BARRIER ISLAND HABITAT CREATION AT DECADAL SCALES

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Abstract: Two shoal-bypassing events at the updrift end of Kiawah Island, South Carolina (USA), between 1990 and 2006 added ~4 million cubic meters (m^3) of sand and created a 5-kilometer-long barrier beach/lagoon system. The volumes in the bypassing shoals were sufficient to advance the shoreline over 500 meters (m) and to form an ~100-hectare lagoon. Oceanic habitat was rapidly transformed to sheltered lagoon/marsh habitat with salt marsh dominating the lagoon within ~10 years. The accretion density of the bypassing shoals was ~1,000 m^3/m relative to the prior shoreline. This volume input accounts for the large advancement of the shoreline. Habitat evolution is being monitored via ground surveys and digital terrain models using site-specific elevation criteria for intertidal zones, washover areas, and marsh expansion. The shoal-bypassing events at Kiawah Island are believed to dwarf volumes of any previously documented event. The barrier-beach/lagoon system formed by the episodic influxes of sand demonstrates the potential rapidity of barrier-island formation. Unit accretion density is a simple parameter that can be used to project the shoreline displacement and ultimate width of the lagoon.

Introduction

Barrier islands are wave-built landforms separated from the mainland and generally parallel to the principal strand line of the coast (Hayes 1994). They are most common in microtidal [tide range <2 meters (m)] settings where there is ample sediment supply and a gently sloping inner shelf. The U.S. East and Gulf coasts consist of a nearly continuous string of barrier islands. The separation distance between present-day barrier islands and the mainland varies from tens of meters to more than 50 kilometers (km), while the intervening lagoons may range from shallow open water to marsh-dominated habitat. Barrier spits are related forms attached to the mainland.

The specific modes and rates of barrier island formation remain debatable from site to site with strong evidence for multiple causality (Schwartz 1971). Among the theories receiving acceptance are:

- Emergent Bar Formation – whereby sediments in shallow bars are pushed landward and upward by waves to create the feature (e.g., Johnson 1919).

- Spit Growth and Breaching – whereby spits grow via longshore transport from sediment-rich headlands, then breach leaving an isolated island and the enclosed lagoon (Gilbert 1885).

- In-place Drowning of Coastal Ridges – whereby high-relief dunes at the shoreline become isolated from the coastal plain as sea-level rise inundates lower interior areas (e.g., Hoyt 1967).

- Transgressive/Regressive Interfluve Hypothesis – whereby delta deposits associated with drowned river valleys provide ample sediments to constrict the mouths of estuaries and to create inlets and beach-ridge barrier islands once the rate of sea-level rise slows (e.g., Hayes 1994).

The rate at which barrier islands and their associated lagoon habitats form and evolve remains uncertain. Kana (2002) presented evidence for small-scale barrier-island or barrier-spit formation at decadal time scales via the process of shoal bypassing. Using case examples from South Carolina, Kana demonstrated that episodic bypassing events involving shoals of the order one million cubic meters tend to cause the receiving shoreline to jump hundreds of meters seaward. The new beach ridge creates a lagoon in its lee which is soon converted from a high-energy oceanic environment to a sheltered estuarine environment.

The present paper builds on this idea of emergent bar formation of barrier islands, using an example from the eastern end of Kiawah Island, SC (Fig 1). It provides additional evidence for barrier-island habitat creation at decadal scales. The unit density of the accreting shoal above closure depth is shown to be an important parameter in establishing scales of the incipient barrier-island system.

Fig. 1. Study location.

Setting and Recent Shoreline History

Kiawah Island (SC, USA) is a 15-km-long beach-ridge barrier island with a history of accretion in the 20th century (Hayes 1994). It is flanked by Stono Inlet at the updrift (east) end and has a characteristic drumstick morphology due to the sheltering effect of the adjacent ebb-tidal delta. Stono Inlet is one of the largest on the U.S. East Coast with a delta volume of the order 100 million cubic meters (Sexton and Hayes 1996). Gaudiano and Kana (2001) reported frequent shoal-bypassing events from the ebb-tidal delta to the eastern end of Kiawah Island, ranging in volume from ~25,000–421,000 cubic meters (m^3) with a mean event interval of ~7.6 years. Kiawah Island is a mixed-energy setting (Hayes 1994) with a spring tidal range of 1.92 m and typical breaking wave height of ~0.5 m.

