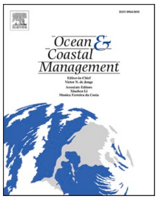
Ocean and Coastal Management 214 (2021) 105946

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman



Can long-term beach erosion be solved with soft management measures? Case study of the protected Jandía beaches

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ARTICLE INFO

Keywords:
Coastal management
Arid aeolian sedimentary system
Beach erosion
Beach nourishment
Passive management

ABSTRACT

Land uses have long modified aeolian sedimentary dynamics as has occurred in the Jandía isthmus (Fuerteventura, Canary Islands, Spain), where changes in vegetation cover, the reduction of sediment available for transport and the building of barriers to sediment transport have induced beach erosion. In the last 62 years the beach area has experienced a reduction of 800,000 m^2. The aim of this paper is to analyse the current situation (in terms of sediment availability, longshore drift and the distribution of protected plant species) in order to make soft management proposals to respond to the current erosive situation. Based on a methodology that combines field work, coastline digitalization and longshore drift calculations, it is found that each year the system loses about 96,000 m^3 of sediment which needs to be replaced in order to stop erosion. Four possible ways to manage the system are discussed: passive non-intervention management to allow the ecosystem to evolve and adapt to the new conditions; remobilization of the sedimentary deposits of the isthmus that feed the beaches; beach nourishment from other areas of the system or from outside the system, and; mechanical recirculation of the sands. The viability of each management system is analyzed, particularly with regard to long-term sustainability, as well as its compliance or otherwise with the protection measures that are in place. Paradoxically, the only measures that can alleviate the problem in the long term are incompatible with the current protective measures. In other words, the isthmus and the Sotavento beaches in Jandía are an example of an ecosystem in which the restrictions imposed as a result of its protected status, that do not take into account the tendences of the ecosystem, in fact constitute an obstacle to its conservation and do not allow the adoption of measures that could slow down the degradation process and, ultimately, impede its disappearance.

1. Introduction

Beach-dune systems are an important tourism resource for many coastal economies (Klein et al., 2004). In recent decades recreational seashore activities have been concentrated mostly on sandy shores (Caffyn and Jobbins, 2003), with more than 70% of the world's beaches now experiencing erosion (E.g.: Bird, 1996; Sajinkumar et al., 2020; Bitan et al., 2020; Hasiotis et al., 2021). Sandy shores are fragile environments and the adoption of management measures without the appropriate technical reports can produce irreversible long-term changes for these ecosystems. This has happened in many coastal areas and is commonly related with the need to adapt beaches and dune systems to user preferences (Peña-Alonso et al., 2018; San Romualdo-Collado et al., 2021a), the construction of marine infrastructure (Depellegrin et al., 2014; Mamo et al., 2018) and urban development (Alonso et al., 2002; García-Romero et al., 2016). In this process of transformation several changes can take place. For example, in the case of beaches, these changes include, among others, erosion (Bird and Lewis, 2015), progradation (Guillén and Palanques, 1997; Anthony et al., 2014; Moussa et al., 2019) and modifications to the type of sediment (Marrero et al., 2017). In the specific case of aeolian sedimentary systems, research studies have discovered changes in landforms (García-Romero et al., 2016) and aeolian sedimentary activity (dune stabilization) (Marrero-Rodríguez et al., 2020a), reductions of pioneer plants in mobile dunes and decreased species richness (Kutiel et al., 1999; Curr et al., 2000; Faggi and Dadon, 2011), sediment

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https://doi.org/10.1016/j.ocecoaman.2021.105946
Received 27 June 2021; Received in revised form 10 October 2021; Accepted 14 October 2021

remobilization (Arens et al., 2013), alteration of the direction and speed of wind flows (Smith et al., 2017; García-Romero et al., 2019) and, on occasions, surface area reductions (Marrero-Rodríguez et al., 2020b).

The above shows that, although they provide an important variety of ecosystem services (habitat of many species, buffer against extreme events, among many others) including direct economic, recreational and wellness benefits for humans (Defeo et al., 2009; Schuhmann and Mahon, 2015), the conservation of aeolian sedimentary systems has been relegated to the background. It was observed in a recent review of dune management that management measures have been promoted (introduction of grazing, sand remobilization, creation of blowouts, etc.) which, despite their good intentions and the aim of conserving habitats where priority species appear, have actually contributed to the degradation of these systems (Delgado-Fernandez et al., 2019). In this context, soft management measures have been applied in many areas (Roig et al., 2009) to slow down erosion and degradation (San Romualdo Collado et al., 2021b). However, in some areas such solutions are insufficient to compensate the consequences of human interventions or changes in dynamic conditions. Large-scale measures and expensive solutions are therefore sometimes required to save what is often the driving force of a local economy (Landry et al., 2003; Huang et al., 2007).

In the case of the isthmus of Jandía (Fuerteventura, Canary Islands, Spain), management is complex due to the high number of protection status figures that have been declared and imposed on a relatively small area. As in other coastal areas, conflicts arise between the conservation of the economic resource identified by the majority of users (the beach) and the conservation of the habitat as a whole (beach-dune system and shallow waters) and its natural dynamics, since the erosion of the beach can suppose important economic losses, as has happened in other coastal systems (Thinh et al., 2019; Alexandrakis et al., 2015).

In this context, the aims of this work are:

i) To carry out an analysis of the current situation of the system with respect, above all, to the coastal dynamics (evolution of coastline and longshore drift), the state of the aeolian sedimentary system (sediment availability and vegetation), and the evolution of land uses.

ii) To discuss four soft management proposals (beach nourishment, remobilization of aeolian deposits, passive management or mechanical sand recirculation) that are appropriate for the dynamics of the system and which do not contravene the protection measures of the study area that are presently in place, or which, failing that, at least do not require significant changes in the current legislation.

2. Study area

The study area is made up of a set of beaches that are located in the municipality of Pájara in the south of the island of Fuerteventura (Fig. 1). The genesis of the Sotavento beaches is related to contributions of sediments, mostly biogenic and carried by the N wind component (Fig. 2) from the interior of the isthmus of Jandía, that resulted from the erosion of aeolianite deposits and quaternary calcareous crusts (Alcántara-Carrió, 2003).

The isthmus of Jandía corresponds to an area of approximately 50 km^2 covered to a large extent by sands of organogenic origin. The continued contribution of these materials in large quantities has allowed the formation of the extensive Sotavento beach. After being deposited in this sector, the dominant swell generates a longshore drift that transports the sediments from these beaches southwards. As a result of this longshore drift, new beaches formed south of the mouth of the Pecenescal ravine.

