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Dual wave farms and coastline dynamics: the role of inter-device spacing

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Abstract

In dual wave farms, i.e., arrays of wave energy converters (WECs) with a dual function – generation of renewable power and mitigation of coastal erosion – the spacing between the WECs is a fundamental design parameter. The present research has the objective of establishing how this parameter affects the shoreline evolution behind the array and, on this basis, to propose and apply a method to determine the optimum spacing for coastal protection. The method is demonstrated on a beach subjected to severe erosion. Five case studies are considered: four with different inter-WEC spacings, and one without the wave farm (baseline). A spectral wave propagation model is applied to analyse the variations in significant wave height behind the WEC array. Longshore sediment transport rates are calculated, and a shoreline model is applied. We find that in all the case studies the dry beach area is greater than in the baseline (no farm) case study, which proves the capacity of the dual WEC array to mitigate the erosive trends of the system. Importantly, we obtain that the inter-WEC spacing plays a fundamental role in the evolution of the shoreline and, consequently, in the effectiveness of the WEC array for coastal protection. The case studies with intermediate spacings yield the best performance in terms of dry beach area. More generally, the benefits of dual wave farms in terms of protection of coastal properties and infrastructure, and the ensuing savings in conventional coastal

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defence measures (coastal structures, beach nourishment, etc.) contribute to the development of wave energy by enhancing its economic viability. The methodology presented in this paper can be used to optimize the design of dual wave farms elsewhere.

Keywords: Wave energy; coastal defence; erosion; sediment transport; shoreline evolution; sustainable development

1. Introduction

In the last decade, the exploitation of renewable energy resources as sustainable alternatives to fossil fuels has received increasing research interest [1, 2]; indeed, the replacement of carbon fuels by carbon-free alternatives is one of the main challenges that society will face in the XXI century [3]. Among the different renewable energy sources, wave energy is becoming more important thanks to the extensive worldwide resource [4] and comparatively low environmental impacts [5].

Previous works on wave energy have concentrated on: the development of the technology [6–13], the assessment and characterization of the resource [14–27], the selection of potential sites [28–31], the economics [32–35], the synergies with other renewable energy sources [36–40] and the environmental impacts, as described below.

Wave farms modify wave propagation patterns and, therefore, the spatial distribution of wave heights [41–43], which may be used for erosion control and coastal protection [44, 45]. *Dual wave farms*, i.e., wave farms with the dual purpose of renewable energy production and coastal protection, have been recently proposed [46]. One of the areas where dual wave farms may be useful are deltaic coasts, which have been particularly affected by erosion in recent decades, in part due to human interventions (river damming) in their catchment areas [47–52], in part due to climate change [53–55].

The impacts of wave farms on the dynamics of sandy beaches have been extensively addressed [56–60]. However, the alterations of wave farms on mixed

24 and gravel-dominated coasts, which are common on high-latitudes and steep
25 hinterlands coasts worldwide, have been comparatively less studied. In partic-
26 ular, to our best knowledge, the effects caused by the spacing between wave
27 energy converters (WECs) on wave height and longshore sediment transport
28 (LST) have not been addressed so far.

29 This work has a fundamental objective, namely to investigate the effects
30 of the inter-WEC spacing on wave propagation, LST patterns and coastline
31 evolution. For this purpose, we applied a wave propagation model (SWAN)
32 previously calibrated for the study site; the output of this model was used to
33 assess the LST rates and, on this basis, a shoreline model was run for each case
34 study.

35 2. Study Site

36 Playa Granada is a 3-km-long gravel-dominated beach located on the south-
37 ern coast of Spain that faces the Mediterranean Sea (Figure 1). The beach
38 corresponds to the central stretch of the Guadalfeo deltaic coast and is bounded
39 to the west by the Guadalfeo River mouth and to the east by *Punta del Santo*,
40 the former location of the river mouth [61]. The deltaic coast is bounded to the
41 west by Salobreña Rock and to the east by Motril Port.

