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Analysis of the factors affecting erosion in the beach-dune system of Guardamar del Segura, Spain

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ABSTRACT

Dune systems have recently become fundamental natural solutions for the protection of the coast. The study of its morphodynamic features in storm situations is well documented in the literature. However, the morphological behaviour of these ecosystems when they are artificially modified by humans is still not adequately known. In this study, the morphological parameters of the restored dunes of Viveros Beach in Guardamar del Segura, Spain, are analysed. For this, a profile study was carried out using digital elevation models (DEM). In addition, the waves and incident storms are studied and, finally, a statistical analysis of the different variables that define the three dune zones is conducted. Results show that during periods of increased wave intensity and duration (2016–2017 and 2017–2020), there is correspondingly greater erosion in the dune. Additionally, the slope and the height of the dune present a strong correlation with changes in its volume. Greater volumetric losses occur the greater the slope of the foredune and the dune height. This situation occurs especially in the northernmost area, located next to the breakwater at the mouth of Segura River (Zone 1), where they reach up to 53° and 10.24 m, respectively. A better understanding of these factors provides coastal managers with effective tools for designing new dune landforms or conserving existing ones.

1. Introduction

Coastal dunes are complex systems with high geomorphological dynamism due to the constant exchange of sediments between land and sea caused by wind and waves (Kolb, 1973; Masselink et al., 2014). These dunes fulfil many valuable ecosystem functions, as they act as protective buffers against storm surges and wave attack, reducing damage to the ecosystems located behind them during severe storms (Sigren et al., 2014). These, when dynamically linked to the adjacent beach, provide sediment to the beach berm during periods of erosion, so any change in weather conditions can produce important variations in their landforms in short periods of time (Carter, 1990; Cowell and Thom, 1994). However, away from the influence of wave erosion, these dunes can be stabilized by vegetation or continue evolving under the influence of wind action (Jones et al., 2008).

Coastal dunes as part of the coastal sedimentary system are controlled by the interaction of various processes, including the balance of coastal sediment, the climate of waves and winds, the tidal regime, and the characteristics of the sediments (Delgado-Fernandez et al., 2019). Human interaction has led to the destruction or loss of the natural character of the dunes (McGranahan et al., 2007) due to activities such as: i) cultivation and grazing (Martínez et al., 2013); ii) construction and mining (Feagin et al., 2005); iii) recreation and leisure (van Slobbe et al., 2013); and, above all, iv) urban and industrial human demographic expansion (L. Aragonés et al., 2016a; Baeyens and Martínez, 2008). The reduction in sediment influx caused by river damming and the interruption of sediment transportation by breakwaters and jetties have deteriorated the natural processes of coastal dune formation in many areas of the world (L. Aragonés et al., 2016a; Kondolf et al., 2014). Sea-level rise, as a result of climate change, also further contribute to the problem (Feagin et al., 2005), as do the increasing impacts of coastal storms that have increased in intensity and frequency (Gutierrez et al., 2007; Leatherman et al., 2000).

Coastal storms are recognized as one of the most important driving agents responsible for the morphological changes observed in beach and dune systems (Dissanayake et al., 2015). Coastal erosion is generally amplified during storms and, under severe hydrodynamic conditions, can eventually lead to ruptures and landslides of coastal dune systems.

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These landslides are caused by the impact of waves directly on the dune slope on the sea side, which can cause a descent of the crest, allowing overtopping (flood regime) and generating instability in dunes. It has been proved that dune systems during storms behave in different ways depending on their morphological characteristics (Muller et al., 2017). For example, it has been shown that gentle slopes (<1:3) usually do not present stability problems (Verhagen, 2019), in addition to providing greater ecological benefit. Also, the positive correlation between the maximum water level on the dune crest and the erosion of the dune crest itself induced by storms is highlighted. In contrast, dune width is anti-correlated with the maximum water level, so erosion is amplified in low and/or narrow dune profiles (Muller et al., 2017). Therefore, it is important to understand how the beach/dune profile responds along the coast under clusters of storms to properly interpret the consequent changes in resilience and, in turn, the vulnerability of the dune system to the repetition of high energy shocks (Dissanayake et al., 2015).

Consequently, there is growing concern about how to best protect coastal areas to safeguard the settled human population and developed infrastructure (Shepard et al., 2011) and therefore much attention has been paid to the need for conservation and restoration of remaining coastal dunes, especially for the ecosystem services they provide (Everard et al., 2010). As such, coastal protection based on natural barriers has emerged as an alternative to hard solutions to minimize the negative effects induced by erosion and to protect the coast (Sutton-Grier et al., 2015; van Slobbe et al., 2013). Natural coastal dunes have been highlighted as one of the most relevant ecosystems for coastal protection and its use has grown significantly in recent decades (Temmerman et al., 2013; van Slobbe et al., 2013). However, there are still some gaps in experimental data to validate their protective role when the morphological features of these ecosystems have been artificially modified by humans, as is the case of artificial dunes.

In this study we have analysed the morphological parameters of the dunes of Guardamar del Segura, Alicante (Spain), a significantly anthropized ecosystem where the continued retreat of the shoreline has caused the disappearance of the beach berm (Pagán et al., 2017) and the destruction of buildings located within the Maritime-Terrestrial Public Domain (DPMT). The objective of this research is to know the relationship between the morphological features of the dune (height, slope, width, etc.) with respect to erosion, as well as the influence of storms on its morphological changes. The results obtained will allow coastal planners to adequately design dune restoration for coastal protection and to ensure that it lasts over time.

2. Study area

The study area corresponds to the dune system of Viveros Beach (Fig. 1) located in the north of the Mediterranean town of Guardamar del Segura (Alicante, Spain). This 1.4 km long beach is delimited by the

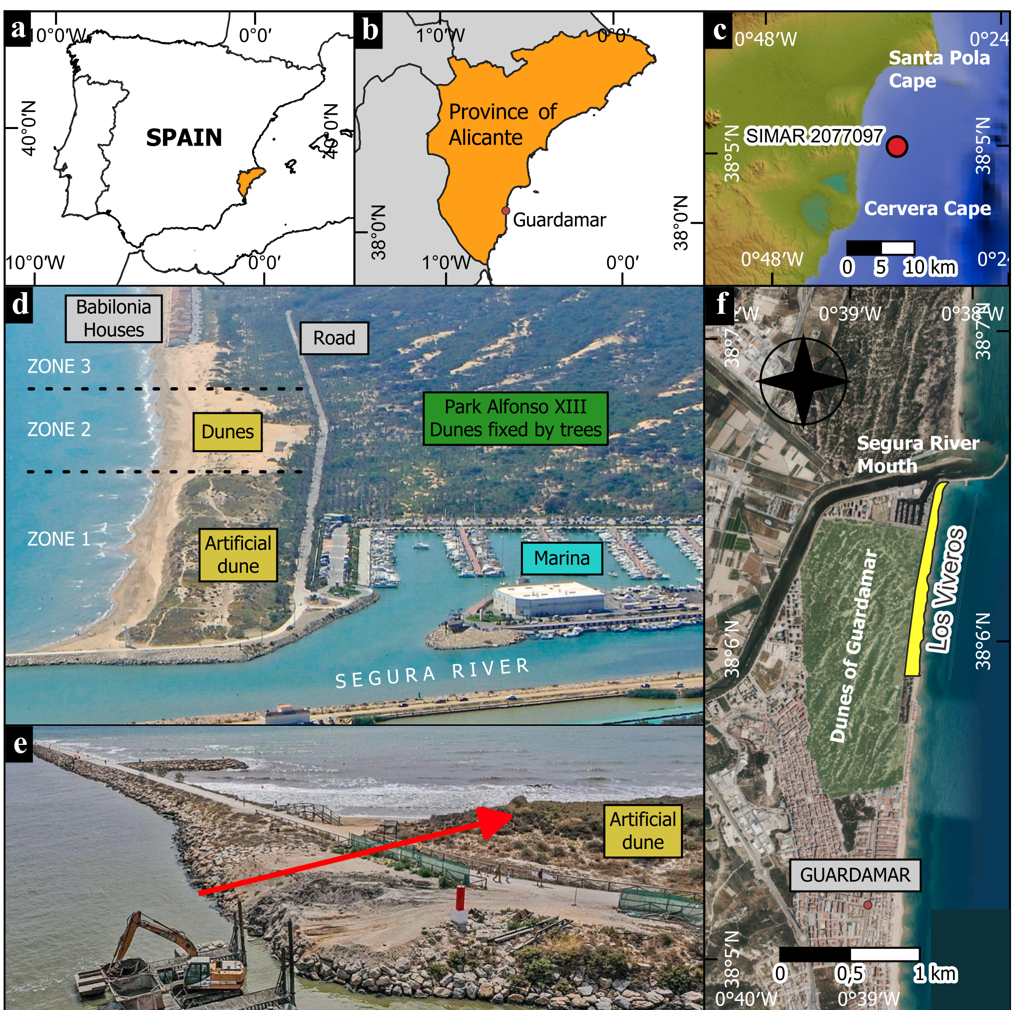


Fig. 1. (a) Study area located in Spain and (b) in the province of Alicante, (c) town of Guardamar del Segura, with location of the SIMAR node used for wave data, (d) aerial image of the mouth of the Segura River, (e) Dredging from the marina relocated in the artificial dune area (f) location of the beach and significant elements of the Guardamar del Segura shoreline.

mouth of the Segura River to the north and by the so-called Babilonia houses to the south (Fig. 1d). It is a dissipative beach, with an average width of 45 m and made up of fine golden sand with an average size of 0.228 mm. In terms of the marine dynamics, the study area, like the rest of the Mediterranean, barely experiences tidal variation, with atmospheric pressure fluctuations having a greater impact than the tide itself. As such, astronomical tides have minimal significance, with values that oscillate around 0.3 m, while meteorological tides can reach up to 0.45 m (Ecolevante, 2006).

