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MODELING SEDIMENT STORAGE AND TRANSFER FOR SIMULATING REGIONAL COASTAL EVOLUTION

Magnus Larson[1], Nicholas C. Kraus[2], and Kenneth J. Connell[2]

The regional coastal evolution model Cascade was enhanced to better describe the transfer and storage of sediment. Focus was on the cross-shore exchange of material from the subaerial to the sub-aqueous portion of the beach and on shoal evolution at coastal inlets. Cross-shore material exchange now includes erosion due to wave impact and overwash, and barrier and dune build-up by wind. Cascade was validated with a data set from Ocean City, Maryland, for the long-term response of a barrier island to these types of cross-shore exchange. The sub-model of the inlet shoals now includes the flood shoal, which previously has not been described by Cascade, and all coupling coefficients specifying the transfer of material between the inlet morphological elements were obtained through analytical expressions. The capability of Cascade to simulate inlet shoal evolution was evaluated with data from the south shore of Long Island, New York. Predictions have yielded robust and reliable results, although further testing is required to determine empirical coefficient values needed in the model.

INTRODUCTION

Background

Regional management of sediment requires predictive technology that can represent multiple sediment-sharing systems interacting and evolving within long-term cumulative change. Larson et al. (2002) and Larson and Kraus (2003) developed a numerical model to simulate sediment transport and coastal evolution at regional scale. The model was named Cascade in recognition that processes at different spatial and temporal scales act simultaneously in what can be viewed as cascading of scales from regional to local. For example, offshore contours of a coastal region might have a curved trend, upon which local projects are emplaced (and interact) that may individually appear to have straight trends in shoreline position.

Cascade was calibrated and validated for the south shore of Long Island, New York, through simulations of the regional shoreline response and ebb shoal complex development with opening of two inlets (Shinnecock Inlet and Moriches Inlet). The coastal area extended from Montauk Point at the eastern boundary to Fire Island Inlet on the western boundary, with different types of sediment sources and sinks acting, such as beach nourishment and cliff erosion. Further model validation was performed for a coastal area extending from Cape Henlopen in Delaware to Chincoteague in Virginia. This coastal stretch, known

[1] Water Resources Engineering, Lund University, Box 118, 221 00 Lund, Sweden.

[2] U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180, U.S.A.

as Delmarva Peninsula, includes two inlets (Indian River Inlet, Delaware, and Ocean City Inlet, Maryland), as well as northern Assateague Island, where overwash is frequent. Model simulations compared favorably with measured shoreline positions and recorded volumes of ebb shoal complexes for the inlets.

In these previous simulations, model enhancements were identified. Several processes in the model involve storage and transfer of sediment, for example, by beach nourishment, cliff erosion, and overwash, and these processes were mainly treated as sources and sinks in the original version of the model, although the strength of the sources and sinks could vary in time and space. For beach nourishment, high-quality input data are available. Concerning overwash and cliff erosion, there is often limited information, whereas data on the factors forcing these processes are typically obtainable. Thus, including mathematical procedures to calculate the subaerial response (e.g., overwash) in Cascade eliminates the need for rarely available input data and also improves prediction of the physical processes. Another enhancement to be described in this paper is refinement of modeling of inlet shoal complexes, improving the description of how sediment is stored and transferred at an inlet by resolving the flood shoal and improving simulated interactions between morphological elements at an inlet (Kraus 2000). Thus, the main objective of this study was to further develop the Cascade model to more realistically simulate several physical processes involving storage and transfer of sediment, with emphasis on beach morphology response and inlet shoal growth and bypassing.

Cascade Model

Cascade simulates longshore sand transport and coastal evolution at the regional and local scale. The model can efficiently calculate for time scales of centuries. A typical coastal setting to which Cascade may be applied is a chain of barrier islands separated by inlets with or without jetties (Larson et al. 2002), where the sediment is transferred around the inlets through the inlet-shoal complex. Until now, several processes have been represented as sediment sources and sinks that vary in time and space, for example, dune and cliff erosion, and wind-blown sand, without connection to the related driving forces. The shoreline of the barrier island chain typically displays a curved trend at the regional scale with local variations in-between the inlets. Cascade can serve to provide high-quality regional boundary conditions to conduct coastal engineering studies such as with the GENESIS shoreline change model (Hanson and Kraus 1989), which allows representation of a wide range of structures and engineering actions.

