MEASUREMENTS OF MORPHODYNAMIC AND HYDRODYNAMIC OVERWASH PROCESSES IN A LARGE-SCALE WAVE FLUME

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Abstract

Overwash is an important process that controls short-term barrier dynamics, as well as long-term barrier migration, but this process is difficult to study in the field due to its rare occurrence and the challenging conditions under which it occurs. This paper uses data collected during BARDEX II experiment in the Delta Flume, the Netherlands, where a proto-type barrier was subjected to a range of wave and water level conditions. The objectives of this research are to: (1) compare the morphologic response to overwash on a gravel barrier (BARDEX 2008 experiment) with that on a sandy barrier (BARDEX II); (2) understand the

influence of wave period on overwash characteristics and sediment transport; and

(3) improve current knowledge of overwash hydrodynamics. The comparative

analysis shows that barrier overwash can be affected by negative feedback that

stabilises the barrier through barrier crest accretion on gravel barriers, and by

submerged bar development on sandy barriers. An increase in the wave period

induced a reduction in overwash frequency over the crest, but no significant

relation was found between wave peak period and overwash discharge.

Nevertheless, overall water discharge during an overwash episode significantly

correlates with overall overwash sediment transport rate. Overwash flow depths

during the experiment were relatively shallow and velocities were similar

compared to those measured during previous studies and reported in the

literature. Despite the controlled laboratory conditions, collection of reliable and

accurate measurements of overwash velocities remains challenging.

key-words: BARDEX; storm; coastal hazard; overwash; barrier island

1. INTRODUCTION

Overwash is a natural process that results from a singular combination of oceanographic and coastal geomorphologic conditions. Factors controlling the frequency and intensity of overwash, and the resulting morphologies include oceanographic conditions (e.g., Fisher et al., 1974), the orientation of a coast relative to a storm (e.g., Fletcher et al., 1995), nearshore bathymetry (e.g., Houser, 2012), beach topography (e.g., Leatherman, 1976), back-beach elevations (e.g., Morton and Sallenger, 2003), dune morphology (e.g., Donnelly and Sallenger, 2007), engineering structures (e.g., Hayden and Dolan, 1977), location and orientation of footpaths and roads (e.g., Nordstrom and Jackson, 1995), and shorefront infrastructures (e.g., Hall et al., 1990).

Overwash occurs both on sand and gravel barriers. Field studies of overwash in sandy environments are more common (e.g., Leatherman, 1976; Holland et al., 1991; Priestas and Fagherazzi, 2010; Matias et al., 2010) than on gravel beaches.

Overwash sediment transport on sandy beaches has been measured using pre- and post-storm traditional surveys (e.g., Guillén et al., 1994; Stone et al., 2004) or Lidar surveys (e.g., Sallenger et al., 2006; Stockdon et al., 2009), and have been evaluated with ground photographs and vertical aerial photographs (e.g., Rodríguez et al., 1994; Cleary et al., 2001). Important field studies on gravel barriers are reported by Orford et al. (1999, 2003), Lorang (2002) and Bradbury et al. (2005).

Overwash mainly occurs during storms when accurate in-situ field measurements are hazardous and difficult to obtain. Laboratory experiments on overwash provide numerous advantages in relation to fieldwork, including the ability to control the hydrodynamic conditions to ensure overwash occurs as well as

1 logistical benefits (more preparation time, capacity to recruit researchers, less
2 stressful schedules, simplification of equipment installation and power supply and
3 provision of a safe environment for people and equipment). Investigations in
4 small-scale physical models can be used to study coastal processes using well
5 established scaling laws, but shortcomings due to scale effects remain and are not
6 well understood (Van Rijn et al., 2011). Several small-scale experiments on
7 overwash have been undertaken by: Hancock and Kobayashi, 1994; Obhrai et al.
8 (2008), Donnelly (2008), Kobayashi et al. (2010), Park and Edge (2010), Figlus et
9 al., (2011). Scaling problems can be overcome when a large-scale facility is used
10 for quantifying physical processes that are almost impossible to measure in nature
11 (Dette et al., 2002). Therefore, large-scale experiments can provide a valuable
12 complement to field datasets (Tomasicchio et al., 2011; D'Alessandro et al., 2012).
13 Large-scale experiments on overwash have been undertaken during Barrier
14 Dynamics Experiment (BARDEX 2008) reported by Williams et al. (2012). During
15 BARDEX 2008, overwash was simulated with waves that reached 1.0 m at breaking
16 (Matias et al., 2012) and thus this experiment was at a significantly larger scale
17 than previous laboratory experiments, where wave heights were in the range
18 0.14 m (Park and Edge, 2010) to 0.33 m (D'Alessandro et al., 2010).
19 Repeated overwash processes are important for long-term natural evolution of
20 transgressive barrier islands, whereby the net volume of sand contained in the
21 barrier structure is often maintained, but environments translate landward (e.g.,
22 Dolan and Godfrey, 1973). Overwash processes may reinforce or disrupt barrier
23 resilience; this is partly a function of barrier-lithosome volume, which determines
24 the amount of sediment that needs to be eroded before a critical state is reached,
25 and thus provides a buffering effect (Masselink and van Heteren, 2014).
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1 Sandy beaches are affected by storms in different ways, depending on the
2 character of the storm and the morphology of the beach. Sallenger (2000) defined
3 four classes or regimes: swash regime, collision regime, overwash regime and
4 inundation regime. The overwash regime can even be refined in to overtopping
5 and overwash. Orford and Carter (1982) established that overtopping is
6 characterised by crest accretion and an increase in crest elevation; and overwash
7 is characterised by lowering of the crest by erosion and formation of washover
8 deposits landward of the crest.
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10 In this work, overwash simulations during BARDEX II experiment (Masselink et al.,
11 this issue) are described. The first objective of this research is to compare the
12 morphologic response of a gravel barrier (BARDEX 2008 experiment) and a sandy
13 barrier (BARDEX II experiment) to overwash, including differences in feedback
14 mechanisms and barrier resilience. The second objective is to assess whether
15 elevated water levels with shorter period waves or lower water levels with longer
16 period waves are more important to barrier evolution. The first tends to produce
17 high frequency overwash flows and the latter tends to generate less frequent
18 overwash flows. The third objective is to improve current knowledge of in-situ
19 overwash hydrodynamics.
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2. EXPERIMENTAL SETUP AND METHODS

2.1. Experimental setup

Experiments to study sandy barrier overwash were undertaken at prototype-scale in the Delta Flume (The Netherlands, Fig.1) during the BARDEX II project (Masselink et al, this issue). A barrier (75 m long, 5 m wide and 4.5 m high, Fig.1) was constructed in the flume using medium-size sand (median=1.2 ϕ ; 0.43 mm), with the mid-barrier crest located at a distance of 100 m from the wave paddle (Fig. 1). The sand barrier was separated from the lagoon by a permeable wall to allow water to move freely between back-barrier slope and lagoon, but prevent the ingress of sand into the lagoon during overwash tests.

Overwash was studied by exposing the barrier to variable wave and water-level conditions. Test Series D consisted of seven sequences (D1 to D7; Table 1), each comprising a number of 20-min wave runs. During each series, the water depth at the wave paddle (h_s) was gradually increased in 0.15 m steps to achieve a sequence of swash – overtopping – overwash. Significant wave height (H_s) remained constant at about 0.8 m and peak wave period (T_p) ranged from 4 s to 10 s (Table 1). In Test Series E the morphological response of the barrier under fully developed overwash conditions was investigated. Each run during Test Series E lasted 13 minutes with sea level and waves were kept as constant as possible (Table 1). All wave conditions conformed to a JONSWAP spectrum, specified by H_s and T_p .

