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Storm overwash of a gravel barrier: Field measurements and XBeach-G modelling

Almeida, L.P., Masselink, G., McCall, R., Russell, P.

Abstract

Gravel barriers provide a natural form of coastal protection and flood defence for many sites around the UK and worldwide. Predicting their vulnerability to different storm impact regimes that cause overtopping and overwash is crucial as these processes can lead to hazardous consequences such as inundation of the back of the barrier or breaching. This paper presents the first field measurements of storm overwash events on a gravel beach (Loe Bar, Cornwall, England). High frequency in-situ observations (2 Hz) were performed using a 2D laser-scanner and allowed a complete characterization of the overwash flows (velocity and depth) and morphological response along a cross-shore section of the barrier. These novel measurements are used to validate the numerical model XBeach-G, to forecast overwash discharge. Several simulations were performed with XBeach-G to investigate the thresholds for the different storm impact regimes, given a variety of water levels and wave heights. Wave period and wave spectral shape are found to significantly affect these thresholds. While short period waves dissipate most of their energy by breaking before reaching the swash zone and produce short runup excursions, long period waves due to their low steepness arrive at the swash zone unbroken with enhanced heights (due to shoaling) thus promoting large runup excursions. When the offshore wave spectrum has a bimodal shape, wave transformation in shallow water causes the long period peak to dominate the swash giving large runup excursions. Long period waves or strongly bimodal waves result in enhanced runup thereby reducing the thresholds for barrier overtopping or overwashing.

30 **1. Introduction**

31 Gravel barriers are widespread on many high-latitude, wave-dominated coasts around the
32 world such as in the UK, Ireland, USA, Russia and New Zealand. Their shape and long-term
33 evolution are mainly controlled by three hydrodynamic regimes: (1) swash, when runup is
34 confined to the foreshore, resulting in berm formation and/or beach erosion, e.g., Buscombe
35 and Masselink, (2006); (2) overtopping, when runup exceeds the crest, resulting in crest
36 build-up and/or lowering, e.g., Matias et al., (2012); and (3) overwash, when runup exceeds
37 the crest and promotes major modifications over the entire barrier, resulting in barrier
38 transgression via rollover, e.g., Carter and Orford, (1993). Predicting long-term evolution of a
39 gravel barrier therefore requires in-depth understanding of the conditions under which each of
40 these regimes occurs. Most research on gravel barriers has focused on hydrodynamic
41 conditions within the swash regime, mostly during mild (e.g., Austin and Masselink, 2006;
42 Masselink et al., 2010), but more recently also under energetic wave conditions (e.g., Poate et
43 al., 2013; Almeida et al., 2015). There is a paucity of measurements under overtopping or
44 overwash conditions and, most of the times the observations are mostly based on pre and
45 post-storm barrier topography (e.g., Orford et al., 2003). Bradbury (2000) has attempted to
46 establish an empirical model (Barrier Inertia Model - BIM) which relates the probability of
47 overwash on gravel barriers to the near breaking wave steepness and the dimensionless
48 barrier inertia parameter (ridge height x barrier area scaled against near-breaking wave
49 height). Obhrai et al. (2008) extended the range of validity of the BIM to lower and higher
50 steepness waves. Although this model is used in many locations in UK, the data from which
51 was derived is site specific (Hurst Spit in the south of England). In addition to this BIM does
52 not deal with the velocity of overwash flows and shear stress capacity at the bed (sediment
53 size) which are key aspects regarding the wave runup on coarse-grained beaches. Is therefore
54 possible that this model may not be valid for other gravel barriers of the coast of the UK.

55 Field observations during overtopping or overwash conditions are extremely challenge for
56 instrumentation and safety surveying operations. To overcome this limitation, research effort
57 has been devoted to the investigation of gravel barrier dynamics in controlled laboratory
58 environments (e.g., Obhrai et al., 2008 or Williams et al., 2011). These experiments have
59 provided insights into the influence of infiltration and exfiltration processes for sediment
60 transport within the swash zone (Masselink and Turner, 2012), the role of antecedent
61 conditions (overtopping and crest build up) in reducing overwash likelihood (Matias et al.,
62 2012), and the definition of thresholds for morphological changes under varying wave
63 conditions and water levels (Matias et al., 2012).

64 These laboratory datasets have also contributed to the development of the predictive skills of
65 the processed-based numerical model Xbeach (Roelvink, et al., 2009), initially developed for
66 sandy beaches, but recently adapted for gravel beaches (XBeach-G; McCall et al., 2014 and
67 2015). This model accounts for a large number of hydrodynamic processes (e.g., wave
68 transformation, groundwater interactions, runup), together with sediment transport and
69 morphological evolution, on a wave-by-wave time scale. It allows the forecast of the
70 morphological evolution of a gravel barrier under the full range of hydrodynamic regimes
71 (swash, overtopping and overwash), and represents a important improvement over existing
72 predictive tools (McCall et al, 2013).

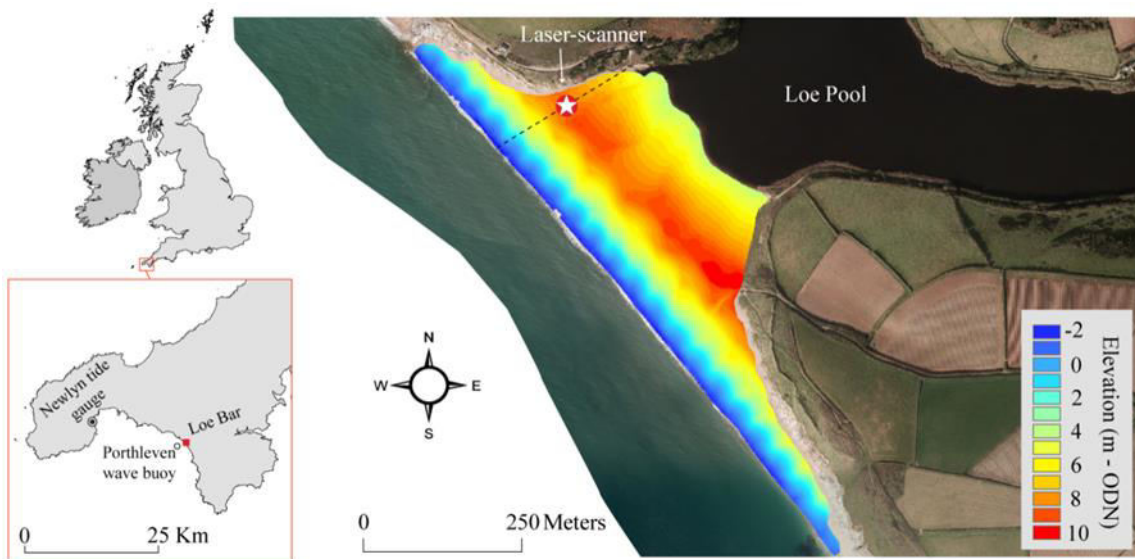
73 Recent developments in field instrumentation, particularly in remote sensing techniques, have
74 demonstrated the potential to overcome traditional limitations of field experiments on gravel
75 barriers during extreme storm conditions. More specifically, the use of 2D laser-scanners to
76 measure nearshore processes enables the acquisition of high-frequency and high-resolution
77 measurements of the hydrodynamics (e.g., water level and runup) and morphological
78 evolution under extreme storm conditions (Almeida et al., 2013, 2014 and 2015).

79 This study presents new field measurements of the hydrodynamics and morphological
80 response of a fine gravel barrier (Loe Bar, Cornwall, England) under extreme impact regimes
81 (overwash) using a 2D laser scanner. These field measurements (hydrodynamics) are
82 compared with the predictions of XBeach-G, and the validated model is used to explore
83 which hydrodynamic conditions that define the thresholds for different storm impact regimes
84 (e.g., swash, overtopping and overwash) on a fine gravel barrier.

85 2. Methods

86 2.1. Study site and field deployment

87 The field experiment was conducted on 1 February 2014 at Loe Bar in the southwest of
88 England (Figure 1) with the aim of measuring overwash dynamics (hydrodynamics and
89 morphological response) on a gravel beach during extreme storm conditions.

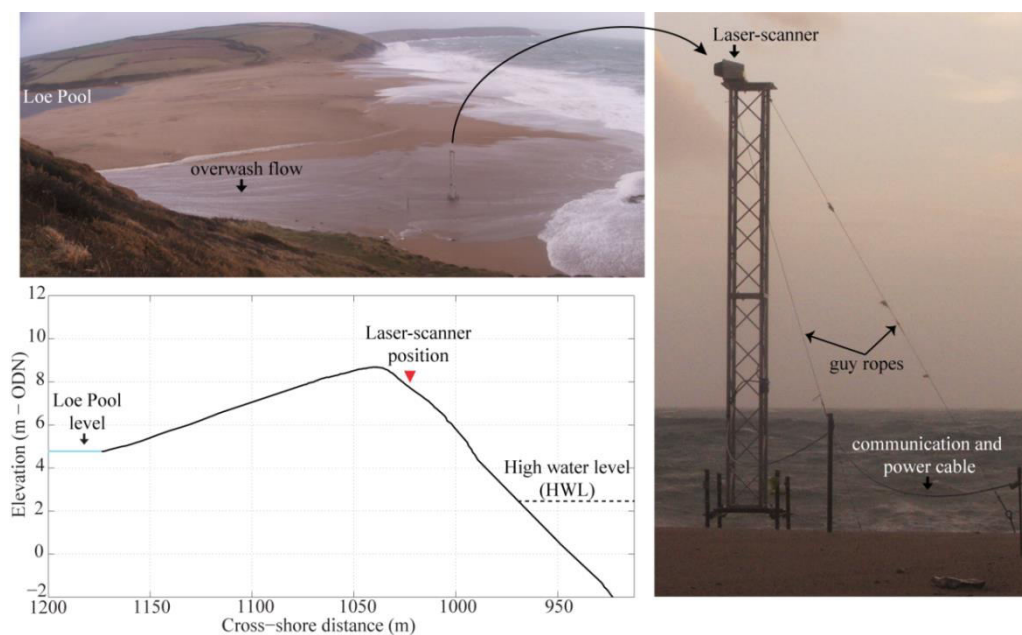


90
91 **Figure 1.** Location of the Loe Bar study site, the Porthleven wave buoy and the Newlyn tide gauge (inset maps).
92 Aerial photograph of Loe Bar with the overlap of the digital terrain model from a Lidar survey (survey
93 performed by the Channel of Coastal Observatory in 2013) with the laser-scanner position and scan profile
94 indicated.