The present study, which is intended to lead to Cascade Version 2, enhances the model to represent flood shoal development within the inlet sediment storage and transfer routine, and to calculate subaerial beach response due to cross-shore sediment transport. The latter includes dune and barrier island erosion, overwash, and dune build-up by wind. The theoretical basis for

Cascade is first given, after which implementation of Cascade with field data sets is discussed.

THEORETICAL DEVELOPMENTS

Coastal Inlet Modeling

A distinguishing feature of Cascade is representation of morphology change at inlets and bypassing to the adjacent beaches. The Inlet Reservoir Model (Kraus 2000) is employed, but previously only the ebb shoal, bypassing bar, and attachment bar were included, and the flood shoal and main channel neglected. Here, an attempt is made to include the flood shoal in Cascade. Explicit expressions are given for the coupling coefficients (which specify transfer of sediment between the morphological units) based on physical reasoning to reduce the number of parameters to set during a simulation.

Figure 1 is a schematic layout of the morphologic system at an inlet and how the flood shoal interacts with the other elements. The simple case of sediment being transported from the left is considered, where Q_{in} is the incoming sediment transport rate around the jetty (if such a structure is present). Sediment at a rate Q_b is leaving the ebb shoal, feeding into the bypassing and attachment bars (not shown in Figure 1). The transport Q_{in} is split into one portion that goes to the ebb shoal, Q_{e1}, and one portion that goes into the channel, Q_c. Once in the channel, the sediment might be transported to the ebb shoal, Q_{e2}, or to the flood shoal Q_f. The volume of the ebb and flood shoal at any given time is V_e and V_f, respectively, with the corresponding equilibrium values of V_{eq} and V_{fq}.

The mass conservation equation of sediment for the ebb shoal is,

$$\frac{dV_e}{dt} = Q_{e1} + Q_{e2} - Q_b \tag{1}$$

and for the flood shoal,

$$\frac{dV_f}{dt} = Q_f \tag{2}$$

where t is time. Following Kraus (2000), transport out of the ebb shoal is:

$$Q_b = \frac{V_e}{V_{eq}}\left(Q_{e1} + Q_{e2}\right) \tag{3}$$

Transport rates between elements are defined through coupling coefficients,

$$\begin{aligned} &Q_{e1} = \delta Q_{in}; \quad Q_c = (1-\delta)Q_{in} \\ &Q_{e2} = \beta Q_c = \beta(1-\delta)Q_{in}; \quad Q_f = (1-\beta)Q_c = (1-\beta)(1-\delta)Q_{in} \end{aligned} \tag{4}$$

where δ and β are coupling coefficients. Eqs. 1 and 2 may thus be written:

$$\frac{dV_e}{dt} = \delta Q_{in} + \beta(1-\delta)Q_{in} - Q_b \qquad (5)$$

$$\frac{dV_f}{dt} = (1-\beta)(1-\delta)Q_{in} \qquad (6)$$

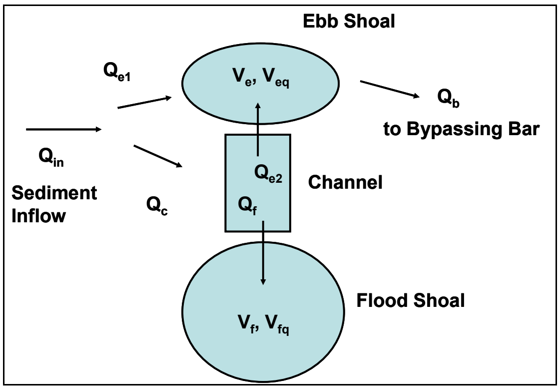

Figure 1. Schematic of the interaction between ebb and flood shoal at an inlet.