Within the study area, several anthropogenic actions have been carried out that have gradually modified its coastal morphology and have been widely studied (Aldeguer Sánchez, 2008; L. Aragonés et al., 2016a; Pagán et al., 2019, 2017), these actions are summarized as follows:

i. 1900–1934: Sand dune fixation.
ii. 1934: Construction of Babilonia houses whose initial function was to prevent the saline spray of the sea.
iii. 1988: Channelling of the Segura River.
iv. 1988–1990: Supply of the beaches with sand from adjacent lots.
v. 1998: dredging of 200,000 m^3 for the construction of the marina at the mouth of the Segura River, which was dumped on the beach to create an artificial dune between 4.5 and 8 m high.
vi. 2002–2011: restoration for the recovery of the dune ridge.

In order to facilitate the study of this area, the restored beach-dune system of Guardamar del Segura has been sectored into 3 zones according to their morphological features (Fig. 1d):

1. The Zone 1 is located at the northern end of the study area, next to the mouth of the Segura River. This section presents a profile completely altered by the dumping of dredged materials from the construction of the marina (Fig. 1e). It has a trapezoidal section, up to 10 m high, and a slope of up to 40°, which is not related to the texture and natural cohesion of the sand.
2. The Zone 2, where the dune advances inward and has a gentler and longer slope, with a height of up to 4 m. In this sector, in 2011 a restoration was carried out in which the dune was regrown and reseeded with the aim of stabilizing it.
3. The Zone 3 north of Babilonia Houses, where the dune has a very steep slope towards the sea and is vegetated, mainly by eucalyptus and acacia trees. The dune here has a considerable height, about 5 m. This sector was also restored in 2011.

3. Methods

3.1. Data collection

The data on the dune ridge were obtained from digital elevation models (DEM) for the following dates: 13/11/2009, 18/08/2016, 12/06/2017, 23/11/2020 and 30/11/2021. The data for 2009 and 2016 came from LiDAR flights that are part of the National Plan for Aerial Orthophotography (PNOA, in Spanish) government surveys and are publicly available under the CC-BY 4.0 license. The data for 2017, 2020 and 2021 were obtained with UAV flight campaigns. All data refer to Datum ETRS89. The procedures described by (Bañón et al., 2019; Pagán et al., 2019, 2017) were followed to process and obtain of the base data, and generate the DEMs. The morphological parameters of the dune to be studied were the following: distance from dune toe to the shoreline, dune width, maximum dune height, foredune slope and dune volume (Fig. 2).

In order to perform geospatial analyses such as DEM comparison, slope change maps, or shoreline transects, it is necessary to incorporate datasets into a GIS environment. In this research, the GGIS 3.20.3 software was used. Given the diversity of formats in which the data are provided (vector, raster, LAS point clouds), the first step consisted of the creation of a terrain dataset for each date. A terrain dataset is a multiresolution TIN-based surface created from measurements stored as features in a geodatabase. The slope of the surface, expressed in sexagesimal degrees, was generated from the DEM, which allows analysing whether the present slopes correspond to the natural slope (when the slope is below the friction angle of the sand, 35°). If it is higher, it means that it can be caused by anthropogenic actions. The characteristics of the elevation models are shown in Table 1.

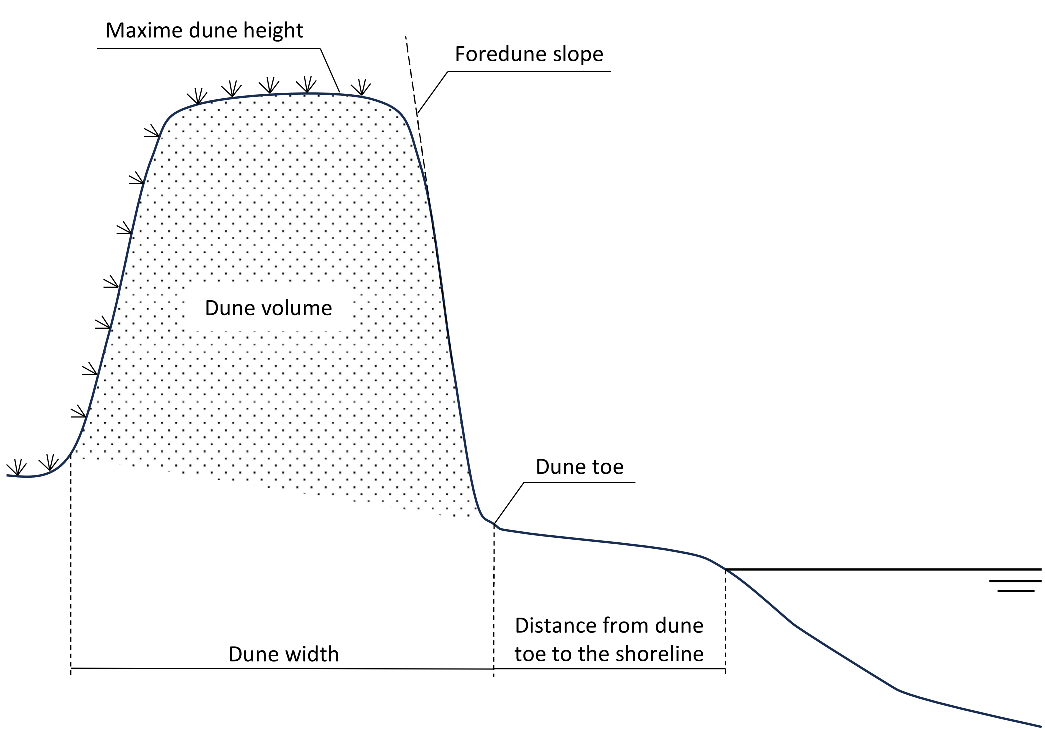


Fig. 2. Morphological parameters of the dune to be studied.

Table 1
Characteristics of the sources to obtain the elevation models.

Date	Source	Resource type	Point density	Pixel size	RMSE z	Spatial reference
13/11/2009	CNIG	LiDAR	>0.5pt./m^2	2 m/pixel	<0.40 *m*	UTM ETRS89 H30N
18/08/2016	CNIG	LiDAR	>0.5pt./m^2	2 m/pixel	<0.20 *m*	UTM ETRS89 H30N
12/06/2017	UA	Drone flight	>20pt./m^2	0.1 m/pixel	<0.10 *m*	UTM ETRS89 H30N
23/11/2020	UA	Drone flight	>20pt./m^2	0.1 m/pixel	<0.10 *m*	UTM ETRS89 H30N
30/11/2021	UA	Drone flight	>20pt./m^2	0.1 m/pixel	<0.10 *m*	UTM ETRS89 H30N

An advantage of using DEM is that it is possible to interactively generate shoreline transects anywhere in the study area for each date surveyed. In this case, profiles were generated every 50 m, generating a total of 27 profiles. The position and height of the dune toe and the maximum dune height were also visually identified. The criterion followed to identify the dune toe was to find the point where a significant change in slope occurred between the beach berm (6°-15°) and the front slope of the dune, that is, >25° (Fig. 2). Regarding obtaining the shoreline, it was vector-digitized using QGIS from the images derived from the LiDAR and drone flights. The methodology consists of the visual identification of the last wet tide mark on the beach profile, that is, the wet-dry limit in the intertidal zone (Ojeda Zújar et al., 2010). On the Mediterranean coast this criterion is appropriate due to the low variation of the tides.

The beach profiles for each year have been calculated from the parameter A obtained for the study beach (Aragonés et al., 2017). It must be noted that this is the equilibrium beach profile, and not the real beach profile, the equilibrium beach profile being the average of the profiles that occur on the beach both in summer and winter. This equilibrium beach profile and its final distance (the depth of closure) have been widely studied by the authors, in which they have shown that the variations of the equilibrium beach profile in 22-year studies are minimal with respect to the equilibrium beach profile studied in a single season (Aragonés et al., 2018; L. Aragonés et al., 2016b; López et al., 2019, 2018).

Finally, the changes between the four available periods were detected; i) 2009–2016; ii) 2016–2017; iii) 2017–2020; and iv) 2020–2021.

3.2. Maritime climate

The waves in the area are conditioned by Santa Pola Cape to the north, by the island of Tabarca to the east and by Cervera Cape to the south (Fig. 1c); thus, the range of incident waves (direction of the waves that reach the coast) is between N47°E and N62°E, and between N67°E and N180°E. Wave data (height, period, and direction) were provided by Puertos del Estado, based on the SIMAR series, specifically the SIMAR Node 2,077,097 (0.58°W, 38.08°N) was used, located about 6 km east of the study area (Fig. 1c). SIMAR dataset is composed of simulations carried out through numerical modelling of the atmosphere and waves that cover the entire Spanish coast. The wave fields have been generated by WAM and WaveWatch models, fed by wind fields of the model provided by the Spanish Meteorological Agency (Puertos del Estado, 2020). In addition, SWAN model is applied to these wave fields to take into account the transformations that the waves undergo when approaching the coast. In general, these data are collected during the period 1958–2022 with an hourly frequency and a spatial resolution of less than 3 km.

