In 1937, the U.S. Congress passed legislation authorizing development of the Cape Hatteras National Seashore on 119 km of Bodie, Hatteras, and Ocracoke Islands of the North Carolina Outer Banks (Stick, 1958). Cape Hatteras National Seashore is composed of a series of barrier-island segments located between eight villages (Fig. 1A). The U.S. Department of Agriculture purchased land on the south side of Oregon Inlet, and President Roosevelt established Pea Island Migratory Waterfowl Refuge by Pea Island, Oregon Inlet, and Bodie Island, northern Outer Banks, North Carolina, in Kelley, J.T., Pilkey, O.H., and Cooper, J.A.G., eds., America's Most Vulnerable Coastal Communities: Geological Society of America Special Paper 460, p. 43–72, doi:10.1130/2009.2460(04). For permission to copy, contact editing@geosociety.org. ©2009 The Geological Society of America. All rights reserved.

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ABSTRACT

Pea Island, Oregon Inlet, and Bodie Island, North Carolina, are severely human-modified barrier-island segments that are central to an age-old controversy pitting natural barrier-island dynamics against the economic development of coastal North Carolina. Bodie Island extends for 15 km from the Nags Head–Kitty Hawk urban area to the north shore of Oregon Inlet and is part of Cape Hatteras National Seashore. Pea Island extends 19.3 km from the southern shore of Oregon Inlet to Rodanthe Village and is the Pea Island National Wildlife Refuge. Bodie and Pea Islands evolved as classic inlet- and overwash-dominated (transgressive) simple barrier islands that are now separated by Oregon Inlet. The inlet was opened in 1846 by a hurricane and subsequently migrated 3.95 km past its present location by 1989. With construction of coastal Highway 12 on Bodie and Pea Islands (1952) and the Oregon Inlet bridge (1962–1963), this coastal segment has become a critical link for the Outer Banks economy and eight beach communities that occur from Rodanthe to Ocracoke. The ongoing natural processes have escalated efforts to stabilize these dynamic islands and associated inlet in time and space by utilizing massive rock jetties and revetments, kilometers of sand bags and constructed dune ridges, and extensive beach nourishment projects. As the coastal system responds to ongoing processes of rising sea level and storm dynamics, efforts to engineer fixes are increasing and now constitute a “human hurricane” that pits conventional utilization of the barriers against the natural coastal system dynamics that maintain barrier-island integrity over the long term.
presidential executive order in 1938. Today, this is the Pea Island National Wildlife Refuge, managed by the U.S. Fish and Wildlife Service. Pea Island is a 19.3-km-long barrier segment separated from Bodie Island on the north by Oregon Inlet and bounded on the south by the village of Rodanthe (Fig. 1B). Establishment of Pea Island National Wildlife Refuge did not include a right-of-way for North Carolina Highway 12 to connect the Oregon Inlet ferry with the Outer Banks villages to the south. Rather, a high-way right-of-way through the refuge was obtained by a deed of easement. Highway 12 was built from Nags Head to Cape Hatteras in 1952. In 1962–1963, the Oregon Inlet ferry was replaced by a 3.86 km bridge (Fig. 2) that connected Highway 12 on Bodie Island with Pea Island. Construction of this infrastructure was critical for the economic development of the Outer Banks.

Wildlife refuges have specific functions and become highly managed ecosystems designed to meet those functions. Pea Island National Wildlife Refuge’s function is to preserve and manage Pea Island for migratory birds and other wildlife. Federal legislation passed in 1997 protects the function of national wildlife refuges by prohibiting construction of roads that interfere with refuge functions. However, the cumulative impact of sea-level rise and numerous storms (hurricanes and nor’easters) through time has promulgated increased efforts to maintain and/or reconstruct the transportation infrastructure, unfortunately at the expense of the natural barrier-island dynamics within Pea Island National Wildlife Refuge.

The Pea Island ocean shoreline is receding westward at rates up to about –4 m/yr (Everts et al., 1983; Stone et al., 1991; USACE, 1993; Benton et al., 1997; Fisher et al., 2004) as the island attempts to migrate upward and landward in response to a rise in sea level in northeastern North Carolina (Riggs and Ames, 2003; Horton et al., 2009; Kemp et al., 2009). Each storm that breaches the constructed dune ridges either destroys the road or covers it with overwash sand, which is then mined and used to reconstruct the dune ridges. This engineering of the ocean front impedes the natural island-building processes of inlets and over-
The purpose of this paper is threefold: (1) summarize the basic barrier-island processes operating on the North Carolina Outer Banks that are essential for the short-term maintenance and long-term evolution of a healthy barrier island–inlet system; (2) outline the growing conflict between the natural dynamics and the rapidly increasing economic development on the Outer Banks; and (3) provide a framework for the multiple user groups in the public domain to define an acceptable strategy for managing the barrier-island resources while maintaining a viable coastal economy. This manuscript does not include a technical summary of previous barrier island–estuarine studies in other geographic portions of the world.

METHODS

The work conducted here is part of the North Carolina Coastal Geology Cooperative (NCCGC) research program funded by the U.S. Geological Survey (USGS) Coastal and Marine Geology Program, U.S. National Park Service (USNPS), and U.S. Fish and Wildlife Service (USFWS). Since 2000, the NCCGC has carried out a broad range of studies that utilize geophysical surveys in the estuaries to develop the detailed supporting information for the following are the most relevant to understanding the origin and evolution of the northeastern North Carolina coastal system. The overall goal of the NCCGC research program is to develop a comprehensive understanding of: (1) the Quaternary stratigraphic framework of the coastal system (Fig. 1A); (2) the climate and sea-level history since the Last Glacial Maximum, when the current coastal system was formed; and (3) the modern process-response dynamics of both the natural and human-modified coastal systems.

For this study, core materials were subjected to sedimentologic, micropaleontologic, and stratigraphic analyses. The resulting data were placed in a three-dimensional framework derived from geophysical (seismic and GPR) data and a temporal framework derived from Pb-210, Cs-137, C-14, and optically stimulated luminescence techniques (Riggs and Ames, 2003, 2007; Culver and Horton, 2005; Culver et al., 2007, 2008; Mallinson et al., 2005, 2008; Horton et al., 2006, 2009; Vance et al., 2006; Corbett et al., 2007; Parham et al., 2007; Horton and Culver, 2008; Smith et al., 2008; Kemp et al., 2009). Geomorphic classification and mapping of the North Carolina barrier islands (Riggs et al., in press) were based on a series of conceptual models of barrier-island evolution developed from process-response studies and modern field surveys of the North Carolina Outer Banks. These studies utilized time-slice analysis of georeferenced aerial photography (1932–2006) and topographic surveys (1849–1917) of sites between Kitty Hawk and Cape Lookout, North Carolina. The modern data were integrated with historical data to develop the evolutionary responses of geomorphic-ecologic systems to sea-level rise, storms, and human modification. Light detection and ranging (LIDAR) data were used to aid in mapping the geomorphic components.

Numerous M.S. thesis and Ph.D. dissertation studies were carried out on specific barrier-island segments and portions of the estuaries to develop the detailed supporting information for understanding the origin and evolution of the northeastern North Carolina coastal system. The following are the most relevant to the present manuscript: Sager (1996), Rudolph (1999), Parham...

**OUTER BANKS BARRIER-ISLAND SYSTEM**

**Simple and Complex Barrier Islands**

Barrier-island segments within the North Carolina Outer Banks are classified into two types: simple and complex (Fig. 3). This determination is based upon the barrier-island geomorphology, which is a product of the evolutionary history, available sediment supply, and physical dynamics operating upon the islands (Riggs et al., in press).

Barrier-island segments with a relatively limited sediment supply are low, narrow barriers dominated by inlet and overwash processes (Figs. 3A and 3B) (Riggs et al., in press). Since these barriers are sediment-poor, and little additional sand is added to them through time, they tend to be extremely dynamic and are dominated by modern and paleo-inlet flood-tide deltas. The deltas extend into the back-barrier estuary, building island width while overwash fans build island elevation. Examples of simple barrier islands in northeastern North Carolina include all of Core Banks and most of the northern Outer Banks that are in Cape Hatteras National Seashore and Pea Island National Wildlife Refuge (Fig. 1A). This includes most of Ocracoke Island, the island segments between the villages of Hatteras to Frisco, Buxton to Avon, Avon to Salvo, Rodanthe to Oregon Inlet, and Oregon Inlet to Nags Head (Fig. 1A).

Complex barrier islands are high and wide islands in response to major inputs of additional sediment onto the barriers at various times in their evolutionary history (Figs. 3C and 3D) (Riggs et al., in press). Complex islands are generally characterized by a young overwash-dominated component that has migrated toward and became welded onto an older barrier-island component on the mid- and back sections of an island that is composed of beach ridges and dune fields. Due to the large volume of sand, normal storm surges have little potential for opening new inlets through complex islands, and oceanic overwash only occurs along the modern, front side of the barrier. Thus, salt spray is minimal, allowing extensive maritime forests to develop on the mid- and back sections of complex barrier islands. Complex barriers form a continuum that ranges from well developed to poorly developed. Kitty Hawk, Nags Head Woods, and Buxton Woods are examples of well-developed complex islands (Fig. 1A). Ocracoke and Hatteras villages are situated on moderately developed complex islands, while the villages of Rodanthe, Waves, Salvo, and Avon are on poorly developed complex islands (Fig. 1A). Most urban development occurs on complex barrier islands.

