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CHARACTERISATION AND MODELLING OF WASHOVER FANS

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Abstract: Pre- and post-storm topography and aerial photography, collected in regions where new washover fans were formed, were studied to determine the extent of morphologic, vegetative and anthropogenic control on washover shape and extent. When overwash is funnelled through a gap in a dune ridge and then spreads laterally on the back barrier, decelerating and depositing sediment, it forms washover fans. Fans were shown to primarily occur at pre-existing gaps in the foredune. During overwash, these gaps, or overwash throats, widened and deepened. The shape and extent of the fan was shown to depend on not only the pre-storm topography, but also the existence of beach tracks, roads and other anthropogenic influences and vegetation. The cross-shore overwash profile change model by Larson et al. (2005) and Donnelly et al. (2005) was modified to include pre-storm throat widths and a lateral spreading angle estimated from the pre-storm topography as inputs and tested using cross-shore profiles through the fan centres. These new inputs make the model more generalised, such that the calibrated model is applicable to a wider range of cross-shore profiles.

INTRODUCTION

Recent increases in frequency and intensity of tropical storms highlight the importance of understanding physical storm phenomena such as overwash. Overwash is the transport of water and sand landward of the beach crest by elevated wave and water levels, sometimes as far as the back barrier bay or lagoon (in the case of barrier island overwash). The sediment deposited by overwash is usually described as washover.

Washover contributes to the sediment budget of barrier islands and is thought to maintain the width of barrier islands as they migrate landward. It can also provide specific habitat for endangered species such as the piping plover. Overwash can also be a hazard, particularly on developed coasts where water and sand intrusion, scour (of coastal roads for example), and even structural damage by debris entrained in the overwashing flow cause problems. The ability to predict the occurrence, magnitude and shape of overwash deposits is therefore of importance to coastal managers, authorities and residents alike. The causes of overwash and overwash processes are well documented (e.g. Hayes 1967, Leatherman 1976, Donnelly et al. 2006), and the ability to predict overwash occurrence (Sallenger et al. 2000) and model beach profile change due to overwash (Wise et al. 1996 , Larson et al. 2005, Donnelly et al. 2005) is just beginning to emerge.

Washover fans are formed when overwash is focused through a local gap in the dune ridge. This gap is known as an overwash throat. Behind the dune ridge the overwashing flow spreads laterally. At the same time the flow decelerates due to the combined effects of lateral spreading, friction and infiltration. Local topography changes may also decelerate (or accelerate) flow. As the flow decelerates, entrained sediment is deposited, forming a washover fan. Such features are commonly identified on the US Gulf and Atlantic coasts following major hurricanes and northeasterly storms.

Data consisting of high resolution, three-dimensional, pre-and post-storm topography collected by lidar, and oblique aerial photography, were collated for several washover fans. The data showed washover fans on Hatteras Island, NC, following Hurricane Isabel, 2003. This high quality data provided the unique opportunity to, for a number of deposits, analyse washover fan shapes and morphologies, measure pre- and post-storm washover throat widths, identify topographical and surface texture restraints on lateral spreading, and in some cases, estimate a potential lateral spreading angle.

Using measurements of the throat width, B_{pre}, and the potential lateral spreading angle, β, an existing algorithm for overwash flow behind the crest of a mainland or barrier beach by Donnelly et al. (2005) and Larson et al. (2005) was tested with these new inputs. Previously these dimensions have been included in the model through coefficients which were calibrated to the post-storm data. The inclusion of these new inputs makes the model more generalised, and hence a calibrated model should be applicable to a wider range of profiles.

DATA EMPLOYED

Hatteras Island is an 80 km long barrier island located in North Carolina, on the Atlantic Coast of the U.S.A. The island has a distinct bend at Cape Hatteras such that the southern portion of the island is facing south-southeast while the northern portion of the island faces east-southeast (Figure 1). The island is relatively undeveloped, with a population of just 4000. A paved road extends parallel to the shore along the island. Hurricane Isabel made landfall as a category 2 hurricane on September 18, 2003 near Cape Hatteras causing numerous washover deposits along the coast. Maximum sustained winds of 128 km/hr were measured near the cape, and maximum deepwater wave heights were estimated to exceed 15 m offshore of the cape. Along the Hatteras coast, the storm surge exceeded 2m (Fauver 2005).

