MODELING AND MANAGING THE LONG-TERM EFFECTS OF ARTIFICIAL DUNE CONSTRUCTION IN THE OUTER BANKS OF NORTH CAROLINA

by

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Abstract

The goal of this paper is to gain a better understanding of long-term interactions between natural processes and human activities, and how protective measures produce long-term, unintended consequences. Protective measures can disrupt natural processes in such a way that can intensify property damages from natural hazards. Current management practices aimed at defending transportation infrastructure in the Outer Banks of North Carolina are creating such long-term effects. A numerical model examines the long-term, coupled geomorphic and economic consequences of constructing and maintaining artificial dunes. By subjecting a simulated barrier island to a probabilistic storm climate, storm impacts are described in terms of probability distributions of outcomes, which can be translated into quantifiable risk to coastal development. Furthermore, the evolution of this risk over time is investigated as economic activities-- and subsequent mitigation measures-- are impacted by and alter natural processes of barrier island evolution. Given the magnitude of change that coastal systems will be subject to under climate change, current management strategies designed to maintain system stability are certainly unsustainable and may even be self-defeating in the long-term.

Keywords: Sea Level Rise, Protective Measures, Coastal Processes, Barrier Islands.

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1. Introduction

1.1 Background

Human interactions with the natural landscape are becoming overwhelming complex. New protection and mitigation technologies are enabling the development of dynamic natural landscapes at a larger scale than ever before. As development encroaches further into dynamic natural landscapes, lives and property are increasingly impacted by natural hazards. In response to such impacts, humans manipulate the natural landscape through protective measures, such as levee or artificial dune construction, to maintain conditions stable enough for development. However, a fundamental inconsistency exists between the temporal and spatial scales at which human activities and natural processes operate. Protective measures are typically designed to stabilize a natural system over planning or development time scales, but are often too near-sighted to account for natural system change occurring beyond a decade or two (NCDOT, 2008). When slower-acting natural processes are disrupted, they can produce unforeseen, long-term effects that can intensify property damages from natural hazards. This has important implications for management policies that aim to stabilize natural landscapes for development, because adverse effects often manifest themselves beyond the scope of planning capabilities. Given the magnitude of change that natural landscapes will be subject to under climate change (IPCC, 1995; Moore et. al., 2006; Vellinga and Leatherman, 1989; Meehl et. al., 2000; Cowell et. al, 2006), management strategies designed to maintain system stability are certainly unsustainable and may even be destructive in the long-term. Without proper understanding of the interactions between management actions and natural processes, protective measures can be self-defeating. The goal of this paper is to investigate the long-term, unintended consequences of human manipulations of natural landscapes for protection from natural hazards.

Coastal systems, in particular, are subject to potentially harmful management practices in the long-term because of high population densities and frequent natural disturbances. Over 2 billion people, or around 37 percent of the global population, live within 100 km of a coastline (Cohen et. al., 1997), which is exacerbated by the fact that in many countries coastal populations are growing at double their national rates (Turner et. al., 1996). Cooper and Pilkey (2004) state that "Prediction of sea level rise and the resulting shoreline retreat are among the most important tasks facing coastal and global change scientists, particularly given the population concentration in coastal zones" (p. 158). Coastal communities are engaged in a continuous battle between the protection of lives and property and damages inflicted by oceanic storms and sea level rise. Supported by high property tax and tourism revenues, coastal communities mobilize costly and extensive protective measures to hold-back the sea.

Protective measures are usually designed to minimize the frequency and severity of storm impacts to coastal development. Current management practices on the eastern coast of the United States focus on shoreline stabilization and property fortification through such means as beach nourishment, hard stabilization, and artificial dune construction (Bush et. al., 1996; Overton et. al., 2000). This approach is typically successful in filtering-out damages from small, frequent storms and obtaining localized, short-term stability for coastal communities. Such moderate successes have helped form a management paradigm that deals mostly with immediate, concrete threats to an ever-expanding coastal population. Management has most likely evolved in this manner because of standard economic discounting methods and the short planning time horizons they encourage (Bush et. al., 1996; Smith et. al., in review; Pompe and Rinehart, 1994, 1995, 1999). However, in the longer-term, large-scale shoreline responses are the product of infrequent, large storms and sea level rise. Management actions that protect development from frequent impacts can impair barrier island resilience by disrupting the long time scale natural processes that rely on frequent disturbances to maintain a longer-term steady-state. Therefore, current management practices often have the unintended consequence of intensifying damages from large storms by reducing barrier island resilience in the interim.

The phenomenon of unintended consequences from management/policy actions has been studied in both human and natural systems. Forrester (1971) investigated the counter-intuitive behavior of social systems in response to inner-city corrective programs. Corning (2003) defines ‘disergy’ as interactions between seemingly unconnected system components that induce a destabilizing effect on a system. Smith and Wilen (2003) demonstrate how narrow-sighted fisheries management policies fail to account for destructive, reactionary behavior of fishermen in response to fishing restrictions. However, many studies in the coastal zone management literature have failed to fully recognize the phenomenon of unintended consequences. Instead, attention has been focused on minimizing storm impacts to coastal systems, rather than investigating how those impacts change through time in response to management actions. These approaches strive to measure and manage the vulnerability of coastal development (Elko et. al., 2002; Judge et. al., 2003; OBTF; Overton et. al., 2000; Rosati and Stone, 2007; Stockdon et. al., 2007; USGS, 2000). Although, several studies have coupled human manipulations with natural landscape dynamics in an attempt to capture emergent, long-term consequences of current management practices. Such cases have revealed valuable insights into interactions between humans and the natural landscape, and include Assateague Island and Ocean City, MD (McNamara and Werner, in press (a); McNamara and Werner, in press (b)), the Carolina coasts (Slott et. al., 2006), and the Los Angeles Basin (Magliocca, 2006).

Long-term, emergent effects of protective measures are becoming particularly important in the Outer Banks of North Carolina. The Outer Banks offer one of the most beautiful and isolated natural settings on the East Coast. However, its serenity is misleading because of continuously rising sea level. The Outer Banks are a ribbon of highly mobile islands that jut out into the Atlantic Ocean. As a result, they are subjected to a high energy wave climate generated by tropical hurricanes and winter nor’easters (Murray and Ashton, 2001). In a ‘natural state’, the barrier islands consist of wide, low elevation islands that-- subjected to small, frequent disturbances-- freely adjust their morphological features. If dunes are present, they are typically small and act as a constraint on wave run-up. During storm events, the beach cross section expands and contracts in response to wave energy during wave run-up (Dolan, 1972). If wave run-up is sufficiently high, waves impact the dunes and transfer sediment onto the beach and offshore through erosion and/or over the dune crest through a process known as *overwash*. Overwash consists of storm-generated wave transport and redistribution of beach and dune sediment landward of the duneline, which builds the island’s elevation relative to sea level. Barrier islands are extremely dynamic, constantly expanding and contracting in response to wave energies and sea level rise. Most of the time these adjustments are of little geomorphic or economic significance, but large storms and long-term trends of sea level rise can prompt dramatic shifts in shoreline position, beach width, and dune structure. Unfortunately, the ‘natural state' is not conducive to permanent development, and humans have responded by constructing artificially high and continuous dunes to protect coastal property from storm impacts.

The Outer Banks were first stabilized in the 1930's through the construction of an extensive dune system by the Works Progress Administration-Civilian Conservation Corps (Dolan, 1972). These artificially high dunes blocked the penetration of any overwash and allowed for widespread property and infrastructure development. Currently, the dune system is maintained and rebuilt after storms using on-site overwash sediment by the North Carolina Department of Transportation (NCDOT), U.S. Army Corps of Engineers (USACOE), and the National Park Service as a part of the Outer Banks Task Force (OBTF). Although a costly protective measure in the long-run, artificial dune construction is justified by revenues from tourism and an enormous tax base drawing from high property values. Coastal development oriented towards luxury vacation homes and seasonal businesses support massive tourist and real estate industries. The artificial dunes also serve to protect NC Highway 12-- lifeline of this economic system-- which makes travel on the barrier islands convenient. In addition, NC highway 12 is the only evacuation route off of the islands, and thus maintaining a passable road is a top priority. Unfortunately, the continuous construction and maintenance of artificial dunes-- and the removal of overwash sediment that is required-- has forced the beach system into a state that may ultimately have a higher susceptibility to more frequent and severe overwash events and a lower resiliency to such impacts.

1.2 Hypotheses

This paper investigates the long-term, coupled geomorphic and economic consequences of constructing and maintaining artificial dunes in the Outer Banks. To investigate the effects of protective measures on such large spatial and temporal scales, a numerical model simulates the evolution of a typical barrier island along the Outer Banks. Highway 12 at Rodanthe, NC is frequently overwashed and serves as the specific study site. The model investigates the long-term geomorphic stability and economic viability of current management practices by addressing three main questions:

1) What natural processes maintain a steady state barrier island cross-section?

2) How do current management practices alter/perturb this steady state in the long-term subject to sea level rise and/or an intensified storm climate?

3) In what manner and to what extent do current management practices alter storm impacts on long time scales?

Two hypothesized effects of artificial dune construction are tested by the numerical model. First, artificial dunes filter-out small, frequent overwash events that help build the island's width and elevation. Second, the overwash regime is shifted toward large-scale, low-frequency storm impacts. Because only large storms exceed artificial dunes, obstruction of smaller, island-building overwash effectively fixes island elevation despite rising sea level. Thus, when a storm large enough to overwash artificial dunes occurs, impacts are much worse than they otherwise would have been without the disruption of regular overwash. These two effects are interrelated and they both increase the likelihood that large storms will produce catastrophic damages to homes and infrastructure.

2. Methods

2.1 Approach

Traditional modeling endeavors have simulated either the geomorphic processes of erosion, overwash, and barrier island migration (ACOE, 2004; Donnelly et. al., 2006a; Donnelly et. al., 2006b; Foote and Horn, 2002; Gares and White, 2005; Holman, 1986; Larson et. al., 2004a; Larson et. al., 2004b; Leadon, 1999; Peng et. al., 2004; Schwartz, 1982; Tinh, 2006; Tuan et. al. 2006), or have developed sophisticated economic models that explore the economic incentives and/or policies that drive patterns of resource management (Brown and Pollakoswi, 1977; Pompe and Rinehart, 1994, 1995, 1999; Smith et. al., in review; Smith and Wilen, 2003). These models simulate real-world processes with extensive detail, but they are unable to fully capture entire system behaviors that are the product of interactions between natural and human systems. A few attempts have been made to incorporate both the natural and human system dynamics into coupled, integrated models. These models explore the interactions between natural processes and human activities on long time scales using dynamical, complex systems modeling approaches (McNamara and Werner, in press (a); McNamara and Werner, in press (b); Slott et. al., 2006). These models are rigorously constructed and are able to reproduce complex behavior patterns observed in the real world. However, they may be too sophisticated to enter mainstream management use at this time.

