Predicting overwash on gravel barriers

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ABSTRACT

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A process-based non-hydrostatic flow model, which includes the effect of infiltration and exfiltration, but no morphology, is applied to simulate overwash events on gravel barriers. After calibration, the model is shown to produce similar predictions for overwash as the empirical Barrier Inertia Model for parameter combinations within the validity range of the empirical model. When applied to 25 historical storm impacts, the process-based model shows improvement over the empirical model in predicting overwash. The model is applied to study the sensitivity of overwash to input parameters outside the validity range of the empirical Barrier Inertia model. This analysis shows that two parameters currently missing in the Barrier Inertia Model, the depth of the gravel beach toe and the gravel beach slope, greatly affect the threshold criteria for overwash.

ADDITIONAL INDEX WORDS: *Gravel beaches and barriers, storms, erosion, overtopping, overwash, rollback, empirical models, process-based modelling*

INTRODUCTION

Gravel beaches and barriers occur on many high-latitude, wave-dominated coasts across the world. They are widely regarded as an effective and sustainable form of coastal defence due to their ability to dissipate large amounts of wave energy. However, during extreme events waves may succeed in lowering and overtopping the barrier crest, causing overwash damage on the back barrier, barrier rollback, or even barrier destruction. Although rare, such events can lead to loss of lives and significant damages to land and infrastructure in the hinterland. Currently, coastal managers rely on empirical models to determine the risk of storm impacts on gravel coasts. Although these models are relatively easy to use, they inherently suffer from limitations in the data from which they are derived and the assumptions made to parameterise the data.

One empirical model that is commonly used in the UK is the Barrier Inertia Model (BIM; Bradbury, 2000). This model relates the probability of overwash on gravel beaches to the wave steepness of the incident waves S_w, and the dimensionless barrier inertia parameter BI, defined as:

$$S_w = \frac{H_s}{L_m} \qquad BI = \frac{R_c A}{H_s^3} \tag{1}$$

in which H_s is the significant wave height measured at 6–8 m water depth (m), L_m is the deep water wave length of the mean period wave (m), R_c is the freeboard, or height of the barrier crest above still water level (m), and A is the cross sectional area of the barrier above the still water level (m^2). From analysis of laboratory and field data, Bradbury (2000) found barrier overwash is unlikely to occur when:

$$BI > 0.0006 S_w^{-2.54} \tag{2}$$

Although the BIM is used in many locations in the UK, the data used to derive the threshold overwash relation are specific to the site and conditions where they were measured (Hurst Spit in the south of England). The model may therefore not be valid for other sections of the coast of the UK.

In this paper we attempt to improve the applicability of the BIM by studying the importance of its limitations. Various factors affecting gravel barrier storm response, such as wave transformation across a shallow foreshore, the effect of the beach slope on the runup height and the effect of the permeability of the barrier are not included in the model. By correctly understanding the effect of these factors, the range of application of the BIM may be extended.

Since field data of gravel barrier breaching are limited and do not cover the full range of parameter space that occurs in nature, we use a newly developed process-based hydrodynamic model for gravel beaches to augment field data.

MODEL APPROACH

In this paper we use an existing open-source, process-based model for the nearshore and coast called XBeach (Roelvink et al.,

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2009) to simulate storm hydrodynamics on gravel barriers. The XBeach model has been shown to have quantitative skill in hindcasting storm impact, overwash and breaching processes on sandy beaches (Roelvink *et al.*, 2009; McCall *et al.*, 2010) and simulating overwash hydrodynamics on a gravel barrier (McCall *et al.*, 2012). The XBeach model is able to simulate non-hydrostatic flow in a manner similar to the one-layer version of the SWASH model (Smit et al, 2010; Zijlema et al., 2011), thereby enabling XBeach to solve flow and surface elevation variations due to short waves in intermediate and shallow water depths ($kh \lesssim 2.5$) with relative dispersion and celerity errors less than 5%. XBeach has been extended to include the effect of infiltration and exfiltration on gravel beaches through the use of a non-hydrostatic groundwater model (McCall *et al.* 2012).