95

96 Loe Bar is a 1 km long fine gravel ($D_{50} = 2\text{--}4$ mm) beach. The central section of the beach is
 97 backed by Loe Pool and extends 430 m between the adjacent headlands, with an average
 98 width of 250 m, a seaward gradient of 0.1, backslope gradient of 0.02 and average crest
 99 elevation of 8.7 m ODN (Ordnance Datum Newlyn). The barrier is orientated 230° (SW) and
 100 is exposed to energetic Atlantic swell and wind-waves with an annual average significant
 101 wave height (H_s) of 1.2 m, an average peak period (T_p) of 10 s and a direction (θ_{wave}) of 235°
 102 (wave statistics derived from Porthleven wave buoy measurements, October 2011 to
 103 December 2014; data freely available from <http://www.channelcoast.org>). The tidal regime is
 104 macrotidal with MHWS (mean high water spring) and MLWS (mean low water spring) at 2.5
 105 m and -2.2 m ODN respectively (Ordnance Datum Newlyn; 0 m ODN \sim 0.2 m below the
 106 mean sea level in UK).

107 A 2D laser-scanner (SICK - LD-OEM3100) was deployed on the top of an aluminium tower
 108 (5.2 m high), fixed to a scaffold frame inserted into the beach near the barrier crest and
 109 stabilized by guy ropes (Figure 2).



110

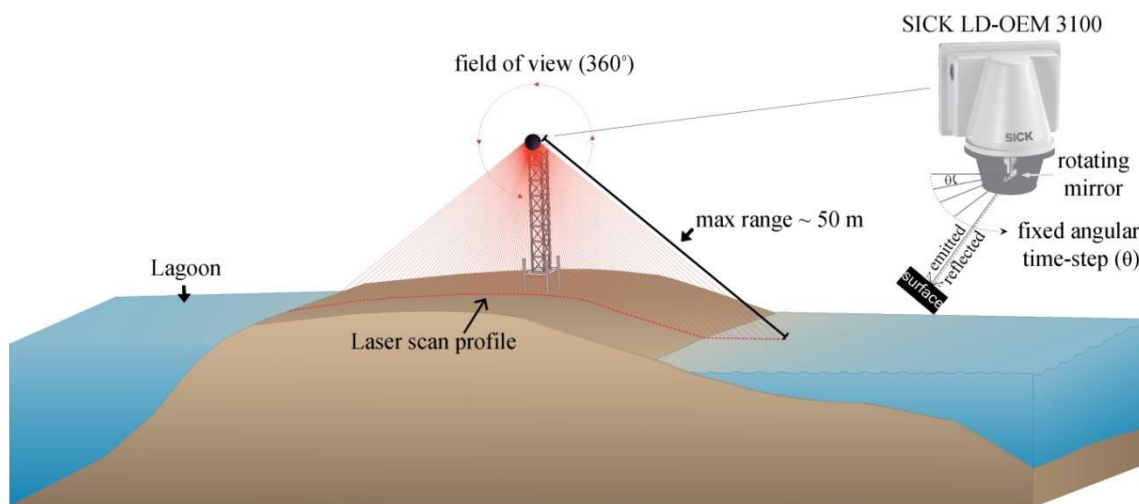
111 **Figure 2.** Field photographs showing the laser-scanner setup (right panel) and the deployment of the scanner on
 112 the crest of Loe Bar during overwash conditions (top left panel), and detailed cross-shore profile of the barrier
 113 indicating position of the laser scanner and sea and lagoon water levels (bottom left panel).

114 Offshore wave conditions were measured by the Porthleven directional wave buoy located in
115 approximately 15 m water depth at low tide (Figure 1). Due to lack of local tide
116 measurements, tide predictions for Porthleven harbour (2 km northwest of the study site)
117 were corrected by adding the meteorological tide (surge) measured at the Newlyn tide gauge.

118 2.2.2D Laser-scanner and working principle

119
120 The LD-OEM3100 (manufactured by SICK) laser scanner model was selected for the present
121 work. This model is a two-dimensional mid-range (maximum range ≈ 100 m; SICK, 2009)
122 laser-scanner that emits pulsed laser beams (invisible infrared light; $\lambda = 905$ nm) that are
123 deflected on an internal mirror (inside the scanner head) that rotates at regular angular steps
124 and scans the surroundings (360°) in a circular manner (Figure 3). The scanner head rotates at
125 2.5 Hz with an angular resolution of 0.125° and the distance to the target is calculated from
126 the time from emission to reception of the reflection at the sensor.

127



128

129

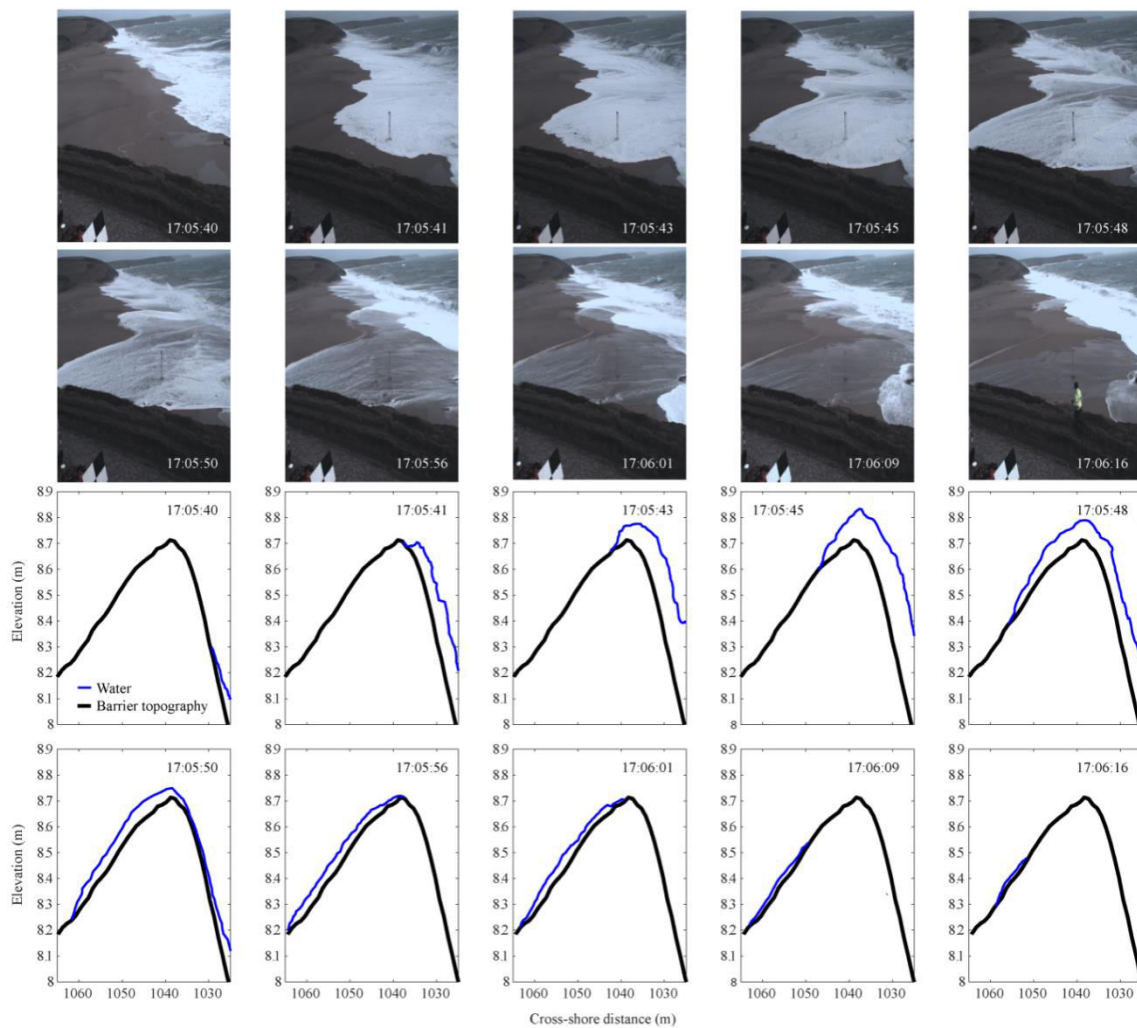
Figure 3. Sketch of the laser-scanner deployment at Loe Bar and working principles.

130

131 Measurements performed with the laser-scanner were processed following the method
132 presented by Almeida et al. (2015). After this initial data processing, the laser measurements
133 are separated in two distinct time series: (1) continuous beach topography; and (2) swash
134 hydrodynamics (including water elevation and runup edge). These time series form the basis
135 of the analysis of the present work.

136 An example of the type of measurements performed during this field experiment is shown in
137 Figure 4 and illustrates the ability of the laser-scanner in tracking the entire overwash process
138 (an overwash event is defined here as a single passage of water over the barrier crest).

139



140

141 **Figure 4.** Sequence of video snapshots (top) and corresponding laser-scanner measurements (bottom) during an
142 overwash event over the barrier.

143

144 From these observations it is possible to quantify the free surface of the entire wave overwash
145 event, including the wave runup on the beach face (17:05:40-41s – Figure 4), the overtopping
146 of the crest (17:05:43s), the wave intrusion and propagation into the back of the barrier until
147 reaching the Loe lagoon (17:05:45-56s), and the infiltration on the overwash body into the
148 gravel bed on the back of the barrier (17:06:01-16s). As the water body infiltrates into the bed
149 or returns to the sea (backwash), the surface of the barrier becomes exposed, allowing the
150 laser-scanner to quantify any morphological changes (e.g., 17:06:16s).