Extensive studies of changing depositional patterns placed within a chronostratigraphic framework (based upon an exten-

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**Figure 3.** Schematic cross-sectional diagrams show a (A) sediment-poor, inlet- and overwash-dominated simple barrier island, and a (C) sediment-rich, beach ridge–dominated complex barrier island (modified from Riggs et al., in press). (B) 1998 infrared aerial photograph shows a barrier-island segment northeast of Hatteras village, North Carolina, a classic example of a simple barrier island. (D) 1983 infrared aerial photograph shows Kitty Hawk, North Carolina, a classic example of a complex barrier island.
Eye of a human hurricane

Approximately 70%–85% of the Outer Banks have had one or more inlets at some time during their past 500 yr history (Riggs et al., 1995; Smith, 2006; Riggs et al., in press). Pea Island, from Oregon Inlet south to the village of Rodanthe, is a simple barrier-island system dominated by inlets and overwash dynamics. Based upon historical sedimentological and geophysical data, three historic inlets (Fig. 5) have been documented on Pea Island (Stick, 1958; Fisher, 1962; Everts et al., 1983; Payne, 1985; Smith, 2004; Smith, 2006; Culver et al., 2006; Smith et al., 2008).

Function of Inlets on Simple Barrier Islands

Inlets are high-energy components of coastal systems, and their formation and location are difficult to predict. Since the barrier islands form a sand dam between the ocean and estuaries, inlets are opened and closed by storms that produce storm surges driven from either the ocean or estuarine side of the islands (FitzGerald and Hayes, 1980). Once open, an inlet allows the interchange of freshwater and ocean water. Thus, inlets are also outlets, since they let the water flowing off the land escape into the ocean. Inlets construct extensive flood-tide deltas on the estuarine side of the barrier islands and ebb-tide deltas on the ocean side, where the tidal energy is dissipated into the larger water bodies and sediment is deposited to form the flood-tide and ebb-tide deltas (Hayes and Michel, 2008). Both the ebb-tide delta and flood-tide delta shoals are critical elements of the coastal sediment budget and contribute to the long-term evolution of the barrier islands. Inlet flood-tide delta shoals are essential for building back-barrier island width. Within the context of a rising sea level, barrier islands migrate onto the shallow flood-tide delta shoals by overwash dynamics (Fig. 4). Multiple channels often characterize the flood-tide deltas and flow into the inlet throat that occurs between the adjacent barrier islands (Figs. 4A and 4B).

Inlets act as safety valves by adjusting and shifting in size and location in response to each storm. The dynamism of inlets means that a stable, deep channel is rarely maintained naturally. Constant dredging and/or inlet jetties are utilized in efforts to maintain a fixed navigation channel. However, these practices generally disrupt the self-adjusting, safety-valve function of the inlet, the sediment bypass system between islands, and the exchange of sediment between the flood-tide delta and ebb-tide delta. In addition, removal of ebb-tide delta and/or flood-tide delta sand for beach nourishment changes both the geometry and dynamics of an inlet and modifies the natural sediment budget. If enough sand is removed, it will affect the amount of channel migration and related shoreline erosion on the adjacent barrier islands.

(1) Chickinacommock Inlet was open irregularly between ca. 1650 and ca. 1775;
(2) Loggerhead Inlet was open frequently between ca. 1650 and ca. 1870; and
New Inlet was open numerous times between ca. 1650 and 1945.

Oregon Inlet is the only active inlet today in the Pea Island–Bodie Island area (Fig. 6). It opened during a hurricane on 7 September 1846 in the vicinity of the current Bodie Island Lighthouse and has migrated ~4 km southward to its current position.

Function of Overwash on Simple Barrier Islands

Simple barrier islands are dependent upon storm overwash to build island elevation and width, a critical process for the health and evolution of the islands (Godfrey and Godfrey, 1976; Riggs and Ames, 2007; Riggs et al., in press). Small storm surges produce waves that overtop the island berm, resulting in small-scale

Figure 4. Georeferenced aerial photograph time-slice series, (A) 1945, (B) 1962, and (C) 1998, show the history of the Swash Inlet area on North Core Banks. The Swash Inlet zone shows the evolutionary succession of an inlet that builds island width through deposition of a flood-tide delta along the estuarine side of the barrier island. With time, overwash processes build a berm that ultimately closes the inlet, builds elevation, and becomes vegetated. The platform marsh develops on the intertidal portions of the flood-tidal deltas. The right-hand sides of the photographs show an older and much larger inlet flood-tide delta complex with well-developed platform marshes and tidal channels on the estuarine side and an active overwash ramp on the ocean side that becomes vegetated through time. The red lines are the 1998 digitized shorelines superimposed on the older photographs to show the sequence of changes. The ebb-tide delta (ETD) and flood-tide delta (FTD) are labeled in B.
Figure 5. The georeferenced 1852 U.S. Coast Survey topographic map (A) and 1998 infrared aerial photograph mosaic (B) shows the approximate locations for opening of the paleo-historic inlets (dashed red arrows) and the inlet location when final closure took place (solid red arrows). Oregon Inlet opened north of the location on the 1998 aerial photograph mosaic (B). See Figure 6 for the migration of Oregon Inlet.
overwash fans on the ocean side of the barrier. Figure 7 shows a series of small overwash fans that have added up to 2 m of elevation on the ocean front and middle portions of the island. Large storm events produce meters of water overtopping the island berm and result in large, arcuate overwash ramps that bury the back-barrier platform marshes and occasionally build shallow shoals extending well into the estuarine system (Fig. 8) (Godfrey and Godfrey, 1976). Through time, overwash events bury the platform marshes and associated peat deposits that formed on the flood-tide delta shoal system and fill the inlet channels with overwash sand (Smith, 2004; Smith, 2006; Culver et al., 2006; Riggs and Ames, 2007; Smith et al., 2008; Riggs et al., in press).

The 1932 aerial photographs (Fig. 8A) of the Loggerhead Hills barrier-island segment predate major human modification. The extensive overwash fan extends across the entire island into Pamlico Sound. This storm product renews the estuarine shoreline and produces broad shallow flats that subsequently become important habitats for marsh grass and submerged aquatic vegetation. The aerial photographs from 1999 (Fig. 8B) show the same barrier segment that has experienced the building and rebuilding of constructed dune ridges since the late 1930s and a paved Highway 12 since 1952. These constructed dune ridges minimize oceanic overwash and allow for the extensive growth and development of vegetation. Today, the estuarine shoreline is characterized by eroding salt marshes and local, thin strand-plain beaches in coves between peat headlands (Fig. 8B).

The 1999 photographs in Figure 8B postdate Hurricane Dennis, which had a minor impact on this coastal segment in fall 1999. The constructed dune ridge was severely damaged by the storm and eroded away in a few areas, allowing for small overwash fans to develop. However, overwash covered the road only locally, and in no place did it extend to the estuarine shoreline, and thus naturally renourish the back-barrier marsh. More frequent, smaller storms with small to intermediate storm surges produce small overwash fans that rarely extend all of the way across a barrier island. Consequently, they generally do not build island width (Riggs and Ames, 2007).

**Evolution of Pea Island during Rising Sea Level**

The rate of sea-level rise in the Outer Banks region for the past two millennia has been ~10 cm/100 yr (Horton and Culver, 2008; Horton et al., 2006, 2009; Kemp et al., 2009). This rate increased around the beginning of the nineteenth century to...
~15 cm/100 yr and increased again around the beginning of the twentieth century to its current rate of ~40 cm/100 yr. Within this context, Figures 9 and 10 demonstrate the various changes through time on a segment of Pea Island. The ocean shoreline receded landward between 210 and 510 m from 1852 to 1962. The Loggerhead Hills area (top of Figs. 9 and 10) had widened in the landward direction through deposition of a major overwash plain prior to the 1917 topographic survey (possibly by the 1899 hurricane), and this overwash plain was reactivated by the 1932 storm (Fig. 8A). The lower portions of Figures 9 and 10 have experienced island narrowing, and the narrow central portion is highly vulnerable to the opening of a new inlet in the near future.