Therefore, an appropriate model must be detailed to capture and reproduce emergent natural phenomenon, but transparent to easily illuminate the processes and interactions that drive emergent behaviors. Murray (2003) describes such a model as holding an intermediate position along a spectrum of modeling approaches. ‘Simulation models’ on one end of the spectrum are highly detailed and strive to reproduce a natural system as completely as possible. A contemporary example of this type of model is the dauntingly complex general circulation model (GCM) used in climate change prediction. ‘Exploratory models’ are highly simplified, idealized models that are used to investigate which processes and interactions are responsible for poorly understood phenomenon. Whether using a simulation or exploratory model, natural phenomenon can be approximated by two different approaches. Murray (2003) describes the traditional modeling approach as ‘explicit numerical reductionism’, which strives to simulate processes at the smallest scale possible. These models are “based ultimately on knowledge of some ‘fundamental’ building blocks and their interactions” (Murray, 2003). To be successful, these models avoid parameterization as much as possible and attempt to treat the smallest possible scales explicitly under the expectation that natural phenomenon will emerge in the same manner as in nature. In contrast, Werner (1999) supports a hierarchical modeling approach that is of a more ‘top-down’ nature (Murray, 2003; Werner, 1999). This approach consists of an explicit hierarchy of models operating at different scales dictated by the system of interest. Only a small amount of essential information generated by scale-specific dynamics is passed between levels. From the perspective of emergent phenomena, it is the interactions between variables of commensurate scale to the phenomenon of interest that drive larger-scale behavior (Murray, 2003). Hierarchical complex system modeling allows the modeler to focus investigation on larger-scale processes, which enables a transparent representation of complex phenomena. The model proposed here utilizes this hierarchical approach.

The model proposed here is also a hybrid between conventional and coupled approaches. This model abstracts many of the details in conventional geomorphic models on time scales of hours or days to a simulation on the order of years to decades. This is possible because as the time and spatial scale of simulation increases, system dynamics can be described using fewer variables (Werner, 1999). For example, modeling surf zone morphology at the scale of seconds entails knowing individual sand grain motions. However, modeling the evolution of surf zone morphology at the time scale of days requires knowledge of only spacing and orientation of dune-like ripples on the ocean floor (Werner, 1999). Equations for longer-term processes can be written that capture the dynamics and resultant patterns of short-time scale processes. Two advantages of this approach exist. Abstraction of fast time scale processes to longer time scales reduces the likelihood that errors resulting from modeling imperfections will propagate up through higher scales (Nuttle, 2000; Werner, 1999). Also, critical interactions between system components can be communicated succinctly without the distraction of overwhelming detail. Thus, by abstracting fast-operating natural processes to the time scale of management concern (figure 1), influences of human activities on long-time scale natural processes become more transparent.

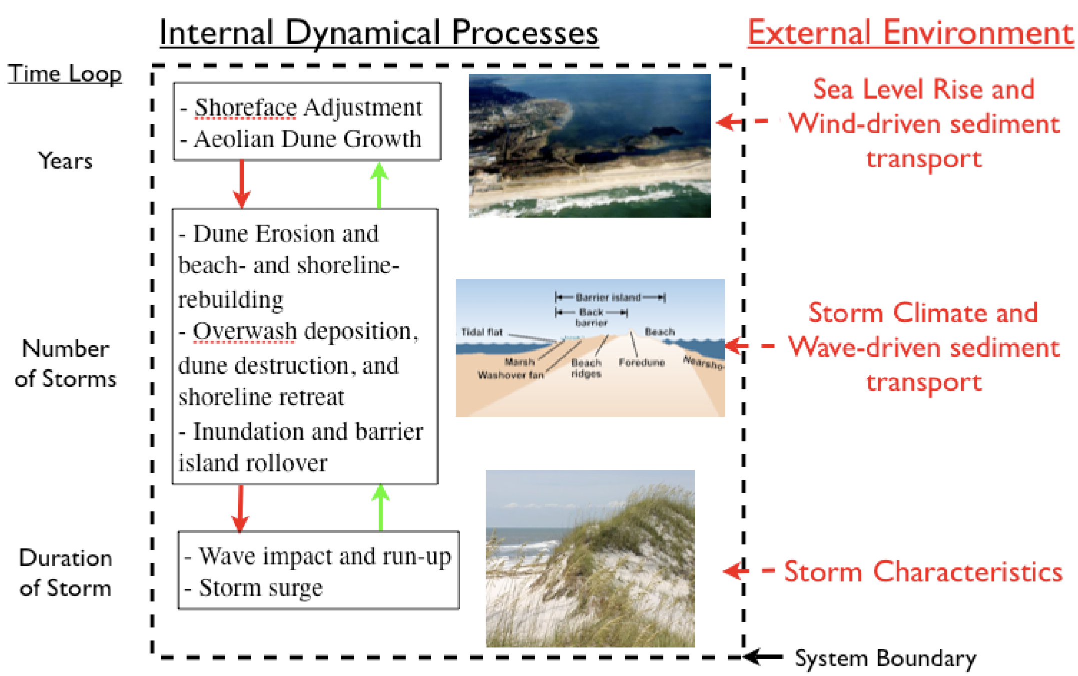


Figure 1: A hierarchical systems organization of the proposed barrier island model. Internal dynamical processes controlling island height and width are hierarchically organized on the time and spatial scales at which they operate. Processes at each time scale influence and are influenced by processes at longer and shorter time scales, which are connected by positive (green arrows) and negative (red) feedbacks. Physical forcings on barrier island evolution (red font and dashed arrows) are external and represent one-way interactions that drive internal system change. Sources: http://www.beg.utexas.edu/UTopia/contentpg_images/gloss_barrier_island2.jpg; http://www.savethecape.com/images/dunes.jpg

Middle-term human activities, which operate within a year in response to storm impacts, are represented with the use of rules. Rules are often used to capture system dynamics for which equations are not yet established or accepted (Murray, 2003). Based on observations of management activities on relatively large scales, only human activities that create long-term impacts to natural processes on a commensurate time scale are simulated. Rules recreate human behavior in response to the simulated scenario. This again has the benefit of focusing on the interactions that are driving large-scale, emergent system behaviors instead of utilizing extensively detailed equations. In this way, a coupled human-landscape model can be created for primarily *management* use that simulates the long-term consequences of protective measures in an accurate yet transparent form.

2.2 Model Structure

A numerical model investigates the long-term morphological consequences and associated mitigation costs of artificial dune construction on the Outer Banks. The model captures a cross-shore barrier island profile of continuous vertical heights with respect to sea level and discrete horizontal distances of one meter grid cells. Simulated island morphology represents that seen on actively eroding beaches. Shoreface structure and processes are not represented explicitly, but rather are accounted for in the sediment budget and long-term processes of active shoreface adjustment, such as shoreline retreat due to sea level rise. The extent of the active shoreface is defined at a depth of 10 meters at a distance of 1 kilometer offshore. Marsh and sound environments are explicitly represented with average elevations for Crotan and Albemarle sounds taken from National Geophysical Data Center (NGDC) bathymetry data (NGDC, 2007).

The barrier island profile is subjected to a probabilistically simulated storm environment (Elsner et. al., 2000; FRF, 2007; Hirsch et. al., 2001; USGS, 2006; Zhang et. al., 2000) under both current and intensified storm climate conditions, and continuously rising sea level due to climate change (IPCC, 1995; Moore et. al., 2006; Vellinga and Leatherman, 1989). Storm statistics such as maximum wave height, dominant wave period, storm duration, and tide are approximated from a normal distribution with a mean and variance taken from storm records at Duck, NC (Field Research Facility, 2007a). Storm surge levels are simulated based on historical observations (USGS, 2006), and verified and validated based on post-storm reports for Hurricanes Bonnie and Fran (Field Research Facility, 2007b; Field Research Facility, 2007c; USGS, 2006b; USGS, 2007). In relation to existing island morphology, storm impacts are categorized into regimes of erosion, overwash, and inundation in which their quantitative impacts are calculated using specialized equations.

2.3 Physical Processes

Internal, dynamical processes that control the width and elevation of the island and external physical forcings are organized into a hierarchical complex systems framework (Werner, 1999) (figure 1). Processes that occur on the time scale of storm events are of primary concern in this model. Thus, many of the fast time scale processes operating during storms, such as wave impact and variations in storm surge and wave run-up are accounted for, but are only dealt with through their cumulative effects on the time scale of many storms. By abstracting fast time scale

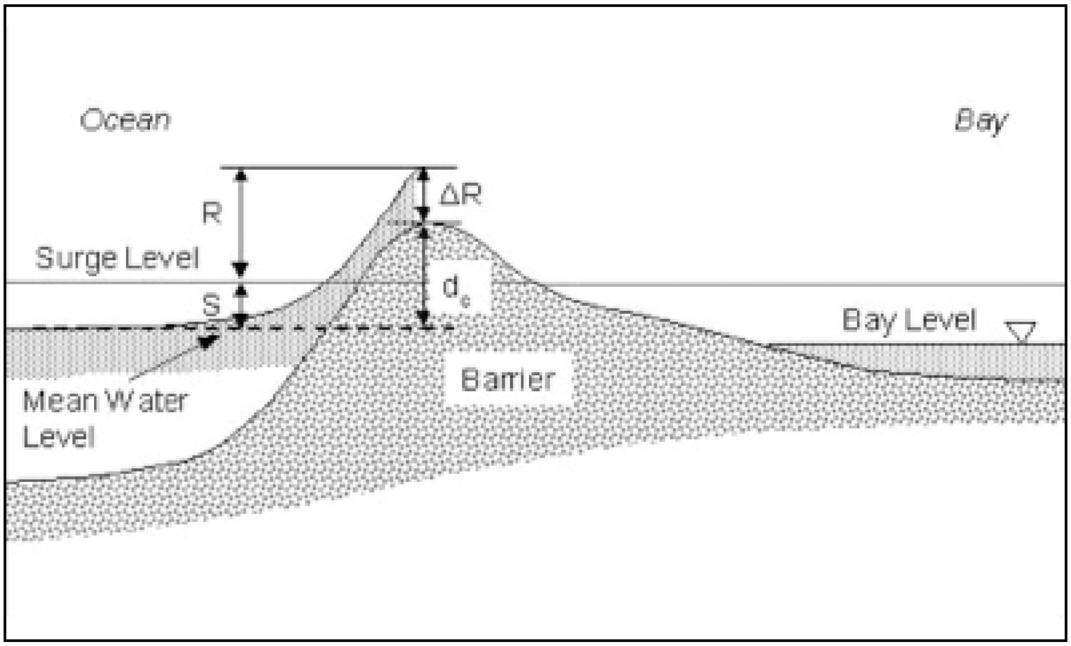


Figure 2: Definition sketch of a barrier island cross-section subject to overwash by wave run-up. Source: Donelly et. al. (2006b).

processes to the middle-term, the long-term behaviors that emerge can be tied directly to the interactions between mid-level system components. Since these are the processes that most impact and are impacted by human activities, their formalization in this manner can act as a powerful management tool.

