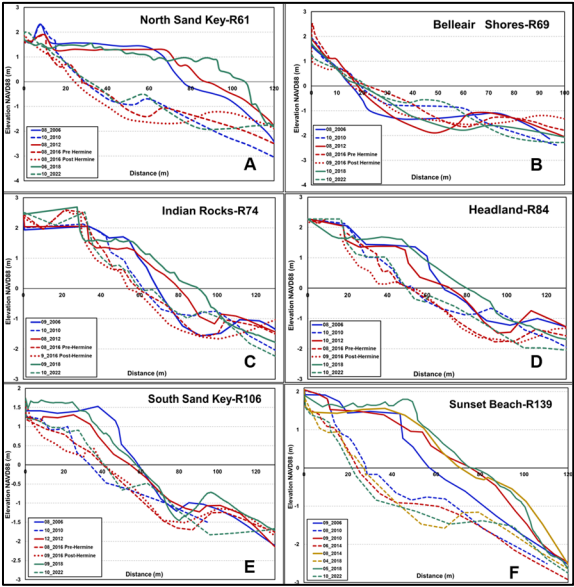


Fig. 3. Beach profile changes at the beginning and end of each nourishment cycle at the 6 sites.

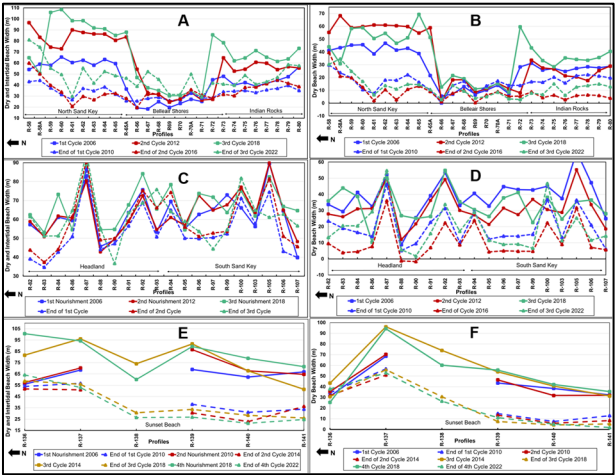


Fig. 4. Contour location changes at the start and end of each nourishment cycle at -0.5 m (left panels) and +1 m (right panels), representing the dry and intertidal beach and the dry beach.

the dry and intertidal beach remained rather similar (Figs. 4A and 4B). Along this section, the dry beach width changes ranges from a ~7 m gain, to a ~10 m loss, both occurred at R-67 (Fig. 6A). The dry beach width gained during the 2006

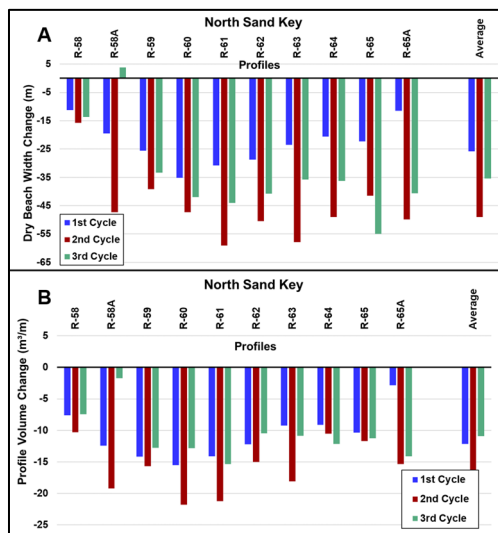


Fig. 5. North Sand Key dry beach width change and dry beach profile-volume change.