All our observations are in the overwash regime on the storm impact scale of Sallenger (2000). The differentiation between overtopping and overwash on

morphological response as suggested by Orford and Carter (1982) was not noticeable during the course of the experiment. Therefore it was considered that a run measuring overtopping would be dominated by shallow water depths over the barrier crest with limited water intrusion after the crest (Fig. 1a); whilst runs measuring overwash would be dominated by larger water quantities passing by the crest (Fig.1b).

2.2. Morphological measurements

Barrier morphology was surveyed before and after each run using a roller and actuator which followed the bed profile from an overhead carriage (Fig.1), thereby allowing profile measurement of both the sub-aerial and submerged parts of the beach. The position and elevation of the barrier crest (h_{crest}) was determined at the end of each run, whereby the crest was defined as the location on the profile with the maximum elevation above flume floor (z maximum). Beach slope ($\tan\beta$) was calculated for the barrier section between mean water level and the upper limit of the beach face.

The sub-aerial barrier was monitored at 4 Hz using acoustic bed-level sensors (BLS) deployed at 0.5-m spacing (Fig. 1d) and approximately 1 m above the bed. These sensors are described in detail in Turner et al. (2008) and were also used by Matias et al. (2014) to investigate overwash dynamics during BARDEX 2008. Detailed analysis of BLS data was undertaken for runs D18, D25, D34, D44, D53, D64, D74, E1-E5 for which repeated overwash and significant water depths were measured by BLS array.

During overwash, even slight alongshore variations in elevation lead to overwash flow convergence, often resulting in the development of a scour channel at the back of the barrier which acted as a conduit for landward sediment transport. To avoid this channel back-cutting up the barrier crest over successive runs and thereby affecting wave runup at the front of the barrier, the backbarrier morphology was manually reconstructed after each run by filling in the scour channel and levelling the barrier top and backbarrier slope. The vertical retaining wall that was used to separate the barrier from the lagoon (Fig. 1c) reduced the available space to accommodate overwash sedimentation and retained part of the overwash water that reached the backbarrier. Despite the pumps used to transfer water from the backbarrier to the 'sea' operating at full capacity, pooling of water occurred in the backbarrier region. The bed profiler also could not survey the backbarrier region because of an instrumentation carriage located above this region of the flume. Therefore, only the foreshore and barrier top morphologies, up to $x = 110$ m, are considered during the overwash experiments. Due to this limitation, the overwash/overtopping sedimentation volume was determined indirectly. The pre- and post- morphological profiles measured with the profiler were subtracted for the region seaward and landward of the barrier crest. Because the flume is a closed system, all sediment eroded from the region seaward of the barrier crest was attributed to overwash/overtopping sedimentation landward of the barrier crest. The sediment transport rate ($\text{m}^3\text{m}^{-1}\text{min}^{-1}$) was obtained considering the duration of each run (20-min and 13-min, for Test Series D and E, respectively).

Beach morphodynamic parameters were computed: the Iribarren number (ξ , eq. 1) and the surf scaling parameter (ϵ , eq. 2).

$$\xi = \tan\beta / (\sqrt{H_s/L_0}) \quad (1)$$

$$\varepsilon = a w^2 / (g \tan^2 \beta) \quad (2)$$

where L_0 is the offshore wave length, a is wave amplitude, w is wave radian frequency and g is gravitational acceleration.

2.3. Overwash flow measurements

In this study, an overwash event is defined as a single passage of water over the barrier crest. For hydrodynamic measurements, overtopping and overwash events were not separated, because the most reliable separation is given by morphological criteria and there is no water depth criterion to separate overtopping from overwash. Consequently, during each overwash/overtopping test run a large number of overwash events were recorded at each BLS position. BLS records were pre-processed to separate overwashes (water peaks) and bed level (bed elevation before and after the overwash event). For all BLS positioned landward of the beach, every overwash event was identified and isolated. For each overwash event, maximum and average water depth, skewness of the water depth distribution and duration of the event were computed. The number of events per duration of run is referred to as the ‘frequency’ and the average time between two consecutive overwash events is referred to as the ‘return period’.

Overtopping and overwash on the top of the barrier were also monitored with a video-camera. This video camera was one out of three and was installed on a scaffold platform over the sandy barrier and looked obliquely from the back-barrier over the top of the barrier in the direction of the sea (see Fig. 1c). The video-camera belonged to a standard Argus configuration (Holman and Stanley,

2007). The video-images were recorded during all the runs with a frequency of 20 Hz. The central line of the video-images, close to the cross-shore profile measurement line, was selected from all video-images. These successive cross-shore lines showed the back-barrier, the top of the barrier and the beach, and were used to construct a time-stack image (Fig. 2). The mean position of the top of the barrier during each run was clearly visible and easy to detect in the time-stacks of video images. This mean position (cross-shore pixel position) was calibrated against the bar crest positions of the profile measurements (Fig. 1d; cross-shore position in m). All bar crest positions were quite stable during a single run.

Overwash events were now defined as those events where the water crossed the top of the barrier and also crossed a landward located line at 80 pixels from the top of the barrier position (at 0.376 m; see Fig. 2). The detection of the leading edge of the water mass at the two locations in the images was done by looking at the gradient of the light intensity values in time. All leading edges were characterized by a rapid increase in light intensity where the wet sand (dark) suddenly changed to water (light). This resulted in high positive values of the light intensity gradient. The detected times when a water mass was passing the top of the barrier were used to compute the frequency and return period of events in the successive runs.

Based on various morphologic and hydrodynamic parameters, Matias et al. (2012) defined the Overwash Potential (OP , Eq.(1)) as a parameter for quantifying the likelihood of overwash in gravel barriers. Matias et al. (2013) demonstrated that the same equation could also be used for sandy barriers. OP compares the vertical wave runup to the elevation of the barrier crest:

$$OP = 1.1 \left(0.35 \tan \beta \sqrt{H_0 L_0} + \frac{\sqrt{[H_0 L_0 (0.563 (\tan \beta)^2 + 0.004)]}}{2} \right) + \eta - h_{crest} \quad (3)$$

where η is sea level, including astronomical tides and storm surge, and h_{crest} is the barrier crest elevation. The first term of the equation is the expression for the 2% vertical runup exceedance level developed by Stockdon et al. (2006). When OP is negative, swash processes are expected, when $OP=0\pm0.2$ m overtopping is expected on gravel barriers and when $OP>0.5$ overwash is expected (Matias et al., 2014).

Overwash velocity was calculated from the time delay associated with the arrival of the leading edge of the overwash at two BLS spaced 1.0 m apart and located at either side of the barrier crest (BLS18 and BLS20). The time of arrival of the overwash at each of these sensors was defined by the time at which the water depth exceeded 0.02 m determined from interpolated BLS time series to increase temporal resolution. The definition of 2 cm as the leading edge is somewhat arbitrary; however, this water depth has been used in coastal engineering applications (e.g., Pullen et al., 2007) as well as in the study of BARDEX 2008 overwash velocities (Matias et al., 2014). The Froude number (Fr) was calculated for all overwash events (Eq. 4) to characterize the type of flow as supercritical ($Fr>1$), critical ($Fr=1$), or subcritical ($Fr<1$).

$$Fr = u_{crest} / (\sqrt{gh_c}) \quad (4)$$

where u_{crest} is overwash velocity over the crest (ms^{-1}) and h_c is overwash depth over the crest (m).

Overwash discharge per unit m was computed for all overwash events using the product of the leading edge velocity and mean overwash depth (m). The discharge integrated by the duration of each overwash (l m^{-1}) provides the individual amount of water discharge over the crest during each event. Note that this method

will provide an upper bound estimate of discharge because it is based on the initial crest velocity which is expected to subsequently reduce.

