

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

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6 **Key points**

- 7 1. New predictor for barrier island breaching and washover deposition
- 8 2. Idealized Delft3D morphodynamic simulations of barrier island overwashing flows,
9 washover formation, and inlet formation
- 10 3. Tests of new predictor against Delft3D simulations and Hurricane Sandy observations
11 shows reasonable correspondence for natural barriers

12 **Abstract**

13 Waves and water level setup during storms can create overwashing flows across barrier
14 islands. Overwashing flows can cause erosion and barrier island breaching, but its sediments can
15 also be deposited as washover fans. These widely different outcomes remain difficult to predict.
16 Here we suggest that breaches develop when the sediment transported by overwashing flows
17 exceed the barrier subaerial volume. We form a simple analytical theory that estimates
18 overwashing flows from storm characteristics, barrier morphology, and dune vegetation, and can
19 be used to assess washover deposition and breaching likelihood. Barrier width and storm surge
20 height appear as two important controls on barrier breaching. We test our theory with the
21 hydrodynamic and morphodynamic model Delft3D as well as with field observations of 21
22 washover fans and 6 breaches that formed during hurricane Sandy. There is reasonable
23 correspondence for natural but not for developed barrier coasts. Our analytical formulations for
24 breach formation and overwash deposition can be used to improve long-term barrier island
25 models.

26 **1 Introduction**

27 Storms can have large impacts on barrier islands. Overwashing flows and waves can
28 move sediment across barrier islands and result in washover deposition (Fig. 1a) or barrier island
29 breaching (Fig. 1b) (Pierce, 1970). These outcomes are strongly sensitive to barrier
30 characteristics and storm intensity (Suter et al., 1982; Plomaritis et al., 2018). Hurricane Sandy
31 hit the U.S. East Coast in 2012 and resulted in widespread overwashing and numerous breaches
32 (Fig. 1) (Sopkin et al., 2014). Breaching is likely to be increasingly common as a result of sea-
33 level rise (Passeri et al., 2020). At the same time, washover deposition is a critical landward-
34 directed sediment flux that can support barrier aggradation and prevent barrier drowning.
35 Reliable predictions of barrier breaching and washover deposition prior to landfall remain
36 difficult.

37 In this study we propose that barrier islands breach when the cumulative sediment flux of
38 an overwashing flow exceeds the barrier subaerial volume. A washover deposit forms when an
39 overwashing flow does not erode the barrier down to sea-level. Washover volumes increase as
40 overwashing flows approach the washover-to-breaching threshold.

41 The objective of this study is to test this theory using Delft3D simulations and
42 observations from hurricane Sandy. We systematically explore the effect of barrier island
43 morphology, storm characteristics, and dune vegetation on overwashing flows and the
44 morphologic response of barrier coasts.



45
 46 **Figure 1.** Storm response to Hurricane Sandy, showing (a) the deposition of a washover fan and
 47 (b) the formation of a breach. These examples are #24 and #1, respectively, of the supplementary
 48 data table.

49 **2 Background**

50 *2.1 Overwashing flows*

51 Storm winds setup surges and generate waves that can lead to erosion of beaches and
 52 dunes. These impacts are often assessed based on relative elevation of wave runup and water
 53 levels against the dune toe or dune crest (Sallenger, 2000). Waves and water levels reaching the
 54 dune toe can induce slumping and dune erosion. Overwashing flows occur when wave runup
 55 and/or water levels exceed the island elevation (Fisher & Stauble, 1977; Kobayashi, 2010).

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

60 Several studies have aimed to determine the relative influence of wind, waves,
 61 infragravity waves, and water level gradients on water and sediment fluxes transported in
 62 overwashing flows. A recent study by Engelstad et al (2018) on an overwashing flow across the

63 Dutch island of Schiermonnikoog showed that sediment transport was primarily controlled by
64 currents, but that occasional high sediment concentrations were found on wave infragravity
65 timescales. Wave conditions (McCall et al., 2010) and foredune size (de Winter et al., 2015) are
66 important controls on foredune erosion and determining locations of overwashing flows, whereas
67 the water level gradient controlled the amount of overwashing sediment and its deposition in the
68 back barrier.

69 The evolution and magnitude of overwashing flows also depends on dune morphology
70 and vegetation patterns (Houser et al., 2008; Kobayashi, 2010; Passeri et al., 2018), which can
71 constrict the flow and deepen the throat. Flow acceleration through the throat can also widen the
72 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) show the sensitivity of the initial barrier geometry on barrier resilience to
78 overwash. Their results are validated by experimental and field evidence but do not include the
79 effect of currents on sediment fluxes. We refer to Donnelly (2006) for a review on overwashing
80 flows.

81 2.2 *Washover deposition*

82 Washovers form through the settling of sediment transported by overwashing flows
83 (Woodruff et al., 2008). A compilation from Hudock et al (2014) shows large variability in
84 washover area, but many are less than 1 km². Carruthers et al (2013) report washover volumes
85 normalized per unit width alongshore and obtain a median of 30 m³/m. A scaling analysis of
86 experimental and natural washover deposits finds that they are typically longer than they are
87 wide, with a width/length ratio of ~0.5 (Lazarus, 2016).

88 The length and size of washover deposits is controlled by storm characteristics (Morton
89 et al., 2003). Barrier islands formed by washover fans could therefore reflect long-term storm
90 history, and island width could be limited by the maximum transport distance of storm into the
91 lagoon (Hayes, 1979; Leatherman, 1979). Barrier island land cover such as the type of

92 development or vegetation can also affect washover characteristics (Sedrati et al., 2011; Rogers
93 et al., 2015), as does competition for flow from neighbouring washover throats (Lazarus &
94 Armstrong, 2015). The latter can result in a characteristic spacing of washover deposits.

95 2.3 Breaching

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

103 Models generated from breaches of sand dikes (Visser, 2001; Tuan et al., 2008) focus on
104 the expansion of the overwashing throat and find that breaches originate by head cutting and
105 erosion along the dune-side of the throat. Basco and Shin (1999) found that surge level
106 differences between ocean and bay regulate flow conditions and are an important predictor of
107 barrier island breaching. Further evidence from model and field studies specifically showed that
108 the timing of surge levels between the ocean and the bay, and the resulting water level gradients,
109 affect breaching likelihood and direction (Smallegan et al., 2016). A large time lag in surge
110 levels between the ocean and the bay make breaching towards the ocean more likely (Shin,
111 1996).