151 **2.3.XBeach-G model**

152 To explore the impact of the full range of hydrodynamic regimes under different freeboard
153 levels on a gravel barrier, the process-based numerical model XBeach-G (McCall et al., 2014;
154 Masselink et al., 2014; McCall et al., 2015) was first validated using the field data and then
155 implemented to investigate different forcing scenarios. This model is an extension of the
156 existing Xbeach open-source storm morphodynamic model (Roelvink et al., 2009),
157 specifically adapted for gravel beaches. In contrast to Xbeach, XBeach-G uses a one-layer,
158 depth-averaged, non-hydrostatic scheme, similar to the SWASH model (Zijlema et al., 2011),
159 that allows the solution of wave-by-wave flow and surface elevation variations due to short
160 waves in the nearshore zone. This aspect is particularly important on pure gravel beaches
161 where swash motion is mainly at incident frequencies (Buscombe and Masselink, 2006). The
162 model accounts for upper swash infiltration losses and exfiltration effects on the lower swash
163 using a newly developed groundwater model coupled to Xbeach (McCall et al., 2012). Due to
164 relatively large hydraulic conductivity of coarse sediments, infiltration\exfiltration can
165 become significantly important process (e.g., Masselink and Li, 2001). The most important
166 equations implemented in XBeach-G to solve the nearshore hydro- and morphodynamics are
167 described in McCall et al. (2014)and McCall et al. (2015).

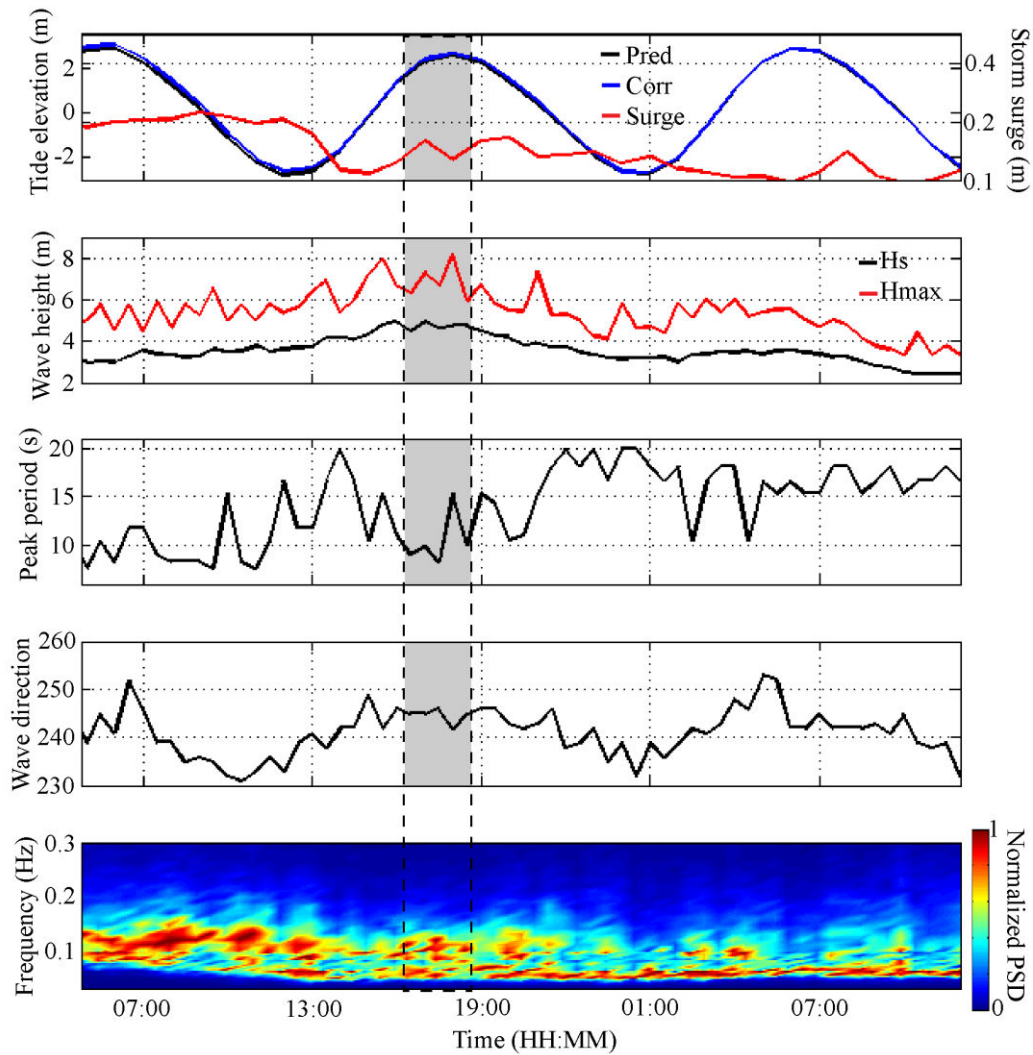
168 XBeach-G hydrodynamics (McCall et al., 2014) and morphodynamics (McCall et al., 2015)
169 have been extensively validated using laboratory (Williams et al., 2011) and field datasets
170 (Poate et al., 2013), with results showing that the model has very good skills in predicting
171 both aspects.

172 **3. Results**

173 **3.1. Field measurements: waves, tides and laser-scanner**

174 During the field experiment, storm waves from the southwest ($\sim 240^\circ$) with significant (H_s)
175 and maximum (H_{max}) wave heights of 4 m and 8 m, respectively, were recorded at offshore
176 depths (Porthleven wave buoy), with peak periods (T_p) ranging from 10 to 15 seconds (Figure
177 5). Despite the small storm surge level observed at Newlyn tide gauge (~ 0.15 m) the peak of
178 the storm coincided with the peak of a spring high tide (2.45 m), thus providing optimal
179 conditions for the occurrence of overwash events.

180 Interestingly during this storm event the offshore wave buoy recorded waves with a bimodal
181 spectrum shape (Figure 5), indicating that this event was a result of two distinct swell events,
182 one with shorter wave periods ($T \sim 10$ s) and another with longer wave period ($T \sim 16$ s –).



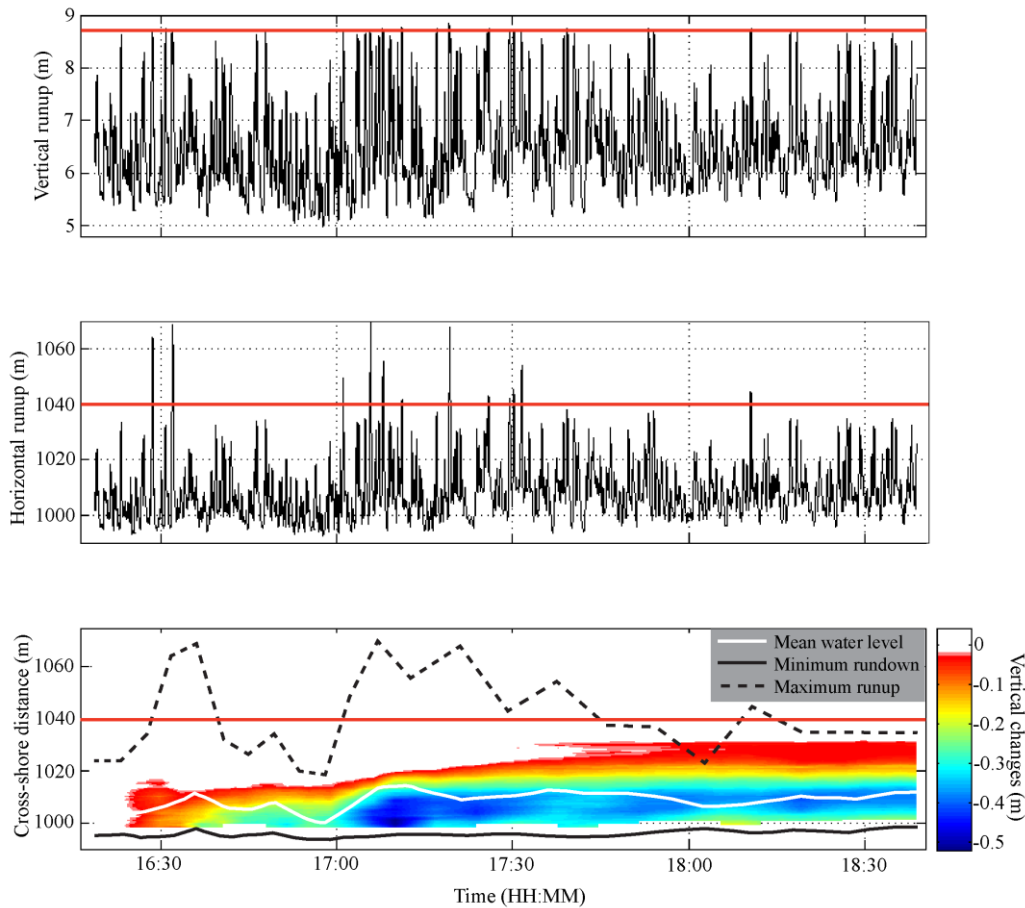
183

184 **Figure 5.** Corrected tide level (blue) and surge measurements (red) for Porthleven harbour - correction was
 185 performed by adding the surge computed at Newlyn gauge to the predicted tide for Porthleven harbour (top
 186 panel); offshore wave conditions, including significant and maximum wave height (second panel), peak period
 187 (third), wave direction (fourth panel) and normalised power density spectra of sea surface elevation (bottom
 188 panel), measured at Porthleven offshore wave buoy; shaded area corresponds to the period of time when laser
 189 measurements were performed.

190

191 The measurements performed with the laser-scanner lasted approximately 2 hours and 30
 192 minutes and covered the most energetic period of the storm, during which numerous
 193 overtopping and overwash events were observed (Figure 6). Measurements include: vertical
 194 and horizontal runup excursions (R_z and R_x respectively) and morphological response.

195



196

197 **Figure 6.** Vertical (top panel) and horizontal (second panel) runup excursions and morphology cumulative
 198 changes (bottom panel) measured by the laser-scanner. Vertical datum is ODN and horizontal coordinates are in
 199 local coordinate system (origin is located offshore at 18 m depth). Red line indicates the location of the crest of
 200 the barrier.

201

202 Time series of vertical runup show that a large number of waves reached close to the crest of
 203 the barrier (> 8 m ODN), although only a small percentage of these did actually overtop or
 204 overwash the barrier, as the time series of horizontal runup illustrate (Figure 6).

