CRITICAL WIDTH OF BARRIER ISLANDS AND IMPLICATIONS FOR ENGINEERING DESIGN

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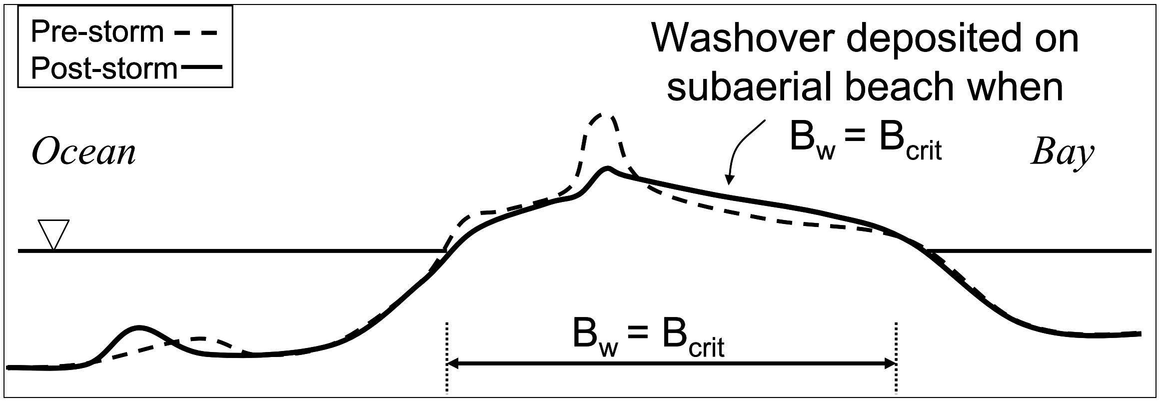
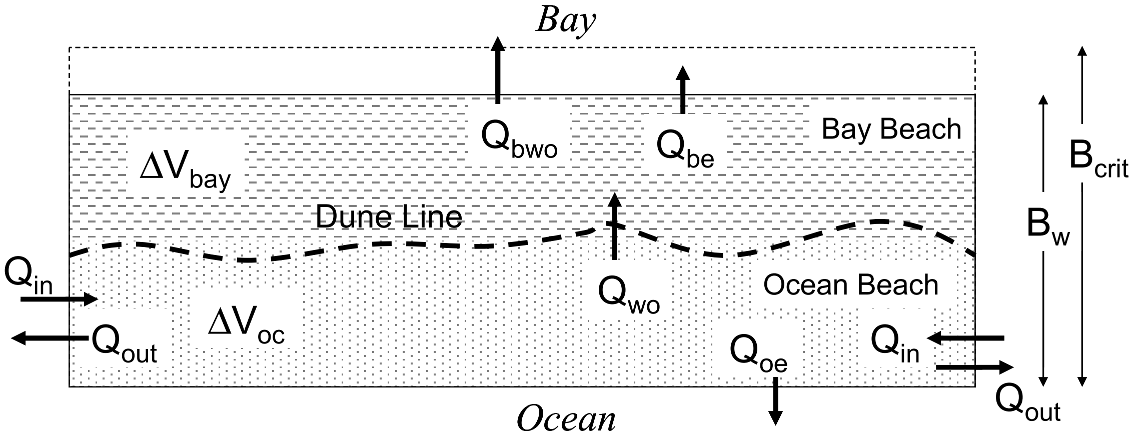
Abstract: The critical width of a barrier island is defined as the smallest cross-shore dimension that minimizes net loss of sediment from the island over periods from decades to centuries. This concept is of importance for large-scale restoration of barrier islands which involves rebuilding these islands to a specified geometry. Within constraints of coastal forcing and geologic and regional characteristics at the site, islands having critical width will capture deposition of washover sediment onto the subaerial beach over the project lifetime. This study reviews previous investigations of barrier island critical width and applies a newly-developed model of barrier island migration, consolidation, and overwash to assist engineering design.

INTRODUCTION

The term "critical width" has been discussed with reference to barrier islands, overwash, and washover deposits since the 1970s (e.g., Leatherman 1976, 1979; Jiménez and Sánchez-Arcilla 2004). Critical barrier width is defined herein as the smallest cross-shore dimension that minimizes net loss of sediment from the barrier island over periods from decades to centuries. The magnitude of critical width is related to availability and volume of littoral sediment in addition to that in the dune system. In addition, the influx of sediment via longshore sediment transport is important, for example during post-storm recovery. To illustrate the definition and introduce terminology, Figure 1 shows a barrier island and sediment transport pathways. If the barrier width equals or exceeds the critical value, transport of washover sediment from the ocean beach, Q_{wo} , is deposited entirely on the bay beach, and residual loss of this washover into the bay, Q_{bwo}, equals zero. For barrier widths less than the critical value, $Q_{bwo} > 0$.



