

# Barrier breaching versus overwash deposition: parameterizing the morphologic impact of storms on coastal barriers

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## Abstract

Waves and water level setup during storms can create overwashing flows across barrier islands. Overwashing flows can cause erosion, barrier breaching, and inlet formation, but their sediments can also be deposited and form washover fans. These widely different outcomes remain difficult to predict. Here we suggest that a breach develops when the sediment volume transported by overwashing flows exceeds the barrier subaerial volume. We form a simple analytical theory that estimates overwashing flows from storm characteristics, barrier morphology, and dune vegetation, and which can be used to assess washover deposition and breaching likelihood. Our theory suggests that barrier width and storm surge height are two important controls on barrier breaching. We test our theory with the hydrodynamic and morphodynamic model Delft3D as well as with field observations of 21 washover fans and 6 breaches that formed during hurricane Sandy. There is reasonable correspondence for natural but not for developed barrier coasts, where traditional sediment transport equations do not readily apply. Our analytical formulations for breach formation and overwash deposition can be used to improve long-term barrier island models.

1 **Barrier breaching versus overwash deposition: predicting the morphologic impact of**  
2 **storms on coastal barriers**

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6 **Key points**

- 7 1. New analytical theory compares overwashing flow against barrier volume to predict  
8 breaching and washover deposition
- 9 2. We test our theory against Delft3D simulations and Hurricane Sandy observations:  
10 vegetation and elevation help to prevent island breaching
- 11 3. Developed barrier islands do not follow predicted trends, suggesting alternative controls  
12 on overwashing and breaching

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15 islands. Overwashing flows can cause erosion, barrier breaching, and inlet formation, but their  
16 sediments can also be deposited and form washover fans. These widely different outcomes  
17 remain difficult to predict. Here we suggest that a breach develops when the sediment volume  
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23 morphodynamic model Delft3D as well as with field observations of 21 washover fans and 6  
24 breaches that formed during hurricane Sandy. There is reasonable correspondence for natural but  
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26 apply. Our analytical formulations for breach formation and overwash deposition can be used to  
27 improve long-term barrier island models.

## 28 **1 Introduction**

29 Storms can have large impacts on barrier islands. Overwashing flows and waves can  
30 move sediment across barrier islands and result in washover deposition (Fig. 1a) or barrier island  
31 breaching (Fig. 1b) (Pierce, 1970). These outcomes are strongly sensitive to barrier  
32 characteristics and storm intensity (Suter et al., 1982; Plomaritis et al., 2018). Hurricane (also  
33 called ‘superstorm’) Sandy hit the U.S. East Coast in 2012 and resulted in widespread  
34 overwashing and numerous breaches (Fig. 1) (Sopkin et al., 2014). Breaching is likely to become  
35 more common as a result of sea-level rise and barrier island flooding (Nienhuis & Lorenzo-  
36 Trueba, 2019a; Passeri et al., 2020). At the same time, washover deposition is a critical  
37 landward-directed sediment flux that can support barrier aggradation and prevent barrier  
38 drowning. Reliable predictions of barrier breaching and washover deposition, whether for long-  
39 term models or short-term assessment prior to landfall, remain difficult.

40 In this study we propose that storms make barrier islands breach when the cumulative  
41 sediment flux of an overwashing flow exceeds the barrier subaerial volume. Conversely, a  
42 washover deposit will form when an overwashing flow does not erode the barrier down to sea-  
43 level, with increasing washover volumes as overwashing flows approach the washover-to-  
44 breaching threshold.

45 The objective of this study is to test this theory using Delft3D simulations complemented  
46 with observations from Hurricane Sandy. We systematically explore the effect of barrier island  
47 morphology, storm characteristics, and dune vegetation on overwashing flows and the  
48 morphologic response of barrier coasts.

## 49 **2 Background**

### 50 *2.1 Overwashing flows*

51 Overwashing flows occur when wave runup and/or water levels exceed the island  
52 elevation and produce a water surface slope across the island (Fisher & Stauble, 1977;  
53 Kobayashi, 2010). High water levels often result from storm winds that generate surges and  
54 waves, and their impact is often assessed based on relative elevation of wave runup and water  
55 levels against the dune crest (Sallenger, 2000).

56 Overwashing flows and sediment transport have been studied in the laboratory and in the  
57 field (see Donnelly et al., 2006 for a review). They are highly variable over time and space and  
58 can flow in both directions across barrier islands (Wesselman et al., 2018; Goff et al., 2019)  
59 depending on storm characteristics and the (storm and tide-induced) phase lag of lagoon water  
60 levels compared to the ocean (Shin, 1996).

61 Several studies have aimed to determine the relative influence of wind, waves,  
62 infragravity waves, and water level gradients on water and sediment fluxes transported in  
63 overwashing flows. A recent study by Engelstad et al (2018) on an overwashing flow across the  
64 Dutch island of Schiermonnikoog showed that sediment transport was primarily controlled by  
65 currents, but that occasional high sediment concentrations were found on wave infragravity  
66 timescales. Wave conditions (McCall et al., 2010) and foredune size (de Winter et al., 2015) are  
67 important controls on foredune erosion and determining locations of overwashing flows, whereas  
68 the water level gradient controlled the amount of overwashing sediment and its deposition in the  
69 back barrier (McCall et al., 2010; Engelstad et al., 2018). The evolution and magnitude of  
70 overwashing flows also depends on dune morphology and vegetation patterns (Houser et al.,  
71 2008; Kobayashi, 2010; Passeri et al., 2018), which can constrict the flow and deepen the throat.  
72 Flow acceleration through the throat can also widen the gap (Houser et al., 2008).

73 Predictions for sediment fluxes during wave overwashing in the absence of currents have  
74 been formulated using laboratory studies (Williams, 1978; Nguyen et al., 2009). These formulae  
75 show reasonable correspondence to a variety of field settings and highlight a quadratic  
76 dependence of wave overwash fluxes to wave runup. A similar wave overwash model from  
77 Kobayashi et al (2010) shows that overwash volumes are sensitive to barrier geometry. Their  
78 results are validated by experimental and field evidence but do not include the effect of currents  
79 on sediment fluxes. We refer to Donnelly et al. (2006) for a review on overwashing flows, who  
80 note explicitly that the morphologic evolution of overwash flows and initiation of breaching  
81 remain poorly quantified.