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3. RESULTS

3.1. Morphological response of the barrier

Test Series D was composed of runs with swash, overtopping and overwash runs, whilst during Test Series E fully developed overwash runs were recorded (Table 1). During the 37 runs in Test Series D and E, overtopping was recorded in 17 runs and overwash in 12 runs. During the remaining 8 runs, wave run-up did not reach the barrier crest and swash action only affected the beach face.

The run that presented most morphological changes was D1 (Figs. 1d and 3a), with significant barrier crest retreat of about 5 m, which was related to barrier readjustment after the different conditions that were used during preceding Test Series A to C (see Masselink et al., this issue). During D1, a small bar developed around a cross-shore distance $x = 85$ m as the water level was raised (Fig. 3a). The submerged bar was still a significant beach feature evident in the profiles of run D2, but it was subsequently eroded and almost disappeared by the end of D3 (Fig. 3b). During D3 a submerged terrace developed around $x = 83$ – 88 m (Fig. 3b), with a steep beach face (above 2 m). Between D4 and D7 the submerged face progressively flattened and beach sub-aerial and submerged morphology became more continuous (Figs. 1d and 3c). The submerged morphology of the beach profile during Test Series E evolved to generate a small bar around $x = 90$ m (Fig. 4a).

During runs D1 to D7, the average beach slope was 0.17, with the steepest slope during D1 (0.27, Fig. 5a) and the gentlest gradient during D3 (0.12). The beach gradient did not vary consistently during swash, overtopping and overwash runs. During Test Series E, the slope varied little ($0.17 < \tan\beta < 0.19$) and the average

slope was 0.18. During Test Series D and E, the Iribarren number (ξ) varied between 0.9 and 2.7 (plunging breaker, according to limits from Battjes, 1974), and surf scaling parameter (ϵ) varied between 1.4 and 12.4 (reflective to intermediate beach, according to limits from Wright et al., 1979).

During Test Series D, the barrier crest elevation h_{crest} underwent a moderate increase and decreased during Test Series E (Fig. 5b). The BARDEX II sandy barrier did not experience crest accretion during every overtopping runs, conflicting with the overtopping definition proposed by Orford and Carter (1982). During overtopping small amounts of erosion and accretion (maximum crest elevation variation of ± 0.01 m) were recorded (Fig. 5b). The barrier crest elevation did not systematically decrease during the overwash runs of Test Series D (Fig. 5b), but did reduce during the overwash conditions of Test Series E (Figs. 4a and 5b).

The sediments eroded from the barrier crest were deposited landward, against the vertical wall (Fig. 1c). During the Test Series D overwash runs (D18, D25, D34, D44, D53, D64, D74, Table 1) and during Test Series E, the average sediment transport rate across the barrier crest was only $0.017 \text{ m}^3\text{m}^{-1}\text{min}^{-1}$ and $0.056 \text{ m}^3\text{m}^{-1}\text{min}^{-1}$, respectively (Fig. 5d). The overall volume of sediment deposited at the backbarrier was relatively small, with a minimum of $0.2 \text{ m}^3\text{m}^{-1}$ (during D3) and a maximum of $0.9 \text{ m}^3\text{m}^{-1}$ (during E5). In total, c. $5 \text{ m}^3\text{m}^{-1}$ of sediment was deposited at the back-barrier during the experiment, of which 60% was deposited during Test Series E.

An event-by-event analysis of local bed-level change was made by using data from bed-level sensors (BLS). It was noticed that barrier crest variations induced by overwash flows were not always in the same direction; rather, a high number of

very small positive or negative bed changes were recorded, mostly in the range <1 cm. These positive (accretion) and negative (erosion) changes tended to almost balance out over the duration of each run leading to extremely small average bed changes per overwash event: 0.005 cm to 0.02 cm in Test Series D and -0.04 cm to -0.13 cm in Test Series E. Considering the whole back-barrier morphological changes during each run (D34, D74 and E5 as examples in Fig. 6), it is sometimes possible to determine which of the overwash events induced most morphological change. For example, during run D34, accretion in the vicinity of the crest region occurs by many of the smaller overwash events, but it is not until the large swash events at $t = 8.97, 9.08$ and 9.16 hour (Fig. 6a) that sediment is transported onto the back-slope of the barrier. The largest overwash event $t = 9.16$ hour is of particular interest, because this event washed a significant amount of sediment from the back barrier into the lagoon (landward of $x = 112$ m). During other runs, such as run D74 (Fig. 6b), barrier accretion and erosion occurred alternately throughout the run; with evident contribution to back-barrier erosion provided by events around $t = 15.47$ and 15.62 hour. Run E5 was characterised by net erosion of the beach and barrier crest region, and back-barrier accretion (Fig. 6c), but specific events cannot be related to specific morphological changes. Figure 6 indicates that there are instances where certain morphological changes can be attributed to specific overwash flows, but in other instances, during high-frequency overwash runs (Test Series E), this is less obvious.

The time-stacks of the video-images of the central cross-shore line clearly showed that the position of the barrier crest hardly changed during the D runs. There were no individual events that triggered a migration and the position over the runs

remained constant (see also Figs. 1 and 3b,c). The position of the barrier crest moved significantly towards the lagoon during the E runs, in line with Fig.4.

3.2. Overwash hydrodynamics at the barrier crest

Due to the increasing water levels through each test series, there was an increase in Overwash Potential (OP , Eq. (1), Fig. 5d). At the beginning of each test, with swash processes occurring on the beach face, OP was mostly negative; for OP values between 0 to 0.5 m overtopping generally occurred and overwash was the dominant process when $OP > 0.5$ m (last runs of Test Series D and all Test Series E, Fig. 5d). All through Test Series E, overwash occurred under the same wave and tide conditions (Table 1), but OP increased (from $OP = 0.7$ m to $OP = 1.0$ m; Fig. 5d) because the overwash processes progressively lowered the barrier crest (Fig. 5b).

Fig.7 shows example time series of overwash during runs D34, D74 and E5, representing a range of wave period ($T_p = 4, 10$, and 8 s, respectively). During the overwash runs of Test Series D, the wave height was kept the same, the wave period T_p increased from 4 s to 10 s (Fig. 8), and the sea level h_s decreased from 4.21 m to 3.57 m (Table 1). In general, the increase in wave period during Series D translated to an overall decrease in the number of overwash events (Fig. 7 and Table 2) and a corresponding increase in the return period of overwash events from 14 s ($T_p = 4$ s) to 22 s ($T_p = 10$ s, Fig. 8 and Table 2). However, the relatively low frequency in run D53 (Table 2) can be explained by the relatively low water depth at sea (Table 1). Although the number of events decreased, the number of overwashes per wave remained the same (c. 1 overwash every 3 waves). The