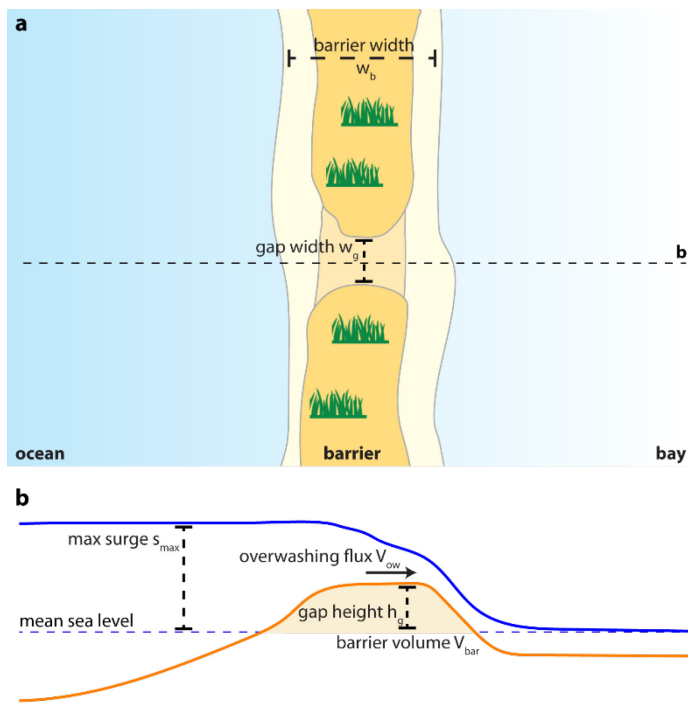
112 Site-specific process-based models of dune erosion and barrier breaching include Delft3D
113 (Deltares, 2014) and XBeach (Roelvink et al., 2009; Van Dongeren et al., 2009; McCall et al.,
114 2010; Elsayed & Oumeraci, 2016). De Vet et al (2015) applied XBeach on the well-documented
115 “Wilderness” breach on Fire Island, NY and find that bed roughness, including vegetation
116 roughness, is a sensitive and poorly constrained parameter that is important for properly
117 hindcasting the emergence of a breach. Recent model-coupling between Delft3D and XBeach
118 (e.g., van Ormondt et al., 2020) show promise for forecasting barrier breaching, but accurate,
119 site-specific process-based simulations of overwashing flows and barrier breaches remain
120 challenging.

121 On a conceptual level, Kraus et al (2002) postulated that breach susceptibility is
 122 controlled by the storm surge water level and is inversely proportional to the tidal range, used as
 123 a proxy for barrier island elevation. A modelling study by Nienhuis and Lorenzo-Trueba (2019a)
 124 also showed that breaches are more common in micro-tidal settings, in their case because it
 125 limits the lifetime of existing tidal inlets and increases potential tidal prism available to new
 126 breaches. Their model also suggests that, similar to alongshore competition for washover flow
 127 (Lazarus & Armstrong, 2015), there is alongshore competition for tidal flow that results in a
 128 characteristic spacing of successful breaches. However, there remains a large gap in model
 129 studies between detailed, site-specific simulations of overwashing flows, and large-scale barrier
 130 island models.

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

137 **3 Analytical theory**

138 In our theoretical model we define the washover volume as the total overwashing
 139 sediment flux into the lagoon, bayward of original barrier shoreline. Following Shin (1996), we
 140 classify a barrier as breached when the dune gap erosion exceeds mean sea-level and there is no
 141 subaerial barrier left after the storm. Here, we hypothesize that barriers breach when the storm-
 142 integrated overwashing flux V_{ow} (m^3) exceeds the barrier subaerial volume V_{bar} (m^3) (Fig. 2).



143

144 **Figure 2: Conceptual model of an overwashing flow through a dune gap. (a)** Plan-view
 145 barrier coast separating the bay from the ocean, **(b)** cross-section through the dune gap
 146 highlighting the overwashing flux V_{ow} and the barrier volume V_{bar} .

147 We use a simple sediment transport-based predictor to relate storm conditions to the
 148 overwashing sediment flux and dune gap erosion. This predictor is based on steady, uniform
 149 flow for bed shear stress (e.g. depth-slope product) and Engelund and Hansen (1967) for the
 150 resulting sediment transport. We do not simulate (wave-dominated) erosion and/or formation of
 151 a dune gap, but instead follow earlier studies that showed that water level gradients are a first-
 152 order control on overwashing flows, washover deposition, and barrier breaching (Basco & Shin,
 153 1999; McCall et al., 2010; Engelstad et al., 2018). Combining the depth-slope product (ρghS)
 154 and Engelund and Hansen (1967) yields the following prediction for overwashing sediment
 155 transport through the dune gap $Q_{ow,t}$ (m^3s^{-1}),

$$156 \quad Q_{ow,t}(t) = \frac{0.05}{C_f} \left(\frac{\rho ghS}{(\rho_s - \rho) \cdot g \cdot D_{50}} \right)^{2.5} D_{50} \cdot \sqrt{R \cdot g \cdot D_{50}} \cdot w_g, \quad (1)$$

157 where C_f is a non-dimension friction factor, ρ is the density of water ($\sim 1000 \text{ kg m}^{-3}$), ρ_s is the
 158 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

159 gravity (m s^{-2}), D_{50} is the median grain size (m), R is the relative density of sand (~ 1.65), w_g is
 160 the dune gap width (m).

161 We estimate the water depth h midway through the gap as $\frac{1}{2}(s_{max} - h_g)$, where s_{max} is
 162 the maximum surge level (m) and h_g is the height of the dune gap (m) (Fig. 2b). For simplicity,
 163 we assume the bay water level is zero (mean sea level). The water surface slope can then be
 164 approximated as the surge level $s(t)$ (m) as a function of time t (s), divided by the barrier width
 165 w_b (m).

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

$$167 \quad Q_{ow,t}(t) = \frac{0.05}{C_f} \left(\frac{s_{max} - h_g}{2} \right)^{2.5} \left(\frac{s(t)}{w_b} \right)^{2.5} \frac{\sqrt{g}}{R^2 D_{50}} \cdot w_g, \quad (2)$$

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

$$170 \quad V_{ow,t} = \int_0^{T_{storm}} Q_{ow,t}(t) \cdot c_c \, dt, \quad (3)$$

171 where T_{storm} (s) is the duration of the storm. c_c is a calibration coefficient of 0.1 to reduce the
 172 observed overprediction of our theory compared to the Delft3D simulations, $V_{ow,d3d}$. We found
 173 (in section 5.3) that an unadjusted predictor (without c_c) resulted in an overprediction of the
 174 sediment flux of about a factor ~ 10 . This is likely caused by the linearity of our predictor,
 175 including the assumption of a constant water depth h , and the absence of a threshold for motion.

