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Published in:
Proceedings of the Institution of Civil Engineers. Maritime Engineering

DOI:
10.1680/maen.2009.162.3.105

2009

Proceedings of the Institution of Civil Engineers
Maritime Engineering 162
September 2009 Issue MA3
Pages 105–114
doi: 10.1680/maen.2009.162.3.105

Paper 700024
Received 02/10/2007
Accepted 23/01/2009

Keywords:
coastal engineering/hydraulics & hydrodynamics


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A numerical model of coastal overwash

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Overwash, the flow of water and sediment over the crest of a beach, contributes to flooding and the deposition of sand landward of the beach crest. Washover, the sand deposited by overwash, contributes to the sediment budget and migration of barrier islands. The ability to predict the occurrence, location, and thickness of overwash deposits is important for coastal residents, coastal town planners, environmental planners, and engineers alike. In this study, a numerical model that simulates the sediment transport and one-dimensional barrier profile change caused by overwash was developed. The magnitude of overwash and the morphology of washovers are dependent on the overwash regime. New formulae are developed to estimate the sediment transport rate over the beach crest for both run-up overwash, using ballistics theory, and inundation overwash, treating flow over the crest as weir flow. Two-dimensional flow is described on the back barrier by considering the continuity of a block of water at steady state, taking into account lateral spreading, friction, and infiltration. The model is tested against 26 different beach profile sets from several different locations, and several different storms, exhibiting a variety of initial morphologies. The model is capable of reproducing varying overwash morphology responses including dune crest erosion, dune destruction, barrier rollback, the thinning of a washover deposit on the backbarrier, and overwash over a multiple dune system.

NOTATION

B	width of block of water moving on back barrier slope
B_D	width of the bore front at beach crest (initial block width)
C_d	weir coefficient
C_{infilt}	infiltration parameter
C_{ls}	lateral spreading parameter
C_u	bore celerity coefficient
E_{RES}	residual error
E_{RMS}	root-mean-square error
$\mathbf{f}_c$	friction coefficient
$\mathbf{g}$	acceleration due to gravity
h	depth
h_D	depth of the bore front at beach crest
K_B	sediment overwash coefficient
K_c	transport coefficient for back barrier
k_f	friction-related parameter
l	length of block of water moving on back barrier slope
N_p	number of points across profile
$\mathbf{q}$	cross-shore sediment transport rate
$\mathbf{q}_D$	cross-shore sediment transport rate over the beach crest
$\mathbf{q}_{DI}$	cross-shore sediment transport rate over the beach crest, inundation overwash
$\mathbf{q}_{DR}$	cross-shore sediment transport rate over the beach crest, run-up overwash
$\mathbf{q}_f$	cross-shore sediment transport rate on back barrier
$\mathbf{q}_{sw}$	cross-shore net sediment transport rate in the swash zone.
R	run-up height
S	the surge level above MSL
s	distance travelled by block of water moving on back barrier slope
s'	non-dimensional distance
T	swash period, taken to be equal to wave period
t	time after discharge over the crest
t_D	duration of overtopping
$\mathbf{u}$	velocity of bore
$\mathbf{u}_D$	velocity of overtopping bore at crest
$\mathbf{V}$	volume of block of water moving on back barrier slope
$\dot{V}_{DI}$	average volume flow during inundation overwash
$\dot{V}_{DR}$	average volume flow during run-up overwash
$\mathbf{v}$	infiltration rate
x	cross-shore coordinate
x_D	position of the beach crest
x_{sw}	position of boundary between swash and surf zone
y_c	calculated bed level
y_i	initial bed level
y_m	measured bed level
z	vertical distance from SWL
z_D	vertical position of beach crest relative to SWL
α	proportionality constant for infiltration rate
α'	non-dimensional infiltration term
β	back barrier slope

μ	linear lateral spreading rate
ξ	non-dimensional velocity term

1. INTRODUCTION

Overwash is the flow of water and sediment over the crest of a beach, usually occurring during severe storms or hurricanes. Overwash causes transportation and deposition of sediment landward of the beach crest, sometimes as far as the back barrier bay or lagoon. At the same time, the beach face generally retreats landward. Overwash deposits, known as 'washover', contribute to the sediment budget of barrier islands and are thought to maintain the width of barrier islands as they migrate landwards,[1] and provide vital habitat to coastal flora and fauna. On developed coasts, overwash may be a hazard, causing flooding, sand intrusion, scour (of coastal roads for example[2]), and even structural damage, often by debris entrained in the overwashing flow. The ability to predict the magnitude, penetration and thickness of overwash deposits is important for coastal residents, coastal town planners, environmental planners, and engineers alike.

The magnitude and morphology of washovers are dependent on the overwash regime. The beach or dune crest is hereafter referred to as the beach crest. Run-up overwash occurs when wave run-up heights exceed the beach crest elevation, but the mean water level including surge (S) is below the beach crest elevation. Inundation overwash occurs when S exceeds the beach crest elevation,[3,4] which is illustrated in Figure 1. Other processes which significantly affect washover morphology include lateral spreading, friction and infiltration. A comprehensive review of overwash processes and overwash literature was compiled by Donnelly *et al.*[4]

The purpose of this study was to develop an overwash algorithm to simulate two-dimensional beach profile response to storms, including penetration and thickness of overwash deposits. Numerical models to predict beach profile response to storms currently exist and are widely used and rigorously tested. These models, however, did not include overwash transport, until a simple algorithm to simulate overwash deposition landward of the beach crest was developed and added to the SBeach model by Kraus and Wise.[5] SBeach[6] simulates storm-induced beach erosion, employing geometrically based empirical methods to estimate sub-aerial eroded volume and dune retreat. A predecessor of SBeach that is based on similar governing equations for sediment transport is EDune.[7]

The Kraus and Wise[5] overwash algorithm uses the run-up extent and geometry to calculate the overwash penetration length, and relates the magnitude of onshore transport to the run-up height exceeding the beach crest. Deposition between crest and the landward extent is calculated using a simple geometrical relationship. Inundation overwash is not accounted for. This algorithm was shown to reproduce observed profile response to overwash for a specific data set,[8] but landward penetration of overwash is often underestimated by the algorithm, and profiles undergoing significant inundation overwash are difficult to simulate. The assumptions behind this model were intuitively based, so it was considered necessary to develop a model with a more solid physical foundation.