1 overwash return period of series E remained relatively constant, around 10 s
2 (Table 2), and together with peak wave period of 8 s suggests that most waves
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7 The average overwash depth was shallow (0.04 m and 0.07 m for series D and E,
8 respectively) with average peak depth of just 0.07 m and 0.11 m for series D and
9 E, respectively (Table 3). Overwash events are characterised by a peak in the
10 water depth shortly after the arrival of the leading edge at the barrier crest,
11 followed by a long shallow 'tail'. The high positive average value of water depth
12 distribution skewness in Test Series D (0.15, Table 3) reflects this shape. The more
13 symmetrical overwash depth distribution during series E, characterised by an
14 average skewness of only 0.02 (Table 3), is ascribed to the lower barrier crest
15 causing overwash to be more similar to propagating waves.
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18 Overwash velocity over the crest (u_{crest}) was computed using the leading edge
19 method for all overwash events for which this was possible. The number of
20 calculated velocities was 323 for Test Series D and 292 velocities for Test Series E.
21 For Test Series D, the average leading edge u_{crest} was 1.8 ms^{-1} and the maximum
22 u_{crest} obtained was extremely high, reaching 9.3 ms^{-1} . About 94% of measured
23 overwash flows on Series D (305 events) were supercritical flows with an average
24 $Fr = 2.3$. For Test Series E the average u_{crest} was 2.2 ms^{-1} and the maximum u_{crest}
25 was 6.8 ms^{-1} . About 93% of overwash flows (272 events) were supercritical flows,
26 with an average Fr (2.2) similar to that during Test Series D.
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29 The overwash discharge during Test Series E was generally larger than during Test
30 Series D (Fig. 8 and 9). The majority of individual overwash discharges recorded in
31 all runs for both Test Series D and E were $< 0.2 \text{ m}^3\text{m}^{-1}\text{s}^{-1}$. Average discharge for
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1 Test Series D and E was $0.09 \text{ m}^3\text{m}^{-1}\text{s}^{-1}$ and $0.17 \text{ m}^3\text{m}^{-1}\text{s}^{-1}$, respectively. The total
2 amount of overwash water that passed over the barrier crest during each
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4 overwash event varied between about 90 l m^{-1} and 490 l m^{-1} (Fig. 10a). The
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6 volume of overwash water per overwash episode (run) increased during the
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8 experiment, but not consistently, from D18 ($0.6 \times 10^4 \text{ lm}^{-1}$) to D64 ($1.4 \times 10^4 \text{ lm}^{-1}$,
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10 Fig. 10b), and this trend persisted, also not consistently, during Test Series E until
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15 $4.9 \times 10^4 \text{ m}^3\text{m}^{-1}$.
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4. DISCUSSION

4.1. Overtopping, overwash and barrier resilience

In the following section a comparison is made of the morphological response of a gravel and sand barrier to overtopping and overwash, during the BARDEX 2008 and BARDEX II laboratory experiments (Fig.11). BARDEX II morphology mimics sand barriers with a backbarrier lagoon and no dune development, which can be found for example in the Ria Formosa barrier system, Portugal (Fig.11c). Similarly, BARDEX 2008 morphology mimics gravel barriers such as Slapton Sands, Devon, U.K. (Austin and Masselink, 2006) or Loe Bar, Cornwall, U.K., (Poate et al., 2013; Figure 11d). For the purpose of comparison it is worth briefly mentioning the experimental setup of BARDEX 2008 experiment. It was undertaken in the same flume (details in Williams et al., 2012) on a gravel barrier (Fig. 4b). The morphological response of the barrier due to overtopping and overwash was studied by manipulating wave and sea-level conditions in a similar manner to that during the BARDEX II experiment (details in Matias et al., 2012). Testing was undertaken using a similar methodology to BARDEX II with the addition of a final test series (Test Series E10) which consisted of 15-min runs in which the water level ($h_s = 3.75$ m), peak wave period ($T_p = 8$ s) and significant wave height ($H_s = 0.8$ m) were kept constant to study the behaviour of the barrier under fully-developed overwash conditions (details in Matias et al., 2014).

Sallenger's (2000) Storm Impact Scale includes overwash and inundation as part of a four-regime framework; however it does not include overtopping as a separate regime, probably because his classification was based on observations of sandy

1 beaches and barriers. Orford and Carter (1982), on the other hand, studied the
2 impact of extreme water levels on gravel barriers and stated that the key to barrier
3 retreat lies in the relative balance between overtopping and overwash. These two
4 previous approaches do not conflict by definition, since overtopping and overwash
5 are both within the general definition of overwash in Sallenger's classification.
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8 However, the morphological evolution observed during BARDEX 2008 and
9 BARDEX II experiments have shown that overwash and overtopping are
10 fundamentally different.
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12 The sandy barrier during BARDEX II experienced almost negligible crest elevation
13 variations during overtopping runs (maximum change of 0.01 m), unlike
14 observations on gravel barriers both in the field (e.g. Orford et al., 1995) and in the
15 laboratory (Matias et al., 2012). During gravel beach overtopping, the barrier crest
16 undergoes considerable accretion, raising the crest elevation (c. 0.5 m on BARDEX
17 2008). Overtopping flows over the sandy barrier were extremely shallow (Fig. 1a)
18 and slow, generating only small discharges with limited sediment transport
19 capacity. Overtopping flows on gravel beaches are stronger, but do not result in
20 overwash because of greater infiltration. The importance of this finding is that
21 crest accretion on gravel barriers during overtopping provides a negative feedback
22 on morphological evolution through raising the barrier crest, and inhibiting
23 overwash. This would suggest that gravel barriers are more resilient than sandy
24 barriers under conditions around the threshold between overtopping and
25 overwash, because the gravel barrier crest build-up delays the onset of overwash.
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27 The morphologic response of the sand and gravel barriers to overwash was also
28 contrasting (Fig. 4a and 4b). In the gravel barrier case, the beach face started very
29 steep ($\tan\beta = 0.20$ Fig. 11a). During overwash, the beach face flattened (until $\tan\beta$
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= 0.10) and the crest lowered by about 0.5 m, with sediments being transported landward by overwash (Fig.11b). On the sandy barrier, the beach face started equally steep ($\tan\beta = 0.20$), but the crest was higher (Fig.11a), probably related to larger wave conditions during BARDEX II. During overwash the beach remained steep ($\tan\beta = 0.17\text{--}0.19$), but the barrier crest was only lowered by 0.2 m (Fig. 4b), with sediments being transported landward to the backbarrier and lagoon and seaward to the inner surf zone. Overwash flow discharges in gravel were larger (average $0.30\text{ m}^3\text{m}^{-1}\text{s}^{-1}$; Matias et al., 2014), suggesting less water returned seaward as backwash. During the sandy barrier experiment, smaller overwash discharges (average $0.16\text{ m}^3\text{m}^{-1}\text{s}^{-1}$, for Test Series E) and the steeper beach face increased backwash flow and thus more sediment was transported seawards into the inner surf zone. This offshore sediment transport resulted in the development of a submerged bar around $x = 90\text{ m}$ (Fig.11b). The extra store of sediment in the inner surf zone enhanced wave energy dissipation, reducing the wave energy available for wave runup and therefore overwash discharge and sediment transport. The flattening of the gravel barrier beach face also contributed to some wave energy dissipation, but its effect was not as strong as the additional sand volume in the nearshore. Sandy barrier inner-surf build-up is a negative feedback process that tends to hinder further overwash. Therefore, once the overwash process is developed, sandy barriers appear more resilient than gravel barriers due to surf zone induced wave energy dissipation.

From the above it can be deduced that barriers have a certain capacity to the accommodate disturbance, i.e., they have resilience. Gravel barriers are more resilient to the onset of overwash, whilst sandy barriers have a higher resilience to overwash intensification. However, barrier resilience has a limit ('critical

resilience'); and once barrier critical resilience is overcome, for example by an increase in wave height or surge level, the morphological trajectory, i.e., the barrier profile evolution changes (towards inundation, breaching, etc). Natural systems provide examples of barriers in situations both below and above critical resilience. Extreme events are likely to disturb barriers beyond the critical resilience, which is particularly well documented when associated with hurricanes (e.g., Morton and Sallenger, 2003). Non-storm overwash (e.g. Baldock et al., 2008) or moderate storm overwash (e.g. Nielsen and Nielsen, 2006) are mostly below critical resilience; hence, these barriers experience overwash without total disruption, because impacts are diminished by negative feedback processes that represent the self-organization capacity of barriers.