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

$$178 \quad V_{ow,t} = \frac{\sqrt{2}}{560} \frac{T_{storm} \sqrt{g}}{D_{50} R^2 C_f} (s_{max} - h)^{2.5} \left(\frac{s_{max}}{w_b} \right)^{2.5} c_c \cdot w_g. \quad (4)$$

179 We expect the barrier to breach if $V_{ow,t}$ exceeds the subaerial barrier volume V_{bar} , where
 180 $V_{bar} = \frac{1}{2} h_g \cdot w_b \cdot w_g$. The factor $\frac{1}{2}$ is included because the barrier profile underneath the dune gap
 181 is roughly triangular towards the beach and the lagoon (Fig. 2b). We write the theoretical
 182 normalized overwash volume $V_{norm,t}$ as,

$$V_{norm,t} = \frac{V_{ow,t}}{V_{bar}} = \frac{c_e \cdot w_g \cdot \frac{\sqrt{2}}{560} \cdot \frac{T_{storm} \sqrt{g}}{D_{50} R^2 C_f} \cdot (s_{max} - h_g)^{2.5} \left(\frac{s_{max}}{w_b}\right)^{2.5}}{\frac{1}{2} h_g \cdot w_b \cdot w_g}, \quad (5)$$

where a barrier is expected to breach if $V_{norm,t} > 1$. We expect the subaerial barrier to be maintained if $V_{norm,t} < 1$. If that is the case and the overwashing sediment flux will deposit as a washover fan, $V_{ow,t}$ will give an indication of the washover fan volume.

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

Some of the trends in equation (5) align with observations from Wesselman et al. (2019), who found that dune height compared to surge elevation is important for sediment fluxes through dune gaps. Gap width was found to be less important and mostly linearly related to sediment fluxes except for smaller widths where flow contraction became significant. The prediction here (eq. 1-5) does not account for the effect of flow contraction nor the potential effect of neighboring overwashes that lower water level gradients. It also neglects many other important processes that occur in overwashing flows such as sheet-flow transport (Basco & Shin, 1999; Tuan et al., 2008).

We will test our theoretical predictions against Delft3D model simulations and observations from hurricane Sandy for varying storm conditions (T , s_{max}) and barrier morphologies (w_b , h_g) and barrier land cover (C_f). These data sources provide modelled and observed washover volumes ($V_{ow,d3d}$ and $V_{ow,obs}$) that we can compare against the predicted washover volume ($V_{ow,t}$). We will also test if breaches occur for $V_{norm,t} > 1$ by comparing it to

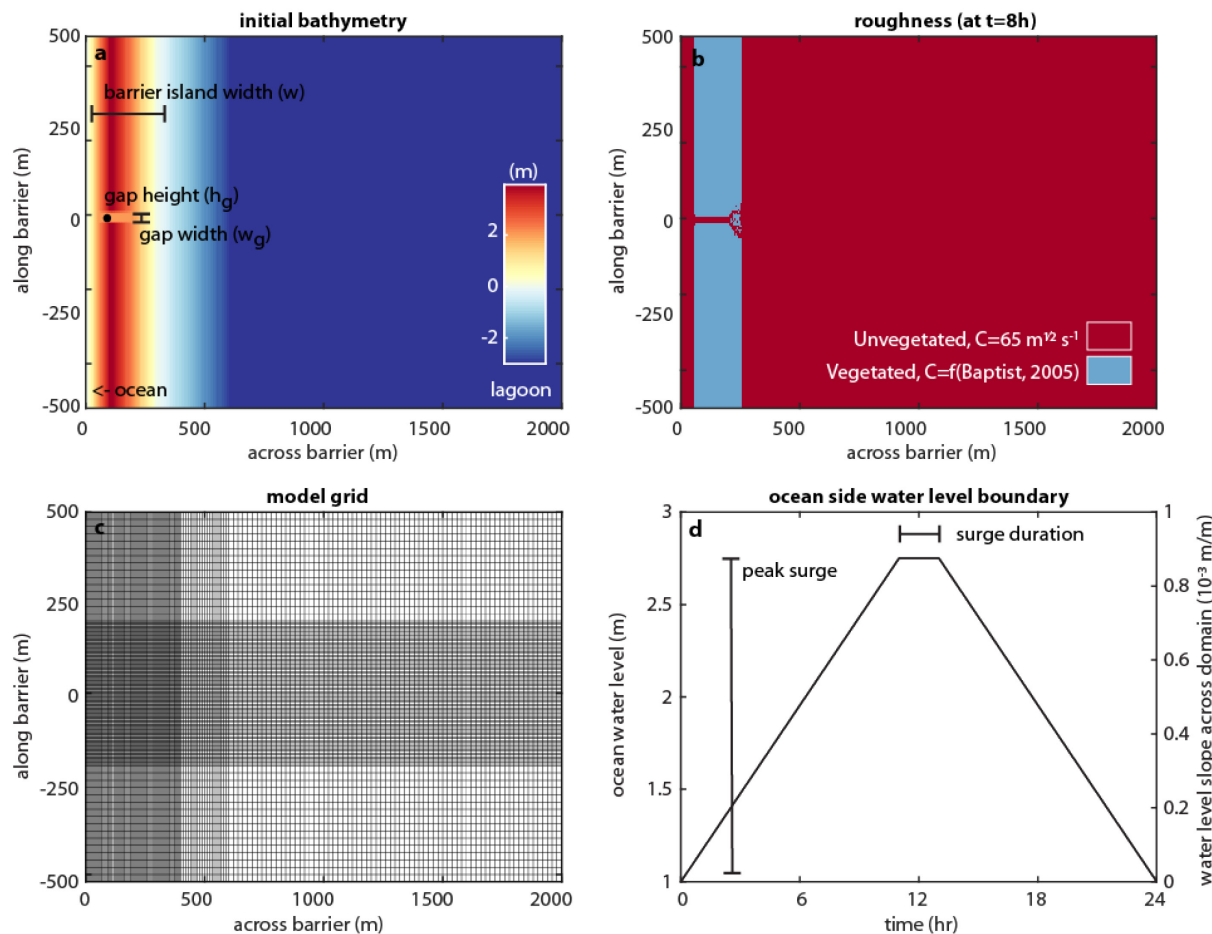
$$V_{norm,d3d} = \frac{V_{ow,d3d}}{V_{bar}} \text{ and } V_{norm,obs} = \frac{V_{ow,obs}}{V_{bar}}.$$

4 Methods

Section 4.1 describes the Delft3D model setup and section 4.2 describes the Hurricane Sandy analyses.

211 4.1 Delft3D model setup

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



217
 218 **Figure 3: Delft3D model domain and setup to study washover deposition and barrier**
 219 **breaching. (a)** Initial bathymetry and barrier morphological parameters, **(b)** bed roughness (after
 220 8 hours of flow to illustrate the model dynamic effects of overwashing flow), **(c)** model grid, and
 221 **(d)** model boundary conditions across the domain. Model setup files and model output is
 222 available at dx.doi.org/10.17605/OSF.IO/3KNXA.

223 We vary barrier morphology and storm characteristics between 139 model simulations
224 (Fig. 3, Table 1). The model setup is similar to one used in an earlier study by Nienhuis et al
225 (2018), who investigated the morphologic evolution of river levee gap into avulsions and
226 crevasse splays. A notable difference here is that there is no sediment supply from the ocean
227 boundary. As opposed to river crevasses, dune gaps cannot heal but instead simply stop
228 expanding when the storm recedes.