42 The Andalusian littoral of the Mediterranean Sea is characterized by the
43 presence of high mountainous relief and short fluvial streams, and the main
44 contributor of sediments to the beach is the Guadalfeo River. Its basin has
45 an area of 1252 km² and includes the highest peaks on the Iberian Peninsula
46 (~ 3400 m.a.s.l.). Consequently, the river is associated with one of the most
47 high-energy drainage systems along the Spanish Mediterranean coast [62].

48 The river was dammed 19 km upstream from the mouth in 2004, regulat-
49 ing 85% of the basin runoff [63]. The total capacity of the Rules' Reservoir
50 (117 hm³) was planned to be used for the following purposes: irrigation (40%),
51 supplies for residential developments along the coast (19%), energy generation
52 (9%), flood control (30%) and environmental flow (2%). However, the river

Figure 1: Upper left panel: Location of the study site (Guadalfeo delta, southern Spain). Central panel: bathymetric contours, grids used in the wave propagation model, position of the wave farm and location of the Salobreña Rock, Guadalfeo River mouth, Playa Granada, Punta del Santo, Poniente Beach and Motril Port.

53 damming modified the natural flow regime and altered the behaviour of the sys-
 54 tem downstream [64]. As a consequence, the deltaic coast, whose dynamics have
 55 been historically governed by the sediment supply of the river during intense
 56 events [65, 66], currently presents coastline retreat and severe erosion problems
 57 (Figure 2a).

58 The studied stretch of beach, which is occupied by an exclusive leisure resort,
 59 golf courses, restaurants and summer homes [67], has been particularly affected
 60 and has experienced higher levels of coastline retreat in recent years than both
 61 western and eastern stretches, known as Salobreña and Poniente Beach, respec-
 62 tively (Figure 1). For this reason, artificial nourishment projects have been
 63 frequently performed since the entry into operation of the dam (Figure 2b).

Figure 2: Terminal erosion (a) and renourishment works (b) in Playa Granada.

64 However, the success of these interventions has been very limited since they
 65 lasted on average less than three months [68, 69].

66 Climatic patterns at the study sites exhibit a significant contrast between
 67 summer and winter. The region is subjected to the passage of extra-tropical
 68 Atlantic cyclones and Mediterranean storms, with average wind speeds of 18-22
 69 m/s [70], which generate wind waves under fetch-limited conditions (approx-
 70 imately 300 km). The storm wave climate is distinctly bimodal with the prevail-
 71 ing west-southwest (extra-tropical cyclones) and east-southeast (Mediterranean
 72 storms) wave directions [71]. Peak significant wave heights during typical and
 73 extreme storm events exceed 2.1 m and 3.1 m, respectively [72]. The astronom-
 74 ical tidal range is ~ 0.6 m (micro-tidal conditions), whereas typical storm surge
 75 levels can exceed 0.5 m [73].

76 3. Materials and methods

77 To investigate the effects of the inter-WEC spacing, four sea states were
 78 considered with the WEC array (Section 3.1), defined as combinations of the
 79 two prevailing wave directions (E and W) and low and high energy conditions
 80 ($H_s = 0.5$ m and $H_s = 3.1$ m, with 50% and 99.9% non-exceedance probability,
 81 respectively). They were modelled by means of the joint application of the wave
 82 propagation model SWAN [74], the LST formulation proposed by [75] and the
 83 one-line model [76] considering four different case studies (Section 3.1). The

parameters for the four sea states were defined on the basis of the most frequent values of peak period and wave direction associated with the above significant wave heights (Table 1). With a view to establishing the effects of the persistence of the sea state on the trends of the coastline and dry beach area, each of the four case studies thus defined was modelled for four different values of persistence (12h, 24h, 36h, 48h).

Table 1: Parameters of the sea states modelled: significant wave height (H_s), spectral peak period (T_p) and mean wave direction (θ) in deep water.

	Low		High energy	
	East	West	East	West
H_s (m)	0.5	0.5	3.1	3.1
T_p (s)	4.5	4.5	8.4	8.4
θ ($^\circ$)	107	238	107	238

3.1. Definition of the case studies

To analyze the effects of inter-WEC spacing (S) on wave transmission, LST and the evolution of the coastline, four case studies (CS) were defined. The overtopping WEC device *WaveCat*, developed by [77], was considered, since it has been widely demonstrated to be efficient for coastal defence [43, 44, 59, 60].