4.2. Role of peak wave period in overwash properties

Series D was designed to enable a comparison of overwash hydrodynamic and morphological properties generated by different combinations of wave period and water level (Table 1). Although in nature storms with high waves are generally associated with large wave periods, coastal erosion can also be generated by elevated water levels (e.g., Morton et al., 2000; Bendixen et al., 2013) or spring tides (e.g., Kochel et al., 1993; Matias et al., 2010) which can coincide with shorter wave periods.

In Fig. 8, a range of variables from the overwash runs during Test Series D (D18, D25, D34, D44, D53, D64, D74) are compared. As designed, peak wave period increased throughout the series from 4 s to 10 s; and the return period of overwash flows also increased from about 14 s to 29 s. The percentage of time that

1 the barrier crest was submerged by overwash did not vary greatly (6–8%),
2 considering that the number of overwash events per run varied between 41 (D74)
3 and 85 (D18 and D25). Individual overwash events during earlier runs had a
4 smaller average water discharge (92 l on D18, Fig.10a) than for latter runs (294 l
5 on D74). The sediment volume that was deposited on the backbarrier by overwash
6 processes varied irregularly between c. 0.2 and 0.5 m³m⁻¹ during D18-D74 (Fig. 8).
7 This was because an increase in the volume of overwash water that passed the
8 crest from 5.8 m³m⁻¹ to 10.3 m³m⁻¹, from D18 to D74 (Fig. 8) was partially
9 balanced by a decrease in the number of overwash events (Table 2). The likelihood
10 of overwash occurrence was high for all runs of Test Series D, as *OP* was larger
11 than 0.5 m (Fig. 8).

12 From the above it can be deduced that a high overwash frequency with an elevated
13 water level may not necessarily translate into more water discharge. This
14 experiment shows that the peak wave period has no significant correlation to
15 overwash discharge ($R^2=0.04$; compare size of circles in Fig. 10a and 10b). Long
16 waves have a longer runup (which translates into longer overwash duration at
17 crest), but lower frequency (which translates into a small number of overwash
18 events). Overall, during an overwash episode over sandy barriers large overwash
19 water volumes can be achieved by either a large number of small overwash events
20 or a small number of large overwash events.

21 This experiment showed a positive correlation between the overall overwash
22 discharge over the barrier crest during an episode and the overwash
23 sedimentation that occurs on the backbarrier (Fig. 10b), with a $R^2=0.87$, which is
24 significant with 99% confidence interval. This conclusion may be applicable only to
25 sandy barriers, where sediment entrainment as bed load is achieved by weaker

1 flows. On gravel barriers, such as the one built for BARDEX 2008 with $D_{50} = 11$
2 mm, weakest flows (e.g., with velocity $< 0.5 \text{ ms}^{-1}$) have no ability to erode
3
4 sediments from the barrier crest and transport them into the backbarrier. Even if a
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6 high number of small overwash events generate a large overall overwash water
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8 discharge, the morphological effects would be different from a few stronger
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10 overwash events (e.g., with velocity $> 3 \text{ ms}^{-1}$) with the same overall discharge.
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18 **4.3. Overwash hydrodynamics: advances and limitations**

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20 Overwash hydrodynamics were based on two main variables: water depth and
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22 flow velocity. In BARDEX II, instruments deployed to measure these variables were
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24 bed-level sensors (Fig.1), 3 video cameras, a 2D scanning Lidar, an acoustic
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26 Doppler velocity profiler (Vectrino II) and two electromagnetic current-meters
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28 (EMCMs). Details about location and settings of these instruments can be found in
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30 Masselink et al. (this issue). Data recorded by these instruments were carefully
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32 analysed for quality-check and reliability of results. Both Vectrino II and EMCMs
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34 had a poor quality signal, where some overwash events could be identified, but
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36 most were indistinct. Data obtained with the LiDAR was not of use as it was
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38 installed too low and the laser angle of incidence on the crest in relation to the
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40 vertical ideal position was very high ($> 80^\circ$), which lead to high distortion, too
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42 much shadowing from the morphology and poor spatial resolution. BLS were used
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44 to estimate both leading edge velocity measurements and for depth-averaged
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46 velocity using the 'continuity method' described by Blenkinsopp et al. (2010),
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48 however it was found that 'continuity velocities' were not reasonable because they
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50 were unrealistically high.
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1 The analysis of the video time-stack images of the overwash events were very
2 robust. The top of the barrier could easily be detected in the time-stacks and was
3 quite constant during each run. The time-series of the light-intensities of the
4 position of the barrier top and of a location at 80 pixels on the back-beach were
5 successfully used to detect overwash events. High values of the gradients in light-
6 intensities over time corresponded with the leading edge of the water films
7 passing by the locations. The detection of leading edge passages made it possible to
8 compute the frequency of overwash events and to compute the average period
9 between the overwash events. The computed overwash events were all plotted in
10 the time-stack images to validate the results (see for example Fig. 2). All visual
11 detected overwashes were detected by the method. In summary, the BLS and video
12 were the only instruments that could be used with confidence to measure
13 overwash.

14 Average overwash leading-edge velocity during BARDEX II was 2.0 ms^{-1} , which
15 was similar to overwash velocities obtained from literature. Overwash flow
16 velocities around 2 ms^{-1} are within the typical range of measurements in the field
17 (from 1.5 ms^{-1} ; Guillén et al., 1994; to 3.5 ms^{-1} ; Fisher and Stauble, 1977; Fig. 12)
18 and in the laboratory (from 1.2 ms^{-1} ; Srinivas et al, 1992; to 3.0 ms^{-1} , Matias et al.,
19 2014).

20 During BARDEX II, overwash depths over the crest were relatively shallow,
21 averaging less than 0.1 m (Figs. 8 and 9). Fieldwork undertaken during overwash
22 has shown a range of overwash peak flow depths from 0.7 m (Fisher and Stauble,
23 1977) to 0.13 m (Holland et al., 1991; Fig. 12). Typically, laboratory experiments
24 exhibit very shallow flows, such as 0.04 m (Donnelly, 2008) due to the small scale

used, except during BARDEX 2008, where a maximum overwash depth of 0.77 m was recorded.

A relationship between overwash depth and velocity has been attempted by several researchers as a means to estimate overwash velocities, which are difficult to measure directly. The relation applied to BARDEX II data using data collected at the barrier crest (Fig.12) was:

$$u_{crest} = 2.03\sqrt{gh_c} \quad (5)$$

where u_{crest} is overwash velocity (ms^{-1}), g is acceleration due to gravity (ms^{-2}) and h_c is overwash water depth (m). The curve adjustment using Eq. (5) had R^2 of 0.10 and RMSE of 0.94 ms^{-1} . The small R^2 was due to a large dispersion of data, particularly for the small values of $h_c g$ (Fig.12). The power model of Eq. (5) was based on the classical dam break equation that has been used for the tip of bores in the swash zone (e.g., Jiang et al., 2010; Blenkinsopp et al., this issue), in which the constant of proportionality is 2. Other constants were found by Donnelly (2008; 1.53), Matias et al. (2014; 2.35) and Holland et al. (1991; 2.6). From Fig. 12, it can be deducted that the power fitting adjustment to fieldwork data sets would provide a smaller constant of proportionality, since for the deepest flows, the velocities are relatively slower than for the experimental data. From the above, an unexpected conclusion can be deducted: although overwash velocity measurements are more challenging and have higher uncertainty, BARDEX II results are within the expected data range; whereas the high-quality overwash depth results are substantially smaller than expected. Eq. (5) may have a poor correlation because of the unusual overwash depth dataset.