a. Cross-section



b. Planview

Legend

Q_{in} = longshore transport rate into barrier system
Q_{out} = longshore transport rate out of barrier system
ΔV_{oc} = volume change rate on ocean beach
ΔV_{bay} = volume change rate on bay beach
B_w = barrier width
Q_{oe} = rate transported offshore
Q_{be} = rate transported into bay
Q_{wo} = washover rate from ocean beach
Q_{bwo} = washover rate lost into bay
B_{crit} = critical barrier width

Fig. 1. Definition of terminology

Application of this concept is important for the large-scale restoration of barrier islands such as is being considered for degraded islands along the Northern Gulf of Mexico, particularly in Louisiana. These barrier islands have lost subaerial volume through time due to a combination of factors, including a lack of littoral sediment in the regional system, wave erosion due to tropical cyclones and winter storms on both the Gulf and Bay shores, and rapid relative sea level rise. Large-scale restoration involves reconstruction of the island to specified height, width, length, and spacing (for multiple islands) using sediment derived from an external source. The goal in large-scale restoration is to maximize the lifetime of the island in protecting the bay, estuary, and mainland shores, while minimizing the cost of the project. In the North-Central Gulf of Mexico, loading of the compressible substrate with additional sediments increases consolidation. Thus, the volume of sediment used to restore a barrier becomes critical in that a larger restoration project will incur more losses due to consolidation when compared to a smaller volume (Rosati et al 2006, 2007).

In this study, we applied a migration, consolidation, and overwash model to determine the critical barrier island width given forcing and geologic parameters. Storm characteristics and consolidation characteristics of the underlying substrate were varied. The study concludes with preliminary recommendations for critical design width for large-scale restoration of barrier island systems that overlie a compressible substrate.

PREVIOUS STUDIES

Leatherman (1976, 1979) investigated overwash and washover along the northern end of Assateague Island, Maryland, and found that overwash processes were effective in migration of the barrier "…only where the barrier width is less than a critical value (122 to 213 m)." The island did not narrow below these values because overwash processes were effective at transporting sediment to the bayshore, therefore keeping pace with the rate of ocean shoreline migration. Sections of the island with greater widths experienced washover deposits that did not reach the bayshore, and the island narrowed due to ocean shoreline migration until it reached the critical width. The only process that widened the barrier beyond the critical width was breaching, formation of a partially subaerial flood shoal, and subsequent inlet closure (Leatherman 1976).

Eitner (1996) discussed potential response of the East Frisian barrier islands due to a 1-m rise in sea level occurring over approximately 170 years. Although critical width is not discussed, the most likely future outcome proposed is one in which the barrier islands maintain width while increasing in height and migrating landward. This stability of barrier cross-section implies that a critical width is maintained over the long term.

Jiménez and Sánchez-Arcilla (2004) applied the concept of critical width in a decadal-scale barrier evolution model to determine when overwash processes would contribute to bayshore accretion. They developed the model for the Ebro Delta, Spain, and estimated the critical width of the barrier spit as 225 m. When the barrier island was wider than the critical width, washover deposition on the bayshore was zero. When the barrier width was less than or equal to the critical width, washover deposition was estimated as:

$$Q_{bwo} = Q_{wo}\left(\frac{B_{crit}}{B_w}\right)^{\alpha} \quad or \quad B_{crit} = B_w\left(\frac{Q_{bwo}}{Q_{wo}}\right)^{1/\alpha} \tag{1}$$

where Q_{bwo} is the volumetric washover rate of deposition to the bayshore, Q_{wo} is the volumetric washover rate on the oceanside of the barrier, B_{crit} is the critical barrier width, B_w is the barrier width at any time, and α is a parameter greater than or equal to 1 to incorporate sediment eroded from the subaerial barrier during overwash events (notation has changed slightly from original reference for consistency herein). Jimenez and Sanchez-Arcilla evaluated the influence of α values ranging from 1 to 2; greater α values increased the rate at which the barrier reaches an equilibrium condition, but did not change the final equilibrium state. For α values greater than 1, volumetric overwash into the bay will be greater than that transported from the ocean for all values of barrier width less than the critical width.

A sediment budget approach can be applied to estimate the critical width (Figure 1). Applying the requirement that Q_{wo} remain on the subaerial beach at critical width (i.e., $Q_{bwo} = 0$ when $B_w = B_{crit}$), and assuming that transport of the washover sediment into the bay, Q_{bwo}, is linearly related to the critical width, then:

$$\begin{aligned} B_{crit} &= B_w\left(\frac{Q_{wo}}{Q_{wo}-Q_{bwo}}\right), \quad or \\ B_{crit} &= B_w\left(\frac{Q_{in}-Q_{out}-Q_{oe}-\Delta V_{oc}}{Q_{be}+\Delta V_{bay}}\right) \end{aligned} \tag{2}$$

Stone et al. (2004) compiled total volumes for four barrier sub-environments at Santa Rosa Island, Florida (Gulf, Berm, Dune, Bay Beach, and Bay Platform) over a 6.5-year period which can be used in Eq. 2 to determine the critical width. Considering volumetric change from February 1996 to 2002, a sediment budget can be formulated as shown in Figure 2. In formulating this budget, it was assumed that all volumetric change was due to cross-shore transport, and the gradient in longshore transport was zero. Applying Eq. 2 with a barrier width B_w = 220 m, Q_{in} - Q_{out} = 0 cu m/yr, Q_{oe} = 12.8 cu m/yr, ΔV_{oc} = -40.8 cu m/yr, Q_{be} = 0 cu m/yr, and ΔV_{bay} = 24.5 cu m/yr, the critical width can be estimated as B_{crit} = 220* (0-12.8+40.8)/(0+24.5) ~ 250 m.