Since the XBeach model has not yet been developed to simulate gravel sediment transport, the model cannot predict the morphological response of the barrier during storm conditions. However, estimates of the type of response of the gravel barrier to storm forcing (erosion of the beach, overtopping of the crest, overwash of the barrier, barrier rollback, or barrier destruction) may be inferred from the simulated hydrodynamics on the initial barrier profile as discussed below.

Following engineering design guidelines for the stability of rip-rap structures under overwash conditions (Simm, 1991; Frizell *et al.*, 1998), threshold average discharge levels can be estimated for the start of damage to the barrier crest (2 l/s/m), the start of damage on the back barrier (20 l/s/m) and severe damage on the back barrier slope (100 l/s/m). If a tentative relation is made between damage to the barrier crest and overtopping morphology, and between damage on the back slope and overwash morphology, these guidelines may be used to estimate barrier storm response to simulated overtopping discharges.

The model approach used in this paper is tested by comparison of the estimated barrier response, using the simulated overtopping discharge and overtopping thresholds, to the response predicted by the BIM for the range of conditions for which the model is valid. In addition, the XBeach model approach is applied to known storm events for which the BIM is not strictly valid to show the skill of the process-based model relative to the empirical model.

To be able to vary the barrier geometry in the model simulations, the shape of a typical gravel barrier is reduced to a set of parameters (Figure 1) describing the crest height above still water level (R_c), the depth of the toe of the gravel barrier (D_{toe}), the width of the barrier (W_c), and the angle of the seaward and landward slopes of the barrier and the seabed slope (β_{beach}, β_{back} and β_{seabed}).

MODEL CALIBRATION

To confirm that the process-based hydrodynamic model, combined with the discharge threshold estimates for overwash, is able to predict the same morphological response as the BIM, over 900 XBeach simulations were run. In these calibration simulations, the hydrodynamic forcing parameters and the geometry of the barrier are varied randomly within the range of conditions from which the empirical BIM was derived (see Table 1 for a summary). A random JONSWAP wave time series was imposed on the model boundary in every simulation and the average overtopping discharge (q_c in Figure 1) was calculated over a 20-minute period.

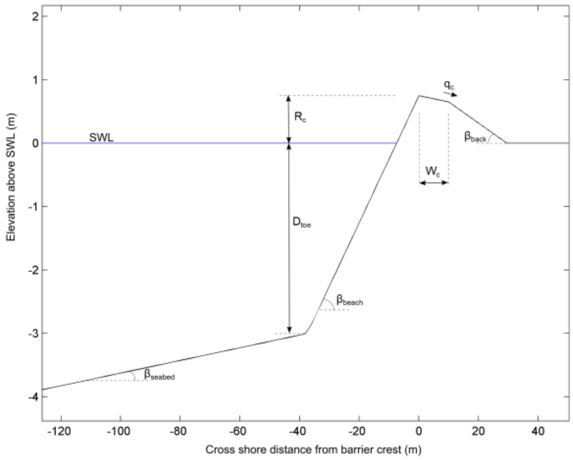

Figure 1. Cross-section of a schematic gravel barrier and the geometric parameters describing its shape.

The results of the calibration simulations are shown in BIM parameter space in Figure 2. In the upper panel, the threshold for overtopping discharge in the XBeach model to classify as overwash is set at 20 l/s/m. The figure shows reasonable agreement between the threshold for overwash in the BIM (black curve) and XBeach predictions of overwash (black squares). The XBeach model generally predicts overwash in most simulations with low BI values and a reduction in overwash probability for higher wave steepness. However, approximately 9% of the XBeach simulations that lie above the empirical BIM threshold curve are predicted to produce overwash (false positives), indicating that the hydrodynamic model may be overestimating the overtopping discharge due to the lack of morphological feedback in XBeach, or the threshold of 20 l/s/m is too low to classify as overwash on gravel barriers.

In the lower panel in Figure 2, the threshold for overtopping discharge in the XBeach model to classify as overwash is set at 100 l/s/m. The results show good quantitative agreement between the threshold for overwash in the BIM (black curve) and the upper limit of XBeach simulations with overwash (black squares). In this case fewer than 2% of the XBeach simulations that lie above the empirical BIM threshold curve are predicted to produce overwash (false positives). However, at this discharge classification level for overwash, many simulations (60%) below the BIM threshold curve are predicted *not* to cause overwash by the XBeach model. These predictions are not necessarily false negatives, since the BIM only states that overwash is unlikely to occur *above* the empirical threshold. However, the use of 100 l/s/m as a classification for overwash is probably not a conservative measure for engineering purposes.