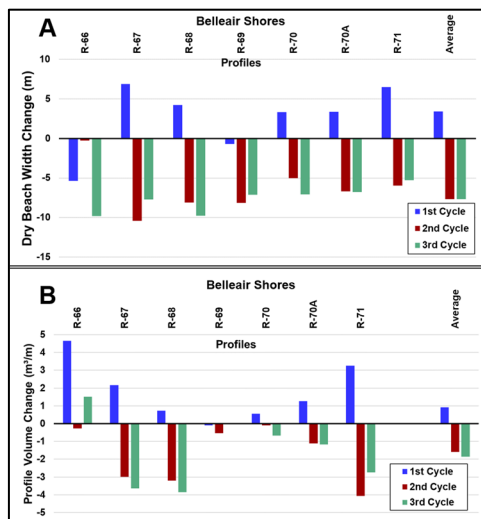


Fig. 6. Belleair Shores dry beach width change and dry beach profile volume change.

nourishment cycle but showed loss during the 2012 and 2018 cycles. The average beach width change, excluding R-66 and R-71 at the two ends, was +4 m, -8 m and -8 m in 2006, 2012 and 2018 respectively. Similar to the beach width change, the volume change shows a significant temporal and spatial variation (Fig. 6B).

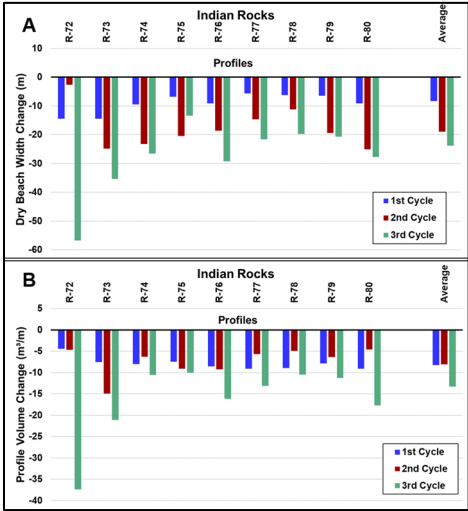


Fig. 7. Indian Rocks dry beach width change and dry beach profile volume change.

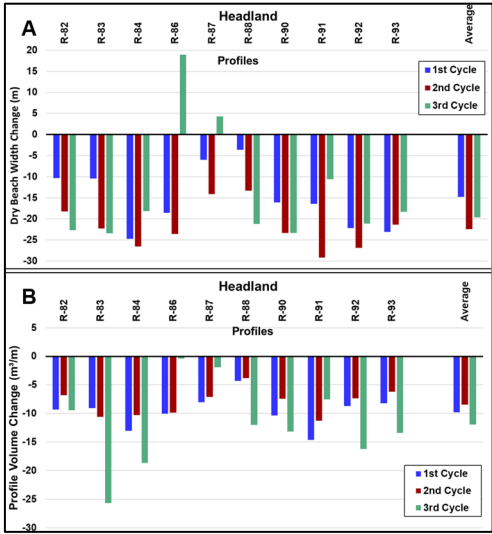


Fig. 8. Headland dry beach width change and dry beach profile volume change.

The average profile-volume change was $\sim 1 \text{ m}^3/\text{m}$ gain, $1.6 \text{ m}^3/\text{m}$ loss and $1.9 \text{ m}^3/\text{m}$ loss for each cycle. Overall, the non-nourished section, despite being located directly next to an aggressively nourished beach, did not gain persistent amount of sand on the dry beach and in the intertidal zone.

The Headland section has a shoreline orientation change of 65° from northwest to southwest facing (Fig. 1). The beach profiles at the end of each cycle retreated to a similar position (Fig. 3D). Hurricane Hermine caused more erosion on the dry beach at this example than at the other examples (Fig. 3). Different from the 3 sections to the north, there are considerable longshore variations in terms of beach width along this section (Figs. 4C and 4D). The width of the dry beach was considerably less than the dry-intertidal beach, suggesting a wider and gentler intertidal zone. A complication arose during the 2018 nourishment of this section. Profiles R-86 and R-87 were not nourished due to land-ownership issues. The dry beach width gains at these 2 locations (Fig. 8A) resulted from longshore spreading of adjacent nourished profiles. To make matters more complicated, the +1 m contour location (Fig. 9, black arrows) did not properly reflect the beach width change. This also explains the small profile-volume loss despite the substantial dry beach width gain. The dry beach width losses range from 3.5 m to 29 m (Fig. 8A). The average beach width loss, excluding R-82 and R-93 at both ends, as well as R-86 and R-87, was 15 m, 22 m and 20 m in 2006, 2012 and 2018, respectively. The average profile-volume loss was $10 \text{ m}^3/\text{m}$, $8 \text{ m}^3/\text{m}$ and $12 \text{ m}^3/\text{m}$, respectively (Fig. 8B). Overall, the dry beach width change, and profile volume loss were greater during the 2012 and 2018 cycles, than during the 2006 cycle. The large loss in 2016 was related to Hurricane Hermine.