For each of the periods established in the previous section, the following were studied: the maximum wave height (H_{max}), the wave height with a probability of being exceeded by 0.137 % ($H_{s,12}$), and their corresponding periods, directions, and probabilities of occurrence. In addition, the direction of average wave flow corresponding to the wave height was calculated with a probability of 0.137 % for each analysis period and for each of the three study areas (Liste et al., 2004).

An analysis of the storms that occurred has been carried out. It has been considered a storm when a significant wave height of the 95th percentile, corresponding to the entire historical series, was exceeded for a minimum period of 6 consecutive hours and with a delimitation of at least 24 h without exceeding said threshold (Morales-Márquez et al., 2018; Toledo et al., 2022; Wiggins et al., 2019). The end of the storm will occur when at least one full day has elapsed without exceeding that wave height at any time of the day. This study will focus on the duration of the storms, the predominant direction and the Storm Power Index (SPI), which measures the severity of the storms that have occurred during a year and is defined as the maximum wave height square multiplied by the average duration of the storms (in hours), thus obtaining an approximation of their total energy (Senechal et al., 2015).

3.3. Statistical analysis

A statistical analysis was also conducted to correlate the variables obtained in the previous subsections (beach and dune width variation, volume variation of the foredune, dune height, slope, and wave heights) in order to understand which factors have the most significant influence on the erosion of the three areas that make up the beach-dune system of Guardamar del Segura and to provide guidelines that coastal engineers can follow when designing a new dune ridge parallel to the shoreline.

On one hand, a study of bivariate correlations has been carried out to determine a possible relationship between the different dune characteristics, as well as the different wave parameters: H_{max}, $H_{s,12}$, SPI, etc. In this study, Pearson correlation coefficient has been used, which is obtained by dividing the covariance of two variables by the product of their standard deviations. To evaluate the strength of the correlation, Evans scale has been used (Evans, 1996): r = 1–0.8 (very strong); r = 0.8–0.6 (strong); r = 0.6–0.4 (moderate); r = 0.4–0.2 (weak); r = 0.2–0 (very weak).

In addition, it was determined if there are significant differences between the dune morphological parameters in the different profiles studied. For this, three study areas are established in accordance with the areas established both by (MAPAMA, 2001) in the restoration of the dune ridge, and by (Pagán et al., 2019) in the monitoring of the study area. Thus, Zone 1 was identified by profiles from 1 to 10 (the most anthropized zone with the artificial dune), Zone 2 by profiles from 11 to 20 (low-height, low-slope restored dune area), and Zone 3 by profiles from 21 to 27. It was also determined if there are significant differences in the variations suffered by the different dune characteristics obtained in the different periods studied. For this, an ANOVA analysis was carried out using SPSS software. Before ANOVA, it is verified if there are differences in the variances by applying the Levene test. If a significance level of 95 % is considered, a significance value (sig,) less than or equal to 0.05 indicates differences between the means of the groups studied. In the case of equal variances, the Tukey statistic is used to determine the equality or difference between the means, while if the variances are different, the Games-Howell statistic is used.

4. Results

4.1. Study of the morphology of the dune system

Fig. 3a–e illustrates the shaded topography of the foredune, identifying the 3 different zones described inSection 2. One key analysis performed was the evolution of slope maps over time (Fig. 3f–j). A

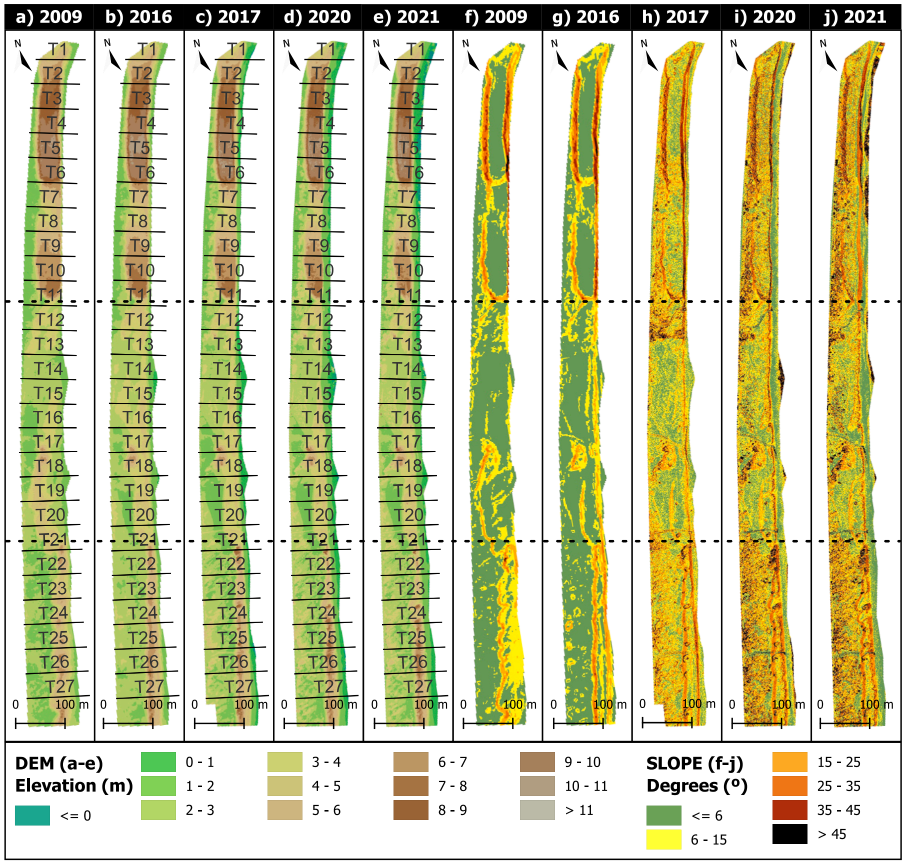


Fig. 3. Digital elevation models (DEMs) (a–e) and slope (f–j) at each date.

progressive increase in the slope on the sea side of the dune is detected throughout the study area, that is, in 25 of the 27 transects analyzed. The color scale has been adjusted to identify areas with a slope greater than the internal friction angle of the sand. In this regard, zone 1 shows slopes greater than 35° on both sides (land and sea side) and as time passes, the slope increases, reaching the entire length of the shoreline from 2017, with values even greater than 45°.

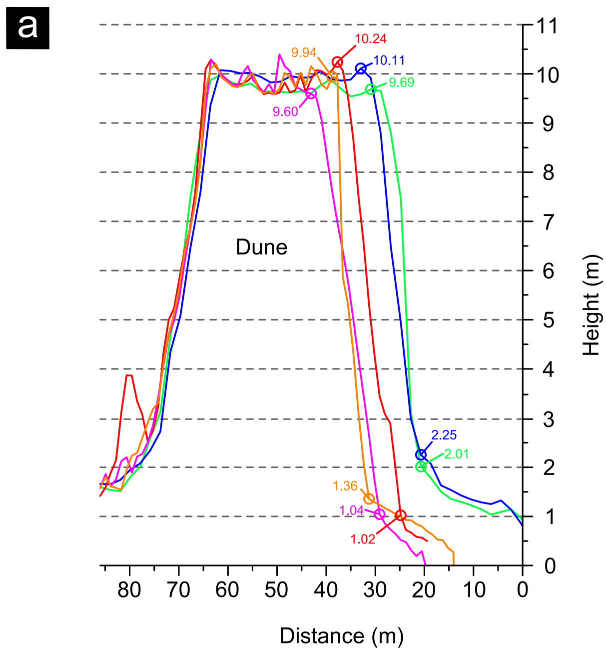
This situation of increased slope of the dune edge is repeated in zone 3, where it went from slopes less than 25° until 2009 to slopes of up to 35° in 2016. In addition, in 2017 there was a significant increase in slopes of the coastal front of that area, appearing maroon colors indicating slopes greater than the natural ones (Pagán et al., 2019). On the land side, the dune slope has increased considerably in the last two years, reaching values greater than 45°. In zone 2 there is also an increase in slope from 2009 to 2021, although the values in this section are generally below 35°, which indicates that the reconstructed profile is similar to the natural profile before the dune was affected by the sea (Fig. 4).

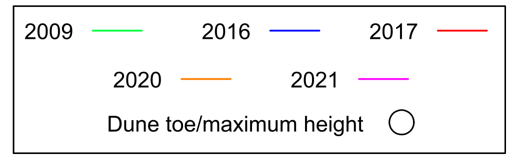
In Zone 1 (Fig. 4a) there has been a retreat and a decrease in elevation at the dune toe. The change experienced between 2016 and 2017 is significant, where the dune toe retreated 3.8 m in just one year and reduced its height by more than 1 m, causing the berm to disappear. The regression continued, reaching 6.4 m in the 2017–2020 period. This year (2020), the height of the dune toe recovered slightly (1.36 m) because a landslide of part of the foredune temporarily raised the height of the berm. However, the berm height was eroded again the following year, reaching just over one meter in height (1.04 m). Regarding the height of the foredune, it has not suffered great variations over time, ranging between 9.6 and 10.2 m. With regard to the slopes, they have remained unstable on the sea side of the dune, going from 38° in 2017 to 53° in 2020 and later to 33° in 2021. Erosion caused the destabilization of the profile in 2020, causing the loss of material, making the 2021 profile gentler (Fig. 4a). For that reason, the crest of the dune retreated 4.3 m in just one year. While on the land side it has remained practically stable, with slopes around 31° to 34° thanks to the presence of vegetation that fixed the movement of the dune.