The results of the calibration simulations show that even without a morphodynamic component, the hydrodynamic XBeach model can predict the likely morphological behaviour (as inferred from overwash volumes) of gravel barriers described by the BIM in the majority of the calibration simulations. Due to the lack of any morphodynamic feedback in the model, the prediction of cases that lie close to the BIM threshold is less accurate. In these

Table 1. Overview of the hydrodynamic forcing and barrier geometry parameter ranges used in the model calibration simulations.

H_s (m)	S_w (%)	R_c/H_s (-)	W_c (m)	D_{toe} (m)	β_{beach} (-)	β_{back} (-)	β_{seabed} (-)	K (m/s)
1.0–4.0	1.7–4.0	0.0–3.0	5.0–20.0	5.4	0.14	0.03	0.005	0.05

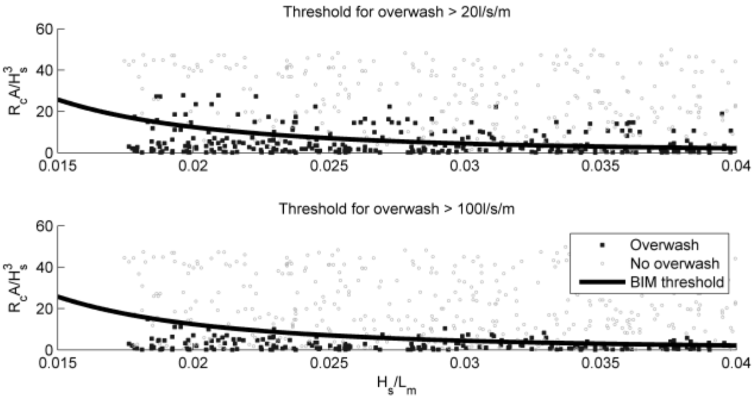

Figure 2. Estimated cases of overwash (black squares) and non-overwash (grey circles) in the calibration simulations, for two different overwash discharge thresholds. According to the BIM, overwash is unlikely to occur in the parameter space above the black curve.

cases, the storm response of the barrier should be estimated using a conservative lower bound of 20 l/s/m and an upper bound of 100 l/s/m for overtopping discharge to classify overwash.

MODEL VALIDATION

A series of 22 documented storm impacts on gravel barriers and three BARDEX physical model experiments (see Table 2) are hindcast in order to validate the XBeach model approach. In these hindcast simulations, the barrier geometry is parameterised in a similar manner to the calibration simulations, using documented topographic and bathymetric data to estimate the toe depth, beach slope, seabed slope, crest height and barrier width. The hindcast models are forced using documented maximum wave conditions and surge levels where available, and estimates combined with sensitivity bands where accurate data are not available. Due to uncertainties in the hydraulic forcing conditions and pre-storm crest elevation, cases C78, C78, S01, S04 and HI are simulated using the range of hydraulic forcing and barrier geometries presented in Table 2. Recorded data of the barrier hydraulic conductivity are used for the simulation of the BARDEX, Chesil Beach and Loe Bar cases; for other locations the conductivity is approximated from the conductivity of beaches with similar grain sizes.

The documented barrier storm response of the 25 hindcast events are categorised into four levels of storm response (rollback and severe overwash; overwash damage on back barrier; overtopping and crest build-up; and beach erosion with no change to crest) according the extent of the observed profile change during the storm and the amount of flooding of the area behind the barrier. The simulated overtopping discharges in the hindcast simulations are plotted in Figure 3 according to the location of the storm event in BIM parameter space and according to the classification of the barrier storm response. Note that the vertical scale in Figure 3 is logarithmic.

HS, BE10 and C79 are classified as barrier rollback or severe overwash events. HS and BE10 showed significant lowering and retreat of the crest and flooding of the hinterland. C79 also showed severe flooding of the hinterland and lowering of the crest, but no barrier retreat. Figure 3 (upper panel) shows that XBeach predicts overtopping discharge rates greater than 100 l/s/m at HS and BE10, and over 20–100 l/s/m at C79. All three events would be classed as overwash events in the XBeach model according to the threshold values found in the model calibration. Although HS and BE10 are both below the BIM overwash threshold, C79 is located above the threshold curve and would therefore not be predicted to be an overwash event by the BIM.