229 The initial bathymetry of the domain consists of a 1 km long coastal barrier and an
230 adjacent lagoon. Barrier widths vary between 150 and 400 m, with the rest of the 2 km cross-
231 profile modelled as a 3 m deep lagoon (Fig. 3). The domain consists of 172 by 112 cells in the
232 cross-shore and alongshore direction, respectively. The resolution ranges from 5 by 5 m near the
233 dune gap to 20 by 20 m along the sides and into the lagoon. The dune gap is in the middle of the
234 simulated barrier island. We vary the height and width of the gap between simulations (Table 1)
235 and use a uniform 0.2 mm sand across the barrier and lagoon.

236 The effect of vegetation is included using the Baptist (2009) ‘Trachytopes’ function,
237 which estimates an effective bed roughness depending on the vegetation height and density
238 relative to the water depth (Deltares, 2014). We use values typical for American Beachgrass.
239 Vegetation height is 0.5 m, stem density is 50 m^{-2} , and the aerial fraction is between 0% and 20%
240 for different model runs (Biel et al., 2017). Note that these simulations are not aimed at
241 representing any specific barrier island. Although the observations are limited to Hurricane
242 Sandy, the spread between model scenarios is meant to encompass storm characteristics and
243 barrier island morphologies globally.

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

252 As the water level rises on the ocean side, the dune gap becomes wet and a water surface
 253 slope appears across the island. Sediment transport fluxes are calculated following van Rijn
 254 (2007), using a 0.1 m water depth threshold for sediment transport for model stability. This is a
 255 different sediment transport predictor than what we use in our theoretical model (eq. 1). We
 256 choose van Rijn (2007) for our Delft3D simulation because it is more accurate than Engelund
 257 and Hansen (1967). We use the latter for our theoretical model because it does not require many
 258 parameters that could be difficult to assess in the field. Dry cells along the edges of the dune gap
 259 erode if erosion occurs in the dune gap itself. Delft3D uses a “dry cell erosion factor”, set here to
 260 0.9, to distribute the erosion between the wet cell and the dry cell. This factor can be viewed as a
 261 simple proxy for a critical bed slope for bank failure.

262 Overwashing flows are generated from a water level gradient across the barrier island
 263 through the dune gap. Based on this gradient, the barrier width and roughness, and available
 264 subaerial barrier volume, morphologic simulations then form either washover deposits or result
 265 in barrier breaching. See Table 1 for an overview of model settings. The supplementary data for
 266 the model code and model output to reproduce our findings are available at
 267 [dx.doi.org/10.17605/OSF.IO/3KNXA](https://doi.org/10.17605/OSF.IO/3KNXA).

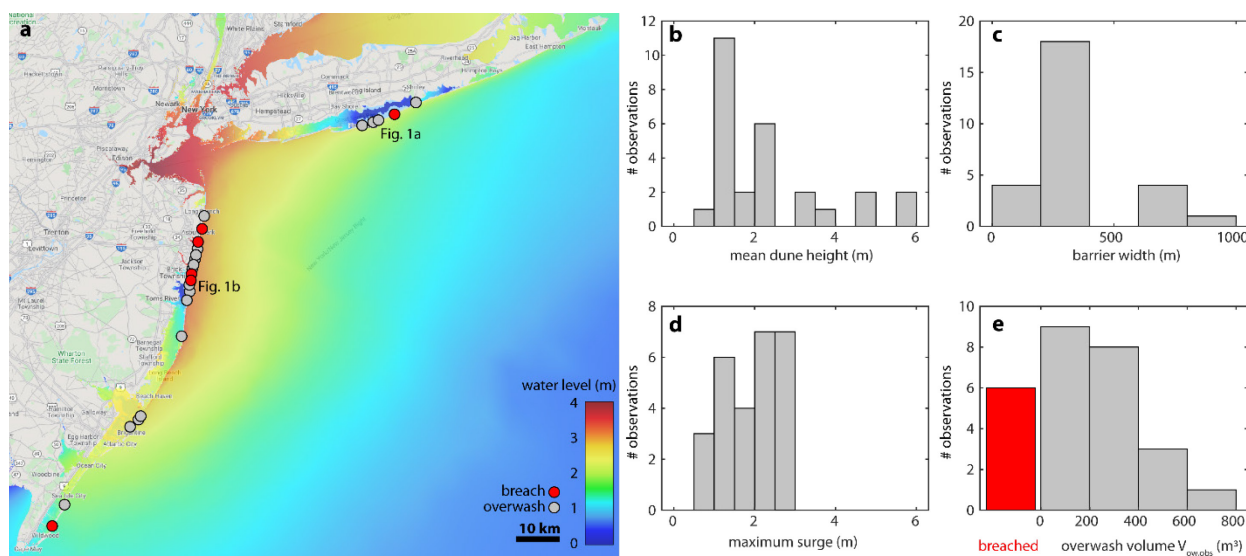
268 **Table 1.** Delft3D model simulation settings

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	50	m^{-1}	stem density
Cd	1		drag coefficient of vegetation
Cb	65	$m^{0.5} s^{-1}$	bed roughness chezy
C_f	$3.3 \cdot 10^{-3} \dots 4.2 \cdot 10^{-3}$		flow roughness (including vegetation, for ~ 0.5 m water depth)
Dryflc	0.1	m	Threshold depth for drying and flooding
EqmBc	FALSE		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

269

270 4.2 Hurricane Sandy analyses



271

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

275 Hurricane Sandy observations allow us to test our theoretical model and our
 276 morphodynamic Delft3D simulations. Sandy made landfall on the New Jersey coast on October
 277 29, 2012, and resulted in numerous breaches and washover fans (Sopkin et al., 2014), including
 278 the well-documented “Wilderness” breach on Fire Island (van Ormondt et al., 2020). We
 279 analyzed 27 overwashing sites, of which 6 resulted in breaches and 21 in overwash fans. For
 280 these sites we also retrieved the local storm conditions that led to their formation (Fig. 4).

281 Storm characteristics are determined using the ADCIRC+SWAN hindcast model
 282 simulation (Dietrich et al., 2012) via the Coastal Emergency Risk Assessment (CERA), available
 283 at www.coastalrisk.live. ADCIRC is a hydrodynamic model that computes time dependent tide,
 284 wind, and pressure driven surge (Luettich et al., 1992). Coupling with SWAN (Booij et al., 1999)

285 allows for assessment of wave-driven setup. We use these time-explicit surge hindcasts instead
286 of maximum surge level maps because they allow us to extract water surface slopes. We refer to
287 documentation of CERA for more information.

288 We extract water level timeseries for the lagoon and ocean sides of the barrier islands at
289 the 27 overwashing locations. These timeseries are then converted to surge water level
290 differences across the islands, as well as storm durations. The hindcast simulations for Sandy
291 show that the water level differences between the ocean and lagoon ranged from 0.8 to 2.6 m
292 (Fig. 4d).