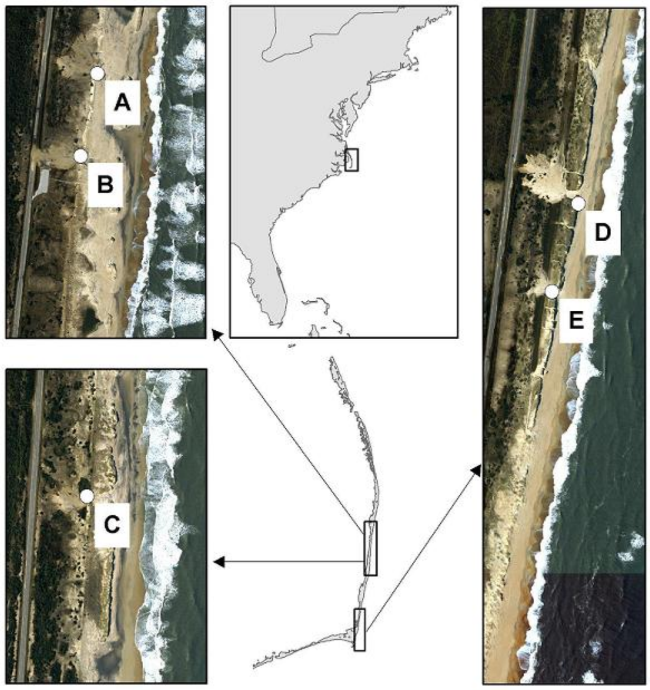


Figure 1. Location map showing U.S. Atlantic Coast, Hatteras Island, and aerial photographs showing locations of the studied fan deposits.

Airborne topographic lidar (light detection and ranging) surveys were used to collect topographical data along the Hatteras Island shoreline immediately prior to and after the landfall of Hurricane Isabel. The pre-storm survey was made September 16, 2003, immediately prior to the first storm wave impacts on the shoreline (Fauver 2005) and the post-storm survey was made on September 21, 2003. The topographic survey data analyzed in this study was collected approximately 45 km northeast of the point of landfall. Oblique and geo-rectified aerial photographs of the Hatteras coastline were also taken on September 21, and these may be compared with pre-storm oblique aerial photographs taken after the previous major storm in 1999.

Lidar surveys allow the rapid collection of large regions of topographic data. Further information about the lidar survey technique and its application in the coastal environment can be found in Brock et al. (2002). In a study statistically comparing data collected using lidar with three traditional ground survey techniques, the accuracy of the individual lidar elevation measurements was deemed to be approximately 15 cm (Sallenger et al. 2003). This level of accuracy is generally suitable for studying changes due to overwash. Large deposit regions with thicknesses of the order of 10-15 cm are observed; however if the measurement error is not systematic, the existence of these deposits is true, even if the accuracy of the deposit thickness may vary from that measured.

Three regions of pre- and post-storm topographic lidar data in which washover fans occurred were selected (Figure 1). All data is from the section of shoreline north of Cape Hatteras. Each region encompassed a stretch of coastline approximately 650 m long and 250 – 300 m wide from the shoreline landwards. The survey data was linearly triangulated onto a 2 x 2 m grid and plotted on contour maps to evaluate the pre- and post- storm topography. A difference grid, showing the differences in elevation between the pre-storm and the post-storm grids was also calculated and plotted as a contour map, the topography differences map. Cross-sections and alongshore sections were extracted from the grid data for regions of interest.

Hydrodynamic data was also available. A 3-hourly time-series of significant wave-height and peak wave period was extracted from NOAA's WAVEWATCH III model (Tolman 1997, 1999) for a period spanning the pre- and post-storm surveys. The data was extracted at the pre-storm location of the Diamond Shoals wave buoy (41025, depth 54.9 m), which stopped recording some hours prior to storm landfall, hence the use of hindcast wave characteristics. The nearest NOAA tidal gauge, Hatteras Fishing Pier, also failed during the peak of the storm; however, water level data is available from the NOAA Duck Field Research Facility tidal gauge (8651370) which was shown to correlate well with the Hatteras gauge prior to failure (Fauver 2005).