## 82 2.2 *Washover deposition*

83 Washovers form through the settling of sediment transported by overwashing flows  
84 (Woodruff et al., 2008). A compilation from Hudock et al (2014) shows large variability in  
85 washover area, but many washovers are less than 1 km<sup>2</sup>. Carruthers et al (2013) report washover

86 volumes normalized per unit width alongshore and obtain a median of 30 m<sup>3</sup>/m. A scaling  
87 analysis of experimental and natural washover deposits finds that they are typically longer  
88 (cross-shore) than they are wide (alongshore), with a length/width ratio of ~2 (Lazarus, 2016).

89 The length and size of washover deposits is controlled by storm characteristics (Morton  
90 et al., 2003). Barrier island morphology and land cover such as the type of development or  
91 vegetation can affect its response to storms and the character of its washovers (Hayes, 1979;  
92 Leatherman, 1979; Sedrati et al., 2011; Rogers et al., 2015). Rogers et al (2015) find a mean of  
93 62 m<sup>3</sup>/m for natural environments but 38 m<sup>3</sup>/m and 8 m<sup>3</sup>/m for residential and commercially  
94 developed islands, respectively. Washovers can compete for flow with their neighbors, which  
95 can result in a characteristic spacing of washover deposits (Lazarus & Armstrong, 2015).

### 96 2.3 *Breaching*

97 Overwashing flows can also lead to barrier island breaching. Many studies of barrier  
98 breaching focus on the exposed U.S. East Coast, where storm surges from hurricanes and  
99 extratropical storms frequently result in breaches (Kraus & Hayashi, 2005). Ground-penetrating  
100 radar images of the North Carolina outer banks shows that at least 24% of the modern barrier  
101 island chain has been breached (Mallinson et al., 2010). Breaching also occurs along barrier  
102 coasts elsewhere, including the Ebro Delta (Sánchez-Arcilla & Jiménez, 1994), California (Kraus  
103 et al., 2002), and Florida (Morgan, 2009).

104 Models generated from breaches of sand dikes (Visser, 2001; Tuan et al., 2008) focus on  
105 the expansion of the overwashing throat (or dune gap, Fig. 2) and find that breaches originate by  
106 head cutting and erosion of the barrier on the lagoon-side of the throat. Basco and Shin (1999)  
107 found that surge level differences between ocean and bay, and the resulting water level gradients,  
108 regulate flow conditions and are an important predictor of barrier island breaching. The timing  
109 and magnitude of surge level differences across an island are controlled by storm characteristics,  
110 bay size, distance to neighboring inlets, and other factors. A large time lag between ocean and  
111 bay surge peaks makes breaching towards the ocean more likely (Shin, 1996; Smallegan et al.,  
112 2016).

113 Site-specific process-based models of overwashing flows include Delft3D (Deltares,  
114 2014) and XBeach (Roelvink et al., 2009; Van Dongeren et al., 2009; McCall et al., 2010;

115 Elsayed & Oumeraci, 2016), and have been employed to predict breaching. De Vet et al (2015)  
116 applied XBeach to the well-documented “Wilderness” breach on Fire Island, NY and found that  
117 bed roughness, including vegetation roughness, is a sensitive and poorly constrained parameter  
118 that is important for properly hindcasting the emergence of a breach. Recent model-coupling  
119 between Delft3D and XBeach (e.g., van Ormondt et al., 2020) show promise for forecasting  
120 barrier breaching, but accurate, site-specific process-based simulations of overwashing flows and  
121 barrier breaches remain challenging.

122 On a conceptual level, Kraus et al (2002) postulated that breach susceptibility is  
123 controlled by the storm surge water level and is inversely proportional to the tidal range, used as  
124 a proxy for barrier island elevation. A modelling study by Nienhuis and Lorenzo-Trueba (2019a)  
125 also showed that breaches are more common in micro-tidal settings, in their case because low  
126 tidal range makes that existing inlets fill in faster, increasing the potential tidal prism available to  
127 new breaches. Their model also suggests that, similar to alongshore competition for washover  
128 flow (Lazarus & Armstrong, 2015), there is alongshore competition for tidal flow that results in a  
129 characteristic spacing of successful breaches.

130 Models for long-term (decades-centuries) barrier island dynamics have shown that the  
131 persistence of breaches (i.e. lifetime of tidal inlets) is a function of bay size, tidal range, storm  
132 climate, and other controls (Kraus, 1998; Nienhuis & Lorenzo-Trueba, 2019b). They do not  
133 represent the effect of storms explicitly but rely on overwash and breaching parameterizations.  
134 There remains a large gap in model studies between detailed, site-specific simulations of  
135 overwashing flows during storms, and large-scale barrier island models.

136 Here we try to bridge the gap between process-based site-specific models vs. conceptual  
137 studies of breaching and washover deposition. We develop an analytical theory of overwashing  
138 flows on storm timescales (hours-days) that can aid short-term risk assessment and help  
139 parameterize storm impact for long-term morphologic models. We test this theory using an  
140 idealized Delft3D model of overwashing flows on storm timescales combined with observations  
141 of washovers and breaches from Hurricane Sandy.

### 142 3 Analytical theory

143 At the heart of our theoretical model, we compare the volume of overwashing sediments  
144 ( $V_{ow}$ , in  $m^3$ ) against the subaerial volume of the barrier ( $V_{bar}$ , in  $m^3$ ) (Fig. 1). Following Shin  
145 (1996), we classify a barrier as breached when erosion reduces the elevation of the barrier to  
146 below sea level and there is no subaerial barrier left after the storm.

147 Next, we aim to predict the volume of overwashing sediments for different storm  
148 characteristics, barrier morphologies, and barrier landcovers. We make a simplified predictor  
149 with two important assumptions. (1) Overwashes flow from the ocean to the bay. Although our  
150 analytical theory is symmetrical and can be applied also in reverse, with flows toward the ocean,  
151 we do not do that in this study. (2) We neglect sediment input from the shoreface or from  
152 alongshore, assuming that overwashing sediments are eroded from the subaerial barrier. This  
153 makes our theory mostly suitable for short-term (storm timescale) analysis and not post-storm  
154 recovery. Breaches that we predict will form might fill in or stay open post storm depending on  
155 conditions that are not considered here, such as the tidal prism, or alongshore sediment transport  
156 (e.g., Escoffier, 1940).