In the present study a model to simulate the vertical changes in a cross-shore beach profile due to overwash was developed based on a more physical description of the governing processes. The simple one-dimensional (1-D) model, with two-dimensional (2-D) considerations was formulated to be as general as possible and is intended to apply both to barrier islands and mainland beaches, regardless of the presence or absence of dunes. It is intended to predict the occurrence of overwash and present a good quantitative indicator of the landward penetration and thickness of overwash deposits as well as the movement of the beach crest. Processes deemed important to include are: overwash regime, the depth and 1-D velocity of flow at the crest, lateral spreading, and infiltration. Simplification of the overwash problem to 1-D can be justified as representing the dominant flow directions and velocities that drive the overwash process. Various equations, taking into account these processes, were formulated to describe the flow and sediment transport rate. The model employs readily available data: pre-storm beach profiles, time-series of offshore wave height and period, and grain-size properties.

The model was tested against 26 unique beach profile sets from six different locations along the US Atlantic coast. Profiles were measured prior to and following storms (north-easters and hurricanes) that caused overwash. The locations tested exhibited a wide variety of initial morphologies and overwash responses (see Table 1). This paper presents the new theory for calculating overwash sediment transport and profile changes, then introduces unique, new data sets used to verify the model. It then describes how the model was calibrated and verified, and finally, the results are discussed, including limitations and suggested improvements. The model runs quickly using readily available beach profile and hydrodynamic data, and calibrated models were verified on profiles in the same region. The new overwash model is shown to successfully predict both the quantitative and qualitative profile response to overwash for a wide variety of new data sets.

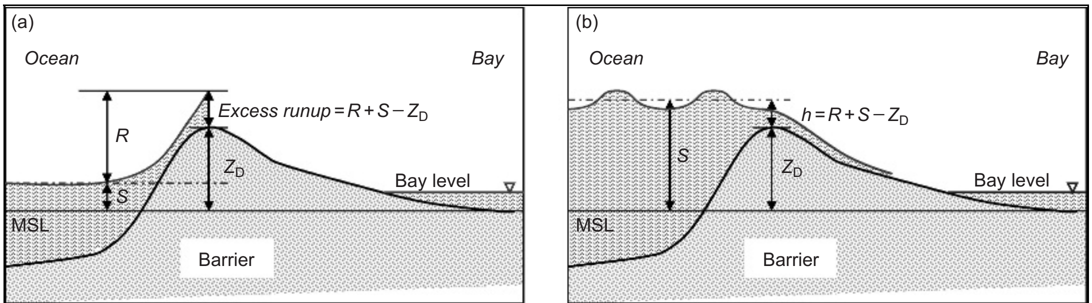

Figure 1. (a) Schematic of a barrier undergoing run-up overwash; (b) schematic of a barrier undergoing inundation

Location	Storm	Peak H_s: m	Peak S: m	Number of profiles	Calibrated profile	Verified profiles
Manasquan, NJ[8]	March 1984 north-easter	6·4	2·1	2	Mn-4	Mn-7
Metompkin Island, VI[1]	Hurricane Gloria, 27 September 1985	4·7	2·2	2	Mt-10	Mt-26
Garden City Beach, SC[9]	Hurricane Hugo, 21 September 1989	6·7	2·8	2	GC-4930	GC-4920
Folly Beach, SC[9]	Hurricane Hugo, 21 September 1989	6·7	2·8	8	F-2883	F-2801, F-2813, F-2818, F-2823, F-2850, F-2878, F-2880
Ocean City, MD[8]	Winter 1991/1992 storms (3)	4·2	2·0	6	OC-45	OC-52, OC-63, OC-74, OC-86, OC-103
Assateague Island, MD[10]	January 1998 north-easters (2)	4·1	1·9	6	A-3720	A-2330, A-4850, A-GPS1, A-GPS3, A-GPS4

Table 1. Summary of data used

2. THEORETICAL BACKGROUND

The overwash model focuses on the sub-aerial beach which is divided into three zones: the swash zone, the beach crest, and the back barrier. The beach crest zone is considered to be of limited spatial extent, and the transport at the crest acts as a boundary condition between the regions on either side of the crest

2.1. Swash zone transport

A model describing sediment transport in the swash zone was derived for an earlier version of the overwash model and was presented by Larson *et al.*[10] It is based on the bed-load sediment transport formula by Madsen[11] and employs ballistics theory to describe the hydrodynamics in the swash zone. For the case of overwash, the swash zone sediment transport is matched to the transport rate at the crest using a formulation suggested by Wise *et al.*[8] Thus, sediment transport in the swash zone is calculated according to

$$\boldsymbol{q} = \boldsymbol{q}_{\mathrm{D}} + (\boldsymbol{q}_{\mathrm{sw}} - \boldsymbol{q}_{\mathrm{D}})\left(\frac{x - x_{\mathrm{D}}}{x_{\mathrm{sw}} - x_{\mathrm{D}}}\right)^2 \qquad x_{\mathrm{D}} < x < x_{\mathrm{sw}} \tag{1}$$

where $\boldsymbol{q}$ is the sediment transport rate, x is a cross-shore coordinate, the subscript D refers to conditions at the beach crest, and the subscript sw refers to conditions at the surf–swash zone boundary. The sediment transport rate at the beach crest, $\boldsymbol{q}_{\mathrm{D}}$, is derived in the section below. The sediment transport rate at the surf–swash zone boundary, $\boldsymbol{q}_{\mathrm{sw}}$ is an input parameter to the model, and may be estimated by coupling the model to a beach and dune erosion model.

2.2. Sediment transport over the beach crest

Sediment transport over the beach or dune crest is considered to be a function of the overwash regime, and the local depth and velocity of flow at the beach crest. If run-up overwash occurs, the overtopping rate is calculated from the velocity and water depth at the crest. Velocity at the crest is again calculated from ballistics theory, and assuming that the front of the uprushing wave behaves like a bore, the water depth can be derived from a simple bore front equation. The average volume of flow per overtopping wave ($\dot{\boldsymbol{V}}_{\mathrm{DR}}$) is then obtained by multiplying the overtopping rate by an overtopping duration derived from ballistics theory and dividing by the wave period, *T*, which is taken to be equal to the swash duration

$$\dot{\boldsymbol{V}}_{\mathrm{DR}} = \frac{2\sqrt{2\boldsymbol{g}}}{C_{\mathrm{U}}^2}(R - z_{\mathrm{D}})^{3/2}\sqrt{1 - \frac{z_{\mathrm{D}}}{R}} \tag{2}$$

where C_{U} is the bore front coefficient (of order 1), R is the run-up height above S (mean water level including surge level), z_{D} is the elevation of the beach crest above MSL and $\boldsymbol{g}$ is acceleration due to gravity. For inundation overwash it was proposed that the ocean side of the crest acts as a large reservoir and the beach crest as a weir, with flow accelerating over the crest onto the back barrier. In this case, the overtopping flow rate ($\dot{\boldsymbol{V}}_{\mathrm{DI}}$) may be described using the weir equation

$$\dot{\boldsymbol{V}}_{\mathrm{DI}} = \frac{2}{3}C_{\mathrm{d}}\sqrt{2gh_{\mathrm{D}}}^{3/2} \tag{3}$$

where C_{d} is a weir coefficient and h_{D} is the excess water level over the crest, taken to be $S - z_{\mathrm{D}}$.