GPR data in Figure 11 documents the Chickinacommock Inlet channel. The flood-tide deltas of these two inlets were subsequently buried by fining-upward sediment sequences of several overwash fans, which gave the island both width and elevation (Smith, 2004; Culver et al., 2006; Smith et al., 2008). The barrier segment between the two inlets in Figure 10 is very narrow with a molar-tooth platform marsh adjacent to Highway 12. The importance and processes of molar-tooth platform marshes in the evolutionary history of simple barrier islands are presented by Riggs et al. (in press) and displayed in Figure 4. Molar-tooth platform marshes are remnants of a former flood-tide delta shoal system that have converted to intertidal marshes upon inlet closure. The platform marshes occur on shoals that are separated into smaller segments by the old flood-tide delta channel system. With time and ongoing recession of the ocean shoreline, the oceanward side of the molar-tooth platform marsh is buried, and the associated tidal channels are filled with overwash sand. Ultimately, as the island segment narrows, the molar-tooth platform marsh extends under the entire island, cropping out during storms on the beach and upper shoreface. As the storm surge flows over the narrowed island, the exposed marsh peat surface resists overflow erosion, while the sand-filled tidal channels readily blow out to produce new sub–sea-level inlet channels and an initial flood-tide delta as the storm recedes. Figure 11 presents GPR data obtained along Highway 12 across the molar-tooth platform marsh. The northern section is characterized by a horizontal reflector off the top of the underlying peat surface of the platform marsh and dipping reflectors representing small tidal channels. This area is vulnerable to inlet formation necessary to build new island width.

Inlet and overwash processes interact through time to produce a stable barrier island that is in equilibrium with both storm dynamics and rising sea level. The georeferenced maps and photographs in Figure 12 demonstrate the evolutionary succession of the Loggerhead Hills segment of Pea Island from narrow inlet-dominated (1852) to wide overwash-dominated (1917 and 1932), to a human-dominated barrier system (1962 and 1998). Two channels of Loggerhead Inlet were open from ca. 1650 to 1680 and again from 1843 to 1870 (Payne, 1985). Sometime prior to 1917, the flood-tide delta and its channels were buried by a massive overwash, possibly during the 1899 hurricane that severely impacted this region. The 1932 aerial photograph shows the broad overwash plain that was reactivated by the 1932 storm just prior to the photographs. The tidal channels, associated fan deltas, and well-developed back-barrier berms along the estuarine shoreline display fresh structures resulting from the hydrologic flow during the recent storm. The 1998 aerial photograph shows the influence of humans, which began in the late 1930s with construction of dune ridges along the ocean beach and within the overwash flats in an effort to stabilize the moving sand and, since 1952, to protect Highway 12. The constructed dune ridges, designed to prevent overwash, dramatically increased island vegetation cover and shifted this barrier segment into an island-narrowing mode (Fig. 9), with shoreline erosion occurring on both sides of the island (Smith et al., 2008).
The data presented in Figure 13 integrate the time-slice analysis, remotely sensed data, and lithostratigraphic, biostratigraphic, and chronostratigraphic data to produce the interpretations presented in Figure 14. Pea Island consists of four segments; the evolutionary history of each is displayed in Figure 14. Two young segments (stage 1, New Inlet; stage 2, Loggerhead Hills on Fig. 14) have gained substantial island width through development of inlets and overwash plains during the past 150 yr. Two older segments (stages 3 and 4 on Fig. 14) are characterized by substantial island narrowing from both the ocean and estuarine shorelines during the period from 1852 to 1998 (Fig. 13). They consist of molar-tooth platform marshes that are split by tidal channels extending across most of the barrier island. Marsh peat extends seaward beneath Highway 12 and the ocean beach, where it often crops out in the surf zone during storms.

Predicting Potential Inlet Locations on Pea Island

Based upon an analysis of Fisher’s (1962) maps, Riggs et al. (1995) estimated that >78% of the Outer Banks has had one or more inlets in the past. It is clear that the potential for inlet formation exists everywhere along the simple barrier islands of the Outer Banks. However, the potential varies as a function of many variables. These variables fall into six major categories: (1) dynamics of each storm event; (2) physical geometry of coastal compartments; (3) barrier-island geomorphology; (4) subsurface geology of coastal system; (5) geometry and dynamics of the back-barrier estuarine system; and (6) degree and type of human modification.

Since Pea Island is a low and narrow, inlet- and overwash-dominated, simple barrier island system with a minimal sand
supply (Figs. 3A and 3B), the entire length of the island is vulnerable to inlet formation (Fig. 15). However, three locations (sites 1 through 3) have a high likelihood of becoming inlets if one or more major storms or a series of smaller storms (hurricanes or nor'easters) occur during any given year. Site 1 is a very narrow island segment consisting of molar-tooth platform marsh with sand-filled overwash tidal channels that underlie the barrier island. Site 2 is the location of historic New Inlet and associated flood-tide delta, and it has several large sand-filled inlet channels that underlie the barrier island. Site 3 is the location of historic Chickinacommock Inlet, which has a single large sand-filled inlet channel that underlies the barrier island.

Sites 4 and 5 (Fig. 15) have an intermediate likelihood of inlet formation in the sand-filled overwash tidal channels on each side of a large molar-tooth platform marsh. A large flooding or ebbing storm surge could flank the existing jetty at Oregon Inlet and open small flanking channels. Sites 6 and 7 are the widest portions of Pea Island and have low likelihoods of new inlets in the short term (annual to decadal scale). However, as the ocean and estuarine shorelines erode and the island continues to narrow, these segments will evolve (at the decadal scale) to the point where they will need new inlets to rebuild island width. These sites could also experience major overwash events that would maintain a back-barrier shoal system and build island elevation. Site 8 is the northernmost segment of Pea Island, and it is hardened by a 938-m-long rock jetty at Oregon Inlet and the rock revetment around the base of Oregon Inlet bridge. The likelihood of Oregon Inlet migrating further

Figure 9. The georeferenced 1852 U.S. Coast Survey topographic map (A) and the 1962 aerial photograph mosaic (B) shows most of the same area as in Figure 8. This figure demonstrates the long-term recession of the ocean shoreline, as well as dramatic changes in island narrowing and island widening. A large overwash plain substantially widened the area north of km 17 sometime after 1852 and before 1917 (see Fig. 12). The area south of km 17 consists of an old inlet flood-tide delta (Chickinacommock Inlet) buried by an overwash plain that predates 1852 and has been undergoing island narrowing since. The red outline on the 1962 photographs is the 1852 digitized shoreline. The 1962 aerial photographs are from the North Carolina Department of Transportation, Raleigh, North Carolina.
south or of an additional inlet breaking through these massive structures is low. However, the site could experience overwash events and associated damage.

ARRIVAL OF THE HUMAN HURRICANE

Pre-1930 Outer Banks

Prior to 1584, the Outer Banks operated as a natural barrier-island system dominated by storms and locally populated by small and nomadic groups of Native Americans involved in subsistence living. Europeans landed on Roanoke Island in 1584 and led to the “dawn of British Colonialism” (Stick, 1983). For the next ~350 yr, small populations of Native Americans and immigrants lived in small villages on the estuarine side of the barrier islands, often within maritime forests that grew on the wider and higher portions of complex barrier islands. The population was primarily involved in fishing, hunting, guiding, boat building, life-saving, shipping, and ship salvage. They lived off the water and land with a few domestic animals and small gardens. Water transportation was largely by personal boats, supply boats, and toll ferries, with movement on the islands largely by horse and wagon. In the first half of the twentieth century automobiles traveled along the ocean beach or estuarine side of broad overwash ramps.

The impact that these small groups of people had upon the barrier islands included digging channels and ditches, constructing ponds, logging for ship building, and grazing domestic animals. However, the net consequences of these human impacts were overwhelmed by the natural storm dynamics of the coastal system that opened and closed inlets, built beach ridges and back-barrier dune fields, and flooded the islands with large overwash ramps.

Transition Years: 1930s to 1960s

According to the U.S. Census Bureau (USCB, 2007), the population of Dare County in 1930 was 5202 and showed a very low growth (14%) to 5935 by 1960. The 1930s saw the beginning of a series of large-scale projects that would represent both the framework for the coming tourist economy and the long-term changes to the natural dynamics of the North Carolina Outer Banks. Driven largely by the long-term economic potential of the Outer Banks, a group of developers, businessmen, politicians, and state agency officials began a three-pronged approach at laying the groundwork (Stick, 1958). Appendix 1 contains a chronology of major impacts affecting the barrier-island dynamics.

Constructed Barrier Dune Ridges

The Works Progress Administration (WPA) of the federal government put people to work in late 1930s building sand fences to form constructed dune ridges that would act as a “fort wall” to protect the islands from storms and overwash (Fig. 16). The constructed dune ridges extended from the Virginia State line south to Ocracoke Inlet. The dune ridge “fort wall” provided a critical, but false, sense of security. Oceanfront land behind the dune ridges was sold at premium prices, houses and businesses were constructed, and roads were built with little concern for storm overwash, ocean shoreline recession, or inlets breaching the islands. However, maintenance and rebuilding of the constructed dune ridges have become an overwhelming and costly task. Further, the short-term gain of protection leads to long-term failure because the natural processes of overwash and inlet flood-tide delta formation, essential for maintaining the barrier island’s health and evolution in response to rising sea level, are curtailed.
The North Carolina WPA and the USNPS erosion control project along 174 km of the northeastern North Carolina coast convened in 1935–1936 (Toll, 1934; Senter, 1939; Stratton et al., 1939). The purpose of the project was to “eliminate the flow of ocean water over the Banks” by constructing “a barrier sand dune along the crown of the beach” that would form a “windbreak to allow transplanting of vegetation in its lee on the sandy flats” (Stratton, 1943, p. 4). Within 12 mo, the project had succeeded in closing all “shallow, useless inlets…that are not of value to the fishing industry or for drainage purposes and invariably caused transportation difficulties” (Stratton, 1943, p. 6). The accomplishments of the shoreline protection project included 1258 km of constructed dune...
ridges, >26.5 km² of grass plantings, >3.4 million tree and shrub plantings, and 120 km of dikes and jetties (Stratton, 1943).

