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Effectiveness of Dune Reconstruction and Beach Nourishment to Mitigate Coastal Erosion of the Ebro Delta (Spain)

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Abstract: Coastal areas facing increasing erosion are resorting to sand displacement strategies to mitigate the erosive impact, which is exacerbated by climate change. In the face of climate change, coastal managers are more frequently resorting to sand displacement strategies to recover eroding coastlines. These vulnerable coastal zones require innovative approaches to minimize the need for frequent sand replenishment, extend their effectiveness and lower their maintenance expenses. This study undertakes a comparison of four primary nourishment strategies—a conventional uniform nourishment technique and the placement of a single sand dune evaluated at three different positions—in contrast to a scenario where no intervention is carried out. The investigation employs the XBeach numerical model to assess the outcomes of these diverse strategies under both low- and high-energetic storm conditions. The case study is a degraded coastal beach in the Ebro Delta (Spain). The results reveal a significant decrease in erosion when the dune is positioned closest to the shoreline. However, this erosion mitigation effect diminishes as the dune is situated further inland. Conversely, the sand nourishment measure exhibits minimal fluctuations in the volume of eroded sand when compared to the scenario with no intervention.

Keywords: coastal restoration; coastal resilience; nature-based solution; coastal dunes; nourishment; Ebro Delta; XBeach; beach erosion

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1. Introduction

Sea storms are natural phenomena which are characterized by an increase in the mean water level together with higher energetic wave conditions than usual. These conditions usually produce beach erosion and coastal flooding, increasing the risk in highly pressured coastal areas such as the Mediterranean [1]. Climate change is expected to increase those impacts: the most probable scenario forecasted by the IPCC [2] is a Sea-Level Rise (SLR) of +0.84 m (a.s.l) by the end of the century. In addition, climate change will increase the frequency and intensity of storms and thus the risk of coastal flooding and erosion [3,4].

Anthropic impacts on coastal areas play a significant role in this scenario, using the beach to place urban settlements, to extract minerals and groundwater that contribute to the subsidence phenomenon [5,6], and to carry out human activities such as agriculture and grazing, leisure activities and tourism. In some cases, humans have altered the entire coastal system by introducing structures along the physiographic unit (i.e., ports, breakwaters, groynes) or on its relative watershed (i.e., dams), interrupting the sediment transport [7].

In this regard, Nature-based Solutions (NbS) can have positive and sustainable effects on human well-being and biodiversity by protecting against natural calamities and restoring natural or modified ecosystems [8], and can be a valuable alternative to traditional gray engineering interventions.

In this context, the restoration of coastal dunes is of great value. Coastal dunes are sand deposits, usually located at the back of a berm, which constitute an important coastal ecosystem. They play an important role in providing habitats for biodiversity [9], in the carbon sequestration process [10], in coastal protection from erosion—exchanging sand with the submerged beach under storm conditions—and natural hazards [11,12], as well as from wind, onshore aeolian transport and salt spray [13].

In the past, coastal dune restoration was considered only where they would have a positive impact on the hinterland land use. However, in recent years, dune restoration has been aimed not only at recovering fragile and degraded ecosystem functionalities [14], but also at addressing problems like flooding and beach erosion in sensitive coastal areas.

Harley and Ciavola [15] used the hydro-morphodynamic model XBeach coupled with the meteo-marine operational forecast system of Emilia-Romagna (Italy) to propose a real-time coastal inundation Early Warning System for this coastline. They also used the DuneMaker tool to show how the combination of coastal inundation predictions and the modeling of different "what if" scenarios, in terms of artificial dune placement, could provide a decision-making tool for coastal managers.

Silva et al. [16] carried out experiments in a wave flume, testing two different beach–dune systems (with or without berm) forced by mild, moderate or intense storm wave conditions. Various vegetative coatings (none, low, medium and high) were tested. Their results suggest that the response of the dune to the storm depends on the erosion mode. When the erosion mode is swash, the dune cedes sediment to the beach profile; this material can be deposited at the toe of the dune or at the submerged part of the profile, generating a small bar, or may even be lost further from the closure depth. On the other hand, when the erosion mode is overwash, the sediment is carried to the back part of the dune. Moreover, they found out that vegetation can reduce the volume of material lost by the dune, especially for swash and collapse erosion modes.

De Winter and Ruessink [17] performed the process-based model XBeach to analyze the effect of SLR and offshore wave angles on the 1:10,000-year dune erosion event for two representative beach profiles along the Dutch coast. Results suggest that larger water levels in front of the dune and offshore wave angles cause an increase in the erosion volume. Moreover, adding sand to the beach profile with an amount equal to the water volume increase (due to SLR), considerably reduces the eroded sand volume. However, the ratio of reduction to the total added volume remains low, for all mitigation options. The authors suggest that directly increasing the volume of sand in the dunes may be more efficient from a morphological perspective.

Fernández-Montblanc et al. [18] used XBeach, including a vegetation energy-dissipation module, to evaluate the effectiveness of a natural dune system as a potential green-based solution to address coastal erosion issues and the risk of flooding in the Bellocchio nature reserve (Italy), under vegetated and non-vegetated dune conditions, and current and future sea-level rise scenarios.

A few years later, at the same location, Unguendoli et al. [19] used XBeach to investigate the effectiveness of two NbS (i.e., dune restoration and seagrass meadow) to mitigate coastal flooding and erosion under various historical storms. Their results suggest that the synergic effect of the two NbS improves the capacity to mitigate both inundation and coastal erosion. The presence of seagrass meadows greatly reduces the incoming wave height, and therefore the flooded areas and maximum inundation depths, as well as the beach erosion volume. The artificial dune can lead to a even higher mitigation in terms of inundation of the lagoon, also avoiding any morphological variations behind it.

Likewise, Musumeci et al. [20] investigated the effects of vegetation to mitigate coastal flooding under present and climate change scenarios at the south-eastern Sicilian coastal lagoon and wetland area of Cuba-Longarini. Using the numerical model XBeach, a restoration intervention including a plantation of *Phragmites Australis* in the estuary area and an extension of the vegetated dune strip for the entire coastline of Granelli. Authors underline that the presence of revegetation contributes to the reduction of flooded volumes.

The extension of the dune strip intervention also contributes positively, reducing the flooding in the proximity of the urban center.

Fontán-Bouzas et al. [21] examined beach topographic data, collected by high-frequency field surveys, to analyse the wave impact on the 2300 m long-shore Mira beach-dune system on the Portuguese coast over the winter 2016–2017. That study focused on evaluating the beach-dune vulnerability to the wave impact, identifying the locations where total water level reached the dune toe causing sand removal from it and the locations where overwash of the dune crest occurred.