Note that it is assumed that inundation overwash occurs when water level not including wave set-up inundates (exceeds) the beach crest. Although wave set-up is significant during overwash processes, at shallow inundation depths the effects of waves on sediment transport over the beach crest are more significant than the effects of the inundation-induced flows. This assumption therefore accounts for wave processes at the transition between run-up and inundation overwash.

The sediment transport rate is assumed proportional to the flow rate. Based on laboratory experiments of overwash in a flume,[12,13] a linear relationship between the overtopping flow rate and the volume of sediment in the overtopping flow was found. This implies that the concentration of sediment in the overtopping flow is constant, which gives the following equations for overwash transport over the beach crest for run-up ($\boldsymbol{q}_{\mathrm{DR}}$) and inundation ($\boldsymbol{q}_{\mathrm{DI}}$) overwash, respectively

$$\boldsymbol{q}_{\mathrm{DR}} = 2K_{\mathrm{B}}\sqrt{2\boldsymbol{g}}(R - z_{\mathrm{D}})^{3/2}\sqrt{1 - \frac{z_{\mathrm{D}}}{R}} \tag{4}$$

$$\boldsymbol{q}_{\mathrm{DI}} = 2K_{\mathrm{B}}\sqrt{2\boldsymbol{g}}h_{\mathrm{D}}^{3/2} \tag{5}$$

in which K_{B} is a coefficient taking into account both the sediment concentration and the bore properties (for the case of run-up overwash), and the sediment concentration and weir coefficient (for the case of inundation overwash). K_B is not necessarily the same for Equations 4 and 5, but if the equations are compared for the inundation case – that is, run-up overwash occurs for a duration $t_D/T = \sqrt{1 - z_D/R}$ and h corresponds to $R - z_D$ – the mathematical formulations become identical, indicating that it is convenient to assume that the empirical coefficient is the same for the two equations. Although using the same coefficient for both run-up and inundation overwash is a marked simplification, this assumption provides a convenient formulation to make the overwash model easy to apply.

2.3. Hydrodynamics and sediment transport landward of the beach crest

Landward of the beach crest, the processes are considered the same for either run-up or inundation overwash. Initially, due to the force of gravity on the rear slope, the flow accelerates; however, the distance over which acceleration occurs is assumed to be short and the flow is therefore considered to be steady (due to the balance of frictional and gravitational forces) and described by a block of water moving down a slope. This block represents the volume overtopping the crest for run-up overwash, but in the limit of inundation overwash the same mathematical description is employed. As the block of water moves down the slope, it widens due to lateral spreading, and becomes shallower due to infiltration. The schematised block is illustrated in Figure 2.

It is assumed that infiltration is proportional to the height of the block, where α is the proportionality constant. The balance of forces (gravity and friction) will yield a velocity for the block, and the continuity equation can then be solved yielding the following exponential expression for the height of the block, h, as a function of time, t, from the start of discharge over the crest

$$h = \frac{B_D}{B} h_D e^{-\alpha t} \quad (6)$$

where B_D and h_D are the width and height of the block at the beach crest. The width of flow, B, at any distance along the slope, s, can be estimated assuming a linear spreading rate, $\boldsymbol{\mu}$. If the time after discharge over the crest, t, is replaced by the velocity of the block, and the distance travelled by the block, s, ($s = \boldsymbol{u}t$) an implicit equation for h results. (see Appendix 1 for full derivation of Equations 6 and 7.)

$$h = \frac{1}{1 + \boldsymbol{\mu} s/B_D} h_D e^{-\frac{\alpha}{k_f}\frac{s}{\sqrt{gh}}} \quad (7)$$

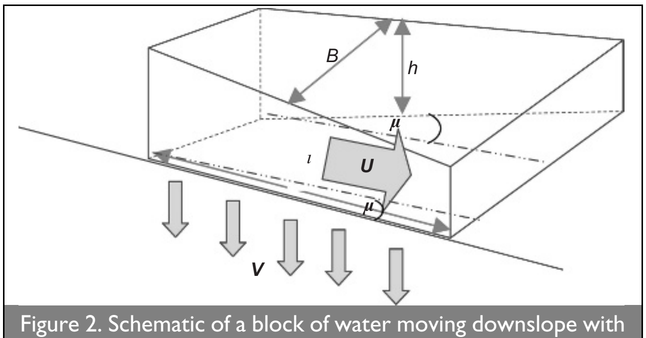

Figure 2. Schematic of a block of water moving downslope with lateral spreading and infiltration

To facilitate the rapid solution of Equation 7, it was made non-dimensional by replacing the water depth, h, with $\boldsymbol{u}$. Sediment transport on the back barrier was calculated assuming a transport rate proportional to the velocity cubed to yield:

$$\boldsymbol{q}_f = K_c \frac{\boldsymbol{u}^3}{\boldsymbol{g}} \quad (8)$$

In order to employ the overwash model, boundary conditions are needed at the seaward end of the swash zone, as well as a realistic coupling between the sub-aerial and sub-aqueous portion of the beach. For this study, the overwash algorithm was coupled with the SBeach model which is a numerical model for simulating storm-induced beach change;[6] however, any similar beach profile erosion model could have been used. Utilisation of the SBeach model allows for simulation of waves, sediment transport, and beach profile change seaward of the swash zone. Input to SBeach typically consists of deep water wave conditions, which are readily available for most engineering studies. A finite-difference scheme was used to solve the sediment continuity equation for each time-step after the transport rates had been calculated in accordance with the formulas presented previously. Implementation of the overwash model within the SBeach dune erosion model is briefly described in Appendix 2.

3. DATA EMPLOYED

Pre- and post-storm profile data were used to calibrate and verify the overwash model. The input data required to model beach profile change in the overwash model (and SBeach) is a measured beach profile prior to a storm in which overwash occurred, a median sand grain size for the surf zone, and the hydrodynamic data (wave height, wave period and water level) for the duration between the input measured profile and the point in time at which a profile estimate is required (i.e. after the storm). For the calibration and verification of the model, a measured, post-storm, beach profile is also required. Temporal resolution of the water level data is important, and it is recommended that a resolution of 60 min is not exceeded in order not to miss the storm surge peak.