Overwash events are indentified by damage on the back barrier and limited flooding of the hinterland. These events include C78, which caused some flooding behind the barrier, S01, which caused significant damage to the main road located on the barrier, and five separate storms between 1994 and 2000 at Medmerry (MMo). Figure 3 (upper centre panel) shows that the XBeach model correctly predicts the possibility of overwash ($q_c > 20$ l/s/m) at SL01, and overwash for one storm event at Medmerry. However, C78 and the four other Medmerry storms are predicted to have an overtopping discharge less than 20 l/s/m and would therefore incorrectly be classed as non-overwash events. None of the storms in this category would, however, be predicted as possible overwash events by the BIM.

Overtopping events are classified as events during which the crest builds up (increase in crest elevation), the extent of the morphological change just reaches the crest, or the documentation describes occasional waves overtopping the crest. These include S04, HI and BE1. The XBeach model predicts overtopping discharges less than 20 l/s/m at all these sites and are therefore correctly classified as non-overwash events. The model does predict limited overtopping of the barrier crest (2–20 l/s/m) at SL04 and HI, which corresponds with the notion of occasional waves overtopping the crest.

The final classification is for storm events which affected the beach, but did not reach the crest. These events are called erosion events, and include three storms at Medmerry (MMs), four storms at Loe Bar (LB), the four largest storms each year between 2007 and 2010 at Chesil Beach (C07) and BC1. In a similar fashion to the overtopping events, the overwash discharge hindcast by the XBeach model is less than 20 l/s/m, and would therefore correctly be classified as non-overwash events. All events except the storms at Medmerry are predicted to have less than 2 l/s/m overtopping discharge, which corresponds with the notion of no waves reaching the crest.

Table 2. Overview of the model sites, the documented barrier response to the storm event, the number of events modelled, and the hydrodynamic forcing and barrier geometry parameter ranges used in the XBeach validation hindcast simulations.

Case (abbreviation)	***Response***	***No. events***	H_s **(m)**	T_p **(s)**	R_c **(m)**	W_c **(m)**	D_{toe} ***(m)***	β_{beach} **(-)**	β_{seabed} **(-)**	K **(m/s)**
Hurst Spit 1989[1,2] (HS)	Rollback	1	2.6	9.0	1.0	10.0	5.4	0.14	0.005	0.05
BARDEX E10[3] (BE10)	Rollback	1	0.8	8.0	0.2	5.0	3.3	0.14	0.010	0.15
Chesil Beach 1979[4,5,6] (C79)	Severe overwash	1	5.3–6.3	16.3	8.2–11.2	10	17.3	0.20	0.010	0.05
Chesil Beach 1978[4,5,6] (C78)	Overwash	1	4.0–5.0	12.0	8.3–11.3	10	17.2	0.20	0.010	0.05
Slapton Sands 2001[7,8] (S01)	Overwash	1	3.0–4.0	9.4	1.8–3.3	30.0	10.8–11.3	0.10	0.010	0.02
Medmerry 1994–2000[4,9] (MMo)	Overwash	5	1.7–3.0	8.0–10.3	2.3–3.4	25	2.1–3.2	0.11	0.020	0.05
BARDEX E1[3] (BE1)	Overtop	1	0.9	4.6	0.9	6.0	3.2	0.20	0.010	0.15
Hayling Island 2005[10] (HI)	Overtop	1	2.4–3.3	16.4–18.2	3.3–4.3	10	7.3–8.3	0.13	0.002	0.05
Slapton Sands 2004[7,8,11] (S04)	Erosion / overtop	1	3.0–4.0	7.6–8.4	2.5–4.3	30.0	9.8–10.5	0.10	0.010	0.02
BARDEX C1[3] (BC1)	Erosion	1	0.8	4.5	1.5	6.0	2.0	0.14	0.010	0.15
Chesil Beach 2007–'10[6,10] (C07)	Erosion	4	4.4–5.9	9.1–12.5	10.4	10	17.1	0.20	0.010	0.05
Loe Bar 2011–'12[10] (LB)	Erosion	4	3.2–5.5	12–18	6.4–7.6	45.0	11.2–12.4	0.077	0.010	0.01
Medmerry 1993–2002[4,9] (MMs)	Erosion	3	2.1–2.4	9.1–9.6	2.5–2.8	25	2.7–3.1	0.11	0.020	0.05