During the past 150 years, the eastern end of Kiawah Island has grown ~1.5 km seaward via successive shoal-bypassing events. Bars emerge off the eastern end of the island near the terminus of the Stono Inlet ebb-tidal delta. The delta provides a broad, shallow swash platform in water depths less than the local, estimated depth of closure of (~)-4 m mean sea level (MSL). Bars coalesce by waves and emerge at low tide some distance off the beach. Shoal bypassing is the sequence of bar emergence, shoreward migration, and welding to the receiving beach (Kana et al 1999).

Figure 2 shows the eastern end of Kiawah Island in 1973, 1983, and 1994. A prominent salient in the shoreline occurs 1 km west of Stono Inlet, giving Kiawah its bulbous updrift form.

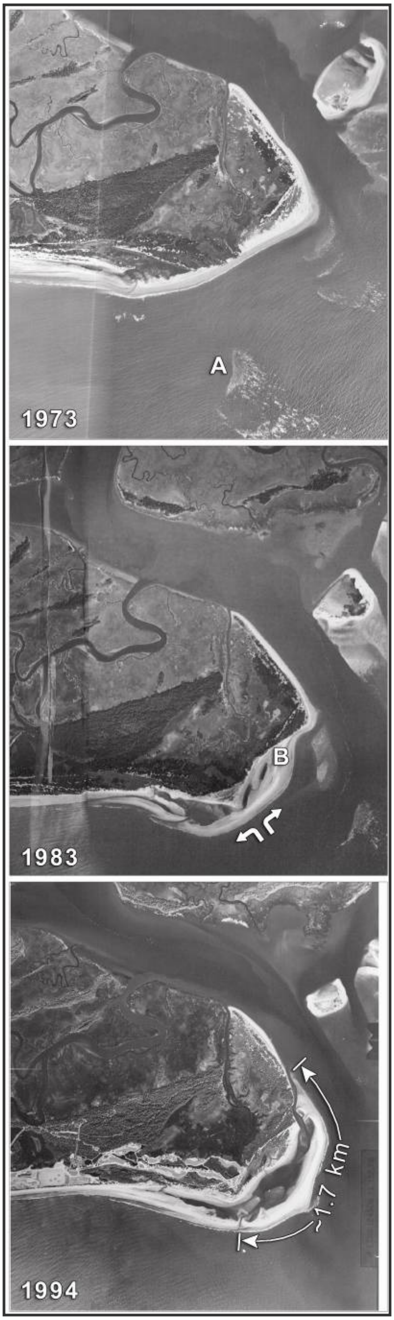

Fig. 2. The eastern end of Kiawah Island and Stono Inlet. See text for explanations.
[Source Images: USDA Soil Conservation Service]

Bypassing shoals typically originate south of the salient (see breaking waves over Shoal A in the 1973 image). As shoals emerge and are subject to wave breaking and overtopping at high tide, they migrate onshore at rates of the order 50–100 meters per year (m/yr). Once attached to the beach, the shoal volumes spread laterally in both directions (arrows on 1983 image). During the attachment period, swales in the lee of the shoal will become isolated until washovers push sand into the area and complete the cycle of beach-ridge building. Signatures of past shoal-bypassing events are ubiquitous at Kiawah Island with numerous forested ridges separated by brackish wetland or salt-marsh swales.

Between 1983 and 1990, the eastern half of the accreting shoal (B) in the middle image of Figure 2 merged with the beach and became vegetated over its length. A subsequent shoal-bypass event was initiated around 1990, leading to an even larger accumulation of sand in the form of a mini barrier-island/lagoon system at the eastern end of the island by 1994 (Fig 2, lower image). Measured from inlet to inlet, the mini barrier island in the 1994 image is over 1.7 km long. The incipient outer beach is positioned ~500 m seaward of the 1983 shoreline, leaving an ~30-hectare (ha) lagoon in between. While no comparative surveys are available for the 1990 to 1994 period, the scale of the incipient barrier island/lagoon system is estimated by the authors to have a unit volume density* of the order 1,000 cubic meter per meter (m^3/m). Thus, the developing system illustrated in the 1994 image represents roughly 1.5–2 million cubic meters of accretion.