The selected wave farm case studies have the same number of WECs (11) and rows (2), but different spacings between WECs: D , $2D$, $3D$, and $4D$ (Figure 3), with $D = 90$ m [58]. The geometrical centres of the defined case studies are all located at the same position (Figure 1), which was found to be optimum from the standpoint of the wave power available to the WECs [31]; whereas the selected number of WECs and layout have been proved to be adequate for coastal protection purposes in recent years [43, 58, 78, 79].

3.2. Wave propagation model

Wave transmission from deep water to the nearshore was computed by means of the SWAN model [74]. This model was previously calibrated and validated

Figure 3: Definition of the four case studies.

for the study site by [68] through comparison with hydrodynamic data measured during extensive field surveys.

The two computational grids used for the calibration and validation process, shown in Figure 1, were also used in this work. Grid I is a coarse 82×82 -cell grid covering the deltaic region, with cell sizes varying from 170×65 m to 80×80 m. Grid II is a finer nested grid of 244×82 cells covering the area of the wave farm location, with cell sizes of about 25×15 m. This finer grid allows modelling properly the effects of the wave farm on wave propagation. The spectral resolution of the frequency space consisted of 37 logarithmically distributed frequencies ranging from 0.03 to 1 Hz; whereas for the directional space 72 directions in increments of 5° were considered to cover the 360° .

The interaction between WECs and wave field was modelled through the transmission (K_t) and reflection (K_r) coefficients, which were chosen on the basis of physical modelling of the *WaveCat* [9] and numerical modelling of the interaction between the wave farm and the wave field [43, 44, 59, 60]. The Motril

Port and the Guadalfeo river jetties were also modelled as artificial obstacles. Based on the results from the wave model, two main tasks were performed: the role of the inter-WEC spacing in wave transmission was established, and the wave breaking variables were determined for the application of the LST formulation (Section 3.3).

To quantify the changes in the significant wave height at breaking with respect to the natural (no farm) case study, the non-dimensional significant wave height reduction was used. This parameter is defined as,

$$\eta = 1 - \left(\frac{H_{s,br}}{H_{s,br0}} \right), \quad (1)$$

where $H_{s,br}$ and $H_{s,br0}$ stand for the breaking significant wave height, respectively, in the case study in question and in the baseline.

3.3. Longshore sediment transport formulation and one-line model

LST rates were quantified through the following formulation, which was proposed by [75]:

$$Q_m = 0.00018 K_{swell} \rho_s g^{0.5} (\tan \beta)^{0.4} (D_{50})^{-0.6} (H_{s,br})^{3.1} \sin(2\theta_{br}), \quad (2)$$

where Q_m is the LST rate; $\tan \beta$ denotes the slope of the beach profile in the surf zone; K_{swell} represents the swell factor, which measures the effects of swell on the LST rate; D_{50} and ρ_s stand for the size and density of the sediment; g is the gravitational acceleration; and $H_{s,br}$ and θ_{br} denote, respectively, the significant wave height and the wave angle with respect to a line normal to the coastline under breaking conditions. The latter parameters were determined through the propagation model for 341 evenly distributed beach profiles (with a spacing of 20 m between consecutive profiles) along the shoreline between Salobreña Rock and Motril Port (Figure 1).

Changes in LST rates produced by the wave farm with respect the baseline case study were assessed by means of the non-dimensional LST rate reduction (τ), defined as,

$$\tau = 1 - \left(\frac{Q}{Q_0} \right), \quad (3)$$

145 where Q_0 and Q are, respectively, the LST rates in the baseline case and the
 146 case with wave farm under consideration.