MCO MODEL

The Migration, Consolidation, and Overwash (MCO) model (Rosati et al. 2006, 2007) was applied to develop guidance for barrier island critical width. This model simulates cross-shore evolution of a barrier island over periods extending from years to centuries, with given substrate and storm characteristics. Methodology underlying the model is briefly reviewed in this section.

Overwash

Overwash is any wave uprush which passes over the crown or crest of the barrier beach, and the feature created by the overwash is the washover deposit (Leatherman 1980). Overwash and the associated washover are one of the mechanisms through which the barrier island migrates towards the bay, in the cross-shore direction.

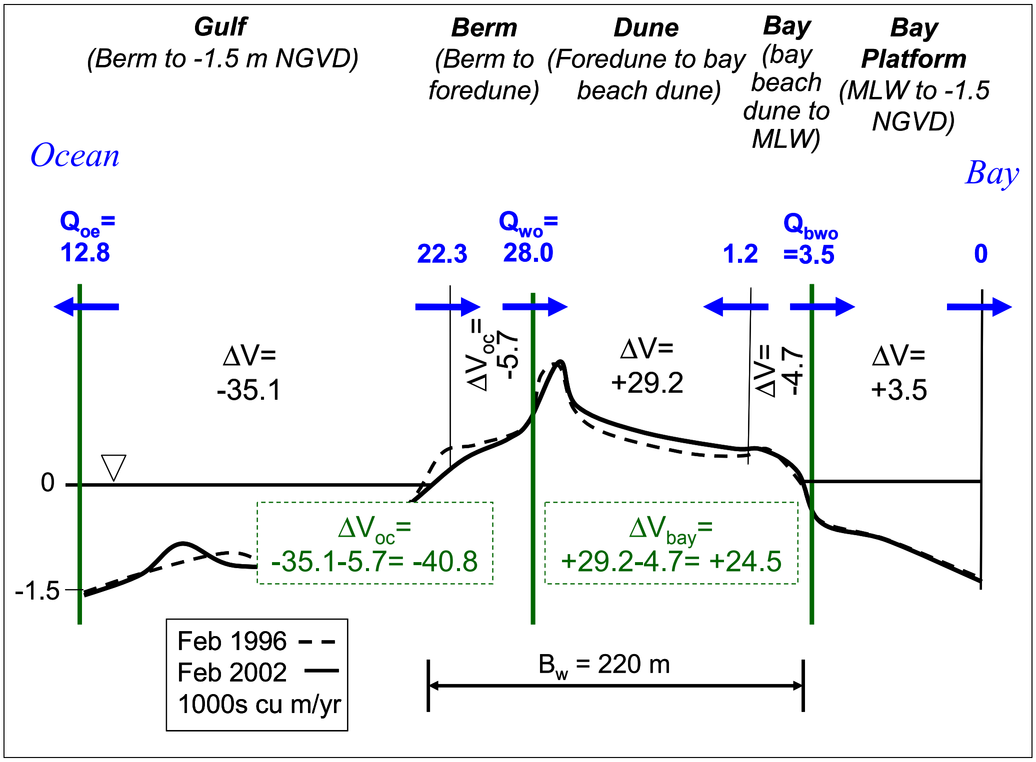


Fig. 2. Cross-shore sediment budget for Santa Rosa Island, Florida, from Feb 1996 to 2002 (data from Stone et al. 2004)

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):

$$q_{DR}(t) = 2K_R\sqrt{2g}\,\frac{z_R(t)^2}{R(t)}, \quad 0 < z_R(t) \text{ and } S(t) < b_h(t) \qquad (3)$$

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). 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):

$$R_{u2\%}(t) = 4.4\,S(t)\tan\beta(t)^{0.70}\left[\frac{M_F(t)}{\rho g S(t)^2}\right]^{1/2} \qquad \text{for } \frac{1}{30} \le \tan\beta(t) \le \frac{1}{5} \qquad (4)$$

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:

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

$$\text{where}\quad A_0(t) = 0.6392\left(\frac{H_{mo}(t)}{S(t)}\right)^{2.0256} \tag{5}$$

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

The zeroth-moment deep water wave height is $H_{mo}(t)$, with associated peak period, $T_p(t)$. In applications described herein, these were randomly generated about a user-specified mean.