205 The cumulative morphological changes observed by the laser-scanner during this storm event
 206 show that the only significant modification of the barrier occurred on the seaward side of the
 207 barrier, with the erosion of the mid swash zone (between $x = 1000$ and 1020 m - Figure 6).
 208 The patch of erosion starts at approximately 16:30 when the first overwash events occurred,
 209 and with the rising of the tide this patch moves onshore. The peak of erosion (beach erosion

210 by about 0.5 m) occurs between 17:00 and 17:30, when a group of waves overwash the
211 barrier and also when a large number of runup events reach close to the barrier crest. Since no
212 sediment accumulation was observed at the crest or back of the barrier it is likely that the
213 eroded sediment was deposited seaward from the swash (not measured by the laser-scanner).

214 One of the most important overwash parameters in determining the potential of flooding and
215 damage on the barrier is overwash discharge. Typically this parameter is measured in the
216 field by a combination of traditional *in-situ* instruments, such as electromagnetic current-
217 meters and pressure transducers (e.g., Leatherman, 1976), although recent laboratory
218 experiments suggest that these types of measurements can be estimated by semi-remote
219 sensing methods, such as ultrasonic bed-level sensors (e.g., Matias et al., 2014). In the
220 present experiment the overwash discharge was estimated by computing the product of the
221 overwash depth (h_c), measured at the crest of the barrier, and overwash leading edge velocity
222 (u_{edge}):

223

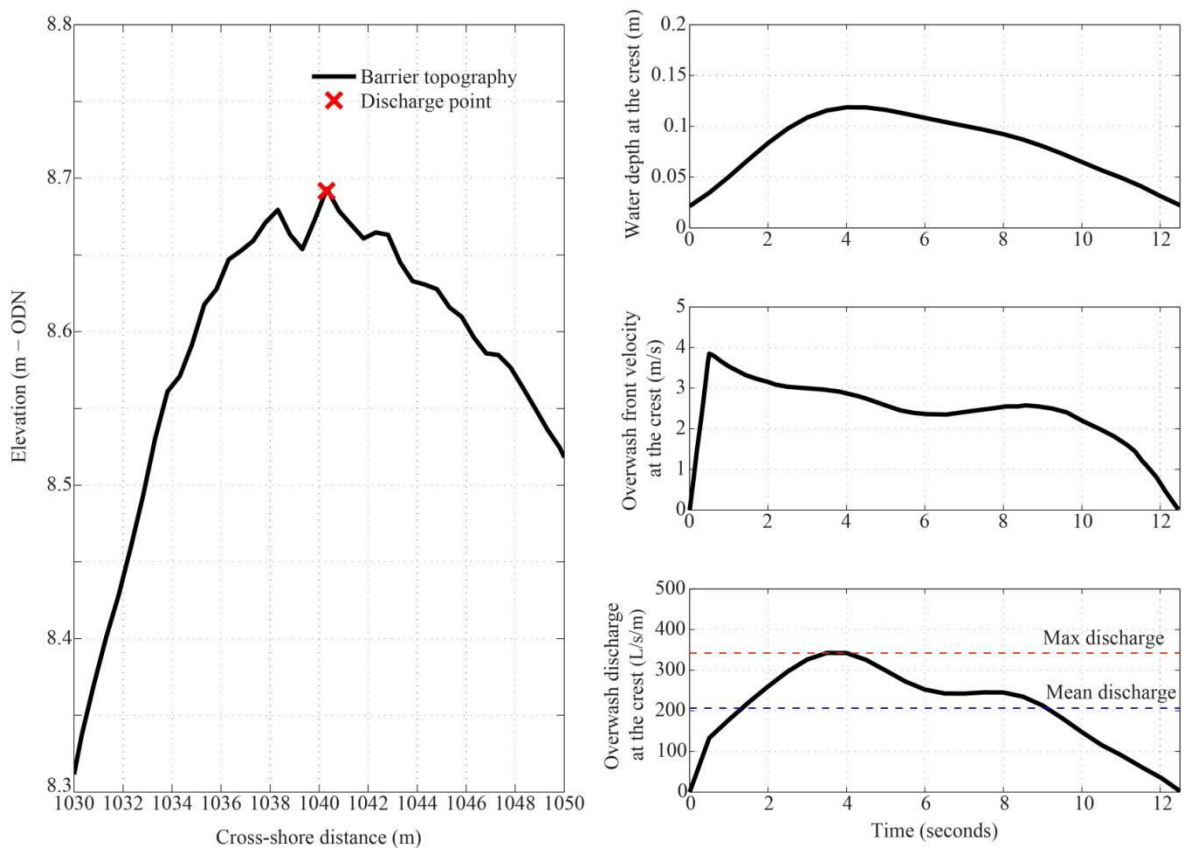
$$q_c = h_c \cdot u_{edge} \quad (eq. 8)$$

224

225 Note that this method assumes that the velocity of the leading edge is representative of the
226 velocity at the barrier crest, which might not be the case when important infiltration or
227 acceleration processes (e.g. due to changes in the backslope of the barrier) affect the
228 overwash flow velocity at the leading edge. At Loe Bar it's assumed that infiltration
229 processes and the gentle back slope will not produce such modifications on the overwash
230 flow. This method has been successfully applied by other authors on gravel (Matias et al.,
231 2014) and sandy barriers (Matias et al., *in press*).

232 For each overwash event the water depth recorded by the laser-scanner at the crest of the
 233 barrier (Figure 7) and velocity along the barrier was used to compute a time-series of
 234 overwash discharge. An example of this type of measurement is presented in Figure 7, where
 235 it is possible to observe the intrusion of one overwash event over the crest of the barrier with
 236 a duration of approximately 12 seconds, maximum water depth of 0.12 m and maximum
 237 velocity of 3.8 m/s, producing a mean and maximum overwash discharge of 200 L/s/m and
 238 333 L/s/m respectively.

239



240

241 **Figure 7.** Cross-shore barrier profile with location of the point (red cross) where overwash discharge was
 242 computed (left panel) and example time series of water elevation (top right panel), overwash front velocity
 243 (middle right panel) and estimated overwash discharge (bottom right) for a single overwash event measured by
 244 the laser-scanner.

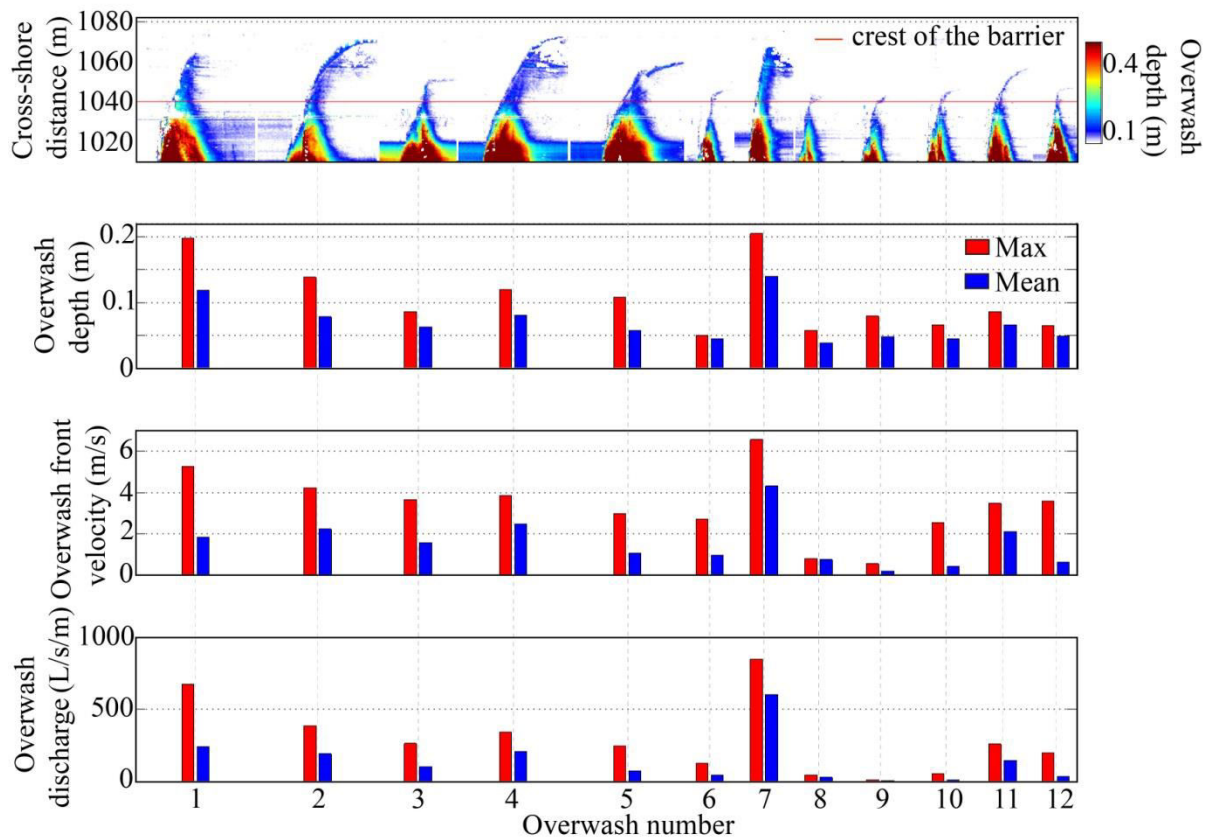
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246 The same procedure was applied to compute mean and maximum overwash discharge for all
 247 the overwash events measured by the laser-scanner (Figure 8). Results show that a variety of

248 overwash events were measured during the present field experiment, with several events
 249 overtopping the crest of the barrier but with limited horizontal intrusion across the back of the
 250 barrier (e.g., numbers 3, 6, 8, 9, 10, 11 and 12 – Figure 8), while another group had larger
 251 horizontal intrusion, reaching the Loe lagoon (overwash numbers 1, 2, 4 and 7).

252 Average overwash depths measured at the crest of the barrier ranged from 0.04 to 0.14 m,
 253 with maximum depths reaching 0.21 m, and average flow velocities varied from 0.05 to 4 m/s
 254 with maximum records reaching 6.3 m/s. These values are within the range of observations
 255 presented by Matias et al., (2014) as the result of a large laboratory experiment, although
 256 field measurements of these parameters have not been hitherto reported.