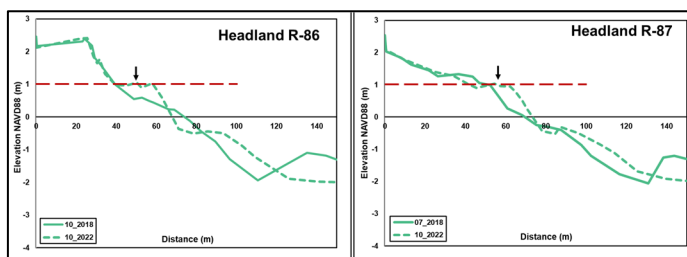


Fig. 9. Beach profiles R86 and R87 that were not nourished in 2018 at the Headland section.

South Sand Key is located south of the Headland facing southwest (Fig. 1). Both the sub-aerial and sub-aqueous portions of the beach profiles showed substantial change after each nourishment cycle (Fig. 3E). It is worth noting that the example profile of R-106 is located near the south end of the Sand Key nourishment project. In addition, the performance of this section of the beach is influenced by a breakwater in the vicinity of profile R-101. The beach was not nourished in the vicinity of the breakwater because the intertidal beach extends almost to the structure since its construction in 1989. The breakwater induced considerable longshore variation (Figs. 4A and 4B). The average beach width loss, excluding R-94 and R-107 at both ends, was 25 m, 22 m and 17 m in 2006, 2012 and 2018, respectively, illustrating a decreasing trend over time (Fig. 10A). The average

volume loss was 12 m³/m, 6 m³/m and 10 m³/m, respectively (Fig. 10B). The beach performance was influenced by the breakwater in the middle of the section.

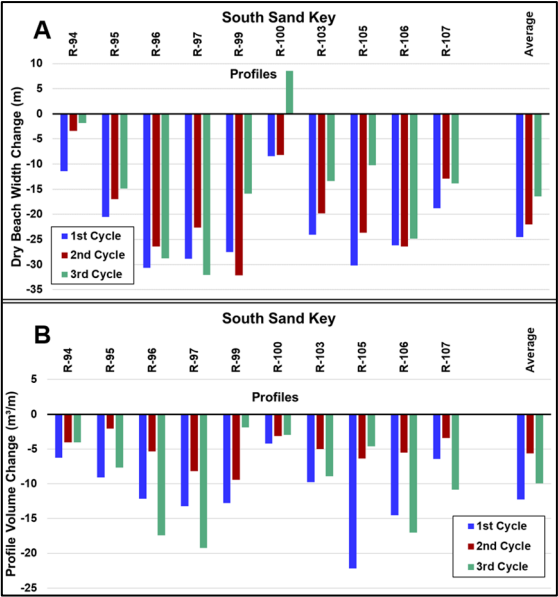


Fig. 10. South Sand Key dry beach width change and dry beach profile volume change.

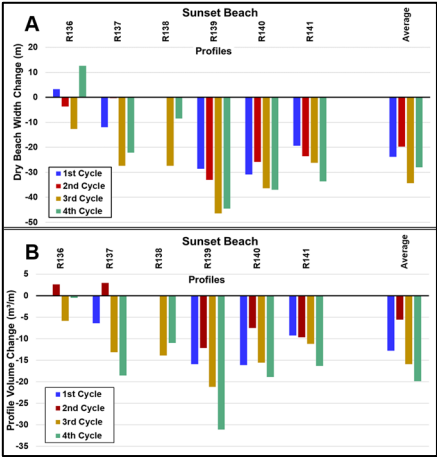


Fig. 11. Sunset Beach dry beach width change and dry beach profile volume change.