157 We predict the overwashing sediment flux and dune gap erosion using a simple sediment  
158 transport-based predictor. This predictor is based on steady, uniform flow for bed shear stress  
159 (e.g. depth-slope product) and Engelund and Hansen (1967) for the resulting sediment transport.  
160 Combining the depth-slope product ( $\rho ghS$ ) and Engelund and Hansen (1967) yields the  
161 following prediction for overwashing sediment transport through the dune gap  $Q_{ow,t}$  ( $m^3s^{-1}$ ),

$$162 \quad Q_{ow,t}(t) = \frac{0.05}{C_f} \left( \frac{\rho ghS}{(\rho_s - \rho) \cdot g \cdot D_{50}} \right)^{2.5} D_{50} \cdot \sqrt{R \cdot g \cdot D_{50}} \cdot w_g, \quad (1)$$

163 where  $C_f$  is a non-dimensional friction factor,  $\rho$  is the density of water ( $\sim 1000 \text{ kg m}^{-3}$ ),  $\rho_s$  is the  
164 density of sand ( $\sim 2650 \text{ kg m}^{-3}$ ),  $h$  is the water depth (m),  $S$  is the water surface slope ( $m \text{ m}^{-1}$ ),  $g$  is  
165 gravity ( $m \text{ s}^{-2}$ ),  $D_{50}$  is the median grain size (m),  $R$  is the relative density of sand ( $\frac{\rho_s - \rho}{\rho}$ ,  $\sim 1.65$ ),  $w_g$   
166 is the dune gap width (m) and should be considered the alongshore extent of a gap with a dune  
167 height gap of  $h_g$  (m) as its average elevation.

168 We include the effects of vegetation on sediment transport by modifying  $C_f$ . Following  
 169 Baptist (2009), the non-dimensional friction factor for emergent vegetation is  $C_f = \frac{g}{C_b^2} + \frac{C_d m D h f}{2}$ ,  
 170 where  $C_b$  ( $\text{m}^{0.5} \text{s}^{-1}$ ) is a Chezy-type bed roughness without vegetation,  $C_d$  is a plant drag  
 171 coefficient,  $m$  ( $\text{m}^{-2}$ ) is the vegetation stem density,  $D$  (m) is the vegetation leaf width,  $h$  is the  
 172 vegetation height (m), and  $f$  is the fraction of the island covered by vegetation.

173 We estimate the flow depth  $h$  midway through the gap as  $\frac{1}{2}(s_{max} - h_g)$ , which is the  
 174 average flow depth between the ocean ( $s_{max} - h_g$ ) and the bay (0), with  $s_{max}$  being the maximum  
 175 surge level (m) (Fig. 2b). The water surface slope during the storm can be approximated as the  
 176 surge level  $s(t)$  (m) as a function of time  $t$  (s), divided by the barrier width  $w_b$  (m).

177 Combined, we can simplify equation (1) to,

$$178 \quad Q_{ow,t}(t) = \frac{0.05}{C_f} \left( \frac{s_{max} - h_g}{2} \right)^{2.5} \left( \frac{s(t)}{w_b} \right)^{2.5} \frac{\sqrt{g}}{R^2 D_{50}} \cdot w_g, \quad (2)$$

179 and write a predictive equation for the integrated eroded sediment volume of the barrier  $V_{ow,t}$   
 180 ( $\text{m}^3$ ),

$$181 \quad V_{ow,t} = \int_0^{T_{storm}} Q_{ow,t}(t) dt, \quad (3)$$

182 where  $T_{storm}$  (s) is the duration of the storm.

183 For a triangular surge timeseries  $s(t) = s_{max} \cdot \left( 1 - \left| \frac{2t}{T_{storm}} - 1 \right| \right)$ , of which the integral  
 184 is identical to  $s(t) = s_{max} \frac{t}{T_{storm}}$ ,  $V_{ow,t}$  evaluates to,

$$185 \quad V_{ow,t} = \frac{0.05}{C_f} \left( \frac{s_{max} - h_g}{2} \right)^{2.5} \left( \frac{s_{max}}{w_b} \right)^{2.5} \frac{\sqrt{g}}{R^2 D_{50}} \cdot w_g \cdot \frac{2}{7} T_{storm}. \quad (4)$$

186 We expect the barrier to breach if  $V_{ow,t}$  exceeds the subaerial barrier volume  $V_{bar}$ , where  
 187  $V_{bar} = \frac{1}{2} h_g \cdot w_b \cdot w_g$ . The factor  $\frac{1}{2}$  is included because the barrier profile underneath the dune  
 188 gap is roughly triangular towards the beach and the lagoon (Fig. 2b). We write the theoretical  
 189 normalized overwash volume  $V_{norm,t}$  as,

190 
$$V_{norm,t} = \frac{V_{ow,t}}{V_{bar}} = \frac{\frac{0.05(s_{max}-h_g)^{2.5}}{C_f} \left(\frac{s_{max}}{w_b}\right)^{2.5} \frac{\sqrt{g}}{R^2 D_{50}} w_g \cdot \frac{2}{7} T_{storm}}{\frac{1}{2} h_g \cdot w_b \cdot w_g}, \quad (5)$$

191 where a barrier is expected to breach if  $V_{norm,t} > 1$ .

192 We expect the subaerial barrier to be maintained if  $V_{norm,t} \leq 1$ . If that is the case and the  
 193 overwashing sediment flux will deposit as a washover fan,  $V_{ow,t}$  will give an indication of the  
 194 washover fan volume.

### 195 3.1 Predictions of our analytical theory

196 Equation (5) estimates that the overwash volume scales with surge height to the power 5  
 197 because it affects the depth of the overwashing flow as well as the water surface slope.  
 198 Breaching probability scales with barrier width to the power -3.5. It predicts that overwash  
 199 volumes scale linearly with dune gap width, and that dune gap width does not affect breaching  
 200 probabilities. It is relatively straightforward to evaluate and apply in data-poor environments.  
 201 Although not applied here, it can be adapted to account for varying water levels in the lagoon as  
 202 well, including tides and surges that lead to flow towards the ocean.

203 Some of the trends in equation (5) align with observations from Wesselman et al. (2019),  
 204 who found that dune height compared to surge elevation is important for sediment fluxes through  
 205 dune gaps. Other trends do not align. We predict here (eq. 1-5) that dune gap width is linearly  
 206 related to overwash volumes, and thereby do not account for the effect of flow contraction nor  
 207 the potential effect of neighboring overwashes that lower water level gradients. Wesselman et al.  
 208 (2019) found that flow contraction became significant for smaller widths.