Storm impacts are categorized by the interactions between a simulated storm-induced water level and island morphology (figure 2). If the storm wave run-up is higher than the dune foot but lower than the dune crest, frontal dune erosion is initiated. Overwash occurs if the wave run-up exceeds the dune crest but the storm-induced water level does not. Inundation occurs when either the storm-induced water level exceeds the dune crest or overwash extends to the bay. The relationship between storm-induced water levels, consisting of wave run-up (R, which is composed of R_{high}, and the 2% exceedence level for vertical wave run-up, S_2) and storm surge level (S, which is composed of surge, N_{mean}, and tide components), and existing dune and beach morphology (D_c) determines which storm impact regime is calculated (Sallenger, 2000). All changes to dune morphology during storms are tracked using specialized sediment flux and transport equations, but only cumulative impacts appear in the model after the storms' completion.

Frontal dune erosion occurs when waves impact the dune face and actively erode sand from the dune and beach. Sediment flux from the dune is based on wave impact and duration from the model proposed by Larson et. al. (2004b). The total volume of sediment (Q_{er}) eroded from the face of the dune is given by:

$$Q_{er}(t) = \frac{\alpha\beta C_s}{T_o}\left[N_{max}\sin\left(\frac{\pi t}{t_{dur}}\right) - Z_d\right]^2 \qquad [1]$$

where α is a scaling coefficient, C_s is an empirical coefficient from Larson et. al. (2004b), T_o is the dominant wave period, t_{dur} is the duration of a storm event, and Z_d is the elevation difference between the dune foot and the beginning of the swash. Beta (β) is a diffusion coefficient that is used to scale alongshore processes in the cross-shore direction. If dune erosion occurs, a volume-- the sum of Q_{er} over the duration of the storm-- is removed from the dune face. The dune foot retreats landward according to conservation of mass and eroded sediment is deposited on the beach and spread over the shoreface. Long-term observations of dune erosion are captured by moving the shoreline seaward, thus abstracting the process of sediment return during post-storm, fair weather periods.

Overwash is characterized by a topping of the dune crest by wave run-up, which transports sediment from the shoreface, beach, and dune into the back-barrier environment. Washover deposits build the island's elevation in response to sea level rise. Overwash volume and extent are based on the flux over and height of wave run-up in excess of the dune crest, respectively (Larson et. al., 2004b). Sediment eroded due to overwash is given by:

$$Q_{ow}(t) = \alpha\beta K_r\sqrt{2g}\frac{R_{excess}(t)^2}{R_{high}(t)} \qquad [2]$$

where K_r is a geometric coefficient (Donelly et. al., 2006b), and g is the gravity constant of 9.8 m/s. R_{excess} is the elevation non-negative difference between dune crest and wave run-up at a given time during the storm. Active erosion and lowering of the dune crest is tracked to capture the non-linear relationship between overwash extent and dune crest height (D_c) through time. The evolution of the dune crest during an overwash event is given by (Larson et. al., 2004b):

$$\frac{d(D_c)}{dt} = -\alpha\gamma\frac{Q_{ow}(t)}{\kappa R_{high}(t)} \qquad [3]$$

where γ is a geometric coefficient for dune width, and κ is a geometric coefficient for dune height. As dune crest height is lowered during a storm, overwash penetration into the back-barrier environment increases exponentially. Overwash extent ($M(t)$) is given by:

$$M(t) = \alpha\beta(gR_{excess}(t))^2 \qquad [4]$$

The instantaneous dune crest height (D_c) in Eq. 3 is used to calculate R_{excess}. The maximum extent of overwash penetration is used to approximate the deposition of sediment obtained from Eq. 2. Washover sediment is deposited in layers that get progressively thicker from the maximum overwash extent to the back of the dune crest. Given that overwash is a 3-dimensional process with washover fans tending to spread horizontally, overwash extent in the cross-shore direction is approximated using a diffusion coefficient (β).

Inundation, in the cross-shore sense, is akin to a breach of the dunes or extensive sheetwash. Inundation lowers the average elevation of the island and builds the island's width in response to sea level rise by depositing sediment in the back-barrier marsh and bay. Using the same equations that describe dune crest height (eq. 3) and overwash extent, inundation occurs when N_{mean} tops the dune crest and/or overwash extends into the marsh/bay. Sediment transport during inundation is adapted from the flux equation presented by Tinh (2006) and the barrier island rollover scheme proposed by Larson et. al. (2004a). The volume of sediment eroded from the subaerial island (Q_{in}) is given by (Rosati and Stone, 2007):

$$Q_{in}(t) = 2a_s S(K_i + K_r)\sqrt{2g}H_{excess}(t)^{\frac{3}{2}} \qquad [5]$$

where K_i is an empirical coefficient (Donelly et. al., 2006b). Alongshore sediment contributions tend to close breaches when they are not deep enough to draw tidal flow. In the event of a severe inundation event, this alongshore breach-closing process is approximated by rebuilding the island to the height of the spring tide. Inlet formation is not addressed due to its spatial complexity, which is beyond the scope of this model.

At the time scale of a year, sea level rise of 5 mm a year (IPCC, 1995) initiates shoreline retreat governed by shoreface processes (Brunn, 1962). The shoreline retreats at a rate represented by the Brunn Rule (Titus and Richman, 2001), which translates sea level rise into a horizontal shoreline retreat. In addition, wind-driven sediment transport drives aeolian dune growth. The rate of dune growth is approximated to match observed rates of dune growth near two meters per decade ([dune ref. from Dylan]). Sediment for dune growth is supplied by dry beach of at least 10 meters wide, and is then deposited at a maximum of 45 meters back from the start of the dune crest at an exponentially decaying rate. Sea level rise and dune growth both result in shoreline migration over the time scale of a year.

2.4 Human Manipulations

Two versions of the model have been created. The version discussed above simulates the natural, undisturbed barrier island system, which attempts to mimic the unabated process of barrier island migration in response to rising sea level. An extension of this model introduces human manipulations into the natural system in the form of artificial dune construction and overwash removal. Mitigation of storm damages often entails bulldozing overwash sand off of roads and private property into artificially tall and continuous dunes. If the desired artificial dune profile cannot be fully constructed with sand on-site, compatible outside sources are integrated into the construction. Artificial dunes are reconstructed to a range of dune heights from 2.4 to 4.6 meters according to observed mitigation projects on other eroding beaches in North Carolina (NCDOT, 2008; Overton et. al., 2000). Artificial dune geometry of a given height is constrained by the angle of repose of beach sediment typical to the area (Rastetter,1991), and a width capable of surviving impacts from a ‘moderate’, or 50-year, storm (NCDOT, 2008, Overton et. al., 2000). Dune reconstruction projects vary greatly in their seaward positions from major roads, but as a rule road relocation occurs when there is insufficient seaward space for the required dune width. The road is relocated 150 meters back from the constructed dune line or in the middle of the island, whichever provides the most setback from the dune line and marsh.

2.5 Model Analysis

The model of the undisturbed barrier island was run over various time scales without sea level rise to establish a theoretical steady-state. Model calibration was done by comparing model output to pre- and post-storm LIDAR profiles and observed single-storm statistics. In particular, the extent of overwash was verified using a post-storm report for Hurricane Bonnie (USGS, 2006b). To validate the model, the same process was repeated with pre- and post-storm LIDAR profiles for Hurricane Fran (USGS, 2006b). Given the abstraction of fast-time scale processes onto the order of years, uncertainty in exact extent of erosion, overwash, and inundation events was quantified and minimized as rigorously as possible. With the established steady-state, sensitivity analysis revealed which parameters produced significantly different steady-states with only slight alterations. These analyses tested whether fluctuations in the island profile were the result of natural non-linearities or errors in the parameterization of the model. When parameters, processes, and feedbacks that maintained the system's characteristic steady state were identified and tested, artificial dunes and sea level rise were incorporated into model.

Statistical analysis consisted of comparing storm impacts to the undeveloped and human-manipulated island morphologies to determine if a significant difference existed. Over a time span of 500 years, average island widths and elevations were recorded. In addition, the models tracked and compared shoreline retreat rates, frequencies of back-barrier flooding, and frequencies and extents of overwash and inundation events. The coupled model also tracked occurrences of removal of post-storm overwash sediment and artificial dune construction and maintenance. Statistical comparisons between the natural and coupled systems tease-out long-term effects of human manipulations by testing the resultant impacts of altering natural processes. By simulating and comparing the long-term behaviors of developed and undeveloped barrier island systems, long-term effects of artificial dune construction are seen through differences in responses to sea level rise and/or changing storm climate.

3. Results

Simulated natural system morphology is dominated by frequent overwash impacts. As sea level rises, overwash events become more frequent and dunes are kept at a relatively low, narrow range of heights. Overwash events deposit sediment onto the island, building its width landward and raising its elevation relative to sea level. When dunes are relatively high, overwash events tend to be less frequent with only small amounts of sediment are deposited landward of the dune line. However, when large storms occur, large amounts of sediment can be deposited subarieally and/or into the bay and dune height is lowered. In a low-dune state, the barrier island is overwashed frequently, building its width and elevation, until stochasticity in the storm climate produces a relatively calm period and dune height increases through aeolian dune growth. This cyclical behavior is evident in phase space plots of the natural system. Phase space plots are a graphical means for representing the behavior of a system in relation to two or more variables. The phase space plot in Figure 3 represents the behavior of the natural barrier island system as a relationship between island elevation and width. Any point in the plot represents the state defined by island elevation and width at a point in time. By following the trajectory of that point, phase space provides information about how island elevation and width change in relation to one another through time.

The phase space of the natural system demonstrates a wide range of island widths and elevations (figures 3, 5). Because the natural system is undeveloped, sediment remains highly mobile and thus the island is free to expand and contract in response to storm impacts. During periods when storms remain too small to overwash to the back of the island, dunes tend to maintain heights large enough to block most overwash events. During these periods, the island tends toward relatively low elevations and high dunes until a storm large enough to overwash the dunes deposits sediment landward of the dune line. As a result, dune height is reduced, back-barrier island elevation increases, and island width is extended. Thus, an attractor exists around which the natural system cycles, as island width and elevation maintain a dynamic steady-state through interactions between sea level rise and subsequent storm impacts.