257



258

259 **Figure 8.** Characteristics of the overwash events measured by the laser-scanner: time series of overwash depth
 260 for each event (top panel); average and maximum overwash depth (second panel); average and maximum
 261 overwash front velocity (third panel); and average and maximum overwash discharge (bottom panel).

262

263 **3.2.XBeach-G validation**

264 The field measurements were used to validate XBeach-G by comparing measured and
265 modelled overwash discharge, extreme runup and the frequency of overwash events.

266 The model bed level was set to the bed measured along the laser-scanner profile, with the
267 sub-tidal section (measured by a previous bathymetric survey) of the profile extended to -18
268 m (ODN) depth (Figure 9). The cross-shore resolution of the model grid was set to vary
269 gradually in the cross-shore direction to correctly capture wave breaking and runup in the
270 model, with an approximately resolution of ~ 2–3 m at the offshore boundary and 0.1 m near
271 the waterline. The grain size properties and hydraulic conductivity of the beach used in the
272 present simulations werederived from McCall et al., 2014 (Table 1).

273

D_{50} (mm)	D_{90} (mm)	K (mm s ⁻¹)
2	3	3

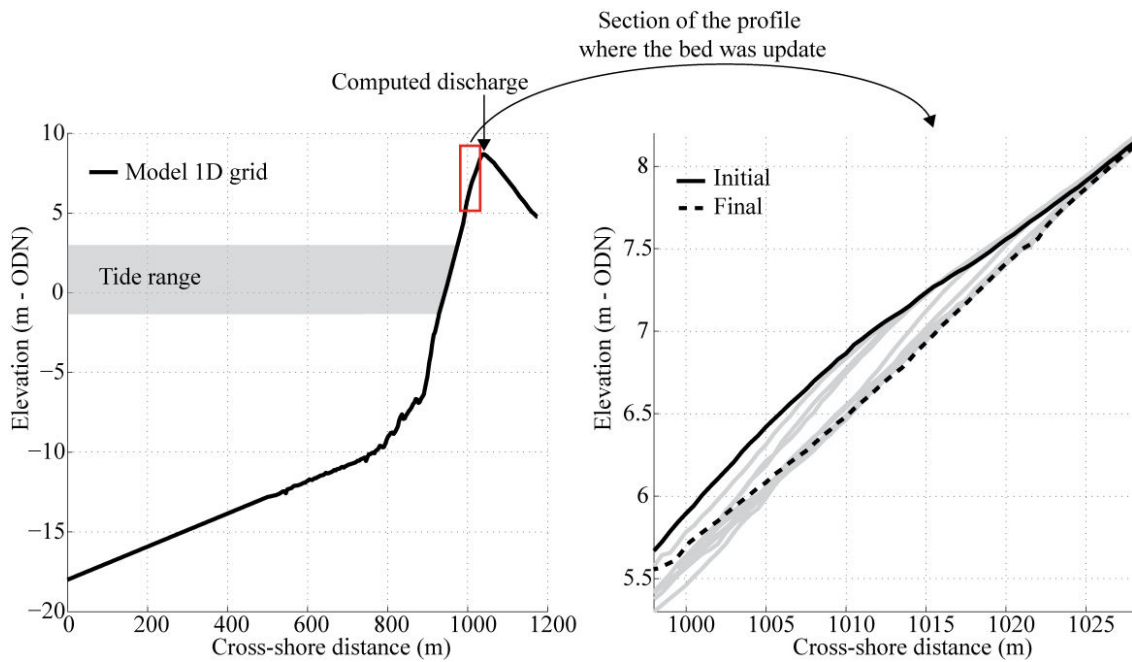
274 **Table 1.** Sediment properties used in the simulations, with grain size distributions (D_{50} and D_{90}) and hydraulic
275 conductivity (K).

276 For each simulation, the model was forced with measured wave spectra retrieved from the
277 Porthleven wave buoy, and tide predictions for Porthleven harbour, corrected for the surge
278 levels measured at Newlyn tide gauge. Note that XBeach-G uses the input wave spectrum to
279 generate a random time series of incident waves and bound low-frequency second order
280 waves at the model boundary, thus comparisons with observations on an event scale are
281 impossible.

282 To test the effect of considering groundwater interactions and morphological evolution, four
283 different model setups were prepared. For Setup 1, the groundwater module was turned on
284 and the bed was fixed during the entire duration (using the initial profile measured in the
285 field). For Setup 2, the groundwater module was on and the morphology was continuously
286 updated using the measured morphological changes along the laser-scan profile (rather than

287 computed sediment transport rate gradients - Figure 9), using the same approach
288 implemented by McCall et al. (2014). For Setup 3, the groundwater was turned off and the
289 profile bed was not updated. For Setup 4, groundwater was turned off and morphology was
290 updated as in Setup 2.

291



292

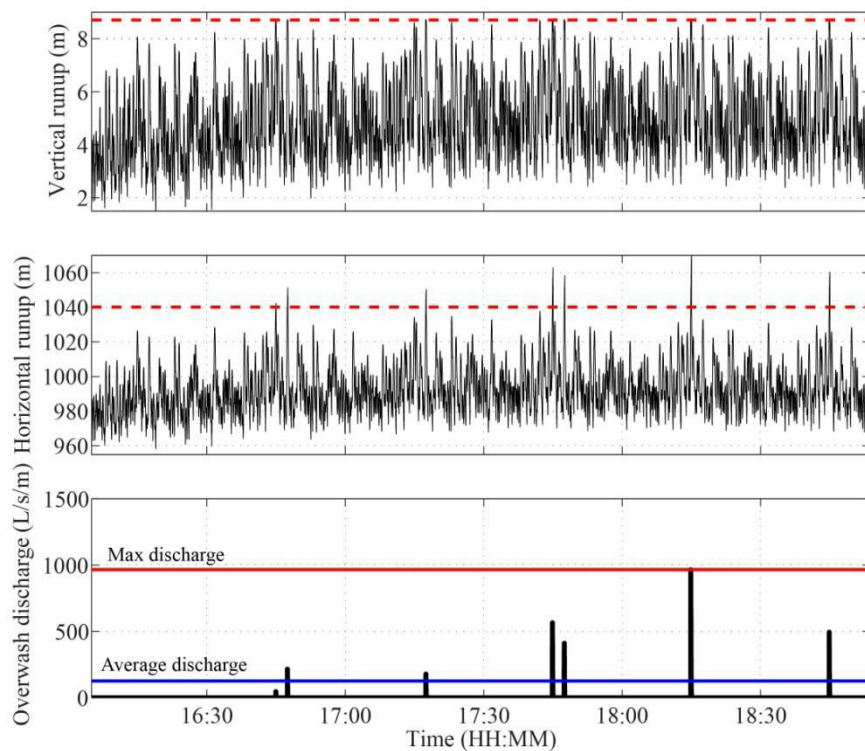
293 **Figure 9.** Cross-shore profile used for the model validation (left panel) measure before the storm event, and
294 example of the bed evolution for Setups 2 and 4 (right panel - gray lines represent the 10 minutes profile updates
295 for setup 2 and 4).

296

297 An example of the model outputs is shown in Figure 10. These results show that runup time
298 series (vertical and horizontal) present values within the range of laser measurements. It is
299 possible to verify that the average backwash limit is lower than what was observed by the
300 laser-scanner, although it is impossible to compare this aspect with the measurements, since,
301 as explained above, the laser was not able to reach the lower swash zone during this
302 experiment. Overwash discharge predictions (Figure 10) also show values within the range of
303 observations, providing a preliminary overall visual assessment of model skill.

304 In order to quantitatively compare model predictions and field observations, the following
305 parameters were computed: 1) 2% exceedance vertical runup ($R_{2\%}$), 2) number of overwash
306 events, 3) average and maximum overwash discharge, and 4) the total overwash volume
307 (computed as the integral of the discharge over the duration of each overwash event). The
308 results are presented in Table 2 and show that, in general, XBeach-G was able to reproduce
309 results close to the field observations.

310 The extreme runup predicted by XBeach-G slightly underestimates the field observations
311 (4.6% less when groundwater was on and less than 3% when groundwater was off – Table 2)
312 and therefore this was also reflected on the number of overwash events predicted by the
313 model and the total volume of water that overwashed the barrier. The only exception was the
314 model simulations using groundwater off and no bed update (Setup 3), which predicted
315 exactly the same number of overwash events as were measured in the field (Table 2).



316
317 **Figure 10** Example of XBeach-G output for the simulations with Setup 1, showing the time series of vertical
318 (top panel) and horizontal (middle panel) runup and the overwash discharge (bottom panel) computed for the
319 storm conditions observed during the present experiment. Red dashed line indicates the position and elevation of
320 the barrier crest.

321 The results show that average and maximum overwash discharge was better predicted when
 322 the model was using groundwater on and slightly overestimated the maximum overwash
 323 discharge when the groundwater was set off (Table 2).

324

	Measured	Setup 1	Setup 2	Setup 3	Setup 4
Morphology	-	fixed	update	fixed	update
Groundwater	-	on	on	off	off
$R_{2\%}$ (m)	6.5	6.2	6.2	6.4	6.3
Overwash events	12	7	7	12	10
Average discharge (L/s/m)**	140	120	100	110	70
Maximum discharge (L/s/m)**	840	960	880	1260	1210
Volume (L)	17550	9071	8485	17203	16121

325 **Table 2.**XBeach-G model validation results for the four different types of model setup.** Discharge is the
 326 average for the period of time that measurements were performed.