Although much literature concerns nourishment made by (re-)constructing an existing coastal dune system and its advantages, a comparison between such a practice and different sand displacement alternatives, like a nourishment on all the emerged beach profile, is absent in literature. In fact, this kind of framework would be useful for a preliminary assessment of nourishment interventions to better optimize sand displacement, and might help decision makers to select the best option against erosion for a certain coastal fringe.

The aim of the present work is to study different coastal nourishment options that can be used to protect the coast from erosion and to evaluate their effectiveness through numerical modelling. The effects of two storm conditions—low and high energy—will be studied on five different baseline scenarios: the actual state of the coast, which will be used as a benchmark; homogeneous sand nourishment along the entire nourished beach; construction of a single dune, placed at three different positions from the shoreline. To allow a consistent analysis, the amount of the displaced sand will be the same for each intervention scenario.

All the five scenarios will be studied using the numerical model XBeach to investigate the effect of the shape, distance and volume of the sand nourishment over the erosion patterns under different wave conditions.

2. Case Study

The case study is the beach of La Marquesa, a sandy beach located on the Ebro Delta, in the north-east of the Iberian Peninsula (Figure 1a). It lies within the Natural Park of the Ebro Delta, which belongs to the municipality of Deltebre (11,482 inhabitants ca.). La Marquesa beach is limited on the south-eastern side by Gola de Pal (mouth of the Bassa de l'Estela depression), and to the north-west by the entrance to the Fangar Peninsula.

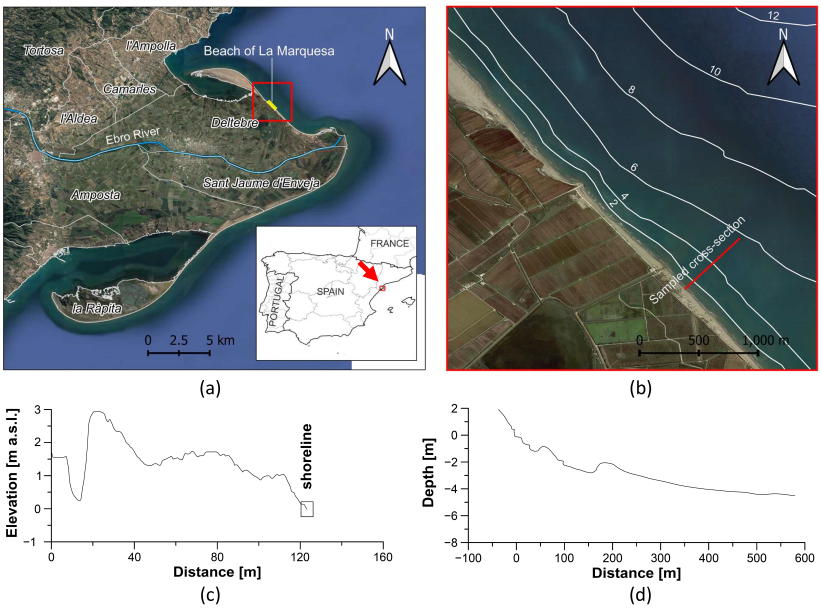

Figure 1. (**a**) Plan view of the Ebro Delta and the beach of La Marquesa, in yellow. (**b**) Bathymetry at the beach of La Marquesa (source: Navionics.com [22]) and identification of the sampled submerged

profile [23], in red. (**c**) Emerged profile of the beach (source: ICGC [24]). (**d**) Submerged beach profile (source: Guillen and Palanques [23]).

The Ebro Delta is a wave-dominated micro-tidal environment with a tidal range of approximately 0.25 m. Wave heights can easily be 97 cm in winter and 63 cm in summer, but these values can be also exceeded by a factor of 5 under extreme wave conditions [25].

From a hydrodynamic point of view, such a coastal fringe is exposed to waves mainly coming from the east and with a significant wave height H_s of 0.84 m, on annual average. This forcing action increases to 5.57 m and 7.39 m when considering a return period equal to 10 and 100 years, respectively [24].

After several centuries of growth, the evolutionary trend of the Ebro Delta changed to erosive a few decades ago [26–28]. This was mainly due to the almost total reduction of river sediment discharges due to the construction of dams in the lower course of the Ebro river [29,30]. Currently, the Ebro Delta is mainly subject to reshaping processes [25]. As a direct consequence, the beach of La Marquesa, which in the past had a solid coastal dune system [31], has been significantly eroding at an estimated rate of 6.38 m/year [24], resulting in the disappearance of the dune strip [32].

3. Materials and Methods

3.1. Data

The main characteristics of La Marquesa beach have been obtained by ICGC [24]. This beach is oriented at 144° N and it is characterised by very well sorted fine sand (8.3% medium sand, 90.1% fine sand, and 1.6% very fine sand). Figure 2 displays the grain size distribution reported on 3 November 2008 by CIIRC, in which it is also specified that D_{50} is equal to 203.5 µm and D_{90} is equal to 247.9 µm.

The beach of La Marquesa experiences waves with a significant height H_s as seen in Section 2. From those values it is possible to obtain the peak period by using the relationship proposed by Boccotti [33]:

$$T_p = 8.5\pi\sqrt{\frac{H_s}{4g}} \quad (1)$$

where g is the gravitational acceleration.