> *[*Volume of sediment per meter of shoreline above depth of closure measured from the pre-bypass beach to the new outer beach.]*

During the late 1990s, a second bypassing shoal emerged off Kiawah's eastern end and proceeded to migrate shoreward (Fig 3). As it merged with the outer beach, the eastern margin of the shoal added new volume to form multiple beach ridges along the "1994" barrier beach. Longshore transport locally directed north into Stono Inlet eventually resulted in closure of the flushing channel at the northern end of the incipient lagoon. Meanwhile, the western flank of the second shoal began to elongate toward the west. By 2005 (Fig 4), the "1997" shoal had formed a new outer beach extending 2,000 m west and positioned up to 800 m from the prior ocean shoreline. Volumes associated with the first and second shoals were believed to be greater than any previously documented shoal-bypass events.

The outer beach/lagoon system created by the two shoals is estimated to represent bypassing volumes of ~4 million cubic meters (CSE 2007). The incipient barrier island/spit added to Kiawah Island between approximately 1990 and 2004 was ~5 km long. The eastern and western lagoons associated with the new barrier-island system covered an estimated 100 ha of rapidly transforming habitat by 2004. The authors measured the rate of shoreward and westward migration of the second shoal at its westernmost point—between 1997 and 2004, the spit migrated at rates averaging 100 m/yr onshore and ~150 m/yr alongshore (Fig 5).

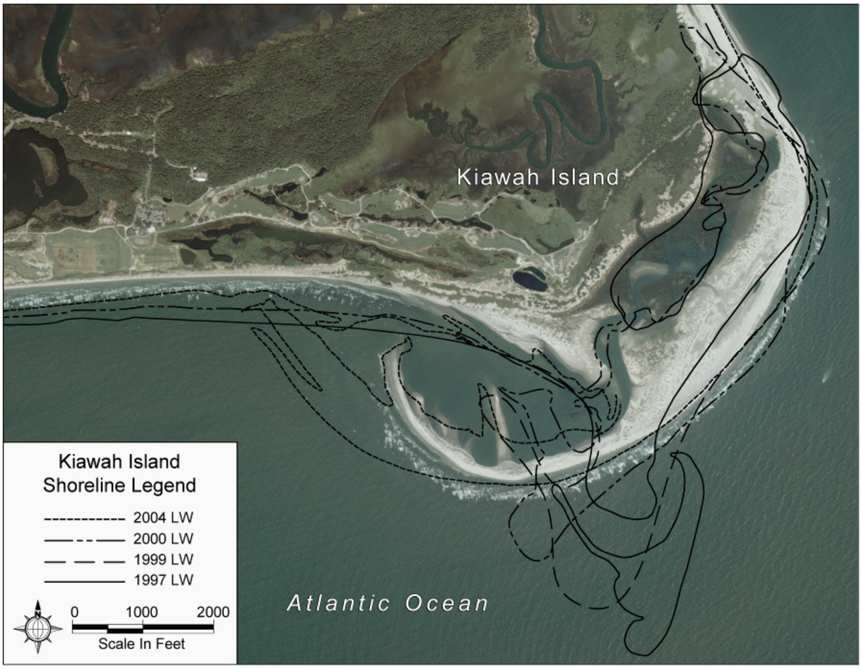

Fig. 3. Onshore and downcoast (to left) movement of a bypassing shoal (1997 to 2004) superimposed on a June 2003 vertical aerial photograph. [Image courtesy of Town of Kiawah Island]

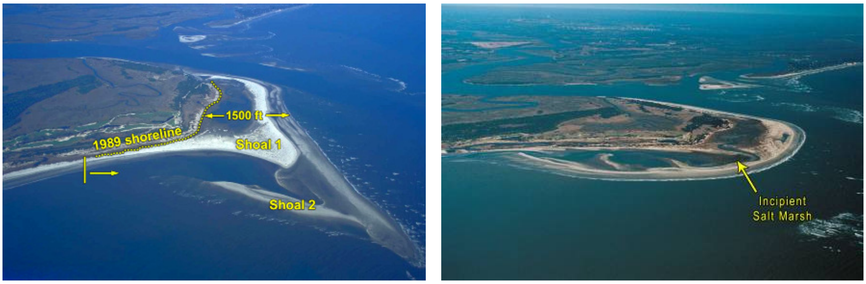

Fig. 4. Oblique aerial photos looking north at low tide – December 1998 (left) and February 2005 (right).

