

LONG-TERM COASTAL EVOLUTION MODELLING OF LONGSHORE BARS

Bárbara Marinho¹, Carlos Coelho¹ Magnus Larson² and Hans Hanson²

An extended version of a numerical model introduced by Larson *et al.* (2013) to simulate long-term cross shore material exchange for the subaqueous portion of the profile has been developed. Efforts have focused on improving the model to better account for beach systems consisting of two bars (inner and outer bar), as well as simulating the feeder response over time of nearshore dredged material bars, intended to function as beach nourishment. The theory for the evolution of a single-bar to a two-bar system was modeled, considering an inner and an outer bar, where the outer bar is of primary interest with the purpose of predicting the behavior of placed dredged material. The cross-shore sediment transport rate is based on the evolution equation for the bar system response to the hydrodynamic forcing by reference to its equilibrium condition, where the change in the bar volume is based on a set of wave criteria, describing the onset of a new breaking zone when the outer bar forms. Empirical formulas are employed for the bar equilibrium volume and for coefficients determining the bar response rate. In this study, a description of the extended model and the results from the model component validation at two different sites in USA (Duck, North Carolina, and Cocoa Beach, Florida) are presented. Duck measurements have detected that some bars form in the nearshore and move all the way offshore (eventually deflating by non-breaking waves). At the same time, it was equally observed that a lot of inner bars formed in shallow water do not move offshore but remain as inner bars all the time. According to this, the developed model considers that the inner bar will not become the outer bar, but material previously dedicated to the inner bar will be available for the outer bar. Overall, the present study demonstrates the potential for using rather simple models, based on the definition of an equilibrium state that is compared to the current state and the magnitude of offshore wave forcing to drive the changes in the profile. The methodology employed here allowed to quantitatively reproduce the main trends in the subaqueous beach profile response in a long-term perspective as a function of the bar volumes disequilibrium, the magnitude of the incident wave height and the dimensionless fall velocity to move the sand with a time varying forcing.

Keywords: subaqueous response, longshore bars, sediment transport, artificial nearshore placement, multi-bar system, shoreline evolution

1. INTRODUCTION

Previous studies show that many wave dominated sandy coastal systems across the world are characterized by the presence of one or more subtidal longshore bars (Larson and Kraus, 1992; Ruessink and Kroon, 1994; Różyński and Lin, 2015; Ruggiero *et al.*, 2016; Bouvier *et al.*, 2017; Walstra and Ruessink, 2017; Aleman *et al.*, 2017; Stewart *et al.*, 2017). On those systems, cross-shore (CS) numerical models are required for simulating the bar-berm material exchange to reproduce: 1) the seasonal behavior of the beach profile; 2) the effects of the sediment release during storms from the dune and the beach to the subaqueous portion of the profile; and 3) the recovery process of the berm during periods of low-energy, when bars tend to lose volume and migrate onshore (eventually welding on to the shore).

According to Larson *et al.* (2016), a proper balance between physical descriptions of theoretical considerations and empirical information, based on data and observations, is the key for simulations addressing large areas and long time periods that will yield useful simulations results. Larson *et al.* (2013) developed a semi-empirical model to simulate the long-term response of longshore bars to incident wave conditions, as well as the material exchange between the berm and bar region. In this model, the variation in the bar volume is taken to be proportional to the deviation from its equilibrium condition and coupled to the berm response (*i.e.*, bar growth implies a decrease in the berm volume and vice-versa). As a first attempt towards modelling regional cross-shore evolution, this model, known as the CS-model, was developed to fill the gap between a sediment budget approach and a detailed profile evolution model. The dynamics of selected CS processes was modeled based on physically based expressions, whereas the longshore transport is included in a simplified way through a continuous sink or source applied to the shoreline position (Larson *et al.*, 2013; Palalane *et al.*, 2016).

This study presents a numerical approach developed to predict the subaqueous cross-shore beach profile response for applications in coastal evolution models, describing processes at the long-term scale. Following the modelling approach proposed by Larson *et al.* (2013), efforts are made to expand the theory of the evolution of one single bar to a multi-bar system, where the volume of the individual bars and their response are described, but without regard to the details of the profile/bar shape or how the material may be deposited in or removed from the surf zone. The actual sediment transport paths resulting in the bar evolution are complex and contributions from both shoreward and seaward sides are expected. As a first step, a two-bar model is developed and validated with field data from Duck, North Carolina, where two bars (inner and outer) frequently form. The prediction of the outer bar response is seen of particular interest

¹ RISCO & Department of Civil Engineering, University of Aveiro, Campus Universitário Santiago, 3810-193, Aveiro, Portugal

² Division of Water Resources Engineering, Faculty of Engineering LTH, Lund University, SE-221 00, Lund, Sweden

in this study, because it is located in water depths where, for instance, typically available equipment can access for nearshore placement of dredged material, providing a method for estimating the response of offshore mounds (artificial bars).

In recognition of the potential attributes of placing material nearshore for serving as a reservoir of sand in promoting beach growth and the dissipation of wave energy, several reports about nearshore disposals have been published (Andrassy, 1991; Bodge, 1994; Larson *et al.*, 1999; Barnard *et al.*, 2006; Larson and Hanson, 2015; Smith *et al.*, 2017; and Marinho *et al.*, 2017a; 2018). Although material placed in the nearshore becomes a part of the littoral system, benefits to the beach are still difficult to quantify. The present model was also employed to numerically solve hypothetical bar equations representing offshore mounds as they migrate towards the shore and become a part of the beach face. The model was applied to simulate nearshore sand placements as a hypothetical natural bar at Cocoa Beach, Florida, where no natural subtidal bars were surveyed.

This work presents a brief description of the model first proposed by Larson *et al.* (2013) and its developments for the two-bar model. Selected cases studies are addressed in section 3. Section 4 presents a discussion of the numerical results and final conclusions are drawn in section 5.

2. MODEL DESCRIPTION

Several theories have been advanced to explain the formation of longshore bars (Ruessink and Terwindt, 2000; Almar *et al.*, 2010; Price and Ruessink, 2011; Splinter *et al.*, 2018). Correlations between bar and wave properties were discussed by Larson and Kraus (1992). According to Ruessink and Kroon (1994), bar parameters (such as volume, height, and mean water depth over the bar crest) can be well-linked to the bar stage. Although important insights into the governing processes of interaction between the seabed and the wave forcing have been achieved by several authors regarding the behavior of longshore bars, the actual sediment transport mechanisms determining the bar evolution are still too poorly understood by researchers to be parameterized in detail. Here, bar generation by depth-limited breaking waves is considered. The semi empirical model developed for one-bar systems have been successfully applied to several sites, also in combination with a dune erosion model (Larson *et al.*, 2013; 2016), suggesting that this equilibrium approach may be also suitable to examine equilibrium behavior of other sand-bar systems. In this section, a brief description of the one-bar theory, as well as the new theoretical developments for two-bar system, is presented. Finally, an adaptation to simulate nearshore mounds resulting from artificial nourishments is described.

