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MORPHOLOGIC EVOLUTION OF SUBSIDING BARRIER ISLAND SYSTEMS

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A model of long-term barrier island morphologic evolution is presented that includes storm-induced processes and consolidation of the underlying sediments. The model was validated with migration and consolidation data for three barrier islands in Virginia, and is applied to investigate the influence of consolidation and storm severity on migration for a typical Louisiana barrier island.

INTRODUCTION

Sandy barrier islands migrate in response to many forcing processes acting over different time scales. These include longshore transport by obliquely incident waves (long term), cross-shore transport during storms and overwash during periods of elevated water level (episodic), sediment transport by tidal currents near existing or new inlets (mid- to long term), and subsidence due to primary consolidation of the underlying sediments (very long term). If barrier islands migrate onto unconsolidated sediments, the increased load will cause consolidation of the underlying clays, silts, and mud, and relative sea level rise for the barrier island system. This problem is a concern for barrier islands with migration rates on the order of meters per year, and for those that receive beach nourishment that will increase the loading on the unconsolidated sediments beneath them.

Barrier island systems that overlay fine-grained and organic-rich sediments are found in modern and ancient deltaic environments, such as on the Texas and Louisiana coasts. Also of concern are those barrier systems that have potential to migrate over ancient peat and bay sediments, such as along much of the East Coast of the U.S., including Maryland, Virginia, South Carolina, and Georgia. These barrier island systems, whether actively migrating over unconsolidated sediments or having increased loading by beach nourishment or by infrastructure, may consolidate the underlying substrate. Without an increase in relative elevation, barrier subsidence increases the likelihood for overwash, breaching, and inlet formation.

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Preliminary development of a long-term morphologic evolution model for barrier islands is presented herein. The model migrates a barrier island of a given height and width as a function of storm conditions, properties of the underlying substrate, and eustatic sea level change. The model is applied herein to evaluate the importance of consolidation on migration rates and longevity of the subaerial barrier island, within a paradigm of the Northern Gulf of Mexico.

MODEL DEVELOPMENT

The Migration, Consolidation, and Overwash (MCO) model was developed to investigate the role of consolidation on migration of sandy barrier islands that overlay compressible sediments. The model was developed to simulate processes typical of the Northern Gulf of Mexico, particularly the Louisiana barrier islands, and is structured as shown in Figure 1.

Initial conditions are defined by a sandy barrier island of a given height and width that overlies a sediment substrate of specified characteristics. The island evolves over years as a function of storm surge, wave conditions, and the rate of eustatic sea level change. In the preliminary MCO model, storm surge, wave height and period are randomly generated about a user-specified mean, with storm intensity and the number of storms each year also varying randomly. Storms approach from the ocean (or Gulf) and the model has the option to generate storm surge and waves on the bay and cause bayshore erosion as is typical for storm passage in the Northern Gulf of Mexico (Stone et al. 2004; Georgiou et al. 2005). This version of the MCO model specifies bay surge and wave conditions as a percentage of the Gulf values.

As shown in Fig. 1, the MCO model calculates inundation overwash, runup overwash, or beach erosion depending on the storm conditions and relative elevation of the barrier, surge, and runup. The barrier is then migrated into the bay (or Gulf, for waves and surge on the bayside of the barrier), and consolidation occurs due to the existing and new loading (if migration occurred onto partially-consolidated sediments). The following sections discuss the theory applied in the model.

Overwash

Overwash is any wave uprush which passes over the “crown,” or crest of the barrier beach (Leatherman 1980, p. 3). Of particular relevance to this study is the morphologic feature created by overwash and deposited on the bayside of the crest, called “washover,” “washover deposit” or “washover fan” (Leatherman 1980, p. 2). The frequency and magnitude of overwash depend on long-term conditions, such as storm climatology, relative sea level rise, and sediment supply. Overwash and the resulting washover are one of the mechanisms through which the barrier island migrates towards the bay, in the cross-shore direction. Two modes of overwash have been identified. One is runup overwash caused by the uprushing wave bore. The other is inundation overwash, which occurs when