Stratton and Hollowell (1940, p. 90) reported that “instead of a barren sand swept stretch of beach it has been transformed” by constructed barrier dune ridges that protect “the banks from the ocean” (Stratton and Hollowell, 1940, p. 6). According to Stratton (1943, p. 6) “results of the work were evident almost immediately. No longer do the ocean tides flow over the Banks to hinder traveling, wash away the beach, and kill out the vegetation. Transportation is no longer difficult, permitting increased numbers of visitors and tourists to flow into the area.”

However, there was controversy over the North Carolina Beach Erosion Control Project as indicated by the memos from other agencies (Senter, 1939). For example, an official from the Branch of Historic Sites reviewed 35 historical maps and concluded that the “historical appearance of the barrier islands remained much the same from 1585 to 1932” (Senter, 1939, p. 1). “If planting continues at the present pace, the historical appearance of the whole area will be changed…as a result of man-made intrusions.” The act authorizing establishment of the Cape Hatteras National Seashore makes it clear that the purpose was to “preserve the area in its primitive condition for the benefit and inspiration of the people.” An official from the NC Geological Survey (Senter, 1939) stated that efforts to close low swales extending across the islands concerned the local people who stated the following: (1) the swales were “safety valves when the water of the sounds rush toward the sea after being bottled up during storms” (Senter, 1939, p. 6); (2) “natural forces are completely opposed to the formation of embankments” (Senter, 1939, p. 4) that are readily breached by water; and (3) it seems certain that

Figure 12. Georeferenced time-slice series, (A) 1852 U.S. Coast Survey map, (B) 1917 U.S. Coast Survey map, (C) 1932 aerial photograph mosaic, (D) 1998 infrared aerial photograph mosaic, shows how inlet and overwash processes interact through time in the historic Loggerhead Inlet segment of Pea Island. The figure shows the evolutionary succession from narrow inlet-dominated barrier (1852) to wide overwash-dominated system (1917 and 1932), to human-dominated system (1998). The purple line is the outline of the 1852 digitized shoreline that has been superimposed on each of the subsequent maps and photographs to show changes through time. The 1932 aerial photographs are from the U.S. Army Corps of Engineers, Field Research Facility, Duck, North Carolina.
the project “will be a never-ending one” (Senter, 1939, p. 4). The Geological Survey concluded with the question, “how far do we wish to go in completely counteracting natural conditions and forces, and how far do we go in preserving natural conditions” (Senter, 1939, p. 4).

Numerous researchers have demonstrated that overwash-and inlet-dominated barrier islands have never been covered by substantial vegetation (Dolan et al., 1973; Godfrey and Godfrey, 1976; Dolan and Lins, 1986; C. Frost, 1999, personal commun.; Riggs and Ames, 2007). Rather, the magnitude of storm dynamics and the frequent salt-water overwash and inlets along large segments of the Outer Banks continually reshape the coastal sand pile. Thus, the temporary halt of these dynamics with constructed dune ridges and vegetation plantings, in concert with subsequent beachfront development, has led to the artificial and temporary stabilization of the barrier islands. Today, the constructed dune ridges continue to be rebuilt during and after each major storm. Great numbers of bulldozers and earth-moving equipment are engaged in a constant effort to “hold the line” against the receding ocean shoreline (Fig. 17).

Acquisition of Large Land Tracts

Large segments of the barrier islands were acquired by various state and federal agencies for incorporation into historic monuments (Fort Raleigh National Historic Site and Wright Brothers National Historic Monument), wildlife refuges (Pea Island National Wildlife Refuge), and parks (Cape Hatteras National Seashore). These projects were important for developing the future tourist-based Outer Banks economy (Stick, 1958). In 1937, the U.S. Congress passed legislation authorizing development of the Cape Hatteras National Seashore, the nation’s first national seashore. The park was officially established in 1953 and today consists of 12,275 ha and stretches for 115 km along the ocean shoreline. Eight coastal villages are nestled in between barrier-island segments of Cape Hatteras National Seashore.

Three management priorities were included in the 1966 Cape Hatteras National Seashore Master Plan (Vincent, 2003): (1) control beach erosion above all other park improvements; (2) contain dune breaches where overwash has denuded areas of vegetation; and (3) rehabilitate the WPA dune system and maintain it in perpetuity. Cape Hatteras National Seashore ultimately realized the futility of these priorities. Consequently, the 1984 General Management Plan stated that “natural processes would be allowed to occur by halting future stabilization measures” with three exceptions: (1) Highway 12, (2) Ocracoke village, and (3) Cape Hatteras Lighthouse (Vincent, 2003, p. 27).

Pea Island Migratory Waterfowl Refuge was established in 1938 at the north end of Hatteras Island. Today, it is the Pea Island National Wildlife Refuge and consists of 2381 ha. The refuge was part of the Migratory Bird Treaty Act of 1918 and was
initially housed within the U.S. Department of Agriculture (Federal Register, 1938). The primary purpose of Pea Island National Wildlife Refuge is to be a refuge and breeding ground for migratory birds and other wildlife. Any other use of the refuge must be compatible with the "wildlife first" mission.

**Infrastructure Construction**

In the effort to begin developing the Outer Banks, the access problem had to be resolved. The first toll bridges and roads were built privately in the late 1920s and early 1930s (Roanoke Island to Nags Head causeway, the bridge from mainland Currituck to Kitty Hawk, and the road from Nags Head to Kitty Hawk). The state of North Carolina took over these facilities and built three more bridges (Croatan Sound, Alligator River, and Oregon Inlet) and paved the road from Nags Head to Ocracoke Village in the 1950s and early 1960s. The Outer Banks were now open to the outside world. This infrastructure opened the door for a real-estate boom that involved development of the tourist industry and its motels, restaurants, and support businesses, as well as a building boom of beach cottages, second homes, and retirement homes.

An Act of Congress in 1951 granted North Carolina Department of Transportation (NCDOT) a permanent easement for Highway 12 through Pea Island National Wildlife Refuge with a 30 m right-of-way. However, most of the original Pea Island right-of-way was soon in the ocean due to ocean shoreline recession (D. Stewart, August 2007, personal commun.). In response, much of the original right-of-way has been moved westward into the refuge through time. In 1997, the U.S. Congress passed the National Wildlife Refuge System Improvement Act, which forbids uses incompatible with the mission and purpose of wildlife refuges. Thus, to remain in compliance with Federal law, Highway 12 cannot be moved further westward into the refuge.

In 1991, Stone et al. (1991) identified eight coastal "hot spots" along the Outer Banks where Highway 12 was increasingly damaged and/or destroyed and maintenance of the constructed dune ridges to protect Highway 12 was becoming increasingly more difficult. These eight locations were island segments where the highway either needed to be relocated or the beaches needed to be nourished in conjunction with reconstruction of the dune.
Figure 15. All of Pea Island is vulnerable to the opening of one or more inlets. This 1998 infrared aerial photograph mosaic extends from Oregon Inlet to Rodanthe and shows the relative likelihood of inlet formation (1—highest likelihood, 8—lowest likelihood). Each site is color coded for its inlet vulnerability.
ridges. Three of these coastal segments occur on Pea Island and will continue to cause severe problems for the future design and maintenance of Highway 12 (Fig. 18).

**Engineering around Limits to Growth: 1960s to the Present**

The human population and its effect on barrier-island dynamics began to increase as the economic development of the Outer Banks became a dramatic success story. According to the U.S. Census Bureau (USCB, 2007), between 1960 and 2000, the Dare County population grew from 5935 to 29,967 (405%). The barrier-island system has become a severely modified and highly engineered system with little chance for the natural dynamics to play their critical role in barrier-island evolution as climate changes and sea-level continues to rise (Riggs and Ames, 2003; Horton et al., 2006, 2009; Kemp et al., 2009).

**History of Oregon Inlet and Oregon Inlet Bridge**

Oregon inlet opened during a hurricane in 1846 near the current Bodie Island Lighthouse (Fig. 1B) (Stick, 1980). This large and potentially useful inlet for navigation between

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**Figure 16.** Historic photographs show the construction of barrier dune ridges by the Works Progress Administration (WPA) during the late 1930s on the low and flat overwash-dominated barrier islands using brush fences to trap sand (A–B). These structures are generally not in equilibrium with the storm beach and overwash dynamics and are generally scarpd, ultimately breached (C), and overwashed by storm surges (D). Photographs are from Cape Hatteras National Seashore Archives.