Previously published data were collated from six different studies. The availability of both pre- and post-storm profiles within a reasonable time period of an event in association with nearby measurements of wave characteristics during the event is rare. The collection of in situ data during overwash events is also difficult and dangerous, so pre- and post-storm beach profile data provide the best indication of sediment transport during an event. All of the field profiles were from the United States Atlantic (east) coast. The data sets cover a wide variety of profiles from low, flat, dune-less barrier islands, to distinctive dune systems. In some cases, the pre- and post-storm profiles encompass a series of north-easter storms causing overwash that occurred in close succession. In total, 26 different cases were tested. The data sets are summarised in Table 1. If the seaward extent of the initial profile was insufficient for modelling in SBeach, the initial beach profile was extended using the equilibrium beach profile shape proposed by Dean[14] based on the representative median grain size. The sensitivity of the simulation results for the sub-aerial portion of the beach in the cases where the offshore profile shape was extended was negligible.

Older data sets were found for Manasquan Beach, New Jersey,[8] and Metompkin Island, Virginia.[1] Manasquan is a relatively narrow urbanised mainland beach which was overwashed in the March 1984 north-easter. This beach was severely eroded and overwashed by a north-easterly storm lasting 2 days. Sub-aerial profile surveys were taken 1 to 2 days prior to and 3 to 4 days after the storm, while a waverider buoy in 15·2 m water depth collected wave height data. Metompkin Island is an undeveloped, low, flat, barrier island which was overwashed by Hurricane Gloria in September 1985. Pre-storm surveys are from November 1993, and post-storm surveys were taken in November 1985.[1]

Ocean City, Maryland, an urbanised shoreline located immediately to the north of Assateague Island, was subject to three north-easterly storms causing overwash in the winter of 1991/1992, which are encompassed in the pre- and post-storm survey period. The beach at Ocean City was nourished, dunes constructed, and pre-storm profiles measured about 4 months prior to the storms. A post-storm survey was taken immediately following the third storm in January 1992. Wave and water level data were available from a buoy in 10 m depth.[8]

Garden City Beach and Folly Beach, South Carolina, are both urbanised barrier island beaches on the South Carolina coast. Overwash occurred at both these beaches during Hurricane Hugo, which crossed the South Carolina coast in September 1989. Profiles at Garden City were taken from the low-lying unarmoured spit to the south. Profiles at Folly Beach were taken from the entire length of beach and collected a few months prior to the hurricane. Post-storm profiles were collected within 10 days after landfall of the hurricane. Water level data were taken from the nearest operating NOAA tide gauge (8667246 at Winyah Bay), and wave data were taken from the WIS database (station 314, see http://frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html). The hindcast WIS data were used in preference to offshore gauge data to avoid modelling the energy dissipation over the continental shelf. The WIS data from hurricane events were deemed accurate enough for this study. There are some profiles encompassing the central portion of Folly Beach where revetments were destroyed and overwashed. A comprehensive description of the effects of Hurricane Hugo on these beaches can be found in Eiser and Birkemeier.[9]

The final data set is from Assateague Island, Maryland, which was subject to two significant north-easterly storms in January 1998, both resulting in overwash. The pre- and post-storm survey period encompasses both storms.[10] Wave height, period, and water level were measured at a nearshore gauge. Assateague is a low, flat, undeveloped, barrier island with remnant foredunes present in some locations.

4. CALIBRATION AND VERIFICATION PROCEDURE

Visual inspection and statistical goodness-of-fit parameters were used to evaluate the model performance for various calibration parameters and for verification. Visual inspection was used for initial calibration, and values of the root-mean-square error (E_{RMS}) and residual error (E_{RES}) were used to fine-tune the overwash parameters. E_{RMS} and E_{RES} are calculated using

$$E_{RMS} = \sqrt{\frac{1}{N_p}\sum_{j=1}^{N_p}(y_m - y_c)^2} \tag{9}$$

$$E_{RES} = \frac{\sum_{j=1}^{N_p}\sqrt{(y_m - y_c)^2}}{\sum_{j=1}^{N_p}\sqrt{(y_i - y_m)^2}} \tag{10}$$

where y_c is the calculated final profile elevation, y_i the initial profile elevation, y_m the measured final profile elevation, and N_p the number of points across the profile. As the focus of this study is on overwash deposits, E_{RMS} and E_{RES} were calculated only on the sub-aerial portion of the measured post-storm profile.

The model was applied to the field data sets using default values of non-overwash calibration parameters present in SBeach which were established following extensive testing of the SBeach model on laboratory and field data.[6,8,15,16] One profile, showing good landward extent (length) of overwash, was chosen to be calibrated for each location, varying the overwash parameter, K_B, the lateral spreading parameter, C_{ls}, and the infiltration parameter, C_{infilt}, where

$$C_{ls} = \frac{\boldsymbol{\mu}}{B_D} \tag{11}$$

$$C_{infilt} = \frac{\alpha}{\boldsymbol{u}_D} \tag{12}$$

The throat width at the crest, B_D, is included within C_{ls}, because such data are usually unavailable with beach profile data, and the inclusion of $\boldsymbol{u}_D$ provided a convenient non-dimensional form of the sediment transport (see Appendix 2). Not all of the available profiles were measured to a point of closure on the landward side, so choosing a profile for calibration with good landward extent of overwash allows for the best estimate of the lateral spreading and infiltration parameters.

The overwash parameters were fine-tuned, using E_{RMS} and E_{RES} for guidance. The error values calculated on the sub-aerial profile were used to choose the final best calibration parameters for the profile. The calibrated model was then verified on other profiles from the same location under the same storm. For model verification, the parameters calibrated for a profile were used to test how well the model performed on other profiles, in this case from the same general location under the same storm. The model was run with the calibrated parameters and the simulated profile compared with the measured profile at the new location. Successful verification of a model is essential to recommend its use in practical applications.