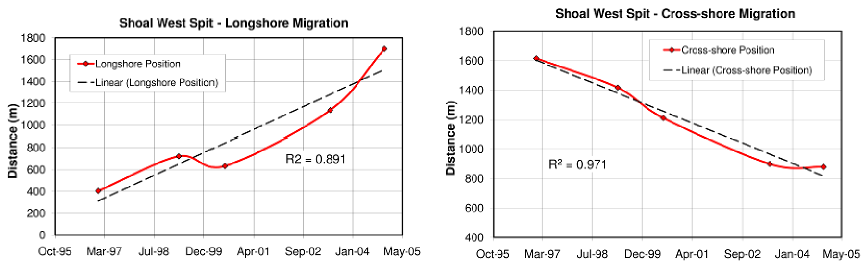

Fig. 5. Rate of onshore and longshore migration at the western terminus of the incipient barrier beach (1997-2004).

Erosion and Beach Restoration Adjacent to the Bypassing Shoal

Shoal-bypassing events add large volumes to the beach but create focused erosion adjacent to the incoming bar (Kana et al 1999). The second event at the eastern end of Kiawah Island resulted in severe erosion along the Ocean Course, a championship golf course fronting the ocean. Between 1999 and 2006, the shoreline at state monitoring station 2775 (just west of the accreting shoal) receded 250 m. Westward migration of the shoal and the lagoon's flushing inlet at the western end threatened to wash out the 18th fairway of the Ocean Course. This led to a plan which involved closing the flushing channel and opening a new channel through the middle of the accreting shoal (CSE 2007).

In June 2006, ~420,000 m³ were excavated by land-based equipment along the outer portion of the accreting shoal and were placed along the eroded shoreline to the west. The project also included excavation of a new flushing channel at the mid point of the shoal, ~1.5 km east of the closed channel. Details of the construction are given in CSE (2007).

The basic goals of the 2006 project were to halt erosion along the Ocean Course, maintain flushing in the incipient lagoon, and realign the new outer beach into a more curvilinear shape. Secondary goals included preservation of washover habitat for the threatened piping plover (*Charadrius melodus*) and acceleration of longshore transport to westerly sections of Kiawah Island once the flushing channel was closed. Piping plovers are a threatened species in South Carolina, which utilize isolated washover spits for roosting. There is no nesting activity in the state. Excavations along the outer beach were recommended by CSE so as to promote washover development in anticipation of further inputs of sand from subsequent bypassing events.

Figure 6 illustrates the condition of the project area three months before and two months after construction of the project (February and September 2006). Conditions in August 2009 are also shown. The fairways of the Ocean Course are west of the flushing channel in the February 2006 image. The majority of the excavations were placed along a 1,000-m segment of shoreline centered at the pre-project flushing channel. The new flushing inlet was positioned between the eastern lagoon/marsh (formed in the 1990s) and the incipient western lagoon.