2.1. One-bar theory

A comprehensive description about the theoretical development of CS-model is given in Larson *et al.* (2013, 2016) and Marinho *et al.* (2017b). The model assumes that the exchange of material between the bar and the berm takes place under sediment volume conservation, which means that no material is lost offshore. Thus, a growth in bar volume causes the corresponding decrease in berm volume (or shoreline retreat), and decay in bar volume causes an increase in berm volume (or shoreline advance). Figure 1 illustrates the cross-shore exchange of material between the subaqueous (bar) and subaerial (berm) portion of the profile. The volume eroded from the berm is stored in one offshore bar (or, its representative morphological volume) that will reach a certain equilibrium volume (V_{BE}). If the bar volume (V_B) at any given time is smaller than V_{BE} , then the bar volume will grow, whereas the opposite ($V_{BE} < V_B$) implies a decay in the bar volume (Larson *et al.*, 2013). The change in bar volume is taken to be proportional to the deviation from its equilibrium value (Eq. 1), depending on the sediment grain size (or fall speed, w), wave height (H_0) and wave period (T), implicitly considered in the λ coefficient:

$$\frac{dV_B}{dt} = \lambda(V_{BE} - V_B) \quad (1)$$

A representative beach slope is also implicitly contained in the fall speed (or grain size) because the equilibrium beach profile depends on this quantity (Dean, 1987). Observations of bar response to storms (*cf.*, Larson *et al.*, 2016) indicate that bars would exhibit a relatively larger growth in the field during energetic wave conditions, whereas the recovery process would be slower (during periods of calmer waves). An additional factor is used when onshore or offshore sediment transport occurs ($V_{BE} < V_B$ and $V_{BE} > V_B$, respectively), as a way to better reproduce the observed bar behavior in the field, defined by a relatively slower response during onshore sediment-transport driving mechanisms (Larson *et al.*, 2016). In order to

apply Eq. 1, the equilibrium bar volume (V_{BE}) also needs to be determined. According to Larson and Kraus (1989), it is desirable to use non-dimensional quantities to obtain general and physically-based relationships relating morphologic features to wave and sand parameters. A larger wave height implies a larger bar volume and a greater fall speed (or larger grain size) implies a smaller bar volume (Larson and Kraus, 1989). For more information about the correlation and regression analyses detailing the degree of dependencies between variables consult Larson and Kraus (1989).

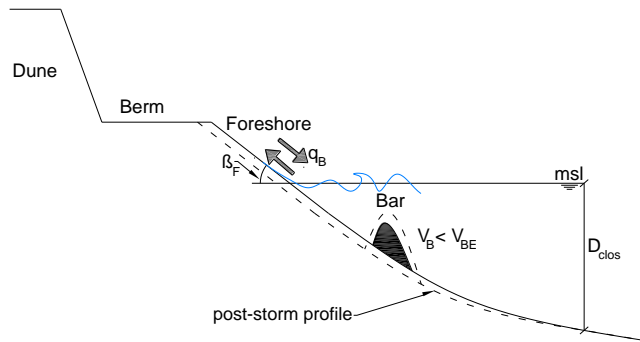


Figure 1. One-bar theory. The variables q_B , β_F , and D_{clos} denote the subaqueous transport rate between the bar and berm, foreshore slope, and depth-of-closure, respectively.

Considering realistic wave input, Eq.1 has to be solved numerically. For each time step Δt , the wave and sediment properties will be constant (V_{BE} and λ are constant values), and so, the following analytical solution is employed,

$$V_B(t) = V_{BE} + (V_{B0} - V_{BE})e^{-\lambda t} \quad (2)$$

where V_{B0} is the bar volume at $t=0$. The bar volume changes equation (Eq.1) is applied during the growth and decay process of the bar, so, if $V_{BE} > V_{B0}$ the bar will grow (with sediment from the berm) and if $V_{BE} < V_{B0}$ the bar volume will decay (transferring sediment to the berm). Thus, the change in bar volume (ΔV_B) during Δt is given by,

$$\Delta V_{B,i} = (V_{BE,i} - V_{B,i})(1 - e^{-\lambda \Delta t}) \quad (3)$$

where subscript i denotes a certain time step. The new volume at time step $i+1$ is obtained from $V_{B,i+1} = V_{B,i} + \Delta V_{B,i}$. With the knowledge of the initial conditions (V_{B0}) and the input wave conditions, Eq. 3 can be used to calculate the evolution of the bar volume, both during bar growth and decay.

2.2. Two-bar theory

Aiming to improve the one-bar model performance, a system consisting of two bars was studied, namely an inner and an outer bar. A simple wave criterion is proposed for predicting the onshore and offshore movement of the inner and outer bar with reference to their equilibrium condition. Overall, when waves are small, only an inner bar forms. However, during high-energy wave conditions (*e.g.*, storms), large waves will break offshore and form an outer bar as well. These large waves will reform in the trough and eventually shoal and break again closer to the shore, resulting in a second but smaller inner bar, in the same manner in which the most seaward main breakpoint bar was formed. Dissipation of energy decreases in the reformed waves, implying a corresponding decrease in the transport rate. The described mechanism is valid for both plunging and spilling breakers (both producing a trough in the profile shoreward of the break point), although the time scale of bar development will be longer under spilling breakers (Sunamura and Maruyama, 1987).

A simple approach is desirable to define how many bars will form and a criteria based on the wave characteristics is employed in the developed model. If the incoming wave height is greater than a certain

wave height (hereafter referred as the critical wave height, H_c) then two bars will develop, otherwise, when $H_0 < H_c$, the system develop towards only one bar. The bar volume is taken as indicator of the transport direction, where a growth in the outer bar volume is associated with a net seaward movement of sediments and a decay in the outer bar volume is caused by onshore sediment transport (inducing degeneration of the outer bar). This assumption allows including eventual inter-annual cyclic bar behavior *per se*, since the bars in the two-bar model responds to the wave forcing at the input time scale. The build-up of the outer bar is taken as an intermittent process confined to the occurrence of high-energy periods. It was earlier demonstrated by Larson *et al.* (2013, 2016) that the empirical equation for the equilibrium bar volume could be employed to calculate the total sediment volume stored in the inner and outer bar. Thus, this equation will be used for a multi-bar system to obtain the sum of the inner and outer bar volumes at equilibrium state. The equilibrium bar volume is then given by,

$$\frac{V_{BE}^{TOT}}{L_0^2} = \frac{V_{BE}^I}{L_0^2} + \frac{V_{BE}^O}{L_0^2} \quad (4)$$

where the superscript TOT, I and O denote total, inner, and outer equilibrium bar volume, respectively. The question arises on how to partition V_{BE}^{TOT} between V_{BE}^I and V_{BE}^O . Defining the ratio $\delta = V_{BE}^O/V_{BE}^I$, then:

$$V_{BE}^I = \frac{1}{1+\delta} V_{BE}^{TOT} \quad (5)$$

$$V_{BE}^O = \frac{\delta}{1+\delta} V_{BE}^{TOT} \quad (6)$$

These equations yield how much of the total bar volume belongs to the inner and outer bar, respectively. If δ can be predicted, by using Eqs. 5 and 6, then, V_{BE}^I and V_{BE}^O can be determined. At a first order approach, δ should depend on the relationship between H_0 and H_c . A larger wave height with respect to the critical wave height (H_c) will produce a relatively larger offshore equilibrium bar volume. Based on this observation, the following empirical relationship is proposed:

$$\text{If } H_0 < H_c, \text{ then} \quad \delta = 0 \quad (7)$$

$$\text{Otherwise, for } H_0 > H_c \quad \delta = \delta_0 \left(\frac{H_0}{H_c} - 1 \right) \quad (8)$$

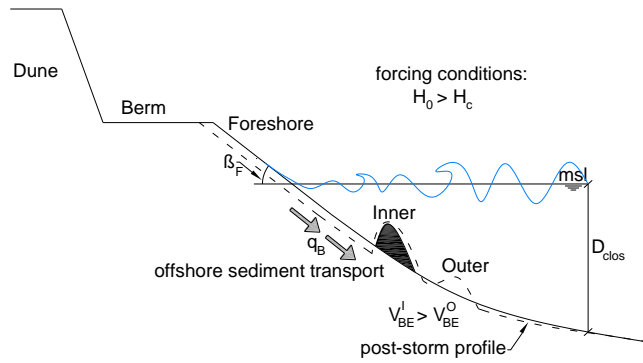
where δ_0 is an empirical coefficient to be calibrated against data (=1 as a first estimate). The subaqueous processes that build the two-bar system are represented in Figure 2. If $H_0 < H_c$, then the outer bar will not form or will tend to disappear ($V_{BE}^O = 0$), whereas $H_0 \gg H_c$ means that the outer bar will grow relatively larger in relation to the inner bar ($V_{BE}^O \gg V_{BE}^I$).