5. RESULTS

In general, it was possible to achieve a good calibration and verification for a wide range of beach profile types and overwash magnitudes, including both run-up and inundation overwash. The model was able to reproduce dune destruction (F-2883 and GC-4930), dune crest erosion (F-2801), barrier rollback (A-3720), and overwash over a multiple dune system. These examples are shown in Figures 3 to 6. Table 2 summarises

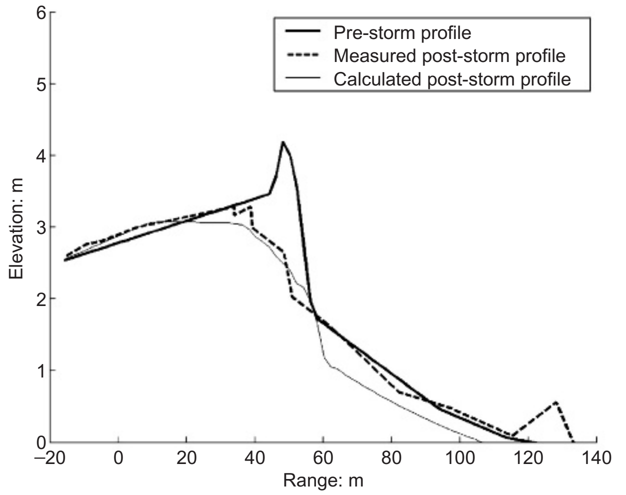

Figure 3. Results of model calibration for profile 2883 at Folly Beach, SC

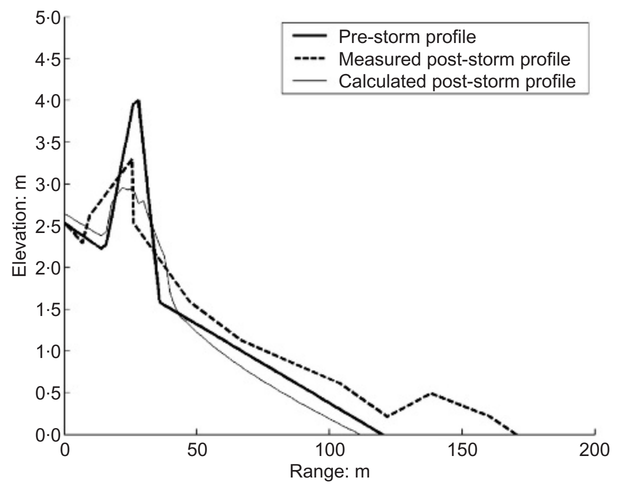

Figure 4. Results of model verification for profile 2801 at Folly Beach, SC

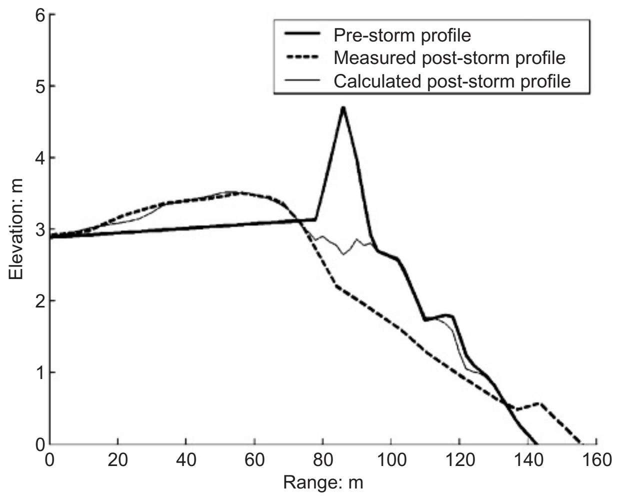

Figure 5. Results of model calibration for profile 4930 at Garden City Beach, SC

the calibration parameters and Table 3 the errors, E_{RMS} and E_{RES}, for the model calibrations and verifications at the various sites.

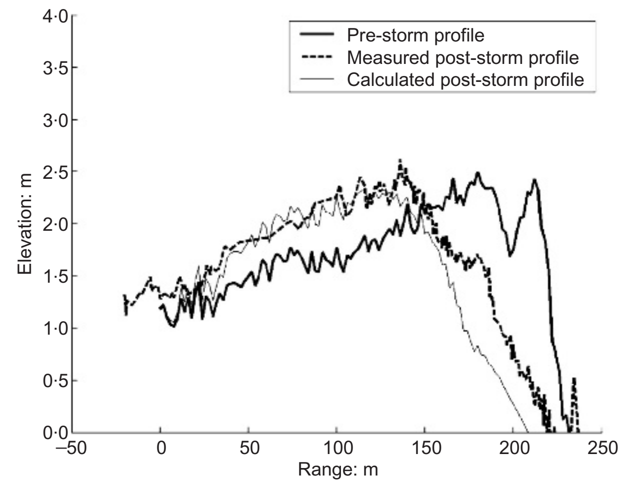

Figure 6. Results of model calibration for profile 3720 at Assateague Island, MD

Satisfactory verifications of the model were made for the Garden City, Manasquan, Metompkin, and some of the Folly Beach and Assateague profiles using these calibrations. With the exception of Ocean City, E_{RMS} for the verified profiles was less than 0·5. This satisfactory result means that the model can be confidently used to predict washover occurrence, penetration and thickness, if a profile from the same region can be calibrated for a similar-sized storm. Verification of the Ocean City profiles was less satisfactory. There is an uphill slope behind the dune crest in each of the Ocean City profiles. The algorithm used on the back barrier cannot take this into account. Furthermore, post-nourishment losses, compaction or settlement may have contributed to profile changes between the pre- and post-storm profiles on this nourished beach. Figure 7 shows the results of a satisfactory verification run at Folly Beach, and Figure 8 shows the results of a satisfactory verification run at Assateague Island where overwash at a multiple dune system is observed. Figure 4 is also from a successful verification run at Folly Beach.

A few of the Folly Beach and Assateague profiles were difficult to validate. Aerial photography and the pre-storm morphology of these regions may provide clues as to why. Five of the eight Folly Beach profiles, which were from the southern end and central parts of Folly Beach, validated poorly using calibration parameters from the north. The washover volume was over-estimated. It was already known that central Folly Beach was revetted and highly urbanised, and aerial photography indicated that the southerly profiles were also taken through a highly urbanised area. Overwash in this region penetrated revetments,[9] so sediment availability for overwash seems to have been reduced at these locations, probably due to concrete surfaces. It was possible to validate the overwash parameters at Folly Beach by reducing the sediment transport rate coefficient for the surf zone within the SBeach model.[6] This coefficient governs the magnitude of the sediment transport rate in the surf zone, and hence the situation of limited sediment available for overwash could be simulated. (Figure 4 shows one such Folly Beach profile.)