Along this approximately 5.8 km long stretch of coast, the most important beaches are: i) the Sotavento beach, generated by wind inputs from the interior of the isthmus (Alcántara-Carrió, 2003) and about 10 km in length. This practically uninterrupted beach is characterized by the presence of a coastal sand bar that delimits an intertidal coastal lagoon; ii) the beaches of Mal Nombre, Esquizo and Butihondo. Along this stretch of coast, about 5.8 km long, the beaches are interrupted by ravine mouths which can fill up with sediment; iii) the El Matorral sector, which constitutes the last point to the south where biogenic

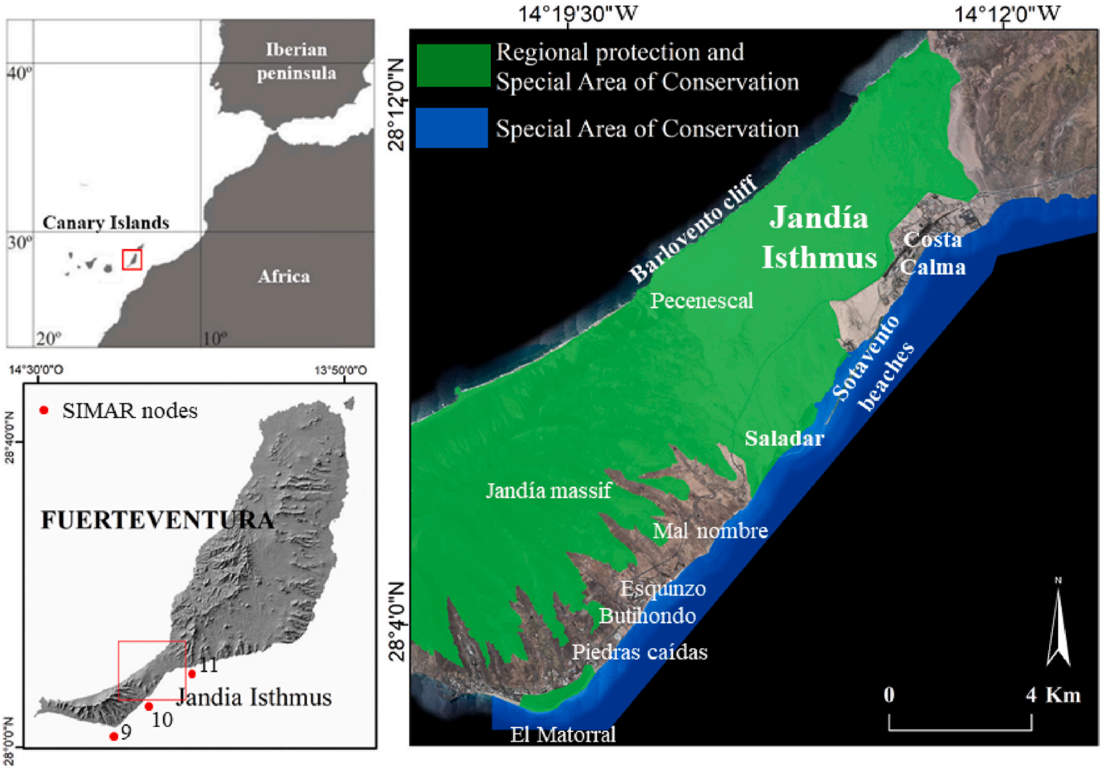

Fig. 1. Location of the study area, protection status and location of the SIMAR nodes (Source of 2018 digital orthophoto: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.).

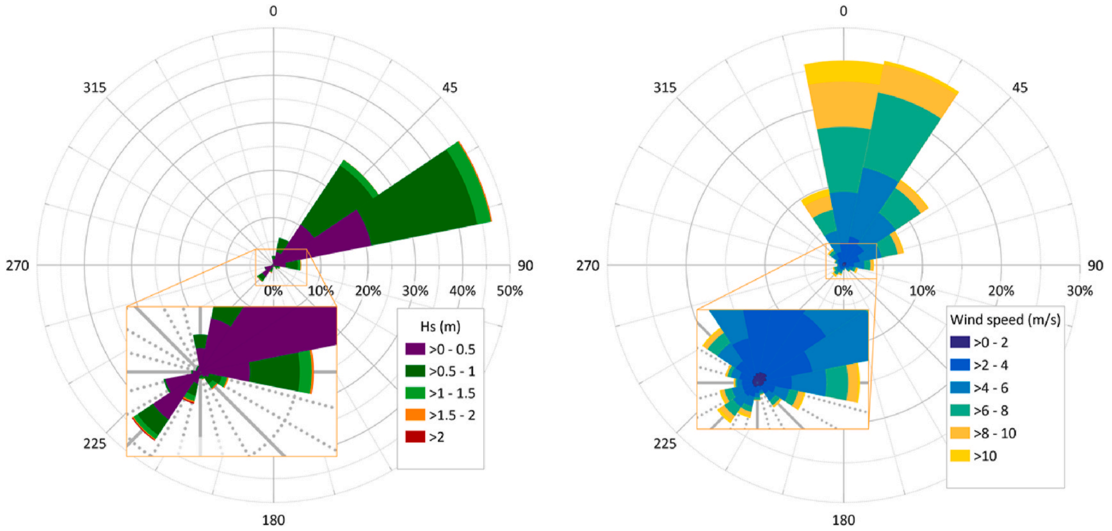

Fig. 2. Wave rose (left) and wind rose (right) of SIMAR node 10 (Location in Fig. 1) (Source: Spanish State Ports (2006–2020)).

sediments from the isthmus appear, is an open, pointed, 4.2 km long beach located opposite a salt marsh (Saladar).

The study area is partially protected as part of the Canary Islands Network of Protected Natural Spaces (Fig. 1 green), as well as being part of a Special Conservation Zone and a Special Protection Zone for Birds (Fig. 1 blue). In addition, the El Matorral-Saladar section is included in the List of Wetlands of International Importance, also known as the Ramsar List.

The climate of the area has been defined as arid with annual average temperatures of around 20 °C (Alcántara-Carrió, 2003), while the scarce and highly irregular precipitations are concentrated in just a few days of the year and do not usually exceed 100 mm (Alonso et al., 2011).

The study area is characterized by waves coming from the ENE and NE with small wave heights ($H_s < 1$ m) and low peak period values (5–10 s) (Fig. 2). That is, wind waves with a short fetch prevail due to the proximity to the African continent (Fig. 1). Stormy events are very scarce, mainly taking place during winter when the prevailing wave direction is from the SW.