Sunset Beach is located near the south end of Treasure Island (Fig. 1). This section is a persistent erosional hotspot. Unlike Sand Key, Treasure Island was nourished 4 times since 2006. The beach profile was constructed further seaward during each nourishment cycle (Fig. 3F). However, the entire profile retreated further landward at the end of each cycle. This suggests the erosion rate is increasing over time. The cause of the erosional hotspot at this location is related to the wave shadow zone from Johns Pass ebb delta to the north and the relic dredge pit from the 1960s about 300 m from the shoreline (Beck and Wang, 2019; Roberts and Wang, 2012). The temporal trend of increasing beach-width loss (Fig. 3F) was measured at all the profiles (Figs. 4E and 4F). The average beach-width loss, excluding R-136 and R-141 at the two ends, was 24 m, 20 m, 34 m and 28 m in 2006, 2010, 2014 and 2018, respectively, illustrating a general increasing trend over time (Fig. 11A). The average profile-volume loss was 13 m³/m, 6 m³/m, 16 m³/m and 20 m³/m, respectively (Fig. 11B). Overall, due to the increasing erosion rate, this section requires more sand to maintain the beach width.

Discussion

The 5 segments on Sand Key and 1 on Treasure Island represent a variety of beach conditions including two erosional hotspots, one section of a narrow beach that has never been nourished, and three typical erosive beaches. The performance of 3 consecutive cycles of nourishment at these beaches are discussed here.

Beach Nourishment Performance at the Erosional Hotspots

The North Sand Key erosional hotspot is caused by a divergent longshore sand transport (Cheng and Wang, 2022). The chronicle and aggressive erosion was caused by a large gradient of longshore transport in both northerly and southerly directions. The erosion by the longshore transport gradient explains the landward shift of the entire profile while the profile shape remains relatively consistent (Fig. 3A). Since the sand that was put on the beach moved alongshore and out of the section, the repeated nourishment has not fundamentally changed the beach process, e.g., patterns of wave shoaling and breaking. At the end of each cycle, up to 85% of the sand that was added to the dry beach was eroded (Fig. 12A). The current nourishment design has successfully maintained a roughly 10 m dry beach width at the end of every cycle. Continued beach nourishment with a similar design at a similar interval will be needed to maintain this beach. If the existing nourishment cycle stops, the existing beach and dune will be eroded.

The Sunset Beach erosional hotspot is caused by a longshore transport gradient due to the shadowing of energetic northerly approaching waves by Johns Pass ebb delta (Beck and Wang, 2019). In addition, a dredge pit at ~300 to 500 m from the

shoreline along this stretch resulted in slightly higher waves as compared to the beach to the north. The dredge pit served as the borrow area for the 1969 beach nourishment. This constitutes as an example of negative impact of nearshore sand borrowing for beach nourishment, which is now largely prohibited. The chronicle erosion along this section was caused by a large gradient of longshore transport in the southerly direction. The erosion by longshore transport gradient explains the landward shift of the entire profile while the profile shape remains consistent (Fig. 3F). The dry beach width decreased progressively after each nourishment, suggesting an increasing erosion rate. At the end of each nourishment cycle, almost 100% of the sand that was added to the dry beach was eroded (Fig. 12B). Therefore, the current design of the Sunset Beach nourishment is not adequate to maintain a stable dry beach. Field observations indicate that active dune scarping is occurring during energetic conditions along this stretch. More sand and a wider beach are required for future nourishments.