**Figure 17.** Photographs show the modern rebuilding of constructed barrier dune ridges to protect Highway 12 (A–C). (A) Recently adopted practice of building a sandbag core buried in the dune ridge. Because the constructed dune ridges are out of equilibrium with natural beach dynamics, the beach becomes increasingly steeper and narrower, resulting in more frequent storm surges eroding and overtopping the constructed dune ridge and jeopardizing Highway 12 (D). Photos in A, B, and C are by S.R. Riggs; photo in D is from Pilkey and Thieler (1992).
the estuary and ocean has a well-documented history of migration and change since its initial opening. Inman and Dolan (1989) calculated the southward migration of Oregon Inlet between 1849 (date of the first topographic survey) and 1975 at an average rate of 23 m/yr for a distance of 2.9 km. The southward migration demonstrated an increased rate between 1975 and 1988, with an average rate of 54 m/yr for a total migration of 0.7 km. The southward migration of Oregon Inlet between 1849 and 1989 of at least 4 km. By 1989, the south end of the Oregon Inlet bridge was being severed from Pea Island, the U.S. Coast Guard Station harbor on the north end of Pea Island was filled with sand, and the station itself was threatened by the eroding shoreline.

Private ferries carried people across Oregon Inlet until the bridge was completed in 1963. The Oregon Inlet bridge arches gracefully across the tumultuous waters moving between Pamlico Sound and the Atlantic Ocean (Fig. 2). The bridge was designed as a permanent structure on a fixed piece of land with a stable body of water and channel beneath it. Thus, it was poorly designed for a high-energy and dynamic coastal ocean environment including an inlet that was rapidly migrating southward, ocean shorelines that were receding at the highest rates in coastal North Carolina, and inlet channels and sand shoals that were as dynamic as the storms driving the coastal system.

The Ash Wednesday 1962 nor’easter occurred during an early stage of construction. The storm opened the inlet to its maximum width by eroding away the northern inlet spit. After the Ash Wednesday storm, the northern spit reformed but continued to oscillate in response to several smaller storms that caused the various inlet channels to migrate. Channel migration was problematic for the maintenance of a navigation channel within the fixed navigation span of the bridge, requiring increased levels of channel dredging. Migration of southern and northern lateral inlet channels caused the shallow bridge piles to be severely scoured, resulting in subsidence of major portions of the bridge. Repiling of both the south (1978–1981) and north sides of the bridge (1989–1991) was required “to prevent the bridge’s imminent collapse” (NCDOT, 1989, p. 19). In addition, a strong nor’easter blew a hopper dredge into the north end of the bridge in 1990, requiring several bridge spans to be rebuilt.

By 1989, erosion of the north end of Pea Island was about to leave the Oregon Inlet bridge isolated in Oregon Inlet. A rock jetty on the south side of Oregon Inlet was proposed to stop the rapid southward migration of Oregon Inlet and alleviate the threat to the south end of the bridge (NCDOT, 1989). The report stated that the rock jetty would stabilize the northernmost 600 m of Pea Island ocean shoreline, but it would not stabilize the ocean shoreline further south. The environmental assessment report (NCDOT, 1989) concluded that construction of the rock jetty and rock revetment on the north end of Pea Island would have no significant adverse effects to biological resources, endangered and threatened species, recreation, cultural resources, water quality, and aesthetic resources either in the project area or up- or down-coast from the project. Therefore, an environmental impact statement was not prepared.

Construction of the rock jetty on the south side of Oregon Inlet was started in 1989 and completed in 1991. One condition of the permit for jetty construction was that NCDOT should monitor the shoreline position, sediment conditions, and associated beach organisms for the area extending 9.5 km south of the jetty. The shoreline monitoring was done by Fisher et al. (2004) and involved three data sets: (1) digital aerial photography of the monitored area flown every 2 mo from 1989 to 2004, (2) historical aerial photography from the 1940s to late 1980s as analyzed by
Beach Erosion and Nourishment on Pea Island

The NCDCM produces a set of erosion rates for the entire North Carolina ocean coast based upon comparison of the wet-dry line between 1949 and 1998 end-point analysis (Benton, et al., 1997). These shoreline change data for Pea Island are plotted along the length of Pea Island on Figure 20 as the 1949–1998 NCDCM data and show average shoreline change rates that range from +1.5 m/yr to –4.8 m/yr. Inman and Dolan (1989) measured the average rate of shoreline change from 1945 to 1986 for the 11 km Bodie Island coastal segment north of Oregon Inlet to be –2.2 m/yr and the 21 km Pea Island coast south of Oregon Inlet to be –2.6 m/yr.

The USACE (1993) has been maintaining the Oregon Inlet ocean bar channel through the ebb-tide delta since 1960 by using various side-cast, hopper, and pipeline dredges (Fisher et al., 2004). From 1980 to 1989, a hopper dredge was used to maintain a 39-m-wide navigation channel under the navigation span of the Oregon Inlet bridge. During this period, ~650,000 m³/yr of sand was removed and disposed offshore of the inlet into water depths in excess of 9 m (McCafferty, 1993; Dolan et al., 2006). The practice of inlet dredging and offshore disposal resulted in a down-drift deficit for the adjacent beaches on Pea Island National Wildlife Refuge. The consequences of this deficit were (1) an increased rate of migration of the south shore of Oregon Inlet to 188 m/yr (McCafferty, 1993) and (2) an increase in the rate of shoreline recession from an average of –3 m/yr prior to the 1980 dredging to –5.2 m/yr during the 1980–1989 period (Overton et al., 1992).

Offshore disposal of dredged sediment was discontinued in 1989 with construction of the rock jetty. From 1989 on, Oregon Inlet dredged materials were discharged to the northern portion of Pea Island. The material obtained by pipeline dredge was pumped to and placed directly on the subaerial beach between 1 and 4 km south of the jetty (D. Stewart, August 2009, personal commun.; Figs. 18 and 20). The material obtained by hopper dredge was deposited offshore between 1.6 and 4.8 km south of the terminal groin in water depths ranging from 4.5 to 6 m. The actual amount of sand dredged from Oregon Inlet and placed on the Pea Island beach from 1989 to 2005 as reported in Dolan et al. (2004), FDH (2005), Dolan and Stewart (2006), and Dolan et al. (2006) is poorly known. Published values for beach discharge range from 0.5 to 3.8 million m³, while the nearshore disposal values range from 1.0 to 1.9 million m³. The most complete data set was supplied by the USACE (G. Williams, November 2007, personal commun.), stated the following: Slightly more than 5.4 million m³ of sand were dredged from Oregon Inlet in 21 operations between 1989 and 2005 and deposited as follows: 3.8 million m³ of sand were dredged and pipelined directly to the subaerial beaches in 10 operations, and 1.6 million m³ were removed by hopper dredge and deposited in the nearshore in 11 operations.

In addition, NCDOT mined sand from the sand fill behind the rock jetty and trucked it to the beaches ~8 km south of the jetty (D. Stewart and J. Jennings, October 2007, personal commun.). In 1992–1993 more than 0.15 million m³ of sand were trucked to the beach for nourishment. In 1996–1997, –0.38 million m³ of sand were mined for construction of new dune ridges at km 7 and 8 after Highway 12 was relocated to the west.
The FDH (2005) study utilized a dredged sand volume of 2.4 million m$^3$ as compared to the USACE volume of 5.4 million m$^3$, a significantly smaller volume of sediment. This is important because the FDH (2005) study utilized the smaller numbers for dredging and beach disposal as the basis for their economic analysis of beach nourishment and dune ridge construction for the new Oregon Inlet bridge and various Highway 12 alternatives across Pea Island through the year 2060 (NCDOT, 2005, 2007a, 2007b).

**Eye of a human hurricane**

The impacts of beach nourishment on the 9.5 km segment of Pea Island National Wildlife Refuge beaches south of the terminal rock jetty in Oregon Inlet have been monitored since jetty construction in 1989–1991. The NCDCM rate of shoreline accretion and recession for Pea Island (Fig. 20, light green and orange colored, respectively) for the period between 1949 and 1998 ranges from $+1.5$ m/yr to $-4.8$ m/yr (Benton et al., 1997). Data also plotted on Figure 20 (dark green and red colored, respectively)
are the Fisher et al. (2004) shoreline accretion and recession data for the 9.5 km monitored segment of Pea Island south of the jetty from 1989 to 2003. The shore segment for ~1 km immediately south of the jetty demonstrates accretion as the filllet was filled with sand and stabilized. However, the next 10 km of shoreline continues to erode at rates that range up to –4 m/yr, with a general decrease in erosion rates from 1.5 to 5 km and a general increase from 5 to 10 km (Fig. 20). The monitoring studies by Dolan et al. (2004, 2006, p. 60) demonstrated that the “mean sand size of the beach has decreased significantly, the heavy mineral content has increased, and the numbers of the organisms indigenous to the active beach have and continue to decrease.” The NCDCM shoreline erosion rates (Benton et al., 1997) for the coastal segment between 15 and 19 km, at the southern Pea Island National Wildlife Refuge boundary with Rodanthe, have average rates of erosion that increase southward from 0 m/yr to –4 m/yr at the refuge border (Fig. 20).