Vegetation is scarce due to the high temperatures, intense sunshine and strong and frequent winds. Land cover is limited and the plants, in general, do not exceed the shrub layer (Alcántara-Carrió, 2003). There are three main vegetation types in the study area: psammophytes in the mobile sand areas; halophytes, concentrated in the backshore zones of Sotavento and El Matorral where salinity and tidal flooding are intense; and thickets of Chenopodiaceae on calcareous crusts and rocky outcrops (Martín-Esquivel et al., 1995).

3. Methods and data

3.1. Historical documents

Historical documents from the Fuerteventura archives were reviewed. The most important historical document considers land uses in the mid-nineteenth century and is titled “Description of the Jandía Grazing Land Estate”. Official reports, acts and decrees of the Fuerteventura Island Government were also consulted. The rest of the historical information was obtained from Marrero-Rodríguez et al. (2020a).

3.2. Orthophotos and aerial photographs

The analysis of coastline evolution was carried out using a set of orthophotos and aerial photographs. The aim was for the study period to be as extensive as possible, with the first available orthophoto dating back to 1956. Although it would have been ideal to have a set of data homogenously distributed over time and the initial idea was to select one flight per decade from this starting date of 1956, this was not always possible. Consequently, the longest interval between images is 13 years and the shortest 7 (Table 1). After selecting the dates, the photograms were georeferenced and a database was created with the archive of available images of the study area. The coastline was manually digitalized on each of the selected photograms and orthophotos. Coastline advance/retreat was obtained on the basis of 27 outlines each separated by 750 m and spread along the entire study area. In each outline and in each orthophoto, the position of the shoreline was determined using the limit between dry and wet area as the defining point. In addition, the evolution of the urbanization process was analyzed and digitalized on the basis of the historical photographs. The bathymetric model was obtained from the Ecocartography Plan of the Spanish coastline carried out by the General Directorate of Sustainability of the Coast and the Sea during 2000 and 2001.

3.3. Wave climate

Wind and wave data were obtained from three SIMAR nodes managed by the Spanish State Ports Agency. These nodes are all located along the southern coastline of the study area. The corresponding codes of these nodes are 40500009, 4051010 and 4052011, renamed for the purposes of this paper as SIMAR 09, SIMAR 10 and SIMAR 11, respectively (Fig. 1). The entire SIMAR dataset comes from numerical models and therefore these are not wind and wave data recorded *in situ*. Nevertheless, comparisons between numerical model and wave gauge data have been performed by other authors, with good agreement and low bias found between the two datasets (Pilar et al., 2008; Rubio, 2020). Other advantages of the SIMAR dataset include its starting date of 1958, very close to that of the first orthophoto, and the fact that it represents an optimal series of wind and wave data covering a period of 62 years.

3.4. Sediment thickness and vegetation

A field campaign was carried out in November 2020 during which 144 field tests were carried out. These tests were distributed throughout the study area to determine the thickness of available sediment that could be transported to the beaches of the isthmus of Jandía. Sampling was performed by digging manually to a maximum depth of 75 cm whenever the hardness of the materials allowed it. In the cases in which all the excavated material corresponded to sand, the thickness was assumed to be 1 m. From these data, a digital terrain model was

Table 1
Photograms and orthophotos used in the digitalization process of the coastline. Source: Spanish National Geographic Institute (Initials in Spanish: IGN) and GRAFCAN.

Year	Type	Resolution (orthophoto)	Scale (photogram)	Georeferencing error	Source
1956	Orthophoto	20 cm/pixel			GRAFCAN
1969	Photogram		1:7000	2.83 m	GRAFCAN
1981	Photogram		1:18000	2.3 m	IGN
1994	Orthophoto	40 cm/pixel			GRAFCAN
2002	Orthophoto	100 cm/pixel			GRAFCAN
2009	Orthophoto	40 cm/pixel			GRAFCAN
2018	Orthophoto	20 cm/pixel			GRAFCAN

generated to represent the variation of the thickness of the sand sheet in the Jandía isthmus. ArcGIS software was used to apply the kriging interpolation tool.

With respect to vegetation data, a list of protected species in the study area was identified on the basis of information obtained from the Canary Islands Biodiversity Databank.

3.5. Calculation of sediment volume

The volume of eroded/accumulated sediment along the coast in the different time intervals was obtained assuming that the displacement experienced by the shoreline, ΔX, is translated into a horizontal displacement of the beach contour parallel to it, which would thus maintain a constant form. In consequence, the variation in volume, ΔV, is given by Eq. (1):

$$\Delta V = \frac{\Delta X}{\Delta t} \cdot \Delta Y \cdot (dc + S) \tag{1}$$

where ΔY is the length of influence of each contour, understood as half the distance between adjacent contours measured on both sides of each contour, *dc* is the depth of closure and *S* is the superelevation attained by the water level.

Of these terms, ΔX/Δt is obtained directly from the analysis of the evolution of the coastline and $\Delta Y$is a fixed measure of 750 m, which is the distance between the different contours. This was an arbitrary distance determined by considering that the studied coastline is slightly larger than 20 km; therefore, we defined 27 fixed lines separated by 750 m from each other to cover the entire study area. In each of these lines the coastline position was measured from the aerial photographs. Depth of closure is a fundamental morphodynamic boundary separating a landward active zone from a seaward less active zone over the period defined by the profile observations used to define closure (Nichols et al., 1996). Its determination is essential to estimate the volume of sediment that is gained or lost in the coastal zone. The equation proposed by Hallermeier (1981) and shown in Eq. (2) was used:

$$d_c = 2.28H_S - 68.5\left(H_S^2 / gT_s^2\right) \tag{2}$$

where H_s and T_s are, respectively, the values of the significant wave height and period, representing high energy conditions (storms) in which contour modification can attain higher depths. In the original formulation of Hallermeier (1981), the characteristic wave is associated to a probability not exceeding 12 times/year. Both H_s and T_s were obtained from the wave dataset corresponding to SIMAR node 10 for the complete available data period (April 1958 to November 2020).

Given the temporal scale of the present study, three different methods were employed to estimate the depth closure. This approach has been followed by other authors in long-term studies to include the probability of the existence of exceptionally energetic years in the period of interest, as storm wave height on a particular coast can increase with longer control periods (Stive et al., 1993; Jiménez, 1997; Jiménez and Sánchez-Arcilla, 2004). In the first approach, the closure depth was calculated on the basis of the strongest storm recorded in the period (February 2010), and the H_s associated to a probability of 12 times/year is 2.87 m, while the associated T_s is 8.78 s. In the second approach, the maximum wave height "recorded" at SIMAR node 10 was used, with in this case the H_s value being 3.89 m and the associated period $T_s = 8.52$ s. The third approach was based on extreme wave climate data, obtained from the Las Palmas Este wave gauge during the period 1992–2017. Wave values for a 10-year return period are $H_s = 4.37$ m and $T_s = 10.49$ s (Spanish State Ports, 2020).