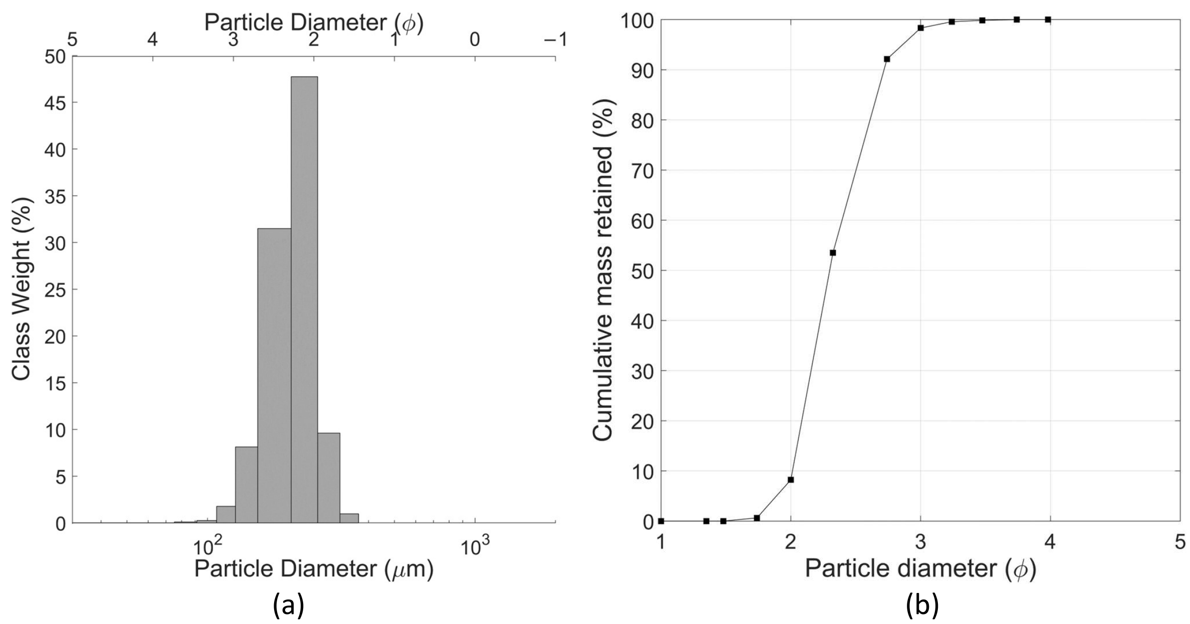

Figure 2. (**a**) Grain size distribution for the sediments at the beach of la Marquesa. (**b**) Cumulative grain size distribution for the same sediments. Both graphics are adapted starting from the report of 3 November 2008 by the CIIRC [24].

According to Bolanos [34], who analyzed 20 years of data collected by the XIOM (Xarxa d'Instrumentació Oceanogràfica I Meteorològica) buoy network, the mean storm duration in the Ebro Delta is 20 h. Martzikos et al. [35] analysed wave conditions data recorded between 1985 and 2019 from 30 buoys in the Mediterranean Sea, finding that the average duration of storms in this area is less than 30 h. On the other hand, Amarouche et al. [36], using a SWAN model, estimated the duration of storms on the "Balearic Basin"area, where the Ebro Delta is located, was from 43 to 52 h over the last four decades.

In this work, the cross section of the beach was constructed from two profiles. The first one is a sampled exposed beach profile (Figure 1c) measured by the cartographic institute on 3 November 2008 [24]. The latter is the submerged beach profile in Figure 1d, sampled by Guillen and Palanques [23] during a survey in 1990–1991 all around the Ebro Delta, whose location is identified in Figure 1b. This last profile presents a littoral bar with a crest height of 1 m, located 200 m from the shoreline.

3.2. Model Setup

XBeach is an open-source, 2DH model that solves the coupled cross-shore and alongshore equations for wave propagation, circulation patterns, sediment transport and bottom changes for sandy coastal systems under changing sea state [37,38]. This numerical model can be used to compute fine sediment transport, both on the emerged and submerged beach; in particular, it can simulate avalanche processes, dune erosion and overtopping, and dune notch formation, which are required for the purposes of the present work.

The computational grid used to run the XBeach numerical model for all the simulations has a cross-shore ($\vec{X}$) extension of 4505 m and a longshore ($\vec{Y}$) extension of 100 m, and the shoreline in still water conditions is placed at $x = 4155$ m. Figure 3 shows this grid for the benchmark case, which will be discussed further in the next subsection. The dimension of the grid meshes, i.e., the resolution of the domain, changes along the two directions. For the cross-shore step Δx, it varies according to the following six regions: from 0 m to 3770 m, $\Delta x = 10$ m; from 3770 m to 4135 m, $\Delta x = 5$ m; from 4135 m to 4155 m, $\Delta x = 2$ m; from 4155 m to 4250 m (i.e., the intervention region), $\Delta x = 1$ m; from 4250 m to 4285 m, $\Delta x = 5$ m; from 4285 m to 4505 m, $\Delta x = 10$ m.

On the other hand, the longshore step Δy is kept constant at 5 m along the longshore direction.

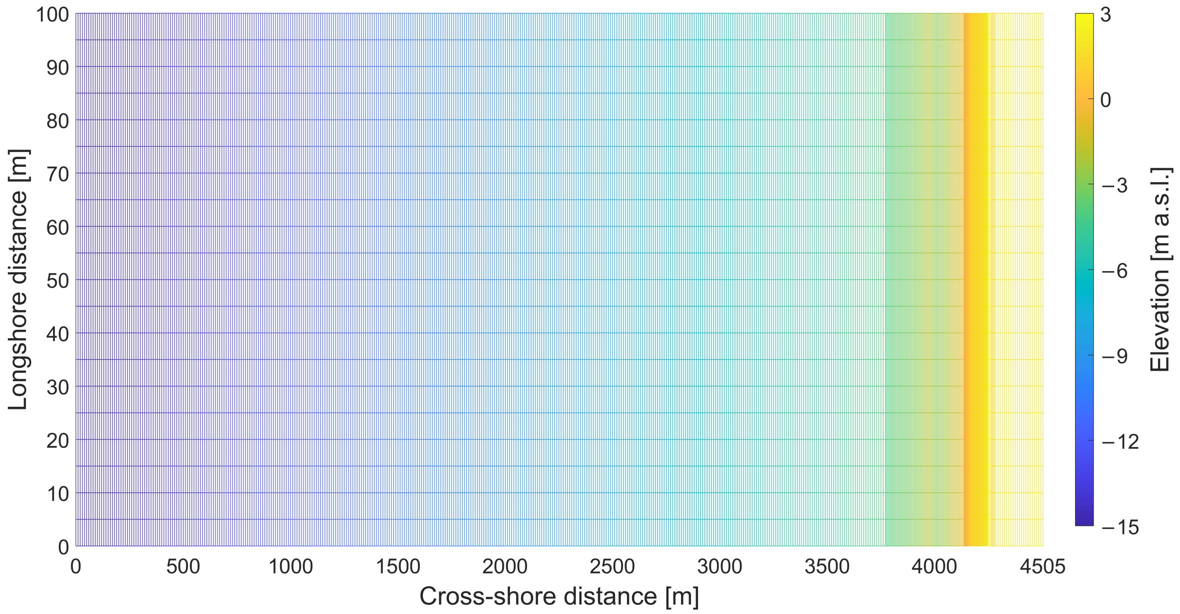

Figure 3. Two-dimensional computational grid, utilized for the numerical simulation on the benchmark scenario.