For each wave condition (at a specific time step), Eqs.5 and 6 together with Eqs.7 and 8 are solved numerically. The change in the inner and outer bar volume is computed in the same manner as for the one-bar system using the analytical solution described in Eq.3,

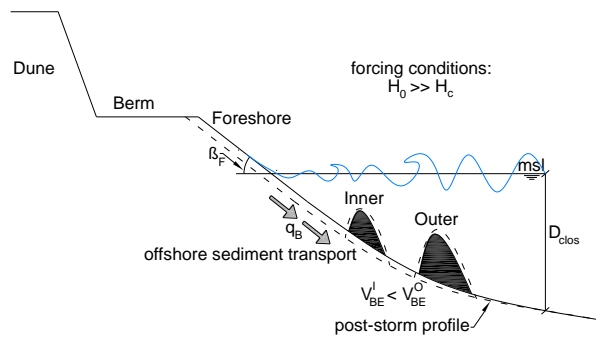
$$\Delta V_{B,i}^I = (V_{BE,i}^I - V_{B,i}^I) (1 - e^{-\lambda_i^I \Delta t}) \quad (9)$$

$$\Delta V_{B,i}^O = (V_{BE,i}^O - V_{B,i}^O) (1 - e^{-\lambda_i^O \Delta t}) \quad (10)$$

The new volume at time step $i+1$ is obtained from $V_{B,i+1}^I = V_{B,i}^I + \Delta V_{B,i}^I$ (for the inner bar) and $V_{B,i+1}^O = V_{B,i}^O + \Delta V_{B,i}^O$ (for the outer bar). The λ coefficient, in Eqs.9 and 10, will depend on whether the inner or outer bar grows or decays. However, as the inner and outer bars are located at different water depths, different behavior should be expected. According to Larson and Kraus (1992), once the outer bar is formed, it will only be exposed to wave breaking and large sand transport during severe storms, with the transport induced by non-breaking waves producing slower changes in the bar shape. As an exchange of material continually takes place within the surf zone, depending on changes in the nearshore wave conditions, an exchange between the inner and the outer bar volumes can be included in the calculations.



a) For $0 < \delta < 1$, the outer bar starts to form and grow.



b) For $\delta > 1$, the outer bar grows relatively larger than the inner bar.

Figure 2. Evolution model for a two-bar system.

The sediment transport volume from the berm to the bars or from the bars to the berm is given by the sum of the total variation for both bars (inner and outer). For cases where exchange of material between the bars is admitted, the outer bar volume variation is computed first (ΔV_B^O) and then the following conditions are checked: 1) if $V_{BE,i}^O < V_{B,i}^O$ (or $\Delta V_B^O < 0$) there is onshore sediment transport, implying that the outer bar is releasing sediment towards the beach. In this case, the sediment will be transported to the inner bar. So, before computing the inner bar volume change, based on its equilibrium value, the inner bar volume must be updated with the volume that comes from the outer, ΔV_B^O ; 2) if $V_{BE,i}^O > V_{B,i}^O$, there is offshore sediment transport and the outer bar is growing. In this case, before computing the inner bar change it is determined whether the inner bar volume has enough sediment to provide to the outer bar, *i.e.*, if $V_{B,i}^I > \Delta V_B^O$. If this condition is not met, the inner bar volume will disappear totally ($V_{B,i}^I = 0$) and the remaining sediment needed to fill the outer bar will be transported from the berm; and 3) if $V_{BE,i}^O > V_{B,i}^O$ and $V_{B,i}^I > \Delta V_B^O$ then the inner bar will provide the sediment needed to the outer bar. In this situation, the same procedure as in the case where there is onshore sediment transport is adopted, computing the sediment transport rate between the berm-bar regions as a function of the inner bar change.

2.3. Bar equation for nearshore placements

Outer bars are typically located in water depths where common dredging equipment can have access, allowing the placement of dredged material in the nearshore. Thus, the present model proposes a simple approach to obtain preliminary prediction of the migration rate of artificial sand mounds by numerically solving a hypothetical bar equation. Based on the theory developed for systems characterized by the presence of two bars, different volumes can be modeled for the inner and outer bar. However, Eq. 4 can also be employed when just one bar forms, where $V_{BE}^{TOT} = V_{BE}^I$ and $V_{BE}^O = 0$. In such situations, the outer bar

will attain an equilibrium bar volume equal to zero which, once nourished artificially with a certain volume (V_B^0), will gradually decay towards the equilibrium state described by $V_B^0=0$. Simultaneously, due to the bar-berm coupling system, a continuous widening of the beach (or shoreline advance) is expected to occur. Based on that, Eq. 10 can be rewritten:

$$\Delta V_{B,i}^0 = -V_{B,i}^0 (1 - e^{-\lambda_i^0 \Delta t}) \quad (11)$$

According to Eq.11, with $V_{BE}^0=0$ the condition $0 < V_B^0$ will always be fulfilled, leading to an uninterrupted onshore sand movement. According to Smith *et al.* (2017), the onshore migration of sand and beach recovery is a gradual process and only prevails during periods of low wave steepness. At the same time, it is considered that the offshore mounds may be exposed to a wide range of wave conditions, including wave breaking. However, the tendency for material to be transported onshore is much greater under the action of non-breaking waves in comparison with breaking waves (Larson and Kraus, 1992).

The depth of placement of the nourishment is also important, because the morphological responses are expected to be different as a result of changing sediment transport rates (Ruessink and Terwindt, 2000). If sand is placed in a more offshore position, a different impact and time adjustment towards equilibrium should be expected (Bodge, 1994). Thus, through the study of the response of natural longshore bars, in particular the response of outer bars, Larson and Kraus (1992) have proposed a procedure for predicting the cross-shore movement direction (onshore/offshore) of material placed in the nearshore zone intended to function as beach nourishment. Here, bar degeneration by depth-limited breaking waves is investigated through a simple approach based on wave height:

$$\begin{aligned} &\text{If } H_0 < H_1, \text{ then (calm wave conditions; non-breaking waves)} \\ &\Delta V_B^0 = -V_{B,i}^0 (1 - e^{-\lambda_1^0 \Delta t}), \lambda_1^0 = C_C^0 \lambda_0 \end{aligned} \quad (12)$$

$$\begin{aligned} &\text{Else } H_0 > H_1 \text{ (breaking conditions)} \\ &\Delta V_B^0 = 0 \end{aligned} \quad (13)$$

where H_1 represents the wave height limit for the groups of waves that will break at depths where the outer bar is located. An example of how the profile may change the evolution of a nearshore sand mound for certain wave conditions is hypothesized. If the waves are small ($H_0 < H_1$), it is assumed that non-breaking waves will act across the bar and the incident waves will break closer to the shore, promoting onshore sediment transport of the dumped material. During energetic conditions described by $H_0 > H_1$, wave breaking prevails and the sediment transport will be considered to be offshore-directed, producing no variation in the offshore mound volume, $\Delta V_B^0=0$. Thus, during smaller waves the nearshore bar is intended to be “active” and designed to release sediments towards the shore, promoting accretion of the beach, whereas for wave heights larger than the breaking wave height, the nearshore mound is regarded to be stationary. As a way to take into account the typical cross-shore transport process on the nearshore mound, inducing dispersion or deflation in relief during non-breaking conditions, it is possible to assume that the material released from the mound go through the surf zone before ends on the berm, admitting in this way transport of the fill material to the inner bar (representative of the inshore portion of the profile).