This is in contrast with coupled system simulations. The critical difference between the natural and coupled systems is the operation of overwash. With the construction and maintenance of artificial dunes, elevation- and width-building overwash events become more infrequent. Back-barrier elevations and island widths decrease for proportionally longer times (table 1). Numerous coupled system simulations indicate the island's behavior is restricted by artificial dunes, and characterized by periods of stability through the obstruction of overwash. Because artificial dunes are frequently rebuilt, the coupled system is maintained in a high-dune, low-elevation state. Artificially high dunes block all but the biggest storms, and thus, on average, the coupled system will tend away from the stready-state seen in the natural system. Phase space plots show that artificial dunes force the coupled system towards relatively low elevations, small island widths, and disproportionately high dunes (figures 4, 6). However, periods of stability are punctured by extensive storm impacts. This is apparent in the large, sudden shifts in island elevation and width seen in coupled system phase space plots (figure 6). Because the island is forced toward a thin, low-elevation state by artificially high dunes, the island exists in a precarious state for the majority of model runs. When storm surge large enough to exceed artificially high dunes finally occurs, impacts are more severe because of the island's precarious state. Thus, the overwash regime of the coupled system is disproportionately shifted towards large-scale storm impacts (table 1).

Flooding events occur when storm-induced water levels exceed back-barrier elevation. Standing water occurs in low back-barrier areas due to an elevation of the water table through salt water intrusion. The natural system exhibits a stable flooding trend of about 1 to 1.5 events per year (figure 7), and slightly increases through time because of sea level rise. In contrast, the coupled system exhibits rapidly increasing flooding frequency through time. The longer the road is defended with an artificial dune, the more flooding events occur. This is due to a lower back-barrier elevation relative to sea level in the coupled system than in comparison to the natural system. Flooding frequency increases as sea level rises and more, smaller storms are able to induce flooding. Some of the longest runs of the coupled system displayed flooding frequencies near 6 events per year. This trend is accentuated as constructed dune height is increased.

Shoreline retreat rates in the natural system of approximately 3.2 meters per year (table 1) are composed of shoreface adjustments to rising sea level, gradients in alongshore transport causing beach and dune erosion, and overwash deposition of shoreface sediment landward. This simulated behavior is consistent with that of a net erosional beach, such as in Rodanthe, NC (NCDOT, 2008; OBTF, 2008). The rate of shoreline retreat in the coupled system is significantly lower (~2 to 2.5 m/y) because of the disruption of overwash. At first glance, it would appear that artificial dunes offer a measure of long term stability by slowing shoreline retreat. However, this is not the case, because averaging shoreline retreat rates over time conceals the start and stop manner in which the developed barrier island migrates. Overwash frequencies in the coupled system are markedly lower than that of the natural system, yet variability in retreat rates is similar to that of the natural system (table 1). This indicates that periods of stability in shoreline retreat are punctuated by dramatic shoreline change every time there is an overwash event. This is correlated with the fact that only large overwash events occur when artificial dunes are high.

The most dramatic differences between the natural and coupled systems are in their overwash regimes. Overwash events occur about every 2 years in the natural system, whereas the coupled system is overwashed about every 4 years (table 1). A smaller average overwash extent in the natural system is characteristic of frequent overwash events. The coupled system overwash regime is dominated by high amplitude, low frequency overwash events. Furthermore, the coupled system exhibits a disproportionate increase in the severity of overwash events. The percent of overwash impacts per decade beyond the setback distance is about five times higher in the coupled system than in the natural system (table 1). Approximately, 11 percent of overwash events in the coupled system per decade exceeded the setback distance (30m) as compared to only about 2 percent in the natural system. Although absolute overwash events beyond the setback distance in the coupled system is about 20-40 percent less than in the natural system, the absolute proportion is more than a 500 percent increase in the coupled system. High amplitude overwash events constitute a larger portion of the overwash regime in the coupled system than in the natural system.

Road and dune maintenance become more frequent through time as dune height increases (table 2). This is due to the obstruction of island-building overwash by artificial dunes and subsequent intensification of impacts from large storms. As sea level rises and the shoreline continues to retreat, artificial dunes promote island-thinning and -lowering by obstructing overwash. The higher the dune height, the longer overwash is blocked, and the lower and thinner the island becomes until overwash finally occurs. Large overwash and/or inundation events can wash-away the road and completely destroy dunes requiring road clearance/relocation and dune reconstruction. No significant difference in road clearance frequency exists between simulations with varying dune heights. However, the road must be relocated, indicating significant single or cumulative storm impacts, at a faster rate when dune height is increased. The road tends to be at a low elevation relative to sea level because of continual overwash obstruction and road clearance, resulting in severe impacts and road relocation. Road abandonment, due to a critically thin island, occurs earlier in a greater proportion of runs for increasing dune heights because of the island-thinning effect of artificial dunes (figure 11). In addition, external sand use increases with dune height because of a lack of on-site overwash sand. Because overwash sand is deposited less frequently with increasing dune height, less sand is available to reconstruct full dunes after major storm impacts (table 2). Counter-intuitively, higher dunes not only require more resources to construct, but they also demand increasing amounts of external sand to maintain through time.

4. Discussion

The above findings are based on hypothetical simulations of a cross-sectional barrier island. Many alongshore processes are parameterized to translate in the cross-shore direction. Processes such as shoreline retreat and overwash have both alongshore and cross-shore components, yet they are only modeled in the cross-shore direction by incorporating alongshore components into a simplified parameter. In reality, shoreline retreat is primarily driven by gradients in alongshore transport, but in model simulations observed erosion rates are replicated for the Rodanthe area by parameterization. Overwash is a spatially complex process which requires scaling a three-dimensional process into the cross-shore direction with a diffusion coefficient. Therefore, such parameterizations require a focus on trends in and comparisons between natural and coupled system behaviors. Explicit numerical results are not as meaningful as the trends they represent, and are merely a means for comparing divergent natural and coupled system behaviors over time.

Artificial dunes have several perverse effects on long-term barrier island evolution. Building artificially high dunes forces the coupled system into long-term lowering and thinning behavior. Maintaining and reconstructing artificial dunes after storm impacts, by physically removing overwash sediment from the back-barrier to rebuild dunes, reinforces this behavior by confining the system into ‘far from equilibrium’ conditions. As sea level continues to rise, storm impacts are accentuated in the long-term because back-barrier elevation is much lower than it otherwise would be if overwash deposition had been allowed to occur regularly. Artificial dunes exclude ‘medium-scale’ storms from the storm impact regime. This promotes thinning of the island by blocking overwash events from storms smaller than Category 3 but large enough to reach the bay (NCDOT, 2008), and small, relatively frequent island rollover events are lost as a result. Also, artificial dunes promote island-lowering by filtering-out high frequency storms that create washover desposits, but are still too small to breach dunes or inundate the entire island. These ‘medium-scale’ storms act as critical middle-term feedbacks that maintain subaerial island elevation in relation to rising sea level (figure 8). As sea level rises, island elevation relative to sea level decreases, which induces more frequent overwash events that build island elevation. By introducing delays into this feedback loop (in the form of artificially high and continuous dunes), humans *re-scale* overwash events to longer temporal and larger spatial scales. Overwash events, and therefore impacts to human development, tend to occur at lower frequency but with higher amplitude.

This effect is evident when comparing natural and coupled system simulations. The natural system exhibits cyclical behavior around a range of steady-state elevations and widths (figure 5). The island is free to contract and expand in response to variability in the storm climate. In such a dynamic setting, dunes act as feedback regulators. Back-barrier elevations are directly influenced by dune crest height. Dune height is moderated by cumulative storm impacts, which in turn influences the elevation and width of the back-barrier environment through overwash. This is not to say that dunes are system drivers, but are rather responsive system elements that translate storm impacts into varying states of island morphologies. When dunes are relatively low, the island is susceptible to overwash, and a trend of island elevation- and width-building dominates (figure 5). In this state, more storms are able to top the dunes and/or deposit sediment in the bay, thus building back-barrier elevation and/or extending the island’s width. This state in the Outer Banks is evident in aerial photos from the 1930’s, which was a period of intense storm impacts to the North Carolina coast (NOAA website). Such states emerge sporadically in the model on long

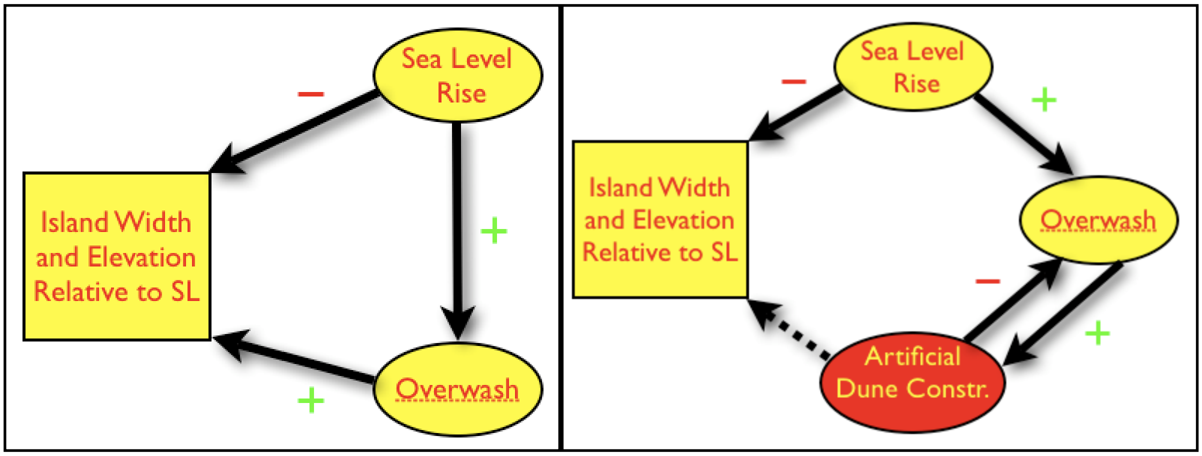


Figure 8: Graphical representation of the feedback loops operating in the natural (left) and coupled (right) systems. Green plus signs designate positive feedbacks and red negative signs indicate negative feedbacks. In the natural system, island width and elevation is balanced by sea level rise through the island-building mechanism of overwash. However, in the coupled system, artificial dunes introduce a delay into the larger feedback loop by initiating an 'arms race' like feedback loop between overwash and artificial dune defenses. The island remains thin and low as a result, despite the continual forcing from sea level rise.

time scales. Conversely, when dunes are relatively high, a trend of back-barrier lowering relative to sea level and island thinning persists. High dunes prevent most small storms from depositing sediment in the back-barrier environment. Typically, this state is characterized by back-barrier deposition rates that lag behind the rate of sea level rise. Less frequent, larger storms are able to top the dunes, however, and gains in back-barrier elevations may be quite large and dune destruction extensive. This type of impact effectively returns the system to a low dune, island widening phase. Transitions between the two states are extremely non-linear and depend on the intensity of the storm climate in relation to existing dune morphology. During periods of fairly frequent moderate storms, dunes are overwashed and lowered before they can recover from previous storm impacts, and the island remains low and wide. However, periods of relatively low storm intensity allow for dunes to re-establish and grow quickly with ample supplies of dry sand, and the island shifts back to the high dune phase.