The hydrodynamic model of XBeach was set by the *surfbeat* option, which allows us to solve the short-wave variations on the wave group scale (short wave envelope) and the associated long waves. The forcing wave condition was imposed by fixing the wave spectrum (i.e., significant wave height H_s, peak frequency f_p) and its duration at the offshore boundary rt, as further discussed in Section3.3. For simplicity, the incident wave ray was assumed to be orthogonal to the shoreline.

Flow boundary conditions were set as an absorbing–generating (weakly reflective) boundary in 2D for the front and back (offshore and landward, respectively) boundary domains, while the Neumann boundary condition (i.e., constant water level gradient) was selected for both left and right boundaries (perpendicular to the shore).

The breaking process was taken into account by the formulation of Daly et al. [39]. It states that waves break completely when the wave height exceeds a threshold (γ) and stop breaking when the wave height falls below another threshold (γ_2):

$$\begin{cases} Q_b = 1 & \text{if } H_{rms} > \gamma h \\ Q_b = 0 & \text{if } H_{rms} < \gamma_2 h \end{cases}$$

where Q_b is the fraction of breaking waves, H_{rms} [m] is the root mean square wave height, and h [m] is the local depth. In the following application, γ and γ_2 are left at their default values of 0.55 and 0.3, respectively.

To reproduce the evolution of the beach profile, the morphological module was activated. The *morfac* parameter allows the user to decouple the hydrodynamic and morphological times. Due to the large amount of computation points (12,285 in total), the *morfac* parameter was enabled in the simulations to reduce the total computational time.

The duration of each simulation described in Section 3.3 is given by the sum of the storm event and two times the wave spectrum duration rt, so that the sea state fully develops throughout the domain.

Given that the present work is an exploratory study, all the other parameters—not shown above—were left to their default values.

3.3. Numerical Simulations

The numerical simulations were run to simulate five different scenarios (Figure 4). The first one (hereafter referred to as "Benchmark") combines the emerged and submerged profiles already seen in Section 3.1. In order to avoid boundary effects on the hydrodynamic processes and the loss of sediment landwards, the cross section was extended by 50 m on the offshore side and 100 m on the onshore side. This case is used as a yard stick (benchmark) against the other four scenarios considered, where different interventions are considered.

The other four intervention scenarios involve a total sand displacement of 436 m^3; that is, 4.36 m^3 per unit width of the beach, distributed on the emerged area between $x = 4166$ m and $x = 4242$ m, in different forms for each case. In the first intervention case (hereafter referred to as "Nourishment"), all the available volume of sand was distributed homogeneously along the emerged beach, creating a uniform layer. The second, third and fourth intervention cases (hereafter referred to as "Dune") assume that the sand is placed in a single continuous dune.

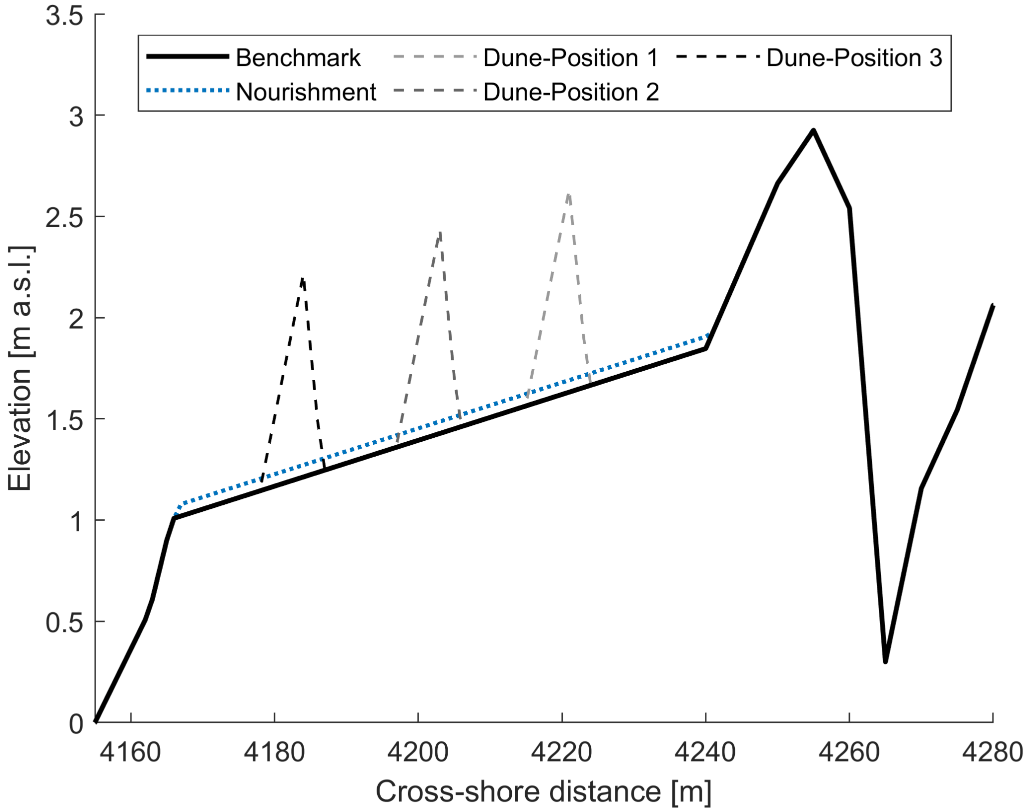

Figure 4. Schematisation of all the simulation scenarios tested on the case study beach: benchmark (continuous black); nourishment (dotted blue); dune-position 1 (dashed light gray); dune-position 2 (dashed dark gray); dune-position 3 (dashed black).

In absence of any field measurements of the historical dunes at the study beach, the results obtained by Calafat et al. [40] during a topographic survey campaign at the beach of Remolar (Barcelona, Spain) between 2004 and 2013 were utilized. Said work shows that embryo dunes at that location reached between 0.75 m and 1.50 m high and approximately 10 m wide, most times located within 100 m from the shoreline. In addition to that, Vega et al. [13] suggest 10° and 20° as literature values for the seaward and landward face, respectively. Based on that, the dune height is set at a suitable value of 1.00 m; by constraining the seaward slope at 10° and landward one at 20°, the dune width achieves a total value of 10 m. What changes between these three dune scenarios is the position of the dune itself; its crest position is placed at $x = 4221$ m, $x = 4203$ m, and $x = 4184$ m, respectively (i.e., within 100 m from the shoreline).