The depth of closure was obtained with each of these datasets using the equation proposed by Hallermeier (1981), and the mean of these values was used to calculate the sediment volume gained or lost in each sector of the study area.

Finally, the *S* term has two components, one due to the tide and the other to the swell. The tidal contribution can be calculated on the basis of the height of the tide at the time the different photograms were taken. However, for this, the indispensable information of the day and the hour when they were taken was not known, and so this term was estimated assuming that the tide was halfway between its mid level and high tide. Given that the mean tidal range for Fuerteventura is 1.72 m (Spanish State Ports, 2020), this tidal component is 0.43 m.

The component due to swell is the run-up, which was calculated through the expression of Holman & Sallenger (1985), Eq. (3):

$$R = 1,07 \ H_0 \cdot \xi_0 \tag{3}$$

where H_0 is the significant wave height in undefined depths and $\xi_0$is the Iribarren number, which is turn defined through Eq. (4) as:

$$\xi_0 = \frac{\tan\beta}{\sqrt{H_0/L_0}} \tag{4}$$

where $\tan\beta$ is the beach face slope and L_0 is the wave length which in turns depends on the wave period.

Considering that $H_0 = 0.42$ m and $T = 5.8$ s are the mean values for SIMAR node 10, and assuming a value of $\tan\beta = 0.04$, an Rvalue of 0.2 m was obtained.

3.6. Surf zone width and breaking depth

For the calculation of longshore drift, which is preferentially produced in the surf zone between the breaker and the shore (Komar, 1998; Rogers and Ravens, 2008), the breaking index γ was used, which marks the relationship between the breaker wave height (H_b) and the depth (d) at which the wave breaks, Eq. (5):

$$\gamma = \frac{H_b}{d} \tag{5}$$

In the absence of direct measures of breaker wave height, this variable was estimated through the expression of Komar and Gaughan (1973), Eq. (6):

$$H_b = 0.39g^{1/5}\left(TH_0^2\right)^{2/5} \tag{6}$$

The breaking index γ was then calculated from the expression given by Sunamura (1980), Eq. (7):

$$\gamma = 1.1\xi_b^{1/6} \tag{7}$$

where $\xi_b$is the Iribarren number, but where H_b is used instead of H_0.

Knowing the mean values of H0 and T both in situations of fair weather and storms for the SIMAR nodes 09 and SIMAR 10, the depth (*d*) at which the wave breaks can be calculated in both situations.

4. Results and discussion

4.1. Historical land uses

The isthmus of Jandía has been exploited as grazing land since practically the beginning of the colonization of the islands in the 15th century (Cabrera, 2001). The grazing model is based on the release of animals (in this particular case of goats and camels) (Roldán and Delgado, 1967; 1970) which are allowed to roam free before being herded together to obtain the animal produce. From approximately 1850 onwards, the vegetation in the area began to be exploited for use as firewood in lime kilns. This use continued until around 1960, resulting in a drastic reduction in plant cover. As reported by Marrero-Rodríguez et al. (2020a), in these conditions the isthmus of Jandía must have experienced important erosion processes which will have accelerated the natural sediment transport in the direction of the Sotavento beaches, resulting in progradation of the aeolian landforms and beaches. The local use of vegetation as fuel for the lime kiln industry fell into decline from 1960 with the arrival of fossil fuels (coal) and the pressure that had traditionally affected the vegetation in the isthmus began to decline as plants were no longer used with that purpose.

Tourist developments first appeared in Fuerteventura in the 1970s, affecting particularly the area surrounding Costa Calma. Numerous quarries were built, scattered throughout the area, as sand was in great demand as a raw material for the construction of the tourism complexes. Practically the entire isthmus became an extraction zone, with numerous tracks and trails over which the material was transported also replacing the sand.

According to oral sources and as a result of the intensive aeolian transport, partially excavated quarries would rapidly and continuously fill up with sand, making its extraction easier. Today, however, there is little accumulation of sand in the old extraction areas and in many of them palaeosol outcrops can be observed. To the reduction of transportable sediment can be added construction of the FV-1 road, which crosses the isthmus lengthwise (10 km long and 20 m wide) and the tourist resorts. In the 1980s and 1990s this road had to be constantly cleared of sand deposited by the wind. Today, such maintenance work is not required, which evidences the decrease since then of aeolian