In the case of Zone 2 (Fig. 4b) in 2009 the dune profile had a natural profile formed by the wind, with the sea side (windward) having a more inclined profile than the leeward side (8° vs 4°). After the restoration of the dune ridge in 2011, a narrower dune was generated, increasing its height by 1.2 m (2016 profile), which increased its slope angle, from 8° in 2009 to 13° in 2016. Also, the height of the dune ridge on the leeward side was artificially increased. Erosion has caused the destruction of the beach berm in 2017 and a reduction of the dune base, destabilizing the slope at that point and causing loss of material. In subsequent years, the slope on the sea side has increased at the same time as the dune narrowed, reaching a value of 32° in 2021, while the slope on the land side remained stable.

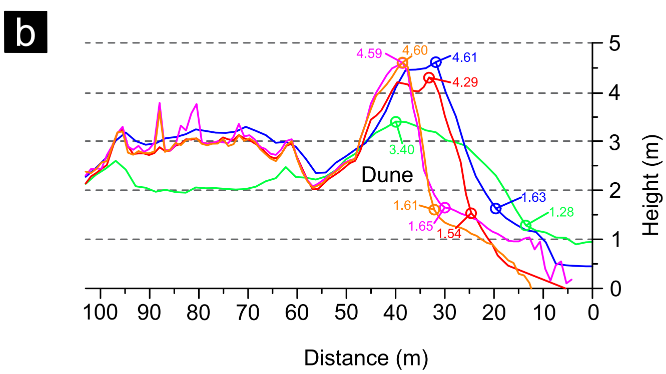
Finally, in zone 3, the behaviour has been somewhat more irregular, due to the continuous restorations of the dune system with the planting of native species over time and which also artificially modified the morphology of the dune (Pagán et al., 2019), as in 2016, where the dune narrowed by 18 m and gained 0.75 m in height (Fig. 4c). However, the following year the dune crest returned to the values of 2009 and continued to decrease until 2021, with a dune height of only 4.82 m (1.48 m less than in 2016). The dune toe has also retreated year by year, highlighting the 17 m lost in the entire period analysed (2009–2021), this has also caused a natural migration of the dune inland. As for the shape of the dune, it has been narrowing and becoming gentler (20° in 2017 and 11° in 2021), especially since 2017, the year after which waves began to erode the dune toe.

Next, it is determined if the volume variation of the beach-dune system is produced to a larger extent by the loss of material in the beach berm or in the foredune ridge. By observing Fig. 5 the following

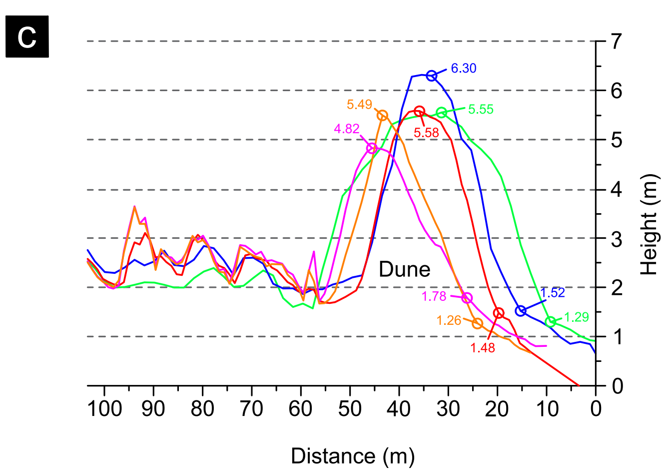




	Seaside slope	Landside slope
2009	43°	33°
2016	40°	31°
2017	38°	34°
2020	53°	32°
2021	33°	32°



	Seaside slope	Landside slope
2009	8°	4°
2016	13°	10°
2017	15°	11°
2020	28°	11°
2021	32°	11°



	Seaside slope	Landside slope
2009	16°	21°
2016	17°	22°
2017	20°	22°
2020	14°	20°
2021	11°	21°

Fig. 4. (a) Profile T5 of Zone 1, (b) Profile T15 of Zone 2, restored dune and (c) Profile T23 of Zone 3, restored dune. The shoreline in 2009 has been taken as the origin of the profiles.

results are obtained: In the periods 2009–2016 and 2016–2017, the losses on the beach are clearly higher than those that occur in the dune. This occurs in 87 % of the transects in the period 2009–2016 and in 83 % in the period 2016–2017. Especially in the latter period, erosions of up to 71 m^3/m are reached for T24 and more than 62 m^3/m for T19. While the material losses in the dune system are clearly lower, exceeding only 50 m^3/m in the T5 transect, being one of the few transects where the erosion of the dune is greater than that of the beach. In the period 2017–2020, the dune begins to be affected by the waves and in this case, it is the dune that presents the greatest losses in 65 % of the profiles with respect to the beach. Erosion in the dune lessens the retreat of the beach, where even in some transects of zones 2 and 3 material gains can be seen, highlighting T23 with up to 47 m^3/m. Losses in the dune system reach 45 m^3/m in T9.

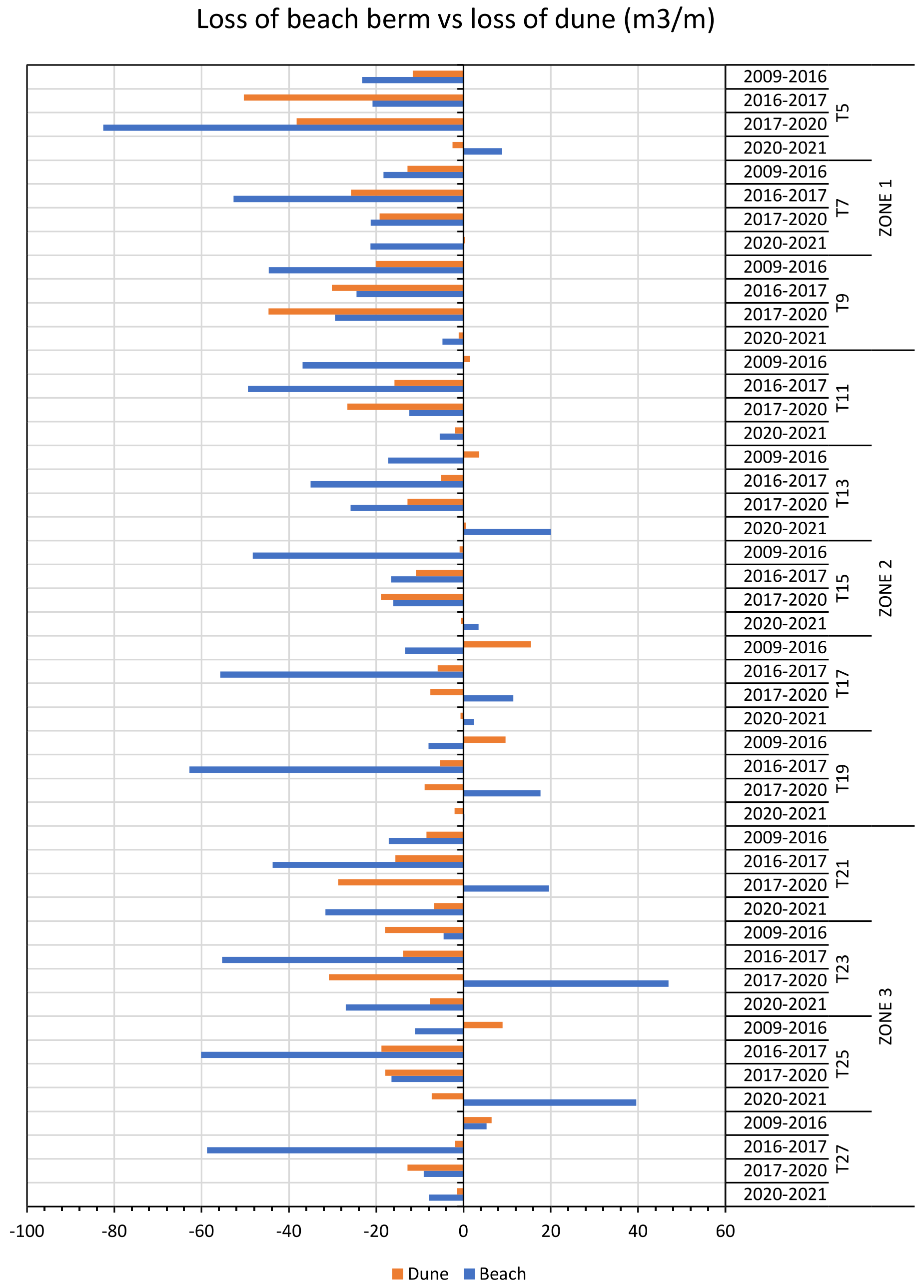


Fig. 5. Volume variation per linear meter (m^3/m) of the beach berm and dune for each transect and period analysed.