293 We use Google Earth images to estimate the pre-storm width and land cover of the
294 overwashing sites. Land cover is categorized as either developed, vegetated, or bare. Chezy
295 roughness coefficients ($= \sqrt{g / C_f}$) of these three land cover types are estimated as 15, 40, and
296 $65 \text{ m}^{1/2} \text{ s}^{-1}$, respectively, for our theoretical model (Passeri et al., 2018). Dune gap heights are
297 retrieved from the USGS dune crest elevation dataset, which provides maximum and standard
298 deviations of dune elevation of 1km alongshore section (Birchler et al., 2015). We estimate the
299 gap elevation as the maximum dune height minus two standard deviations. Gap widths are
300 assumed to be 100 m.

301 Based on the post-storm NOAA Emergency Response Imagery
302 (<https://storms.ngs.noaa.gov/>) we characterize each overwashing site as either a breach (e.g., Fig.
303 1a) or a washover deposit (e.g. Fig. 1b). We use these same images to measure the subaerial
304 surface area of each washover deposit. Unfortunately, there is no readily available data to extract
305 washover volumes for the 21 fans in our dataset. We use the washover fan data compiled by
306 Lazarus et al (2016), where field-scale washover volume / area $\approx 0.3 \text{ m}$, to estimate washover
307 volume ($V_{ow,obs}$). For barrier breaches, which do not leave a washover deposit, we set $V_{norm,obs} >$
308 1.

309 **5 Results**

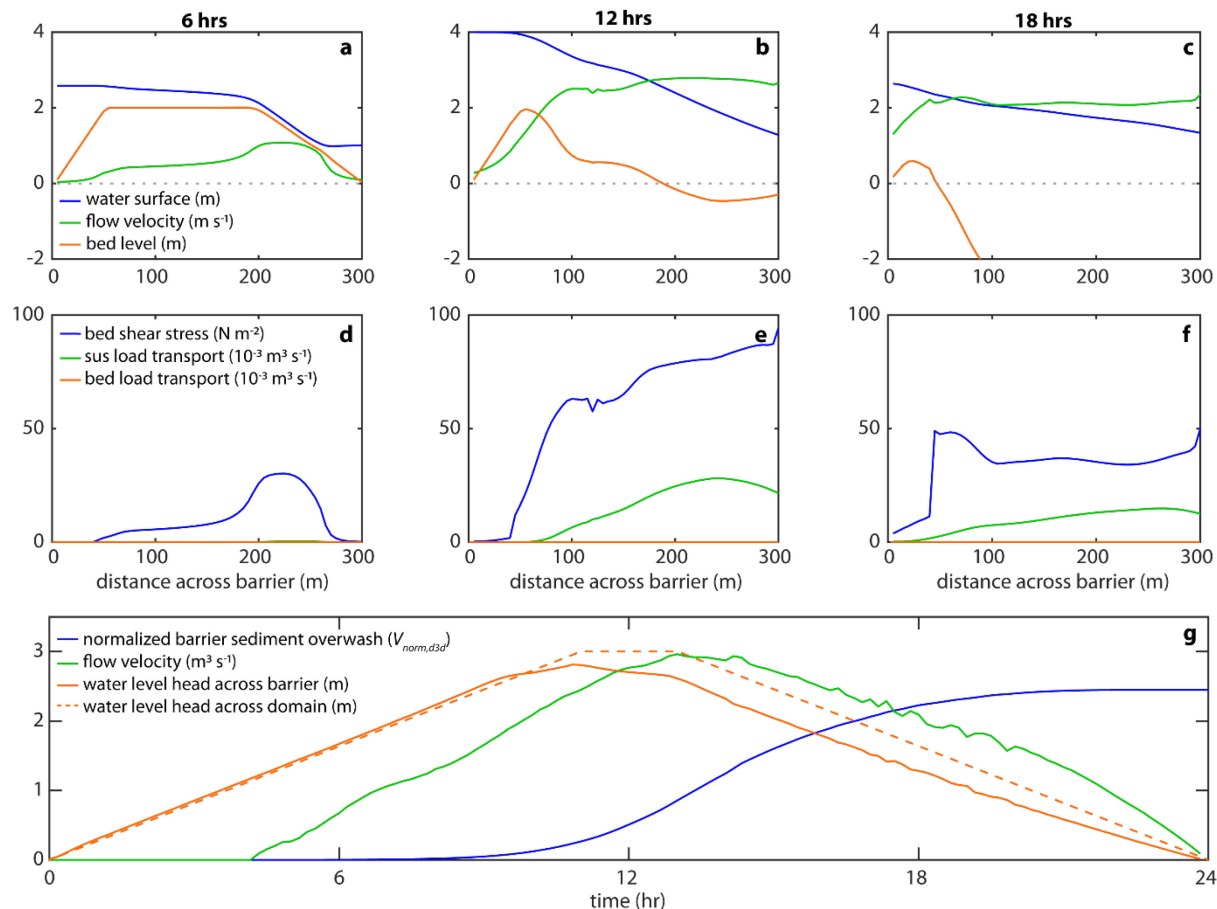
310 *5.1 Mechanics of overwashing flows*

311 We use an example Delft3D simulation of a 300-m wide barrier island to illustrate the
312 model dynamics (Fig. 5). In this case, a breach developed in response to a 3 m storm surge.
313 Water flowing across the gap resulted in high shear stresses, primarily at the back of the dune

314 gap into the lagoon where the water surface slope is greatest. This agrees with model
 315 experiments from Visser (2001). Water level gradients in the lagoon are negligible compared to
 316 gradients across the barrier, reflecting the relative flow roughness of both environments (Fig.
 317 5g).

318 Peak shear stresses of $\sim 50 \text{ N m}^{-2}$ are observed in the overwashing flows. Critical shear
 319 stress for sand movement, $\sim 0.15 \text{ N m}^{-2}$, are negligible compared to these peak stresses. High
 320 concentrations of sediments are suspended and high gradients of sediment transport cause
 321 erosion. Suspended transport magnitude greatly exceeds bedload transport, which is also
 322 observed by De Vet (2015) but not in other studies (Shin, 1996). Discrepancies can arise because
 323 sheet flow conditions are likely for these (high) Shields numbers, and it is debated whether sheet
 324 flow constitutes bed load or suspended load transport.

325 We compared the cumulative sediment transported across the barrier island ($V_{ow,d3d}$) with
 326 the subaerial volume of the barrier under the overwashing throat (V_{bar}). The overwashing flow
 327 transported approximately $60 \cdot 10^3 \text{ m}^3$ across the barrier. The subaerial barrier, on average, 1.67 m
 328 high, 300 m wide, and the gap extends 50 m alongshore, comprising a volume of $25 \cdot 10^3 \text{ m}^3$. The
 329 result is a normalized barrier overwash $V_{norm,d3d}$ ($V_{ow,d3d} / V_{bar}$) of about ~ 2.4 at the end of the
 330 storm. A breach occurred. The trend of the overwash timeseries shows that the greatest transport
 331 occurred after the storm surge peak. Only $\sim 20\%$ of the overwashing flux is transported during
 332 the first 12 hours of the storm.