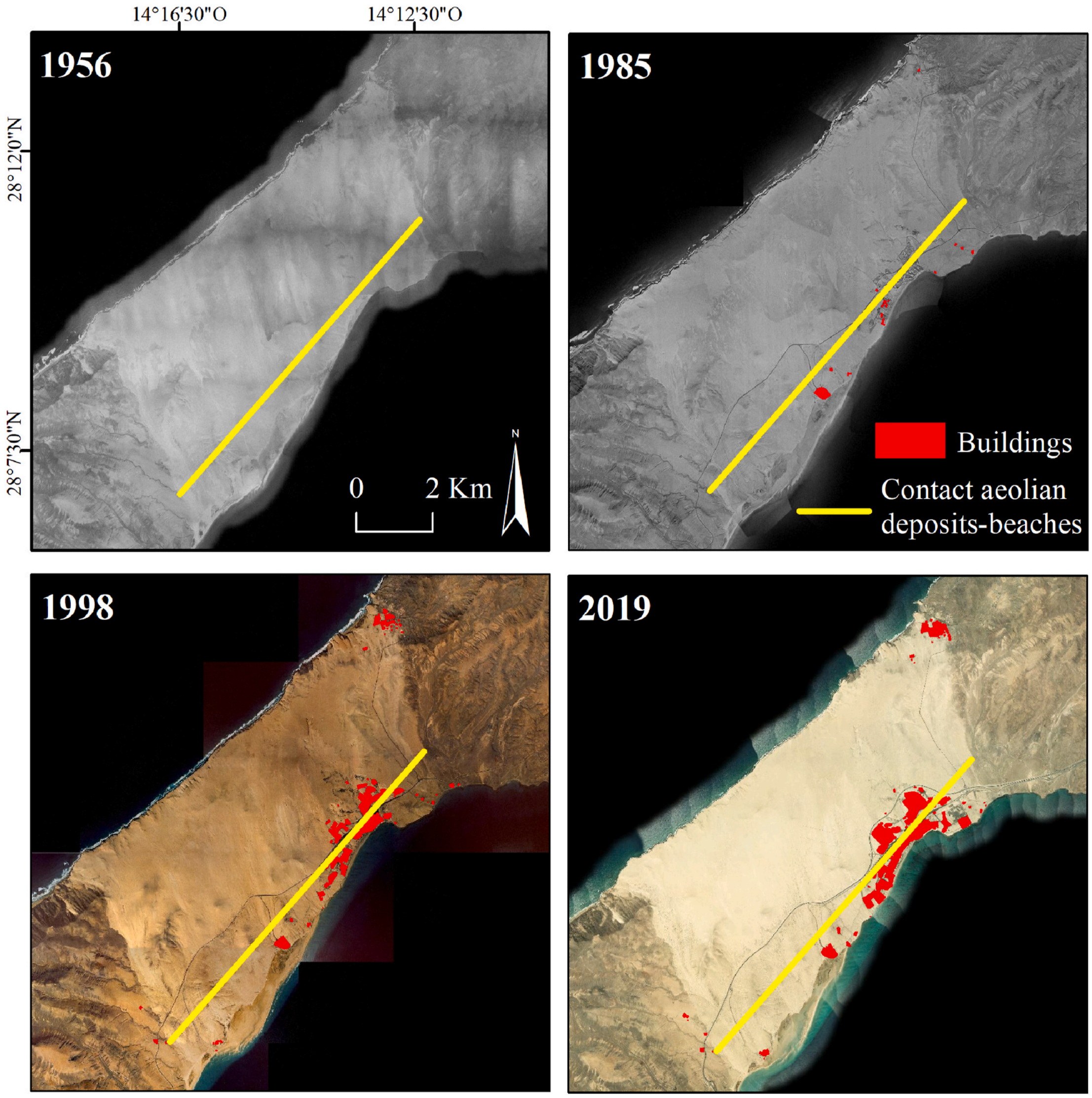

Fig. 3. Urbanization process in the isthmus of Jandía. The line of contact between the aeolian deposits and the Sotavento beaches is marked in yellow (Source of digital orthophotos: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

transport.

For its part, the urbanization process reduced the line along which the sediments can freely circulate from the aeolian deposits to the beaches from 9.6 km in 1956 to 3.3 in 2019 (Fig. 3). This partitioning effect was even more marked with the construction of the FV-1 road and its later upgrading.

4.2. Availability of aeolian sediments

The current aeolian transport is conditioned by numerous factors, such as barriers to transport (urbanization and roads), the reduction of available sediment due to the extraction of aggregates and the recovery of vegetation since the traditional production of lime ceased. However, attention should also be paid to sediment availability in the deposits that have to date fed the Sotavento beaches (Alcántara-Carrió et al., 2010).

The amount of available aeolian sediment varies considerably in the isthmus. Fig. 4, created on the basis of the results of test pits made in the study area, shows that the sectors situated to the northeast of the isthmus have thicknesses that do not exceed 20 cm. However, thickness increases in the central sector of the isthmus, varying between 20 and 60 cm depth over a 24 km^2 area. The thickness is determined by the landforms, with larger amounts accumulating in the thalwegs and significant aeolian deflation being observed in more exposed areas. The greatest thicknesses were found in the Pecenescal ravine, varying between 75 and 100 cm over large areas exceeding 4.5 km^2.

4.3. Vegetation

Vegetation cover in the isthmus has varied over the study period. It was reported by Marrero-Rodríguez et al. (2020a) that the area occupied by vegetation increased between 1963 and 2016, most notably in areas close to the road and to the south of it. As commented in section 4.1, grazing and the use of vegetation as fuel generated an important deforestation process. However, the vegetation has undergone a natural process of recovery in recent decades related to the abandonment of the aforementioned traditional land uses.

With respect to specific species distribution, this is strongly dependent in the isthmus on adaptation to the sandy substrates and ambient salinity. Species adapted to continuous ponding like *Arthrocnemum macrostachyum* appear along the Sotavento coast (Saladar - saltmarsh sector), while along the Barlovento coast the dominant species are those better adapted to higher sediment mobility and burial (*Euphorbia paralias*) and to saline spray (*Tetraena fontanesii*). In areas with caliche outcrops or substrates with less sand content situated in the northeast tip of the isthmus, the species that are found include *Convolvulus caput-medusae, Limonium papillatum, Lotus lancerottensis, Ononis serrata, T. fontanesii* and *Frankenia capitata*. Other species more generally distributed throughout the habitats of the isthmus include *Launaea arborescens, Lycium intricatum* and *Salsola vermiculata*. It should be noted that some species are in different protected categories (Table 2) and are found in different parts of the isthmus (Fig. 5).

Finally, it is important to note the presence of *Cymodocea nodosa* meadows in the submerged sectors between the beaches of Sotavento and Piedras Caídas where the low depth allows it. This phanerogam of up to 60 cm height is usually found on sandy bottoms at depths of between 2 and 10 m, though it can be found at depths of up to 30 m. It stabilizes the sandy substrate where it is located and acts as a natural

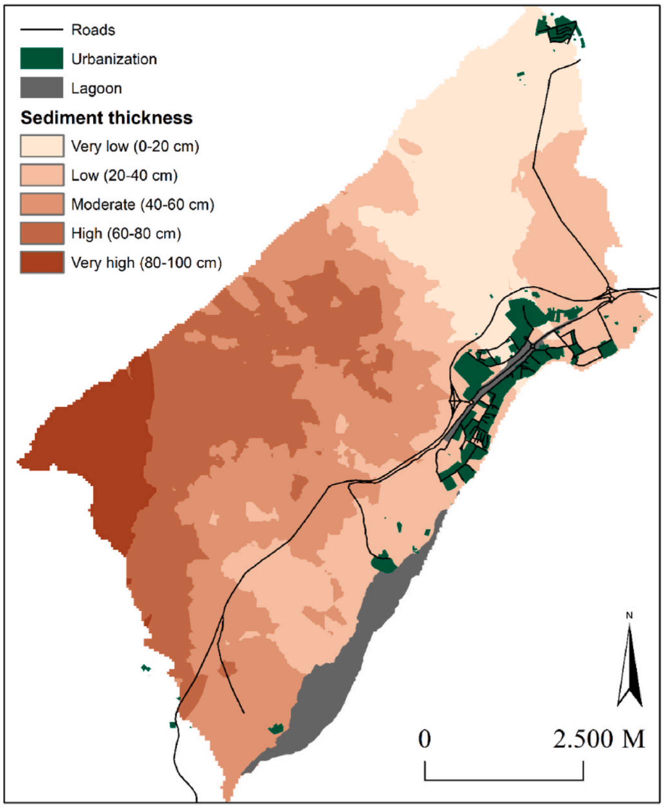

Fig. 4. Thickness of the sand sheet in the isthmus of Jandía.