3. MODEL APPLICATION – CASE STUDIES

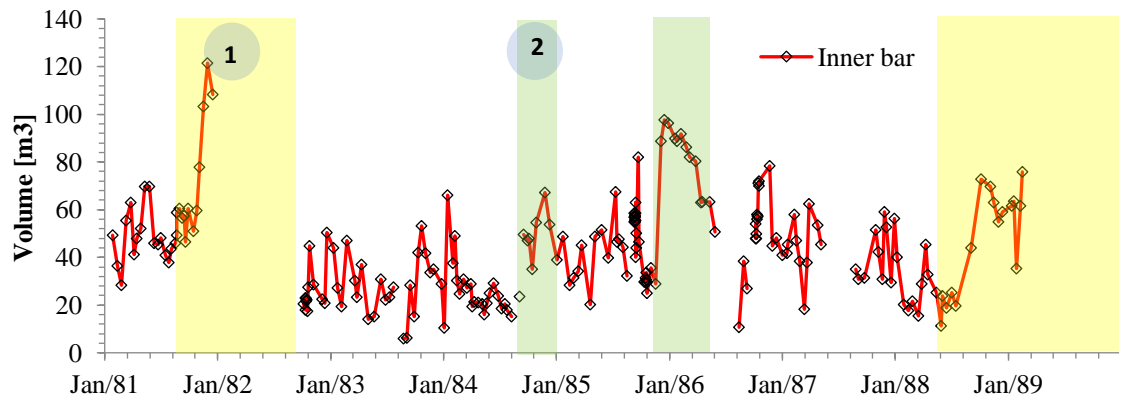
In section 3.1 the two-bar evolution model just described is validated with data collected at Duck, North Carolina, USA, which is a typical site where two longshore bars usually form. In section 3.2, field data sets collected at Cocoa Beach, Florida, USA, in connection with field experiments involving nearshore placement of dredged material, are employed for model calibration and validation.

3.1. Duck, North Carolina, USA

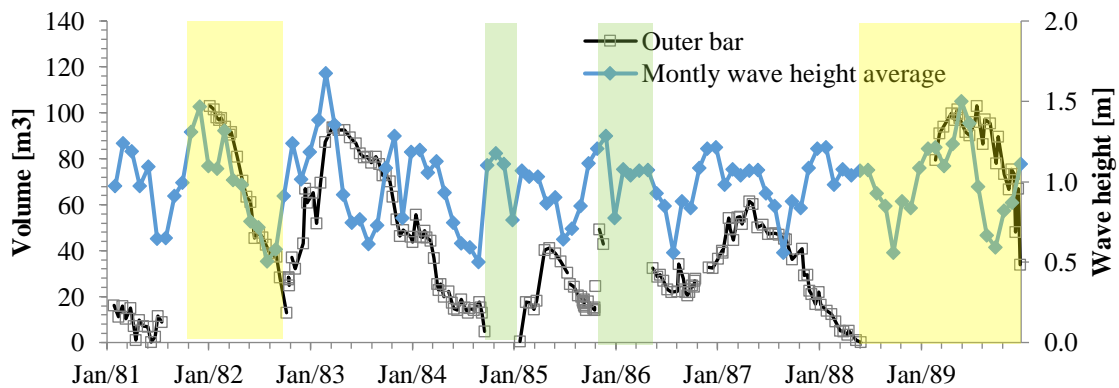
To model the individual volume evolution of two longshore bars (inner and outer), time series of waves and beach profiles measurements, collected 2-3 times per month by the Field Research Facility (FRF) of the U.S. Army Corps of Engineers were used, from 26-Jan-1981 to 28-Dec-1989, at Duck, North Carolina, USA. The nearshore bathymetry at FRF has been surveyed along a cross-shore line located far from the disturbing influence of the research pier (Line 62, see Howd and Birkemeier, 1987). Beach profile data

related to Line 62 have been previously analyzed by Larson and Kraus (1992) to obtain detailed morphological properties of the two bar features (inner and outer), including their volumes. These data were considered for model calibration and validation.

Although a distinction between the inner and the outer bar is appropriate for modelling purposes, this division is not straightforward. In the present study, the question remains under which conditions the inner bar, during its migration stage, should be recognized as the outer bar. For that purpose, the location of the bar was regarded as the decisive parameter. Based on the Larson and Kraus (1992) analysis of the FRF data, Figure 3 displays the volume for the inner and outer bars.



a) Inner bar



b) Outer bar

Figure 3. Volumes for inner and outer bar and monthly average of the measured wave height. Yellow shaded areas correspond to periods when the inner bar has migrated seaward to become the outer bar. Green shaded areas represent the periods when the outer bar has become flat, but reappearing after that at the same location. Numbers 1 and 2 highlight the periods of profile surveying that are further down displayed in Figure 4 and Figure 5, respectively.

Through analysis of the temporal variation in the observed outer bar volumes (see Figure 3), four cycles encompassing bar growth and decay can be identified during the measured period (1981-1989): 26-Jan-1981 to 17-Jul-1981, 07-Oct-1982 to 20-Sep-1984, 25-Jan-1985 to 21-Nov-1985 and 16-May-1986 to 02-Jun-1988. These time periods were based on the first and last survey revealing an identifiable outer bar feature for time series of consecutive surveys with an outer bar present.

As previously mentioned, after the outer bar disappeared, the offshore movement of the inner bar to become the outer bar was observed during two periods: 28-Sep-1981 to 07-Oct-1982 (see Figure 4) and 09-Sep-1988 to 28-Dec-1989. Duck profile measurements have captured the termination of a bar cycle and the onset of the offshore migration of the inner bar from 28-Sep-1981 to 07-Oct-1982 and 09-Sep-1988 to 28-Dec-1989, providing an opportunity to evaluate the trigger point for a new cycle and its relationship to the outer bar response. Figure 4 displays times series of surveyed profiles collected between 28-Sep-1981 and

07-Oct-1982, where the onset of a new bar cycle can be distinguished: the decay process of the outer bar was followed by the onset of the offshore migration of the inner bar, thereby promoting the formation of a new bar near the shoreline.

The surveys indicated that the pronounced migration pattern of the inner bar appearing on the 28-Sep-1981 and 09-Sep-1988 (see Figure 3a), was preceded by a marked growth in the inner bar volume. According to Figure 3b, prolonged intermediate conditions (note that H_s presents a short range of variability), encompassing non- or weakly breaking conditions might be the main factor for the decay of the outer bar. The most distinctive part is that the outer bar became flat before the inner bar entered its migration stage. In fact, the inner bar only started to move consistently offshore when storms arrived at the coast, occurring during the autumn and winter season. During the decay stage of the outer bar, significant fluctuations in inner bar volume and location were observed before the inner bar started to migrate consistently offshore. It was confirmed that even the offshore migration process is not a continuous phenomenon, but an intermittent process restricted to high-energy events.

