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A cross-shore model of barrier island migration over a compressible substrate

Julie Dean Rosati [a,]*, Robert G. Dean [b], Gregory W. Stone [c]

[a] Research Hydraulic Engineer, U.S. Army Corps of Engineers Research and Development Center, Coastal and Hydraulics Laboratory, 109 St. Joseph Street, P.O. Box 2288, Mobile, AL 36628-0001, USA
[b] University of Florida, Coastal and Ocean Engineering Department, 334 Weil Hall, Gainesville, FL 32605, USA
[c] Louisiana State University, Coastal Studies Institute and Department of Oceanography and Coastal Sciences, Baton Rouge, LA 70803, USA

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ABSTRACT

Barrier islands that overlie a compressible substrate, such as islands in deltaic environments or those that overlay mud or peat deposits, load and consolidate the underlying subsurface. Through time, the elevation and aerial extent of these islands are reduced, making them more susceptible to future inundation and overwash. Sand washed over the island and onto back-barrier marsh or into the bay or estuary begins the consolidation process on a previously non-loaded substrate, with time-dependent consolidation as a function of the magnitude of the load, duration of load, and characteristics of the substrate. The result is an increase in the overwash, migration, breaching, and segmentation of these islands.

This research developed a two-dimensional (cross-shore) numerical model for evolution of a sandy barrier island that spans durations of years to decades as a function of erosion, runup, overwash, migration, and time-dependent consolidation of the underlying substrate as a function of loading by the island. The model was tested with field data and then applied to evaluate the effects of a compressible substrate on long-term barrier island evolution. Results illustrate that barrier islands overlying a compressible substrate are more likely to have reduced dune elevation due to consolidation, incur overall volumetric adjustment of the profile to fill in compressed regions outside the immediate footprint of the island, and experience increased overwash and migration when the dune reaches a critical elevation with respect to the prevalent storm conditions.

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1. Introduction

Barrier islands form a dynamic coastal boundary for bays, estuaries, and mainland shores. They buffer these more fragile environments from coastal winds, waves, and storm surges (Stone and McBride, 1998), provide habitat for static and migrant populations (Moore et al., 1990), and foster quiescent, reduced salinity habitat for evolution of juvenile species (Courrat et al., 2009). Estuaries, particularly those on deltaic coasts, represent the most productive ecosystems in the world yet they are the most threatened by anthropogenic activities (Edgar et al., 2000), an inability to expand with relative sea level rise (so-called "coastal squeeze," French, 2006), and disintegration of protective barrier islands (e.g., McBride et al., 1995; McBride and Byrnes, 1997; Penland et al., 2005). Approximately 12% of the world's open-ocean coast is fronted by barrier islands, and 28% of these islands occur in deltaic systems (Pilkey and Fraser, 2003). The benefits and functioning of barrier islands, especially those in deltaic settings, are threatened by reduced sources of sand, relative sea level rise, and anthropogenic activities. Intervention to restore barrier islands through placement of beach-quality sand from an external source has been conducted since the 1930s (Farley, 1923; Marine Board, 1995) and continues to be considered in increasingly large-scale, regional applications (van Heerden and DeRouen, 1997).

Barriers evolve in form and migrate in response to coastal processes, sediment availability, and geologic setting on time scales ranging from hours to decades to centuries. On time scales of hours to days, cross-shore processes during storms can erode the foreshore and overwash the island and deposit sediment on the back-barrier or into the bay (e.g., Leatherman, 1979; Kahn and Roberts, 1982; Dingler and Reiss, 1990; Doughty et al., 2006). Over seasons, years, and decades, a gradient in longshore sand transport, change in regional sediment supply, and adjacent inlet processes can erode, accrete, and migrate a barrier island (e.g., Penland et al., 2005; Morton, 2008). On geologic time scales ranging from decades to centuries, processes in the vertical dimension such as eustatic sea level change, regional down-warping or uplift, and consolidation of sediment may contribute to the long-term evolution of coastal morphology (e.g., Storms et al., 2002; Stolper et al., 2005; FitzGerald et al., 2008; Moore et al., in press). For barrier islands overlying poorly-consolidated sediment, such as deltaic, bay, estuarine, and peat deposits, consolidation of the underlying substrate

* Corresponding author. Tel.: +1 251 694 3719; fax: +1 251 690 3464.
E-mail address: Julie.D.Rosati@usace.army.mil (J.D. Rosati).

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due to the weight of the island can accelerate long-term morphologic response (Guber and Slingerland, 1981; Gayes, 1983; Dean, 1997; Bourman et al., 2000; Rosati, 2009).

Deltaic, bay, estuarine, and peat deposits compress, or consolidate as a function of the load that is applied, duration of loading, and characteristics of the substrate itself. River deltas experience consolidation wherever the river deposits organics and fine sediments, such as silt and clay. Deltaic systems that experience accelerated subsidence include the Mississippi River, U.S.A. (Coleman et al., 1998); Rhine–Meuse River, The Netherlands (Berendsen, 1998); Ebro River, Spain (Sánchez-Arcilla et al., 1998); Nile River, Egypt (Stanley and Warne, 1998), the Ganges–Brahmaputra Rivers, Bangladesh, India (Allison, 1998); and the Yangtze River, China (Xiqing, 1998). Compaction of the subsurface can also occur with fine sediment and peat deposited in estuaries and bays (e.g., Bloom, 1964; Kaye and Barghoorn, 1964; Cahoon et al., 1995; Long et al., 2006; Meckel et al., 2007). For barrier islands overlying a soft substrate, whether the subsurface is riverine, estuarine, or organic in origin, the weight of the island compresses the subsurface resulting in a time-dependent reduction of the island elevation. The net effect is an increase in the likelihood for overwash of the island and subsequent migration. New washover deposits begin to consolidate previously non-loaded sediment, thus perpetuating the morphologic change process.