209 Our predictions also do not consider other important processes that occur in overwashing  
 210 flows such as supercritical flow or wave breaking (Basco & Shin, 1999; Tuan et al., 2008). It  
 211 neglects the (wave-dominated) erosion and/or formation of a dune gap. Instead it follows earlier  
 212 studies that showed that water level gradients are a first-order control on overwashing flows,  
 213 washover deposition, and barrier breaching (Basco & Shin, 1999; McCall et al., 2010; Engelstad  
 214 et al., 2018).

## 215 4 Methods

216 We test our theoretical predictions against Delft3D model simulations and observations  
217 from hurricane Sandy for varying storm conditions ( $T_{storm}, S_{max}$ ), barrier morphologies ( $w_b, h_g$ ),  
218 and barrier land cover and vegetation density (both affecting  $C_f$ ). Delft3D simulations are not  
219 meant to reproduce individual Hurricane Sandy overwashing flows. Instead, Delft3D simulations  
220 should be viewed complementary to Hurricane Sandy observations. Both serve as a test of our  
221 theoretical model. Delft3D provides modelled washover volumes ( $V_{ow,d3d}$ ) and Sandy provides  
222 observed washover volumes ( $V_{ow,obs}$ ) that we can compare against the predicted washover  
223 volume ( $V_{ow,t}$ ). We will also test if breaches occur for  $V_{norm,t} > 1$  by comparing it to  $V_{norm,d3d} =$   
224  $\frac{V_{ow,d3d}}{V_{bar}}$  and  $V_{norm,obs} = \frac{V_{ow,obs}}{V_{bar}}$ .

### 225 4.1 Delft3D model setup

226 We simulate the morphodynamics of overwashing flows using the hydro- and  
227 morphodynamic model Delft3D (Deltares, 2014). Delft3D couples shallow water equations with  
228 sediment transport formulas to simulate morphologic change. We use idealized barrier island  
229 geometries and simulate overwashing flows through a dune gap. Storm surge levels and  
230 durations are represented as a water level boundary on the ocean side of the domain (Fig. 3d).

231 The model setup is similar to one used in an earlier study by Nienhuis et al (2018), who  
232 investigated the morphologic evolution of river levee breaches into avulsions and crevasse  
233 splays. A notable difference in our study here is that there is no sediment supply from the  
234 upstream boundary. Crevasses are fed by river sediments. Our modelled overwashing flows are  
235 not fed by sediments from the ocean; our dune gaps therefore cannot heal but instead simply stop  
236 expanding when the storm recedes.

237 The initial bathymetry of the domain consists of a 1 km long coastal barrier and an  
238 adjacent lagoon. Barrier widths vary between 150 and 400 m between model runs, with the rest  
239 of the 2 km cross-profile modelled as a 3 m deep lagoon (Fig. 3). The domain consists of 172 by  
240 112 cells in the cross-shore and alongshore direction, respectively. The resolution ranges from 5  
241 by 5 m near the dune gap to 20 by 20 m along the sides and into the lagoon to speed up the  
242 computation (Fig. 3c). The dune gap is in the middle of the simulated barrier island. We vary the

243 height and width of the gap between simulations (Table 1) and use a uniform 0.2 mm sand across  
244 the barrier and lagoon.

245 The effect of vegetation is included using the Baptist (2009) ‘Trachytopes’ function,  
246 which estimates an effective bed roughness depending on the vegetation height and density  
247 relative to the water depth (Deltares, 2014). We span a range of values typical for dune grasses  
248 (Cheplick, 2005; Biel et al., 2017; Hacker et al., 2019). Vegetation height is 0.5 m, leaf width is  
249 5 mm, stem density is varied between 0 and 200 m<sup>-2</sup>, and the aerial fraction is between 0% and  
250 20% for different model runs. Note that these simulations are not aimed at representing any  
251 specific barrier island, the spread between model scenarios is meant to encompass storm  
252 characteristics and barrier island morphologies globally.

253 The water level boundary condition on the ocean side of the barrier is prescribed as a  
254 simplified storm surge lasting 24 hours (Fig. 3d). We vary the peak surge water level and the  
255 duration of the peak between simulation to represent different storm magnitudes. Note that we  
256 use a slightly altered surge time series than what is assumed in eq. 4. We therefore use eq. 3 to  
257 obtain  $V_{ow,t}$  for the Delft3D simulations. The water level at the lagoon is kept constant at 1 m,  
258 such that there is no return flow possible through the dune gap. Breaches and washover fans can  
259 only appear on the lagoon side of the barrier. There is no flow possible through the side  
260 boundaries up and down coast from the breach.

261 As the water level rises on the ocean side, the dune gap becomes wet and a water surface  
262 slope appears across the island. Sediment transport fluxes in Delft3D are calculated following  
263 van Rijn (2007), using a 0.1 m water depth threshold for sediment transport for model stability.  
264 This is a different sediment transport predictor than what we use in our theoretical model (eq. 1).  
265 We choose van Rijn (2007) for our Delft3D simulation because it is more accurate than  
266 Engelund and Hansen (1967). We use the latter for our theoretical model because it does not  
267 require many parameters and combines bed load and suspended load transport. Dry cells along  
268 the edges of the dune gap erode if erosion occurs in the dune gap itself. Delft3D uses a “dry cell  
269 erosion factor”, set here to the default value of 0.9, that distributes the erosion between wet cells  
270 and dry cells. This factor can be viewed as a simple proxy for a critical bed slope for bank  
271 failure.

272 We vary barrier morphology, dune vegetation, and storm characteristics and run 150  
273 model simulations (Fig. 3, Table 1). These simulations generate overwashing flows through the  
274 dune gap from the water level gradients across the barrier island. Based on this gradient, the  
275 barrier width and roughness, and available subaerial barrier volume, morphologic simulations  
276 then form either washover deposits or result in barrier breaching. We classify a simulation as  
277 “breached” when the maximum elevation of the dune gap thalweg lies below sea level. Reported  
278 washover volumes are the sum of post-storm deposition and erosion in the lagoon, not including  
279 any subaerial changes on the island tops. We restrict ourselves to washovers in the lagoon for a  
280 fair comparison with our Hurricane Sandy analysis, section 4.2. See Table 1 for an overview of  
281 model settings. The supplementary data for the model code and model output to reproduce our  
282 findings are available at [dx.doi.org/10.17605/OSF.IO/3KNXA](https://dx.doi.org/10.17605/OSF.IO/3KNXA).