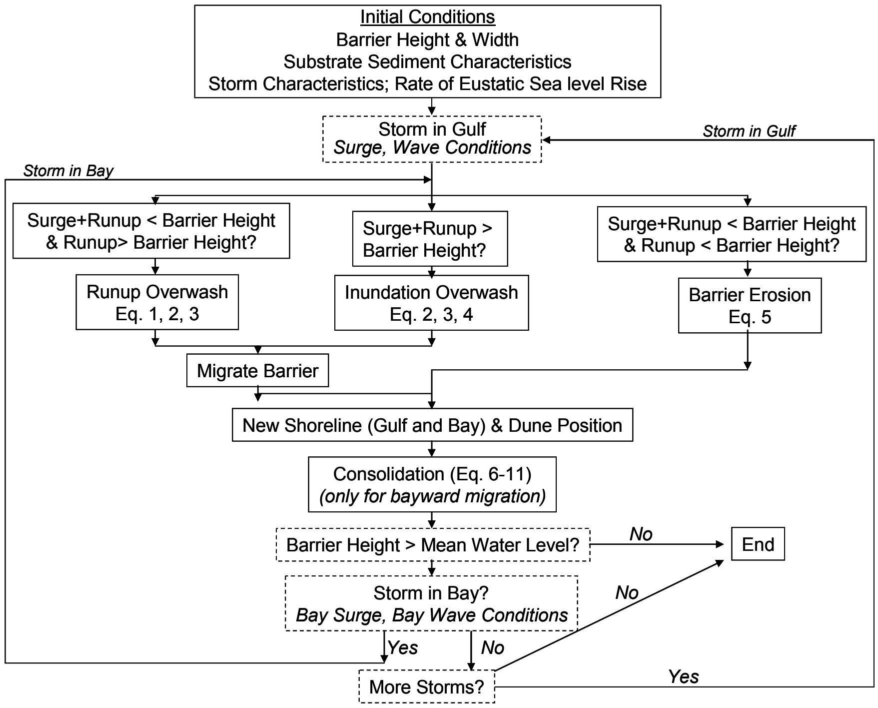


Figure 1. Flowchart for MCO Model.

the storm surge level and wave setup exceed the elevation of the barrier island crest. The entire barrier island may become completely submerged (Donnelly et al. 2006).

The overwash transport rate over the beach crest due to runup overwash per unit length of beach, $q_{DR}(t)$, can be described as (Donnelly et al. 2006),

$$q_{DR}(t) = 2K_R\sqrt{2g}\,\frac{z_R(t)^2}{R(t)}, \quad 0 < z_R(t) \text{ and } S(t) < b_h(t) \tag{1}$$

where K_R is a calibration coefficient that accounts for sediment stirring and properties of the wave bore; g is the acceleration due to gravity; $z_R(t)$ is the elevation of the runup, $R(t)$, relative to the dune crest elevation, $b_h(t)$, and S(t) is the total water depth (including storm surge) (Fig. 2a). For calculations herein, K_R was set equal to 0.005 (Donnelly et al. 2006).

The two-percent runup, $R_{u2\%}(t)$, is calculated as (Hughes 2004),

$$R_{u2\%}(t) = 4.4\, S(t) \tan\beta(t)^{0.70} \left[\frac{M_F(t)}{\rho g S(t)^2} \right]^{1/2} \qquad \text{for } \frac{1}{30} \le \tan\beta(t) \le \frac{1}{5} \qquad (2)$$

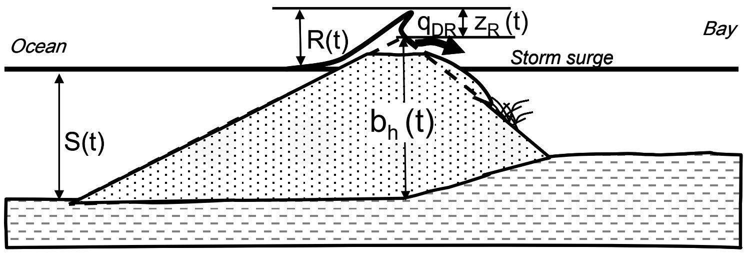
in which $\tan\beta(t)$ is the beach slope, ρ is the density of water, and the maximum dimensionless depth-integrated wave momentum flux per unit width is

$$\left[\frac{M_F(t)}{\rho g S(t)^2} \right]_{\max} = A_0(t) \left[\frac{S(t)}{g T_p(t)^2} \right]^{-A_1(t)}$$