327

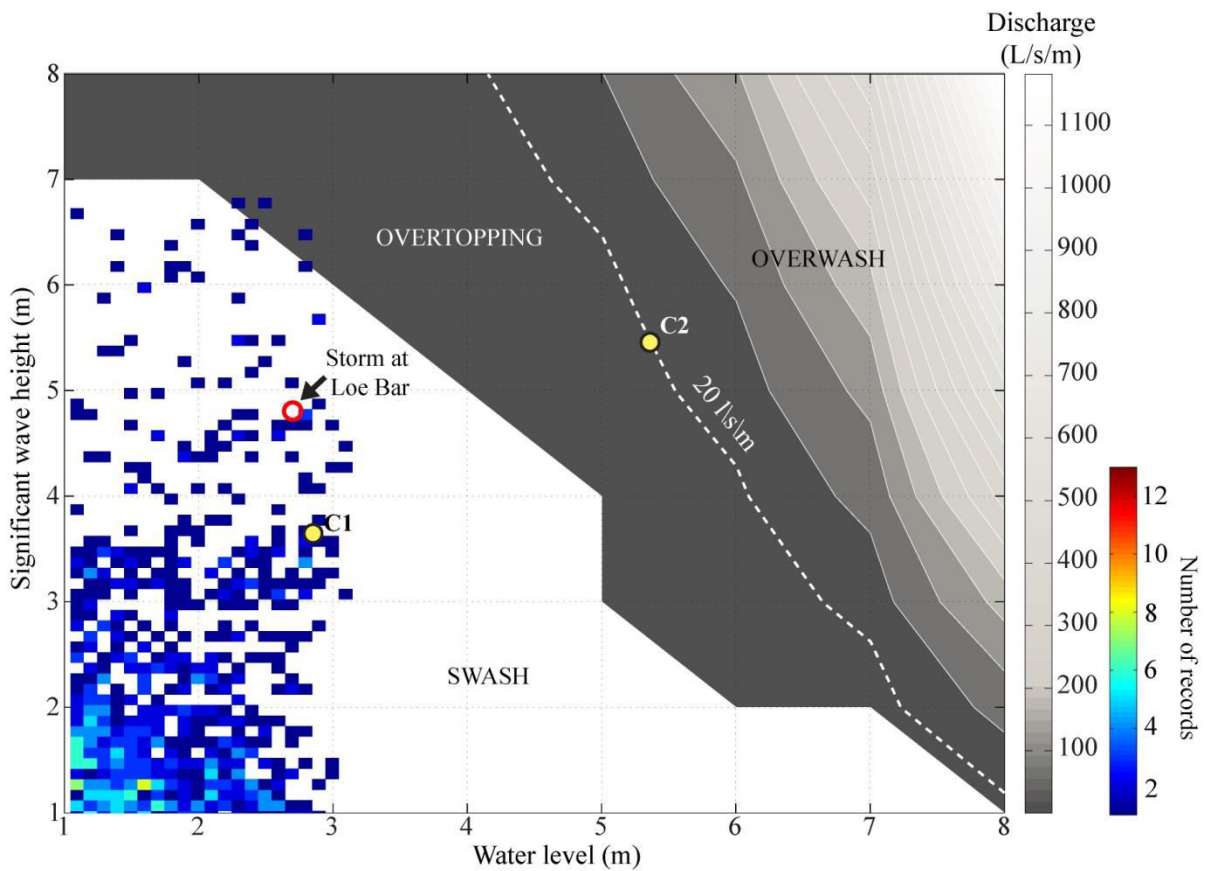
328 **3.3.UsingXBeach-G to investigate overtopping and overwashing discharge** 329 **under variable wave height and water levels**

330

331 Wave runup can exceed the barrier crest under storm and non-storm conditions, when the
 332 combination of the water levels and wave conditions allows this (Morton et al., 2000). To
 333 investigate and quantify the conditions under which the Loe Bar barrier overwashed, 64
 334 XBeach-G simulations were performed, using combinations of eight significant wave heights
 335 (H_s 1–8 m) and eight water levels (1–8), and a fixed peak wave period ($T_p = 10$ s) and mean
 336 wave period ($T_m = 8.4$ s; representing the average wave period calculated from 4 years of
 337 measurements at Porthleven wave buoy). Each model was setup using the measured pre-
 338 storm profile (Figure 9), and the forcing waves were characterized by the standard unimodal
 339 Jonswap spectrum ($\gamma = 3.3$). Each model was run for 5400 s (1 h and 30 min) with
 340 stationary water level, with the initial 1800 s used to spinup the model and the remaining
 341 3600 s for analysis.

342 Figure 11 shows the results of the simulations by means of a contour map of overwash
 343 discharge under variable water levels and wave heights. To contextualize these discharge

344 values in terms of potential damage to the barrier (e.g. damage to the crest or back of the
 345 barrier), three main hydrodynamic regimes that occur at Loe Bar barrier under storm or non-
 346 storm conditions are identified. Swash regime is representative of cases when runup is
 347 confined to the foreshore, when no overtopping is observed (white area on the map - Figure
 348 11), while overtopping and overwash regimes describe conditions when the wave runup
 349 exceeds the crest of the barrier.



350
 351 **Figure 11.** Contour map of the average wave overtopping and overwash discharge under different significant
 352 wave height and water level conditions, overlain by a bivariate histogram of measured H_s and water level for
 353 waves with $T_p > 10$ s (wave data source: Porthleven wave buoy; tide source: Newlyn tide gauge). The yellow
 354 filled circles represent the mid-regime forcing conditions for which the effect of changing wave period, spectral
 355 shape and groundwater interactions will be explored later in this work.

356
 357 To identify the boundary between overtopping and overwash regime, the approach used by
 358 McCall et al., (2013) was followed. It defines the threshold for overwash discharge based on
 359 engineering guidelines for the stability of rip-rap structures under overwash conditions.

360 According to these guidelines (Simm, 1991; Frizell et al., 1998), an average overwash
361 discharge above 20 L/s/m is expected to cause severe damage to the crest and back of the
362 barrier; therefore, that value was used here to define the threshold for an overwash regime.

363 By overlapping the joint distribution of waves and tides (based on four years of wave and
364 tide measurements, for $T_p > 10$ s) on the discharge map (Figure 11), it is clear that only a very
365 small number of actual observations lie within the overtopping domain, and none inside the
366 overwash regime. A preliminary interpretation of this result is that Loe Bar has an extremely
367 low vulnerability to overtopping and overwash events. This assumption is supported by
368 recent studies performed at this site (e.g., Poate *et al.*, 2013 or Almeida *et al.*, 2015), which
369 observed a lack of overtopping even under energetic wave conditions.

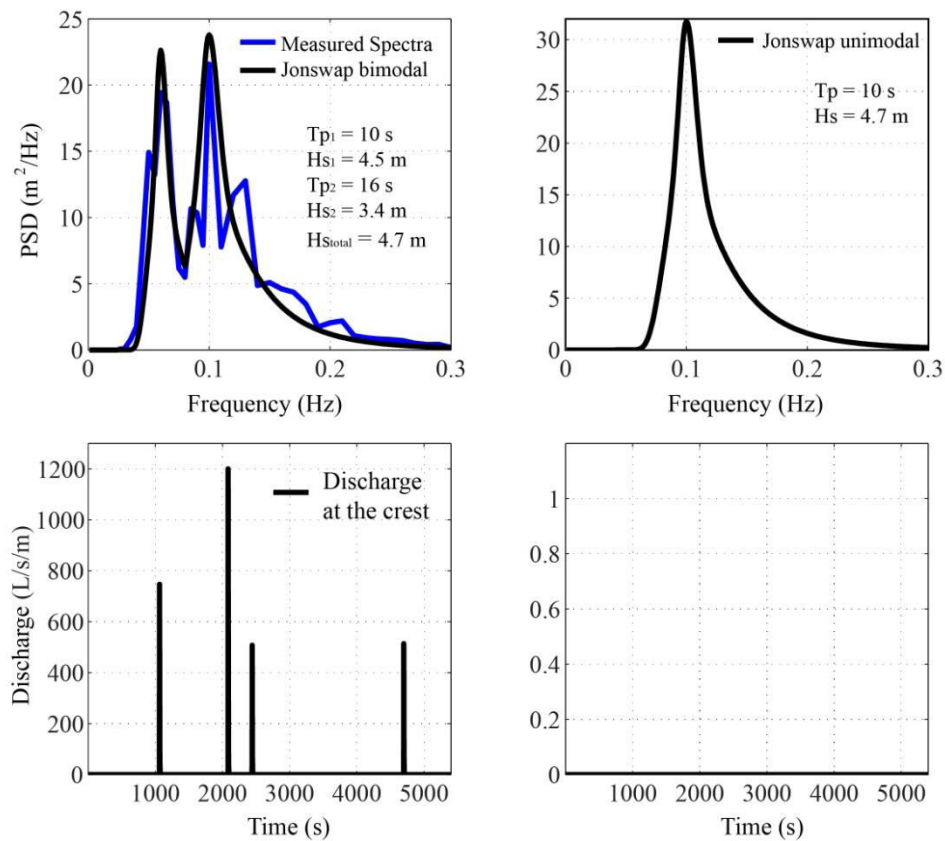
370 Interestingly, on the current discharge map, the present storm measurements fall within the
371 swash regime (red dot – Figure 11), when, according to field measurements and model
372 validation (Table 2), this result should be within an overwash regime. An important
373 difference between the model setup during the validation section and the regime analysis was
374 the fact that, in the validation section, the bimodality of the offshore wave spectrum was
375 taken in account, whereas, on the discharge map, the simulations were performed using a
376 unimodal spectrum shape.

377 Previous authors have shown bimodality of offshore wave spectra to be an important factor
378 when considering the prediction of wave runup on gravel beaches (Polidoro et al., 2013) and
379 potentially the overtopping discharge (Masselink et al., 2014).

380 To investigate why the present storm conditions do not fall within the overwash regime in
381 Figure 11, two new model simulations were performed using a bimodal Jonswap wave
382 spectrum with similar shape to the measured wave spectrum (measured at Porthleven wave

383 buoy) and another model using a unimodal Jonswap wave spectrum with equivalent energy
 384 (identical H_s and T_m - Figure 12).