The combination of pre- and post storm topographic data and aerial photography taken immediately prior to and following a hurricane landfall, the sections plotted from the data, and the associated hydrodynamic data, allowed the opportunity to study the morphologic, anthropogenic and surface texture controls on washover fan formation, and model cross-shore profile change caused by overwash using knowledge of these controls.

DATA ANALYSIS

The post-storm changes on the island can be evaluated by examining the topography differences map (the difference between the post-storm and pre-storm elevations) and the post-storm aerial photography. Figure 2 shows an example of a topography differences map (left) beside the pre-storm topography map (right). Positive values of topography difference indicate deposition, and negative values indicate erosion. A general inspection of these maps indicates erosion of the dune face and crest and isolated deposits behind the pre-storm dune location. These are washover fan deposits (dashed outline, Figure 2).

Five distinct washover fans were observed in the three regions. These are labelled *Fan A* to *Fan E* from north to south, as shown in Figure 1. Immediately seaward of the washover fans the rear dune slope is also eroded and a region of higher erosion rates exists through the dune. This is the overwash throat (solid outline, Figure 2). During overwash, overtopping flow is channelled through pre-existing gaps in the foredune and then spreads laterally behind the dune where the topographical restraints on the flow are more limited. Sheet overwash can occur when the entire dune ridge is overwashed, but this study is limited to confined overwash.

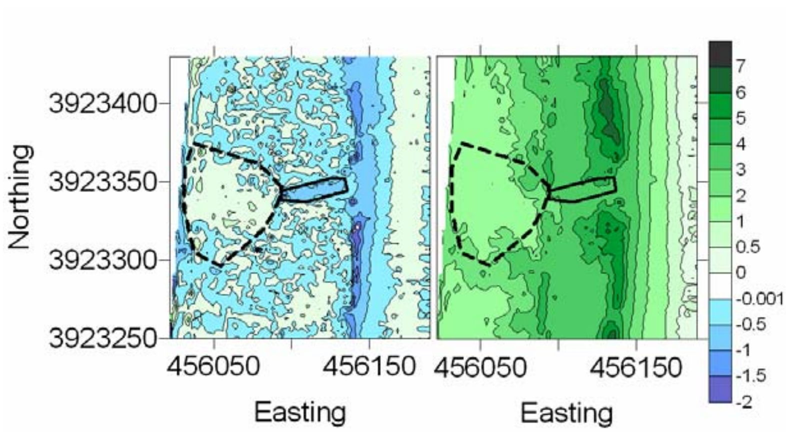


Figure 2 – Pre- and post-storm Topography Differences Map (left) and Pre-storm topography map (right), showing the region of deposition in the washover fan (dotted line) and the region of erosion in the overwash throat (solid line) for Fan C.

Overwash Throats

Comparison of the post-storm throat locations with the pre-storm topography indicates that the location of the overwash throats is primarily determined by pre-existing gaps in the foredune ridge, as can be seen on Figure 2, for Fan C. This has been recognised in overwash literature (e.g. Cleary and Hosier 1979, Dolan and Hayden 1981). The pre-storm photography indicated a pre-existing washover fan at this location.

In the regions where Fans C, D and E occurred, prominent foredune ridges, up to 7 m in height existed. No pre-existing washover fans were observed at the locations of Fans D and E, but the pre-storm topography indicates gaps in the foredune at these locations.

Fans A and B occurred behind a secondary dune ridge. The pre-storm topography does not indicate pre-existing gaps in this dune ridge; however, there were gaps in the foredune ridge directly in front of the fan locations. Additionally, the aerial photography indicates a beach access path passing through the rear dune ridge at the location of Fan B. The pre- and post-storm topography maps for Fan B are shown in Figure 3. The post-storm topography shows that most of the foredune was destroyed. It is suggested that the overwashing flow channelled in the foredune overwash throat had sufficient velocity to overwash the rear-dune, forming an overwash throat through which subsequent overwash was channelled. Along most of this coastal section, the pre-existing foredune throats widened, until eventually they merged. Rapid widening of washover throats was observed in experiments conducted by Donnelly et al. (2005) and Tuan et al. (2006). Sheet overwash of the beach crest would then have been possible. Note that there is some remnant of the foredune remaining directly in front of the rear dune throat, indicating that channelling during the entire storm contributed to the fan formation through the rear dune at this location.