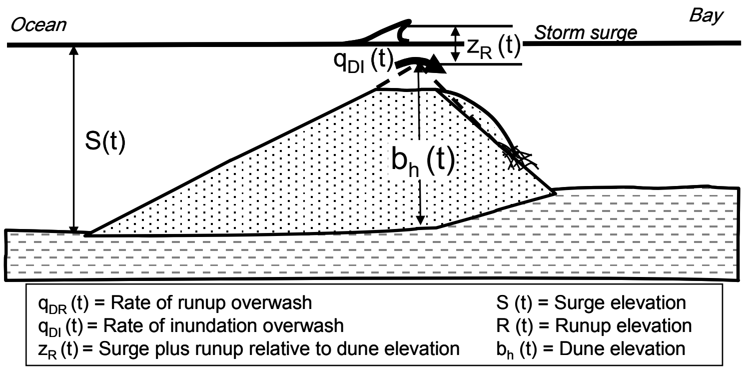
$$\text{where} \quad A_0(t) = 0.6392 \left(\frac{H_{mo}(t)}{S(t)} \right)^{2.0256} \qquad (3)$$

$$\text{and} \quad A_1(t) = 0.1804 \left(\frac{H_{mo}(t)}{S(t)} \right)^{-0.391}$$

The zeroth-moment deep water wave height is $H_{mo}(t)$, with associated peak period, $T_p(t)$.



a. Overwash due to runup.



b. Overwash due to inundation.

Figure 2. Terminology for overwash calculations.

The transport rate over the beach crest per unit width of beach due to inundation overwash, $q_{DI}(t)$, is given by (Donnelly et al. 2006) as,

$$q_{DI}(t) = (K_I + K_R)\, 2\sqrt{2g}\; z_R(t)^{3/2}, \quad 0 < z_R(t) \text{ and } S(t) \geq b_h(t) \tag{4}$$

in which K_I is an empirical coefficient, and $z_R(t)$ is as defined previously (Fig.2b). For calculations herein, K_I was set to 0.001 (Donnelly et al. 2006).

Erosion

When the storm surge plus wave runup do not exceed the barrier island elevation, the time-dependent berm erosion, $E(t)$, is calculated using the Convolution Storm Erosion Method (Kriebel and Dean 1993),

$$E(t) = \frac{E_\infty}{2}\left\{1 - \frac{\beta_t^2}{1+\beta_t^2}\exp\left(-\frac{2\sigma t}{\beta_t}\right) - \frac{1}{1+\beta_t^2}\left[\cos 2\sigma t + \beta_t \sin 2\sigma t\right]\right\} \tag{5a}$$

in which the maximum potential erosion retreat is given by

$$E_\infty = S(t)\left(\frac{W_b(t) - \dfrac{h_b(t)}{\tan\beta(t)}}{B + h_b(t) - \dfrac{S(t)}{2}}\right) \tag{5b}$$

and β_t is the ratio of the erosion time scale to the storm duration,

$$\beta_t = \frac{2\pi T_s}{T_D} \tag{5c}$$

In Eq. (5a), the term $\sigma = \pi/T_D$, where T_D is the total storm duration. The characteristic erosion time scale of the system is given by,

$$T_s = 320\frac{H_b(t)^{1.5}}{g^{0.5}A^3}\left(1 + \frac{h_b(t)}{B} + \frac{\tan\beta(t)\,W_b(t)}{h_b(t)}\right)^{-1} \tag{5d}$$

in which $H_b(t)$ is the breaking wave height, $h_b(t)$ is the breaking depth, B is the berm elevation, and $W_b(t)$ is the distance to the breaker line calculated as

$$W_b(t) = \left(\frac{h_b(t)}{A}\right)^{1.5} \tag{5e}$$

in which A is the equilibrium beach profile parameter, set herein to 0.063 $m^{1/3}$ representing 0.1 mm sand, which is typical of Louisiana barrier islands.