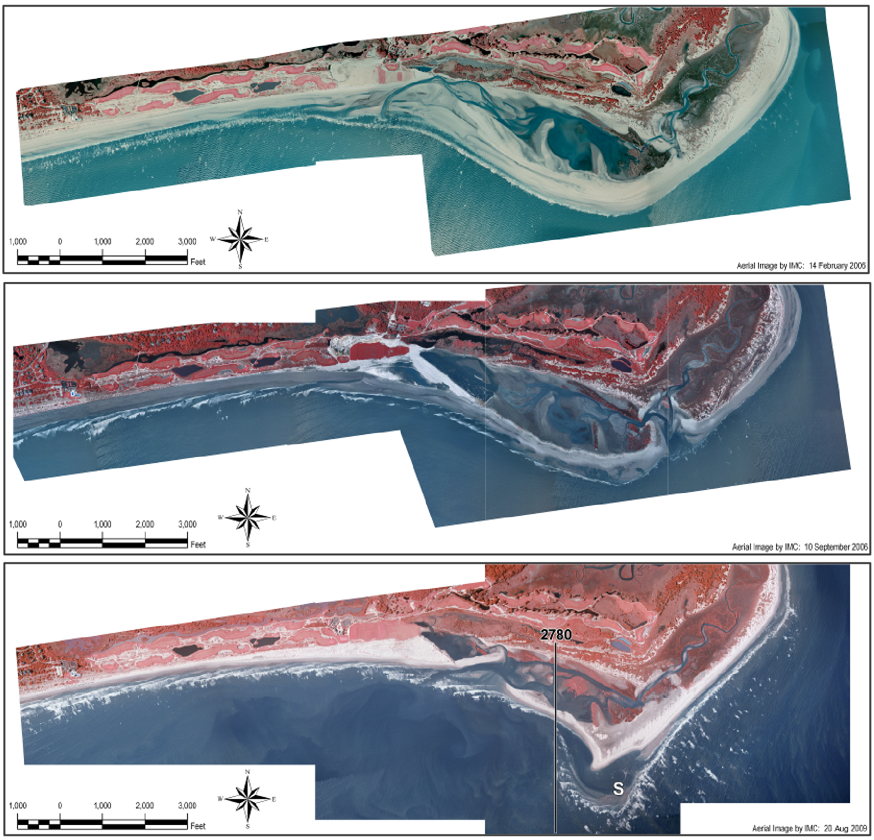

Fig. 6. Ortho-rectified aerial photos of the project area at low tide. February 2006 pre-construction (upper), September 2006 post-construction (middle), and August 2009 (lower). Note "2007" bypassing shoal (S) in the lower image. [Images courtesy Town of Kiawah Island]

Habitat Mapping

The authors monitored the evolution of habitats within a 636-acre (~254-ha) survey polygon which encompasses the 2006 project area and inshore zone. Yearly digital terrain models (DTMs) were produced by detailed ground-truth surveys via Trimble® R8 GNSS at ~60-120 m profile spacing across the lagoon out to closure depths and via supplemental continuous surveys over accessible beach areas. Habitat areas are distinguished by their depth (elevation) and degree of exposure to littoral or estuarine processes. High-energy areas include the outer beach, inshore zone, and outer portions of inlets. Low-energy areas, where mud and vegetation are likely to accumulate, include the incipient lagoon. The eastern lagoon (formed in the 1990s) is not included within the survey polygon.

Studies have shown that barrier-island/lagoon/marsh habitats are related to substrate elevation and the degree of normal tidal flooding (Teal 1958; De Laune et al 1983; Kana et al 1986). While it is not possible to precisely relate habitat (e.g., low marsh areas) to a specific elevation (Nixon 1982), there tends to be a relatively narrow elevation range at which some species thrive. Kana et al (1986) found that low marsh vegetation along the central South Carolina coast (principally *Spartina alterniflora*) is inundated by tides ~10-15 percent of the time, whereas high marsh species (eg – *Salicornia* sp, *Juncus* sp, and *Borrichea frutescens*) are inundated 1-5 percent of the time. Washover habitat tends to be at elevations matching the normal dry-sand berm which, for the open coast along central South Carolina, is at elevations of (~)+6 ft NAVD (1.8 m above ~MSL). This elevation represents the typical spring-tide, wave runup level under average wave conditions.

Habitats within the survey polygon were delineated using the following elevation criteria:

> *Subtidal Habitat*: −3 ft (−0.9 m) NAVD* or deeper (exposed if seaward of the barrier beach; sheltered if landward of the beach).
> [*NAVD – North American Vertical Datum of 1988 which approximates present MSL.]
>
> *Intertidal Habitat*: −3 ft to +2.5 ft (−0.9 m to 0.75 m) NAVD, which is approximate local mean low water and mean high water (respectively).
>
> *Washover Habitat*: +2.5 ft to 6.0 ft (0.75 m to 1.8 m) NAVD.
>
> *Stable Dune Habitat*: (>)+6.0 ft (>1.8 m) NAVD.
>
> *Marsh Habitat*: Vegetation as visible on rectified aerial images [typical elevation would be ~0-2 ft (0 m to 0.6 m) NAVD].

The above-listed elevation bands were applied within the survey polygon to delineate corresponding areas in those ranges. The resulting subdivisions were color-coded and superimposed on rectified digital orthophotographs obtained at the same time as the ground-truth surveys. Areas of marsh habitat were digitized by hand using the photography and removed from the remaining intertidal areas. Sheltered habitats were distinguished from exposed habitats by establishing logical sub-boundaries along the outer beach alignment. After the pre- and post-project habitat maps of 2006, subsequent surveys were performed in late summer of each year (2007-2009).