All scenarios were forced by two design storms. The Low Energy storm (referred to as LE from now on) follows the storm definition (according to the ROM [41]), which defines a storm as an event which exceeds the minimum wave height of 2.0 m. This condition was also used by Mendoza and Jiménez [42] as the minimum storm conditions required to generate a significant impact on the coast measured in terms of erosion and inundation. The High-Energy storm (indicated with HE) came from ICGC [24]; matching a 10-year return period storm with $H_s = 5.57$ m. The peak periods for both significant wave heights were obtained following Equation (1), whereas a duration of 36 h, or 1.5 days, was chosen for the simulated storms, as a compromise among the values suggested in Section 3.1.

Table 1 resumes all the numerical simulations performed.

Table 1. Scheme of all the simulations performed on the case study, varying the simulation scenario under Low Energetic (LE) or High Energetic (HE) storm conditions.

ID	Simulated Scenarios	Storm Condition	H_s [m]	T_p [s]	Storm Duration [d]
1 2	Benchmark	LE HE	2.00 5.57	6.03 10.09	1.5
3 4	Nourishment	LE HE	2.00 5.57	6.03 10.09	1.5
5 6	Dune-Position 1	LE HE	2.00 5.57	6.03 10.09	1.5
7 8	Dune-Position 2	LE HE	2.00 5.57	6.03 10.09	1.5
9 10	Dune-Position 3	LE HE	2.00 5.57	6.03 10.09	1.5

4. Results

The results of the simulations are analyzed below, first for the scenarios forced by the LE storm and then for the same scenarios forced by the HE wave condition.

The LE storm was used for all the scenarios. This event led to almost zero morphological evolution; the volume eroded from the beach is always around 0.10 m^3/m and the erosion stops before reaching the intervention area at $x = 4166$ m. This is due to the low values of H_{rms}, which remains low (1.4 m) when entering the offshore boundary and arrives close to the shoreline with a value of around 0.1 m, after the breaking process—also related to the littoral bar—occurs. This means that the assumed interventions cannot contribute significantly to reduce the beach profile erosion because of their rear position.

The displaced sand comes into play when more severe storms attack the shore. When HE storm was run, the waves entered the domain with higher values of H_{rms} (around 3.5 m), shoaled and came to break nearshore, but retained enough energy to model the emerged beach ($H_{rms} \approx 1$ m, which corresponds to a significant wave height H_s of about 1.4 m, using Equation (2), which is effective for the JONSWAP spectrum).

$$H_s = 1.416 H_{rms} \tag{2}$$

Figure 5 shows the values of H_{rms} from the offshore boundary to the shoreline both for the LE and the HE storm.

The choice of a wave motion orthogonal to the shoreline, together with the fact that the beach is an extruded beach profile, has resulted in a very homogeneous evolution of the beach profile in the longshore direction. A simple way to describe this feature, for the generic beach profile, is to calculate the longshore standard deviation of the elevation values all along the evolved profile. Table 2 summarizes the maximum and minimum values of that standard deviation for each simulated scenario.

A direct consequence of the low longshore variability in the resulting beach profiles is that a generic cross-section (2D) can be considered as representative of the beach evolution. Henceforth, the central profile will be used for the following analysis.

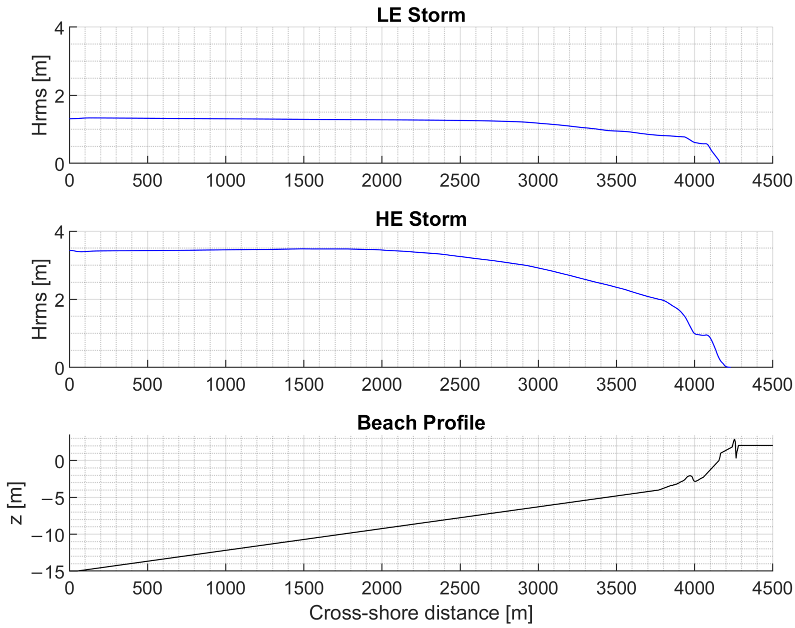

Figure 5. Values of H_{rms} from the offshore boundary to the shoreline, for the LE storm and the HE storm.

Table 2. Maximum and minimum values of the longshore standard deviation of the evolved beach profile elevation, computed for every simulated scenario.

Simulated Scenarios	Standard Deviation	
	Max	Min
Benchmark	0.017	0.000
Nourishment	0.024	0.000
Dune-Position 1	0.027	0.000
Dune-Position 2	0.017	0.000
Dune-Position 3	0.019	0.000

The benchmark scenario is shown first (Figure 6a,b). It can be seen that a large amount of sand left the emerged beach towards the submerged beach, which is reasonable given the intensity of the storm. It is also worth noting that the bar experienced both a lowering of about 0.11 m and a small displacement (up to 4 m) of its offshore slope towards greater depth. This suggests that the bar was not at its equilibrium configuration, which would be at greater depth instead. Thus, the utilized bar is most likely related to a lighter storm.

The results of the numerical simulation for the intervention scenarios are now presented. It is clear that the nourishment scenario (Figure 7a) produced a result very similar to the benchmark case. All the dune scenarios (Figure 7b–d) show a reduction in the erosion process and in the sediment moved towards the submerged beach, and a tendency for the dune to limit the landward extension of the erosion. Such a tendency seems to be more pronounced the closer the dune is to the shoreline. In Appendix A, the nearshore erosion and deposition areas for all the intervention cases are displayed in Figure A1.