#### 283 4.2 *Hurricane Sandy analyses*

284 Hurricane Sandy observations allow us to test our theoretical model and our  
285 morphodynamic Delft3D simulations. Sandy made landfall on the New Jersey coast on October  
286 29, 2012, and resulted in numerous breaches and washover fans (Sopkin et al., 2014), including  
287 the well-documented “Wilderness” breach on Fire Island (van Ormondt et al., 2020). We  
288 analyzed 27 overwashing sites, of which 6 resulted in breaches and 21 in overwash fans. 6 sites  
289 were vegetated, 4 were barren, and 17 were developed. For these sites we also retrieved the local  
290 storm conditions that led to their formation (Fig. 4).

291 Storm characteristics are determined using the ADCIRC+SWAN hindcast model  
292 simulation (Dietrich et al., 2012) via the Coastal Emergency Risk Assessment (CERA), available  
293 at [www.coastalrisk.live](http://www.coastalrisk.live). ADCIRC is a hydrodynamic model that computes time dependent tide,  
294 wind, and pressure driven surge (Luettich et al., 1992). Coupling with SWAN (Booij et al., 1999)  
295 allows for assessment of wave-driven setup. We refer to documentation of CERA for more  
296 information. We use these time-explicit surge hindcasts instead of maximum surge level maps  
297 because they allow us to extract water surface slopes.

298 We extract water levels for the lagoon and ocean sides of the barrier islands at 12, 6, 4  
299 and 0 hours before landfall. Unfortunately, CERA does not produce water levels post landfall, so  
300 we assume a symmetric surge event to estimate water levels at 4, 6, and 12 hours post landfall.  
301 Surge timeseries are then converted to surge water level differences across the islands, and we

302 interpolate to find the duration where the surge difference exceeded 0.5 m ( $T_{storm}$ ). The hindcast  
303 simulations for Sandy show that the maximum water level differences ( $s_{max}$ ) between the ocean  
304 and lagoon ranged from 0.8 to 2.6 m between sites (Fig. 4d).

305 We use Google Earth images to estimate the pre-storm width and land cover of the  
306 overwashing sites. Land cover is categorized as either developed, bare, or vegetated. Roughness  
307 coefficients ( $C_f$ ) for bare and developed land are estimated as  $1.6 \cdot 10^{-1}$  and  $5 \cdot 10^{-3}$ , respectively  
308 (Passeri et al., 2018). Vegetated  $C_f$  is estimated using Baptist (2009) using bed roughness  $C_b = 45$   
309  $m^{0.5} s^{-1}$ , stem drag coefficient  $C_d = 1$ , stem density  $m = 20 m^{-2}$ , leaf width  $D = 5 mm$ , vegetation  
310 height  $h = 0.5 m$ , and an island fraction covered of  $f = 0.2$ , resulting in  $C_f = 1 \cdot 10^{-2}$ .

311 Dune gap elevations are retrieved from the USGS dune crest elevation dataset, which  
312 provides mean and standard deviations of dune crest elevation for 1 km alongshore segments  
313 (Birchler et al., 2015). Dune gaps are (by definition) lower than these mean elevations. We  
314 estimate dune elevations to be gaussian (following Birchler et al., 2015) and choose the dune gap  
315 elevation ( $h_g$ ) to be the lowest 5% (mean minus 2 s.d.) of an 1 km alongshore section. Dune gap  
316 widths ( $w_g$ ) are also 5% of the same alongshore segment, here 50 m.

317 Based on the post-storm NOAA Emergency Response Imagery  
318 (<https://storms.ngs.noaa.gov/>) we characterize each overwashing site as either a breach (e.g., Fig.  
319 1a) or a washover deposit (e.g., Fig. 1b). We use these same images to measure the subaerial  
320 surface area of each washover deposit, contrasting it with pre-storm images. Unfortunately, there  
321 is no readily available data to extract washover volumes for the 21 fans in our dataset. We use  
322 the washover fan data compiled by Lazarus et al (2016), where field-scale washover volume /  
323 area  $\approx 0.3 m$ , to estimate washover volume ( $V_{ow,obs}$ ). For barrier breaches, which do not leave a  
324 washover deposit, we set  $V_{norm,obs} > 1$ . This does not affect our analysis.

## 325 **5 Results**

### 326 *5.1 Mechanics of overwashing flows*

327 We use an example Delft3D simulation of a 300-m wide barrier island to illustrate the  
328 model dynamics (Fig. 5). In this case, a breach developed in response to a 3 m peak surge that  
329 lasted 2 hours. Water flowing across the gap resulted in high shear stresses, primarily at the back  
330 of the dune gap into the lagoon where the water surface slope is greatest. This agrees with model

331 experiments from Visser (2001). Water level gradients in the lagoon are negligible compared to  
332 gradients across the barrier, reflecting the relative flow roughness of both environments (Fig. 5c).

333 Peak shear stresses of  $\sim 50 \text{ N m}^{-2}$  are observed in the modeled overwashing flows (Fig.  
334 5b). Critical shear stress for sand movement,  $\sim 0.15 \text{ N m}^{-2}$ , are negligible compared to these peak  
335 stresses. High concentrations of sediments are suspended and high gradients of sediment  
336 transport cause erosion. Suspended transport magnitude greatly exceeds bedload transport, which  
337 could be because the Delft3D implementation of Van Rijn (2007) separates bedload and  
338 suspended load based on a reference height above the bed. Observations of overwashing flows  
339 show that these flows are thin and that sheet-flow conditions are likely, which are usually  
340 considered bed load (Shin, 1996).

341 Simulated overwashing timeseries show that the greatest transport occurred after the  
342 storm surge peak (Fig. 5c). Continuous erosion and deepening of the overwash throat led to  
343 increasing sediment transport during the event;  $\sim 80\%$  of the overwashing sediments were  
344 transported in the 2<sup>nd</sup> half of the storm. The barrier breached after approximately 20 hours.