4.2. Study of the maritime climate

To determine the influence of the waves on the dune ridge, the evolution of the waves by periods and directions is studied first (Fig. 6). The periods analysed seem to have similar behaviour in pairs, with the periods 2009–2016 and 2017–2020 having one behaviour, while 2016–2017 and 2020–2021 present another behaviour. In general, the most frequent directions are those from ENE and those from E, while the directions with the greatest energy are those from NE, ENE and E. In addition, NE direction presents wave upturns in periods 2009–2016 and 2017–2020 with wave heights $H_{s,12}$ of 4.1 m and 3.6 m, respectively. Moreover, the directions of ENE (5.6 m vs. 3.8 m) and E (3.7 m vs. 3.1 m) increased considerably in the period 2017–2020 and 2016–2017, respectively. Finally, in the southern directions an alternation in the increase in wave height is observed, in the SE direction the highest heights occur in 2016–2017 and 2020–2021 (2.2 m and 2.1 m, respectively), while in the SSE direction, they occur in 2009–2016 and 2020–2021 (1.9 m and 1.7 m, respectively).

These variations in wave frequencies and heights mean that the average flow is also affected (Table 2). In the three areas, the average wave flow has rotated by 2° on average between the periods 2009–2016 and 2020–2021. In zone 1 the average flow enters slightly more from the south than in zones 2 and 3, due to the presence of the breakwater at the mouth of the Segura River, which limits the entry of waves from the NE. From there, in the last period analysed, a value of 95.65° is obtained in zone 1, and 92.02° and 92.62° in zones 2 and 3, respectively. However, this rotation is not observed in the orientation of the beach, which has remained relatively stable over time. The beach has a practically rectilinear alignment, with deviations of just 4° between zone 1 and zone 3. Finally, it is highlighted that there are no differences in the wave height $H_{s,12}$ for the 3 zones described in any of the 4 periods, so for the rest of the analysis the maritime climate data at the midpoint of the global study area will be used.

The number of wave data that reaches the study area amounts to

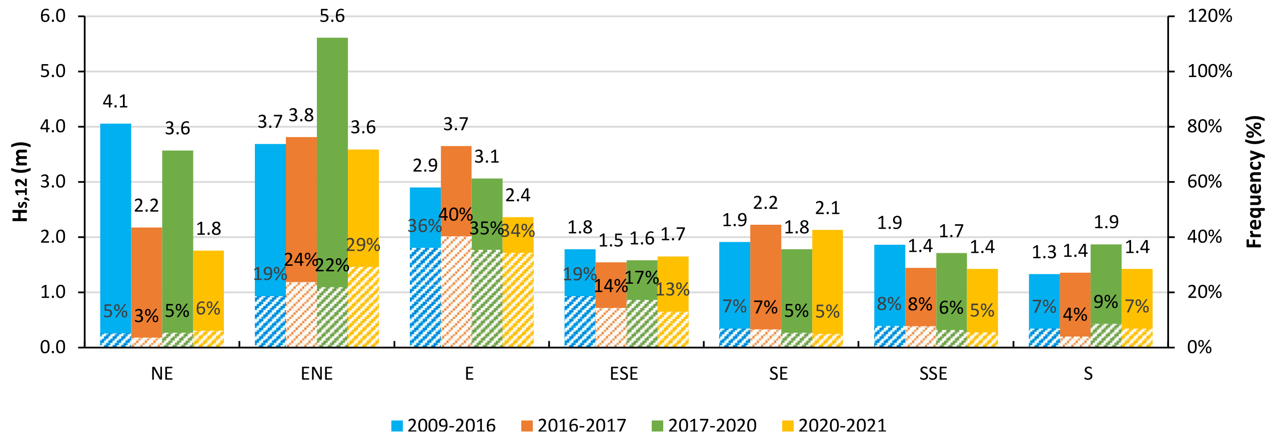


Fig. 6. Evolution of the wave height $H_{s,12}$ and the frequency of the waves classified by directions and by periods.

Table 2
Average wave flow (AF) and beach orientation (BO) by zones and periods.

	ZONE 1			ZONE 2			ZONE 3		
Period	$H_{s,12}$ (m)	AF (°)	BO (°)	$H_{s,12}$ (m)	AF (°)	BO (°)	$H_{s,12}$ (m)	AF (°)	BO (°)
2009–2016	2.84	97.89	98.64	2.87	93.87	96.24	2.88	94.52	95.32
2016–2017	3.33	96.69	99.29	3.32	93.16	97.72	3.32	93.87	96.21
2017–2020	3.46	96.18	98.79	3.47	92.45	98.30	3.51	93.12	95.66
2020–2021	2.66	95.65	99.56	2.63	92.02	97.36	2.65	92.62	95.02
2009–2021	3.00	97.53	–	3.01	93.48	–	3.03	94.12	–

81,181 (Table 3). This data corresponds to 76.88 % of the total waves recorded. This percentage rose from 2016 to remain above 80 % in the next periods, highlighting the 2016–2017 period with 82.83 % of the total waves. On the other hand, the average and maximum values of the waves have been obtained for the different periods. It is highlighted that in the periods where the highest maximum wave heights are recorded, the highest average waves are not produced. This is the case of the 2017–2020 period, where despite registering a maximum wave height of 6.78 m, an average wave height of 0.66 m was barely obtained. Finally, the 132 maritime storms that occurred in the study area in the entire period 2009–2021 stand out.

In Fig. 7, storms have been analysed considering the threshold wave height of 1.45 m (significant wave height of the 95th percentile in the period 1958–2021). In general, Viveros Beach has presented stability in the average values of storm parameters over time, except at specific moments. Analysing the duration of the storms first, storms have an average duration of 28 h, with values lower in all cases than 110 h. The period 2016–2017 stands out with an average of 53 h. The maximum wave height of the storm is usually between 1.5 m and 4 m, highlighting a wave height of 6.78 m in a storm lasting 88 h in 2020. This storm, called 'Gloria', can be considered the most powerful storm recorded along the entire eastern coast of the Iberian Peninsula since at least 1950, which caused significant material damage to the Babilonia Houses, located to the south of the study area (Oliva Cañizares and Olcina Cantos, 2022). The value of the SPI is very relevant. Although it remains practically constant throughout the period studied with an average of 230 m^2h, a double increase is observed in the period 2016–2017 (509 m^2h), which reflects a significant increase in the duration and maximum wave height. If we look at the directions, the most powerful storms come mainly from the ENE, although seven important storms from the SSE and S stand out, with a maximum wave height of around 2 m and a duration of more than 10 h.

Table 3
Number of wave data, % of waves that reach the study area with respect to the total, average and maximum value of H_s and number of maritime storms by periods and in the entire time series.

	No. Wave data	% Waves	H_s average (m)	H_s max (m)	No. Storms
2009–2016	43,650	73.63 %	0.64	4.24	52
2016–2017	5924	82.83 %	0.75	4.18	10
2017–2020	24,298	80.35 %	0.66	6.78	47
2020–2021	7309	81.87 %	0.78	3.61	23
2009–2021	81,181	76.88 %	0.67	6.78	132

4.3. *Statistical analysis*

Regarding the analysis of the significant differences between the three areas studied (Fig. 8), three distinct groups are generally observed, meaning that the three areas present significant differences between them. For example, the dune width in zone 1 is an average of 60.6 m, while zone 2 presents an average of 76.3 m and zone 3 of 88.9 m. The maximum dune height also presents differences in the three zones with an average of 7.4 m in zone 1 and 4.0 m and 6.1 m in zones 2 and 3, respectively. The only variable in which the three zones are completely equal with respect to the average is the distance from the dune toe to the coast, although the spread of the data (25 %~75 %) increases from zone 1 (10.9 m ~ 15.5 m) to zone 3 (8.0 m ~ 16.5 m). Regarding the slope of the foredune and the dune volume, zones 2 and 3 are similar to each other (with averages of 21.2° and 70.9 m^3, and 22.3° and 87.4 m^3, respectively) but completely different from zone 1 (36.3° and 201.9 m^3).