Table 2

Protected species found in El Jable. Protected categories: Canary Catalogue: Act 4/2010, of June 4, on Canary Catalogue of Protected Species; National Catalogue: Royal Decree 139/2011, of February 4, on the development of the List of Protected Wild Species and the Spanish Catalogue of Threatened Species; Habitat Directive 92/43/EEC, dated 21 May of 1992, on the conservation of natural habitats and of wild fauna and flora; Flora Instruction, dated 20 February of 1991, on the protection of the wild vascular flora of the Canary Islands Autonomous Community. Source: Canary Islands Biodiversity Databank.

Scientific name	Canary Catalogue	National Catalogue	Habitat Directive	Flora Instruction
Tetraena fontanesii				Annex II
Herniaria fontanesii				Annex II
Limonium papillatum	Of interest for Canary ecosystems			
Traganum moquinii	Vulnerable			
Arthrocnemum macrostachyum	Of interest for Canary ecosystems			
Aichryson pachycaulon				Annex II
Aichryson pachycaulon ssp. *pachycaulon*				Annex II
Tamarix africana				Annex II
Tamarix canariensis				Annex II
Frankenia boissieri				Annex II
Convolvulus caput-medusae	Vulnerable	Special Protection Regime	Annex II and IV	
Pulicaria burchardii	Endangered species	Endangered species		
Pulicaria burchardii ssp. *burchardii*	Endangered species	Endangered species		
Artemisia reptans	Of interest for Canary ecosystems			
Cymodocea nodosa	Of interest for Canary ecosystems	Vulnerable		
Land species		Marine species		

Table 3
Estimations of depth of closure (*dc*) on the basis of different methods of application of the formula of Hallermeier (1981).

	Data period	H_s	T_s	dc
Mean SIMAR values	1958–2020	2.87	8.78	5.80
Maximum SIMAR values	1958–2020	3.89	8.52	7.41
10-year extreme climate values	1992–2017	4.37	10.49	8.75
Mean value				7.32

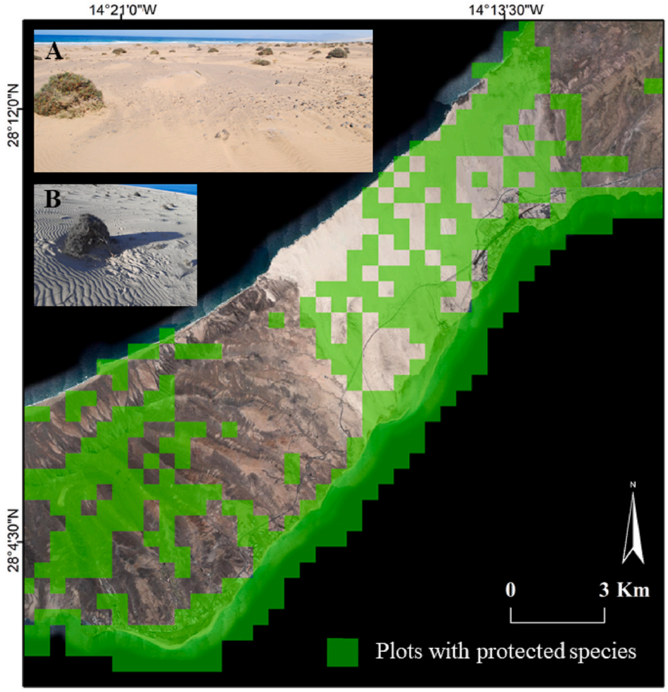

Fig. 5. Distribution of protected species (Source: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.). A: Monospecific thicket of *Launaea arborescens* in present day grazing land area. B: Goat resting area in a nebkha formed by *L. arborescens.*

defence against sea storms. However, in recent years these meadows have undergone significant declines in the Canary archipelago (Tuya et al., 2014).

4.4. Coastline evolution

The coastline of the study area displays a clear erosive tendency throughout the study period. However, there are some important spatial and temporal differences (Fig. 6). South of the Costa Calma tourist resort there is a clear erosive tendency (this area has the highest degree of erosion where 250 m of beach have been lost), causing the beginning of the sand bar to progressively shift southwards (Fig. 6a) with a consequent decrease in size of the lagoon area. The apex of the sand bar is the most varying coastal point in the whole study area and where the most significant changes are. The trend in this area is slightly in favour of progradation, indicating a net sediment accumulation. Finally, the southern tip shows no clear trend, with the final coastline position being the same as in 1956.

The gain or loss in coastal area throughout the study period and between the different dates was calculated on the basis of the digitalized coastlines. In order to carry out a more detailed analysis the coastline was divided into 6 zones (Fig. 7). These six zones represent different environments of the study zone that present different changes among them: i) zone 1: beaches in front of the urbanization of Costa Calma; ii) zone 2: littoral bar; iii) zone 3: apex of the littoral bar; iv) zone 4: beaches located at the mouths of ravines; v) zone 5: eastern sector of the Matorral point; vi) zone 6: western sector of the Matorral point.

Zone 1 is a space which experienced both losses and gains in the study period, but in each case in small amounts. A loss of 80000 m^2 took place between 1956 and 1981, followed by a gain of 66000 m^2 in the period between 1981 and 2002, a further period of erosion from 2002 to 2009, and accumulation once again between 2009 and 2018. The net balance for the whole period was a negative one of some 40000 m^2. Given the size of this zone, this represents a mean coastline retreat rate of 0.25 m/year.

Zone 2 corresponds to the sand bar and underwent the highest losses, which were generally constant throughout the study period though with a particularly high incidence in the 2002–2009 period when 268000 m^2 were lost. A total negative balance of 580000 m^2 was recorded from whole study period (1956–2018), the equivalent of a mean coastline retreat rate of 2.3 m/year.

Zone 3, comprising the apex of the sand bar is a highly varying area influenced by the tides, with sharp losses between dates followed by sharp gains (Fig. 6B). Thus, this zone lost 18000 m^2 in the 1956–1969 period, gained 9600 m^2 in the 1969–1981 period, lost a further 76500 m^2 in the 1981–1994 period, recovered 97800 m^2 in the 1994–2002 period, and finally again lost 79000 m^2 between 2002 and 2018. The overall result is a negative balance of 66000 m^2, equivalent to a net coastline retreat of 0.36 m/year.

The longest of the six zones at 7 km is Zone 4 (Fig. 7). Here, the changes were less significant as the different beaches are narrower and separated by cliff sections and ravine mouths. Again, periods of erosion alternated with periods of accretion, with an overall net surface area loss of 54000 m^2, equivalent to a rate of retreat of just 0.12 m/year.

Zone 5 also has a negative 1956–2018 balance, in this case of 43000 m^2. Gains took place in the 1956–1969 and 1981–2002 periods of 21000 m^2 and 75600 m^2, respectively, while losses of 46600 m^2 and 93000 m^2 were found for the 1969–1981 and 2002–2018 periods, respectively (Fig. 7C).