Results

The project area experienced rapid adjustment including formation of a breach channel through the outer beach and closure of the excavated flushing channel in fall 2007 (Fig 7). The outer beach was left vulnerable to breaching by design so as to maintain washover habitat. The excavated channel likely closed rapidly because of an influx of sand associated with a subsequent shoal-bypassing event that began in 2007. As the 2009 orthophoto in Figure 6 illustrated, the other significant evolution between 2006 and 2009 was infilling of the western lagoon, resulting in expansion of marsh habitat.

Fig. 7. Oblique aerial photos at low tide in February 2007 (left) and December 2007 (right) showing infilling of the excavated channel (upper right on each image) and a natural breach channel through the outer (washover) beach (right image). Note marsh-filled east lagoon with incised channels at the top of the December image; that area was open lagoon habitat in 1994 (see Fig 3 – lower).

Figure 8 shows the DTMs for pre-project (February 2006), post-project (September 2006), and recent (August 2009) habitat areas. Individual polygons were used to estimate areas of each habitat for the available survey dates (Fig 9). Areas are given in English units according to the original data. [Note: 1 acre ≅ 0.4 ha.] Some results of note are as follows:

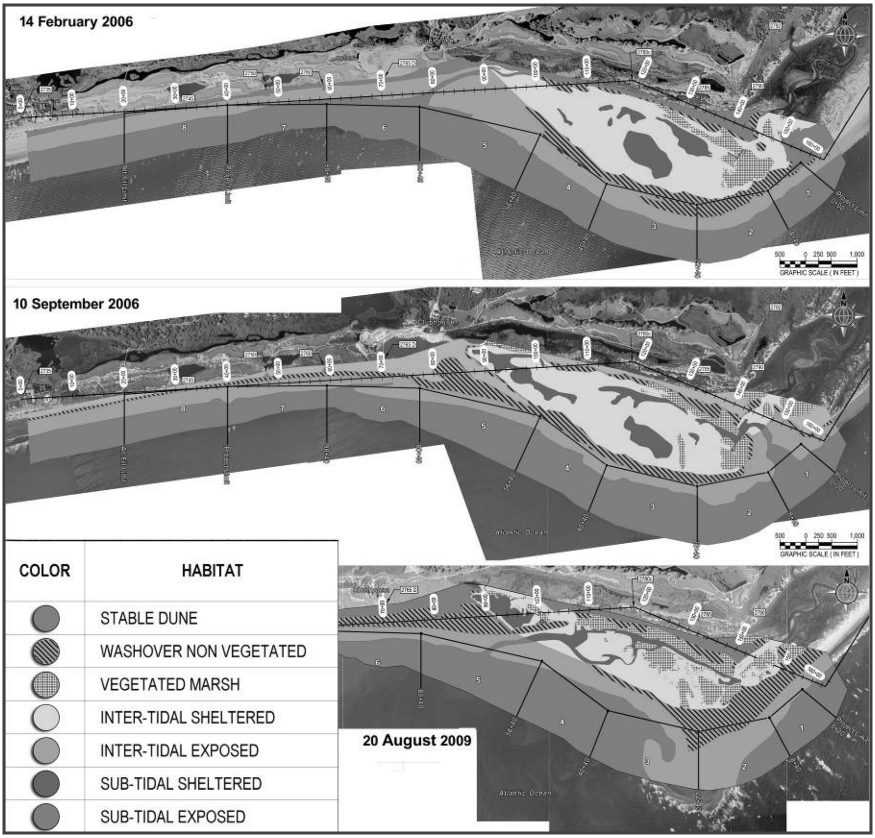

Fig. 8. DTMs of habitat areas within the survey polygon. Pre-project (upper), post-project (middle), three years post-project (lower).

1) Washover habitat generally increased steadily between pre-project conditions (February 2006) and August 2009, nearly doubling in area to 94 acres (38 ha).
2) Vegetated marsh habitat expanded from 19 acres to 35 acres (~7.5 ha to 14 ha).
3) Sheltered intertidal area of the lagoon decreased from ~110 acres to 79 acres (44 ha to 31.5 ha). Some of this reduction is due to expansion of marsh.
4) Sheltered subtidal area of the lagoon decreased from 22 acres to 6 acres (9 ha to 2.5 ha).