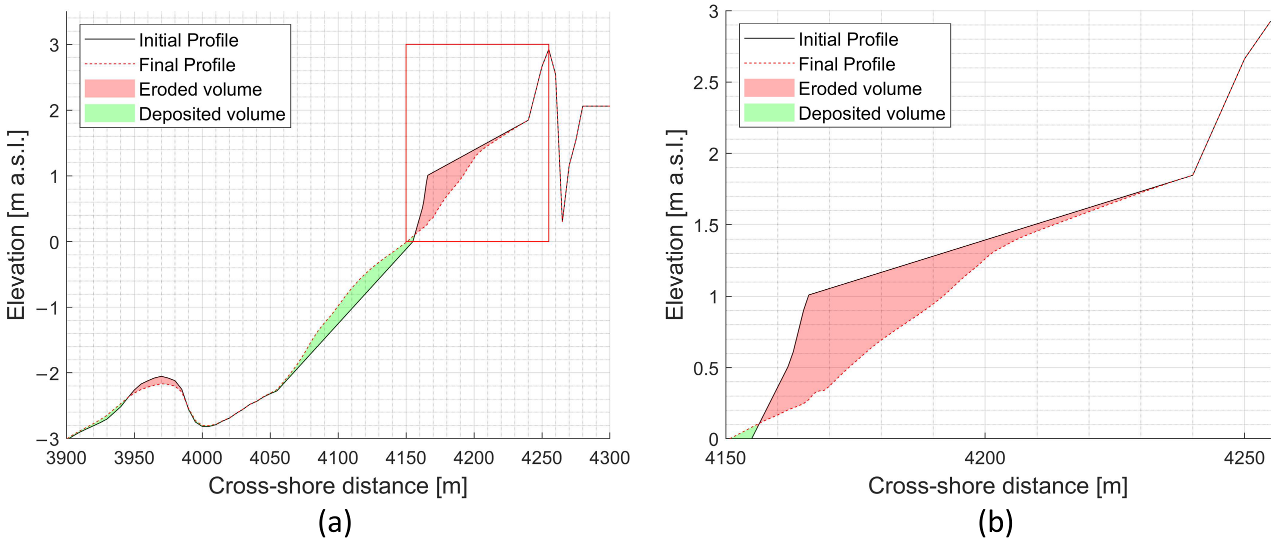

Figure 6. Morphologicalevolution of the beach profile resulting from the numerical simulation for the benchmark scenario: (**a**) nearshore erosion and deposition areas; (**b**) zoom on the erosion and deposition areas on the intervention location.

In order to evaluate the importance of the erosion process, it is necessary to quantify the volume of sand eroded.

Remember that the simulated 3D domain behaves as if it were two-dimensional. This means that, for comparison purposes, the volume calculated via the 3D domain is directly proportional to its cross-section (2D surface), i.e., the volume per unit width can perfectly represent the total volume.

With this in mind, the erosion and deposition volumes per unit width [m^3/m] are obtained by measuring the erosion and deposition surfaces above the zero height from the cross-sections already shown (Figures 6 and 7). It is now possible to compute the net eroded volume for each simulated scenario by subtracting the deposition area from the erosion area.

In order to compare the erosion of the benchmark scenario with that of the intervention scenarios, it is important to remember that the initial sediment budget is different between benchmark and intervention cases. Therefore, the corrected eroded volumes must be calculated for each intervention scenario as the difference between its net eroded volume and the amount of displaced sand placed on the beach (i.e., 4.36 m^3/m).

Table 3 shows, for each simulated scenario, the values of these quantities, together with the variation in the eroded volume—absolute [m^3/m] ad percentage variations—compared to the benchmark case.

The best response to the erosion process comes from the Dune-Position 3 scenario, i.e., the dune closest to the shoreline. It leads to a reduction in sediment loss of up to 52.3% (994 m^3 in 100 m of width). Immediately after that, the Dune-Position 2 scenario exhibits very good behaviour with regard to the forcing storm; this sand displacement setting again leads to a reduction in the eroded sand volume, this time of 12.0% (227 m^3 in 100 m of width).

Dune-Position 1 and the homogeneous nourishment scenarios still have a positive effect on the tested beach, as the net eroded volume in both cases is lower than that recorded for the benchmark scenario (15.22 m^3/m and 18.48 m^3/m, respectively, compared to 19.01 m^3/m of the benchmark case). However, these positive effects are very limited and, considering only the eroded volumes, they do not produce an advantage for the beach but an increase in the percentage sediment loss (−3.0% in the dune scenario and −20.1% in the nourishment scenario).