333

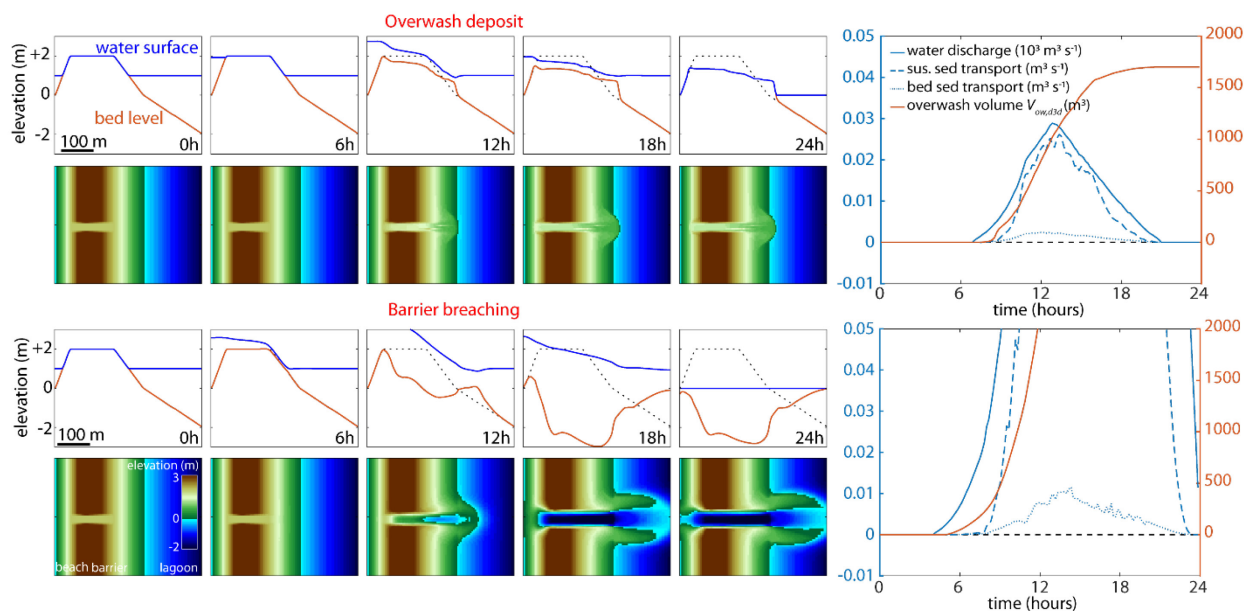
334 **Figure 5.** (a, b, c) Snapshots of water levels, flow velocities, and bed erosion across a dune gap
 335 at 6, 12, and 18 hours of a 24 hour storm surge event. (d, e, f) Bed shear stress and sediment
 336 transport through the dune gap. (g) Time-series of water level differences and velocities across
 337 the barrier, resulting in a high normalized barrier overwashing flux ($V_{norm,obs}$) of ~ 2.4 . This
 338 indicates that the barrier is likely to be breached.

339 **5.2 Breaching vs. washover deposits**

340 We contrast the event from section 5.1 that resulted in a breach with another simulation
 341 where a washover was deposited (Fig. 6). The washover formed following a 2.2-m storm surge.
 342 Water discharge and suspended sediment transport across the dune gap develop in tandem, and
 343 erosion primarily acts on the back of the dune gap. A small, 1700 m³ washover fan develops
 344 (Fig. 6, top panel).

345 We find similarities between the initial development of the barrier breach and washover
 346 deposit: a small washover fan also appears in response to the breach, although it is more disperse

347 (Fig. 6, at 12h). This makes intuitive sense, sediment eroded from a breach must deposit
 348 somewhere. These “breach” deposits are not commonly found. Under natural conditions these
 349 deposits could be transported oceanward during a return flow through the breach (Basco & Shin,
 350 1999).



351
 352 **Figure 6.** A 2.2 m and 3 m peak storm surge resulted in the development of a washover (top
 353 panel) and barrier breach (bottom panel), respectively. Corresponding figures show the
 354 morphologic evolution during the storm and timeseries of overwashing water and sediment.
 355 Dotted lines indicate pre-storm barrier profile.

356 5.3 Predicting breach and washover events

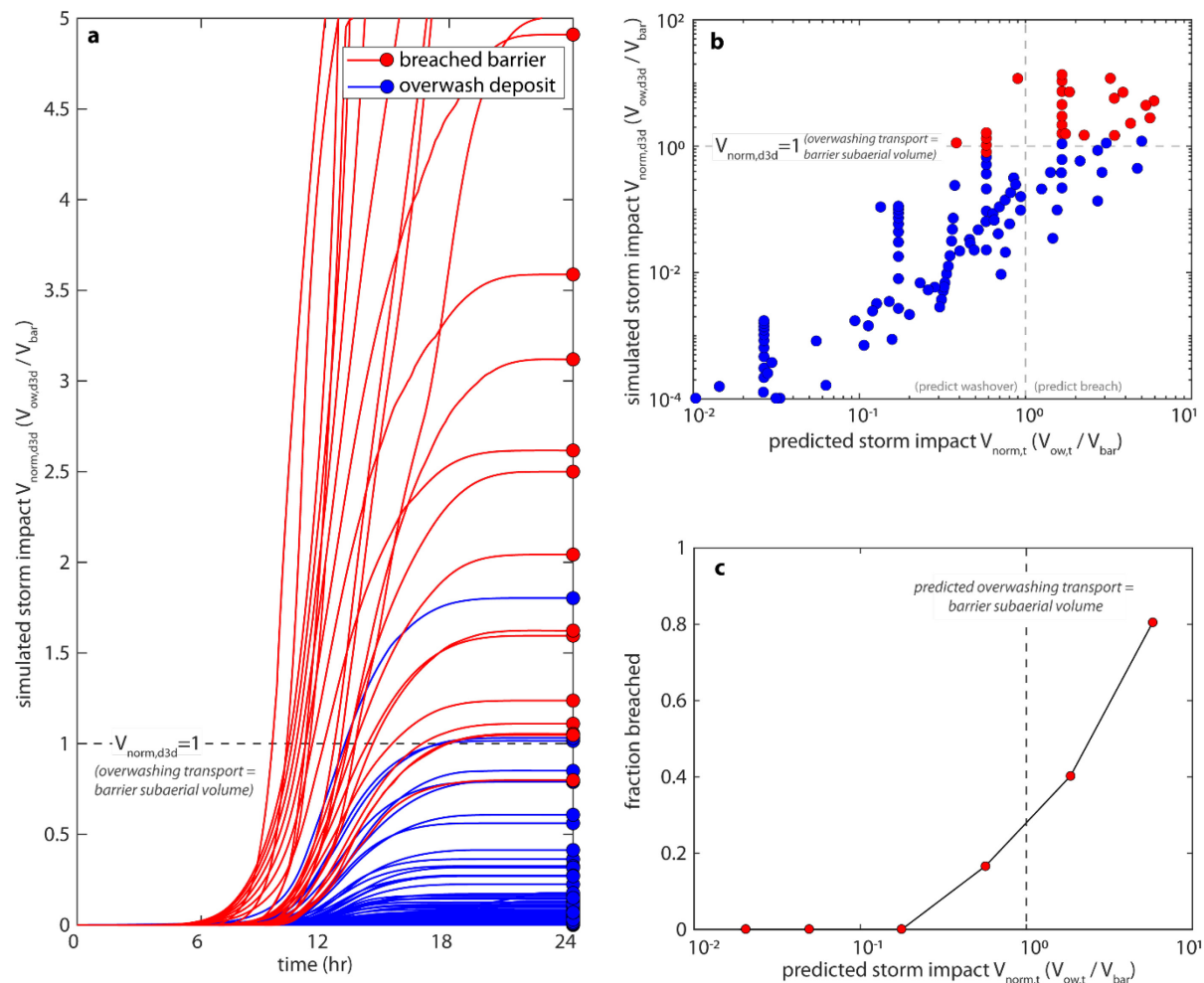
357 In 139 simulations we varied storm characteristics and barrier morphologies (Table 1) to
 358 better understand controls on washover and barrier breach development. Across all simulations,
 359 we find that the overwashing sediment transport fluxes ($V_{ow,d3d}$) range from 0 (no overwash) to
 360 $3.3 \cdot 10^5 m^3$. Barrier subaerial volumes (V_{bar}), in comparison, range from $2.6 \cdot 10^3$ to $5.2 \cdot 10^4 m^3$.
 361 Normalized overwashing fluxes ($V_{norm,d3d}$) vary between 0 and 12.7.