147 The coastline evolution and the values of dry beach surface for the defined
 148 wave conditions (Table 1) and case studies (Figure 3) were quantified through
 149 the one-line model, which computes the changes in the shoreline position based
 150 on the LST gradients. The model is based on the following equation [76]:

$$\frac{\partial y_s}{\partial t} = \frac{1}{D} \left(-\frac{\partial Q_t}{\partial x} \right), \quad (4)$$

151 where y_s is the shoreline position, Q_t is the LST rate (in m^3/s) and D is the
 152 sum of the height of the berm and the closure depth. The coupled numerical
 153 scheme used in this work (SWAN model, LST formulation of [75] and one-line
 154 model) was proven in previous work [68], versus field data, to successfully model
 155 the variation of the coastline in Playa Granada. In the cases of non-calibrated
 156 numerical models, it could be advisable to perform sensitivity analysis to check
 157 the uncertainty of the model results depending on the variations in the input
 158 parameters, e.g. with Monte Carlo simulations.

159 To analyse the effects of the inter-WEC spacing with respect to the natural,
 160 no-wave farm case study, we used as indicator the non-dimensional shoreline
 161 advance (v), defined as,

$$v = \frac{\Delta y - \Delta y_0}{\max(|\Delta y_0|)}, \quad (5)$$

162 where Δy_0 and Δy represent the displacement of a point on the coastline, re-
 163 spectively in the baseline and the case under consideration.

164 4. Results

165 4.1. Wave propagation patterns

166 In this section, the impacts caused by the dual WEC array on wave trans-
 167 mission are analysed. The inter-WEC spacing is found to play a relevant part
 168 (Figure 4). Under high energy, W waves, a more compact array results in a more
 169 pronounced and narrower wake, i.e., smaller wave heights but concentrated near
 170 Punta del Santo (Figure 4a1-a2). When the inter-WEC spacing is larger, the

171 wake of the array is less pronounced, for the wakes of the individual WECs do
 172 not merge with one another (Figure 4a3-a4).

Figure 4: Ratio of the significant wave height in each of the wave farm cases (H_s) to the baseline (H_{s0}); from top to bottom, case studies 1 - 4; W (a, left) and E (b, right) high energy conditions.

173 Under high energy, E sea states, a similar behaviour is observed, with a
 174 higher reduction in wave height for the first two case studies, in particular in
 175 the vicinity of the Guadalfeo River mouth (Figure 4b1-b2). The wakes of the
 176 individual WECs merge under E waves, resulting in a more pronounced wake
 177 (Figure 4b1-b4).

178 Under W waves, the greatest reduction is achieved in the east part of the
 179 beach, near Punta del Santo, with CS1 producing the highest impact in this
 180 zone for both low and high energy conditions (Figure 5a2-a3). However, CS2

181 to CS4 lead to a more pronounced attenuation mid-beach under low energy
 182 conditions.

183 Considering each case in turn, the overall impact on Playa Granada may be
 184 quantified in relative terms (relative to the breaking wave height in the baseline)
 185 by means of the alongshore average of the non-dimensional significant wave
 186 height reduction, η (Table 2). Under W waves the impact is considerably greater
 187 in low energy sea states than in high energy conditions. In low energy conditions,
 188 CS2 leads to the greatest wave height reduction, with $\bar{\eta} = 18\%$, whereas CS4
 189 produces the lowest impact ($\bar{\eta} = 16\%$). Under high energy conditions, $\bar{\eta}$ values
 190 are significantly lower, with CS1 leading to the highest reduction ($\bar{\eta} = 1.3\%$),
 191 followed by CS3 ($\bar{\eta} = 1.15\%$).

Figure 5: Aerial photograph of Playa Granada (a1-b1). Alongshore variation of the non-dimensional significant wave height reduction under W (a) and E (b), low energy (2) and high energy (3) conditions.