To derive predictive expressions for the coupling coefficients, two simplifying hypotheses for the sediment transport are employed: (1) If sediment is transported towards the inlet just after opening with no shoals present, all sediment will fall into the channel (or be trapped by the inlet flow), and the shoals are only fed by the transport in the channel. Thus, δ should be 0 when V_e=V_f=0. On the other hand, if the shoals are at equilibrium, all sediment should bypass the inlet, corresponding to δ=1; and (2) after the sediment has been transported to the channel, it is instantaneously transferred to the shoals and in proportion to how far each shoal is from its equilibrium volume (thus, no representation presently exists for changes in channel volume).

Hypothesis 1 leads to:

$$\delta = \frac{V_e + V_f}{V_{eq} + V_{fq}} \qquad (7)$$

Concerning transport in the channel, the ratio of Q_c that goes to the ebb shoal, β_1, is assumed proportional to the difference between the equilibrium shoal volume and the actual volume according to $\beta_1 \propto \left(V_{eq} - V_e\right)/V_{eq}$. In a similar manner, the ratio that goes to the flood shoal, β_2, is expressed as $\beta_2 \propto \left(V_{fq} - V_f\right)/V_{fq}$. The condition β_1+β_2=1 must be fulfilled, which yields,

$$\beta_1 = \beta = \frac{1 - V_e / V_{eq}}{2 - V_e / V_{eq} - V_f / V_{fq}} \tag{8}$$

where β_2=1-β. Thus, Eqs. 5 and 6 can be solved using Eq. 3, and expressions for the coupling coefficients are then given by Eqs. 7 and 8.

Subaerial Response Modeling

Sediment exchange between the subaerial and sub-aqueous portion of the beach occurs primarily across-shore, driven by wave motion in the swash zone. Water level is a leading factor because it defines the starting point of the swash zone and to what elevation the uprushing waves may reach. Depending on the morphology of the subaerial beach, different types of response to incident waves are expected, implying supply or depletion of sediment from the sub-aqueous beach with associated advance or recession of the shoreline, respectively. Erosion of dunes or soft cliffs supplies the beach with sediment. During severe storms, the dunes might overwash, causing transport of sediment onshore over the dune crest and deposition on the landward side of the dune crest (Donnelly et al. 2006). Thus, a physically based approach to model the sediment exchange between the subaerial and sub-aqueous beach requires description of dunes subjected to wave impact and overwash. Barrier islands sometimes have dunes, but often they are gradually sloping features both landward and seaward with a discernable crest. Because they are often low-crested, overwash plays an important role in shaping evolution of barrier islands.

Figure 2 is a schematized cross section of a barrier island defining variables employed in Cascade of cross-shore response to wave impact and overwash (a dune is also described in the same manner using a triangular shape, although the side slopes are greater and volume considerably smaller). The transport rate induced by the impacting waves q_I is estimated from (Larson et al. 2004),

$$q_I = 4C_s \frac{(R + \Delta h - z_o)^2}{T} \tag{9}$$

where R is the runup height estimated from $a\sqrt{H_o L_o}$, in which H_o is the deepwater RMS wave height, L_o the deepwater wavelength, and a a coefficient (about 0.15, which represents an average foreshore slope), Δh the surge level (including tide), z_o the elevation of the beach where the wave impact starts (e.g., dune foot elevation), T is wave period, and C_s is an empirical coefficient. The transport rate q_I corresponds to the volume ΔV_o eroded from the seaward side of the beach over time Δt. Also, the portion of q_I transported offshore is denoted q_o and the portion transported over the crest (overwash) q_B, so that q_I=q_o+q_B. If $R + \Delta h < z_o$, then waves will not reach high enough to erode the beach and $q_I = 0$. The ratio q_B/q_o must be specified to determine the sediment volume supplied to the offshore, acting as a source of material for the coastal area. This ratio is a function of several parameters (e.g., excess runup height $\Delta R = R + \Delta h - s$, where s is the dune height), although it may be taken as a constant as a first approximation in the type of regional model discussed here.