Different processes affected the similarity of the profiles at Assateague Island. Assateague is a dynamically changing, undeveloped barrier island, and the morphology of the tested profiles varied from low, dune-less barrier island, to multiple

Location	Calibrated profile	K_B	C_{ls}	C_{infilt}
Manasquan, NJ	Mn-4	0·0010	0·001	0·001
Metompkin Island, VI	Mt-10	0·0007	0·003	0·005
Garden City Beach, SC	GC-4930	0·0004	0·020	0·040
Folly Beach, SC	F-2883	0·0010	0·020	0·040
Ocean City, MD	OC-45	0·0050	0·005	0·005
Assateague Island, MD	A-3720	0·0010	0·003	0·005

Table 2. Calibration results for the various data sets

Location	E_{RMS}: calibrated	E_{RMS}: range verified	E_{RES}: calibrated	E_{RES}: range verified
Manasquan, NJ	0·352	0·4	0·272	0·3 to 0·9
Metompkin Island, VI	0·279	0·3	1·410	0·5 to 1·4
Garden City Beach, SC	0·383	0·3 to 0·4	0·509	0·5 to 0·9
Folly Beach, SC	0·311	0·2 to 0·5	1·078	0·4 to 1·1
Ocean City, MD	0·563	0·2 to 1·1	0·777	0·3 to 1·5
Assateague Island, MD	0·328	0·1 to 0·3	0·437	0·3 to 0·7

Table 3. Summary of error parameters for the calibrated and verified data sets

systems of dunes. Three of the six profiles performed excellently with the calibrated parameters: the other three performed poorly with the same parameters. An attempt was made to calibrate

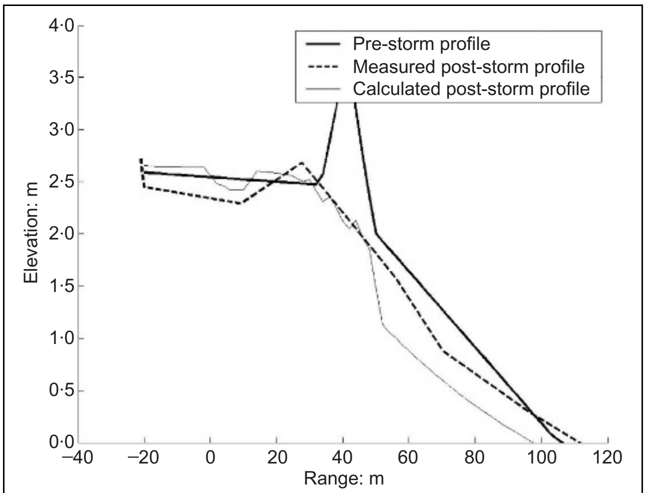

Figure 7. Results of model verification for profile 2880 at Folly Beach, SC

these profiles in order to try to link variation in the calibration parameters with physical overwash processes. The profile at A-GPS4, appears to have been severely inundated, hence lateral spreading and infiltration parameters were lower than for the other profiles in the same region. The overwash transport parameter, for reasons discussed below, was also reduced. The calibrated profile at A-GPS4 is shown in Figure 9, showing barrier island rollover caused by inundation overwash. The profile at A-GPS1 required yet different calibration parameters, but it was possible to verify these parameters at A-GPS3. These results indicate that some further local processes affect these parameters.

6. DISCUSSION

The overwash transport parameter (K_B) was shown to vary over an order of magnitude depending on location and storm. Profiles in regions without dunes or where dunes were rapidly destroyed by overwash underwent inundation overwash. These profiles required a much smaller K_B value for calibration/verification than those profiles which mostly underwent run-up overwash. The coefficient, K_B, takes into account the concentration of sediment in the overtopping flow and the hydraulic

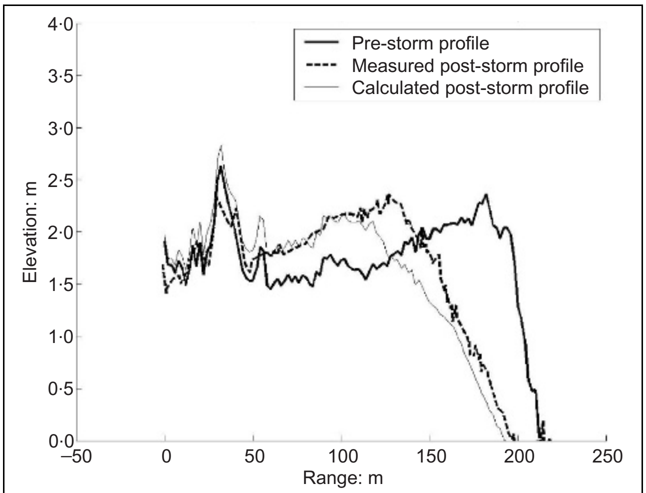

Figure 8. Results of model verification for profile 2330 at Assateague Island, MD

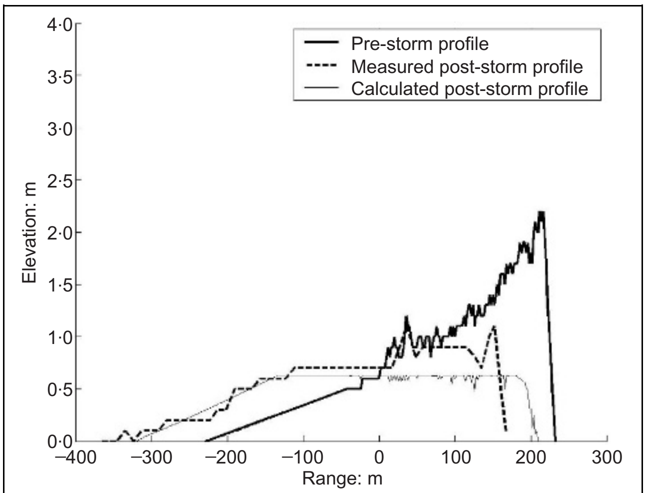

Figure 9. Results of model calibration for profile A-GPS4 at Assateague Island, MD

conditions at the crest. For the case of inundation overwash, the latter should be a weir coefficient, whereas for the case of run-up overwash it should be a bore coefficient. This indicates good reason to separate the two coefficients from the original model formulations; however, without through-storm profile data, the relative contributions of the two parameters would be difficult to determine. The model is therefore expressed in terms of K_B with the acknowledged limitation that the calibrated model is most applicable only for the same overwash regime (run-up or inundation) as it varies depending on the relative duration of run-up and inundation overwash during an event.

The lateral spreading and infiltration parameters, C_{ls} and C_{infilt}, were site specific. The C_{ls} value varies depending on whether or not a profile is located in the throat of a washover and the location and amount of vegetation on a profile. The C_{infilt} parameter varies with how saturated the incipient barrier region is prior to overwash. Whether or not inundation overwash occurs and the magnitude of inundation also affected these values. For example, lower values of C_{ls} and C_{infilt} were used to calibrate the Assateague Island profiles at which unconfined inundation overwash occurred (GPS4, Figure 9). C_{infil} was low in this case because inundation overwash was not confined, and lateral spreading was therefore negligible. It is suggested that C_{infilt} was low because an inundated barrier would quickly become saturated. Successful verifications indicate that the same lateral spreading and infiltration parameter values could be applied to all profiles in a region. This is of value because often, specific data regarding infiltration rates and lateral spreading rates are unavailable.