192 By contrast, under E waves there is little difference in the overall impact be-

193 tween the low and high energy conditions. For low energy sea states, a greater
 194 attenuation is achieved in the western part of the beach, with the impact de-
 195 creasing eastwards (Figure 5b2). The highest alongshore-averaged reduction
 196 under low energy conditions is induced by CS4 ($\bar{\eta} = 21\%$, Table 2), since in
 197 this case the reduction is extended until Punta del Santo (Figure 5b2). On the
 198 contrary, CS1 leads to the lowest value of the alongshore-averaged reduction
 199 ($\bar{\eta} = 16\%$). Under high energy conditions, the highest impact is produced in
 200 the central part of Playa Granada, decreasing both eastwards and westwards
 201 (Figure 5b3). The highest alongshore-averaged reduction ($\bar{\eta} = 17\%$) is obtained
 202 for CS2, followed by CS1 ($\bar{\eta} = 16\%$), whereas CS3 and CS4 produce the lowest
 203 impact, with $\bar{\eta} = 14\%$ and $\bar{\eta} = 12\%$, respectively.

Table 2: Longshore average of the non-dimensional significant wave height reduction ($\bar{\eta}$).

	Low energy		High energy	
	West	East	West	East
CS1	17%	16%	1.3%	16%
CS2	18%	19%	1%	17%
CS3	17%	20%	1.15%	14%
CS4	16%	21%	1%	12%

204 4.2. Longshore sediment transport

205 As for the wave height at breaking, under W waves the wave farm causes
 206 LST rates to decline primarily in the vicinity of Punta del Santo (Figure 6a2-a3),
 207 in particular under low energy conditions. In fact, under high energy conditions
 208 the attenuation in wave heights around the Guadalfeo mouth is negligible (CS3
 209 and CS4) or even negative (CS1 and CS2).

210 The overall impact of the wave farm on the sediment transport patterns may
 211 be quantified by means of the alongshore average of the non-dimensional LST
 212 rate reduction (τ), hereafter denoted by $\bar{\tau}$ (Table 3). In low energy conditions,
 213 the greatest decline in LST rates ($\bar{\tau} = 42\%$) occurs in CS3, followed by CS4, CS2
 214 and CS1 ($\bar{\tau} = 33\%$). Under W, high energy sea states, the wave farm is less

215 effective at attenuating longshore sediment transport. The most pronounced
 216 attenuation occurs in CS4 ($\bar{\tau} = 11\%$) and CS3 ($\bar{\tau} = 10\%$), with a mere $\bar{\tau} = 2\%$
 217 in CS1.

Figure 6: Aerial photograph of Playa Granada (a1-b1). Alongshore variation of the non-dimensional LST rate reduction (τ) under W (a) and E (b), low energy (2) and high energy (3) sea states.

218 Under E waves, LST rate reduction patterns follow the trends of the signifi-
 219 cant wave height in the surf zone, with maximum reductions in the west part of
 220 the beach, decreasing eastwards in low energy conditions; by contrast, in high
 221 energy conditions this most pronounced reduction occurs in the central area of
 222 the beach (Figure 6b2-b3). Considering the entire beach, CS4 generates the best
 223 overall results under low energy conditions ($\bar{\tau} = 59\%$, Table 3), followed by CS3
 224 ($\bar{\tau} = 54\%$), CS2 ($\bar{\tau} = 48\%$) and CS1 ($\bar{\tau} = 40\%$). Under high energy conditions,

225 the best case study in terms of coastal protection is CS2 ($\bar{\tau} = 45\%$), followed
 226 by CS3 and CS1, whereas CS4 provides the worst protection ($\bar{\tau} = 37\%$).

Table 3: Longshore average of the non-dimensional LST rate reduction ($\bar{\tau}$).

	Low energy		High energy	
	West	East	West	East
CS1	33%	40%	2%	40%
CS2	40%	48%	5%	45%
CS3	42%	54%	10%	42%
CS4	41%	59%	11%	37%

227 4.3. Shoreline position

228 In this section, the results concerning the changes in the shoreline position,
 229 obtained by means of the LST rates presented in the previous section and the
 230 one-line model, are analysed. Accretionary responses with respect to the natural
 231 case study dominate under low energy conditions (Figure 7). CS1 and CS2, with
 232 a smaller spacing between WECs, lead to the maximum accretion with respect
 233 the baseline in the east part of the beach (Figure 7a1-a2). However, in CS3
 234 and CS4, formed by WECs with a longer spacing between them, the accretion
 235 with respect to the natural case study is lower at the east of the beach, but
 236 an accretionary response is also observed in the central part of Playa Granada
 237 (Figure 7a3-a4).