Because of its artificially high dunes, the coupled system exhibits behavior similar to that of a natural system in the high dune state, but impacts from large storms are accentuated in the long-term. Constructed dunes force the system in the direction of high dune heights, long periods of back-barrier elevation at or near high tide level, and reduced width. In addition, the phase space plot in Figure 6 illustrates the restrictions constructed dunes place of system behavior. Although the intention is to stabilize the system, constructed dunes create more precarious island morphology in relation to rising sea level. Periods of stability made possible with constructed dunes are punctuated by major storm impacts at a proportion higher than in the natural system. Despite only a 20 to 40 percent decrease in large-scale overwash events in the coupled system, such impacts exhibit a 500 percent increase in the overwash regime in the coupled system over the natural system (Table 1). Again, these numbers are not meant to provide quantitative precision, but rather illustrate trends in behavior. When large storms finally overtop the dunes, the back-barrier environment is much lower than it otherwise would have been, and impacts tend to be less frequent but more severe.

Sections of Rodanthe, North Carolina resemble island morphology similar to that of coupled system simulations. In Rodanthe, Highway 12 is being actively defended with artificial dunes and the road cleared of overwash sand. As a result, certain stretches are as thin as 150 meters with a more typical width around 300 meters-- resembling average island widths in simulations. In fact, sections of Highway 12 have been relocated repeatedly, and during the stretch of 1990-1994, $31 million was spent on maintenance and defense of Highway 12 between Nags Head and Hatteras Inlet (Degregory, 1994). The majority of this cost came from removing overwash sand off of the road into artificial dunes. These are ‘middle-term’ solutions that have long-term consequences.

Several caveats should be considered. First, simulated barrier island behavior is qualitatively robust, as the model can reproduce currently understood behaviors of barrier island migration. Thus, the processes that drive barrier island migration are accurately replicated in the model. However, simulated barrier island behavior is not quantitatively accurate because some alongshore processes are parameterized into the cross-shore direction. As a result, storm impacts are typically of the correct order of magnitude, but are not sufficiently precise to make predictions of the timing and exact scale of future storm impacts. Second, alternative feedbacks may emerge-- stemming from economic solutions, unforeseen natural system responses to climate change, and/or alternative management strategies-- that alter future storm impacts. Increasing storm intensity and/or accelerated sea level rise could augment simulated barrier island behaviors. Artificial dunes may become more aggressively defended in response-- and as a result further delay natural feedback mechanisms-- which could force island morphology to a more precarious state. Although this is an end-case scenario, what is apparent from simulated coupled system behavior is that periods of stability maintained by artificial dunes are interrupted by large amplitude disturbances. When the highly dynamic but resilient feedback mechanism of the natural system becomes so impaired that it cannot maintain a long-term equilibrium elevation and width, a tipping point may emerge where the island cannot sustain morphology suitable for development in the face of rising sea level.

The tendency for protective measures to disrupt dynamic natural processes and accentuate low frequency, large-scale impacts represents a new environmental management problem. Solutions to this new class of environmental problems are often unknown or prohibitively difficult/expensive to implement. Artificial dune construction and overwash removal introduce delays into the natural process of barrier island migration, and thus create long-term conditions of increased susceptibility to storm impacts. However, these perverse effects are not easily recognized because of the discordant time scales over which natural processes and management activities operate. Large-scale natural processes often operate on long time scales (Werner, 1999). Therefore, when human manipulations become intertwined with natural processes, environmental problems do not become apparent until well after the initiation of disruptive activities. This suggests that human activities and natural landscape processes can no longer be treated as separate entities, but rather as potentially coupled, interconnected systems.

Investigating protective measures as potential agents of system coupling provides a framework for describing and analyzing human-landscape interactions. Previous approaches to modeling human and natural systems typically treat them as separate and contained within a time and spatial scale of interest. This bias is reflected in or is a product of current approaches to environmental problems. Typically, coupled systems are divided into individual system components to create a management plan for the whole. While this may be easier logistically, it fails to capture the synergistic relationships between natural and human systems on multiple temporal and spatial scales. Failure to recognize coupled interactions persists because current research and management perspectives focus on more immediate system behaviors that often mask longer-term, human-landscape interactions. Current research and management paradigms must be reconstructed in order to design scientifically-sound, long-term coastal management strategies.

The 'coupled systems perspective' adopted in this study focuses on modeling the interdependencies between coupled systems and the long-term behaviors that result. Modeling in this manner allows for the exploration of interactions between human and natural systems in a dynamic setting. The goal of this mode of inquiry is to facilitate an understanding of the relationship between human and natural systems beyond short-term management efforts. Managers must realize that the natural system dynamics that produce landscape-scale behaviors can be altered by coupling them to management activities. Thus, the model can be manipulated to investigate the effects of various management strategies on time scales that would not be feasible for field research. This approach enables an articulation of the dynamics of human-landscape interactions on multiple spatial and temporal scales, which can elucidate the forces driving problematic interactions. This research is critical for recognizing coupled human-landscape interactions as organizational drivers and leverage points for action. The hope is that this approach engages managers in a policy design process that aims to reconstruct or uncouple destructive human-landscape interactions.

5. Appendix

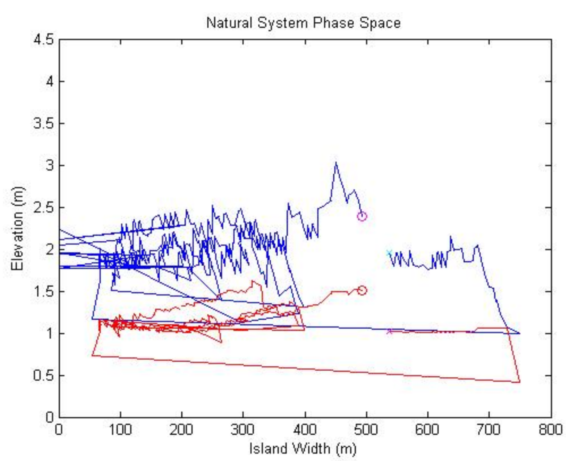


Figure 3: Phase space behavior for a typical natural system simulation. Average island elevation (m) is in red, and dune crest elevation (m) is in blue. Although the system is not restricted to any elevation or width, it loosely cycles around a steady-state dune height, island elevation, an island width. The system occupies a wide range of widths and elevations, owing to frequent overwash events and the occasional island rollover event.

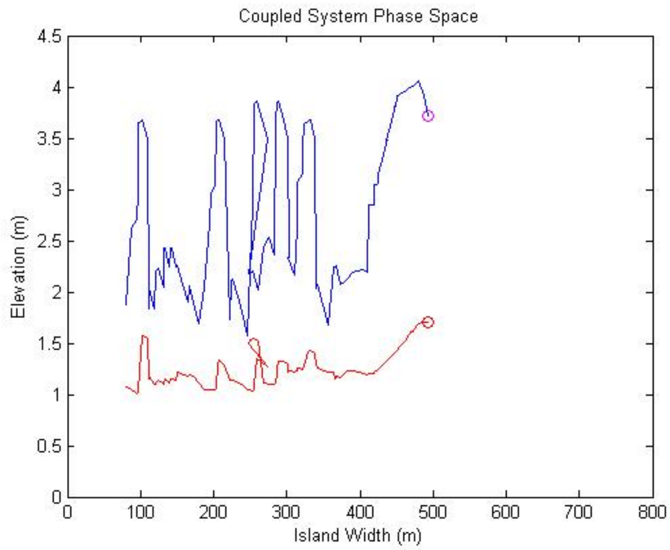


Figure 4: Phase space behavior for a typical coupled system simulation. Average island elevation (m) is in red, and dune crest elevation (m) is in blue. Artificial dunes reinforce the trend of island-lowering and -thinning by blocking overwash. Spikes in the dune elevation represent dune reconstruction in response to a significant storm impact. Thus, a coupled system is forced toward a very precarious morphological state in the face of rising sea level.

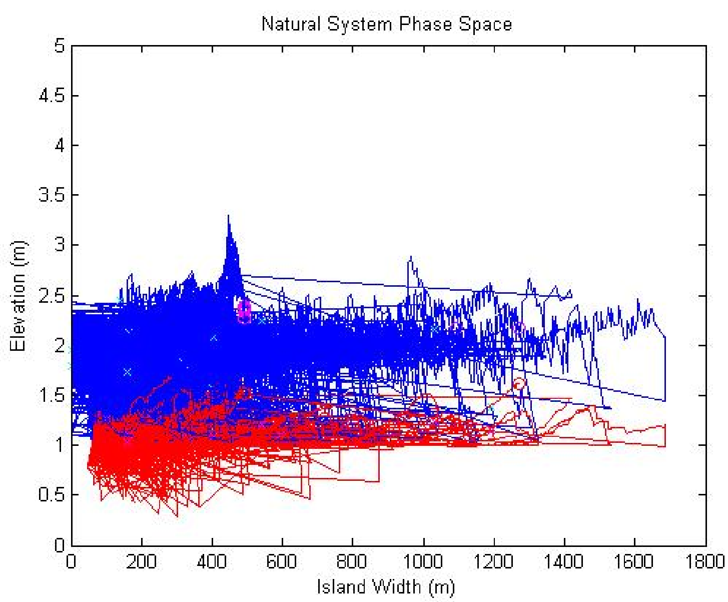


Figure 5: Phase space behavior for 100 runs of the natural system simulation. Average island elevation (m) is in red, and dune crest elevation (m) is in blue. All runs survived the 500 year run period. Typical natural system behavior exhibits a wide range of widths owing to a low average dune height and frequent overwash events. Steady state dune height and average island height

attractors emerge, as the forces of island-building process and sea level rise are balanced by varied storm impacts.