If the barrier island is submerged, the transport rate over the beach crest per unit width of beach, $q_{DI}(t)$, is given by (Donnelly et al. 2006) as:

$$q_{DI}(t) = (K_I + K_R)\,2\sqrt{2g}\; z_R(t)^{3/2}, \quad 0 < z_R(t) \text{ and } S(t) \geq b_h(t) \tag{6}$$

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

The rate of washover deposition q_f varies as a function of distance over the dune crest (Larson et al. 2004):

$$q_f = \frac{q}{1 + \mu s / B_D} \tag{7}$$

where q is the transport rate over the dune crest as calculated in Eq. (1) or (4), s is a coordinate originating at the dune crest and increasing with distance over the dune, μ is an empirical coefficient, and B_D is the width of flow over the dune crest. For calculations, μ/B_D=0.12 (Larson et al. 2004).

Erosion

If 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):

$$E(t) = \frac{E_\infty}{2}\left\{1 - \frac{\beta_t^2}{1+\beta_t^2}\exp\left(-\frac{2\sigma t}{\beta_t}\right) - \frac{1}{1+\beta_t^2}\left[\cos 2\sigma t + \beta_t \sin 2\sigma t\right]\right\} \tag{8a}$$

in which the maximum potential erosion retreat distance is given by:

$$E_\infty = S(t)\left(\frac{W_b(t) - \dfrac{h_b(t)}{\tan\beta(t)}}{B + h_b(t) - \dfrac{S(t)}{2}}\right) \tag{8b}$$

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

$$\beta_t = \frac{2\pi T_s}{T_D} \tag{8c}$$

In Eq. (8a), 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:

$$T_s = 320\frac{H_b(t)^{1.5}}{g^{0.5}A^3}\left(1+\frac{h_b(t)}{B}+\frac{\tan\beta(t)W_b(t)}{h_b(t)}\right)^{-1} \tag{8d}$$

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 wave breaker line calculated as:

$$W_b(t) = \left(\frac{h_b(t)}{A}\right)^{1.5} \tag{8e}$$

in which A is the equilibrium beach profile scade parameter, set to 0.063 $\mathrm{m}^{1/3}$ representing 0.1 mm sand 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 smaller permeability; thus, the excess pressure dissipates much more slowly, and consolidation continues for a much longer time.

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. For one-dimensional vertical flow, the final consolidation, z_c, for a given increase in loading, $\Delta W(t)$, can be calculated as:

$$z_c = z_0\left(\frac{C_c}{1+e_0}\log_{10}\frac{W_0+\Delta W(t)}{W_0}\right) \tag{9}$$

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. 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 mud; 1 to 3 for prodelta mud; 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:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \tag{10}$$

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

$$M(t) = \frac{1}{z_0} \int_0^{z_0} \frac{u}{u_0} dz = \frac{e(t) - e_f}{e_0 - e_f} \tag{11}$$

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:

$$z(t) = z_c \left(\frac{e_0 - e(t)}{e_0 - e_f} \right) \tag{12}$$

Combining Eqs. (11) and (12) gives,

$$z(t) = z_c (1 - M(t)) \tag{13}$$

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

$$M(t) = 8 \sum_{n=1}^{\infty} \frac{e^{-[(2n-1)\pi]^2 c_v t / 4 z_0^2}}{(2n-1)^2 \pi^2} \tag{14}$$

APPLICATION

To determine the influence of barrier island width on migration, barrier island evolution was simulated with a storm surge and wave climate randomly generated about a mean value that ranged from 0.5 to 2 m relative to Mean Sea Level (MSL) (Figure 3). Dune elevations for the barrier islands were independently varied from 0.75 to 2 m MSL, with and without consolidation of the underlying substrate. All simulations ran for 100 years, and results from the MCO model are shown in Figures 4 through 8.

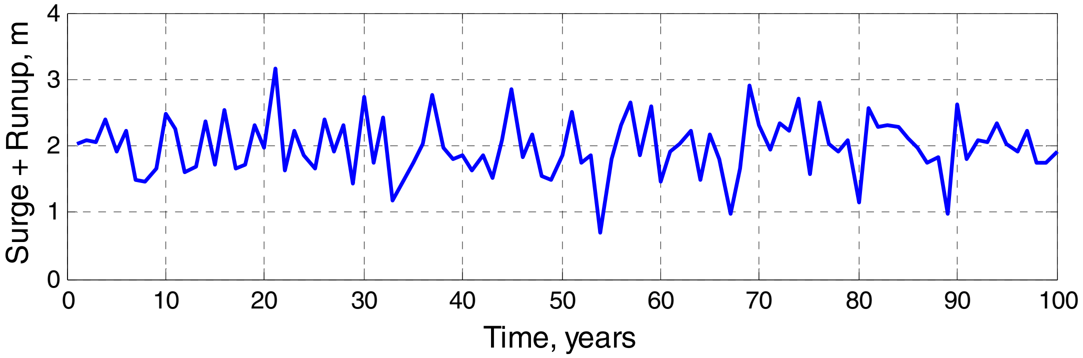


Fig. 3. Example storm surge plus wave runup time series randomly generated about a 2-m MSL mean

For each simulation, the minimum width at which migration does not change has been noted as the critical width. Results from these simulations can be summarized as:

(1) The magnitude of critical width increases for decreasing dune height. This finding implies that there is a critical cross-section required for minimum migration.