The unit volume density associated with the incipient barrier spit is illustrated in the comparative profiles of Figure 10. State profile 2780 extends offshore across the outer beach along the alignment shown in Figure 6. In 1999, this transect was exposed ocean beach with the shoreline positioned ~100 m seaward of the survey monument. By 2008, the new outer beach was positioned ~600 m seaward of the benchmark. The estimated accretion density at that point in time was nearly 1,200 m^3/m, which is equivalent to an average annual accretion over 130 m^3/m/yr. The unit volumes associated with the 1999 beach and 2008 outer beach (measured from the foredune crest to −2 m) were calculated to be similar (212.8 versus 188.0 m^3/m, respectively).

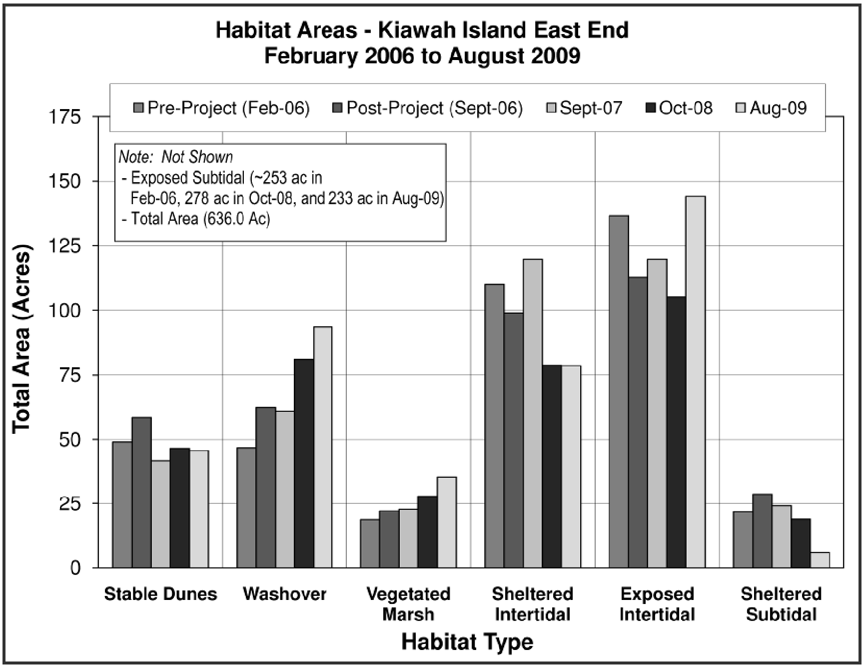

Fig. 9. Habitat areas within a survey polygon encompassing the 636 acre (254 ha) project area. Exposed subtidal (oceanic) habitat is excluded.

Discussion and Preliminary Findings

The evolution of habitats reflected in the DTMs illustrates the rapidity of change in an incipient barrier-island/lagoon system. In 1999, only the easternmost ~700 m of the 4,900-m-long survey polygon would have encompassed any incipient lagoon habitat. The remaining shoreline to the west was exposed, high-energy beach.

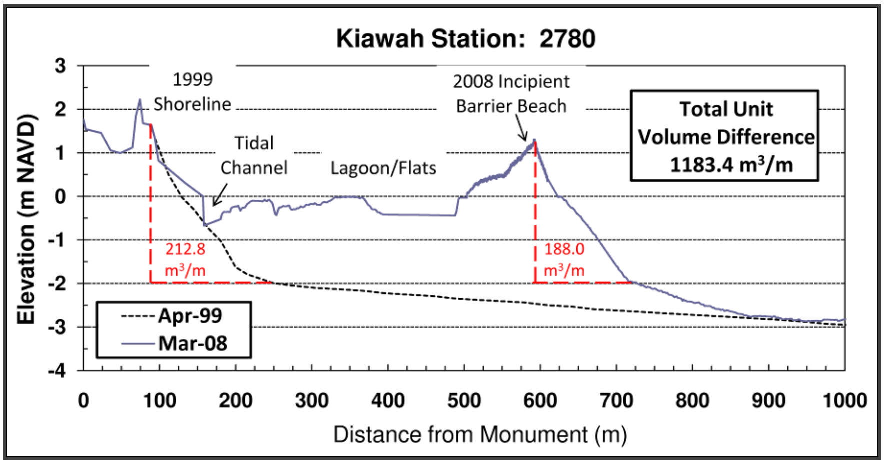

Fig. 10. Representative profiles from state survey monument 2780 (see Fig 6 lower) showing accretion density associated with the incipient barrier beach/lagoon system. Note similarity of unit volumes of each beach to −2 m depth in 1999 and 2008.