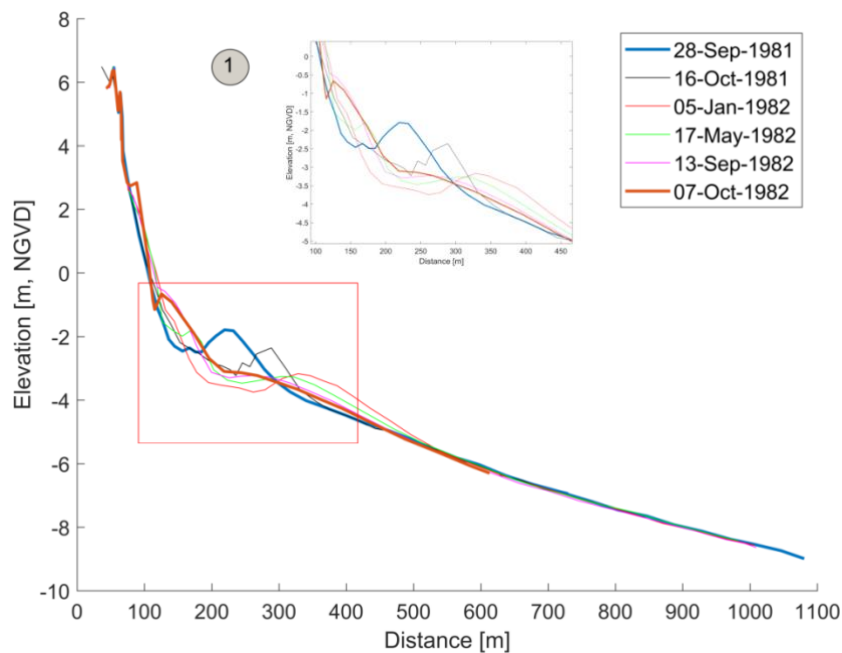


Figure 4. Surveyed profiles for Line 62 during the offshore progression of the inner bar to become the outer bar (28-Sep-1981 to 07-Oct-1982).

The decay and growth of the outer bar was also observed during 20-Sep-1984 to 25-Jan-1985 and 21-Nov-1985 to 16-May-1986. However, during these periods no evidence was detected in the surveys regarding a cross-shore progression of the inner bar towards the outer zone. Instead, the observations indicated that the outer bar has regenerated itself and reformed in deeper water (see Figure 5).

It has to be kept in mind that inner and outer bar definition and volume assumptions were just considered for modelling purposes, for comparing observations with the model results. The bar evolution equation (Eq.1) was applied to simulate the two-bar system behavior at Duck, where a numerical solution was employed following Eq. 4. The model was applied for the time period between 26-Jan-1981 and 28-Dec-1989, using wave measurements with a six-hour time step ($\Delta t=6\text{hr}$). The time series of the bar measurements were divided into two main periods, where the first one (extending from 1981-1985) was selected for calibration and the second one (from 1985-1989) was used for model validation. Test calculations demonstrated that employing a smaller coefficient to quantify the bar response rate of the outer bar relative to the inner bar yielded improved agreement between calculated and measured bar volumes.

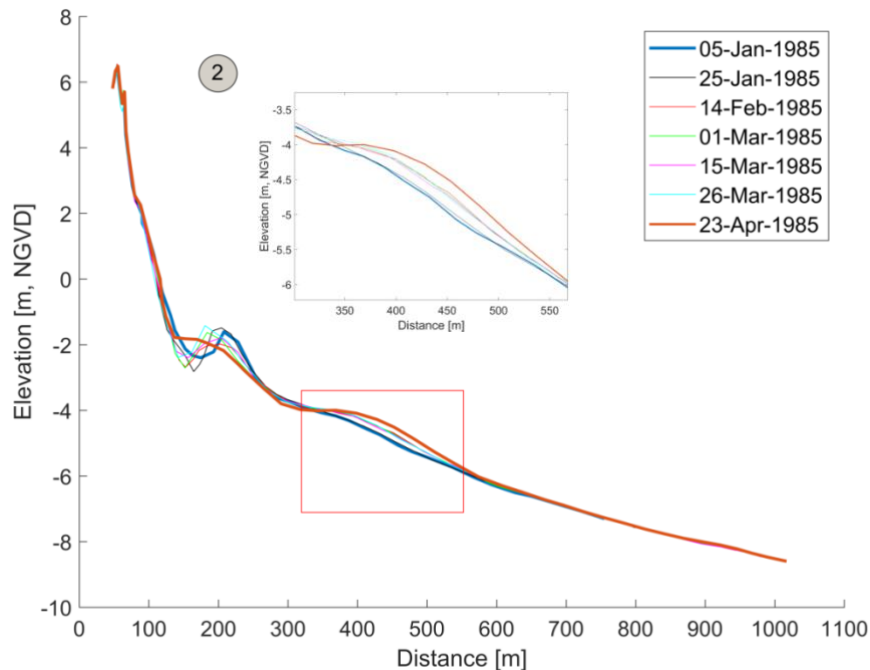


Figure 5. Surveyed profiles for Line 62 during the outer bar formation offshore (5-Jan to 23-Apr, 1985).

The initial bar volumes ($t=0$) were assigned to the initial observed values (calculated from the survey data), that is, $49.2 \text{ m}^3/\text{m}$ and $16.2 \text{ m}^3/\text{m}$ for the inner and outer bar, respectively. The empirical coefficient δ_0 was calibrated to 3 based on the observed typical relationship between the inner and outer bar volumes. The critical wave height H_c was assumed to be around 2 m. To test the model, two schematic cases were set up by admitting (or not) exchange of material between the two bars.

3.2. Cocoa Beach, Canaveral, Florida, USA

The model for estimating the response of artificial nearshore bars intended to perform as feeder berms was employed for reproduction of a field experiment carried out at Cocoa Beach, Florida. Dredged sand from 1992-1994 maintenance activities at the Port Canaveral Entrance channel was placed in a nearshore disposal area offshore of Cocoa Beach (8.4 to 11.3 kilometers southward of the source), in order to retain beach-compatible sand in the littoral system. The goal of this intervention was to minimize local beach erosion (mainly attributed to the presence of the inlet), by constructing a shore-parallel bar within the active littoral zone that could benefit, directly or indirectly, the shoreline. The fill activities started in 1992 (from 6-June through 24-Jul), involving the deposition of $121\,000 \text{ m}^3$ of sand. In 1993 and 1994, more disposal activities were undertaken, implying a total sand volume mobilized of around $263\,000 \text{ m}^3$. After monitoring data evaluation, a specific set of high-quality monitoring data related to the first intervention (1992) were selected for model application. This data set encompasses five bathymetric surveys collected for several lines alongshore, spaced about 40 to 75m apart, intercepting the placement site. These lines were surveyed before (pre-project, Jun-1992) and after the fill placement (post-project, Jul-1992) and then on three different occasions until one year after construction was completed (Dec-92, May-93, Jul-93). The data collection extended from 45m seaward of the disposal area to about 245m landward thereof, or from the -8.4m to -3.4m MLW (Mean Low Water) depth contours. Figure 6 depicts the surveyed profiles along two distinct lines: one located in the northern part of the designated placement area and the other in the southern part, where no fill material was placed during the first disposal.

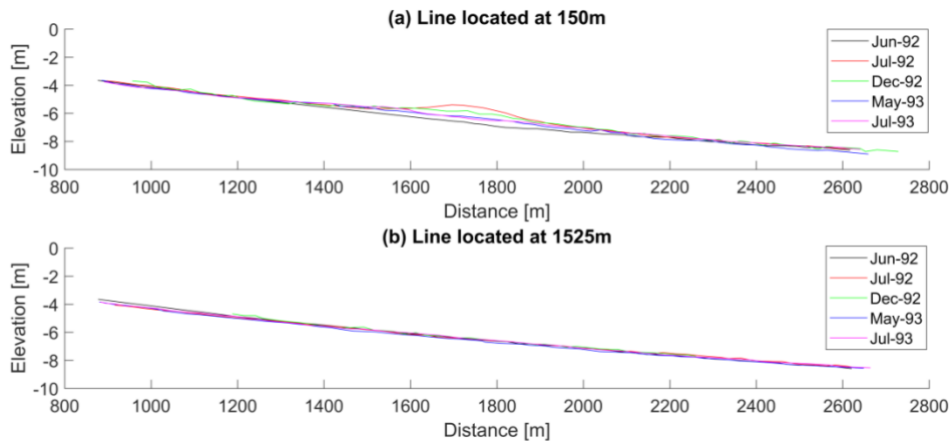


Figure 6. Selected survey profiles intercepting the permitted disposal area (0m to 2 895m in the local alongshore coordinate system): (a) northern part and (b) southern part.