Assuming q_B/q_o constant, evolution of a triangular barrier island or dune can be determined analytically. Larson et al. (2006) developed the governing equations for the three main variables specifying this evolution, namely the height to the crest, s, and locations of the beach or dune front, x_o, and back, x_B. The analytical solutions for the response is given by,

$$s = \frac{2V_{Do}}{l_{Do}} \sqrt{1 - \frac{q_o t}{V_{Do}}} \tag{10}$$

$$x_o = x_{oo} + l_{Do} \left(1 + \frac{q_B}{q_o} \right) \left(1 - \sqrt{1 - \frac{q_o t}{V_{Do}}} \right) \tag{11}$$

$$x_B = x_{Bo} + l_{Do} \frac{q_B}{q_o} \left(1 - \sqrt{1 - \frac{q_o t}{V_{Do}}} \right) \tag{12}$$

where V_D is the barrier (dune) volume ($V_D = (x_B - x_o)s/2$), l the barrier (dune) width ($l_D = x_B - x_o$), and subscript o denotes the value at t=0. The barrier (dune) volume decrease linearly with time because of the offshore losses according to $V_D = V_{Do} - q_o t$.

In long-term modeling of coastal evolution, wind-blown sand transport should be taken into account, especially for simulating barrier-island or dune build-up and recovery. A simplified model was developed and included in Cascade based on the sediment volume conservation for the barrier (dune) and the transport equation proposed by Bagnold (1954) modified to include the slope. After erosional storms, during which the barrier loses sand and its height is reduced, sand is supplied from the landward side, and the barrier is built up towards a height that corresponds to equilibrium conditions where s=s_e. The sand volume conservation equation is given by (see Fig. 3),

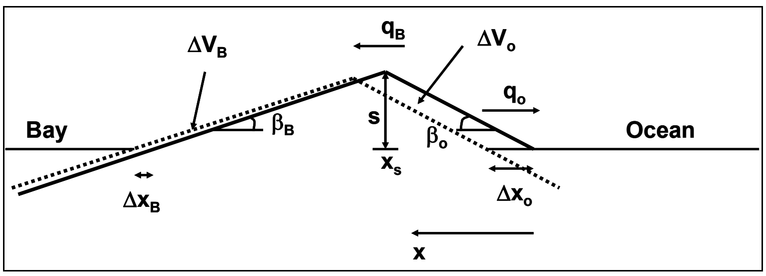

Figure 2. Schematic of a beach cross section subject to wave impact and overwash.

$$\frac{ds}{dt} = \frac{1}{K_\beta}\frac{q_w}{s} \qquad (13)$$

where $K_\beta = 1/\tan\beta_o + 1/\tan\beta_B$ and the transport by wind (q_w) is calculated from,

$$q_w = K_w \frac{u_*^3}{g}\left(1 - \frac{s}{s_e}\right) = q_{wo}\left(1 - \frac{s}{s_e}\right) \qquad (14)$$

in which u_* is the wind shear velocity, and K_w an empirical coefficient that quantifies the influence of sediment properties on the transport rate. The wind shear velocity may be estimated from $u_* = aU - b$ (Hotta 1984), where U is the wind speed at a specific elevation, and a and b are empirical coefficients (for example, Kawata (1950) proposed a=0.053 and b=0, with U taken at 10 m). Eq. 14 was proposed based on the transport Bagnold formula, adding a slope term that will limit the transport as the barrier (dune) is built towards its equilibrium height. For simple input conditions, Eqs. 13 and 14 may be solved analytically to yield the build-up of a dune following an erosional event,

$$s_o - s + s_e \ln\left(\frac{s_e - s_o}{s_e - s}\right) = \frac{q_{wo}}{s_e}\frac{t}{K_\beta} \qquad (15)$$

where s_o is the barrier (dune) height at t=0, and q_{wo} corresponds to the sand transport by wind over a flat surface (s=0).

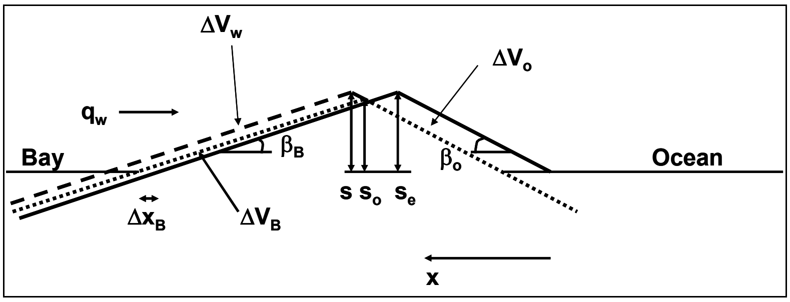

Figure 3. Schematic of a beach cross section subject to wind-blown sand transport.