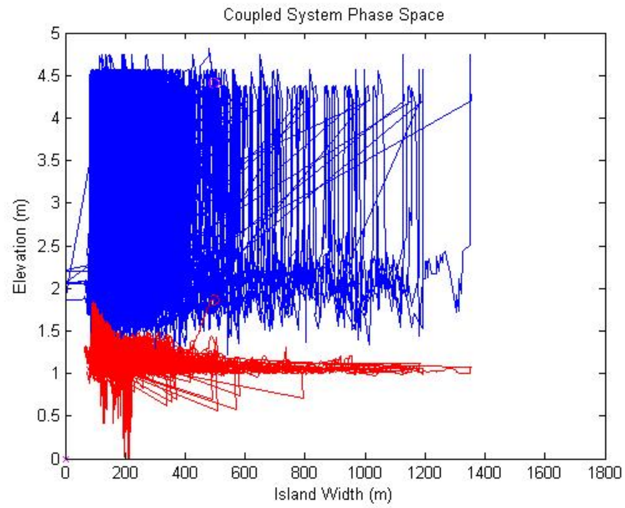
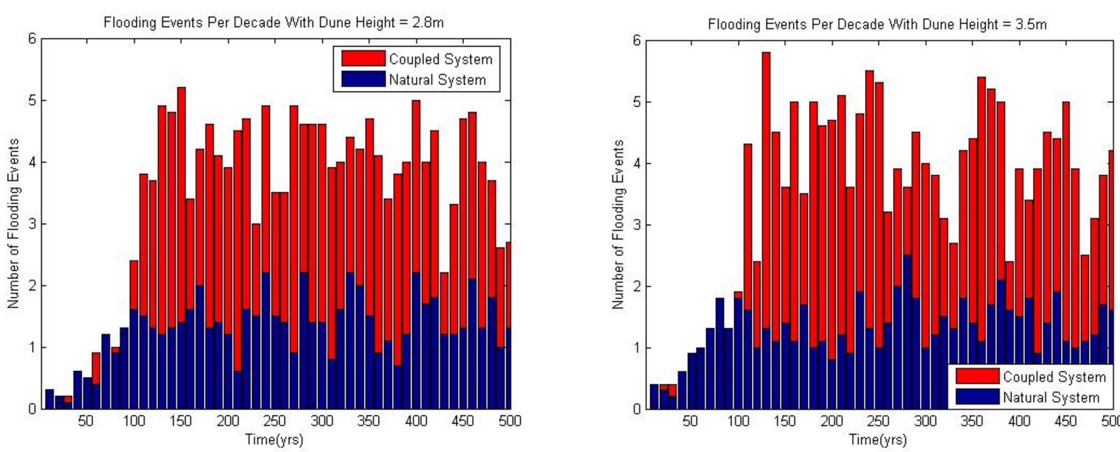
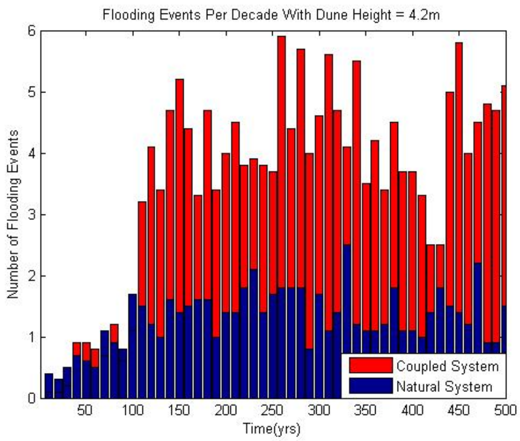


Figure 6: Phase space behavior for 100 runs of the coupled system simulation. Average island elevation (m) is in red, and dune crest elevation (m) is in blue. All runs were set for 500 years, but most terminated early because the island became too thin to relocate the threatened road. With high average dune heights, the coupled system is forced towards island-thinning and -lowering. Large-scale impacts, such as inundation events, were more pronounced in coupled system simulations. This is apparent in the large, sudden shifts in island elevation and width seen in the coupled system phase space plots.





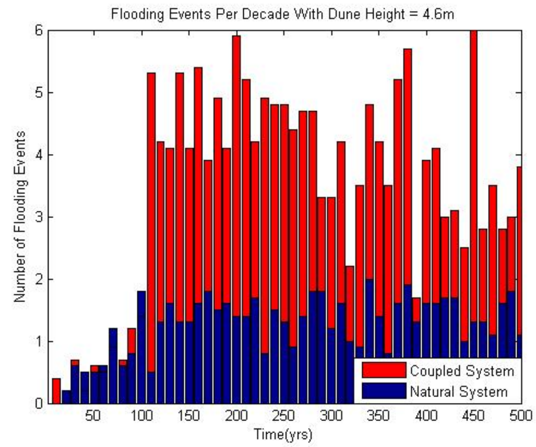


Figure 7: Flooding events per decade for constructed dune heights of 2.8m, 3.5m, 4.2m, and 4.6m (from top left to bottom right, respectively). Red represents the coupled system, and blue represents the natural system. Although there is high variability in the number of events per decade in the coupled system, it is clear that over time flooding occurs more frequently in the coupled system than the natural system. This is due to a lower back-barrier elevation relative to sea level in the coupled system than in comparison to the natural system. Flooding frequency increases as sea level rises and more, smaller storms are able to induce flooding.

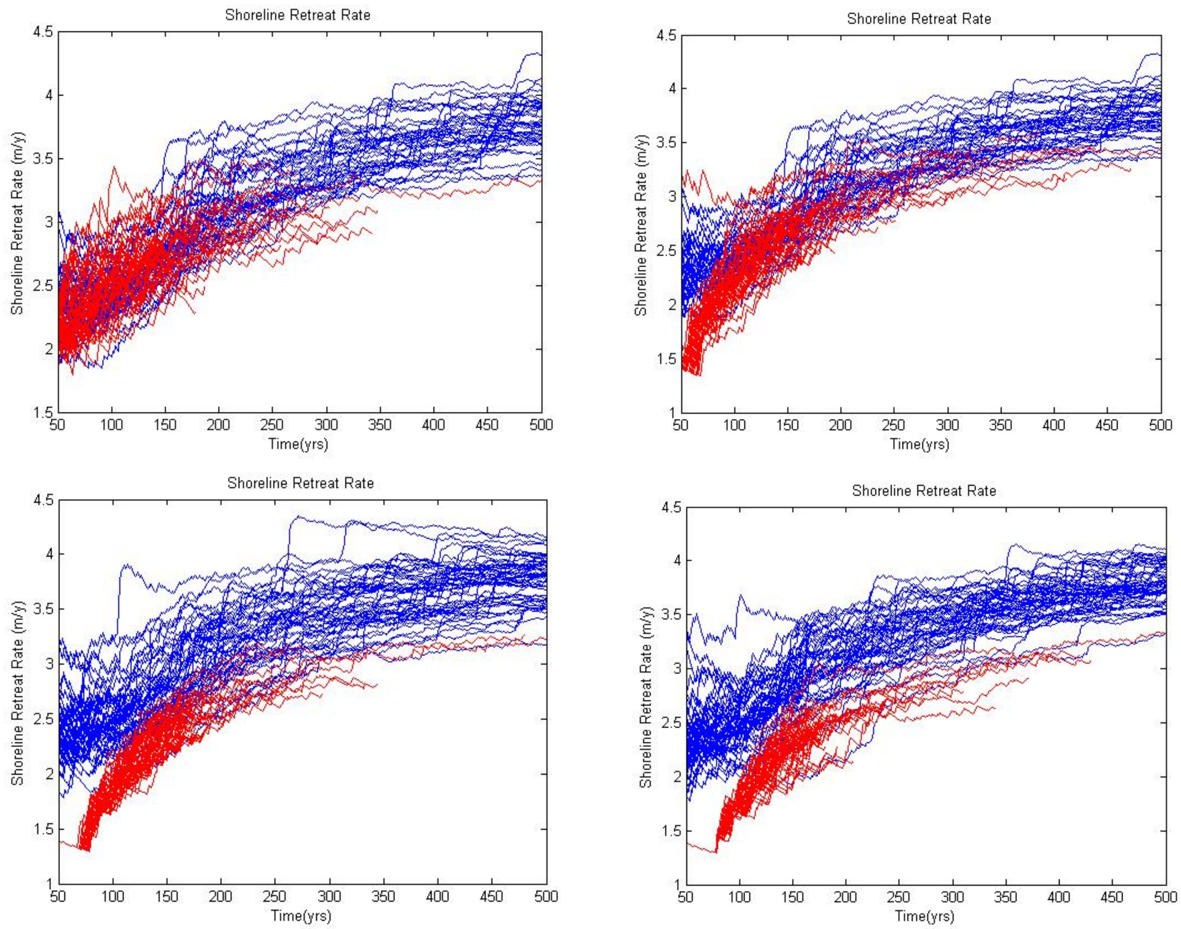


Figure 9: Coupled system is in red and the natural system in blue. Constructed dune heights are from top left to right bottom 2.8, 3.5, 4.2 and 4.6, respectively. Shoreline retreat rates are compared between the natural and coupled system. Retreat rates become lower as dunes are built higher demonstrating the short-term stabilizing effect of artificial dunes.