South of the monitored beach segment, between 11 and 15 km south of the terminal jetty and opposite historic New Inlet and Loggerhead Inlet, the erosion data of NCDCM (Benton et al., 1997) show a shoreline segment accreting at rates up to +1.5 m/yr (Fig. 20). The data for this coastal segment led Fisher et al. (2004), FDH (2005), and Overton and Fisher (2005) to conclude that the NCDCM erosion data represent a condition of permanent accretion that will be stable for the long-term future, while the adjacent segments continue to erode at rates up to –4 m/yr. By making this assumption, the studies conclude that ~4 km of Highway 12 would not be threatened through year 2060. Thus, there would be no maintenance costs associated with moving the highway, elevating it onto a causeway or bridge, constructing dune ridges, or nourishing this beach segment (NCDOT, 2005, 2007a, 2007b). However, if the historic New Inlet and Loggerhead Inlet area were to remain as an accreting shoreline for the next 25, 50, or 100 yr, with the adjacent shorelines receding at rates up to –4 m/yr, a headland or cape structure would form. This is not only highly improbable along one of the highest energy shorelines of the U.S. Atlantic margin, but this scenario is contradicted by the longer-term shoreline recession data of Smith et al. (2008) and the georeferenced time slice analyses of Riggs et al. (2010, in press).

Figure 12 is a georeferenced time-slice analysis that shows the evolution of the historic New Inlet and Loggerhead Inlet coastal segment from the 1852 topographic survey to the 1998 aerial photographs (Riggs et al., in press). The ocean shoreline in the “accretion zone” of Fisher et al. (2004), FDH (2005), and Overton and Fisher (2005) has gone through two stages of erosion (1852–1917 and 1932–1998) and a major stage of accretion between 1917 and 1932. Figure 21 approximately represents the “accretion zone” and shows a detailed pattern of shoreline change during the generally recessional period from 1932 to 1996. Notice that the ocean shoreline goes through stages of erosion and accretion that are dependent upon storm abundance and intensities, inlet openings and closings, and human activities associated with inlet dredging, beach nourishment, and dune-ridge construction. All of these processes interact through time to produce the complex short-term patterns of deposition and erosion. Even though the dates of the historic shorelines do not exactly match the time of the following events, there is a general correlation reflected in the patterns of accretion and erosion. Examples of changing processes that are reflected in the historic shorelines include the following.

(1) The period from 1932 to 1962 was an intense storm period, while 1962–1971 was an extremely mild period in northeastern North Carolina (Riggs and Ames, 2007).

(2) New Inlet was open, according to the 1932–1940 aerial photographs, with deposition along its north flank, erosion along its south flank, and sand in an ebb-tide delta. New Inlet closed in
Highway 12 Alternatives

Oregon Inlet Bridge and North Carolina wash in the near future to maintain island integrity. The southern 4–4.5 km of Pea Island (Figs. 12 and 20) is commonly referred to as the S-curves due to previous road relocations, and continues today to require extreme efforts to protect the highway. This area contains paleo-inlet deposits (Figs. 5, 10, and 11), is the portion of the island that is most vulnerable for new inlets (Fig. 15), and has among the highest ocean shoreline erosion rates in North Carolina (Figs. 13 and 20). In addition, this island segment is in stage 4 of its evolutionary cycle (Fig. 14) and would benefit from one or more new inlets and abundant overwash in the near future to maintain island integrity.

Oregon Inlet Bridge and North Carolina

Highway 12 Alternatives

NCDOT held a public hearing in February 2007 in which they presented two main alternatives for a new Oregon Inlet bridge and Highway 12 across Pea Island (Fig. 22).

Alternative One: Pamlico Sound Bridge and Causeway. This alternative consists of a 27 km bridge and causeway that crosses the Oregon Inlet flood-tide delta, bypasses Pea Island in the deeper water of Pamlico Sound, and comes onshore in the village of Rodanthe. The cost estimates of building and maintaining the Pamlico Sound bridge and causeway until year 2060 range from $1.3 billion to $1.8 billion.

Alternative Two: Parallel Bridge. This alternative would cross Oregon Inlet adjacent and parallel to the current Oregon Inlet bridge. Five options (A through E) exist for Highway 12 on Pea Island, and estimated costs until year 2060, together with the bridge, range from $602 million to $1.6 billion. Options A through D for Highway 12 use beach nourishment together with constructed dune ridges to maintain a 69 m distance from the pavement edge to the ocean shoreline as “a critical buffer zone” (Overton and Fisher, 2005). These options will be built as needed and are based on the assumption that sand for beach nourishment is available from offshore borrow sites as described by Boss and Hoffman (2000). Unfortunately, these borrow deposits are very poorly defined. Option A will maintain the transportation corridor on Pea Island in its present location, utilizing beach nourishment and constructed dune ridges. Option B will relocate Highway 12 west of the predicted 2060 shoreline. The northern section will utilize beach nourishment and constructed dune ridges, and the southern section will utilize a bridge built on the island to allow for overwash and inlet dynamics to take place beneath it. Option C is similar to option A, except the southern section will utilize a back-barrier bridge to move Highway 12 off the barrier for the southern 4–4.5 km in Pea Island National Wildlife Refuge to the village of Rodanthe. Option D is similar to option B, except the southern section will utilize a back-barrier bridge similar to option C. Option E acknowledges the high erosion rates of the ocean shoreline, narrowing of the island, and high likelihood for inlet(s) to open within the southern section of Pea Island. This option will maintain Highway 12 in its present location with a bridge and/or raised causeway along the northern section of Pea Island to allow normal overwash and inlet dynamics to take place. The southern section will utilize a back-barrier bridge as in options C and D.

DISCUSSION AND CONCLUSIONS

At present, the North Carolina Outer Banks owe their recovery from summer hurricanes and winter nor’easters to an army of bulldozers that clear the sand off Highway 12. Dredges, trucks, and even more bulldozers stand by to mine the overwash sand, rebuild the barrier dune ridges, and close new inlets that may open along what Pilkey et al. (1998) called the “restless ribbon of sand.” However, those concerned about the long-term future of our barrier-island resources, and the lifestyle and tourist economy they support, must understand and accept the critical role of natural coastal dynamics in ensuring that future.

Flying over the Outer Banks after major storms, it is clear that many barrier-island segments are little more than a conveyance for Highway 12, the lone road that shuttles residents and tourists to and from the eight villages nestled between the Cape Hatteras National Seashore and Pea Island National Wildlife Refuge segments. Use of constructed dune ridges to “reduce the frequency and degree of flooding and overwash during extreme storms” as proposed by Overton and Fisher (2005, p. 23) prevents critical natural barrier-island maintenance and evolution in a setting of increasing rates of sea-level rise (Kemp et al., 2009; Horton et al., 2009; Riggs et al., in press). In addition, the constructed dune ridges prevent the natural, overwash- and inlet-driven evolution of habitats that constitute a major component of the “mission and purpose” of both Pea Island National Wildlife Refuge and Cape Hatteras National Seashore. Piping plovers, oyster catchers, black skimmers, and numerous species of terns and turtles are critically dependent upon overwash and inlet habitats. These natural barrier-island processes are crucial for improving estuarine water quality, increasing productivity, and supporting coastal fisheries. Unfortunately, these are not always factors in the thinking of federal, state, or local agencies that are under pressure to maintain the transportation infrastructure to underpin the concept of ever-increasing economic growth.
However, there is no status quo on dynamic barrier islands. They continually evolve in response to storms and ongoing sea-level rise. "Holding the line" with the Highway 12 corridor on these barrier islands is a form of stabilization that prevents the islands from keeping up with sea-level rise. The constructed dune ridges and highway roadbed deprive the back barrier of storm overwash sand. The long-term consequence is island narrowing, which ultimately can lead to the collapse of island segments. Adding fuel to the fire is the fact that the small villages within the Pea Island National Wildlife Refuge and Cape Hatteras National Seashore continue to be developed with larger houses and expanding businesses, which become increasingly dependent upon the unstable Highway 12 corridor.

As soon as storm waves break through the constructed dune ridges and cover Highway 12 with sand, bulldozers begin moving the sand back into the dune ridges. Often, the entire body of overwash sand, which may extend across the full width of the island, is bulldozed back to reconstruct even larger or multiple dune ridges. Ironically, these constructed dune ridges may be partially responsible for increasing the shoreline erosion along the Outer Banks. The constructed dune ridges are out of equilibrium with the natural storm beach and, consequently, act like a seawall until they are

Figure 22. North Carolina Department of Transportation (NCDOT) map shows two major alternatives for the proposed Oregon Inlet bridge and Pea Island road. In alternative 1, Highway 12 would be built on a 27 km causeway in Pamlico Sound. In alternative 2, five options are described in the text for Highway 12 across Pea Island. The green star designates the short-term accretion anomaly (see text and Fig. 21), where Fisher et al. (2004), FDH (2005), and Overton and Fisher (2005) claim that shoreline recession will not threaten Highway 12 through 2060. Thus, no options are planned and no costs are included for the long-term maintenance of this segment. The island segment designated with the red star has the highest ocean shoreline erosion rate on Pea Island and highest likelihood for new inlets. Thus, most options for this segment would either involve building a causeway on the island or relocating the road to a bridge west of island as needed. Figure is modified from the NCDOT (2007a, 2007b).
eroded away as the beach returns to an equilibrium profile. Constructed dune ridges cause beaches to steepen and erosion rates to increase, and they prevent storm overwash from delivering sand to the mid- and back-barrier areas. In response, the islands narrow and the scale of reconstruction and/or sound-wall relocation of the highway corridor escalate. With time, the relative proportion of the barrier islands dominated by the Highway 12 corridor increases at the expense of the basic functions of both the Pea Island National Wildlife Refuge and Cape Hatteras National Seashore.