The approach presented simplifies a complicated three-dimensional flow problem into a 1-D and quasi-2-D model. The main limitation of this approach is that it is ideally applicable only in the centre of a washover throat or where overwash is uniform alongshore. Often fanning overwash is observed to occur at pre-existing washover throats or low points in dune crests[17] and inundation overwash may be assumed to be widespread and uniform where a longshore section of dune crest is inundated. In the 1-D/quasi-2-D approach, interaction between washover fans is not taken into account; however, this approach does not rule out the inclusion of such interactions in a simplified form in future model formulations.

This new overwash model introduces the capability to predict sub-aerial beach profile response to overwash events given readily available input data. Prediction of overwash occurrence is useful for beach fill profile design and coastal vulnerability assessments. The ability to predict the landward penetration of washovers may be useful for emergency evacuation planning, and town planning of the coastal strip. Prediction of washover volumes may be useful in studying sediment budgets of barrier islands, in ecology studies where washover habitat is important and in emergency response planning, where clean-up volumes of sand need to be estimated. The satisfactory verifications indicate that the sub-aerial overwash model performance, as implicated, is of the same order of magnitude as that of currently used beach and dune erosion models (when overwash does not occur).

7. CONCLUSIONS

A model for calculating beach profile change due to overwash was developed taking into account two different flow regimes over the beach crest, namely run-up and inundation overwash. Testing of the 1-D model with 2-D considerations using 27 profiles from six different locations indicated that the model is capable of reproducing a wide range of overwash morphologies including dune crest erosion, dune destruction, barrier rollback, the thinning of a washover deposit on the backbarrier, and overwash over a multiple dune system.

Ballistics theory was used to calculate the hydrodynamics in the swash zone and the flow rate over the beach crest during run-up overwash, whereas weir overflow theory was used to calculate the flow rate over the beach crest during inundation overwash. The concentration of sediment in the overwashing flow was assumed constant following Kobayashi *et al.*[13] The water flow on the back barrier slope, averaged over many wave cycles, was calculated by considering the continuity of a block of water at steady state, including lateral spreading and infiltration, and the sediment transport rate was assumed proportional to the velocity cubed. The model was implemented within the SBEACH numerical model for simulating storm-induced beach profile change.[6] The model was successfully validated for profiles within the same region, indicating its suitability for predicting beach profile change caused by overwash. The ability to predict the occurrence of, penetration of and volume of overwash may be used for coastal vulnerability assessments, town planning, emergency response planning and beach fill profile design, as well as in ecological and geological studies where barrier island sediment budgets and available washover habitat are of importance.

APPENDIX 1: DERIVATION OF RELATIONSHIP FOR SEDIMENT TRANSPORT ON THE BACK BARRIER SLOPE

The balance of forces (gravity and friction) will yield a velocity for the block

$$u = k_f \sqrt{gh} \quad (13)$$

where

$$k_f = \sqrt{\frac{2\sin\beta}{f_c}} \quad (14)$$

in which f_c is a friction coefficient and β the back barrier slope. The volume of the block, V, is equal to the product of the width, B, the length, l, and the height, h, and therefore, if the infiltration rate, v, is assumed proportional to h, the conservation of water for the block is given by

$$\frac{dV}{dt} + vBl = 0 \quad (15)$$

and

$$\frac{dV}{dt} + \alpha hBl = \frac{dV}{dt} + \alpha V = 0 \quad (16)$$

where α is the proportionality coefficient for the infiltration rate. This continuity equation can then be solved yielding the following exponential expression for the height, h

$$h = \frac{B_D}{B} h_D e^{-\alpha t} \quad (17)$$

where B_D and h_D are the width and height of the block at the beach crest (assuming that l is constant). If the time after discharge over the crest, t, is replaced by the velocity of the block, obtained from Equation 13 and the distance travelled by the block, s, an implicit equation for h results

$$h = \frac{B_D}{B} h_D e^{-\alpha s/\boldsymbol{u}} = \frac{B_D}{B} h_D e^{-\frac{\alpha}{k_f}\frac{s}{\sqrt{gh}}} \quad (18)$$

The width of flow, B, at any distance, s, along the slope from the crest can be estimated assuming a linear spreading rate, $\boldsymbol{\mu}$

$$B = B_D\left(1 + \boldsymbol{\mu}\frac{s}{B_D}\right) \quad (19)$$

which can be substituted into Equation 18, yielding

$$h = \frac{1}{1 + \boldsymbol{\mu} s/B_D} h_D e^{-\frac{\alpha}{k_f}\frac{s}{\sqrt{gh}}} \quad (20)$$

APPENDIX 2: IMPLEMENTATION OF OVERWASH MODEL WITHIN SBEACH

For this study, the overwash algorithm was coupled with the SBEACH model which is a numerical model for simulating storm-induced beach change.[6] To facilitate rapid solution of Equation 20, it was made non-dimensional by replacing the water depth h with $\boldsymbol{u}$, using Equation 13 and introducing the following non-dimensional quantities

$$s' = \boldsymbol{\mu}\frac{s}{B_D}, \quad \alpha' = \frac{\alpha B_D}{\boldsymbol{\mu} u_D}, \quad \xi = \frac{\boldsymbol{u}}{\boldsymbol{u}_D} \quad (21)$$

The principal hydrodynamic equation therefore becomes

$$\xi = \frac{1}{\sqrt{1 + s'}} e^{-\frac{1}{2}\alpha'\frac{s'}{\xi}} \quad (22)$$

where the first term represents the effect of the lateral spreading and the second the effect of the infiltration. Sediment transport on the back barrier was calculated assuming a transport rate proportional to the velocity cubed

$$\boldsymbol{q}_f = K_c\frac{\boldsymbol{u}^3}{\boldsymbol{g}} \quad (23)$$

where K_c is a constant. Normalising with the transport rate calculated for the crest gives

$$\frac{\boldsymbol{q}_f}{\boldsymbol{q}_D} = \left(\frac{\boldsymbol{u}}{\boldsymbol{u}_D}\right)^3 = \xi^3 \quad (24)$$

Linking of the overwash model and SBeach was straightforward, as the SBeach model is already divided into various sediment transport regions. The overwash model was applied landward of the surf–swash zone boundary when overwash conditions were fulfilled. The algorithm for calculating run-up, derived by Larson and Kraus[6] based on empirical analysis of large wave tank data was retained. A hypothetical run-up height was also calculated for the overwash cases, which was the height the run-up would reach if the representative beach slope extended infinitely from the SWL. The beach crest was defined as the highest point on the profile that the run-up would exceed. Thus, if a profile had a dual dune system, the most seaward dune crest was considered the beach crest, unless the hypothetical run-up height exceeded the more shoreward dune crest.