Consolidation

Sediment has the potential to compress significantly under load due to factors such as reduction in void space, biochemical decay of organic materials, and grain shifting and breakage. Pore pressure increases if a load is applied to a saturated soil. For sands, the excess pore pressure is dissipated quickly due to their high permeability. However, clays, organic soils, and silts have much lower permeabilities; thus, the excess pressure dissipates much more slowly, and consolidation continues for a much longer time.

Consolidation of sediment has three stages: (1) initial compression, which occurs as soon as the load is applied due to compression and solution of air in the voids (and, to a small degree, compression of trapped fluid and load transfer to the sediment); (2) primary or hydrodynamic, during which excess pore water pressure is dissipated; and (3) secondary, which occurs after the excess pressure has been eliminated and continues indefinitely, at a decreasing rate due to shifting and fracture of particles and breaking of interparticle bonds (Sowers 1979). Coastal substrates that have the potential for significant consolidation include fine-grained sediment that have not been previously loaded, for example, clays and silts deposited by river systems, organic peaty sediment, and sediment with interlaying organic strata. Sediment loaded at an earlier time in its geologic history, e.g., due to glacial loading or construction of infrastructure, will rebound slightly once the load is removed. If reloaded with a greater weight, they will continue the consolidation process.

Terzaghi (1943) derived a relationship for primary consolidation based upon hydraulic principles. The assumptions for one-dimensional consolidation theory are: (1) a fully-saturated sediment system; (2) unidirectional flow of water; (3) one-dimensional compaction occurring in the opposite direction of flow; (4) a linear relationship between the change in sediment volume and the applied pressure (linear small-strain theory); and (5) validity of Darcy's Law, which states that the specific discharge (flow rate per area) through a porous medium is equal to the hydraulic gradient times the hydraulic conductivity (Yong and Warkentin 1966; Hornberger et al. 1998). For one-dimensional vertical flow, the final consolidation, z_c, for a given increase in loading, $\Delta W(t)$, can be calculated as,

$$z_c = z_0\left(\frac{C_c}{1+e_0}\log_{10}\frac{W_0+\Delta W(t)}{W_0}\right) \tag{6}$$

where z_0 is the initial thickness of compressible sediment; C_c is the compression index, which can be determined experimentally from a consolidation test; e_0 is the initial void ratio, equal to the volume of voids divided by the volume of solids, and averaged over z_0; and W_0 is the initial loading on the sediment (Fig. 3). In a study of the consolidation potential for Louisiana sediment, Kuecher (1994) found values of C_c = 4.7 to 5 for peat and organic muck; 1 to 3 for prodelta mud;