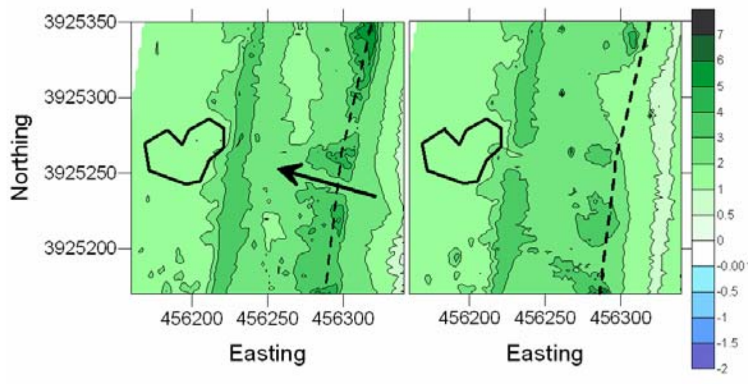


Figure 3 –Pre-storm topography map (left), and Post-storm topography map (right) for Fan B, showing the region of deposition in the washover fan (solid line) and the location of the pre-storm foredune ridge (dashed line).

Alongshore sections taken along the foredune show the deepening and widening of overwash throats during overwash (Figure 4). Pre- and post- storm overwash throat widths were measured from the long sections. The throat width, *B*, was defined as width at the top of the throat (Fig. 4), because observations during laboratory experiments indicated that during overwash, the sides of the throat collapsed into the channel due to notching, such that the sides of the throat were vertical (Donnelly et al. 2007). Pre and post-storm throat widths are listed in Table 1. Note that in some cases widening is not observed when comparing B_{pre} and B_{post}; however widening is observed at the sides and bottom of the throat. At Fan C, for example, vegetation is observed to hinder the widening of the top of the overwash throat.

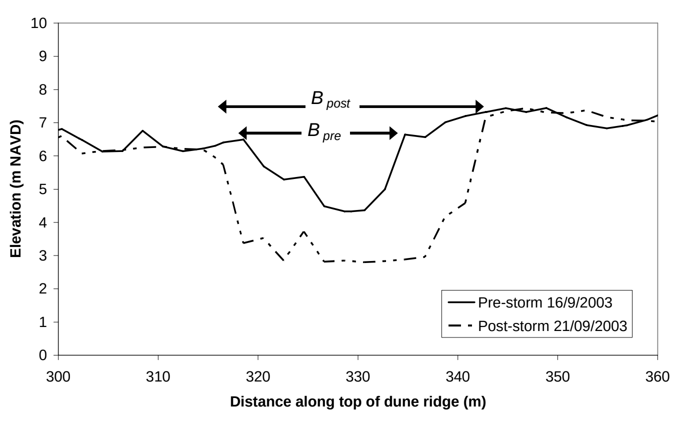


Figure 4- Long-section taken along the foredune at Fan D, defining B_{pre} and B_{post}.

Washover Fans

Table 1 summarises the observed geometry and characteristics of the 5 fans. An outline of the accreted region observed on the topography differences map was compared with the outline of bare sand on the geo-rectified aerial photography taken after the storm

(Figure 5). The outlining of this region was made subjectively due to noise in the data. As expected the two regions are very similar; however, the bare sand region extends seaward through the overwash throat where erosion is observed on the topography differences map. Other small differences in extent are probably due to the resolution of the lidar data. Using the overwash throat and the region of deposited sediment, the lateral spreading angle of the washover throat was measured. In most cases the fans were not symmetrical, so a north, a south, and an average lateral spreading angle was calculated. Additionally, the lengths, *L*, and widths, *W*, of the longest and widest dimensions of the fans were measured, assuming a fan axis parallel to the overwash throat.