Zone 6 was the only zone to have an overall positive balance (of 17500 m^2) when considering the entire study period (1956–2018). Losses in the 1956–1969 period (35000 m^2) and the 2002–2018 period (28000 m^2) were more than made up for by gains between 1969 and 2002 of 84000 m^2.

In short, the study area underwent a considerable surface area loss over the 62 years of the study period (Fig. 7C) of almost 800000 m^2, equivalent to nearly 13000 m^2 each year.

In volumetric terms, it was calculated that the coastal section covered in this analysis has experienced a mean sediment volume loss of some 96000 m^3/year during the period between 1956 and 2018. This is a similar amount to the value obtained by other authors who used different methods (Alonso et al., 2006). The total amount for the whole study period of 62 years amounts to 5900000 m^3 (Fig. 7C). Erosive processes are dominant throughout virtually the entire study area, and are particularly intense in the zone between the strip occupied by the sand bar and the mouths of the Pecenescal and ravines located at the south. The only exception to this generalized erosive tendency is Zone 6.

4.5. Longshore drift

As can be seen in Fig. 8, the bathymetry of the study area is far from homogenous. In general, it can be said that the depth progressively increases along the coastal strip from the northernmost point to the tip of Piedras Caídas (Zones 1–4 in Fig. 7).

In general, the bathymetric depth of −50 m is around 1500 m from the coast, corresponding to a mean gradient of 3.3%. The only exception to this pattern is found at the apex of a cuspate foreland (Profile 2 (P2) in Fig. 8), where the slope is much more marked and a depth of 7 m is found just 100 m from the shoreline. A detailed analysis revealed a very sharp increase in the gradient from the depth of 3.2 m, with a potential consequential loss of sediment.

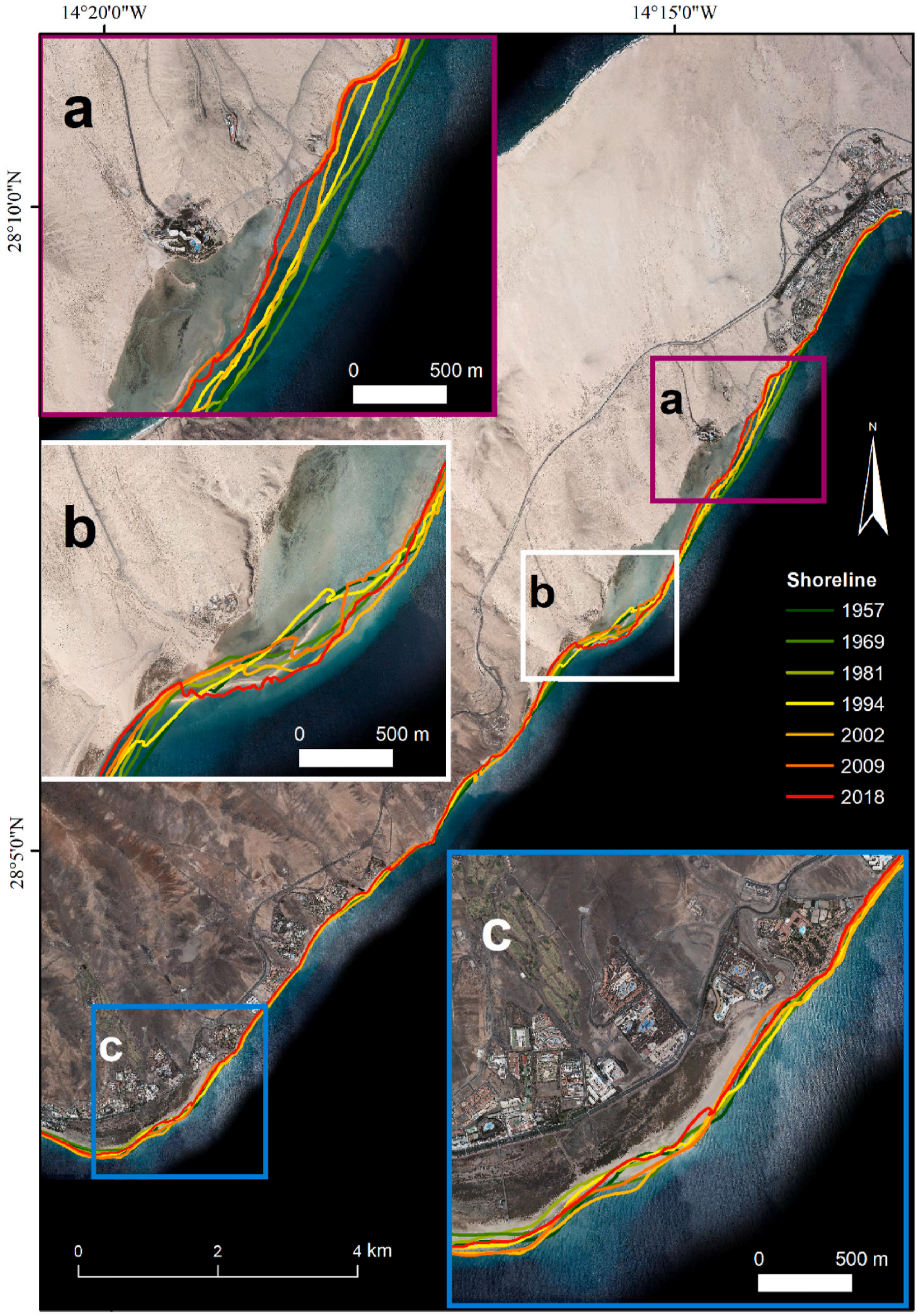

Fig. 6. Evolution of the shoreline between 1956 and 2018 (Source of 2018 digital orthophoto: SDI Canarias, Canary Islands Government, GRAFCAN, S.A.).

At the southern tip of the study area (headland of El Matorral), the gradient becomes dramatically steeper (Profiles 5–8 in Fig. 8). In this section, 100 m of depth are attained at a distance of 1000 m, corresponding to a mean gradient of 10%. In addition to this generalized gradient change, it is also important to note the presence of two large submarine canyons which begin just a few metres from the shore (red ellipses in Fig. 8a). These geomorphological elements have very steep flanks and exceed 100 m in depth. The mean wave and storm wave characteristics for SIMAR nodes 9 and 10 (the closest to El Matorral headland and the apex of the cuspate foreland, respectively) are shown in Table 3. The wave breaking depth is obtained applying the previously described equations for the mean and storm H_s and T_s values for both SIMAR nodes (Table 4).