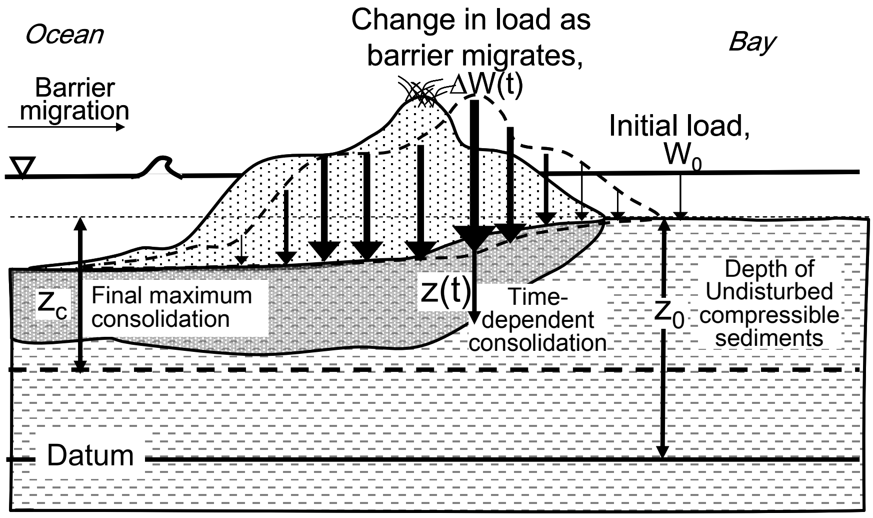


Figure 3. Definition of terms for consolidation model

0.86 for bay sediment; 0.123 for natural levee sands and silts, and 0.063 for point bar sands. Larger C_c values indicate a greater potential for consolidation. For calculations presented herein, C_c was 0.86. The depth of undisturbed sediments, z_0, was determined to be 4.7 m through iteration with the model by reproducing the rate of relative sea level rise measured at Grand Isle, Louisiana (9.9 mm/year) given the eustatic rate in the region (2.4 mm/year, Stone and Morgan 1993).

Terzaghi's (1943) time-dependent relationship for consolidation is,

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \qquad (7)$$

where u is pore water pressure in excess of hydrostatic pressure, t is elapsed time, c_v is a property of the compressible sediment, called the coefficient of consolidation, and z is the vertical coordinate with the origin at the initial sediment surface (Fig. 4). The proportion of the initial pore water pressure remaining at any time, M (t), can be expressed as,

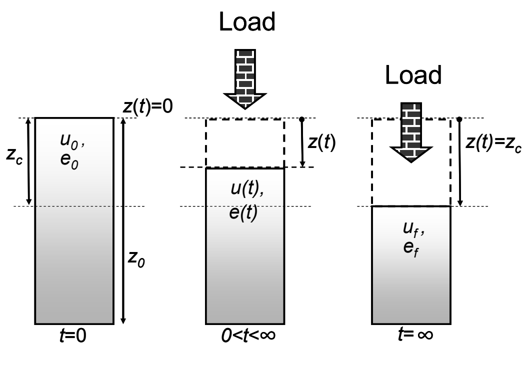


Figure 4. Definition sketch for consolidation

relationship.

$$M(t) = \frac{1}{z_0}\int_0^{z_0} \frac{u}{u_0} dz = \frac{e(t) - e_f}{e_0 - e_f} \qquad (8)$$

in which u_0 is the initial pore water pressure, $e(t)$ is the average void ratio at any time, and e_f is the final average void ratio. The variable M (t) varies from 1 and 0, at time t = 0 and infinity, respectively. The proportion of vertical consolidation that occurs at any time can also be expressed as,

$$z(t) = z_c \left(\frac{e_0 - e(t)}{e_0 - e_f} \right) \qquad (9)$$

Combining Eqs. (8) and (9) gives,

$$z(t) = z_c (1 - M(t)) \qquad (10)$$

where $M(t)$ can be expressed as (Dean 2002, p. 119)

$$M(t) = 8 \sum_{n=1}^{\infty} \frac{e^{-[(2n-1)\pi]^2 c_v t / 4 z_0^2}}{(2n-1)^2 \pi^2} \qquad (11)$$

VALIDATION

Validation of the MCO model was conducted by comparing model predictions to data from Gayes (1983) for sediment core data extending across four profile lines on three barrier islands in Virginia: Assawoman, Metompkin, and Wallops (Fig. 5). In his study, Gayes calculated the coefficient of consolidation representative of most data from laboratory testing of core sediment, equal to c_v=2.5 m^2/year. In the validation, the sediment core with the largest consolidation value at each site was used to determine the value of z_0; these parameters were then held constant for the rest of the data at that site. Values of z_0 determined in this

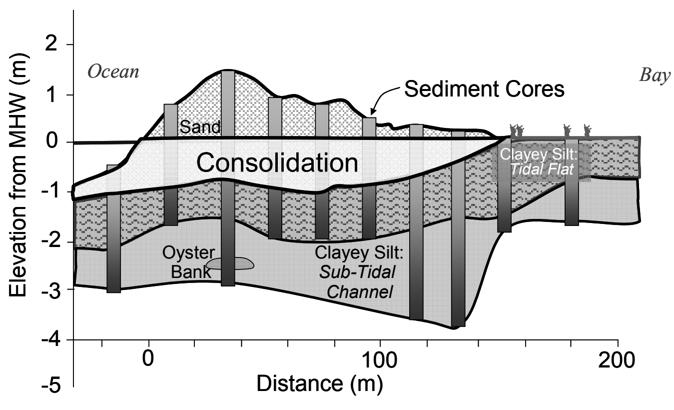


Figure 5. Gayes (1983) data for Assawoman Island, Virginia.

manner were z_0 = 1.38, 1.58, 1.06, and 4.33 m for core data from Assawoman #1, Assawoman #2, Metompkin, and Wallops, respectively. Figure 6 shows predicted and measured elevations, with a squared correlation coefficient R^2=0.87.