(2) The critical width increases with magnitude of storm surge plus wave runup.

(3) Figures 4 through 6 (storm surge plus wave runup from 0.5 to 1.5 m) show that barrier islands with greater consolidation of the substrate (dashed lines) result in greater migration distances and larger values of critical width as compared to barrier islands with lower consolidation substrates (solid lines). This is logical, because islands with greater consolidation reduce elevation as compared to lower consolidation substrates, and thus migrate more rapidly. However, Figures 7 and 8 (storm surge plus wave runup from 2 to

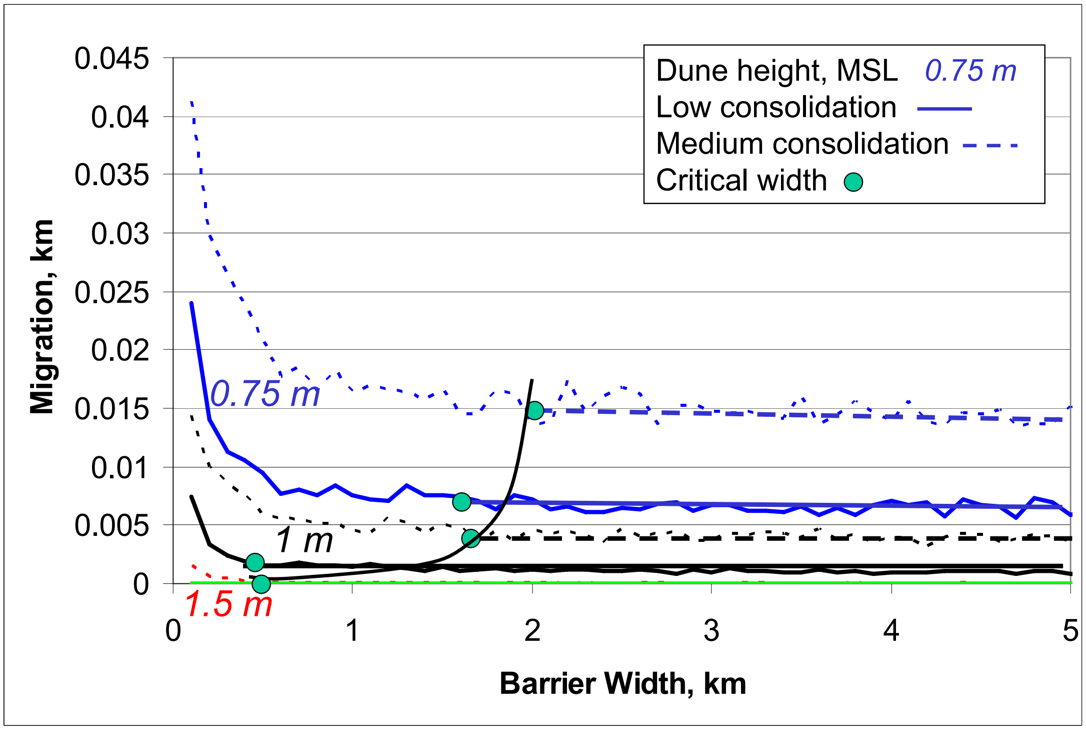


Fig. 4. Influence of barrier island width on migration for storm surge plus runup varied about 0.5-m mean, 100-year simulation