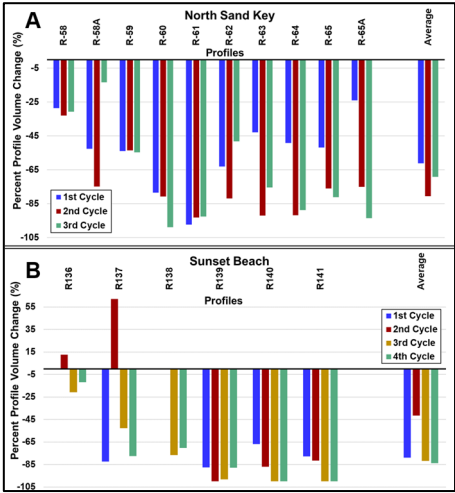


Fig. 12. Percent volume change at the erosional hotspots: Sunset Beach and North Sand Key.

Performance of a Beach Between Two Nourished Sections

The Belleair Shores section is located between the nourished North Sand Key and Indian Rocks sections. Substantial amount of sand from the North Sand Key nourishment is transported alongshore in both directions. The northward moving sand is being impounded by the south jetty of Clearwater Pass (Fig. 1), resulting in a wide and accretionary beach south of the jetty. However, the southward longshore transport did not result in a dry beach gain at Belleair Shores. Some sand deposition occurred in the subtidal zone, resulting in a wider and shallower

platform in the nearshore (Fig. 3B). The dry beach, backed by a seawall has been mostly less than 10 m wide over the past 17 years (Fig. 4B). The beach remained consistently narrow even directly adjacent to the nourishment projects to the north and south. The beach tends to be eroded to the seawall after energetic events and would recover some after (Fig. 3B). There has not been an overwhelming storm during the 17-year study period that overtopped the seawall. After the first nourishment cycle, the beach gained up to 5 m of dry beach width. This small gain did not fundamentally change the beach status and is well within the range of seasonal variations. During the following two nourishment cycles, relatively small dry beach width and profile volume loss were measured (Fig. 6).

Overall, Belleair Shores section did not directly benefit from adjacent beach nourishments, at least in terms of dry beach width. There is no mechanism to impound the southward moving sand from the longshore spreading of the North Sand Key nourishment, nor the northward moving sand from the Indian Rocks section. Therefore, in order for a beach to benefit from adjacent beach fill, a mechanism that can impound longshore moving sand is necessary, e.g., a groin or breakwater. However, groins or breakwaters can have negative impacts to the downdrift beach such as at South Sand Key beach, as discussed in the following.

Beach Nourishment Performance Along Typical Sections

For the Indian Rocks, Headland, and South Sand Key sections, all beach profiles retreated to similar locations at the end of each nourishment cycle (Figs. 3C, 3D, 3E). Different from the two erosional hotspots, a substantial nearshore bar exists. The sand bar tends to move onshore during the summer and offshore during the winter. The offshore sandbar movement can also be driven by energetic events (Cheng et al., 2015; Cheng and Wang, 2018). These sections did not show an apparent and persistent trend of longshore transport gradient, unlike the two erosional hotspots. A substantial amount of the placed sand moved offshore and onshore and stayed within the stretch of the beach.

A dry beach width between 5 to 25 m is maintained by the nourishment cycles. Significant longshore variation occurred along the Headland. This may be caused by spatial variations of offshore bathymetry. The longshore variation at South Sand Key is caused by the breakwater that was constructed in 1989, before the start of the large-scale beach nourishment. The beach profile downdrift of the breakwater experience the largest dry beach loss (Figs. 4C and 4D). Overall, these three sections of the beach were successfully maintained by the nourishment cycles. The current nourishment design is adequate, although the mechanism causing the sand deficit was not eliminated by the nourishment cycles.

Conclusions

The following conclusions can be drawn from the above analysis:

- 1) The repeated nourishment successfully maintained a minimum 10 m dry beach width at the North Sand Key erosional hotspot. The current design at Sunset Beach erosional hotspot is not sufficient because the dry beach becomes progressively narrower at the end of each nourishment cycle.
- 2) The gap in the nourishment on Sand Key did not gain any persistent and significant dry beach width.
- 3) Along typically erosive beach sections, the repeated nourishment successfully maintained the target beach width.
- 4) The current nourishment successfully compensated the sand deficit. Improved nourishment design is needed to mitigate the cause of erosion.

Acknowledgments

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