362 In 26 simulations the storms resulted in barrier breaches, defined as an open water
 363 connection between the ocean and the bay at mean sea level (Fig. 7a). For the large majority of
 364 the simulations, the threshold $V_{norm,d3d} = 1$ separates storm conditions that lead to barrier
 365 washover deposition and barrier breaching. For one simulation we find that a breach occurred

366 despite the normalized overwashing flux $V_{norm,d3d} < 1$ because erosion across the dune gap was
 367 not uniform and resulted in a narrow breach. Similarly, for three simulations, the barrier
 368 remained intact and $V_{norm,d3d} > 1$.

369 Comparing the Delft3D storm impacts ($V_{norm,d3d}$) against predicted storm impact ($V_{norm,t}$
 370 eq. 5) we find that it explains a significant amount of the variation between the model runs (Fig.
 371 7b). Washover volumes increase for increasing predicted overwashing flux ($V_{ow,t}$). The majority
 372 of storms result in barrier breaches for $V_{norm,t} > 1$, and 80% of all simulations result in barrier
 373 breaches if $V_{norm,t} > 4$ (Fig. 7c).

374 Our predictor scales linearly with sediment transport and misses some non-linear effects.
 375 Predicted storm impacts $V_{norm,t}$ vary across 3 orders of magnitude whereas our simulations
 376 ($V_{norm,obs}$) vary across 5 orders of magnitude. One non-linear effect results from the influence of
 377 the dune gap width (w_g) on overwash fluxes. It is apparent in the vertical stacks of experimental
 378 results in Fig. 7b, which arise because the dune gap width does not affect $V_{norm,t}$ (eq. 5). We find
 379 that, in contrast to Wesselman (2019), larger gap widths lead to greater overwashing flow
 380 velocities: the decrease in flow friction for larger gaps outweighs the effects of flow constriction.
 381 A linear increase in gap width results in a supralinear increase in overwashing sediment fluxes.



382

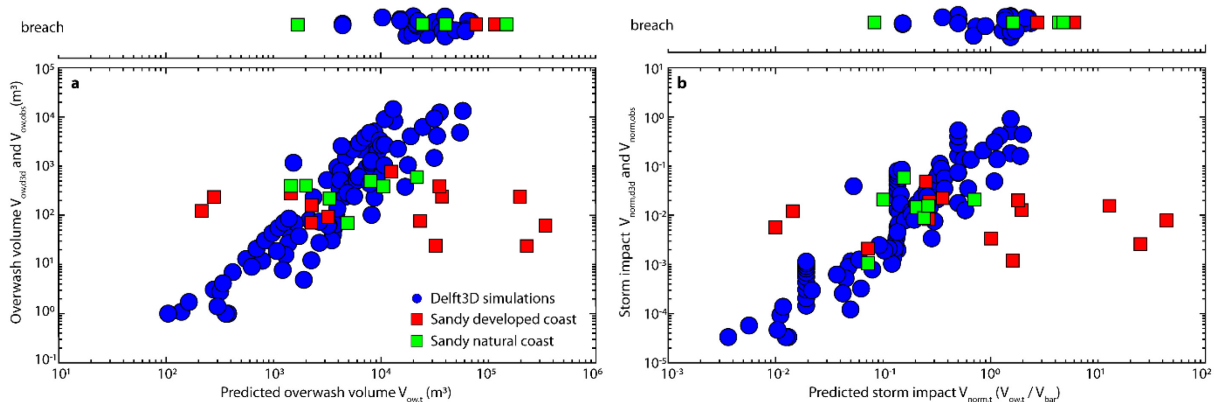
383 **Figure 7.** (a) Time evolution of overwashing sediment transport for varying storm and barrier
 384 characteristics, normalized by the subaerial barrier volume. Red lines indicate simulations where
 385 storms led to barrier breaching. (b) Simulated overwashing sediment flux ($V_{norm,d3d}$) compared to
 386 the predicted sediment flux ($V_{norm,t}$). (c) Fraction of simulations resulting in breached barriers as
 387 a function of predicted storm impact ($V_{norm,t}$).

388 5.4 Comparison of simulations against observations from Hurricane Sandy

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

395 A closer inspection into the Sandy observations shows a large difference between natural
 396 and developed coasts. We find that the overwash volumes for developed coastlines are smaller
 397 than those along undeveloped coasts (mean of 200 m³ and 370 m³, respectively). Although there
 398 is a risk of selection or observation bias (e.g., Lazarus & Goldstein, 2019), other studies have
 399 also found a large effect of development on overwash dynamics. Structures block flow and
 400 pavement limits erosion (Rogers et al., 2015).