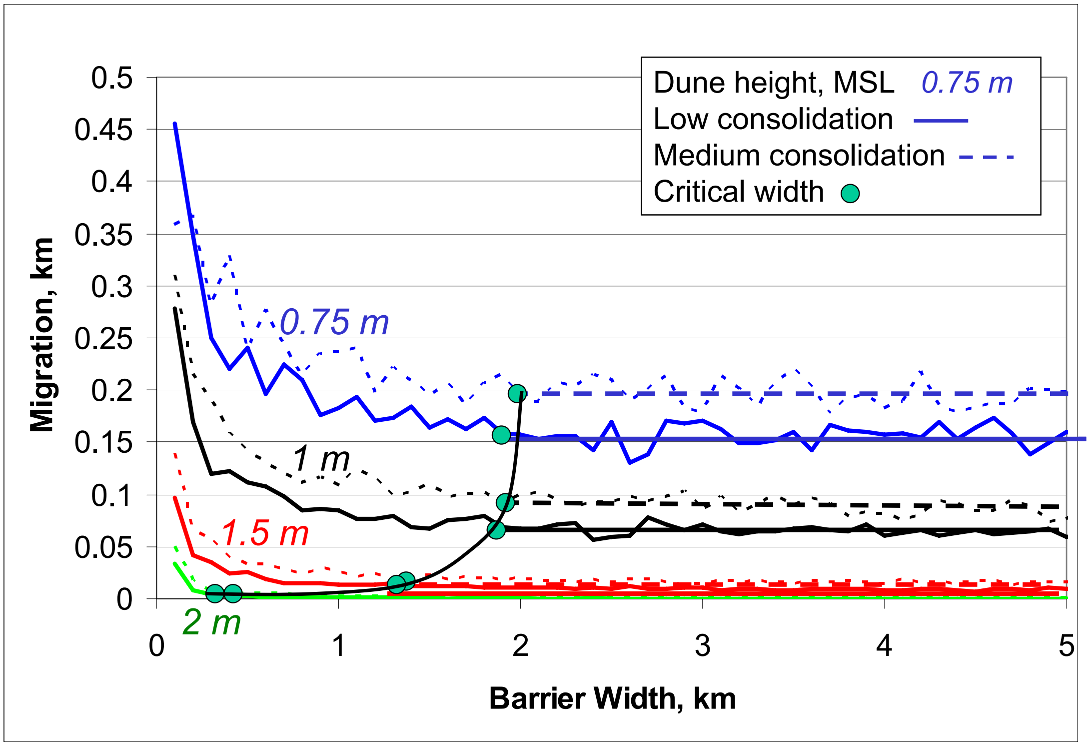


Fig. 5. Influence of barrier island width on migration for storm surge plus runup varied about 1-m mean, 100-year simulation

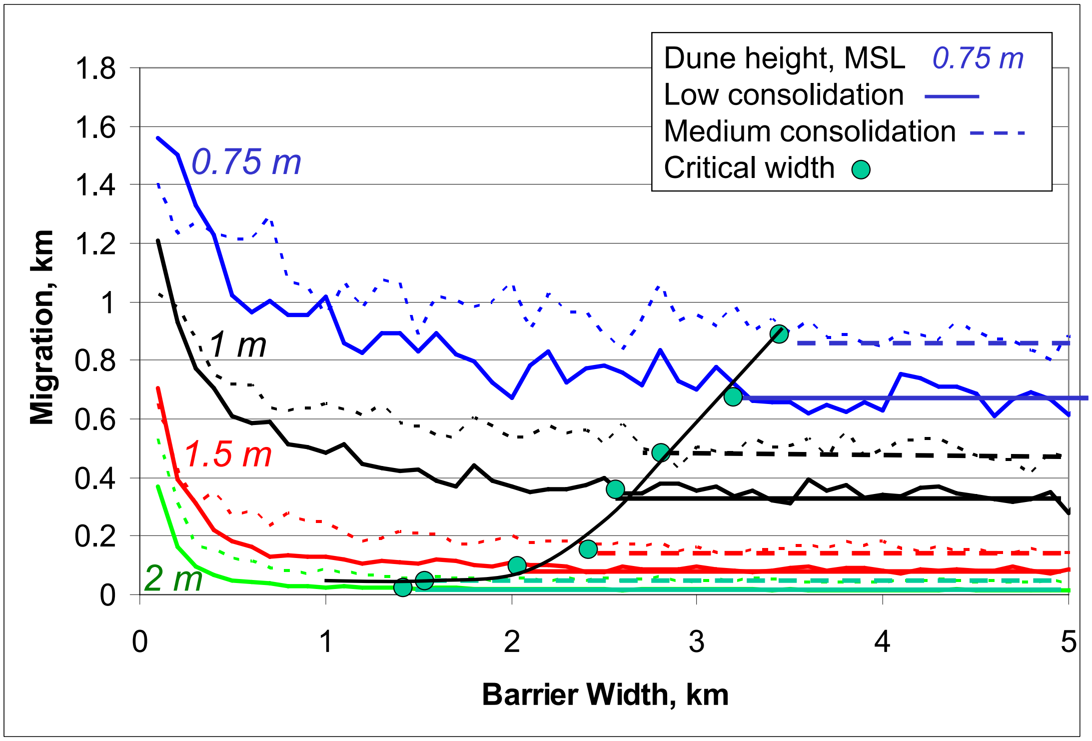


Fig. 6. Influence of barrier island width on migration for storm surge plus runup varied about 1.5-m mean, 100-year simulation