345 Comparing the cumulative sediment transported across the barrier island ( $V_{ow,d3d}$ ) with  
346 the subaerial volume of the barrier under the overwashing throat ( $V_{bar}$ ) for our example Delft3D  
347 simulation also shows that breaching is likely (Fig. 5c). The overwashing flow transported  
348 approximately  $60 \cdot 10^3 \text{ m}^3$  of sediment across the barrier. The subaerial barrier is, on average, 1.67  
349 m high, 300 m wide, and the gap extends 50 m alongshore, comprising a volume of  $25 \cdot 10^3 \text{ m}^3$ .  
350 The result is a normalized barrier overwash  $V_{norm,d3d}$  ( $V_{ow,d3d} / V_{bar}$ ) of about  $\sim 2.4$  at the end of the  
351 storm.

## 352 5.2 Breaching vs. washover deposits

353 We contrast the event from section 5.1 that resulted in a breach with another simulation  
354 where a washover was deposited (Fig. 6, bottom panel). The washover formed following a 2.2-  
355 m, 2-hour long storm surge. Water discharge and suspended sediment transport across the dune  
356 gap develop in tandem, and erosion primarily acts on the back of the dune gap. A small,  $1700 \text{ m}^3$   
357 washover fan develops (Fig. 6, top panel).

358 We find similarities between the initial development of the barrier breach and washover  
359 deposit: an washover fan also appears in response to the breach, although it is more dispersed

360 spatially (Fig. 6, at 12h, bottom panel). This is intuitive, sediment eroded from a breach must  
361 deposit somewhere. Under natural conditions these deposits could end up being part of a flood-  
362 tidal delta, or be transported oceanward during a return flow through the breach (Basco & Shin,  
363 1999).

### 364 5.3 Predicting breach and washover events

365 In 150 simulations we varied storm characteristics and barrier morphologies (Table 1) to  
366 better understand controls on washover and barrier breach development. Across all simulations,  
367 we find that the overwashing sediment transport fluxes ( $V_{ow,d3d}$ ) range from 0 (no overwash) to  
368  $3.3 \cdot 10^5 \text{ m}^3$ . Barrier subaerial volumes ( $V_{bar}$ ), in comparison, range from  $2.6 \cdot 10^3$  to  $5.2 \cdot 10^4 \text{ m}^3$ .  
369 Normalized overwashing fluxes ( $V_{norm,d3d}$ ) vary between 0 and 12.7.

370 In 26 simulations the storms resulted in barrier breaches, defined as an open water  
371 connection between the ocean and the bay at mean sea level (Fig. 7a). For the large majority of  
372 the simulations, the threshold  $V_{norm,d3d} = 1$  separates storm conditions that lead to barrier  
373 washover deposition and barrier breaching. For one simulation we find that a breach occurred  
374 despite the normalized overwashing flux  $V_{norm,d3d} < 1$  because erosion across the dune gap was  
375 not uniform and resulted in a narrow breach. Similarly, for three simulations, internal  
376 redistribution of sediments made that the barrier remained intact despite  $V_{norm,d3d} > 1$ .

377 Comparing the Delft3D storm impacts ( $V_{norm,d3d}$ ) against predicted storm impact ( $V_{norm,t}$   
378 eq. 5) we find that the predictor explains a significant amount of the variation between the model  
379 runs ( $R^2 = 0.81$ , Fig. 7b). Washover volumes of Delft3D simulation ( $V_{ow,d3d}$ ) increase for  
380 increasing predicted overwashing flux ( $V_{ow,t}$ ). The majority of storms result in barrier breaches  
381 when  $V_{norm,t} > 1$ , and 80% of all simulations result in barrier breaches if  $V_{norm,t} > 4$  (Fig. 7c).  
382 There are inaccuracies as well. 10% of the breaches were in simulations where  $V_{norm,t}$  predicted a  
383 washover deposit.

384 Predicted storm impacts  $V_{norm,t}$  vary across 4 orders of magnitude whereas our  
385 simulations ( $V_{norm,d3d}$ ) vary across 5 orders of magnitude, indicating non-linearities that our  
386 (linear) predictor has missed. One non-linear effect evident in the simulations results from the  
387 influence of the dune gap width ( $w_g$ ) on overwash fluxes. The vertical stacks of experimental  
388 results in Fig. 7b arise because the dune gap width affects the simulated overwash volumes

389 ( $V_{norm,d3d}$ ) but is cancelled out when calculating  $V_{norm,t}$  (eq. 5). Our Delft3D simulations show  
390 that a linear increase in gap width results in a supralinear increase in overwashing sediment  
391 fluxes. The decrease in flow friction for larger gaps outweighs the effect that flow constriction  
392 has to increase flow for small gaps. Our simulations are different from findings by Wesselman et  
393 al (2019), who found that flow constriction leads to a relatively large flux for small gaps.

#### 394 5.4 Comparison against observations from Hurricane Sandy

395 How do the observations from Hurricane Sandy fit within the variability of the Delft3D  
396 simulations? First, we find overwash volumes from Hurricane Sandy occupy a narrow range  
397 compared to our simulated volumes from Delft3D (Fig. 8). This range in observed volumes is  
398 also much narrower than what we predict using our analytical model (eq. 4 and 5), and indicates  
399 a (relatively) low sensitivity to storm characteristics and barrier morphology. Earlier studies have  
400 also noted this and resorted to using a sediment transport limiter (e.g., McCall et al., 2010).

401 A closer inspection into the Sandy observations shows a large difference between natural  
402 and developed coasts. We find that the overwash volumes for developed coastlines are smaller  
403 than those along undeveloped coasts (mean of 200 m<sup>3</sup> and 370 m<sup>3</sup>, respectively). Although there  
404 is a risk of selection or observation bias introduced by post-storm cleanup (e.g., Lazarus &  
405 Goldstein, 2019), other studies have also found a large effect of development on overwash  
406 dynamics. Rogers et al (2015) found a 40% decrease in overwash volumes comparing residential  
407 to natural environments. Structures block flow and pavement limits erosion (Rogers et al., 2015;  
408 Lazarus et al., 2021).

409 The magnitudes and trends of Hurricane Sandy overwashes and breaches that formed on  
410 natural (undeveloped) coasts are similar to our Delft3D observations (Fig. 8). This general  
411 agreement highlights the importance of the parameters in our predictor (barrier width, barrier  
412 height, and storm surge height) on barrier morphologic response. Two (out of three) breaches  
413 were predicted correctly ( $V_{norm,t} > 1$  and  $V_{norm,obs} > 1$ ). All of the seven observed washovers were  
414 correctly predicted ( $V_{norm,obs} < 1$  and  $V_{norm,t} < 1$ ), but there is no statistically significant  
415 correlation between the predicted and observed overwash volumes ( $V_{ow,obs}$  vs  $V_{ow,t}$ ).