To preserve the villages and barrier islands, as well as the Pea Island National Wildlife Refuge and Cape Hatteras National Seashore, society must learn to live with natural barrier-island dynamics. Buildings will have to be moved back as coastal erosion continues, and if inlets form, alternative modes of transportation should be developed, such as temporary back-barrier bridges or modern ferry and water-taxi systems. As sand covers the highway, it should remain there, and the new road should be reconstructed at higher elevations, perhaps with a clay-gravel surface or the use of airport-runway matting. As existing constructed dune ridges are destroyed by storms, they should not be rebuilt, thus bringing the islands back to a more dynamically stable, natural state.

Most importantly, National Wildlife Refuges and National Seashores must remain under the control of their parent federal agencies to carry out their primary missions for the benefit of all. Managers of the Pea Island National Wildlife Refuge and Cape Hatteras National Seashore must have the authority and support to allow these barrier islands to function naturally and to manage them for their long-term evolution. However, to do this, they need strong public backing to overcome local economic pressures and the attitude that the prime function for these public lands is to provide a transportation corridor for development of private lands. In addition, the size, density, and type of development occurring within the isolated villages must be governed by the "natural limits to growth" (Riggs and Ames, 2003) dictated by the natural dynamics of barrier-island systems. If we hope to maintain a healthy coastal economy based upon a viable barrier island system as the global climate changes and sea level continues to rise, we must learn to live by the islands' rules.

The Pea Island ocean shoreline continues to recede at rates that are among the fastest in North Carolina, in spite of the frequent reconstruction of barrier dune ridges since the late 1930s, routine Oregon Inlet dredging since 1960, and the frequent beach nourishment projects since 1990. Based upon the data and discussion presented here, several conclusions are clear concerning the long-term future of the Oregon Inlet bridge and Highway 12 across Pea Island National Wildlife Refuge.

1. The terminal jetty has stopped the southerly migration of Oregon Inlet, and the rock revetment has protected the base of the present Oregon Inlet bridge.

2. From 1960 to 1982 an unknown amount of dredged Oregon Inlet sediment was discharged offshore in deep water. From 1983 to 1988 approximately 2.4 million m³ of sediment was dredged in 8 operations by hopper dredge and deposited in the shallow near shore off the northern 4 km of Pea Island. From 1989 to 2005 approximately 5.6 million m³ of sediment was dredged from Oregon Inlet in 21 operations (1.7 million m³ by hopper dredge and 3.9 million m³ by pipeline dredge and discharged to the shallow near shore and beach segments, respectively in the northern 1 to 4 km segment of Pea Island). An additional 0.4 million m³ of sediment was mined from the fillet and placed on the beach in the 7 to 8 km area south of the terminal jetty. From 2006 to 2009 approximately 2.3 million m³ of sediment was dredged from Oregon Inlet in 6 operations (0.9 million m³ by hopper dredge and 1.4 million m³ by pipeline dredge and discharged to the shallow near shore and beach segments, respectively in the northern 1 to 4 km segment of Pea Island) (D. Stewart, September 2009, personal commun.). This represents a total of 10.7 million m³ of sediment (5.0 m³ placed by hopper dredge in the shallow near shore and 5.7 million m³ placed directly on the beach by pipeline dredge) placed on the eroding downdrift beaches of northern Pea Island.

3. Construction of the terminal jetty on the south side of Oregon Inlet stabilized the beach for the first kilometer of Pea Island south of Oregon Inlet. The monitored shoreline from 1 to 11 km south of the Oregon Inlet terminal jetty continues to erode at rates that range up to 4 m/yr. The 1 to 5 km beach segment saw a general decrease in erosion rates from highs of 5 m/yr to lows of 2.5 m/yr due to the extensive and regular discharge of beach nourishment sand primarily to the 1 to 4 km beach segment (conclusion 2). However, the beach erosion rates within the monitored segment from 5 to 10 km have generally increased substantially compared to pre-jetty rates (from 2 to 3 m/yr to 2 to 4 m/yr) in spite of the frequent upstream beach nourishment, installation of sand bags, and construction of barrier-dune ridges.

4. The accretion anomaly within the NC Division of Coastal Management data (coastal segment 11.5 to 15 km south of the terminal jetty) is only a short-term anomaly that is a direct response to inlet dynamics associated with the historical New and Loggerhead Inlets. The long-term changes demonstrate a net landward recession.

5. The construction of the terminal jetty on the south side of Oregon Inlet has not, by itself, trapped any sand on the downdrift beaches of Pea Island beyond the first km. In fact, the terminal jetty has not stopped the processes of shoreline erosion along the Pea Island ocean shoreline from 1 to 5 km. The many additional human modification efforts (e.g., beach nourishment, road bulldozing, barrier dune ridge maintenance and construction, sand bag emplacements, and highway relocations) locally ameliorated and temporarily stopped the net shoreline recession within this segment. However, within the km 5 to 10 segment, erosion rates have substantially increased and shoreline recession continues in direct response to the dredging of Oregon Inlet and construction of the terminal jetty.

6. In evaluating barrier island shoreline changes through time, it is absolutely essential to take into consideration the...
changing dynamics of inlets, storm patterns, and human modification activities within each coastal segment.

7. Highway 12 will continue to be severely impacted on a regular basis by individual storm events and, in the longer term, by ongoing sea-level rise. The barrier island will continue to migrate westward, forcing the westward movement of Highway 12 deeper into the heart of Pea Island National Wildlife Refuge. This will further jeopardize the refuge function and prevent the natural barrier-island functions of overwash and inlet openings and closings.

8. Attempts to “hold the line” with a new Oregon Inlet bridge and Highway 12 across Pea Island for the next 50–100 yr could lead to collapse of extensive segments of Pea Island. If this occurs, there will be a very expensive “dead-end” bridge and road system. Eight villages will be isolated, and the coastal economy will be severely damaged.

During the past 500 yr, Pea Island has been dominated by numerous inlets and development of extensive flood-tide deltas, massive overwash depositional fans, and high rates of ocean shoreline recession, all integral elements of island migration. These natural processes are driven by hurricanes and nor’easters and are crucial for both the short-term health and long-term evolution of the barrier island. Prior to the 1930s, natural dynamics controlled the evolution of the barrier islands. However, beginning in the mid-1930s, the Outer Banks began to be managed for their economic development. Thus, the barrier islands rapidly became dominated by human modifications designed to “lock the barrier islands in place” and to “minimize the impacts of storms.”

Today, Pea Island has become the “eye of a human hurricane” driven by a vision of unlimited growth and development in support of North Carolina’s coastal economy. This growth is on a collision course with an increasing rate of sea-level rise and escalation of storm impacts. For the long-term health and, indeed, survival of our dynamic coastal system, we must develop new approaches to coastal management that blend the development, utilization, and maintenance of the economic infrastructure with the natural dynamics of climate change, including sea-level rise, increased storm frequency, shoreline recession, and habitat evolution and migration.

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APPENDIX 1. DEVELOPMENTAL CHRONOLOGY OF THE PEA ISLAND–OREGON INLET–BODIE ISLAND BARRIER-ISLAND SYSTEM

The following chronology for the three barrier-island segments is based upon the historical record starting in 1775, as well as specific historical studies including the entries listed in the references cited. Various state and federal agencies have produced many documents over the last four decades concerning Oregon Inlet and Pea Island; this chronology highlights only the more important events and reports.