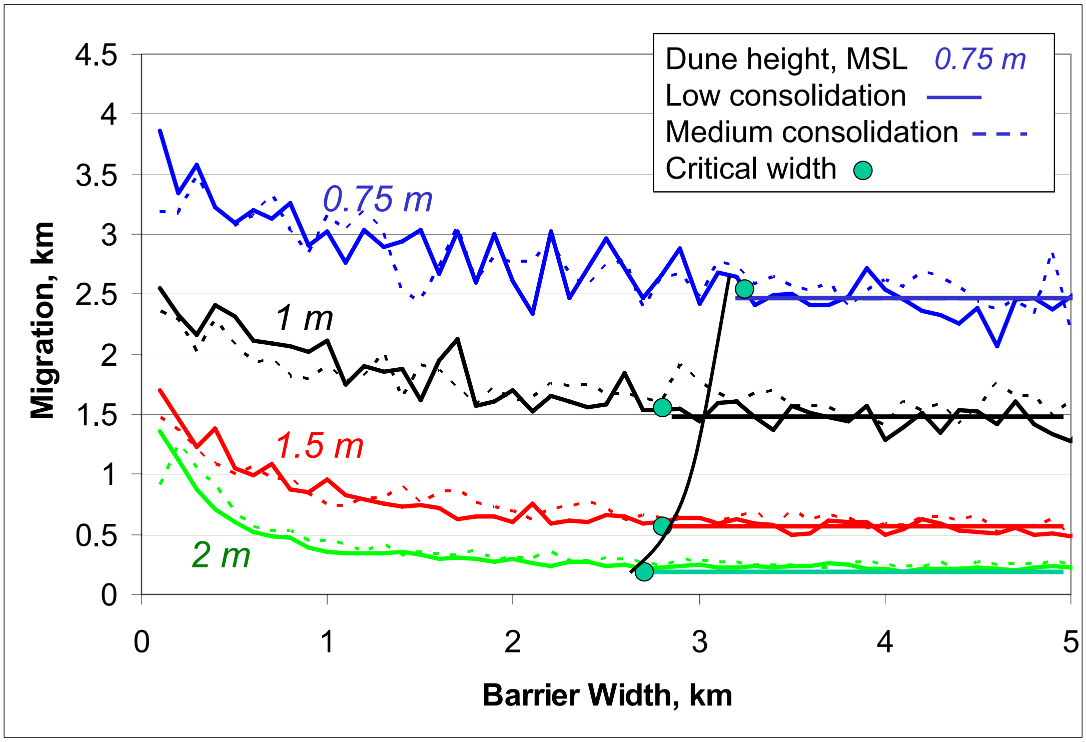


Fig. 7. Influence of barrier island width on migration for storm surge plus runup varied about 2-m mean, 100-year simulation

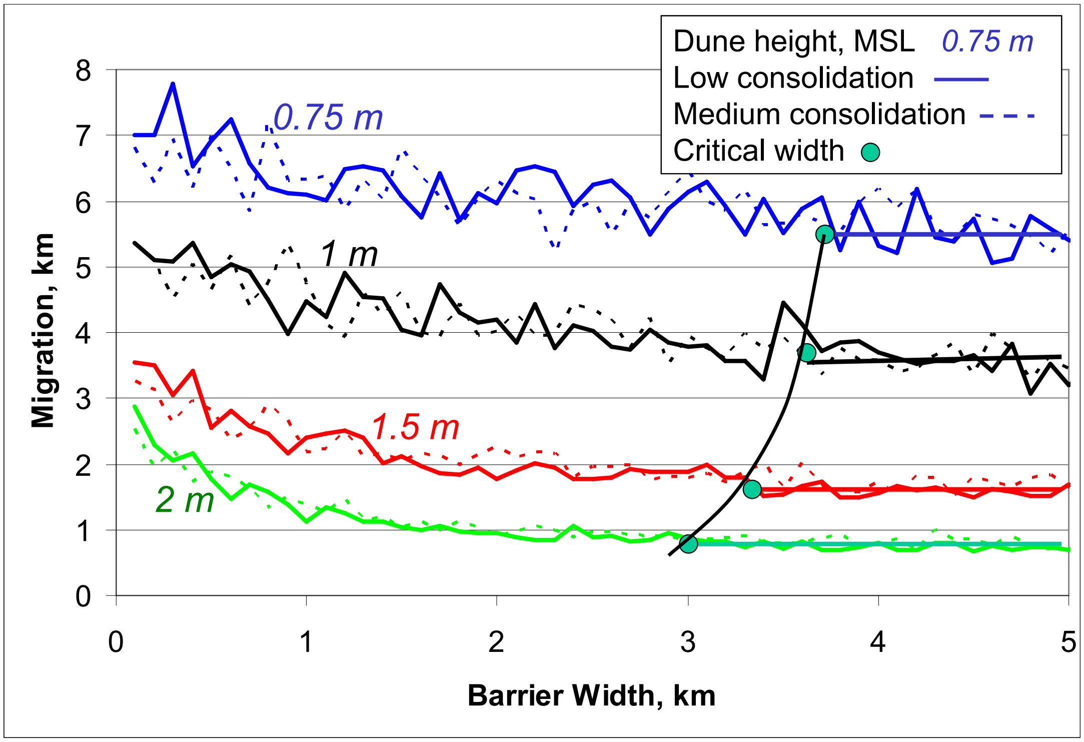


Fig. 8. Influence of barrier island width on migration for storm surge plus runup varied about 2.5-m mean, 100-year simulation

2.5 m) show that both types of substrates have similar migration and critical width values. The explanation for this result is that the barrier loading does not overlay the substrate for sufficient time for consolidation to be significant.