416 In contrast to our observations for natural coasts, we do not observe any trends in the  
417 breaches and overwash fans that formed along developed coasts (Fig. 8). Some of the developed

418 coast breaches had a very low breaching probability ( $V_{norm,t} \approx 0.4$ ), whereas observed overwash  
419 fans along developed coastlines formed despite a predicted breach ( $V_{norm,t} = 43$ ).

## 420 **6 Discussion**

421 In this study we developed and tested an analytical theory for the development of  
422 washover fans and barrier breaches. In general, the simulations and predictors are simplified  
423 compared to natural dynamics of overwashing flows, which allowed us to formulate an analytic  
424 formulation that is integrated over the duration of the storm.

### 425 *6.1 Analytical predictor strengths and weaknesses*

426 Tests of our theory against Delft3D simulations and Hurricane Sandy observations  
427 showed mixed results. Delft3D simulations corresponded well, but natural and developed barrier  
428 response to Hurricane Sandy differed from theoretical expectations. Along natural barrier coasts,  
429 one observed breach was predicted to be a washover (#10 of Table S1). This occurred near Stone  
430 Harbor Point, NJ, on a wide sand flat close to an existing inlet. Likely the tidal conditions created  
431 overwashing flow dynamics to behave differently than our theoretical model. Detailed, site-  
432 specific simulations with more accurate pre-storm morphology (e.g., van Ormondt et al., 2020)  
433 are likely to be better suited to study these individual cases. Comparison against more field data,  
434 comprising different storms and different barrier islands, would also help to expand the range of  
435 observations and potentially improve the fit to predictions.

436 Disagreement between developed barrier response and theoretical expectations could  
437 indicate that important variables are missing in our model. Perhaps it is the erodibility of  
438 pavement or surface heterogeneity that funnels or disperses overwashing flows (Rogers et al.,  
439 2015; Lazarus et al., 2021) that dominates the response to storms for developed coasts. Many  
440 coasts are developed, so the poor performance of our (fairly traditional) sediment transport  
441 predictor indicates a need for morphodynamic formulations and models better suited for these  
442 environments.

### 443 *6.2 Implications for paleo environmental reconstructions*

444 Washover fan deposits are often used to reconstruct storms and climatic conditions (Woodruff et  
445 al., 2008; Shaw et al., 2015; Mulhern et al., 2019). Fan size and internal stratigraphy can record  
446 storm tracks, but bracketing storm intensity remain challenging. Our storm impact predictor (eq.

447 5) can be used as an inverse model to reconstruct paleo-storms where detailed models might not  
448 be appropriate because accurate boundary conditions and initial conditions are difficult to obtain.  
449 For example, our predictor could indicate a minimum storm intensity that would result in the  
450 formation of a washover fan with a certain observed volume or thickness. The presence of a  
451 preserved washover fan might also be used as an indication for a maximum storm intensity  
452 because the storm did not breach the barrier.

### 453 6.3 *Implications for morphodynamic barrier island models*

454 The landward sediment transport of barrier overwashing flows is important for the long-  
455 term survival of barrier islands facing sea-level rise (Storms, 2003; Nienhuis & Lorenzo-Trueba,  
456 2019a). Models have been developed to investigate overwashing fluxes and long-term barrier  
457 dynamics (Ashton & Lorenzo-Trueba, 2018; Nienhuis & Lorenzo-Trueba, 2019b), but scale-  
458 discrepancies still exist between our understanding of individual storms and barrier island  
459 transgression.

460 Current state-of-the-art barrier island models (Lorenzo-Trueba & Ashton, 2014) are  
461 reliant on empirical concepts that estimate washover deposition based on a distance function  
462 away from the current shoreline (Storms et al., 2002) or a certain critical barrier width  
463 (Leatherman, 1979; Jiménez & Sánchez-Arcilla, 2004; Rosati & Stone, 2007). This latter  
464 concept suggests that washover deposition into the lagoon only occurs if barrier width is below a  
465 certain (critical) width. The overwash flux is then estimated based on how much the barrier  
466 width deviates from the critical width, and sometimes is also limited below a certain maximum  
467 flux (Lorenzo-Trueba & Ashton, 2014). The shape and limits of these overwash functions are  
468 important parameters that affect barrier model persistence under sea-level rise.

469 Our predictor could help quantify expected overwash fluxes for different storm climates  
470 and for future sea levels. The maximum overwash flux concept (Lorenzo-Trueba & Ashton,  
471 2014) is not supported by our Delft3D simulations. That said, a possible maximum (storm-  
472 integrated) flux could be the subaerial barrier volume ( $V_{bar}$ ) itself, as any additional flux would  
473 result in a breach. We do find a strong relation between barrier width and overwashing volume  
474 (eq. 4), which, as suggested by the critical width concept, supports a negative feedback that  
475 would help barriers retain a certain width (Fig. 9a). However, assuming no additional influx from  
476 the shoreface or from adjacent dunes, overwash flux exceeding the barrier volume would breach

477 the barrier (Fig. 9b) and potentially result in seaward sediment transport through a return current  
478 (e.g., Basco & Shin, 1999). The suggested negative feedback that maintains barriers facing sea-  
479 level rise through landward transport (Lorenzo-Trueba & Ashton, 2014) may therefore not  
480 always hold.

## 481 **7 Conclusions**

482 In this study we proposed that barrier islands breach when the cumulative sediment flux  
483 of an overwashing flow exceeds the barrier subaerial volume (eq. 5). Washover volumes increase  
484 as overwashing flows approach the washover-to-breaching threshold: the largest washover fans  
485 likely appear when storms were very close to creating a breach. Tests against idealized Delft3D  
486 simulations show good agreement. We find reasonable agreement with observations of natural  
487 coastline response to Hurricane Sandy, and no agreement for overwashing across developed  
488 coasts. This could be because of the complex erodibility and surface roughness heterogeneity of  
489 the built environment.