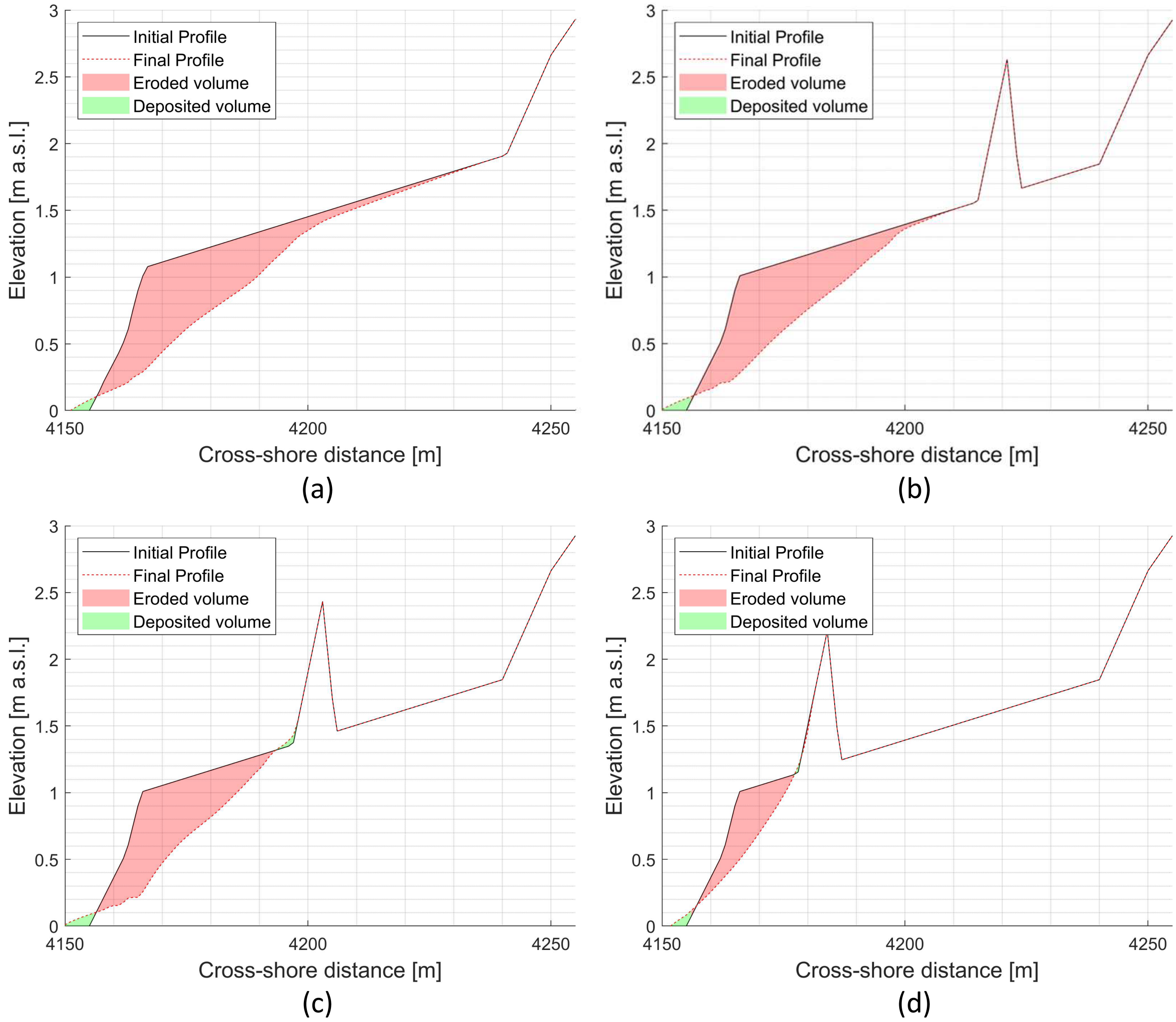

Figure 7. Morphological evolution of the beach profile resulting from the numerical simulation for the intervention scenarios: (**a**) nourishment; (**b**) Dune-Position 1; (**c**) Dune-Position 2; (**d**) Dune-Position 3.

Table 3. Values of the net and corrected eroded volumes for each simulated scenario; absolute and percentage volume variations related to the intervention scenarios, compared to the benchmark case.

Simulated Scenarios	Net Eroded Volume [m^3/m]	Corrected Eroded Volume [m^3/m]	Absolute Volume Variation [m^3/m]	Percent Volume Variation
Benchmark	19.01	19.01	-	-
Nourishment	18.48	22.84	−3.83	−20.1%
Dune-Position 1	15.22	19.58	−0.57	−3.0%
Dune-Position 2	12.38	16.74	2.27	12.0%
Dune-Position 3	4.71	9.07	9.94	52.3%

When considering the maximum distance up to which the erosion occurs, the best solution is still Dune-Position 3 (Table 4). In fact, in this case, the erosion process stops close to the foot of the dune, at 27 m from the shoreline, instead of 83 m as is the case in the benchmark scenario.

The other dune scenarios (Position 1 and 2) show similar behaviour, blocking the erosion with their bodies. This leads to higher values as you move landwards, with distances of 38 m (intermediate dune) and 57 m (furthest dune) from the shoreline.

The homogeneous nourishment cannot fully influence this maximum erosion extension, which coincides with that of the benchmark scenario (83 m). It makes this case the one with the worst response to erosion for the analyzed beach.

Table 4. Maximum distances reached by the erosive process from the shoreline; absolute and percentage distance variations related to the intervention scenarios, compared to the benchmark case.

Simulated Scenarios	Max Erosion Distance [m]	Absolute Distance Variation [m]	Percentage Distance Variation
Benchmark	83	-	-
Nourishment	83	0	0
Dune-Position 1	57	26	31%
Dune-Position 2	38	45	54%
Dune-Position 3	27	56	67%

5. Discussion

5.1. Discussion of Results

The results derived from the numerical model highlight that the presence of a dune can lead the beach system to improve its response against wave-driven erosion. It arises from the reduced sand volume that moves from the emerged to the submerged beach, as well as the more restrained extension of the erosion process which characterize the dune scenarios.

In support of this, Fernández-Montblanc et al. [18] previously indicated, via a modeling study on XBeach, that the inclusion of a dune on a beach profile can restrict overwash and, consequently, lower erosion can be observed. In that case, the erosion process at Bellocchio's beach involved also the dune crest, causing sand deposition not only on the seaward side of the dune but also at its back. This attitude relies on the storm conditions that forced said system, which was characterized by an observed tidal elevation of 1.27 m and an extreme wind waves with $H_s = 4.5$ m. Although the process of wave breaking, which took place around 2–3 m depth ($H_s \approx 3$–4 m), reduced the wave energy, the resulting overwash was strong enough to generate landward transport, which led to a progressive sediment transfer towards the back of the dune.

The presence of a littoral bar causes the waves that reach the shore of the beach of La Marquesa to be much lower than Bellocchio's ones, with H_s almost equal to 1.4 m. Given that the intervention area begins at 11 m far from the shoreline with an elevation of 1.0 m in all the scenarios and that the design dunes have a crest elevation at least equal to 2.2 m a.s.l., the wave-driven reshaping process on the emerged beach is quite limited: waves have enough energy to run-up the beach until the intervention area and to redistribute the sediment accordingly; however, they do not have as much energy as needed to overtop a potential coastal dune (dune 1, 2 and 3 scenarios), nor to overwash it. Hence, the designed coastal dunes induce changes on the beach profile just in front of them, whereas no sediment is moved at their back. This suits the experiment results obtained by Silva et al. [16], who noticed that when the erosion mode is swash [43], the material moved from the dune is deposited either at the toe of the dune or at the submerged part of the profile, even beyond the closure depth.

5.2. Future Management Strategies

Coastal interventions, such as beach nourishment or dune restoration, could act like a hydraulic barrier. In this case, the dunes would limit both the wave run-up excursion and the wave-driven erosion along the fore-beach, so that the changes in the beach profile—erosion and deposition—would only occur in a limited area. A secondary way in which beach nourishment or dune restoration alters the sediment transport pattern in the swash zone is by changing the slope of the beach. This change alters the parabolic run-up excursion, which changes the number and type of run-up/run-down interactions, and therefore the sediment transport behaviour of each swash event [44, 45].

In coastal areas subject to long-term erosion, such as the beach at La Marquesa, these dunes will not survive for long, and the situation will be exacerbated by more severe storms according to future climate change projections. To achieve longer-term stability for such interventions, coastal dune restoration must be coupled with other sustainable measures to increase the dune's resilience to wind waves and storm surges.

Among the most well-known practices, re-vegetation certainly occupies a prominent position. In addition to the benefits to the ecosystem as a whole, vegetation provides additional benefits to the dune: vegetation dissipates wave energy better than bare soil; the presence of plants can increase the dune mechanical resistance; the plant structure allows the dune to recover sand by trapping wind-driven sediments [18,46].