The monitoring data set collected to document the evolution of the offshore mound have detected the absence of natural breaker bars forming in the nearshore. Inter-survey data analysis, along the disposal area, has also revealed that the nourishment activity focused in the north. This is in agreement with Figure 6, where the seabed changes of the most northern-located profile (Figure 6a) demonstrates that the initial bar was constructed here, while no pronounced bar is observed in the southern disposal area (Figure 6b). Thus, since the nourished sand was not uniformly distributed alongshore in the permitted dumping area, six northern evenly-spaced profile lines were selected to evaluate the seabed changes associated with the nearshore bar. For each survey event, the average depth of these six profile lines (intercepting the disposal activity) was computed. Since the first survey was carried out before the fill placement, the corresponding average profile was designated as the “background” (or “pre-project”) profile. Figure 7 plots the average profiles computed for each survey event that occurred between 16-Jun-1992 and 1-Jul-1993.

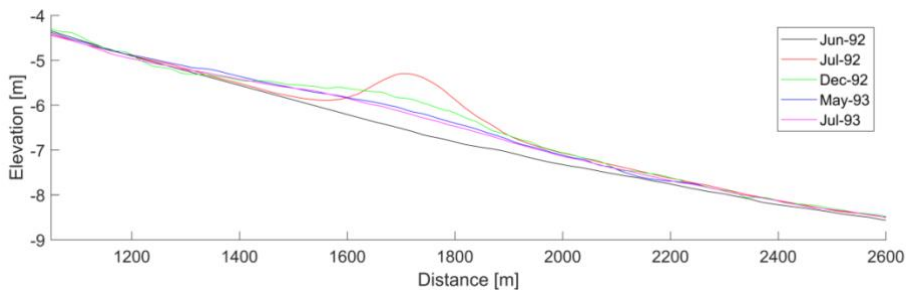


Figure 7. Average profile evolution at northern disposal area (0m to 800m). Distance along the profiles refers to an artificial baseline set at approximately the NGVD shoreline. Elevation in relation to NGVD.

In Figure 7, an artificial nearshore bar can be recognized just after the placement (Jul-92), as well as a subsequent pronounced landward migration of the mound during the following months (Dec-92; May-93; Jul-93) accompanied by a clear shift of the bar crest towards shallower waters. Also, the bar height experienced a significant reduction during the first 5 months after the dredged material was placed, corresponding to the period when most of the flattening occurred. Thereafter, the bar relief decreases more slowly, with the bar almost welding on the shore in Jul-93. Thus, the flattening and onshore movement of the mound contributed to the accretion of material along the inner portion of the profile.

As no natural bars were surveyed in Cocoa Beach, the numerical model was set up to reproduce the behavior of the nearshore mound disposal through the simulation of a hypothetical feature defined by $V_{BE}^0 = 0$ (representing the outer portion of the profile), for the time period from 16-Jun-1992 to 01-Jul-1993. To improve the agreement with the observed mound response (Figure 6) and to better reproduce the transport of the fill material through the surf zone, a representative morphological volume for the inshore area was included in the simulations and the exchange of material is considered to be onshore-directed. Since no wave measurements were made in connection with the profile surveying, a wave hindcast with a 3-hour time step was used in the simulations. Model calibration was performed by adjusting site-specific

input parameters and estimated values based on the pre-surveyed profiles and previous studies. According to Bodge (1994), the median grain size of the pre-disposal seabed was 0.104 mm, whereas samples of seabed during and after the disposal activities indicated a representative median diameter around 0.40 mm. As the native grain size differed significantly from the nourished sand, an average value of 0.21 mm was adopted for d_{50} . Wave heights thresholds of 4.2 m (H_{b1}) and 2.0 m (H_{b2}) were specified to determine onshore movement of material from the outer and inner portions of the profile, respectively, for periods when the offshore wave height does not exceed these values. To validate the model, comparisons were made with measured profiles.

4. RESULTS AND DISCUSSION

This section presents and discusses the main results obtained by applying the developed model.

4.1. Duck, North Carolina, USA

Figure 8 illustrates modeled Duck results for the inner and outer bar volume variation with time and the agreement obtained with the observations during the calibration and validation periods, when no sediment exchange between the inner and outer bar was considered.

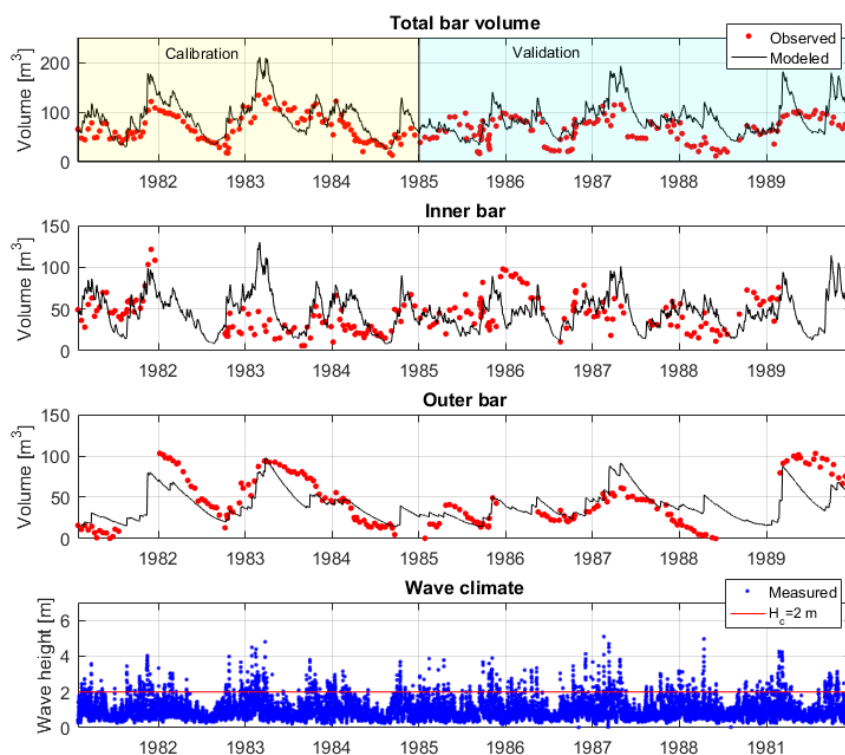


Figure 8. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical simulations without considering sediments exchange between the inner and the outer bar.

Overall, promising results were achieved for the calculated outer bar volumes, though the scatter obtained during the validation period was significantly larger compared with the calibration period (see Figure 8). For the representative total volume stored in both bars, trends in volumes were reasonably reproduced showing a good initial agreement between the two series, but developing discrepancies towards the end of the validation period, corresponding to the time when the outer bar decayed and the inner bar experienced offshore migration (with only one bar appearing). The same is verified for the outer bar volume, with the largest deviation occurring during the summer of 1989, when the inner bar moved seaward as a result of the storms hitting the beach during the winter 1988/1989. Also, mainly during Sep-1989 the

wave periods were considered unusually long (with an average and maximum value of 10.6 s and 23.3 s, respectively) and judged to be outside the range for which the estimated parameter values would be applicable. It should be emphasized that the model confines the outer bar growth to high-energy events, for which the input critical wave height assumes a central role ($H_0 > H_c$). This site-specific parameter describes a change in the forcing conditions characterized by a stronger net seaward movement that would act as a trigger for the onset of the outer bar formation.

Due to the considerable scatter in the observations of the inner bar volume, demonstrating a quite random behavior, part of the data were poorly reproduced. This may be attributed to the fact that the inner bar is typically located within the region of breaking waves, where profile changes are more irregular and with a rapid response, challenging the predictive capability of the model. Limitations on the predictability of the inner bar behavior were also recognized by Splinter *et al.* (2018) when applying a simple equilibrium model to field data of observed sandbar position.