Data sources: [1]Bradbury (2000), [2]Bradbury and Powell (1992), [3]Williams *et al.* (2012), [4]DEFRA (2008), [5]May and Hansom (2003), [6]Heijne and West (1991), [7]Chadwick *et al.* (2005), [8]Austin *et al.* (sub.), [9]Cope (2005), [10]Poate *et al.* (2012), [11]Austin (2005). Additional profile and wave data courtesy of the Channel Coastal Observatory.

The validation hindcast simulations show that the XBeach model correctly predicts the possibility of overwash in five out of ten overwash storms events. Although the absolute accuracy of the XBeach model overwash prediction is only 50% in this validation dataset, the XBeach model still appears to improve upon the BIM, which only identifies two overwash events. The majority of incorrect predictions in the XBeach model are for storm events at Medmerry (four incorrect predictions of erosion or overtopping instead of overwash and three incorrect predictions of overtopping instead of erosion), suggesting that the natural system at Medmerry is not well described by the XBeach model, or by the documented storm data.

MODEL SENSITIVITY

Although the XBeach model does not have perfect skill in predicting overwash events, it does comprise an improvement over the BIM in locations for which the BIM is not strictly valid. In addition, the XBeach model can be used to improve our understanding of the limits of the BIM by studying how overtopping discharge rates in the XBeach model are affected by hydraulic forcing conditions and the geometry of the gravel barrier. These model sensitivities may provide insight in the applicability of the BIM at other locations along the coast of the UK. This sensitivity analysis is carried out using over 13,000 simulations with varying hydraulic boundary conditions and barrier geometries, as summarised in Table 3. All simulations are carried out using random JONSWAP wave time series that are imposed at a depth of 20 m.

The importance of variations in the input parameters on the simulated overwash discharge is examined by comparing the relative difference between the overtopping/overwashing discharges in simulations with the largest and smallest values for one input parameter, and equal values for all other input parameters. In this way the sensitivity to for instance hydraulic conductivity K can be determined by comparing the overtopping discharge in simulations with K = 0.1 m/s and K = 0.001 m/s, with all other parameters constant. The difference between the overtopping discharges is normalised using the larger of the two discharge rates. The results for individual parameter combinations are summarised by computing the median value of all relative differences for one input parameter across all combinations of the other input parameters.

The median relative overtopping differences for six input parameters are shown in Figure 4. Positive values in the figure correspond to a positive correlation between the input parameter and relative overtopping discharges. The figure shows a strong sensitivity of overtopping discharge to the wave height, wave steepness and relative freeboard (R_c/H). These parameters are well known to influence overwash and are included in the

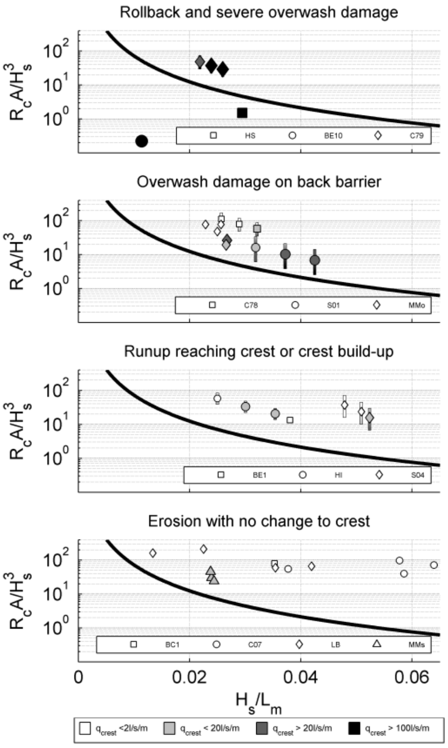

Figure 3. Simulated overtopping discharges (q_c) for all model hindcast sites. Marker colours relate to the simulated overtopping volumes. Note that C79, C78, S04, HI and S01 have multiple markers to show the range of uncertainty in the boundary conditions. Where sensitivity simulations have been carried out with equal wave steepness, error bars indicate the range of simulated overtopping discharge and *BI* values.