5. CONCLUSIONS

The paper provides valuable measurements of the hydrodynamic and morphological evolution of a sandy barrier during overwash at prototype scale. The results of the BARDEX II overwash experiment were compared to those recorded during the BARDEX 2008 experiment undertaken on a gravel barrier, under similar wave and tidal forcing. For gravel barriers overtopping provides a negative feedback on morphological evolution through raising the barrier crest, thereby inhibiting further overtopping or overwash. According to the laboratory results gravel barriers are more resilient than sandy barriers during early stages, when the overwash water intrusion is limited. During overwash on sandy barriers, inner surf zone build-up induces wave energy dissipation and is therefore a negative feedback process that tends to prevent further overwash. Thus, gravel barriers are more resilient to the onset of overwash, whilst sandy barriers have a higher resilience to overwash intensification. However, both cases of barrier resilience have a limit, the “critical resilience”, beyond which the barrier can be breached or inundated.

The role of wave period on overwash characteristics was investigated. The shorter period waves (4 s) with an elevated water level and the long period waves (10 s) with a lower water level induced differences in overwash discharges; however, during some runs, the more frequent smallest water discharges and sedimentation tend to be similar to the less frequent largest discharges and sedimentation rates considering the entire run. This translates into a very similar percentage of time with overwash during Test Series D. Nevertheless, a significant correlation was found between overall overwash discharge per event and overwash induced sedimentation per event, including both Test Series D and E.

1 Not all instrumentation deployed in BARDEX II overwash experiment provided
2 good results on the hydrodynamic measurements; therefore only BLS and video
3 were used for overwash measurements. The depth range of overwash on the sandy
4 barrier was relatively shallow when compared to fieldwork measurements;
5 however the leading edge overwash velocity was of the same order of magnitude.
6
7 The results presented in this study provide valuable insight into overwash on
8 sandy barriers, as well as the fundamental feedback processes that differ on sandy
9 and gravel barriers. Results should be used with care since field and laboratory
10 situations are different; however, given the technical difficulty and hazard of
11 undertaking fieldwork during overwash, the obtained datasets are unique and
12 useful for model development and enhancing our understanding of the
13 fundamental processes.
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References

- Austin, M. J., and Masselink, G., 2006. Observations of morphological change and sediment transport on a steep gravel beach. *Marine Geology*, 229, 59-77.
- Baldock, T.E., Weir, F., Hughes, M.G., 2008. Morphodynamic evolution of a coastal lagoon entrance during swash overwash. *Geomorphology*, 95, 398-411.
- Battjes, J.A., 1974. Surf similarity. *Proceedings of 14th Conference on Coastal Engineering*, ASCE, Copenhagen, Denmark, 446-480.
- Bendixen, M., Clemmensen, L.B., Kroon, A., 2013. Sandy berm and beach-ridge formation in relation to extreme sea-levels: A Danish example in a micro-tidal environment. *Marine Geology*, 344, 53-64.
- Blenkinsopp, C., Turner, I., Masselink, G., Russel, P., 2010. Validation of volume continuity method for estimation of cross-shore swash flow velocity. *Coastal Engineering* 57, 953-958.
- Blenkinsopp, C., Turner, I., Masselink, G., Russel, P., 2011. Swash zone sediment fluxes: field observations. *Coastal Engineering* 58, 28-44.
- Blenkinsopp, C., Matias, A., Howe, D., Castelle, B., Marieu, V., Turner, I.L., this issue. Wave runup and overtopping on a prototype-scale sand barrier. *Coastal Engineering*.

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52
53
54
55
56
57
58
59
60
61
62
63
64
65
- Bradbury, A., Cope, S. N., Prouty, D. B., 2005. Predicting the response of shingle barrier beaches under extreme wave and water level conditions in Southern England. Proceedings of Coastal Dynamics, ASCE, Barcelona, Spain.
- Cleary, W. J., McLeod, M. A., Rauscher, M. A., Johnston, M. K., Riggs, S. R., 2001. Beach nourishment on hurricane impacted barriers in Southeastern North Carolina, USA: Targeting shoreface and tidal inlets sand resources. Journal of Coastal Research SI 34, 232-255.
- D' Alessandro, F., Fortes, C. J., Ilic, S., James, M., Sancho, F., Schüttrumpf, H., Tomasicchio, G. R., 2010. Wave storm induced erosion and overwash in large-scale flume experiments. Proceedings of the HYDRALAB III Joint User Meeting. Hannover, Germany.
- D' Alessandro, F., Tomasicchio, G.R., Musci, F., Ricca, A., 2012. Dune erosion physical, analytical and numerical modelling. Proceedings of 33rd Conference on Coastal Engineering, ASCE, Santander, Spain, paper n. 32.
- Dette, H.H., Larson, M., Murphy, J., Newe, J., Peters, K., Reniers, A., Steetzel, H., 2002. Application of prototype flume tests for beach nourishment assessment. Coastal Engineering, 47, 137-177.
- Dolan, R. and Godfrey, P., 1973. Effects of Hurricane Ginger on the barrier islands of North Carolina. Geological Society of America Bulletin, 84, 1329-1334.
- Donnelly, C., 2008. Coastal overwash: processes and modelling. Lund University, Sweden, 53 pp + papers.

- 1 Donnelly, C., and Sallenger, A.H., 2007. Characterisation and modeling of washover
2 fans. Proceedings of Coastal Sediments '07, USACE, New Orleans, USA, pp. 2061-
3
4 2073.
5
6
- 7 Figlus, J., Kobayashi, N., Gralher, C., Iranzo, V., 2011. Wave overtopping and
8
9 overwash of dunes. Journal of Waterway, Port, Coastal, and Ocean Engineering,
10
11 137, 26-33.
12
13
- 14 Fisher, J.S. and Stauble, D.K., 1977. Impact of Hurricane Belle on Assateague Island
15
16 washover. Geology, 5 (12), 765-768.
17
18
- 19 Fisher, J.S., Leatherman, S.P., Perry, F.C., 1974. Overwash processes on Assateague
20
21 Island. Proceedings of 14th Conference on Coastal Engineering, ASCE,
22
23 Copenhagen, Denmark, pp. 1194-1211.
24
25
- 26 Fletcher, C.H., Richmond, B.M., Barnes, G.M., Schroeder, T.A., 1995. Marine flooding
27
28 on the coast of Kauai during Hurricane Iniki: Hindcasting inundation
29
30 components and delineating washover. Journal of Coastal Research, 11 (1), 188-
31
32 204.
33
34
- 35 Guillén, J., Camp, J., Palanques, A., 1994. Short-time evolution of a microtidal
36
37 barrier - lagoon system affected by storm and overwashing: the Trabucador Bar
38
39 (Ebro Delta, NW Mediterranean). Zeitschrift fur Geomorphologie 38, 267-281.
40
41
- 42 Hall, M.J., Young, R.S., Thieler, E.R., Priddy, R.D., Pilkey, O.H., 1990. Shoreline
43
44 response to Hurricane Hugo. J. Coast. Res., 6(1), 211-221.
45
46
- 47 Hancock, M. W. and Kobayashi, N., 1994. Wave overtopping and sediment
48
49 transport over dunes. Proceedings of 24th Conference on Coastal Engineering,
50
51 ASCE, Kobe, Japan, pp. 2028-2042.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Hayden, B. and Dolan, R., 1977. Storm-surge overwash along the US mid-Atlantic
2 coast. *Bulletin of the American Meteorological Society*, 58 (10), 1128.
3
4
- 5 Holland, K. T., Holman, R. A., Sallenger, A. H., 1991. Estimation of overwash bore
6 velocities using video techniques. *Proceedings of Coastal Sediments '91*, USACE,
7
8
9
10 Seattle, Washington, USA., pp. 489-497.
11
12
- 13 Holman, R.A., and Stanley, J., 2007. The history and technical capabilities of Argus.
14
15
16 *Coastal Engineering*, 54, 477-491.
17
- 18 Houser, C., 2012. Feedback between ridge and swash bathymetry and barrier
19
20
21 island storm response and transgression. *Geomorphology*, 173-174, 1-16.
22
23
- 24 Jiang, A. W., Hughes, M., Cowell, P., Gordon, A., Savioli, J. C., and Ranasinghe, R.
25
26
27 (2010). A hybrid model of swash-zone longshore sediment transport on
28
29
30 reflective beaches. *Proceedings of International Conference on Coastal*
31
32
33 engineering, Shanghai, China.
- 34 Kobayashi, N., Farhadzadeh, A., Melby, J., Johnson, B., Gravens, M., 2010. Wave
35
36
37 overtopping of levees and overwash of dunes. *Journal of Coastal Research*,
38
39
40 26(5), 888-900.
41
- 42 Kochel, R.C., Berntsen, J., Carlson, C.R., 1993. Hydrogeomorphology and vegetation
43
44
45 relationship at topographically nested sites, Parramore Island, Virginia. *Virginia*
46
47
48 *Coast Reserve Long-Term Ecological Research project*. Available at:
49
50
51 <http://atlantic.evsc.virginia.edu/davedocs/VCRASC95/kochel.html>
52
- 53 Leatherman, S.P., 1976. Quantification of overwash processes. Ph.D. Thesis,
54
55
56
57
58
59
60
61
62
63
64
65 University of Virginia, USA.