238 The alongshore averages of the non-dimensional shoreline advance ($\bar{v}$) were
 239 also computed (Table 4). Results show that under western low energy condi-
 240 tions, CS1 provides the best performance with $\bar{v} = 9.6\%$, followed by CS2 and
 241 CS3. Finally, the worst results are obtained with CS4 ($\bar{v} = 7.3\%$). Under east-
 242 ern waves, results are similar in the four case studies, with accretion dominating
 243 in the westernmost area of Playa Granada and less important changes in the
 244 rest of the beach (Figure 7b1-b4). Regarding the alongshore-averaged values,
 245 CS3 and CS2 lead to the best performance in terms of coastal protection with

Figure 7: Alongshore variation of the non-dimensional shoreline advance, W (a) and E (b) low energy conditions.

246 $\bar{v} = 10.6\%$ and $\bar{v} = 10.2\%$, respectively, whereas CS1 and CS4 provide the worst
 247 results (Table 4).

248 Non-dimensional shoreline advance values are lower under W, high energy
 249 conditions (Figure 8a1-a4). Accretion dominates in mid-beach, with erosion at
 250 both the eastern and western boundaries of the beach for CS1 and CS2. In CS3
 251 and CS4, with greater inter-WEC spacings, some accretion occurs also in the
 252 E section. The greatest advance occurs in CS2 ($\bar{v} = 3.2\%$), followed by CS3,
 253 whereas in cases CS1 and CS4 the wave farm is slightly less effective (Table 4).

254 Under E, high energy conditions, in CS1 the wave farm leads to mid-beach
 255 accretion and erosion to the east and west (Figure 8b1). In the other case
 256 studies, the accretionary zone reaches the east limit of the beach (Punta del
 257 Santo). In CS2 and CS3 the greatest alongshore-averaged values are obtained,
 258 with $\bar{v} = 6.3\%$ and $\bar{v} = 6.0\%$, respectively (Table 4); conversely, in CS1 the

Figure 8: Alongshore variation of the non-dimensional shoreline advance, W (a) and E (b) high energy conditions.

259 wave farm performance is rather discrete ($\bar{v} = 1\%$).

260 4.4. Dry beach surface

261 The shoreline position changes, obtained by means of the one-line model and
 262 presented in the previous section, may be used to establish the trends of the
 263 dry beach surface respect to the baseline case study (Figure 9), so that positive
 264 values of the dry beach surface represent coastal protection induced by the wave
 265 farm. Under low energy, W waves, CS1 provides the best results in terms of
 266 coastal protection, with an additional surface area of 1.9 m^2 ; at any rate, the
 267 protection is of the same order of magnitude in the other cases: CS2 (1.8 m^2),
 268 CS3 (1.6 m^2) and CS4 (1.4 m^2). Under low energy, E conditions, the differences
 269 are lower and the maximum values – best protection – are obtained for CS2 and
 270 CS3.

Table 4: Longshore average of the non-dimensional shoreline advance ($\bar{v}$).

	Low energy		High energy	
	West	East	West	East
CS1	9.6%	8.5%	2.5%	1%
CS2	8.8%	10.2%	3.2%	6.3%
CS3	8.0%	10.6%	2.9%	6.0%
CS4	7.3%	9.5%	2.4%	4.0%

271 As expected, the greatest dry beach area differences are obtained under
 272 high energy conditions (Figure 9a2-b2). Under western waves, CS2 provides the
 273 greatest difference (17.4 m²), followed by CS3 (15.9 m²), whereas CS1 and CS4
 274 lead to the worst results (14.2 m² and 13.3 m², respectively). Regarding the
 275 high energy, E conditions, CS2 and CS3 induce similar area differences (34.5 m²
 276 and 33.1 m², respectively), CS4 produces a dry beach surface difference of 22
 277 m² and, finally, the worst results are obtained with CS1 (6.2 m²).

Figure 9: Temporal evolution of the dry beach surface difference between each case study and the baseline for low energy (1), high energy (2), W (a) and E (b) conditions.