For each simulation with small consolidation, values of critical width and initial dune elevation were correlated with the storm surge plus wave runup. Figure 9 shows that the critical cross-sectional area, A_*, is slightly better correlated (R^2=0.72) to the storm surge plus runup, *S*, as compared to the critical width, W_* (R^2=0.64). These results indicate that, for barrier islands with small rates of consolidation of the underlying substrate, the critical cross-sectional area and width to reduce migration of the barrier island are 1,420 and 880 times the long-term (100-year) average surge plus wave runup, respectively.

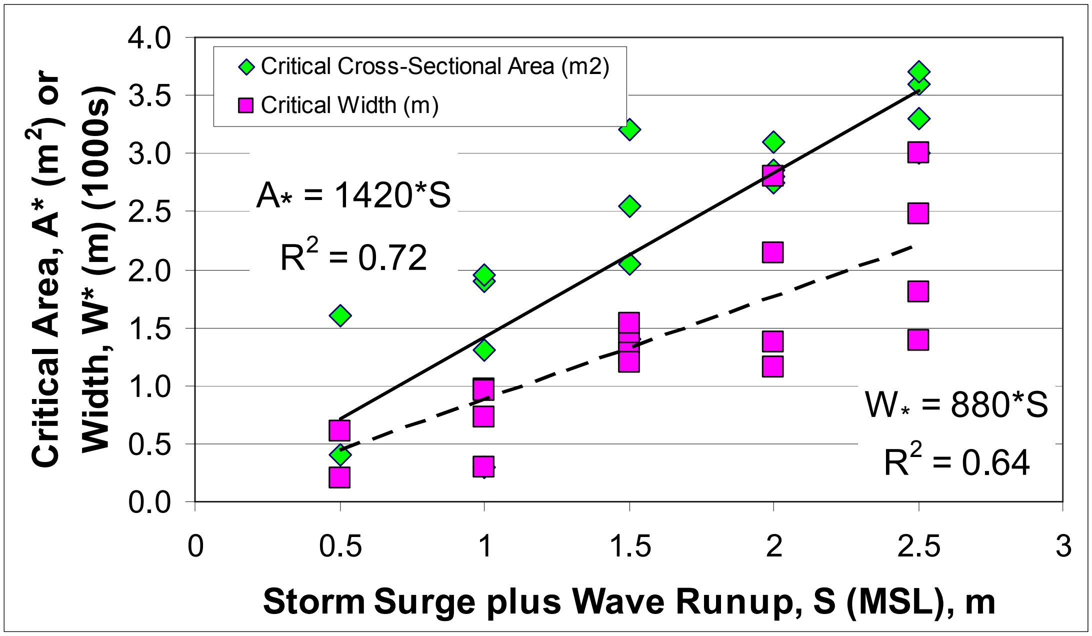


Fig. 9. Correlation between critical width and critical cross-sectional area and storm surge plus wave runup, low consolidation

SUMMARY AND CONCLUDING DISCUSSION

Critical width is the smallest cross-shore dimension that minimizes net loss of sediment from a barrier island and thus reduces migration of the island over periods of decades to centuries. The concept of critical width is important for large-scale barrier island restoration, in which islands are reconstructed to optimum height, width, and length for providing protection for estuaries, bays, marshes and mainland beaches. In this study, a recently Migration, Consolidation, and Overwash (MCO) model was applied to evaluate the dependence of barrier island width on migration rates and longevity of the island. Storm surge and wave forcing were randomly generated about mean values ranging from 0.5 to 2.5 m MSL, and barrier widths ranged from 100 m to 5 km and dune heights from 0.5 to 2 m. Low and medium values of consolidation were applied. Each MCO run simulated 100 years of hydrodynamic forcing and barrier island response.

Results indicated that there is a minimum width, the critical width, at which barrier island migration reaches a relatively constant value, regardless of increasing initial width. However, the barrier island critical cross-sectional area is better correlated to average long-term storm surge plus wave runup as compared to critical width. Preliminary recommendations from this study suggest that the critical cross-sectional area (with initial dune height and width, in square meters) to minimize long-term migration of a barrier island is 1,420 times the average surge plus wave runup (m), relative to a common datum. A slightly weaker correlation was obtained for the critical width, which is recommended as 880 times the average surge plus wave runup (m).

The above findings are based on hypothetical simulations for wave transformation over and sediment transport of non-cohesive sediment. For coastal settings such as in Louisiana, numerical predictions have been shown to overestimate measurements of wave energy during storms as waves are transformed over muddy seabeds (e.g., Sheremet and Stone 2003). Thus, actual storm waves for sandy barrier islands in a muddy environment may be less than predicted here, and this preliminary guidance may be slightly conservative. Also, barrier islands in Louisiana consist both of sand and a partially consolidated core of clay and silt sediments (Stone et al. 1995), which will respond differently to storms than these hypothetical simulations. During erosional wav and water level conditions, the sand surface sand may be eroded from these islands, leaving partially consolidated core clay and silt sediments that are more readily eroded during typical wave and water-level conditions as compared to non-cohesive sediment. Future research will compare these preliminary recommendations to field estimates of critical width.

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