Comparing with the previous simulations, results including an exchange of material between the inner and the outer bar (Figure 9) produced the same main trends in bar volume change, but displaying changes in the inner and total bar volume. The assumption that sediment transported to the outer bar are coming from the inner bar, tends to smooth things out, decreasing the amount of sediment mobilized in the subaqueous portion by the waves and reducing the estimated amount of sediment being transported through the interface between the berm-bar region. Although a scatter is still noticeable for the inner bar volumes, the trends for total bar volume are reasonably well described, with the predicted sum of the calculated bar volumes approximating the measured values. Thus, the exchange of material between the bars yielded improved agreement.

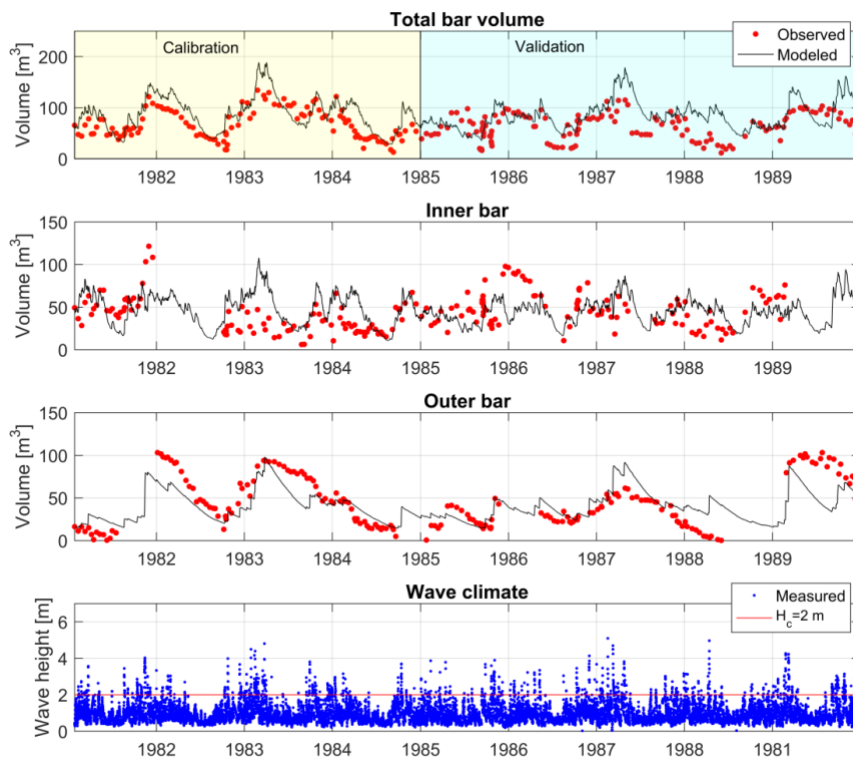


Figure 9. Total, inner, and outer bar volumes and wave climate (Duck, N.C.). Numerical simulations considering sediment exchange between the inner and the outer bar.

4.2. Cocoa Beach, Canaveral, Florida, USA

The model results were quantitatively evaluated by comparing the computed bar volumes with the values estimated from the surveys. Figure 10 depicts the time variation in the calculated bar volume, as well as the agreement obtained between the measured and the predicted values during the first year after nourishment operations.

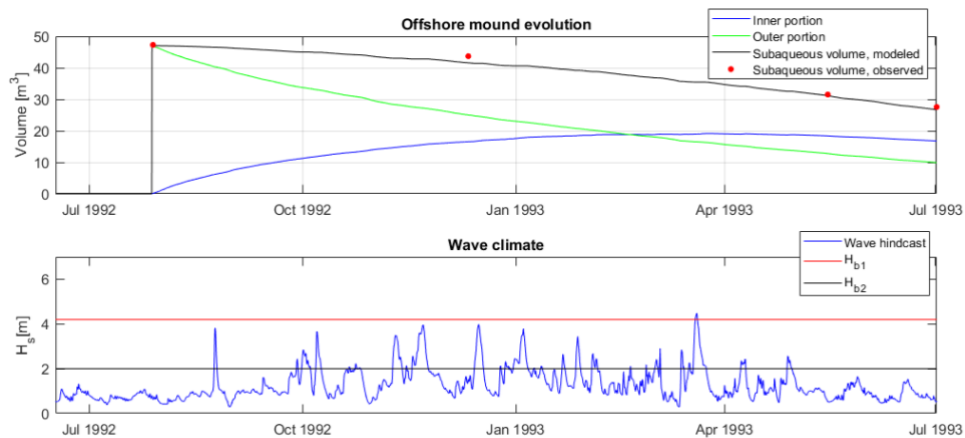


Figure 10. Results of the nourishment simulation using a hypothetical outer bar (Canaveral, Cocoa Beach) considering exchange of material with the inner portion of the profile.

The model prediction is judged to be good by considering the transfer of fill material towards the shore through the most inshore portion of the profile. At the same time as the outer bar started to release sediment, the inner portion filled up as the wave forcing was favorable for such conditions (note that the wave climate was quite energetic during this period). A shift towards low-energy wave conditions (reflected by a general decrease of the values of H_s) appearing simultaneously with the maximum inner volume (Apr-93) suggests a change to a negative sediment budget at the inshore part of the profile, where the volume transported from the outer zone to the inner becomes lower than the volume transported from the inner portion to the beach (see Figure 10). This behavior is in agreement with Figure 7, where the major modifications of the mound shape took place during the first 5 months just after the fill placement (between the “post-survey” and Dec-92), while during the next period (Dec-92 to May-93) a higher volume loss occurred. Overall, the time adjustment of the profile towards an equilibrium state is being properly described by the model, as well as the volume time variation during the measurement period.

5. CONCLUSIONS

The equilibrium bar model, first introduced by Larson *et al.* (2013), designed to calculate bar-berm material exchange, has been developed and applied to simulate long-term coastal bar evolution. The model was enhanced to reproduce the overall shift in material between the subaerial and subaqueous portions of the profile by taking into account the long-term evolution of multi-bar systems and the response of offshore mounds placed in the outer part of the nearshore zone to act as active or feeder bars (for beach nourishment purposes). The model is based on simplifications of the governing processes, where bar volume evolution determines the transport direction, *i.e.*, bar growth implies offshore sediment transport and bar decay corresponds to onshore sediment transport. As a first attempt, efforts were made to simulate coastal systems with up to two longshore bars appearing in the nearshore, where both growth and decay of individual bars are computed with respect to a representative subaqueous morphological volume, or total bar volume, defined at equilibrium. The presented two-bar model, rather than resolving the fine details of the profile response (or bar shape), relies on a simple approach to compute volume changes distributed between the two bars, with the assumption that larger waves result in more material in the bars compared to smaller waves (quantified based on data).

The developed model was calibrated and validated at two field sites in the United States: 1) Duck, NC, where two natural longshore bars (an inner and outer bar) typically form; and 2) Cocoa Beach, FL, where an offshore feeder mound was located in deep water, where no natural bars were detected. It was shown for the Duck case that the response of the outer bar was significantly slower than the inner bar to changes in the cross-shore sediment transport. Although the criteria presented here should provide a first rough estimate of suitable values, parameters such as the critical wave height and wave breaking height (used to define the wave heights thresholds) determining the outer bar formation and the response of mounds,

respectively, are expected to be site-specific and data are needed to apply the model with confidence at a particular site.

The model application showed that the equilibrium model is skilled at predicting the time-varying volume of the outer bar, suggesting that this morphological feature is strongly influenced by offshore wave forcing in a predictable, equilibrium-forced manner. Model skill was lower when predicting the inner bar evolution due to the scatter of the observations, leaving important research questions still unanswered, such as, if inner bars in multiple bar sites indeed display predictable, equilibrium driven cross-shore behavior, similar to outer bars and shorelines. As discussed previously by several authors (Splinter *et al.*, 2018), the behavior of the inner bars is hypothesized to be more conditioned by changes in the tide range and act as sediment transport pathways between the shoreline/berm and the outer bar.