RESULTS

Inlet Shoal Evolution

The south shore of Long Island, New York, is a suitable location for validating the enhanced capability of Cascade to simulate sediment transfer and storage at coastal inlets. Previous studies (e.g., Kana 1995; Rosati et al. 1999) provide substantial information for validation, and the stretch includes many features and processes characterizing coastal evolution at regional scale. The study area extends from Fire Island Inlet to Montauk Point (FIMP) because most available information originated from this coastal stretch. The area includes two inlets (besides Fire Island Inlet at the western boundary), namely Shinnecock Inlet (SI) and Moriches Inlet (MI). The cross-sectional areas of the inlets have varied substantially (Larson et al. 2002), altering the size of the ebb shoal complexes and sediment removed from the nearshore transport system, providing an opportunity to model a complex morphologic system.

Larson et al. (2002) performed two types of simulations with Cascade for the FIMP area: (1) determining the overall annual net longshore transport pattern along the coast (based on shoreline positions and waves from 1983 to 1995), and (2) simulating coastal evolution in connection with opening of MI and SI (simulation period 1931-1983). These simulations were redone here with the new inlet sub-model that includes the flood shoals at SI and MI and for a slightly longer time period. Equilibrium values for the ebb shoal complexes of the inlets were calculated from Walton and Adams (1976), with some adjustment for SI based on the results of Militello and Kraus (2001). Only minor changes occurred in net longshore transport rates and shoreline response after introducing the new inlet sub-model, so these results are not shown here. Instead, focus is on evolution of the morphological elements in the inlet sub-model. The basic input for the Cascade simulations was the same as discussed in Larson et al. (2002) with the time step Δt=24 hr and space step Δx=500 m.

Figure 4 shows the measured and simulated ebb shoal complex volumes (sum of ebb shoal and bypassing bars) for SI and MI. Although the measurement points are sparse, the model quantitatively reproduces the evolution of the shoals rather well. However, at the end of the time period the measurements at SI indicated a significant increase in shoal volume that the model did not capture, either because of an underestimate of the equilibrium volume or of the time response. Equilibrium volumes for the ebb shoal complex at SI and MI were estimated to about 11×10^6 m^3 and 6×10^6 m^3, respectively. Compared to the values employed by Larson et al. (2002), the volume at SI was increased by close to 40% to better comply with the detailed work of Militello and Kraus (2001).

The equilibrium volume of the flood shoal at SI was set to about 4×10^6 m^3 (Militello and Kraus 2001), and MI was assigned the same equilibrium volume. This value agrees well with the predictive formula presented by Carr (1999), if both the near- and far-field volume of the shoal is included. Figure 5 compares the measured and calculated flood shoal volumes for SI and MI. The trend and magnitude of shoal evolution is well predicted, although some points deviate from the calculated values (initially, values are underestimated for MI and overestimated for SI). It is difficult to estimate the size of a flood shoal, and often they are dredged, contaminating measurements (Vogel and Kana 1984).

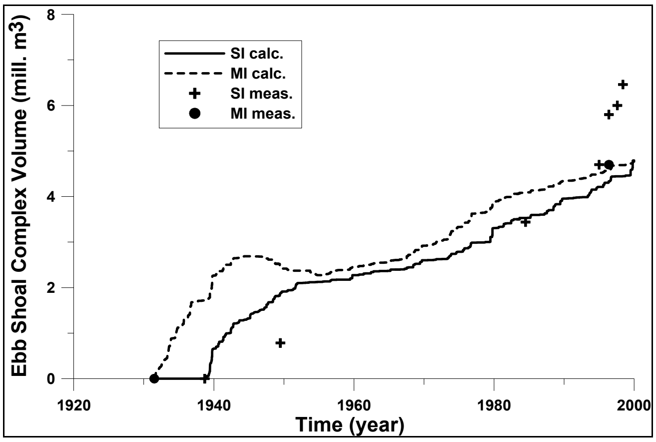

Figure 4. Measured and simulated ebb shoal complex volumes for Shinnecock Inlet and Moriches Inlet (data from Morang 1999).