490 Our study demonstrates the sensitivity of barrier width and storm surge height on barrier  
491 breaching and washover deposition. Increasing storm surge height raises the water depth and  
492 water surface slope of overwashing flows. Increasing barrier width reduces the water surface  
493 slope and increases the barrier subaerial volume. Barrier height and barrier vegetation reduce the  
494 likelihood of barrier breaching, whereas storm duration will increase it. Our predictor could be  
495 useful for estimates of barrier landward sediment fluxes in the face of sea-level rise, as well as  
496 paleo-environmental studies of (extra) tropical cyclone dynamics.

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720 **Table 1.** Delft3D model simulation settings. Morphological parameters reflect ranges reported  
 721 by JALBTCX (coast.noaa.gov/dataviewer/) and Mulhern et al. (2017). Vegetation parameters  
 722 span the range reported by Cheplick (2005), Biel et al. (2017), and Hacker et al. (2019).

| Parameter | Value                                       | Units            | Description  |
|-----------|---|------------------|--|
| $s_{max}$ | 2...4                                       | m                | peak surge above MSL   |
| $T$       | 0...10                                      | h                | surge duration, different from $T_{storm}$                       |
| $w$       | 150...400                                   | m                | barrier width  |
| $h_g$     | 1...2.5                                     | m                | gap height above MSL   |
| $w_g$     | 10...100                                    | m                | gap width  |
| ocean     | $f(s,T)$                                    | m                | function of storm surge and duration, see Fig. 3d                |
| lagoon    | 1   | m                | lagoon water level boundary                                      |
| frac. 1   | 0...0.2                                     |                  | fraction of the island using Trachytope 153 (Baptist 1)          |
| frac. 2   | 1...0.8                                     |                  | fraction of the island using Trachytope 105 (Bedforms quadratic) |
| hv        | 0.5   | m                | vegetation height  |
| n         | 0...200                                     | $m^{-2}$         | stem density   |
| m         | $5 \cdot 10^{-3}$                           | m                | leaf width   |
| Cd        | 1   |                  | drag coefficient of vegetation                                   |
| Cb        | 45  | $m^{0.5} s^{-1}$ | bed roughness chezy  |
| $C_f$     | $4.9 \cdot 10^{-3} \dots 2.9 \cdot 10^{-2}$ |                  | flow roughness (emergent vegetation)                             |
| Dryflc    | 0.1   | m                | Threshold depth for drying and flooding                          |
| EqmBc     | 0   |                  | Equilibrium sand concentration profile at inflow boundaries      |
| SedThr    | 0.1   | m                | Minimum water depth for sediment computations                    |
| ThetSD    | 0.9   |                  | Factor for erosion of adjacent dry cells                         |
| RhoSol    | 2650  | $kg m^{-3}$      | Specific density   |
| $d_{50}$  | 0.0002                                      | m                | Median sediment diameter   |
| CdryB     | 1600  | $kg m^{-3}$      | Dry bed density  |

723

724 **Figure 1.** Storm response to Hurricane Sandy, showing (a) the deposition of a washover fan and  
 725 (b) the formation of a breach. Inset shows their location in the North East USA. These examples  
 726 are #24 and #1, respectively, of the supplementary data table. Pre-storm images from Google  
 727 Earth, post-storm images from NOAA Emergency Response Imagery  
 728 (<https://storms.ngs.noaa.gov/>).

729 **Figure 2: Conceptual model of an overwashing flow through a dune gap.** (a) Plan-view  
 730 barrier island separating the bay from the ocean, (b) cross-section through the dune gap  
 731 highlighting the overwashing volume  $V_{ow}$  and the barrier volume  $V_{bar}$ .

732 **Figure 3: Delft3D model domain and setup to study washover deposition and barrier**  
733 **breaching.** (a) Initial bathymetry and barrier morphological parameters, (b) bed roughness (after  
734 8 hours of flow to illustrate the model dynamic effects of overwashing flow), (c) model grid  
735 cells, and (d) model boundary conditions across the domain. Model setup files and model output  
736 are available at [dx.doi.org/10.17605/OSF.IO/3KNXA](https://dx.doi.org/10.17605/OSF.IO/3KNXA).

737 **Figure 4.** (a) Locations of washovers (grey) and breaches (red) overlain on the maximum water  
738 levels during hurricane Sandy. (b-e) distributions of storm and barrier characteristics of the 27  
739 locations.

740 **Figure 5.** (a) Snapshots of water levels and bed elevation across a dune gap at 0, 6, 12, 18, and  
741 24 hours of a 24 hour storm surge event that resulted in a breach. (b) Bed shear stress and  
742 sediment transport through the dune gap. (c) Time-series of water level differences and velocities  
743 across the barrier, resulting in a high normalized barrier overwashing flux ( $V_{norm,d3d}$ ) of  $\sim 2.4$ .  
744 This indicates that the barrier is likely to be breached.

745 **Figure 6.** A 2.2 m and 3 m peak storm surge resulted in the development of a washover (top  
746 panel) and barrier breach (bottom panel, same simulation as Fig. 5), respectively. Corresponding  
747 figures show the morphologic evolution during the storm and timeseries of overwashing water  
748 and sediment. Dotted lines indicate pre-storm barrier profile.

749 **Figure 7.** (a) Time evolution of overwashing sediment transport for 150 simulated storms,  
750 normalized by the subaerial barrier volume. Red lines indicate simulations where storms led to  
751 barrier breaching. Blue lines are simulations resulting in a washover fan. (b) Simulated  
752 overwashing sediment flux ( $V_{norm,d3d}$ ) compared to the predicted sediment flux ( $V_{norm,t}$ ). (c)  
753 Fraction of simulations resulting in breached barriers as a function of predicted storm impact  
754 ( $V_{norm,t}$ ).

755 **Figure 8.** (a) Predicted vs. observed overwashing volume and (b) storm impacts for Delft3D  
756 simulations and Hurricane Sandy observations. Breaches (which in the case of Sandy  
757 observations have no observed overwash volume) are plotted separately, above. The observed  
758 variability in storm impacts on developed coasts (red squares) is not captured by our predictor.

759 **Figure 9:** (a) Influence of barrier width on barrier washover distance and post-storm width for a  
760 selection of the Delft3D model simulations. Note that the red line is simply the sum of the  
761 original width (x-axis) and the added washover width (y-axis). (b) Influence of barrier width on  
762 the alongshore- averaged overwash flux. A alongshore-averaged flux that exceeds the subaerial  
763 barrier volume ( $V_{bar}$ ) results in a breach. This provides some indication that the maximum  
764 preserved overwash flux could be equal to the barrier volume.