[There are no comparative surveys available from 1999 to quantify the changes in detail.] It is apparent from the vertical photographs (c.f., Fig 6) that the decadal evolution of the area covered by the survey polygon involved the following sequence:

1) Rapid expansion of sheltered subtidal habitat as the outer beach migrated westward and enveloped the incipient lagoon.

2) Expansion of washover habitat as sediment accumulated in the outer beach and produced spit growth to the west as the new beach was migrating shoreward via overwash processes.

3) Reduction of sheltered subtidal habitat and increase in intertidal lagoon habitat as the lagoon infilled with washover deposits.

4) Propagation of salt marsh beginning at the eastern end of the lagoon where sheltering by the bypassing shoal first occurred.

The diminished area of sheltered subtidal habitat, combined with the large area of intertidal habitat, suggests marsh areas will expand rapidly in the next couple of years. This is consistent with visual observations of the eastern lagoon marsh evolution (see Fig 2–lower, and Fig 7).

The profile volume of the outer beach by August 2009 approximately equaled the 1999 unit beach volume prior to barrier formation. The plan form of the outer beach has also evolved to a curvilinear form that more closely parallels the historical shoreline (see Fig 6, lower). These two observations suggest the new barrier beach is approaching equilibrium and that the west lagoon will be of the order 200-300 m wide. As the profile in Figure 10 indicates, lagoon elevations were mostly intertidal by 2009, creating substrate conditions favorable for marsh propagation. Based on the marsh-filled condition of the eastern lagoon (formed in the 1990s), the authors project the western lagoon will be marsh-filled by 2015.

As the lagoon continues to infill via washovers, the 2007 shoal-bypass event (observable on the August 2009 image in Figure 6) is expected to add more volume along the outer beach and transform the washover beach into a stable dune ridge with elevations above normal washover levels. This will complete the cycle of barrier/lagoon formation. The final scale of the system is expected to be con-trolled by the total volumes bypassed since 1990 and the average accretion density along the new beach.

The habitats associated with the incipient barrier-island/spit system are not likely to remain favorable for piping plovers, a species which prefers unvegetated beach habitat adjacent to sheltered lagoon sand/mud flats. The plover population has fluctuated but continues to utilize the outer beach (Fig 11). As the new system stabilizes with a vegetated dune ridge and marsh-filled lagoon (similar to the eastern lagoon), the area is not expected to be as attractive to piping plovers.

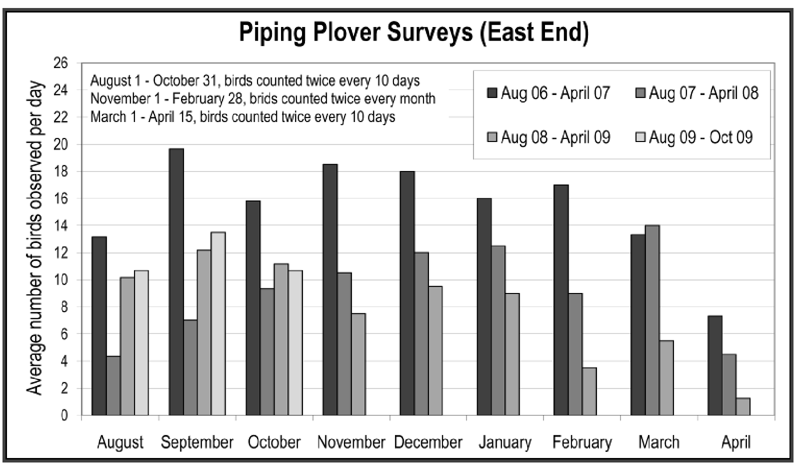

Fig. 11. Piping plover census for the eastern end of Kiawah Island.
[Courtesy Town of Kiawah Island]

Acknowledgments

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