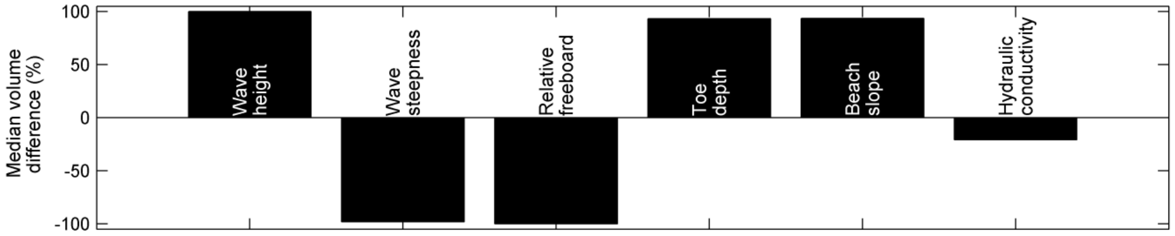

Figure 4. Median relative difference in overtopping volume for input parameters. Positive values indicate increasing overtopping discharge with increasing values of the input parameter.

parameterisation used in the BIM. However, the figure also shows significant sensitivity of the overtopping discharge to the depth of the toe of the gravel beach and the slope of the beach, and some sensitivity to the hydraulic conductivity; these factors are not accounted for in the BIM.

The median relative overtopping difference due to variations in the depth of the beach toe is 93%. Much of this difference is attributed to the shallowest beach toe depth of 0.5 m, which ensures that the majority of wave energy is dissipated before it reaches the gravel barrier. A comparison between a toe depth of 5 m and 10 m leads to a lower median relative overtopping difference of 36%. The effect of the overtopping difference due to the toe depth is shown in Figure 5 (left panels), in which simulated cases of overwash are shown in BIM parameter space. The figure shows a considerable reduction in the upper limit of simulated overwash on beaches with shallow toe depths relative to those with large toe depths. This significant difference could imply that a modification of the BIM for beaches with shallow toes would greatly increase the applicability of the empirical model. Note that in all sensitivity simulations, the water depth for the determination of H_s and T_m in BIM parameter space is chosen as 20 m (instead of 6–8 m in Bradbury, 2000) in order to exclude the effect of prior wave-breaking.

The effect of beach slope variations between 1/5 and 1/20 leads to a median relative overtopping difference of 92%. The difference remains large (80%) for beach slope variations between 1/10 and 1/20. Figure 5 (centre panels) shows that this difference leads to a lowering of the upper limit of overwash on shallow beach slopes relative to steep beach slopes. This lowering is particularly significant for low steepness wave conditions ($S_w < 0.025$), in which the runup may be more greatly affected by the imposed beach slope variations than for steep wave conditions. The incorporation of an empirical runup formulation for gravel beaches in the BIM may greatly improve the empirical model’s applicability on beaches that are not similar in steepness to the original dataset.

The median relative overtopping difference due to variations in the hydraulic conductivity (23%) is smaller than the difference due to the beach toe depth and beach slope variations. Although this variation is not insignificant in terms of its coastal flooding, the difference is not sufficient to significantly alter the threshold for overwash across the entire parameter space. This is reflected in Figure 5 (right panels) in which no clear difference can be found between the upper bound for overwash where K = 0.1 m/s and K = 0.001 m/s. In certain ranges of parameter space, the effect of the hydraulic conductivity on the overwash threshold does become important, in particular for steep waves ($S_w > 0.025$) and relative freeboard values of ~1 (cf. McCall *et al*., 2012). However, since the XBeach model does not include morphodynamics, which are expected to influence overwash under such conditions, no strong conclusions can be drawn from those data.