401 The magnitudes and trends of Hurricane Sandy overwashes and breaches that formed on
 402 natural (undeveloped) coasts are similar to our Delft3D observations (Fig. 8). This general
 403 agreement highlights the importance of the parameters in our predictor (barrier width, barrier
 404 height, and storm surge height) on barrier morphologic response. Of the 4 natural coast
 405 overwashing flows with a predicted storm impact $V_{norm,t} > 1$, 3 resulted in breaches. Of the
 406 overwashing flows with a predicted storm impact $V_{norm,t} < 1$, washover fans appeared in 86% of
 407 the cases. However, caution remains because there is significant scatter around these trends.
 408 Detailed, site-specific simulations (e.g., van Ormondt et al., 2020) are likely to be much more
 409 accurate for individual cases.



410
 411 **Figure 8.** (a) Predicted vs. observed overwashing volume and (b) storm impacts for Delft3D
 412 simulations and Hurricane Sandy observations. Breaches (which in the case of Sandy
 413 observations have no observed overwash volume) are plotted separately. The observed
 414 variability in storm impacts on developed coasts (red squares) is not captured by our predictor.

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

417 breaches had a very low breaching probability ($V_{norm,t} \approx 0.4$), whereas observed overwash fans
418 along developed coastlines formed despite a predicted breach ($V_{norm,t} = 43$). This would imply
419 that variables that are not included in our predictor (to the correct extent), such as the erodibility
420 of pavement or surface heterogeneity that funnels or disperses overwashing flows, dominates the
421 response to storms for developed coasts.

422 **6 Discussion**

423 In this study we developed and tested an analytical theory for the development of
424 washover fans and barrier breaches. In general, the simulations and predictors are simplified
425 compared to natural dynamics of overwashing flows, which allowed us to formulate an analytic
426 formulation that is integrated over the duration of the storm. Here we will discuss potential uses
427 from the resulting formulation and the observed (mis) matches with data.

428 *6.1 Implications for paleo environmental reconstructions*

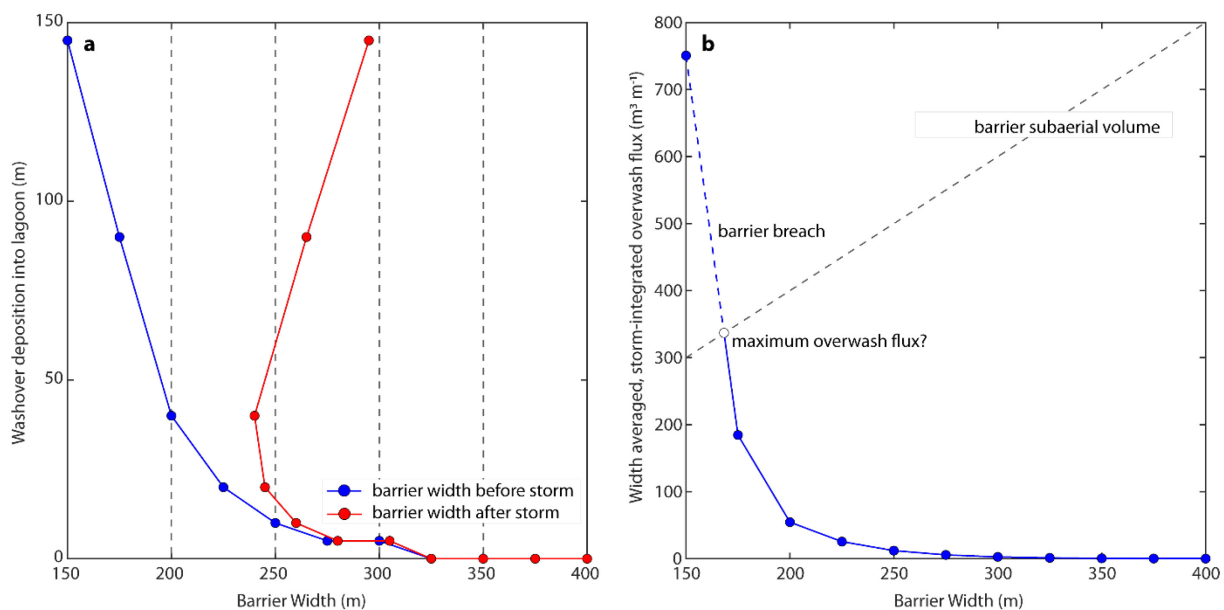
429 Washover fan deposits are often used to reconstruct storms and climatic conditions
430 (Woodruff et al., 2008; Shaw et al., 2015; Mulhern et al., 2019). Fan size and internal
431 stratigraphy can record storm tracks, but bracketing storm intensity remain challenging. Our
432 storm impact predictor (eq. 5) can be used as an inverse model to reconstruct paleo-storms where
433 detailed models might not be appropriate because accurate boundary conditions and initial
434 conditions are difficult to obtain. For example, our predictor could indicate a minimum storm
435 intensity that would result in the formation of a washover fan with a certain observed volume or
436 thickness. The presence of a preserved washover fan also indicates that the storm did not breach
437 the barrier.

438 *6.2 Implications for morphodynamic barrier island models*

439 The landward sediment transport of barrier overwashing flows is important for the long-
440 term survival of barrier islands facing sea-level rise (Storms, 2003; Nienhuis & Lorenzo-Trueba,
441 2019a). Models have been developed to investigate overwashing fluxes and long-term barrier
442 dynamics (Ashton & Lorenzo-Trueba, 2018; Nienhuis & Lorenzo-Trueba, 2019b), but scale-
443 discrepancies still exist between our understanding of individual storms and barrier island
444 transgression.

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

454 Our predictor could help quantify expected overwash fluxes for different storm climates.
 455 We find a strong relation between barrier width and overwashing volume (eq. 4), which, as
 456 suggested by the critical width concept, supports a negative feedback that would help barriers
 457 retain a certain width (Fig. 9a). Delft3D simulations do not point to a maximum overwash flux,
 458 although a possible maximum (storm-integrated) flux could be the subaerial barrier volume. Any
 459 greater overwash flux would breach the barrier (Fig. 9b), and potentially result in seaward
 460 sediment transport through a return current (e.g., Basco & Shin, 1999).



461

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

468 7 Conclusions

469 In this study we proposed that barrier islands breach when the cumulative sediment flux
 470 of an overwashing flow exceeds the barrier subaerial volume (eq. 5). Washover volumes increase
 471 as overwashing flows approach the washover-to-breaching threshold: the largest washover fans
 472 likely appear when storms were very close to creating a breach. Tests against idealized Delft3D
 473 simulations show good agreement, although a calibration factor was necessary. We find
 474 reasonable agreement with observations of natural coastline response to Hurricane Sandy, and no
 475 agreement for overwashing across developed coasts.

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

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 487 supplementary material, available at:
 488 https://osf.io/3knxa/?view_only=263b5ba95f0e43558dccf46bbdd9433e. We will replace this
 489 with a doi upon publication.

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