Overall, the present study demonstrates the potential for using rather simple models, underlying the definition of some equilibrium state that is compared to the current state and some magnitude of forcing available to drive the changes in the profile. The methodology employed here allowed to quantitatively reproduce the main trends in the subaqueous beach profile response in a long-term perspective as a function of the bar volumes' disequilibrium, the magnitude of the incident wave height and the dimensionless fall velocity to move the sand with a time-varying forcing term outside the disequilibrium term. It was also shown that the model has applicability for predicting the evolution of nearshore mounds that migrate towards the shore and become part of the beach face by the action of waves and currents, through the simulation of hypothetical bars defined by zero equilibrium bar volume. This modelling approach could be more widely applied to other beaches to explore shoreline equilibrium behavior, by merging it with a shoreline evolution model, or combining it with a compatible dune erosion module to simulate beach berm response and illustrate its applicability in predicting seasonal changes, as well as the supply effects at medium-term related to the fill project on the shoreline position.

ACKNOWLEDGMENTS

This work has been supported by Fundação para a Ciência e Tecnologia through the PhD grant SFRH/BD/95894/2013.

REFERENCES

- Aleman, N., Certain, R., Robin, N., Barousseau, J. (2017). Morphodynamics of slightly oblique nearshore bars and their relationship with the cycle of net offshore migration, *Marine Geology*, Volume 392, 41-52 pp.
- Almar, R., Castelle, B., Ruessink, B., Sénéchal, N., Bonneton, P., Marieu, V. (2010). Two- and three-dimensional double-sandbar system behavior under intense wave forcing and a meso-macro tidal range. *Cont. Shelf Res.* 30 (7), 781–792.
- Andrassy, C. J. (1991). Monitoring of a Nearshore Disposal Mound at Silver Strand State Park. *Proceedings Coastal Sediments '91*, American Society of Civil Engineers, pp 1970-1984.
- Barnard, P.L., Hanes, D.M., Lescinski, J., Elias, E. (2006) Monitoring and modeling nearshore dredge disposal for indirect beach nourishment, Ocean Beach, San Francisco. *Proceedings 30th Coastal Engineering Conference*, ASCE, 4192-4204.
- Bodge, K. (1994). Performance of nearshore berm disposal at Port Canaveral, Florida. *Proceedings, Dredging'94*, American Society of Civil Engineers (ASCE) Specialty Conference, Orlando, Florida; November 13-16, 10 p.
- Bouvier, C., Balouin, Y., Castelle, B. (2017). Nearshore bars and nearshore dynamics associated with the implementation of a submerged breakwater: topo-bathymetric analysis and video assessment at the Lido of Sète beach. *Proceedings Coastal Dynamics 2017*, Helsingør, Denmark, Paper no.22, 10 p.
- Dean, R. (1987). "Coastal Sediment Processes: Toward Engineering Solutions," *Proceedings Coastal Sediments '87*, American Society of Civil Engineers, pp 1-24.
- Howd, P. A., Birkemeier, W. A. (1987). Beach and Nearshore Survey Data: 1981-1984 CERC Field Research Facility, Technical Report CERC-87-9, Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Larson, M., Kraus, N.C., (1989). SBEACH: Numerical model for simulating storm-induced beach change, Report 1: Empirical foundation and model development. Technical Report CERC-89-9. U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.

- Larson, M., Kraus, N.C., (1992). Analysis of cross-shore movement of natural longshore bars and material placed to create longshore bars. Technical Report DRP-92-5. U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.
- Larson, M., Hanson, H., Kraus, N., Newe, J. (1999). Short- and Long-Term Responses of Beach Fills Determined by EOF Analysis. *Journal of waterway, Port, Coastal, and Ocean Engineering*, 285-293.
- Larson M., Hanson H., Palalane J., (2013). Simulating cross-shore material exchange in long-term coastal evolution models. *Proceedings Coastal Dynamics 2013*, Arcachon, France, 1037-1048 pp.
- Larson, M., Hanson, H. (2015). Model of the evolution of mounds placed in the nearshore. *Journal of the Integrated Coastal Zone Management*, 15 (1): pp 21-33.
- Larson, M., Palalane, J., Fredriksson, C., Hanson, H., (2016). Simulating cross-shore material exchange at decadal scale. Theory and model component validation. *Coastal Engineering*, 116, 57-66.
- Marinho, B., Coelho, C., Larson, M., Hanson, H. (2017a). Short- and long-term responses of nourishments: Barra-Vagueira coastal stretch, Portugal. *Journal of Coastal Conservation*, Springer, 22(3), 475-489 pp.
- Marinho, B., Coelho, C., Larson, M., Hanson, H. (2017b). Simulating cross-shore evolution towards equilibrium of different beach nourishment schemes. *Proceedings Coastal Dynamics 2017*, Helsingør, Denmark, Paper no.121, 15 p.
- Marinho, B., Coelho, C., Larson, M., Hanson, H. (2018). Monitoring the Evolution of Nourished Beaches Along Barra-Vagueira Coastal Stretch, Portugal. *Ocean & Coastal Management*, 157, 24-39 pp.
- Palalane, J., Fredriksson, C., Marinho, B., Larson, M., Hanson, H., Coelho, C., (2016). Simulating cross-shore material exchange at decadal scale. Model application. *Coastal Engineering*, 116, 57-66.
- Price, T.D., Ruessink, B.G., (2011). State dynamics of a double sandbar system. *Continental Shelf Research*. 31 (6), 659–674. <http://dx.doi.org/10.1016/j.csr.2010.12.018>.
- Różyński, G. and Lin, G. (2015). Data-Driven and Theoretical Beach Equilibrium Profiles: Implications and Consequences. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Volume 141(5), 17p.
- Ruessink, B., Kroon, A. (1994). The behavior of a multiple bar system in the nearshore zone of Terschelling, The Netherlands: 1965-1993. *Marine Geology*, 121, pp 187-197.
- Ruessink, B., Terwindt, J. (2000). The behavior of nearshore bars on the time scale of years: a conceptual model. *Marine Geology*, 163, pp 289-302.
- Ruggiero, P., Kaminsky, G., Gelfenbaum, G., Cohn, N. (2016). Morphodynamics of prograding beaches: A synthesis of seasonal- to century-scale observations of the Columbia River littoral cell, *Marine Geology* 376, 51-68 pp.
- Splinter, K., Turner, I., Reinhardt, M., Ruessink, G. (2018). Rapid adjustment of shoreline behavior to changing seasonality of storms: observations and modelling at an open-coast beach. *Earth Surface Processes and Landforms*, 42 (8), 1186-1194 pp.
- Smith, E., D'Alessandro, F., Tomasicchio, G., Cailani, J. (2017). Nearshore placement of a sand dredged mound. *Coastal Engineering*, 126, pp 1-10.
- Sunamura, T., Maruyama, K. (1987). Wave-induced geomorphic response of eroding beaches – with special reference to seaward migrating bars. *Proceedings of Coastal Sediments '87*, ASCE, 884-900 pp.
- Swart, R., Ribas, F., Ruessink, G., Simarro, G., Guillén, J. (2017). Characteristics and dynamics of crescentic bar events in an open, tideless beach. *Proceedings Coastal Dynamics 2017*, Helsingør, Denmark, Paper no. 192, 12 p.
- Walstra, D., Ruessink, G. (2017). Recent insights into inter-annual sandbar dynamics. *Proceedings Coastal Dynamics 2017*, Helsingør, Denmark, Paper no.13, 12 p.