Table 1 – Summary of Fan Characteristics

Fan	Shape	β_{north}	β_{south}	β_{ave}	*L* (m)	*W* (m)	*L/W*	B_{pre} (m)	B_{post} (m)
A	Assymetric	64°	14°	39°	67	82	0.8	na**	26
B	Long Diamond	25°	18°	22°	93	42	2.2	28	30
C	Diamond	30°	30°	30°	55	52	1.1	62	66
D	Wide Diamond	25°	42°	33°	28	57	2.0	16	29
E	Wide Triangle	na	45°	na	90	109	0.8	36	34

**There was no pre-existing gap in the rear dune at this location

In the absence of lateral or landward topographic constraints, the overwashing flow is directed landwards, perpendicular to the dune ridge, but spreads laterally as it leaves the confinement of the overwash throat. The fan develops a diamond shape, as velocities are highest in the centre of the fan, thus transporting sediment furthest inland along the fan axis. In reality, topographic constraints, vegetation and anthropogenic development all influence the eventual shape of the fan. Morton (1979) also showed how wind can influence the washover fan shape development. The results shown in Table 1 indicate that the fans can be long and narrow, short and wide or entirely asymmetric. The pre-storm topography and aerial photography were used to examine how the pre-storm morphology and surface texture control the overwash throat and washover fan shape development.

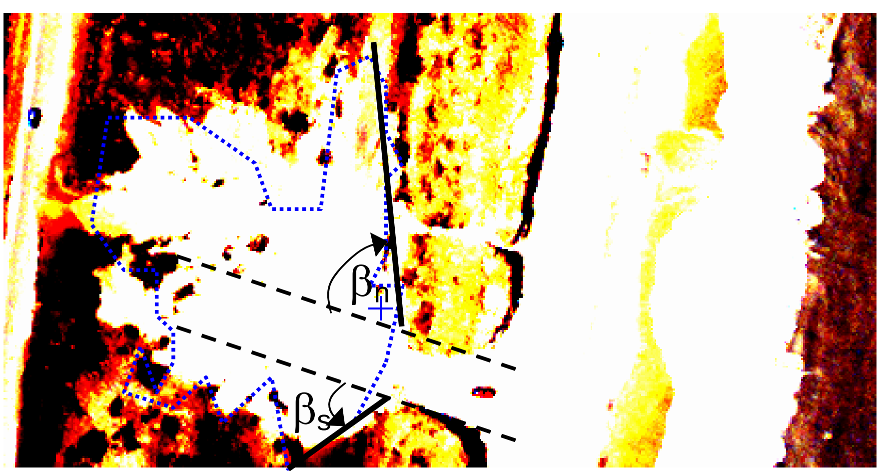


Figure 5 –Geo-rectified aerial photograph at Fan D, and washover deposition region from lidar for Fan D (dotted blue line), and definition of lateral spreading angles, β.

The pre-existing Fan C was extended both landwards and laterally; however, dense vegetation impeded the widening of the overwash throat on the northern side. At Fan C, the lateral spreading angle can be estimated from the pre-storm topography. Lines were drawn from the pre-existing throat to areas of topography at the same elevation as the throat. The angle of these lines to the overwash throat axis, 30^{o}, was similar to that measured on the topography differences maps and geo-rectified photography.

The pre-storm topography indicated that Fans A, B, and D are all relatively unconfined laterally by topography on the back barrier, so it was not possible to use topographical influences to quantitatively predict the fan shape. The fans show a large variation in shape and lateral spreading angle, so factors other than lateral topography must also have a strong influence. Figure 6 shows aerial photographs of Fans A, B, C and E (Fan D is shown in Figure 5).

Fan A is actually two fans merged together. Close inspection of the post-storm photography indicates a smaller throat to the north of the main throat. Additionally, overwashing flow in the main throat appears to have occurred in two directions, perpendicular to the dune ridge and along the northern edge of the dune. There is a small portion of a remnant foredune remaining in front of the overwash throat, and division of flow around this may have lead to two different streams of overwashing flow.

At Fan B, an unpaved beach access track perpendicular to the dune ridge facilitated the development of a long, thin washover fan. Flow along the fan axis, therefore penetrated a lot further landward than would otherwise have been seen. Although not seen in the topography, the track was probably at slightly lower elevation than the surrounding back barrier, and the surrounding barrier is vegetated, indicating less frictional restraint in the track.