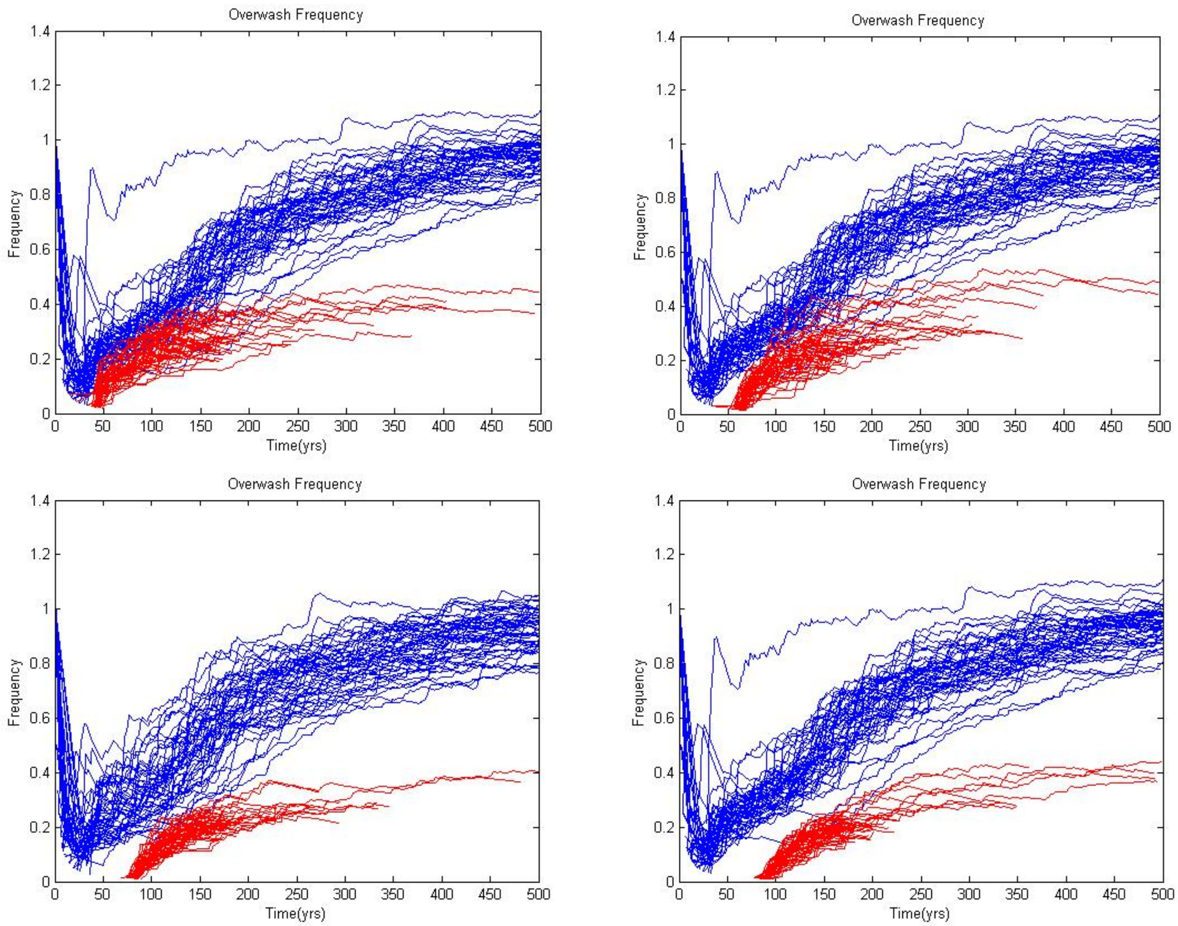


Figure 10: Coupled system is in red and the natural system in blue. Constructed dune heights are from top left to right bottom 2.8, 3.5, 4.2 and 4.6, respectively. Overwash becomes significantly less frequent as artificial dunes are built higher. Fewer red lines extend the length of the figure, which reflects the island-thinning effects of artificial dunes and consequent road abandonment due to critically thin island widths.

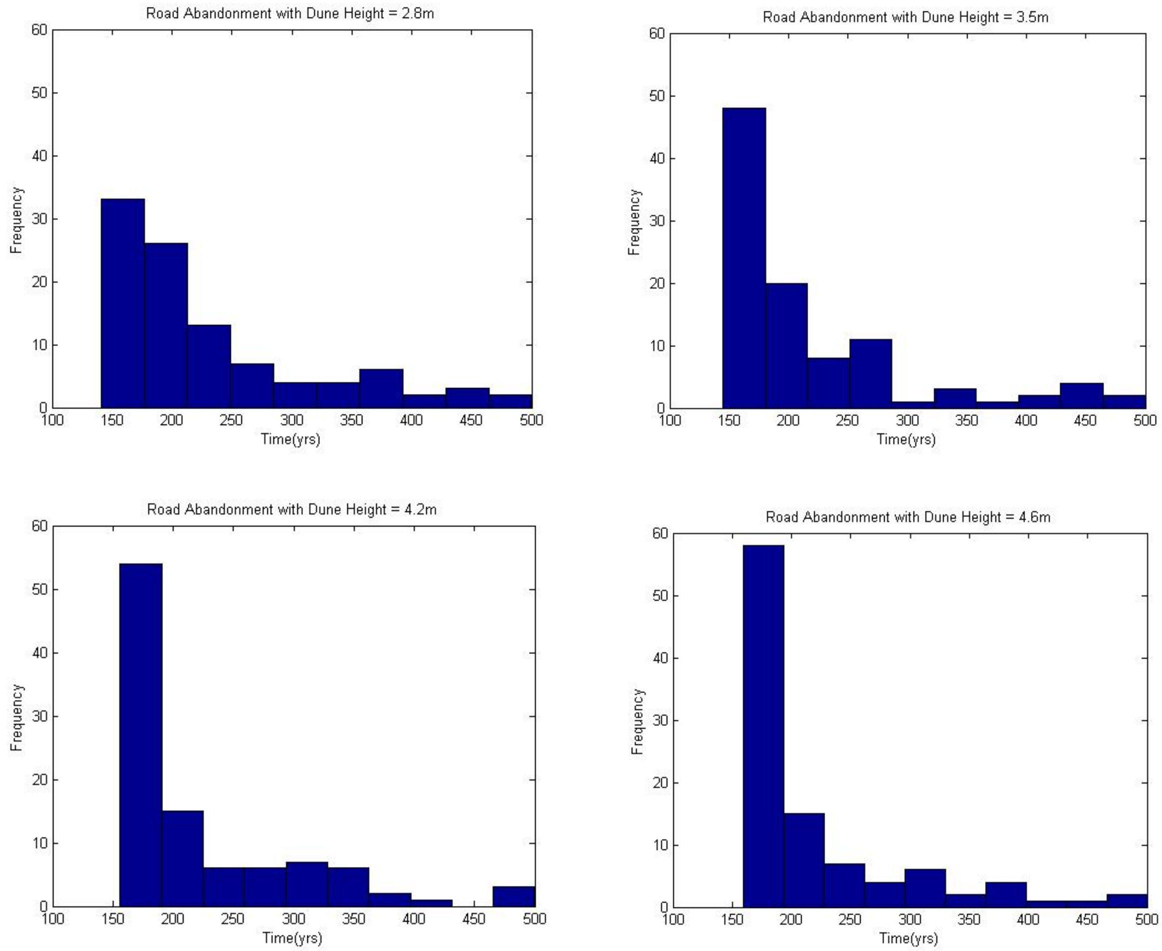


Figure 11: Distribution of coupled system simulation run times. Constructed dune heights are from top left to right bottom 2.8, 3.5, 4.2 and 4.6, respectively. If the island becomes too thin to relocate the road, simulations will stop when the road is abandoned due to insufficient subaerial island area to relocate an impacted road. Otherwise, a simulation can run for the entire 500 year time span. Note that as dune height increases the absolute earliest road abandonment time becomes slightly later. However, road abandonment times become more tightly distributed towards early times, which indicate that the road is more likely to be abandoned sooner as dune height increases.

	Dune Height (m)	Max OW Extent (m)	Std. Ow Extent (m)	OW Return Interval (yrs)	Mean Retreat Rate (m/y)	Std. Retreat Rate (m/y)	Mean Dune Elevation (m)	Std. Dune Elevation (m)	Mean Island Width (m)	Std. Island Width	% OW Beyond Setback Dist. (30m)	Overwash Events Past 30m	% OW Beyond Setback per Decade
Natural	Varied	10.05617	24.94698	1.90734	3.230295	0.637215	2.031114	0.27088	345.274	170.6791	8.566871	12.69	0.02232
Coupled	2.8	21.58709	31.97757	4.234681	2.597916	0.650217	2.633646	0.46621	335.5183	137.0463	22.73275	10.02	0.10895
	3.5	21.39016	30.70599	3.874133	2.320947	0.722692	2.976695	0.770049	339.9118	129.4685	23.12955	8.23	0.117691
	4.2	21.64558	30.6708	3.928723	2.110157	0.692501	3.412852	1.051478	336.2058	126.4758	23.228	7.45	0.110522
	4.6	20.75005	29.16551	4.072779	2.075376	0.658786	3.638146	1.205729	344.8102	132.1263	22.62405	7.34	0.106364

Table 1: Statistical comparisons between natural and coupled system behaviors with successively higher artificial dunes.

Dune Height (m)	Road Clearance Interval	Road Relocate Interval	Mean External Sand Use	Inundation Time	Abandon Time
2.8	6.239568	18.05551	178.2052	78.73	233.16
3.5	5.705422	18.28135	183.4619	93.21	208.41
4.2	6.242349	17.06177	236.6858	108.15	216.2
4.6	6.061573	16.50181	281.1786	116.34	230.03

Table 2: Statistical comparison of storm impacts to particular aspects of coupled system with increasing artifical dune heights.

6. References

Army Corps of Engineers, Engineer Research and Development Center (2004). "Coastal Overwash Part 1: Overview of Processes". Regional Sediment Management (RSM) Demonstration Program Technical Note: ERDC/RSM-TN-14, September 2004.

Baldock, T.E., Hughes, M.G., Day, K., and Louys, J. (2005). "Swash overtopping and sediment overwash on a truncated beach". *Coastal Engineering*, 52: 633-645.

Brown, G.M.J. and Pollakowski, H.O. (1977). "Economic valuation of shoreline". *The Review of Economics and Statistics*, 59: 272-278.

Brunn, P. (1962). "Coastal erosion and the development of beach profiles". *Proceedings of the ASCE, Journal of waterways and Harbors Division,* 88: 117-130.

Bush, D.M., Pilkey, O.H. Jr., and Neal, W.J.. 1996. Living by the Rules of the Sea. Durham, NC: Duke University Press.

Cohen, J.E., Small, C., Mellinger, A., Gallup, J., and Scahs, J. (1997). "Estimates of global population". *Science*, 278: 1211-1212.

Corning, P. (2003). Nature's Magic: Synergy In Evolution and the Fate of Humankind. Cambridge UP, Cambridge, UK.

Cowell, P.J., Thom, B.G., Jones, R.A., Everts, C.H., and Simanovic, D. (2006). "Management of Uncertainty in Predicting Climate-Change Impact on Beaches". *Journal of Coastal Research*, Vol. 22 (1): 232-245.

Degregory, L., Associated Press (1994). "Residents Want Solution to Route 12 Washouts One Suggestion is to Elevate the Road in Some Areas". *The Virginia-Pilot,* Wednesday, December 28, 1994.

Dolan, R. (1972). "Barrier Dune System along the Outer Banks of North Carolina: A Reappraisal". *Science*, New Series, Vol. 176 (4032): 286-288.

Donnelly, C. Kraus, N. Larson, M. (2006a). "State of Knowledge of Measurement and Modeling of Coastal Overwash". *Journal of Coastal Research*, 22 (4): 965-991.

Donnelly, C., Ranasinghe, R., and Larson, M. (2006b). "Numerical modeling of beach profile change caused by overwash," *Proceeding, Coastal Dynamics 05*, CD-ROM.