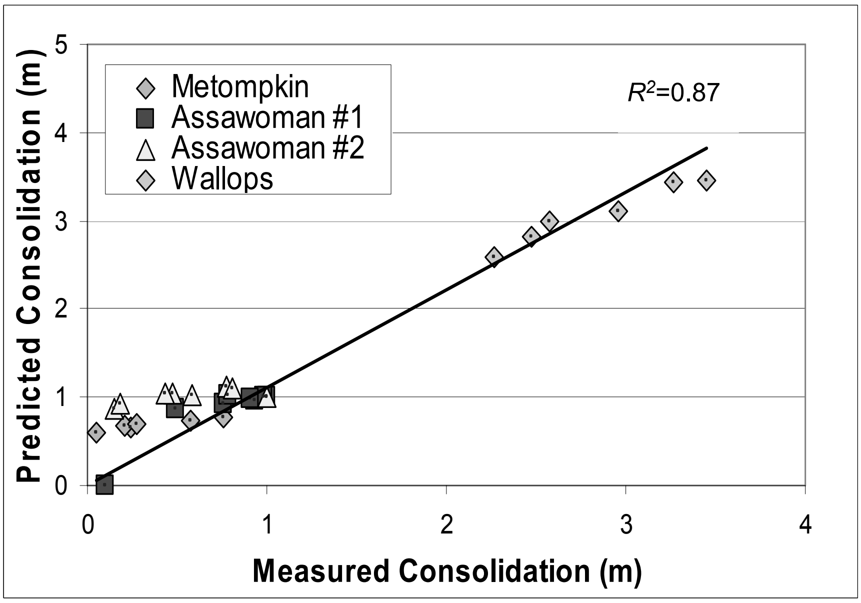


Figure 6. Validation of MCO model with data from Gayes (1983).

APPLICATIONS

In this section, the validated MCO model is applied to evaluate the relative significance of consolidation and increasing storm severity on migration and longevity of the sub-aerial barrier. Barrier island and storm conditions representative of those in coastal Louisiana serve as a "base case," from which variables are modified to evaluate the relative importance of each parameter. The barrier island for the base case was a 1.5-m high dune with 1,500-m wide base, and 0.1 mm sand overlying a compressible substrate. Storms were randomly generated with an average 1.5-m surge, 1.5-m zero-moment deepwater wave height, and a rate of eustatic sea level rise equal to 2.4 mm/year (Stone and Morgan 1993). Figure 7 presents one simulation for the base case, which predicted surge plus runup, consolidation, migration, and dune height over a 200-year period. To smooth out extreme values in the simulations, the remaining applications will be shown with the average and associated standard deviation for 10 simulations, as illustrated in Fig. 8 for the base case. All variables are reported at the dune crest location for the entire simulation.