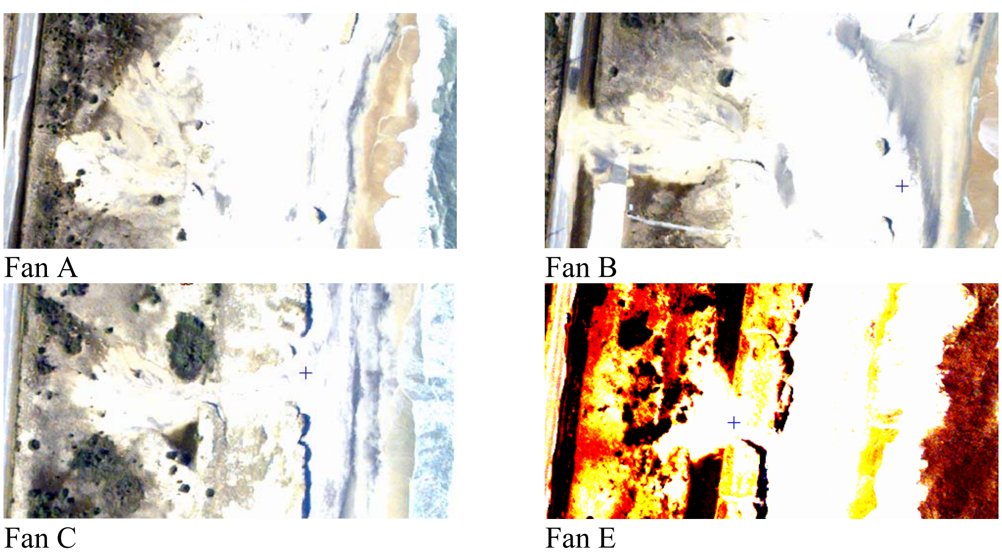


Figure 6 - Post-Storm geo-rectified aerial photography (Fan D is shown in Figure 5)

The shape of Fan D is also affected by an unpaved beach access track perpendicular to the dune ridge, in addition to a paved road located immediately behind and parallel to the foredune ridge. The overwash throat is located 50 m to the south of the track, but the fan extends further inland along the track, and hence is asymmetric. The fan has also extended substantially to the north along the paved road. Finally, Fan E is much wider than it is long due to lateral spreading in both directions along the same paved road and confinement by topography and vegetation on the landward side of the road.

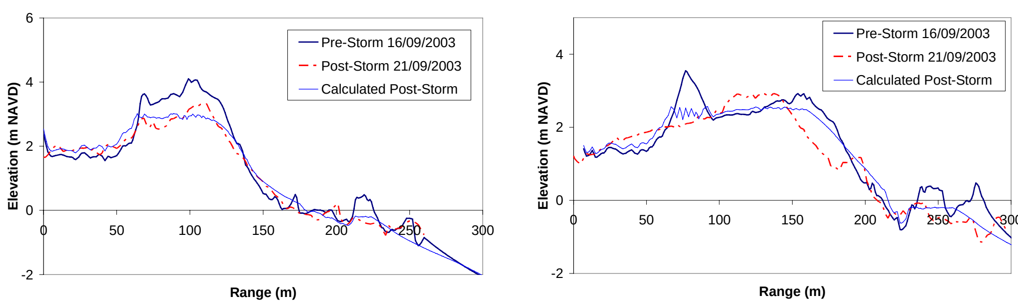
To summarise, washover fans were diamond shaped but varied substantially in length to width ratio. Lateral spreading angles varied from as low as 15^{o} up to 65^{o} but ranged mostly between 20^{o} and 45^{o}. In most cases complicated back barrier topography, dense vegetation, tracks and roads, multiple overwash throats and complicated topography on the foreshore all contributed to the shape development of the washover fans; however, for a simple case, such as at Fan C, topographical confinement alone may be used to quantitatively predict fan shape development. Influences such as tracks and roads can be used to qualitatively predict where overwash will spread. It was seen that overwash flow penetrates further along tracks and roads where friction is reduced.

MODELLING

Larson et al. (2005) and Donnelly et al. (2005) developed an algorithm to calculate beach profile change due to overwash taking into account two different flow regimes over the beach crest, namely runup and inundation overwash, respectively. Ballistics theory was used to calculate the hydrodynamics in the swash zone and the flow rate over the beach crest during runup 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.* (1996). The water flow on the back barrier slope 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 (Larson and Kraus, 1989).