However, the analysis of correlations between the variations of the dune characteristics and the initial data (Table 4) shows a strong relationship between the position of the dune toe and its initial position. The greater the dune toe distance, the greater its retreat. This is explained because, when the distance from the dune toe to the shoreline is long enough, the waves do not encounter obstacles to erode the beach berm. On the other hand, as the distance from the dune toe to the shoreline decreases, the waves begin to hit the dune front, generating avalanches that feed the beach berm, and, therefore, the retreat of the dune toe is minor. The same occurs with the slope of the foredune (the greater the slope of the front, the greater the loss that occurs). The variation in the

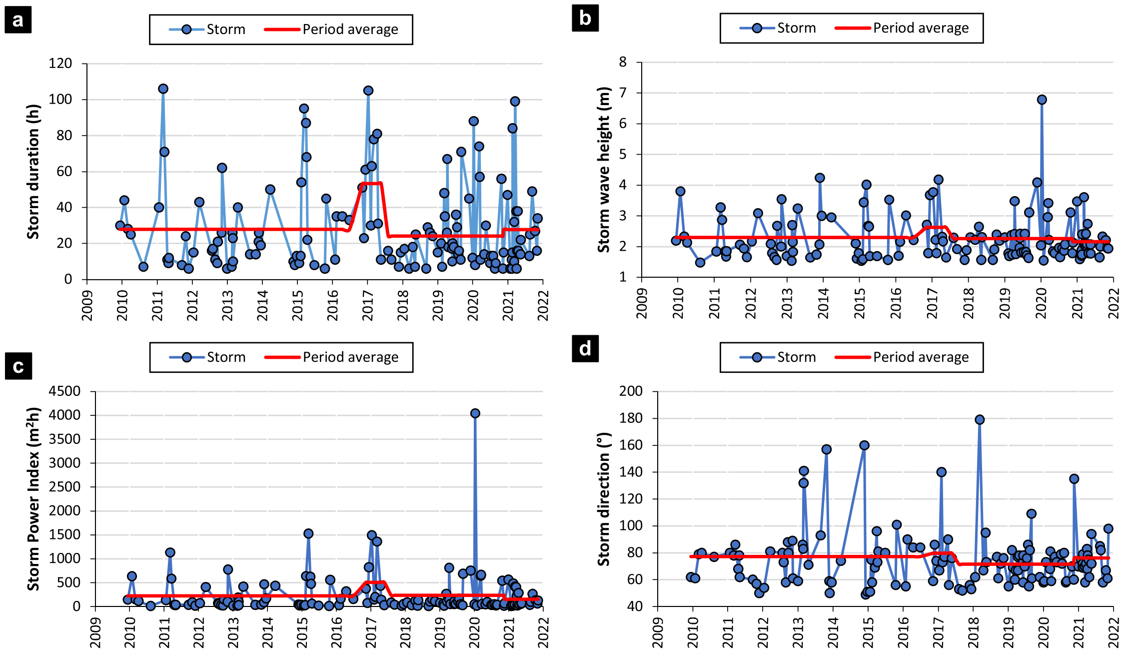


Fig. 7. (a) Storm duration, (b) Storm wave height, (c) Storm Power Index and (d) Wave direction.

dune volume presents a moderate relationship both with the initial height and with the initial volume. The higher both parameters are, the greater the volume loss that occurs. This happens especially in the profiles of zone 1, where the dune ridge has a greater elevation and width and, therefore, is more prone to suffering greater volumetric losses. Although the rest of the correlations are weak or very weak, a greater volume loss occurs when the dune toe distance is shorter, the width of the dune is smaller and the slope of the foredune is greater.

When analysing the significant differences in the variations of the characteristics of the dune ridge by periods (Fig. 9), two distinct patterns are observed. The variation of the dune toe is significantly different between the period 2009–2016 (−4.41 m) and the period 2017–2020 (+4.49 m), while both are similar in the periods 2016–2017 (−1.62 m) and 2020–2021 (+1.23 m). This means that, for example, in the period 2009–2016 the dune is moving naturally inland. The significant differences in the variations of the dune width and the dune height are similar, in the periods 2009–2016 (−7.37 m and + 0.52 m, respectively) and 2017–2020 (−9.51 m and + 0.42 m, respectively), and in the periods 2016–2017 (−1.02 m and −0.23 m, respectively) and 2020–2021 (+0.22 m and −0.15 m, respectively). However, the variations are opposite in both variables. When the width increases, the height decreases, and vice versa. Furthermore, the dune slope behaves similarly in the first three periods, with an increase in slope (+4.6° in 2009–2016, +6.3° in 2016–2017 and + 8.1° in 2017–2020), possibly due to the re-stalling of the dunes and to the feeding, while in the last period a decrease of this one is observed (−7.8°). Finally, in the volume variation, two differentiated behaviours are also observed between the most stable periods 2009–2016 (−2.84 m^3/ml) and 2020–2021 (−3.60 m^3/ml) and the periods of greatest instability 2016–2017 (− 17.94 m^3/ml) and 2017–2020 (−22.53 m^3/ml).

After conducting a global analysis, an analysis of correlations by periods was carried out (Table 5). Although the results are similar to those obtained globally, the greater influence of most of the factors on the variation of both the slope and the dune volume stands out. For example, the initial foredune slope strongly and moderately influences the dune volume variation (the greater the initial slope, the greater the volume lost), which occurred weakly in the overall analysis. The same occurs with the initial dune height (higher elevation implies greater volume loss), the initial dune volume (greater volume implies greater volume loss) and the initial dune width (greater width implies less volume loss). On the other hand, with respect to the slope variation, the behaviour observed in the 2017–2020 period is surprising, as the correlations are inverted with respect to the rest of the periods and the global one, that is, there is a greater loss of slope the lower the height, the lower the initial slope and the lower the initial dune volume. This may be due to the fact that during this period the dune begins to be affected by the waves and the coastal manager subsequently starts to carry out periodic re-stalling of the dune, a process by which the slope of the dune is modified to make it more stable.

Finally, the relationships between the variation of the morphological parameters of the dune with respect to those of the waves are analysed (Table 6). In general, a moderate relationship is observed between the variation of the dune volume and the different factors of the waves. The greater the wave heights, the greater the volume loss. The variation of the dune width is strongly related to the maximum wave height. The greater the maximum wave height, the greater the loss of width. The relationship between the variation of the distance to the dune toe and the maximum wave height, although it presents a weak relationship, shows that as the maximum wave height increases, the distance of the dune toe also increases. This makes sense, as previously stated, as there is a loss of volume and dune width.

Regarding the parameters of the storms, it is observed that there is a strong relationship between the variation in width and the number of storms (Table 6). The more storms there are, the more width loss occurs. There is also a moderate relationship between the height and the number of hours that storms last. The longer the storms last, the greater the loss of elevation occurs. A moderate relationship is observed between the width variation and the number of hours. The greater these parameters are, the greater the dune width. This may be due to the collapse of the dune that loses material from the upper zone and accumulates in the lower part. Finally, a weak relationship is observed between the volume variation and all the storm parameters except for the SPI (moderate) and the number of storms (very weak). A greater volume loss occurs as the storm parameters increase.

5. Discussion

In coastal management, the study of the sedimentary balance of the

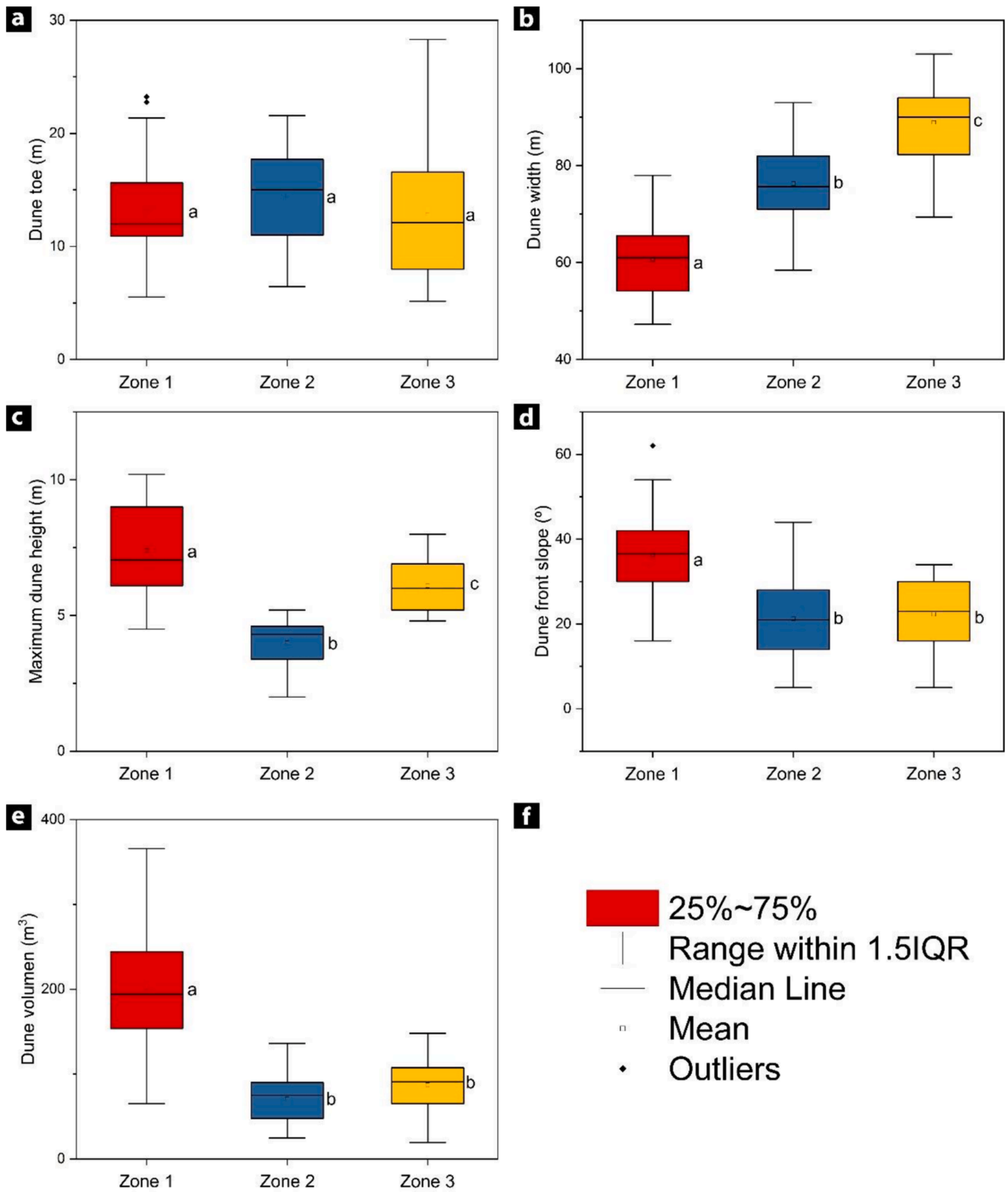


Fig. 8. Characteristics of the dune ridge by zone. a) Distance from the dune toe. b) Dune width. c) Maximum dune height. d) Slope of the foredune. e) Dune volume. f) Legend. Letters a, b, c in different bars denote significant differences ($p < 0.05$).