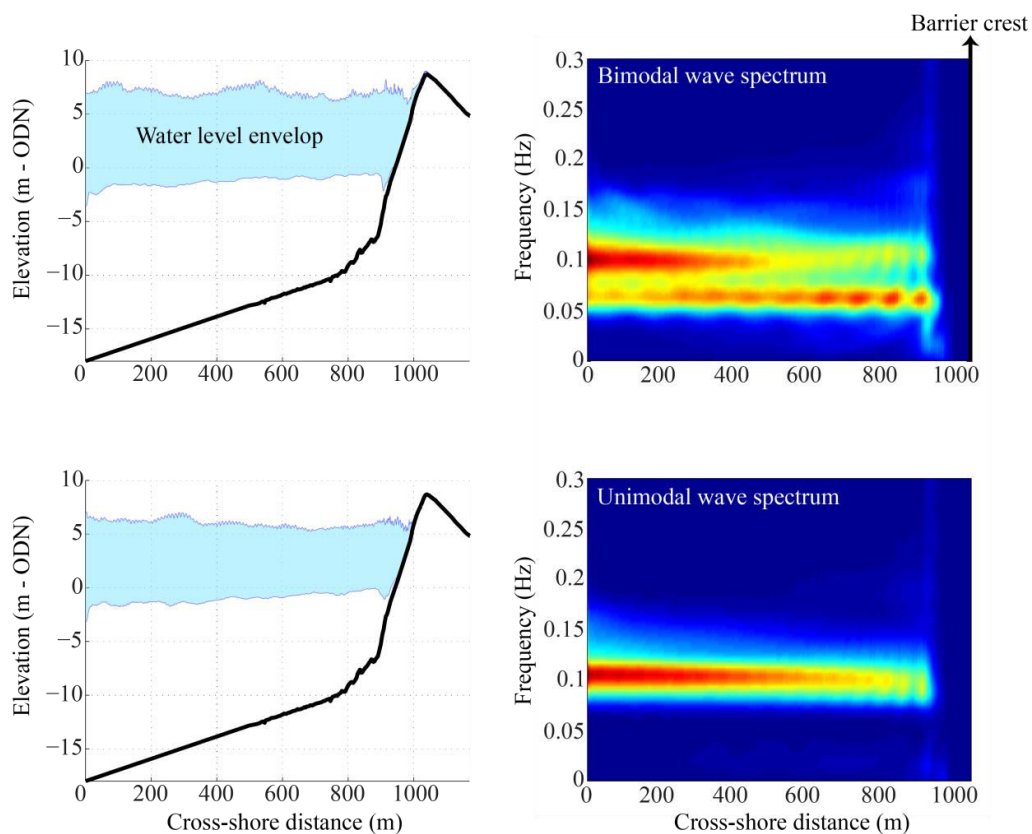
385 The results of these two model simulations show that overwash discharge at the crest occurs
 386 when the model was forced with a bimodal wave spectrum, but no discharge when a
 387 unimodal wave spectrum was used (Figure 12). This result confirms that the presence of a
 388 bimodal wave spectrum can enhance the occurrence of overwash. The fact that the present
 389 storm did not fall within the overtopping regime was merely due to the present regime map
 390 being produced with unimodal wave spectrum shape.



391
 392 **Figure 12.** Results of the overtopping discharge (lower panels) computed using a bimodal (top left panel) and
 393 unimodal Jonswap spectra (top right panel) with the same $T_m = 10$ s and $H_s = 4.5$, using gamma = 2.

394
 395 The wave spectrum was computed for each time series of water elevations predicted for each
 396 cross-shore position of the grid, and is presented in Figure 13. The results show that, for the
 397 bimodal wave forcing, the lower frequency energy increases towards the shore (from $x = 600$

398 to 900 m), whereas the shorter frequency energy dissipates. The swash zone becomes
 399 dominated by the longer period waves, producing a wider swash zone, and there is
 400 development of infragravity waves. When the model was forced with the unimodal wave
 401 spectrum, the peak period waves were dissipated significantly before reaching the swash zone
 402 (between $x = 0$ and 600 m), and swash zone width is slightly narrower than that which
 403 developed under bimodal wave spectrum. No apparent development of energy on the
 404 infragravity band was found under unimodal wave spectrum conditions and no overwash
 405 occurred. These results put also in evidence the importance of the wave steepness regarding
 406 the wave runup processes. While on the bimodal spectrum the low steepness (long period)
 407 waves dominate the swash and promote large runup excursions that overtop the barrier, on the
 408 unimodal case steeper waves (short period waves) are unable to overtop the barrier.



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411

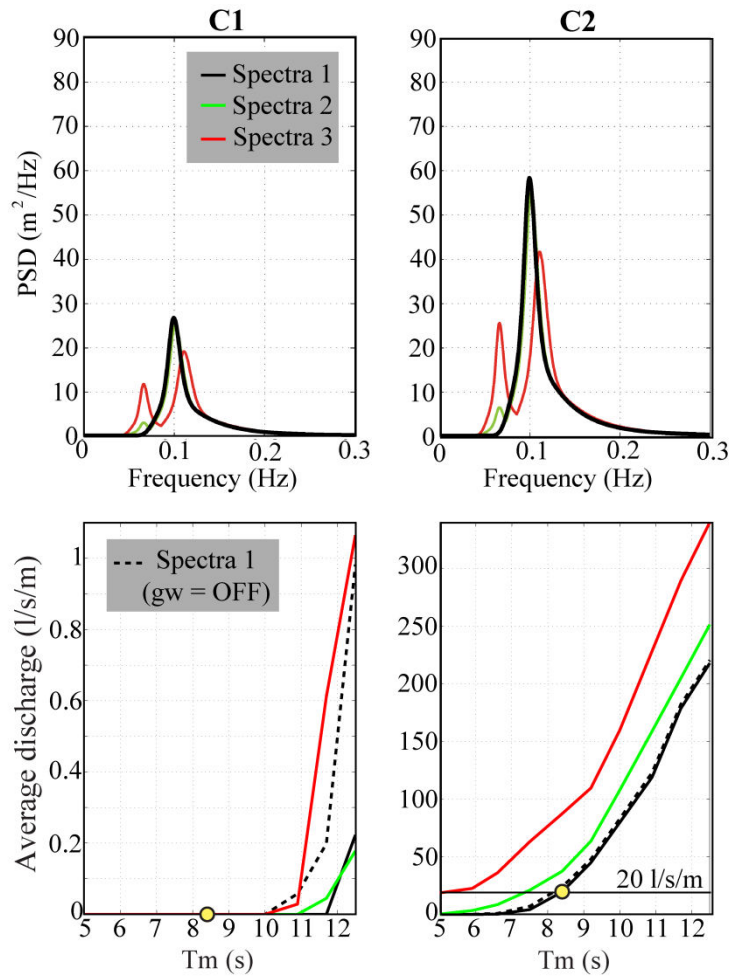
Figure 13. Wave spectrum computed for each time series of water elevations predicted for each cross-shore position of the grid from the model outputs presented in Figure 14.

412 **3.4. XBeach-G: The effect of wave period, spectral shape and groundwater**
413 **on the definition of storm impact regimes**

414

415 To quantify the effect of wave period, spectral shape and groundwater on the impact regimes
416 identified in Figure 11, a new set of XBeach-G model runs was formulated. Two categories
417 of simulations were defined (C1 and C2), and for each category a representative value of
418 water level and H_s was used as a constant during all the simulations (see filled yellow circles
419 in Figure 11). To enable a fair comparison between the different spectral shapes, the mean
420 period T_m ($T_m = m_0/m_1$), where m_1 and m_0 represent the first and zero moment of the wave
421 spectrum, respectively) was kept constant, independently of whether a bimodal or unimodal
422 spectrum was employed.

423 To test the role of wave period, a total of 20 XBeach-G models were set up (10 per category)
424 for 10 classes of T_m (from 5–12 s) using a standard unimodal wave spectrum (Figure 14). The
425 20 simulations were carried out both with and without the groundwater module turned on.
426 Finally, an additional of 60 simulations was set-up to investigate the role of spectral shapes
427 on swash and overwash dynamics. In addition to the unimodal wave spectrum, two bimodal
428 Jonswap spectra were designed by adding a long period swell ($T_{p(swell)} = 15$ s) to the unimodal
429 spectrum (Figure 14).



430

431 **Figure 14.** Shape of the three different wave spectrum tested for each category of simulations(top panels);
 432 Results of discharge under variable T_m values for the two different categories, testing different parameters:
 433 typical Jonswap spectra with groundwater ON (black line); with groundwater OFF (dashed grey line); and
 434 testing different wave spectral shapes (red, blue and green lines). The yellow dots represent the category
 435 values computed for Figure 11.

436

437 Care was taken to ensure that the addition of the long period swell peak was balanced by a
 438 reduction in the wave height and period of the short period wind peak to ensure that the
 439 significant wave height and the mean wave period remained the same. The groundwater
 440 module for these additional 90 simulations was turned on and off.

441 Each simulation was run for 5400 s (1h 30m), with the first 30 minutes to spinup the model
 442 (these data were removed from the analysis), and for each simulation the average discharge
 443 was computed at the crest of the barrier.

444 The average overwash discharge for the three different hydrodynamic regimes for variable
445 wave periods (with and without groundwater) and spectral shapes are presented in Figure 14.
446 The results show that wave period and spectral shape can produce significant modifications
447 on the predicted average discharges, and change the boundaries of the impact regimes
448 presented in Figure 11. Increasing both wave period and energy in the swell peak enhances
449 the likelihood of overtopping and overwashing, and increases overwash discharge.
450 Groundwater interactions only seem to have a significant effect on the swash regime
451 (category C1), when large T_m values are tested, but under overtopping or overwash regimes
452 (C2 simulations) the inclusion of groundwater interaction does not produce a significant
453 difference in modelled discharge (Figure 11).

454 **4. Discussion**

455 In the first section of this work, a new and unique dataset of field measurements of storm
456 runup and overwash events on a gravel barrier (Loe Bar) is presented. This dataset was
457 subsequently used to validate the XBeach-G model predictions of hydrodynamics. The
458 validated model was then used to explore the hydrodynamic conditions under which this
459 gravel barrier is exposed to different impact regimes (swash, overtopping or overwash). This
460 model analysis also included the investigation of the model's sensitivity to wave period,
461 spectral shape and groundwater dynamics.

462 **4.1. Measuring wave overtopping on a gravel barrier with a laser-scanner**

463 During this experiment, 12 overwash events were recorded by a new remote sensing
464 technique, 2D laser-scanner. The laser-scanner measurements provided coverage of an entire
465 cross-section of the barrier, enabling the detection of overwash flow from the top of the beach
466 face to the back of the barrier. Due to the limited range of this laser-scanner (~ 50 m), the
467 amount of information (e.g., backwash limit, morphological change in the lower swash zone)

468 collected from the lower beach face was small, restricting further analysis from that section
469 of the barrier.