Barrier Island Erosion and Overwash

The sub-model developed to compute the subaerial response to storms was applied to simulate the coastal evolution for the northern part of Assateague Island prior to the opening of Ocean City Inlet. At that time, it is surmised that the coast primarily evolved in response to large-scale gradients in the longshore transport associated with the shoreline orientation and cross-shore exchange of material during storms. Wave impact and overwash were taken into account as well as build-up of the island by wind-blown sand between storm events. It was assumed that the supply of sediment by wind to the barrier was derived from the bay side, and the rate was obtained using a representative wind speed, implying that q_{wo} was constant.

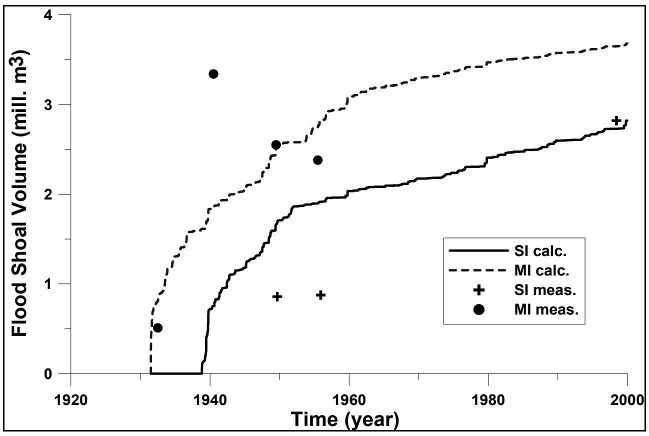

Figure 5. Measured and calculated flood shoal volumes for Shinnecock Inlet and Moriches Inlet (data from Morang 1999 and Vogel and Kana 1984).

Larson and Kraus (2003) exercised Cascade to simulate evolution of the Delmarva Peninsula, covering about 100 km of barrier islands influenced by human alterations and development. Indian River Inlet (IRI), Delaware, and Ocean City Inlet (OCI), Maryland, have trapped significant sediment volumes in their inlet shoals and previous modeling focused on the shoreline response to the opening and further development of OCI and IRI. The overwash that frequently occurs along the northern part of Assateague Island was represented through a sink term varying in space (Δx=500 m). Refining this part of the modeling by using the newly developed routines for the subaerial response was an objective of the present Cascade application.

The basic input to the model encompassed shorelines measured from 1850 and 1933, together with a detailed data set on wave and water level hydrodynamics derived by Grosskopf (2005). Hourly values on wave height, wave period, wave direction, storm surge level, and tidal elevation were available for the period 1930 to 2000, and this data set was used as representative forcing for the simulations during the period 1850-1933. The time step was 24 hr, and the wave information was averaged over this period. However, because the wave impact and overwash calculations require a finer resolution of the wave and water level conditions to yield a good description of the governing processes during a storm, the average forcing parameter ($P = \left(R + \Delta h - z_o\right)^2 / T$) was computed for each 24-hr period and input to the model. The duration of overwash was also determined and supplied as input to the model. In most applications of Cascade, it is not expected that such detailed hydrodynamic input will be available, but instead a limited number of storms may be included that are the main cause of cross-shore material exchange.

Figure 6 plots measured and calculated shoreline change between 1850 and 1933. Only the central portion of the simulation area exhibiting marked overwash is displayed (the area with significant overwash was determined based on barrier crest elevation). Good calibration result was obtained using C_s in Eq. 9 as the main fitting parameter. The optimum C_s-value (about 1×10^{-4}) was in the range of values presented by Larson et al. (2004) for field data. However, a number of other parameters had to be set as well including q_{wo}, s_e, and the ratio between the overwash transport and the transport offshore at equilibrium conditions. The ratio $\lambda = q_B / q_o$ was assumed to be a function of the barrier crest height according to $\lambda = \lambda_e (s_e / s)$, where the index e corresponds to equilibrium. As previously discussed, q_{wo} was computed based on a representative wind speed, and s_e was set to about 1.8 m for the coastal stretch under consideration (s_e is the height above z_o, which was assumed to be 1 m).