Table 4
Correlations between the initial characteristics of the dunes and their variations ($r = 1–0.8$ very strong; $r = 0.8–0.6$ Strong; $r = 0.6–0.4$ Moderate; $r = 0.4–0.2$ Weak; $r = 0.2–0$ Very weak).

	Variation				
	Dune toe	Dune width	Dune height	Foredune slope	Dune volume
Initial dune toe distance	−0.662	0.192	−0.028	−0.104	0.319
Initial dune width	0.053	−0.316	0.297	0.335	0.301
Initial dune height	−0.131	0.165	−0.377	−0.197	−0.493
Initial foredune slope	0.115	0.260	−0.248	−0.612	−0.350
Initial dune volume	−0.272	−0.007	−0.143	−0.033	−0.458

beach is essential to understand the development of coastal dune systems (Hesp and Martínez, 2007), because it allows for determining if the system is regressing, in equilibrium, or moving towards the coast (progradation). As previously observed in the study area (L. Aragonés et al., 2016a; Pagán et al., 2019, 2017), a series of human actions have led to a continued shoreline retreat and the gradual disappearance of the foredune. The construction of breakwaters at the mouth of the Segura River, the development of a marina, and the lack of sediment contribution from the river due to dams, and its subsequent channelling, have altered the natural sedimentary dynamics and has caused severe erosion problems in the studied coastal sections. Additionally, the stabilization of the coastal dunes of Guardamar del Segura in the early 20th century has led to shoreline retreat, likely as a result of immobilizing a large portion of the dune system, preventing the natural movement of the coast, as (Panario and Piñeiro, 1997) described in Polonio Cape (Uruguay). When combined with changes in wave height and incidence (Table 2 and Table 3), this has led to the disappearance of a significant portion of the

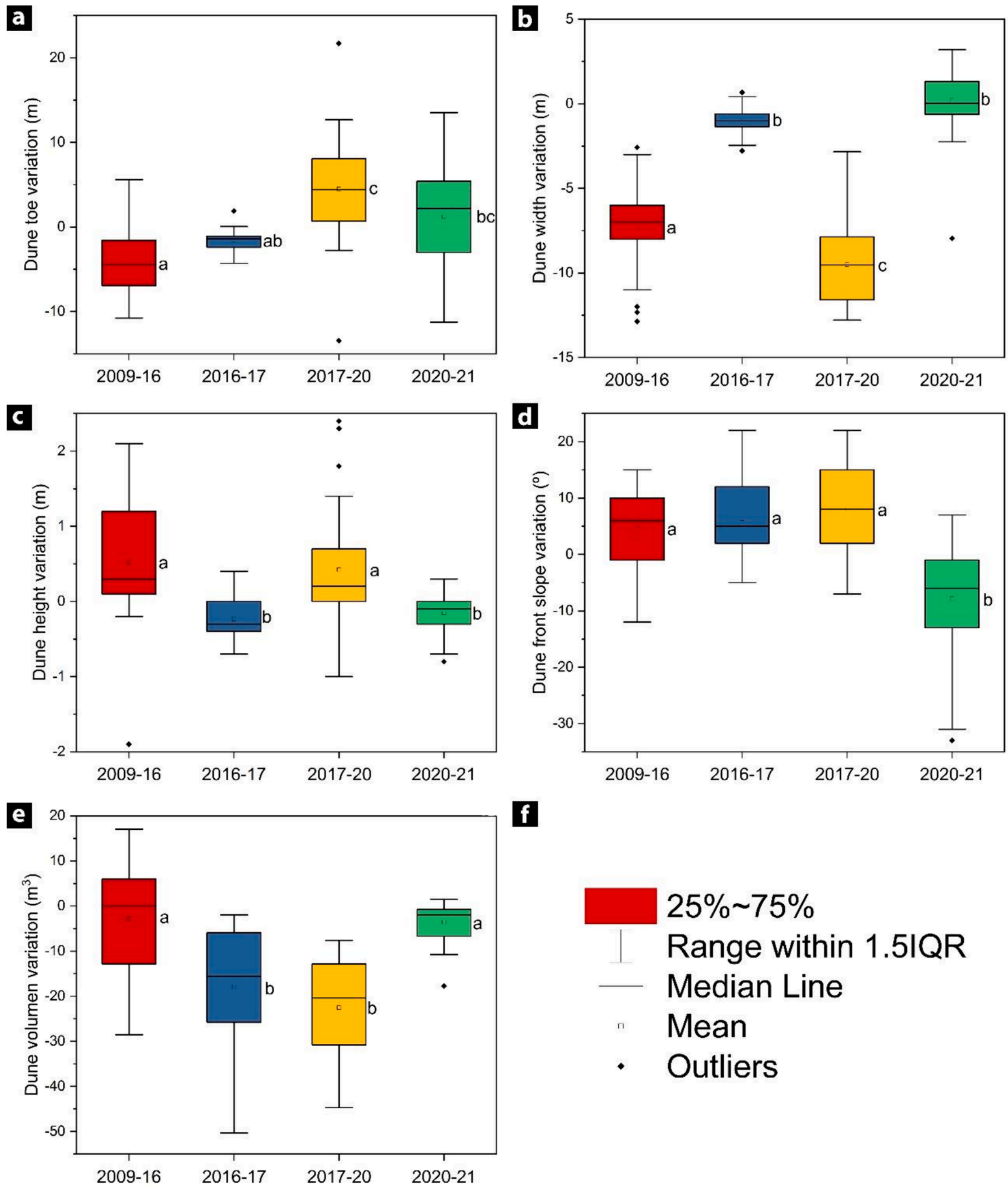


Fig. 9. Variation of the characteristics of the dune ridge by periods. a) Distance from the dune toe. b) Dune Width. c) Maximum dune height. d) Foredune slope. e) Dune volume. f) Legend.Letters a, b, c in different bars denote significant differences ($p < 0.05$).

dune ridge.

5.1. Study of the morphology of the dune system

This research has collected data that provides a detailed view of the morphological changes that occurred in the dune system of Guardamar del Segura between 2009 and 2021 (Fig. 3). In the studied area we observed significant volume loss, especially in the northern area of Viveros Beach and in the foredune. As a result, in this area the dune ridge has stopped growing in height and width (Fig. 4) as reported in (Hesp and Martínez, 2007). The net sub-aerial volumetric change of the dune that has disappeared reached 89 m^3/m between 2016–2020 in the T5 profile (Fig. 4a), which represents around 18 % of the volume that formed the barrier of dune sand that prevents the waves reach the dune extrados in 2016. Most of the sediment losses occur in the dune area, as reported by (L. Aragonés et al., 2016a; Pagán et al., 2019, 2017) the retreat of the shoreline is such that practically the run-up of the average waves produced in the study area make them reach the dune toe, which

Table 5
Correlations between the initial characteristics of the dunes and their variations by study periods (r = 1–0.8 very strong; r = 0.8–0.6 Strong; r = 0.6–0.4 Moderate; r = 0.4–0.2 Weak; r = 0.2–0 Very weak).

	Period	Variation				
		Dune toe	Dune width	Dune height	Foredune slope	Dune volume
Initial dune toe distance	2009–2016	−0.785	0.442	−0.224	−0.391	−0.172
	2016–2017	0.198	0.363	0.192	0.287	0.012
	2017–2020	−0.640	0.213	−0.014	0.107	0.066
	2020–2021	−0.760	0.046	−0.103	0.315	−0.018
Initial dune width	2009–2016	0.604	−0.463	0.086	0.623	0.529
	2016–2017	0.246	0.034	−0.061	0.000	0.667
	2017–2020	0.379	0.002	0.376	−0.654	0.410
	2020–2021	0.102	0.040	0.381	0.579	0.062
Initial dune height	2009–2016	−0.570	0.708	−0.699	−0.397	−0.526
	2016–2017	−0.200	−0.397	0.115	−0.485	−0.838
	2017–2020	−0.163	−0.368	−0.170	0.411	−0.700
	2020–2021	−0.019	0.098	−0.482	−0.255	−0.687
Initial foredune slope	2009–2016	−0.492	0.571	−0.385	−0.781	−0.816
	2016–2017	0.091	−0.458	0.220	−0.557	−0.765
	2017–2020	−0.271	−0.067	−0.029	0.276	−0.565
	2020–2021	−0.015	−0.091	−0.227	−0.813	−0.038
Initial dune volume	2009–2016	−0.618	0.664	−0.478	−0.477	−0.575
	2016–2017	−0.133	−0.201	0.107	−0.277	−0.804
	2017–2020	−0.334	−0.107	−0.021	0.616	−0.559
	2020–2021	0.039	−0.017	−0.488	−0.444	−0.428

Table 6
Correlation of dune variations with waves (r = 1–0.8 very strong; r = 0.8–0.6 Strong; r = 0.6–0.4 Moderate; r = 0.4–0.2 Weak; r = 0.2–0 Very weak).