Donnelly et al. (submitted) calibrated and verified the model for 2-D profiles. Initial overwash throat width, lateral spreading angles and infiltration rates were included together in three overwash coefficients which were calibrated for each location. These coefficients took into account 1) the proportion of sediment in the overtopping flow along with a bore front/weir coefficient for the runup overwash/inundation overwash modules, respectively, (2) the initial throat width and lateral spreading angle, and (3) the infiltration rate. Donnelly et al. (submitted) showed that the model could be verified using calibrated parameters for similarly shaped profiles in the same region, but not for profiles in different regions. This new, 3-D data, allowed the opportunity to input actual overwash throat widths and lateral spreading angles, in order to produce a more generalised cross-shore overwash profile change model. The algorithm was reformulated such that the initial overwash throat width and a potential lateral spreading angle could be entered. For simplicity, infiltration was assumed to be negligible. A single calibration coefficient remains in the algorithm to represent the proportion of sediment in the overtopping flow along with a bore front/ weir coefficient for the runup overwash /inundation overwash modules, respectively.

Figure 8 shows the results of cross-shore profile modelling at Fans B and C. Initial overwash throat widths, B_{pre}, of 28 m and 62 m were identified for Fans B and C, respectively, using an alongshore section of the dune ridge crest. It is acknowledged that the throat width varies during overwash, but in a predictive mode, the pre-storm throat width is specified. This value is kept constant during the simulation. At Fan C, a potential lateral spreading angle, β_{ave}, of 30^o was identified using the pre-storm topography confinement. At Fan B, there was no pre-storm topography confinement and the shape development was affected by anthropogenic influences, so the measured post-storm angle of 17^o was used instead to verify the model. In a predictive mode, lateral spreading angles may be derived, where possible, using pre-storm topography confinement, but note that anthropogenic influences and vegetation affect lateral spreading significantly. Where a previous fan exists, the lateral spreading angle of the old fan may provide a good initial estimate. In the absence of a better estimate, an angle of 30 degrees represents the average lateral spreading angle of the measured fans. The model was calibrated at Fan C and verified at Fan B using the overwash coefficient value determined during calibration. The model was run using the aforementioned time-series for wave characteristics and water level during Hurricane Isabel.



(a) (b)

Figure 7 – Cross-shore profiles showing results of overwash model simulations (a) Calibration Run: Fan C, and (b) Verification run: Fan B

The results indicate the model's capability to predict the subaerial barrier evolution, including destruction of dunes, lowering of the beach crest and the landwards deposition of sediment. Optimal root-mean-square (RMS) error values were reached for the same overwash coefficient, indicating the general applicability of the model for similar locations in a predictive mode. The subaerial RMS value for Fan C was 0.231 and for Fan B was 0.397.

CONCLUSIONS

Several washover fans deposited during Hurricane Isabel, 2003, on Hatteras Island, NC, were studied to determine the controls on washover fan development. Fans were shown to typically form at pre-existing gaps in the dune ridge. Two fans were shown to form behind the rear dune ridge, where a gap pre-existed in the fore dune ridge, indicating that flow channelling in the foredune enabled breaching and subsequent overwashing of the rear dune. Overwash throats were shown to both widen and deepen during overwash.

The washover fans were mostly diamond shaped, with landward penetration maximum along the fan axis. Topography, vegetation and anthropogenic influences such as roads and tracks, however, were shown to obstruct this natural fan development and the fans varied substantially in length to width ratio. Lateral spreading angles varied from as low as 15^o up to 65^o but ranged mostly between 20^o and 45^o. It could be seen that washover spread laterally over a wider region where shore parallel roads and tracks existed, and penetrated further inshore along shore perpendicular tracks. Vegetation was seen to impede both throat widening and lateral spreading. Qualitatively, the shape development of a fan can be predicted using these observations. The quantitative lateral spreading angle was able to be predicted for one fan where vegetative and anthropogenic obstructions were negligible and where the pre-storm topography clearly varied in height on the back-barrier.

Initial throat widths and lateral spreading angles (both predicted and measured) were used as inputs to a generalized version of the overwash model by Larson et al. (2005) and Donnelly et al. (2005). The results indicated the model's capability to predict the subaerial barrier evolution. This more generalized cross-shore overwash profile change model can be applied to cross-shore profiles at which overwash is identified as a potential hazard, ie. at pre-existing gaps in the dune ridge using a measured throat width and a potential lateral spreading angle, if a potential lateral spreading can be predicted from the back barrier topography, vegetation, roads or pre-existing fans. It is otherwise suggested that an angle of 30^o be used, as this is near to the average angle for the studied fans.

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