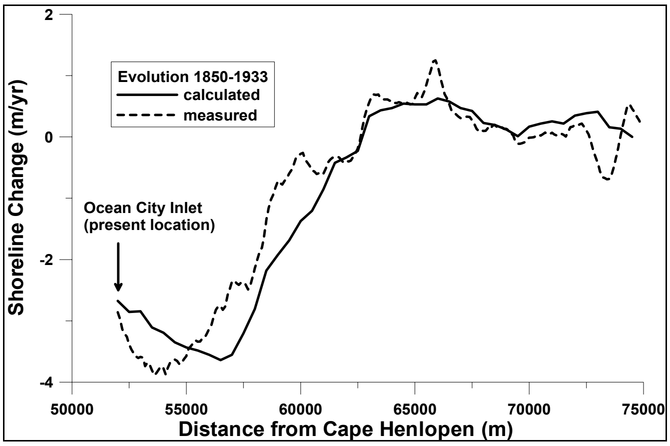

Figure 6. Measured and calculated shoreline change for the northern part of Assateague Island.

Figure 7 shows the calculated time variation of the barrier height during the simulation period. A complex pattern arises with periods of growth when the barrier is recovering by wind-blown sand and periods when wave impact and overwash cause erosion. Because of the limited crest height, transport by wave impact and overwash is common and the barrier does not reach its equilibrium height during the simulation period. For the hydrodynamic input time series (1930-2000), more than 24,000 erosional events were calculated to occur and, out of those, 2,600 were overwash events (for the geometric cross section outlined above).

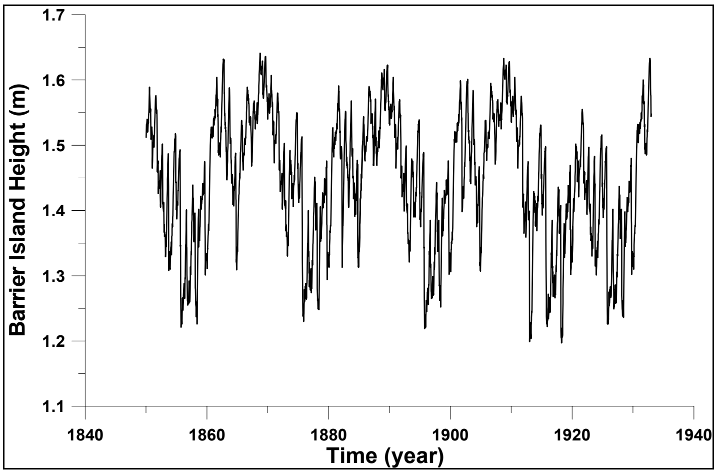

Figure 7. Calculated variation in barrier island height (referenced to maximum foreshore elevation) for the northern part of Assateague Island.

CONCLUDING DISCUSSION

The regional coastal evolution model Cascade was enhanced to improve the description of transfer and storage of sediment in coastal areas, with emphasis on coastal inlets and cross-shore processes in the subaerial part of the beach. In Cascade, the morphological elements of the coastal inlet is modeled using the Inlet Reservoir Model concept (Kraus 2000), and the enhancements included the flood shoal and its interaction with the surrounding elements. Analytical expressions were developed for the coupling coefficients describing the exchange of sediment between the elements. These expressions reduce the need for specifying coefficient values, although additional testing is required before the expressions can be used with confidence in practical applications.

Cross-shore exchange of material between the subaerial and sub-aqueous beach parts was previously described through sources and sinks in Cascade. Version 2 now includes formulas for calculating dune and beach erosion, overwash, and beach build-up by wind-blown sand. Although comparisons between model simulations and measurements indicated good agreement, these formulas contain coefficients for which the values require further validation to confirm general applicability.

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