278 4.5. Overall performance of the wave farm in the case studies

279 On the basis of the previous data, the effectiveness of the dual wave farm
 280 depends on the energy content of the sea state (high energy vs. low energy)
 281 and, even more importantly, on its mean direction (eastern vs. western). For
 282 the purpose of quantifying the coastal protection effectiveness of the farm in
 283 the different case studies, in this section the indicators concerned are pondered
 284 according to the occurrence of E and W, low energy and high energy conditions,
 285 over the last 25 years. This period of time was chosen as representative of
 286 the typical life cycle of a wave farm, following [8] or [80], among others. The
 287 indicators weighted by the occurrence of the respective wave conditions are
 288 denoted by the subindex w (η_w , τ_w , v_w , ΔA_w).

289 The maximum values of the weighted non-dimensional significant wave height
 290 reduction (η_w) occur in the central part of the beach for CS1 and CS2 (Figure
 291 10c), and in the west part for CS3 and CS4, with a greater spacing between
 292 WECs. In all case studies, the minimum values are observed in the east end of
 293 Playa Granada. Alongshore-averaged weighted values show that CS2 and CS1
 294 have the best overall performance, with $\overline{\eta_w} = 9\%$ and $\overline{\eta_w} = 8.9\%$, respectively.
 295 CS3 achieves an alongshore-averaged weighted value of 7.5%, whereas CS4 leads
 296 to the worst performance ($\overline{\eta_w} = 6.3\%$).

297 A similar behaviour is obtained for the weighted non-dimensional LST re-
 298 duction (τ_w). Again, in cases CS1 and CS2 the largest values occur in the
 299 central part of the beach, while in CS3 and CS4 the maxima occur towards the
 300 west (Figure 10d). In this case, CS3 provides the best overall performance with
 301 $\overline{\tau_w} = 26\%$, followed by CS2 and CS4 ($\overline{\tau_w} = 25\%$ and $\overline{\tau_w} = 24\%$). Finally, the
 302 lowest alongshore-averaged weighted value is obtained for CS1 ($\overline{\tau_w} = 21\%$).

303 According to the values of the weighted non-dimensional shoreline advance
 304 (v_w), in CS1 accretion dominates in the central stretch, whereas erosion prevails
 305 in both east and west ends (Figure 10e). In the other cases erosion is limited
 306 to the west part of the beach. This erosion zone is narrower in CS3 and CS4,
 307 although the maxima of the weighted non-dimensional shoreline advance are
 308 lower in these cases than in CS1 and CS2. Alongshore-averaged values show

Figure 10: (a,b) Aerial photograph of the beach; (c) η_w (weighted value of η); (d) τ_w (weighted value of τ); (e) v_w (weighted value of v); and (f) ΔA_w (weighted value of ΔA) in the four case studies.

that the best performance in terms of increased dry beach area occurs for CS2 ($\overline{v_w} = 4.7\%$), followed by CS3 ($\overline{v_w} = 4.5\%$), CS4 ($\overline{v_w} = 3.3\%$) and CS1 ($\overline{v_w} = 1.8\%$).

Finally, the overall impact on the dry beach surface of Playa Granada is shown in Figure 10f, where it is observed that accretion with respect to the baseline dominates for all case studies. CS1, with the smallest inter-WEC spacing, yields the worst overall performance, with a dry beach surface increase of a mere 10.2 m^2 . Conversely, the best results occur in CS2 ($\Delta A_w = 25.9 \text{ m}^2$), followed by CS3 ($\Delta A_w = 24.5 \text{ m}^2$). Finally, CS4 shows that when the inter-

WEC spacing is increased beyond a certain threshold, the coastal protection performance of the wave farm decreases significantly ($\Delta A_w = 17.6 \text{ m}^2$).

5. Discussion

Wave power is poised to play a fundamental part in the decarbonisation of the energy mix. For wave energy to be produced in sufficient quantity, WECs will be deployed in wave farms. Along with the research focused on developing new WECs and improving the performance of existing devices, the effects of wave farms on the shoreline must be investigated. These effects may be used in coastal areas subjected to erosion to alleviate this problem; in other words, wave farms may have a dual function: carbon-free power production and coastal erosion control.