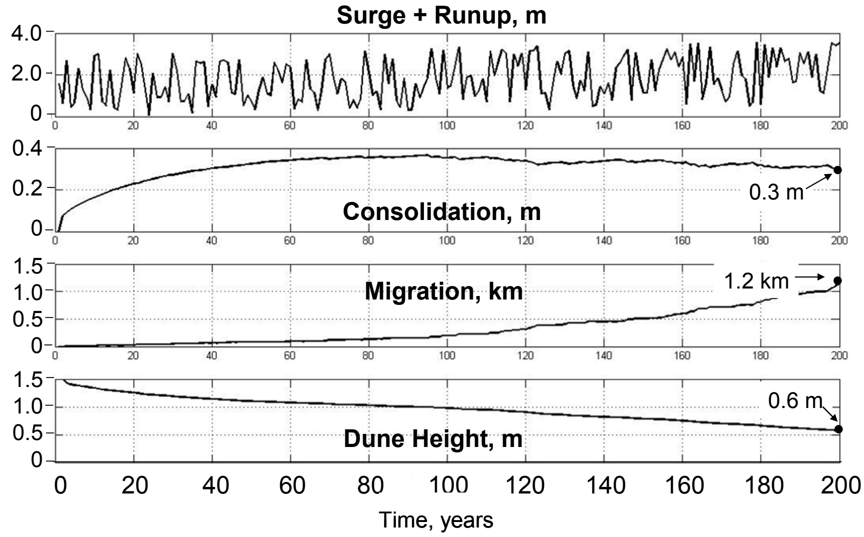


Figure 7. MCO model applied to base case (1.5-m dune, 1,500-m width, 1.5-m storm surge, and 1.5-m deepwater zero-moment wave height).

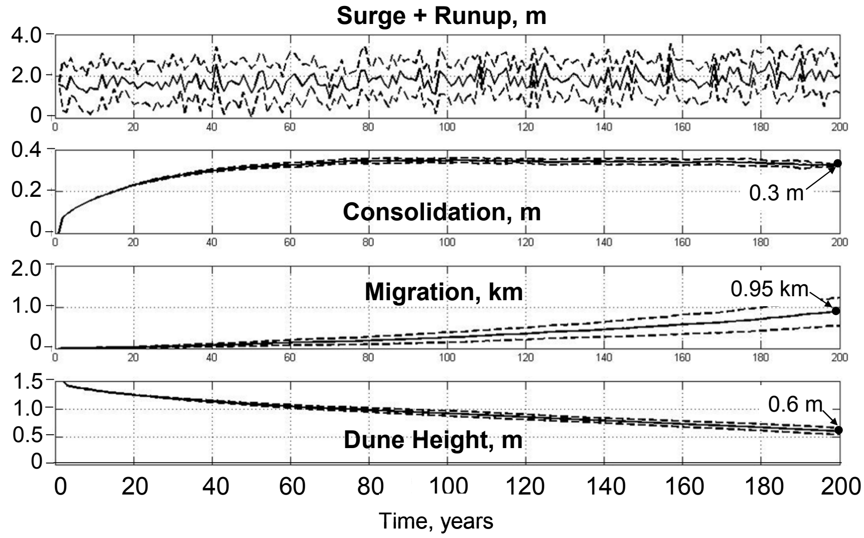


Figure 8. Average and standard deviation for 10 base case simulations.

From Fig. 7, several operational characteristics of the MCO model can be observed. Total consolidation is reduced beneath the dune crest when the barrier migrates a significant distance into the bay after a large storm event (observe large storm event that occurred at approximately 122 years, which reduced consolidation due to washover of the dune onto partially-consolidated sediment in the bay.) At the same time, migration increased due to this event and dune height is reduced slightly. At the end of the 200-year period, Fig. 8 indicates average values for the base case with consolidation equal to 0.3 m, migration of 0.95 km, and final dune height equal to 0.6 m.

The next simulation evaluated the importance of consolidation in migration of the representative barrier island by repeating the same simulation but setting the consolidation parameters equal to zero. Figure 9 shows results of this simulation, for which the consolidation remained at zero, migration was 0.4 km, and dune height at the end of the 200-year period was 1.1 m. Thus, for these barrier island and storm conditions, consolidation increased the migration by 0.55 km and reduced dune height an additional 0.5-m over the 200-year period.