Recently, some authors investigated new possibilities for making dunes more stable over time. An interesting application comes from D'Alessandro et al. [47], who tested and verified the use of a colloidal silica-based grout, a non-toxic transparent mineral suspension of nanometric particles of silicon dioxide (SiO_2), as a technique for consolidating non-cohesive sediment on coastal dunes. The use of this polymeric substance is likely to make the dunes more resistant and resilient to near-surface wind effects and minor storm events.

Alternatively, dunes could be deliberately designed to operate in overwash erosion mode. This means that waves would overtop them and spread their sediment onto the intervention beach, both on the front and the back beach [16]. In this case, no stabilization measure is required, as a more dynamic redistribution of sediment is desired.

6. Conclusions

This study presents an application of the numerical model XBeach to the La Marquesa beach (Tarragona, Spain), which in recent decades has experienced the loss of its coastal dune system and progressive beach erosion due to the construction of dams in the lower course of the Ebro River.

The aim of this work is to compare the effectiveness of consolidated soft solutions to this problem, such as a standard beach profile nourishment, with more sustainable—at least from the ecological perspective—solutions, such as Nature-based Solutions. To this end, four intervention scenarios were considered, involving the displacement of a fixed amount of sediment on the beach: spreading it in a homogeneous layer, constructing a single dune and varying its position with respect to the shoreline (three positions were tested). As a fifth hypothesis, a non-intervention scenario was set as a benchmark. Each scenario was forced by a Low-Energy storm and a High-Energy storm, based on local information.

The results obtained show that the LE storm has little effect on the beach profile. On the contrary, the HE storm shows remarkable discrepancies in the behaviour of the different scenarios. For the case study, the best solution—among those tested—is the construction of a dune close to the shoreline, with its foot at a distance of about 30 m from the coastline. This intervention would provide a large reduction in sediment loss (52.3% less than the benchmark scenario) and would stop erosion close to the shoreline. The other two scenarios that implement the dune construction show that the more the dune moves landwards, the less effective it is in terms of both the volume eroded and the extent of erosion. Homogeneous nourishment does not lead to a significant reduction in either eroded volume or erosion extension compared to the benchmark case.

This application shows how numerical modeling of different alternative scenarios can be a trace upon which decision makers can effectively choose the better intervention against short-term erosion in endangered coastal areas.

Further improvements of the current work could include sea-level rise projections, designing storms with a higher return period, the two-dimensionality of the study area, and conducting topographical and bathymetrical field surveys to take into account refraction and other directional effects. Moreover, to better reproduce the long-term erosion pattern, long-shore currents could be considered in the numerical model.

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Appendix A

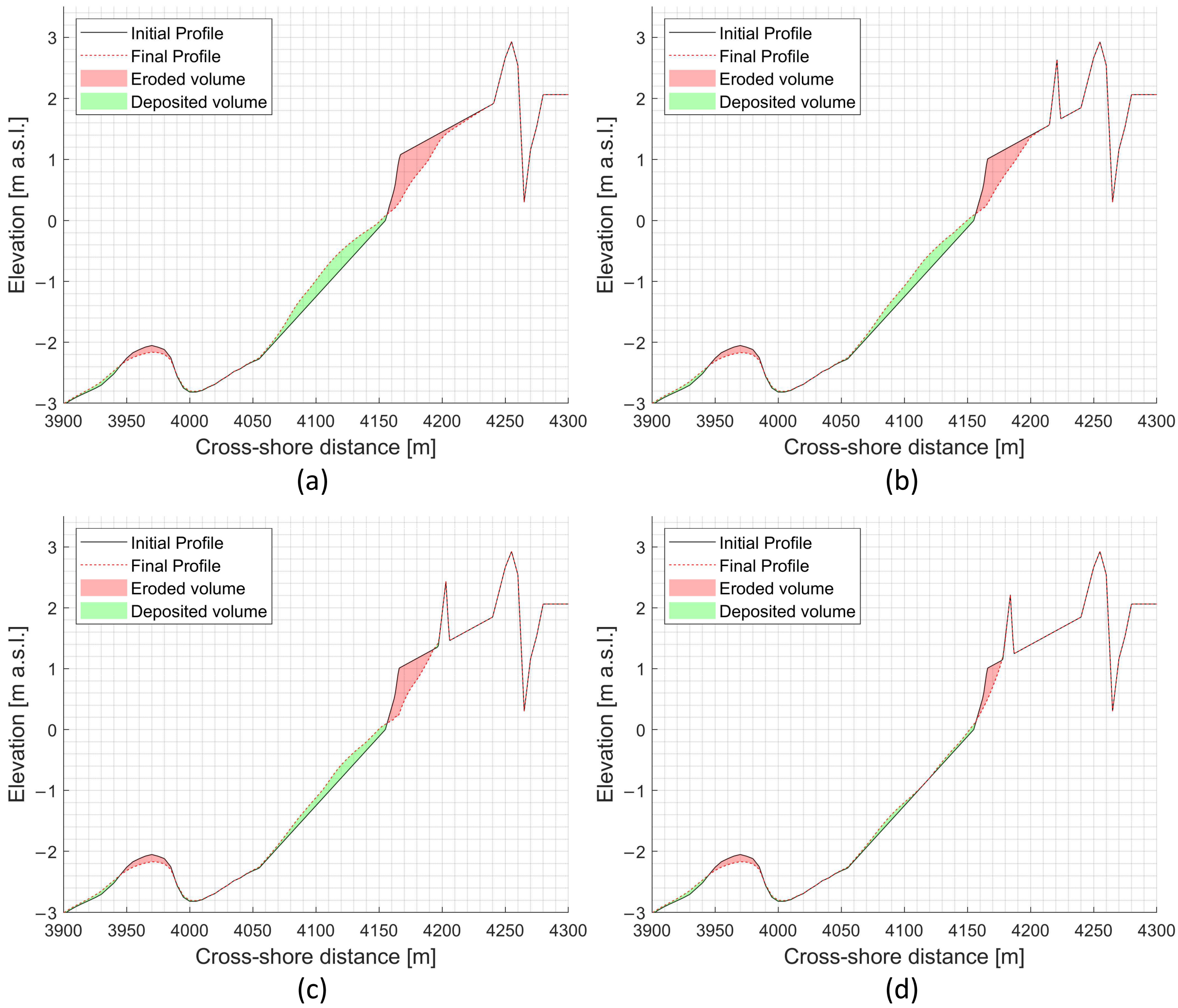

Figure A1. Morphologicalevolution of the emerged beach profile resulting from the numerical simulation for the intervention scenarios forced by the HE storm: (**a**) nourishment; (**b**) dune-position 1; (**c**) dune-position 2; (**d**) dune-position 3.

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