- 1 Lorang, M. S., 2002. Predicting the crest height of a gravel beach. *Geomorphology*
2 48, 87-101.
3
4
- 5 Matias, A., Ferreira, Ó., Vila-Concejo, A., Morris, B., Dias, J. A., 2010. Short-term
6 morphodynamics of non-storm overwash. *Marine Geology* 274, 69-84.
7
8
- 9 Matias, A., Williams, J. J., Masselink, G., Ferreira, Ó., 2012. Overwash threshold for
10 gravel barriers. *Coastal Engineering* 63, 48-61.
11
12
- 13 Matias, A., Masselink, G., Kroon, A., Blenkinsopp, C., Turner, I., 2013. Overwash
14 experiment on a sandy barrier. *Journal of Coastal Research*, SI 65, 778-783.
15
16
- 17 Matias, A., Blenkinsopp, C., Masselink, G., 2014. Detailed investigation of overwash
18 on a gravel barrier. *Marine Geology*, 350, 27-38.
19
20
- 21 Masselink, G. and van Heteren, S., 2014. Response of wave-dominated and mixed-
22 energy barriers to storms. *Marine Geology*, 352, 321-347.
23
24
- 25 Masselink, G., Ruju, A., Conley, D., Turner, I., Ruessink, G., Matias, A., Thompson, C.,
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
- Castelle, B., Wolters, G., this issue. Large-scale Barrier Dynamics Experiment II (BARDEX II): experimental design, instrumentation, test programme and data set. *Coastal Engineering*.
- Morton, R.A. and Sallenger, A.H., 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research*, 19 (3), 560-573.
- Morton, R.A., Gonzalez, J.L., Lopez, G.I., Correa, I.D., 2000. Frequent non-storm washover of barrier islands, Pacific Coast of Colombia. *Journal of Coastal Research*, 16 (1), 82-87.
- Nielsen, J., and Nielsen, N., 2006. Washover geomorphology on a barrier spit, Skallingen, Denmark. *Journal of Coastal Research*, SI 39, 678-681.

- 1 Nordstrom, K.F., and Jackson, N.L., 1995. Temporal scales of landscape change
2 following storms on a human-altered coast, New Jersey, USA. *Journal of Coastal*
3 *Conservation*, 1, 51-62.
4
5
6
7 Obhrai, C., Powell, K., Bradbury, A., 2008. A laboratory study of overtopping and
8 breaching of shingle barrier beaches. *Proceedings of International Conference*
9 *on Coastal Engineering*, Hannover, Germany, pp. 1497-1508.
10
11
12
13
14
15 Orford, J. D., and Carter, R. W. G., 1982. Crestal overtop and washover
16 sedimentation on a fringing sandy gravel barrier coast, Carnsore Point,
17 Southeast Ireland. *Journal of Sedimentary Petrology* 52, 265-278.
18
19
20
21
22
23 Orford, J. D., Carter, R. W. G., Jennings, S. C., Hinton, A. C., 1995. Processes and
24 timescales by which a coastal gravel-dominated barrier responds
25 geomorphologically to sea-level rise: Story Head Barrier, Nova Scotia. *Earth*
26 *Surface Processes and Landforms* 20, 21-37.
27
28
29
30
31
32
33 Orford, J. D., Cooper, J. A. G., Jackson, D., Malvarez, G., White, D., 1999. Extreme
34 storms and thresholds on foredune stripping at Inch Spit, South-West Ireland.
35 *Proceedings of Coastal Sediments '99*, New York, USA, pp. 1852-1866.
36
37
38
39
40
41 Orford, J., Jennings, S., Pethick, J., 2003. Extreme storm effect on gravel-dominated
42 barriers. *Proceedings of Coastal Sediments '03*, Florida, USA, ASCE, CD-ROM.
43
44
45
46
47 Park, Y. H., and Edge, B. L., 2010. An empirical model to estimate overwash. *Journal*
48 *of Coastal Research* 26, 1157-1167.
49
50
51
52 Poate, T.G., Masselink, G., Davidson, M., McCall, R., Russell, P., Turner, I., 2013. High
53 frequency in-situ field measurements of morphological response on a fine
54 gravel beach during energetic wave conditions. *Marine Geology*, 342, 1-13.
55
56
57
58
59
60
61
62
63
64
65

- Priestas, A.M., and Fagherazzi, S., 2010. Morphological barrier island changes and recovery of dunes after Hurricane Dennis, St. George Island, Florida. *Geomorphology*, 114, 614-626.
- Pullen, T., Allsop, N. W. H., Bruce, T., Kortenhaus, A., Schuttrumpf, H., Van der Meer, J. W., 2007. Wave overtopping of sea defences and related structures: assessment manual. *EurOtop. Die Küste*, 73. 178 pp.
- Rodríguez, R. W., Webb, R. M. T., Bush, D. M., 1994. Another look at the impact of Hurricane Hugo on the shelf and coastal resources of Puerto Rico, USA. *Journal of Coastal Research* 10, 278-296.
- Sallenger, A.H., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research*, 16 (3), 890-895.
- Sallenger, A.H., Stockdon, H.F., Fauver, L., Hansen, M., Thompson, D., Wright, C.W., Lillycrop, J., 2006. Hurricanes 2004: an overview of their characteristics and coastal change. *Estuaries and Coasts*, 29, 880-888.
- Srinivas, R., Dean, R. G., Parchure, T. M., 1992. Barrier island erosion and overwash study - Volume 1. Coastal and Ocean Engineering Department, University of Florida, 92 pp.
- Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger, A.H., 2006. Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, 53, 573-588.
- Stockdon, H.F., Doran, K.S., Sallenger, A.H., 2009. Extraction of lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. *Journal of Coastal Research*, SI 53, 59-65.