CONCLUSIONS

A process-based non-hydrostatic flow model has been applied to simulate overwash events on gravel barriers. Since the model currently does not compute the morphodynamic feedback of the gravel barriers to the storm forcing, an estimate of the barrier storm response is inferred from computed overtopping discharges. In this manner, the model was shown to produce similar predictions for overwash as the empirical Barrier Inertia Model for the majority of parameter combinations within the validity range of the empirical model. However, the lack of morphodynamics in the process-based model leads to greater uncertainty in overwash predictions near the empirical threshold for overwash. When applied to 25 historical storm impacts, the process-based model showed improvement over the empirical model in predicting the possibility of overwash, indicating that the process-based model has value as coastal management tool alongside the empirical model. The process-based model was applied to study the sensitivity of overwash to input parameters outside the validity range of the empirical Barrier Inertia model. This analysis showed that two parameters currently missing in the BIM, the depth of the gravel beach toe and the gravel beach slope, greatly affect the threshold criteria for overwash. Hydraulic conductivity was shown to have a less dominant effect on the threshold for overwash than the barrier geometry.

Modifications to the parameterisation of the BIM, based on the sensitivity analysis of the process-based model, may help to increase the applicability of the empirical model. The dependency of the overtopping discharge on the beach slope and wave steepness suggests that the empirical model may be improved through the inclusion of an Iribarren-type formulation for runup in the Barrier Inertia term *BI*. Similarly, the inclusion of the wave height and water depth at the gravel beach toe may improve the accuracy of the BIM on gravel beaches with wide sandy terraces. However, due to the highly non-linear interaction between incident primary waves and secondary low frequency waves on such beaches, a simple parameterisation may not be possible.

Table 3. Overview of the hydrodynamic forcing and barrier geometry parameter ranges used in the model sensitivity simulations.

H_s (m)	S_w (%)	R_c /H_s (-)	W_c (m)	D_{toe} (m)	β_{beach} (-)	β_{back} (-)	β_{seabed} (-)	K (m/s)
2.0–6.0	0.9–5.9	0.1–1.3	10.0–100.0	0.5–10	0.05–0.20	0.03	0.010	0.001–0.10

Although the process-based model used in this analysis has been shown to predict overwash on gravel barriers with equal or better skill than the BIM, there is still much room for improvement before it can be used for engineering purposes. In order to achieve this goal, research is currently being carried out as part of the EPSRC-funded NUPSIG-project[†] to develop and validate the model for storm impacts on gravel beaches.

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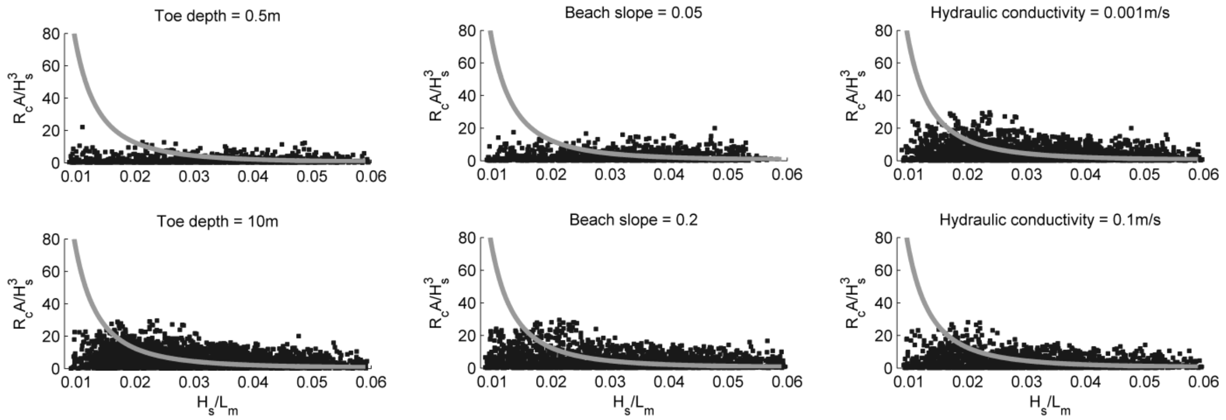

Figure 5. Simulated cases of overwash ($q_c > 20$ l/s/m; black squares) and B.I. model overwash threshold (grey curve) for varying gravel beach toe depths (left panels), varying beach slope (centre panels) and hydraulic conductivity (right panels). Note that H_s and T_m are calculated at a depth of 20 m in all sensitivity simulations.

[†] http://www.research.plymouth.ac.uk/coastal-processes/projects/nupsigsite/home.html