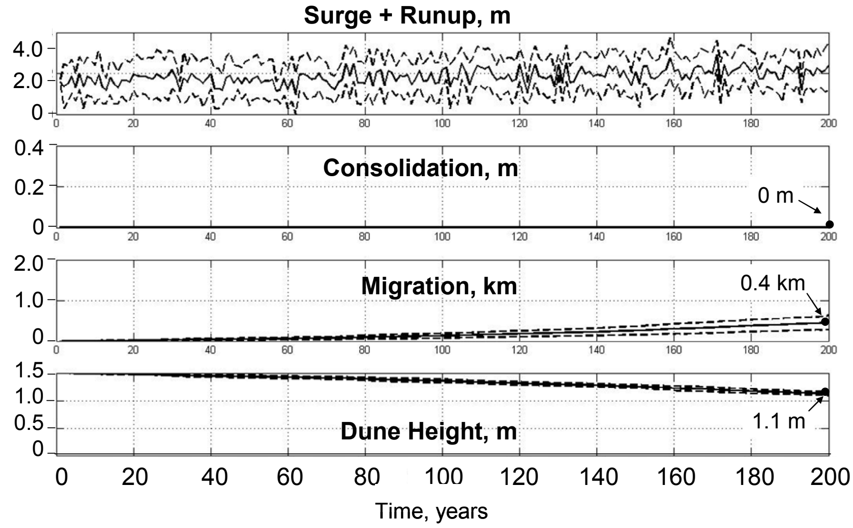


Figure 9. Base case with consolidation equal to zero.

The final example presented evaluates the influence of increased storminess through time, with the surge and wave height increasing by 0.1% each year relative to the original surge and wave height magnitudes. An increase in storminess is a possible consequence of global warming (Intergovernmental Panel on Climate Change 2001) and was implemented to give a total 20% increase in surge elevation and deep water wave heights over the 200 year simulation. The increase in storm severity increases migration by 0.55 km (to 1.5 km as compared to 0.95 m for the base case), and reduces final dune elevation an additional 0.15 m (to 0.45 m as compared to 0.6 m for the base case) (Fig. 10).

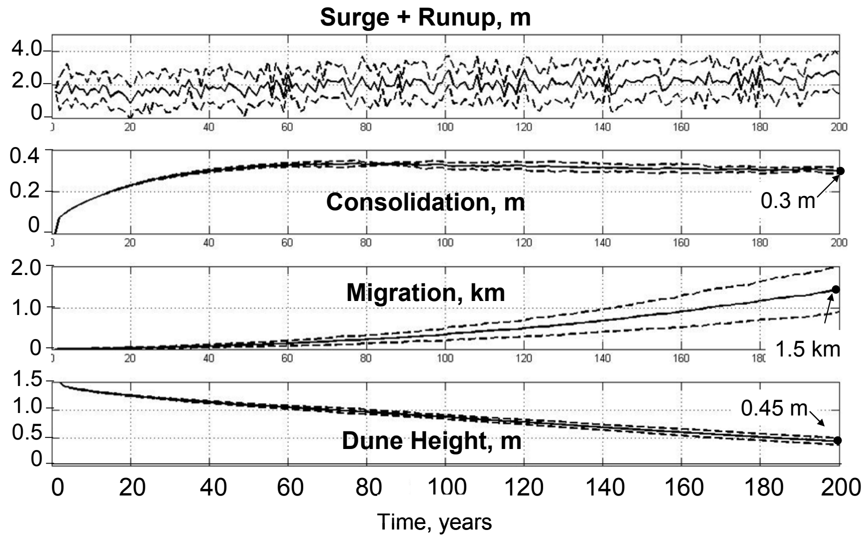


Figure 10. Base case with an increase in storm surge and deep-water wave height equal to 0.1% per year relative to the initial surge and wave height magnitudes.

CONCLUSIONS

A two-dimensional model was developed to simulate long-term dross-shore migration of a sandy barrier island as a function of storm surge, wave conditions, and properties of the underlying substrate. The model was validated with data from four transects with sediment core data from three migrating barrier islands in Virginia that overlie consolidating substrates. Application of the model for conditions representative of the Northern Gulf of Mexico indicates that consolidation of the underlying substrate is a non-negligible process in migration of barrier islands, more than doubling the total migration and loss in dune elevation over a 200-year period for the example case presented herein. The newly developed model was also applied to investigate the influence of potential increased storm severity on barrier response, and illustrated that a 20% increase in storm surge and deep-water wave height over 200 years resulted in a 58% increase in migration and 25% decrease in dune elevation. Future enhancements to the model will add longshore transport sources and sinks, eolian transport, and variable erosive characteristics for vegetated and core sediments characteristic of Louisiana barrier islands (Stone et al. 1997).

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