Ca. 1775: Chickinacommock Inlet on Pea Island closed naturally.
1846: Oregon Inlet opened during a hurricane on 7 September 1846 in the vicinity of the current Bodie Island lighthouse. It migrated southward about 4 km between 1849 and 1989.
1848: First Bodie Island lighthouse was built on the south side of Oregon Inlet and was subsequently destroyed prior to 1859 as the inlet migrated southward.
1849–1866: First detailed topographic survey of the northern Outer Banks from the Virginia State line to Ocracoke Inlet by the U.S. Coast Survey.
1859: Second Bodie Island lighthouse was built on the south side of Oregon Inlet and was destroyed during the Civil War.
1870: Loggerhead Inlet on Pea Island closed naturally.
1872: Third and current Bodie Island lighthouse was built on the north side of Oregon Inlet.
1899: Major overwash ramp burned the Loggerhead Inlet flood-tide delta, probably during the 1899 hurricane.
1923: New Inlet on Pea Island closed naturally.
1924: North Carolina Fisheries officials attempted to open New Inlet artificially without success.
1928: Manteo Causeway bridge was built across Roanoke Sound as a private toll road from Roanoke Island to Whalebone Junction in Nags Head.
1930: Wright Memorial bridge was built across Currituck Sound as a private toll road.
1930: A hard-surfaced road was built from Manteo to the Manteo Causeway.
1931: A hard-surfaced road was built on the barrier island between Whalebone Junction in Nags Head and Kitty Hawk and connected the Manteo Causeway and Wright Memorial bridges.
1932: New Inlet on Pea Island was reopened by two hurricanes.
1932: First aerial photographs of the Outer Banks were flown from Kitty Hawk to Rodanthe after the 1932 hurricanes.
1934: Federal Emergency Relief Administration began an erosion-control project along several kilometers of Currituck County...
beaches. The constructed barrier dune ridges were destroyed by high tides within a few months (Toll, 1934).

1935: North Carolina enacted legislation to prohibit stock from running wild on the barrier islands of Dare County.

1935–1940: North Carolina Works Progress Administration (WPA), under the supervision of the National Park Service, started an erosion-control project to construct barrier dune ridges along 174 km of the North Carolina coast extending from the Virginia State line through Currituck, Dare, and Hyde Counties.

1937: U.S. Congress passed legislation authorizing development of the Cape Hatteras National Seashore within the U.S. National Park Service, the nation’s first national seashore.

1938: Franklin D. Roosevelt established the Pea Island Migratory Waterfowl Refuge at the north end of Hatteras Island by executive order, to further the purposes of the Migratory Bird Treaty Act of 1918.

1945: New Inlet on Pea Island closed naturally after a wooden bridge was constructed across the flood-tide delta.

1950: U.S. Congress authorized the U.S. Army Corps of Engineers, through the River and Harbor Act of 1950 (Public Law 81-516), to dredge the Oregon Inlet ocean bar navigation channel to 4.2 m depth as part of the Manteo Shallowbag Bay, North Carolina project.

1951: North Carolina Coastal Highway 12 was built from Nags Head to Oregon Inlet.

1952–1955: North Carolina Coastal Highway 12 was built from Oregon Inlet to Ocracoke Village.

1953: U.S. Congress officially established Cape Hatteras National Seashore.

1953: The bridge across Croatan Sound was completed from Mann’s Harbor to the north end of Roanoke Island.

1955: Oregon Inlet fishing center was built.

1959: The bridge across Alligator River was completed from Tyrrell County to Dare County.

1962–1963: The 3.9-km-long bridge across Oregon Inlet was constructed from Bodie Island to Pea Island, replacing the private ferry operating across the inlet.

1963: U.S. Congress adopted a resolution to initiate a study of the Oregon Inlet jetty project.

1970: U.S. Congress authorized the U.S. Army Corps of Engineers, through the River and Harbor Act of 1970 (Public Law 91-611, Section 101), to proceed with the Oregon Inlet jetty project to deepen the ocean bar navigation channel from 4.2 to 6 m, stabilize the inlet with two jetties, provide a means to bypass sand across the inlet, and create a 6.07 ha harbor at Wanchese.


1978: North Carolina awarded the contract for construction of the Wanchese Harbor and the development of a “seafood industrial park.”

1978–1981: Severe channel scour eroded support piles on the southern end of the Oregon Inlet bridge, causing bridge subsidence; this portion of the bridge was repiled.

1979–1980: U.S. National Park Service formed a Coastal Advisory Committee (Inman Panel) to study the U.S. Army Corps of Engineers Oregon Inlet Jetty Project. The panel issued its first report, which concluded that the project would adversely affect the adjacent shoreline environments. The panel’s second report was titled “Potential Effects of the Proposed Oregon Inlet Jetties on Shore Processes along the Outer Banks of North Carolina.”


1980–1989: The Oregon Inlet navigational channel was maintained under the high bridge span by hopper dredge with the sand discharged in offshore water depths >9 m off the inlet.

1980–1989: The southward migration rate of Oregon Inlet increased from 23 m/yr prior to 1980, to 188 m/yr in response to the dredging and offshore disposal (Dolan et al., 2006; McCafferty, 1993). Pea Island National Wildlife Refuge ocean shoreline erosion rates averaged 3 m/yr from 1949–1979 and increased to 5.2 m/yr during the 1980s (Overton et al., 1992).

1981–1983: The Department of Interior requested the U.S. Army Corps of Engineers to study a “dredging-only alternative” along with design changes for the proposed two inlet jetties. The USACE (1983) report concluded that the dredging-only alternative was “functionally infeasible” and would produce “catastrophic and unacceptable” beach erosion.

1983: The U.S. Army Corps of Engineers published Supplement I to the Phase II GDM for the Oregon Inlet Jetty Project.

1984: The Outer Banks Erosion Task Force Report recommended that hard structures not be allowed as beach protection and that only temporary measures (e.g., beach nourishment, sandbag bulkheads, and beach pushing) be allowed to protect structures until they can be moved landward or until the effect of a short-term erosion event has passed.

1985: The U.S. Army Corps of Engineers published the Final Environmental Impact Study (EIS) for the Oregon Inlet Jetty Project.

1989–1991: Severe channel scour eroded support piles on northern portions of the Oregon Inlet bridge, requiring this portion of the bridge to be repiled.

1989–1991: The North Carolina Coastal Resources Commission (CRC) issued a variance to NCDOT, and the USFWS issued a right-of-way permit to NCDOT for construction of a 937.5 m rock jetty on the north end of Pea Island National Wildlife Refuge. The U.S. Army Corps of Engineers issued permits to NCDOT for construction of the rock jetty, which was completed in 1991. The purpose of the rock jetty was to stop the southward migration of Oregon Inlet and protect the southern end of the Oregon Inlet bridge.

1989–2005: The U.S. Army Corps of Engineers dredged 5.35 million m³ of sediment from Oregon Inlet; 3.75 million m³ of sediment were placed on the Pea Island National Wildlife Refuge subaerial beaches by pipeline dredging, and 1.61 million m³ of sediment were discharged offshore the Pea Island National Wildlife Refuge beaches in 4.5–6 m water depths by hopper dredges.

1989–2006: A physical and ecological monitor program was carried out for the 9.5 km beach zone south of the rock jetty on Pea Island National Wildlife Refuge.

1990: A hopper dredge used to maintain the Oregon Inlet channel was blown into the bridge during a storm, destroying several bridge spans.

1990: The U.S. Army Corps of Engineers published its third economic analysis for the Oregon Inlet Jetty Project.

1991: An NCDOT study (Stone et al., 1991) defined six critical sections or “hot spots” along Highway 12 between Oregon Inlet and southwestern Ocracoke Island. Three of the “hot spots” were on Pea Island and included from north to south: northern Pea Island, southern Pea Island, and Rodanthe S curves.


1997: U.S. Congress passed legislation that prohibited construction of roads within National Wildlife Refuges that interfere with the primary refuge functions.

2001: The U.S. Army Corps of Engineers published the final versions of Supplement II to the Phase II GDM and Supplement III to the EIS for the Oregon Inlet Jetty Project. These documents shortened both jetties to 3000 m in length, eliminated the sand-blocking central barrier within each jetty, and added a 300 m weir section and 24.3 ha depositional basin in the north jetty.
2001: The U.S. Department of Commerce (DOC) referred the Oregon Inlet Jetty Project to the General Accounting Office (GAO), Council on Environmental Quality (CEQ), on the basis that the project would cause unacceptable environmental harm to commercial and recreational fishery resources.


2004: The NCDOT Bridge Inspection Report rated the current condition of the Oregon Inlet bridge as “poor” with a sufficiency rating of 2 out of 100. The bridge was classified as structurally deficient with a remaining 2 yr practical service life.

2005: The North Carolina General Assembly passed legislation (House Bill 747) for expediting and accelerating the efficient, cost-effective completion of the Oregon Inlet bridge replacement.

2005: Supplemental Draft Environmental Impact Statement and Draft Section 4(f) Evaluation for NC 12 Replacement of Herbert C. Bonner (Oregon Inlet) Bridge was submitted to NCDOT.

2007: Supplement to the 2005 Supplemental Draft Environmental Impact Statement and Draft Section 4(f) Evaluation for NC 12 Replacement of Herbert C. Bonner (Oregon Inlet) Bridge was submitted to NCDOT.

2007: NCDOT held public hearings about two alternatives for a Pamlico Sound bridge corridor (estimated costs range from $1.3 to $1.8 billion to 2060) and five alternatives for an Oregon Inlet parallel bridge corridor with five alternatives for NC Highway 12 on Pea Island (estimated costs ranged from $602 million to $1.6 billion to 2060).

2007: National Environmental Policy Act (NEPA)/Section 404 Merger Meeting Document for NC 12 Replacement of Herbert C. Bonner Bridge (Bridge No. 11) over Oregon Inlet was submitted by NCDOT.

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