Elko, N.A., Sallenger, A.H. Jr., Guy, K. Stockdon, H.F, and Morgan, K.L.M. (2002). "Barrier Island Elevations Relevant to Potential Storm Impacts: 1. Techniques". USGS Open File Report 02-287, May 2002.

Elsner, James B., Liu, Kam-Biu, and Kocher, Bethany (2000). "Spatial Variations in Major U.S. Hurricane Activity: Statistics and a Physical Mechanism". *American Meteorological Society: Journal of Climate*, 13 (July 2000): 2293-2305.

Field Research Facility at Duck, NC (2007a). Army Corps of Engineers, Coastal and Hydraulics Laboratory. Dataset: *Storms at Field Research Facility*, 2007. Weblink: http://www.frf.usace.army.mil/storms.shtml.

Field Research Facility at Duck, NC (2007b). Army Corps of Engineers, Coastal and Hydraulics Laboratory. *Hurricane Isabel - FRF*. Weblink: http://www.frf.usace.army.mil/isabel/isabel.shtml.

Field Research Facility at Duck, NC (2007c). Army Corps of Engineers, Coastal and Hydraulics Laboratory. *Hurricane Isabel - FRF*. Weblink: http://www.frf.usace.army.mil/bonnie/bonnie.html.

Foote, M. and Horn, D. (2002). "Using Video and GIS to Measure Water Surface Elevations in the Swash Zone". *Transactions in GIS*, 6(1): 43-68.

Forrester, J.W. (1971). "Counterintuitive behavior of social systems". *Theory and Decision*, 2 (2): 109-140;

Gares, Paul A. and White, Stephen A. (2005). "Volumetric Analysis of Overwash Fans Resulting from Tropical Storms on North Hatteras Island, North Carolina". *Southeastern Geographer*, 45 (1): 1-15.

Hirsch, Matthew E., Degaetano, Arthur T., and Colucci, Stephen J. (2001). "An East Coast Winter Storm Climatology". *American Meteorological Society: Journal of Climate*, 14 (March 2001): 882-899.

Holman, R.A. (1986). "Extreme Value Statistics for Wave Run-up on a Natural Beach". *Coastal Engineering,* 9 (1986) 527—544.

Intergovernmental Panel on Climate Change (1995). "IPCC second assessment—Climate Change" A report of the Intergovernmental Panel on Climate Change, IPCC: Geneva, Switzerland, 64 p.

Judge, E.K., Overton, M.F., and Fisher, J.S. (2003). "Vulnerability Indicators for Coastal Dunes". *Journal of Waterway, Port, Coastal and Ocean Engineering*, 6(270): 270-278.

Larson, M., Donnelly, C., and Hanson, H. (2004a). "Analytical Modeling of Dune Response Due to Wave Impact and Overwash". Regional Sediment Management Program, U.S. Army Corps of Engineers. Contract Number: GOCE- CT-2004-505420.

Larson, M., Erikson, L. Hanson, H. (2004b). "An analytical model to predict dune erosion due to wave impact". *Coastal Engineering*, 51: 675– 696.

Leadon, M.E. (1999). "Beach, Dune, and Offshore Profile Response to a Severe Storm Event". *Proceedings of the ASCE Coastal Sediments 99 Conference held in Hauppauge, Long Island, NY on June 21-23*: 2534-2549.

Magliocca, N.R. (2006). "Managing Overwhelming Complexity in Human-landscape Interactions". *Proceedings of the 50th Annual Conference of the International Society for the Systems Science*, July 9-14, 2006. Sonoma State University.

Magliocca, N.R. (2007). "Induced Coupling: An Approach to Modeling and Managing Complex Human-Landscape Interactions". *Proceedings of the 51st Annual Conference of the International Society for the Systems Sciences,* August 5-10, 2007, Tokyo, Japan: CD-ROM 2007-727.

McNamara, D.E. and Werner, B.T. (2008a). "Coupled Barrier Island-Resort Model:1. Emergent Instabilities Induced By Strong Human-landscape Interactions". *Journal of Geophysical Research- Earth Surface.* 113(F1): F01016

McNamara, D.E. and Werner, B.T. (in press, b). "Coupled Barrier Island-Resort Model: 2. Tests and Predictions Along Ocean City and Assateague Island National Seashore, Maryland". *Journal of Geophysical Research- Earth Surface.* 113(F1): F01017

Meehi, G.A., Zwiers, F., Evans, J., Knutson, T., Mearns, L., and Whetton, P. (2000). "Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change". *Bulletin of the American Meteorological Society*, Vol. 18 (3): 427-436.

Moore, L.J., List, J.H., Williams, S.J., and Stolper, D. (2006), "Modeling Holocene Barrier Island Morphodynamics and Potential Future Response to Sea- Level Rise, Outer Banks, North Carolina", *Eos Trans, AGU*, 87(52), Fall Meet. Suppl., Abstract H31I-08.

Murray, A.B. (2003). "Contrasting the Goals, Strategies, and Predictions Associated With Simplified Numerical Models and Detailed Simulations". *Prediction in Geomorphology*, Geophysical Monograph 135: 1-15.

Murray, A.B. and Ashton, A. (2001). "Large-scale morphodynamic consequences of an instability in alongshore transport". In *2nd IAHR Symposium on River, Coastal, and Estuarine Mophodynamics*, 355-364 (International Association of Hydraulic Researchers, Obihiro, Japan, 2001).

National Geophysical Data Center (NGDC) (2007). "NGDC- Bathymetry, Topography, & Relief". *NOAA Satellite and Information Service*. Website: http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html.

North Carolina Department of Transportation (NCDOT) (2008). "NCDOT Project Website: NC 12". Website: http://www.ncdot.org/projects/NC12/.

Nuttle, W.K. (2000). "Ecosystem Managers can learn from past successes". *EOS*, 81: 278-284.

Outer Banks Task Force (OBTF). Website: http://www.obtf.org/.

Overton, M. F., Judge, E. K., and. Fisher, J. S (2000). **"**Development of Dune Construction Guidelines: Topsail Island, NC". Proceedings of the International Conference of Coastal Engineering held in Sydney, Australia in July 2000: 1-10.

Pompe, J.J. and Rinehart, J.R. (1994). "Estimating the effects of wider beaches on coastal housing prices". *Coastal Management*, 22:141-152.

Pompe, J.J. and Rinehart, J.R. (1995). "The value of beach nourishment to property owners: Storm damage reduction benefits". *Journal of Regional Studies*, 25: 271-286.

Pompe, J.J. and Rinehart, J.R. (1999). "Establishing fees for beach protection: Paying for a public good". *Coastal Management*, 27: 57-67.

Peng, M. Xie, L., and Pietrafesa, L.J. (2004). "A numerical study of storm surge and inundation in the Croatan-Albemarle-Pamlico Estuary System". *Estuarine, Coastal, and Shelf Science*, 59: 121-137.

Rastetter, E.B. (1991). "A Saptially explicit model of Vegetation-Habitat Interactions on Barrier Islands". In Eds. Turner, M.G. and Gardner, R.H.. *Quantitative Methods in Landscape Ecology*, 82: 353-378.

Rosati, J.D. and Stone, G.W. (2007). "Critical Width of Barrier Islands and Implications for Engineering Design". *Coastal Sediments*, 2007: 1-14.

Sallenger, A.H. (2000). "Storm impact scale for barrier islands". *J. Coast. Res.* 16 (3): 890–895.

Schwartz, R.K. (1982). "Bedform and Stratification Characteristics of Some Modern Small-Scale Washover Sand Bodies". *Sedimentology*, 29: 835-849.

Slott, J.M., Murray, A.B., and Ashton, A. (2006). "Investigating Coastal Processes Responsible for Large-Scale Shoreline Responses to Human Shoreline Stabilization". *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract H33B15-18.

Smith, M.D., Slott, J.M., and Murray, A.B. (in review). "Beach Nourishment as a Dynamic Capital Accumulation Problem". *Journal of Economics and Management*.

Smith, M.D. and Wilen, J.E. (2003). "Economic impacts of marine reserves: the importance of spatial behavior". *Journal of Environmental Economics and Management*, 46: 183-206.

Stockdon, H.F., Sallenger , A.H. Jr., Holman , R.A., and Howd, P.A. (2007). "A simple model for the spatially-variable coastal response to hurricanes". *Marine Geology*, 238: 1–20.

Tinh, N.X. (2006). Modeling of Coastal Overwash: Review and application of state-of-art empirical, numerical and analytical methods". Lund Institute of Technology/Lund University, January 2006: 82 pp.

Titus, J. G. and Richman, C. (2001). “Maps of Lands Vulnerable to Sea Level Rise: Modeled Elevations along the U.S. Atlantic and Gulf Coasts,” *Climate Research* 18: 205–228.
Tuan, T.Q., Verhagen, H.J., Visser, P., and Stive, M. (2006). “Numerical Modeling of Wave Overwash on Low-Crested Sand Barriers”. ICCE 2006: 1-14.
Turner, R.K., Subak, S., and Adger, W.N. (1996). “Pressures, Trends, and Impacts in Coastal Zones: Interactions Between Socioeconomic and Natural Systems”. *Environmental Management*, Vol. 20 (2): 159-173.
United States Geological Survey (USGS). “National Assessment of Coastal Vulnerability to Future Sea-Level Rise”. USGS Fact Sheet FS–076–00, June 2000.
United States Geological Survey (USGS) (2006a). “Hurricane and Extreme Storm Impact Studies”. Coastal and Marine Geology Program. Website: http://coastal.er.usgs.gov/hurricanes/.
United States Geological Survey (USGS) (2006b). “Observation of the impacts caused by Hurricane Bonnie, August 1998, on the North Carolina Coast - USGS Center for Coastal Geology”. Center for Coastal Geology. Website: http://coastal.er.usgs.gov/hurricanes/bonnie/lidar/index.html.
United States Geological Survey (USGS) (2007). “Hurricane Fran - Coastal Change Hazards: Hurricanes and Extreme Storms”. Center for Coastal and Watershed Studies. Website: http://coastal.er.usgs.gov/hurricanes/fran/.
Vellinga, P. and Leatherman, S.P. (1989). “Sea Level Rise, Consequences and Policies”. *Climatic Change*, 15:175-189**.**
Werner, B.T. (1999). “Complexity in natural landform patterns”. *Science*, 284: 102-104.
Zhang, Keqi, Douglas, Bruce C., and Leatherman, Stephen P. (2000). “Twentieth-Century Storm Activity along the U.S. East Coast”. *American Meteorological Society: Journal of Climate*, 13 (May 2000): 1748-1760.