Recent research on the impacts of a wave farm on the coastline has focused on the general layout of the farm [78] and its position alongshore [79]. There was a knowledge gap in relation to one of the fundamental design variables of a wave farm, the inter-device spacing, and in particular to the manner in which the effects of the farm on the coastline are conditioned by it – and therein lies the motivation of this work.

In other words, the focus of this work was the manner in which the capability for coastal erosion control of a dual wave farm depends on the spacing between its WECs, in particular in the case of a gravel-dominated beach. With this purpose, modifications in wave propagation between the baseline and four case studies with different inter-WEC spacings were determined using the SWAN wave propagation model. The case studies analysed do not cover the full range of possibilities, and this research should be continued to explore more values of inter-device spacing.

Another aspect of note is the characteristics of the beach itself. Playa Granada is a gravel-dominated beach, and the results of this work cannot be extrapolated to beaches with different sedimentologies. Along the same S Mediterranean coast of Spain are examples of sandy beaches which could be selected

347 for this purpose.

348 6. Conclusions

349 For wave energy to become a fully-fledged renewable, the current under-
350 standing of the environmental effects of wave farms, i.e., arrays of wave energy
351 converters, needs to be enhanced. In this context, this work dealt with the
352 question of how the inter-device spacing affects the evolution of the coast in the
353 lee of the wave farm.

354 A number of case studies with different inter-device spacings were considered.
355 The interaction of the wave field with the farm, its propagation to the coast and
356 its effects on the coastline were modelled using state-of-the-art tools. Based
357 on these results, longshore sediment transport rates were determined and the
358 one-line was applied to determine shoreline evolution. Finally, *ad hoc* non-
359 dimensional indicators of the performance of the dual wave farm for coastal
360 erosion control were applied.

361 The sea state was found to affect the performance of the dual wave farm. In
362 the case of W waves, a smaller inter-WEC spacing results in a more pronounced
363 wake of the farm and, consequently, a more pronounced reduction in the sig-
364 nificant wave heights in the surf zone and the LST rates. Conversely, a greater
365 spacing reduces the impact of the farm on the shoreline.

366 In the case of E waves, and due to the position of the wave farm vis-à-
367 vis the beach, the effect of the farm on the beach is more intense, whether
368 it be in terms of significant wave heights in the surf zone or LST rates. The
369 differences between case studies, less marked than under W waves, are as follows.
370 A smaller inter-WEC spacing leads to accretion in a narrow stretch and erosion
371 elsewhere. With greater inter-WEC spacings, this erosion is mitigated, but the
372 concentrated accretion is also weaker.

373 The values of the increase in dry beach area (ΔA_w) show that the best
374 performance is achieved with intermediate inter-WEC spacings, i.e., $2D$ and
375 $3D$ (corresponding to case studies CS2 and CS3, respectively). Indeed, these

case studies lead to the greater increases in weighted dry beach surface ($\Delta A_w = 25.9 \text{ m}^2$ and $\Delta A_w = 24.5 \text{ m}^2$, respectively). CS1, with the smallest inter-WEC spacing (D), results in accretion concentrating in a narrow stretch, with significant erosion elsewhere. Finally, CS4, at the other extreme of inter-WEC spacing ($4D$), results in weaker accretion and, overall, a weaker gain in dry beach surface than CS2 and CS3. Based on these results, CS2 (inter-WEC spacing, $2D = 180 \text{ m}$) emerges as the best option in terms of coastal protection among those studied in this work.

The methodology proposed here, coupling a wave propagation model with a longshore sediment transport formulation and a shoreline model, can be used as an optimization tool for the application of dual wave farms to coastal erosion control.

Finally, dual wave farms, i.e. wave farms that fulfill the functions of energy production and coastal protection, may be expected to contribute to: the progress of wave power, by increasing its viability through savings in conventional coastal protection measures, e.g., detached breakwaters, groynes, beach nourishments; and thus, more generally, to the decarbonisation of the energy mix.

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