The transition from the offshore-directed transport at the boundary between the swash zone and the surf zone to the landward transport at the beach crest is described by Equation 1. This equation maintains the derived shape of the swash-zone transport in the seaward part of the swash zone, as a smooth transition towards the transport rate at the beach crest is simultaneously ensured. In order to obtain a smooth transition between run-up and inundation overwash, and to fulfil the perception that the higher the water level, the larger the overwash, the following model is applied

$$\boldsymbol{q}_D = \boldsymbol{q}_{DR}\{R - z_D\} \qquad \text{MWL} < z_D \quad (25)$$

$$\boldsymbol{q}_D = \boldsymbol{q}_{DR}\{R\} + \boldsymbol{q}_{DI} \qquad \text{MWL} > z_D \quad (26)$$

where $\boldsymbol{q}_D$ is the sediment transport rate over the beach crest, and $\boldsymbol{q}_{DR}\{R - z_D\}$ denotes that the run-up overwash transport rate should be calculated for a run-up elevation of $R - z_D$, and $\boldsymbol{q}_{DI}$ is the sediment transport rate for inundation overwash. In the second equation it is not obvious that a contribution from the run-up (as a constant value) can be added in this way, but if such a contribution is not added, there will be a discontinuity in the transport rate as the switch to inundation occurs. The extra contribution from run-up overwash may be seen as the contribution from overwashing waves during inundation overwash.

It should be noted that in the simplifications made to arrive at the sediment transport equation for the back barrier (see Equations 23 and 24), the overtopping velocity at the crest was set equal to the steady flow velocity equation given by Equations 13 and 14. Thus, the transport rate became independent of the back barrier slope. Furthermore, the initial throat width was incorporated into the lateral spreading coefficient in order to avoid an additional quantity to specify (no data were available on the throat width). These simplifications make the model easier to apply for readily available input data, although some of the generality of the model is lost.

ACKNOWLEDGEMENTS

Part of the work was performed under the European Commission research project Floodsite (Contract Number: GOCE-CT-2004-505420). This study was also supported by the Coastal Morphology Modeling and Management work unit of the Regional Sediment Management (RSM) Program, US Army Corps of Engineers. Overwash profile data to test the model were received from William Eiser, Randall Wise and Mark Byrnes and they are thanked for their input. Assistance with the SBEACH interface was provided by Randall Wise. USGS kindly supplied some of the profile data from Assateague Island. Useful comments by the anonymous reviewers improved the paper.

REFERENCES

1. BYRNES M. R. and GINGERICH K. J. Cross-island profile response to Hurricane Gloria. In *Proceedings of Coastal Sediments '87* (ASCE), New Orleans, 1987 (KRAUS N. C. (ed.)). ASCE, New York, NY, USA, 1987, pp. 1486–1502.
2. DOUGLASS S. L., HUGHES S., ROGERS S. and CHEN Q. *The Impact of Hurricane Ivan to the Coastal Roads in Florida and Alabama: A Preliminary Report*. Coastal Transportation Engineering Research & Education Center, University of South Alabama, Mobile, AL, USA, 2004.
3. SALLENGER A. H. JR. Storm impact scale for barrier islands. *Journal of Coastal Research*, 2000, **16**, No. 3, 890–895.
4. DONNELLY C., KRAUS N. C. and LARSON M. State of knowledge on measurements and modelling of coastal overwash. *Journal of Coastal Research*, 2006, **22**, No. 4, 965–999.
5. KRAUS N. C. and WISE R. A. Simulation of January 4, 1992 storm erosion at Ocean City, Maryland. *Shore & Beach*, 1993, **61**, No. 1, 34–41.
6. LARSON M. and KRAUS N. C. *SBEACH. Numerical Model for Simulating Storm-induced Beach Change; Report 1. Empirical Foundation and Model Development*. US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS, USA, 1989, Technical Report CERC-89-9.
7. KRIEBEL D. L. and DEAN R. G. Numerical simulation of time-dependent beach and dune erosion. *Coastal Engineering*, 1985, **9**, No. 3, 221–245.
8. WISE R. A., SMITH S. J. and LARSON M. *SBEACH: Numerical Model for Simulating Storm-induced Beach Change; Report 4, Cross-shore Transport Under Random Waves and Model Validation with SUPERTANK and Field Data*. Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA, 1996, Technical Report CERC-89-9.
9. EISER W. C. and BIRKEMEIER M. Beach profile response to Hurricane Hugo. In *Proceedings Coastal Sediments'91* (ASCE), Seattle, 1991 (KRAUS N. C., GINGERICH, K. J. and KRIEBEL D. L. (eds)). ASCE, New York, NY, USA, 1991, pp. 1681–1696.
10. LARSON M., WISE R. A. and KRAUS N. C. Modeling dune response due to overwash transport. In *Proceedings 29th Coastal Engineering Conference (ASCE), Lisbon*, 2004 (SMITH J. M. (ed.)). World Scientific Press, Singapore, 2005, pp. 2133–2145.
11. MADSEN O. S. Mechanics of cohesionless sediment transport in coastal waters. In *Proceedings Coastal Sediments'91* (ASCE), Seattle, 1991 (KRAUS N. C., GINGERICH, K. J. and KRIEBEL D. L. (eds)). ASCE, New York, NY, USA, 1991, pp. 15–27.
12. HANCOCK M. W. and KOBAYASHI N. Wave overtopping and sediment transport over dunes. In *Proceedings of the 24th Coastal Engineering Conference* (ASCE), Kobe, 1994 (EDGE B. L. (ed.)). ASCE, New York, NY, USA, 1994, pp. 2028–2042.
13. KOBAYASHI N., TEGA Y. and HANCOCK M. W. Wave reflection and overwash of dunes. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 1996, **122**, No. 3, 150–153.
14. DEAN R. G. *Equilibrium Beach Profiles: US Atlantic and Gulf Coasts*. University of Delaware, Newark, Delaware, USA, 1977, Ocean Engineering Report No. 12.
15. LARSON M., KRAUS N. C. and BYRNES M. R. *SBEACH: Numerical model for simulating storm-induced beach change; Report 2, Numerical formulation and model tests.* Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA, 1990, Technical Report CERC-89-9.
16. ROSATI J. D., WISE R. A., KRAUS N. C. and LARSON M. *SBEACH: Numerical Model for Simulating Storm-induced Beach Change; Report 3, User's Manual.* Coastal Engineering Research Center, US Army Engineer Waterways Experiment Station, Vicksburg, MS, USA, 1993, Instruction Report CERC-93-2.
17. DONNELLY C. AND SALLENGER JR A. H. Characterisation and modelling of washover fans. In *Coastal Sediments '07* (KRAUS N. C. and ROSATI J. D. (eds)). ASCE Reston, VA, USA, 2007, pp. 2061–2073.