- 1 Stone, G., Liu, B., Pepper, D. A., Wang, P., 2004. The importance of extratropical and
2 tropical cyclones on the short-term evolution of barrier islands along the
3 northern Gulf of Mexico, USA. *Marine Geology*, 210, 63-78.
4
5
6
7
8 Tomasichio, G.R., Sánchez-Arcilla, A., D' Alessandro, F., Ilic, S., James, M., Sancho,
9 F., Fortes, J.C., Schüttrumpf, H., 2011. Large-scale experiments on dune erosion
10 processes. *Journal of Hydraulic Research*, 49, S1, 20-30.
11
12
13
14
15
16 Turner, I. L., Russell, P. E., Butt, T., 2008. Measurement of wave-by-wave bed-levels
17 in the swash zone. *Coastal Engineering* 55, 1237-1242.
18
19
20
21 Van Rijn, L.C., Tonnon, P.K., Sánchez-Arcilla, A., Cáceres, I., Grüne, J., 2011. Scaling
22 laws for beach and dune erosion processes. *Coastal Engineering*, 58, 623-636.
23
24
25
26
27 Williams, J. J., Buscombe, D., Masselink, G., Turner, I. L., Swinkels, C., 2012. Barrier
28 dynamics experiment (BARDEX): Aims, design and procedures. *Coastal*
29 *Engineering* 63, 3-12.
30
31
32
33
34
35 Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M.P., Cowell, P., 1979.
36
37 Morphodynamics of reflective and dissipative beach and inshore systems:
38
39 Southeastern Australia. *Marine Geology*, 32, 105-140.
40
41
42
43
44
45
46
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FIGURE CAPTIONS

Figure 1. (a) Very thin overtopping flow over the barrier crest, located close to a wooden board attached to the left wall; (b) Overwash flow over the barrier, looking from the landward dipping barrier surface towards the waves; the crest is located where the foam starts seaward; (c) Sketch of the experiment cross-section within the Delta Flume; (d) Barrier cross-shore profiles for the first run of every test of Series D. Crosses on top of the profile represent BLS location and number identification.

Figure 2. Video timestack of run D34. The barrier crest (thick black line) has 9 crossings (red dots) during this 200 s time interval.

Figure 3. Barrier cross-shore profiles from several test series with swash, overtopping and overwash. a) Series D1; b) Series D3; and c) Series D7. Water levels on the 'sea' side (paddle side, to the left) of the first and last run are also represented in dash-lines.

Figure 4. Barrier cross-shore profiles from test series with overwash: a) during Test Series E of BARDEX II and b) during Test Series E10 of BARDEX 2008 (from Matias et al., 2014).

Figure 5. Variation of a) beach slope defined between mean water level and the upper limit of the beach face, b) barrier crest elevation, c) sediment transport rate induced by overwash, d) Overwash Potential ($OP=0$ m is also represented) through BARDEX II test series; swash runs represented by crosses, overtopping runs represented by white circles, and overwash runs represented by black circles.

Figure 6. Contour plots of cumulative cross-shore bed variation during runs D34, D74, and E5. The time-series of water depth at the barrier crest is represented at crest position (100.6 m from wave paddle for D34 and D74, and 102.1 m for E5), with an exaggeration of 100 times for D34 and D74, and 25 times for E5.

Figure 7. Time-series of extracted overwash depth data recorded during runs D34, D74 and E5, as examples, with the peak depth of each overwash event marked with a circle.

Figure 8. Relevant hydrodynamic properties of waves and overwash flows from runs with overwash of Test Series D. Other wave and tide characteristics of these runs are on Table 1. On the two boxplots, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

Figure 9. Relevant hydrodynamic properties of waves and overwash flows from runs with overwash of Test Series E. Other wave and tide characteristics of these runs are on Table 1. On the two boxplots, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

Figure 10. Top: Average volume of overwash water that overcomes the barrier crest during each single event, versus the amount of overwash sedimentation on the backbarrier during each single event, considering all runs with overwash from Test Series E and D. Bottom: Total volume of overwash water discharge at the barrier crest during each overwash episode (run), versus the overall amount of sedimentation on the backbarrier during each overwash episode (run), considering all runs with overwash from Test Series E and D. The size of the markers is proportional to run peak wave period.

Figure 11. Barrier cross-shore profiles from test series E of BARDEX II and Test Series E10 of BARDEX 2008, a) before and b) after 5 runs with overwash. Note that the profiles from gravel barrier were moved landward to have the beach face coincide, facilitating the comparison. c) Photograph of Barreta Island, Portugal as an example of a sandy barrier with similar characteristics to the one built for the experiment BARDEX II. d) Photograph of Loe Bar, Cornwall, U.K. as an example of a gravel barrier (from Poate et al., 2013).

Figure 12. Overwash leading edge velocity at crest (u_{crest}) as a function of overwash depth at crest (h_c), for all runs of BARDEX II experiment. Data from fieldwork, reported in the literature is also represented (dark circles). The line of power fitting adjustment to laboratory data is represented with a dashed line. $R^2 = 0.10$ and $RMSE = 0.94 \text{ ms}^{-1}$.

Table 1. Overwash experimental programme. These parameters were measured with PT sensors, and do not equal planned conditions (in Masselink et al., this issue). H_s = significant wave height; T_p = peak wave period; h_s = water level.

Series	Run	H_s (m)	T_p (s)	h_s (m)	Process
D1	D11	0.71	4.00	3.14	swash
	D12	0.71	4.00	3.29	swash
	D13	0.70	4.00	3.44	swash
	D14	0.70	4.00	3.60	overtopping
	D15	0.71	4.00	3.75	overtopping
	D16	0.72	4.00	3.90	overtopping
	D17	0.73	4.00	4.05	overtopping
	D18	0.74	4.00	4.21	overwash
D2	D21	0.77	4.53	3.45	swash
	D22	0.77	4.53	3.58	swash
	D23	0.79	4.53	3.74	overtopping
	D24	0.79	4.53	3.89	overtopping
	D25	0.80	4.53	4.03	overwash
D3	D31	0.77	6.02	3.44	swash
	D32	0.79	6.02	3.59	overtopping
	D33	0.82	6.02	3.74	overtopping
	D34	0.85	6.02	3.89	overwash
D4	D41	0.81	6.65	3.42	swash
	D42	0.80	6.65	3.58	overtopping
	D43	0.80	7.11	3.73	overtopping
	D44	0.81	7.11	3.86	overwash
D5	D51	0.81	7.64	3.44	overtopping
	D52	0.83	7.64	3.58	overtopping
	D53	0.84	7.64	3.72	overwash
D6	D61	0.83	9.48	3.29	swash
	D62	0.84	9.48	3.44	overtopping
	D63	0.83	9.48	3.58	overtopping
	D64	0.86	9.48	3.72	overwash
D7	D71	0.87	10.04	3.14	overtopping
	D72	0.91	10.04	3.28	overtopping
	D73	0.89	10.04	3.43	overtopping
	D74	0.88	10.04	3.57	overwash
E	E1	0.86	7.11	3.88	overwash
	E2	0.88	7.11	3.90	overwash
	E3	0.89	7.64	3.89	overwash
	E4	0.91	7.64	3.90	overwash
	E5	0.90	7.64	3.90	overwash

Table 2

Table 2. Frequency and return period of the overwash events in the video-timestacks.

Test Series D	Frequency (events / 20 min)	Return period (s)
D34	84	14.28
D44	93	12.97
D53	57	20.78
D64	74	16.02
D74	53	22.12
Test Series E	Frequency (events / 13 min)	Return period (s)
E1	79	9.87
E4	76	10.26
E5	80	

Table 3. Overwash depth characteristics for series D and E.

	Series D	Series E
Average depth (m)	0.042	0.066
Average peak depth (m)	0.067	0.110
Depth standard deviation (m)	0.015	0.030
Maximum depth (m)	0.465	0.529
Minimum depth (m)	0.020	0.020
Average depth skewness	0.154	0.019

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FIGURES

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c) Barreta Island, Portugal (sandy barrier)

d) Loe Bar, Cornwall, U.K. (gravel barrier)

Figure 12
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