In this paper, we develop a two-dimensional (2D) model for barrier island erosion, overwash, and washover, including time-dependent consolidation of the subsurface as a function of local loading by the barrier island (Fig. 1). The model is applied to test the hypothesis that cross-shore barrier island migration and volumetric losses are modified by the characteristics of a compressible subsurface, as a function of the weight and duration of loading. First, we review the state-of-modeling for barrier island morphologic change over a compressible substrate such as deltaic, bay, or estuarine deposits. Next, we present theory of model development, validate the consolidation routine with long-term data from the Mississippi River Delta, and illustrate application through comparison with data from two barrier islands in Virginia, the only cross-shore barrier profile and commensurate sediment core data presently available. We apply the model to evaluate the hypothesis and demonstrate how a compressible substrate modifies barrier island morphologic evolution.

2. Behavior and modeling of barrier islands that overlie compressible sediment

Barrier islands overlying compressible sediment or peat deposits have been observed to rapidly erode, rollover, breach, breakup, and possibly become submerged (e.g., Penland and Boyd, 1981; Leatherman et al., 1982; McBride et al., 1995). Penland and Boyd (1981) defined three stages of deltaic barrier island formation based on evolution of barrier islands associated with the Mississippi River Delta. After a mature active delta was abandoned by the river, Stage 1 began with an erosional headland that fed flanking barrier islands with sand that had been reworked from the mixed deltaic deposit. Over time (millennia), subsidence and wave-induced erosion depleted the source of deltaic sediment. Stage 2 consisted of a transgressive (retreating) sandy barrier island arc. Finally, Stage 3 occurred when erosion and subsidence reduce the barrier island to a subaqueous inner shelf shoal. Until human intervention began in the early 1900s (through levee construction and river diversion), this cycle repeated as the river occupied new locations or former deltas and provided a new source of sediment.

Because of this cycle of delta formation and abandonment, the Louisiana barrier islands are comprised of a relatively thin layer of fine sand that was reworked from the abandoned delta. The islands overlie a thick deltaic sequence of clay and silt that was deposited during the mid-to-late Holocene by the river, and eventually transgressed over back-barrier estuarine deposits (Coleman et al., 1998). Penland et al. (2005) documented long-term (greater than 100 years) and short-term (less than 30 years) shoreline change in Louisiana as −6.1 and −9.4 m/yr, respectively. The rapid erosion of Louisiana's coast is attributed to the predominance of muddy sediment, thickness of peaty marsh soils, rapid rates of subsidence, and frequency of hurricanes (Kuecher, 1994; Penland et al., 2005). Without a source of littoral sand in the regional coastal system, and with rapid subsidence, barrier islands in Louisiana have ultimately drowned (e.g., Ship Shoal, Penland and Boyd, 1981). In the region of the abandoned LaFourche Delta, Kuecher (1994) correlated thicker deltaic sediment with the highest rates of land loss as compared to thinner deposits. Similarly, Penland and Ramsey (1990) found that local rates of relative sea level rise were related to the thickness of Holocene sediment for the Mississippi River Delta and Chenier plains.

Examples of barrier islands with similar cross-sections occur along the Delaware–Maryland–Virginia ("Delmarva") Atlantic coast. Some of the barrier islands in this region, for example in southwestern Delaware Bay, and Wallops, Assawoman, and Metompkin Islands, Virginia, are comparable to the deltaic barriers in Louisiana in that they are composed of a thin veneer of sand over a compressible substrate. However, in this region the origin of the substrate is lagoonal mud and marsh deposits, over which the islands have overwashed and transgressed through time (Kraft et al., 1979; Leatherman et al., 1982; Oertel and Kraft, 1994). The Delmarva lagoonal and mud

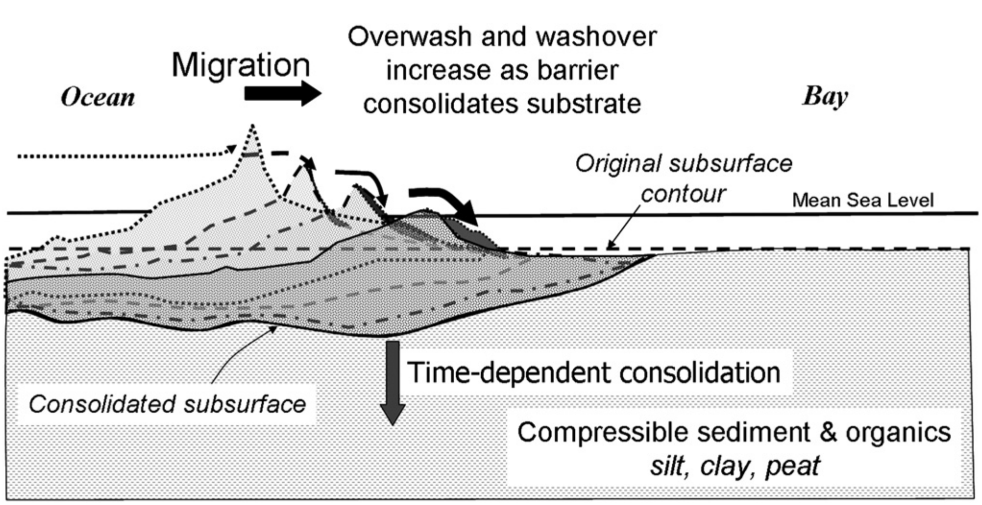

Fig. 1. Increase in overwash and migration of sandy barrier island with consolidation of underlying compressible substrate.