	Variation				
	Dune toe	Dune width	Dune height	Foredune slope	Dune volume
H_{max}	0.392	−0.712	0.275	0.396	−0.490
H_{s12}	0.213	0.291	−0.305	0.194	−0.507
H_{s12} Average wave flow	0.093	−0.282	0.010	0.533	−0.576
Storm duration (h)	−0.074	0.587	−0.401	0.060	−0.240
Maximum wave height of the storm H_{max}	−0.052	0.294	−0.273	0.281	−0.396
SPI	−0.037	0.261	−0.260	0.300	−0.417
Storm direction	−0.157	−0.038	−0.079	0.465	−0.393
No. Storms	−0.109	−0.739	0.474	0.176	0.175

causes a continued collapse of the slope (Fig. 4) and the disappearance of all the sand.

The first elevation data available after the reconstruction of the dune in 2011 is from the 2016 LiDAR survey, and the effects of the restoration can be seen (Fig. 4b, c) in the increase in the dune volume. In zone 1, the dredged material was not removed, and the artificial mound was maintained. In zones 2 and 3, the objective was to fix the dune in its position, maintaining its height and natural slopes (MAPAMA, 2001). However, in these areas an increase in the slope on the sea side and an increase in elevation of more than 1 m was detected (Fig. 4b, c). During the 10-year period of time between the development of the restoration project and its execution, the beach berm receded 10 m, which may have led to modifications during the execution of the restoration project, establishing new objectives: (i) maintain the width of the beach berm as much as possible, and (ii) preserve the dune width. This caused the rebuilding of the foredune closer to the shoreline with steeper slopes, removing the protection of the beach berm (Fig. 4). The lack of sufficient beach berm width could have contributed to the increase in erosion detected in the periods 2016–2017 and 2017–2020. In fact, the attack of the waves at the dune toe can cause the dune profile to incline, causing detachments of material from the upper part of the dune and potentially collapsing due to an avalanche. But waves can also create a notch in the dune toe leading to a massive failure: the collapse of a dune slab. That mechanism could also explain the steeper slope observed on the sea side of the coastal dune (Fig. 4), as happens in other areas of the world (Saathoff et al., 2007). To prevent these landslides from affecting beachgoers, the coastal manager carries out a continuous process of reshaping the dune slope. This process generally forms much steeper slopes, even much greater than the internal friction angle of the soil and thus, appropriate measures must be taken to protect the shoreline and reduce the erosion processes detected. The existing beach in 2017 was a dune area in 2009 (Fig. 4). Considering the increase in erosion rates detected in the last study period, it would only take 16 years for the complete removal of the dune (estimated through extrapolation).

5.2. *Study of the maritime climate*

As observed, the dune system is subject to retreat, with progressive erosion of the foredune during storms and spring tides, not recovered during fair weather periods (Fig. 7). The erosion of the dunes is primarily caused by extreme storms as noted in the study by (Li et al., 2014). Despite no significant differences in storm frequency, the combination of four storms in a short time period, coupled with the near complete elimination of the beach berm, has led to a significant loss of dune volume in the period 2016–2017 and 2017–2020 (Fig. 5). Also, we can see that the coastal defence formed by the dune system is more effective in terms of the volume of sand lost for the same energy compared to the erosion on the beach berm. Sand is carried from the shoreline out to sea during storms and slowly transported back to shorelines by daily wave transport. However, the disappearance of the beach berm and the lack of sediment contribution has prevented the necessary sedimentation for the maintenance of the dune (Pagán et al., 2019).

In addition, as the shoreline recedes, dune vegetation has been exposed to high salinity in an area with low organic matter, resulting in the practical disappearance of the plants responsible for fixing the movement of the dune (Aldeguer Sánchez, 2008; Cabrera et al., 1982), which, together with the strong easterly winds (Fig. 6) has increased the erosion of the dune (Fig. 4). According to (Tsoar et al., 2009), once stabilized by vegetation, dunes cannot be activated naturally even with increased wind power (Levin and Ben-Dor, 2004; Tsoar et al., 2009, 2005), as is happening in the study area. That is why the foredune will little by little be transformed by erosion into an embryo dune and over time it will become a beach berm.

5.3. Statistical analysis

From the correlation study we observed how the direct relationship between the dune volume lost per m with the distance to the shoreline is relatively small (Table 4 and Table 5). This may not be expected (Itzkin et al., 2021), but it has also occurred in other areas of the world (Saye et al., 2005). This situation is due to the fact that the dune does not erode if the waves do not reach the dune toe, regardless of the width of the existing berm. Therefore, if dune ridge is designed with the objective of providing ecosystem services to the study area and not as a defence of the coast, it will be enough to locate it at the minimum distance away from the reach of the maximum recorded storms. However, the dune height, the width and its slope play a fundamental role in the volume lost (Table 4 and Table 5). Indeed, such high and narrow dunes are not necessary (Itzkin et al., 2021), but steeper slopes are necessary to prevent greater loss of volume (Verhagen, 2019). In this type of flexible and natural protection, we observe how the dune volume erodes, particularly during extreme storms (Table 6). These data that must be taken into account in the design, because it can cause socioeconomic losses in the coastal zone and could cause flooding in low-lying areas inland. Observations from the subaerial zone about the nature of these changes are fairly accurate. Thus, it is clear how the continuous loss of sediment from the embankment of the dune has been increasing since 2009, when the shoreline was already only 18 m from the edge of the dune. This circumstance is undoubtedly contributing to the significant loss of sediment volume observed in all beach areas between 2009 and 2021. Prior to this, the loss was relatively limited as the waves barely reached the dune toe (Pagán et al., 2018).

The study of relationships of the morphological parameters of the dunes can give us valuable information for the design of coastal defence using dunes. Traditional engineering solutions, such as those carried out in the study area, are often oversized and static, as they do not respond to changing boundary conditions. Therefore, at the landscape scale, it is possible to reinforce or partially replace engineering constructions for coastal protection with ecological elements, such as dunes and wetlands. Nevertheless, the growth of dunes and wetlands is known to be dynamic, and a period of growth may be followed by a period of lateral erosion (van de Koppel et al., 2005). From the monitoring and understanding of the study area we can obtain the necessary information to understand the dynamic nature of these ecological elements, as reported by (Day et al., 2002).

Coastal defence aims to protect the inland coastline from flooding and shoreline erosion. The goal is twofold: (i) to provide innovative, sustainable and cost-effective coastal protection solutions that address threats related to climate change, such as accelerated sea level rise, and (ii) to minimize the anthropogenic impacts of coastal protection structures on ecosystems and potentially even enhance them (Day et al., 2002). It is important to consider the effectiveness of a coastal defence strategy in relation to maintaining the beach through sand replenishment. The potential effects on the overall morphological system, environment, and other concerns must also be taken into account. One strategy for protecting certain coastal areas may be the creation of coastal sections characterized by a small ridge of dunes to withstand storms and prevent erosion. The correlations obtained in this study between the erosion of the dune with respect to its morphological and storm parameters are totally exportable to other fine sand beaches that need dune ridges parallel to the coast to protect against coastal erosion and flooding.

6. Conclusion

After analysing the natural factors that affect the Viveros beach-dune system in Guardamar del Segura, Spain, the following has been determined:

The dune height and the foredune slope have a strong correlation (between very strong and moderate) with dune erosion (volume variation). Therefore, the lower the slope of the front and the lower the dune height, the lower the volume lost. This study suggests that the greatest stability occurs when the height of the dune is less than 5 m and the slope of the foredune is less than 24°, as this results in the lowest volumetric losses. Therefore, such high dunes are not necessary for its design, but they do have a slope to avoid further loss of sand.

The relationship between the distance from the dune toe to the shoreline with respect to the erosion that occurs on the dune front is relatively small ($r = 0.319$). If the waves do not reach the dune tor, it will not erode, regardless of the berm width. Therefore, a dune ridge designed for ecosystem purposes must be located away from the reach of storms.

The loss of dune width is strongly related to a greater storm maximum wave height ($r = -0.712$) and a greater number of storms ($r = -0.739$), so storm monitoring is crucial to predict the behaviour of the dunes.

Also, the volumetric sand losses from the beach-dune system are lower if they are protected by a dune than only by the beach berm. In Guardamar, once the dune was affected by waves, beach erosion was reduced. The implementation of natural barriers stands out as an effective erosion mitigation strategy in a wide variety of geographic contexts, such as on highly anthropized sandy beaches.

This study provides a series of design guidelines that will be useful to coastal engineers when designing a type of dunes that fulfil their protective function and act as a sand reservoir of the beach berm. We have to live with the erosion of the shoreline, but its defence must be designed by nature itself. To achieve this, a shift in mentality towards new, more sustainable development designs, while respecting the coastal dune framework and taking into account the rising sea level and the protective value of the coastal dune barrier.

CRediT authorship contribution statement

Ignacio Toledo: Writing – review & editing, Writing – original draft, Visualization, Software, Resources. **José Ignacio Pagán:** Validation, Supervision, Resources. **Isabel López:** Writing – review & editing, Software, Investigation. **Luis Bañón:** Writing – review & editing, Methodology, Conceptualization. **Luis Aragonés:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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