470 Despite the lack of ground-truth validation of the present laser-scanner observations, previous
471 laboratory and field experiments have shown that this instrument enable a robust detection of
472 the swash edge (e.g., Almeida et al., 2015 or Hofland et al., 2015) and swash depth (e.g.,
473 Vousdoukas et al., 2014 or Brodie et al., 2015). It is known that the laser beam penetrates the
474 water surface to some extent and is then refracted according to Snell's law, causing a possible
475 source of errors (Streicher, 2013). The penetration depth is controlled by the turbidity and the
476 water surface roughness (Irish et al., 2006), which are two factors characteristic of
477 overtopping and overwash flows (large content of suspended sediment and turbulent foamy
478 bores). Under this conditions strong laser returns are expected to occur just at the surface of
479 the water (Vousdoukas et al., 2014).

480 Due to the absence of field observations of overwash hydrodynamics on gravel beaches
481 worldwide, the present observations may only be compared with earlier measurements
482 performed on sandy beaches or laboratory experiments. The average overwash velocities
483 measured during the present field experiment (Figure 8) are of the same order as those
484 measured in the field on sandy barriers (Leatherman, 1977; Leatherman and Zaremba, 1987;
485 Holland et al., 1991; Bray and Carter, 1992; Matias et al., 2010), where mean velocities
486 varied between 0.5 and 3 m/s, and in laboratory tests using sandy (Srinivas et al., 1992; or
487 Donnelly, 2008) and gravelly sediments (Matias et al., 2014), where average overtopping and
488 overwash velocities ranged from 0.8 and 3.6 m/s.

489 In regard to overwash depths, earlier field observations performed on sandy barriers yielded
490 peak flow depths ranging from 0.10 m to 0.7 m (Fisher and Stauble, 1977; Matias et al.,

491 2010; or Bray and Carter 1992), leaving the present observations within the lower range of
492 values (maximum depths of approximately 0.20 m – Figure 8).

493 These comparisons provide confidence that this remote sensing technique is suitable for
494 measuring these processes on gravel barriers under challenging field conditions.

495 **4.2. The use of XBeach-G to predict overtopping and overwash on a gravel** 496 **barrier**

497 Comparison between the XBeach-G predictions and the field observations presented in this
498 work show some encouraging results, that demonstrate that XBeach-G has skills in predicting
499 the hydrodynamics of this gravel barrier under storm conditions. Despite the limited number
500 of overwash events observed during this storm, the model was capable of reproducing these
501 events (with some level of under-prediction).

502 Using the most complete model setup (Setup 2 – with bed update and groundwater on), the
503 model was able to predict extreme runup ($R_{2\%}$) with only a 5 % underestimation of the
504 observations (Table 2). Modelled averages and maximum overtopping discharge at the crest
505 were also very close to what was measured in the field. Such results are in line with recent
506 validation efforts performed with XBeach-G hydrodynamics, indicating that the model is
507 capable of reproducing wave transformation, runup and overtopping with an average error <
508 10% (McCall et al., 2012; McCall et al., 2014).

509 **4.3. Defining storm impact regimes on Loe Bar**

510 The initial approach was to quantify the overtopping and overwashing discharge under
511 different combinations of water level and wave height for a certain wave period (Figure 11).

512 With this ‘map’ it was then possible to define the three boundaries, based on discharge, that
513 separate the three different impact regimes. These boundaries were defined using existing

514 engineering guidelines that relate average overwash discharge at the crest of defence
515 structures (e.g., dikes) with morphological responses.

516 The resulting impact regime diagram was then compared with the joint distribution of wave
517 height and tide level for the Loe Bar location. This comparison indicated that, according to
518 the XBeach-G model, overtopping/overwashing conditions on Loe Bar are extremely
519 unlikely because this requires unrealistically high water levels (Figure 11). An detail
520 investigation on the effect of wave spectral shape allowed to identify that wave spectrum
521 bimodality can magnify the discharge predictions and modify significantly the definition of
522 the these thresholds (Figure 14).

523 This particular aspect has been previously identified along the south coast of England as an
524 important factor linked to coastal flooding hazards (Hawkes et al., 1998; Masselink et al.,
525 2014). In the present work, this particular aspect is explored by the validated XBeach-G
526 model (Figure 10). The main difference between the unimodal and bimodal spectrum across
527 the nearshore is shown to be the differential mechanism of wave dissipation that both spectra
528 present (Figure 11). While in a bimodal spectrum the short period peak (the peak period)
529 tends to dissipate the energy before arriving to the swash (due to breaking), the long period
530 peak gains due to shoaling processes (Lorenzo, et al., 2001). The result of this differential
531 dissipation of the two peaks of the spectrum causes the long-period peak to become dominant
532 in the swash zone, increasing the vertical runup excursions and swash width (Figure 11). This
533 process is very well captured by XBeach-G numerical model (McCall et al., 2014) which,
534 beyond other important parameters, includes non-hydrostatic pressure correction term that
535 allows wave-by-wave modelling of the free surface elevation, allowing the simulation of the
536 whole wave spectrum, including variable spectral shapes.

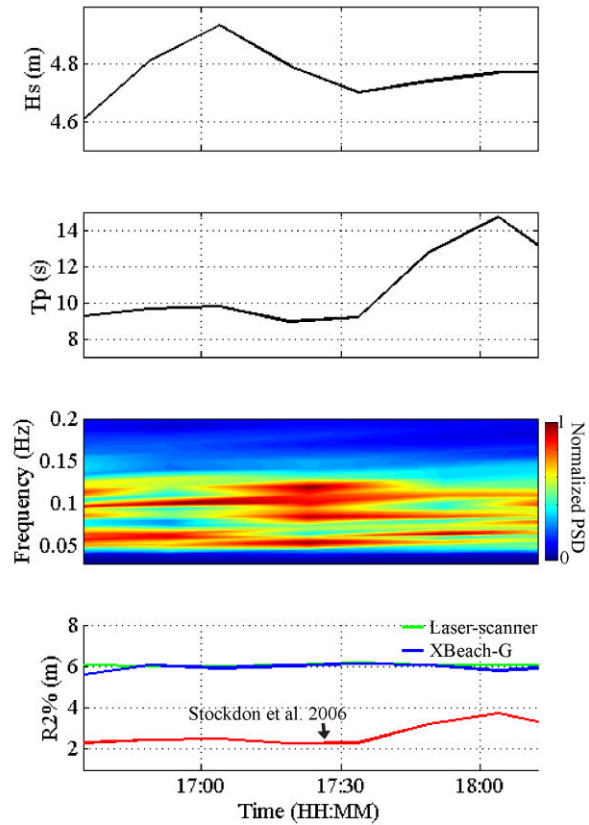
537

538 **4.4. Predicting wave runup on gravel barriers**

539 Predicting accurately the extreme runup on gravel or sandy barriers during extreme storms is
540 crucial to assess the vulnerability of these environments to destructive hazards such as
541 overwashes. On the sandy barriers across the North America the U.S. Geological Survey
542 (USGS) perform this evaluation through the application of the storm impact scale model
543 developed by Sallenger (2000), which implements the Stockdon et al. (2006) to predict the
544 storm induced maximum runup excursions. The same runup equation was recently validated
545 for gravel barriers after extensive testing of different runup equations (Matias et al., 2012).

546 Shortcomings in the application of Stockdon et al. (2006) on gravel barriers may arise from
547 aspects such as the complex nearshore or foreshore features (e.g., several berms) or the effect
548 of wave spectral shape that are not taken in consideration by this runup equation (Plant and
549 Stockdon, 2015).

550 The comparison between extreme runup observations presented in this work and predictions
551 performed with XBeach-G and Stockdon et al. (2006) runup equation show that the latter
552 (based on peak wave period) underestimates significantly the runup elevation (Figure 15).



553

554 **Figure 15.** Comparison between vertical runup observations and predictions using Stockdon et al., (2006) runup
 555 equation and XBeach-G numerical model (bottom panel), forced with 2 hours of wave measurements
 556 (performed at Porthleven wave buoy) during the measured storm; Stockdon et al., (2006) runup equation was
 557 implemented using significant offshore wave height (top panel), peak period (second panel), while XBeach-G
 558 used the full wave spectra (third panel).

559

560 Potential reasons for such evident underestimation is the fact that Stockdon et al. (2006)
 561 equation was not validated for extreme waves ($H_s > 3$ m), and very important processes such
 562 as the wave bimodality is not taken in account on this formulation. From all these reasons the
 563 latter assume particular importance since in the present work it was demonstrated with the
 564 XBeach-G model wave spectrum shape can affect significantly the forecast of wave runup.

565

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567

568 **5. Conclusion**

569 This work presents unique field observations of overtopping and overwash events during a
570 storm on a gravel barrier. These measurements allowed a validation of XBeach-G for this
571 gravel barrier, which showed great skill in predicting hydrodynamics ($< 5\%$ error) during
572 storm events where overtopping and overwash occur.

573 The boundaries between the different impact regimes (swash, overtopping and overwash)
574 were explored for a fine gravel beach, Loe Bar, using XBeach-G. Hundreds of model
575 simulations demonstrate that these boundaries are not only the result of the combination
576 between water level and wave height, but that wave period and spectral shape also play key
577 roles. Wave bimodality encourages the development of higher wave runup and wider swash
578 zones dominated by long-period water motions, enhance the likelihood of overtopping and
579 overwash, and increase the associated discharge. While short period waves dissipate most of
580 their energy by breaking before reaching the swash zone and produce short runup excursions,
581 long period waves due to their low steepness arrive at the swash zone unbroken with
582 enhanced heights (due to shoaling) thus promoting large runup excursions. When the offshore
583 wave spectrum has a bimodal shape, wave transformation in shallow water causes the long
584 period peak to dominate the swash giving large runup excursions.

585 Present modelling efforts allowed to demonstrate that on fine gravel beach like Loe Bar the
586 groundwater have limited effect on the extreme runup and definition of the thresholds for
587 storm impact regimes.

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590

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