From the breaking depths obtained it was found that at the apex of the cuspate foreland (values of SIMAR node 10), the mean wave breaks at less than 1 m depth. In such circumstances, longshore drift is restricted to a narrow strip parallel to the coast along the whole cuspate foreland. However, in storm conditions the strip along which longshore drift takes place is considerably wider, reaching a breaking depth of 3.9 m.

Given that this depth is greater than the 3.2 m where there is a notable increase in the gradient, it is plausible to consider that in high energy wave situations part of the sediment escapes from the coastal strip in the area of the apex of the cuspate foreland. This sedimentary material would accumulate along a plain that extends between depths of 12 m and 25 m and covers an area of some 3 km^2 (green ellipse in Fig. 8).

If considering exclusively the data from the period 1996–2020, 0.17% of the H_s values exceed 2 m. This percentage corresponds to just 15 h a year, during which it is very probable that part of the sediment escapes from the longshore drift and is deposited along the

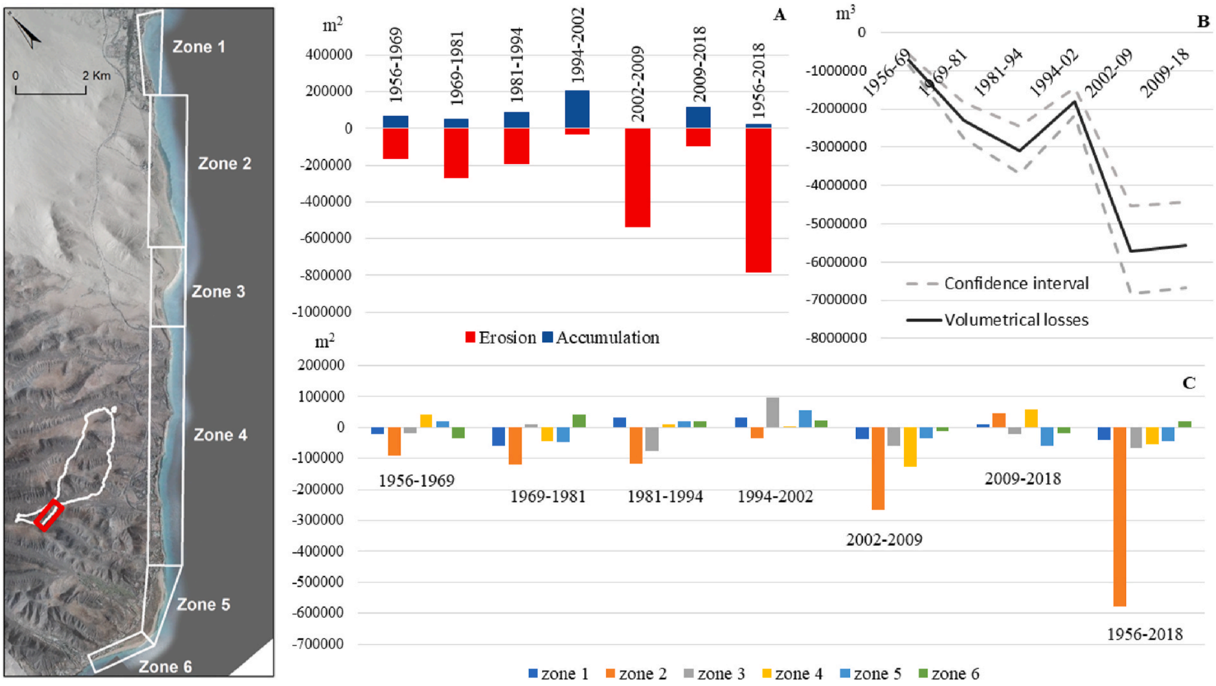

Fig. 7. Erosion and accumulation balance in the study area for the period 1957–2018. A: Erosion and accumulation rates by periods for the entire study area; B: Sediment volumetric loss for the different study intervals between 1956 and 2018. The mean values are presented with the confidence interval between the values obtained on the basis of the SIMAR data and those obtained on the basis of the 10-year extreme climate data (Table 3); C: Erosion and accumulation by sector and period.

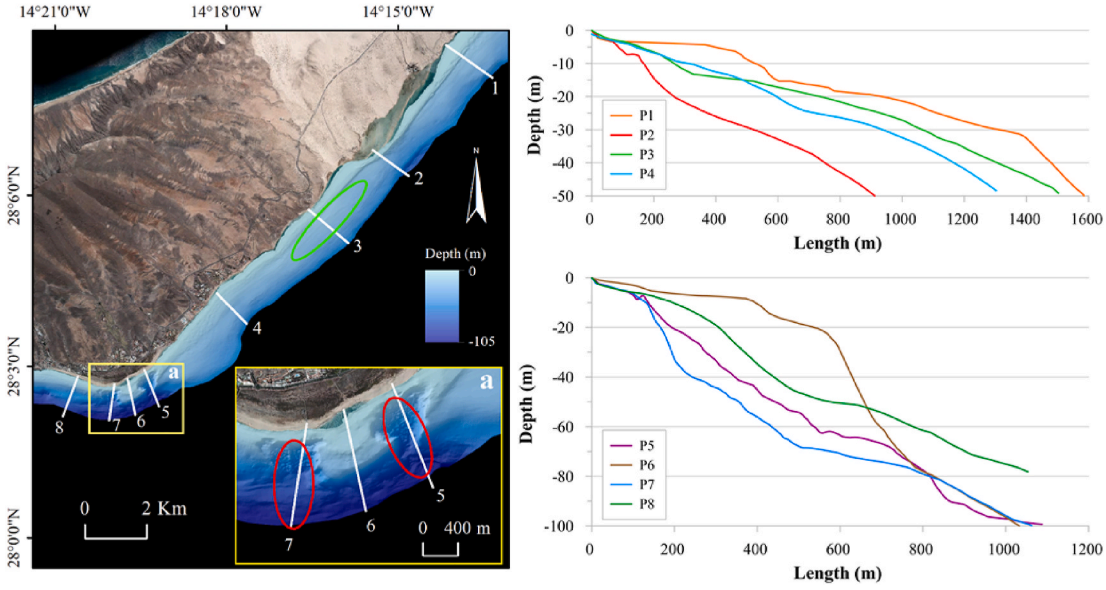

Fig. 8. Bathymetric model of the study area. Different bathymetric profiles representative of the study area are shown (Source: General Directorate of Sustainability of the Coast and the Sea, 2001).

Table 4
Wave breaking depths obtained for both fair weather and storm conditions recorded at each of the SIMAR nodes.

		H_s	T_s	H_b	γ	d
SIMAR 10	Mean wave	0.56	5.70	0.78	0.91	0.85
	Storm wave	2.82	8.78	3.37	0.87	3.88
SIMAR 09	Mean wave	0.87	9.54	1.36	0.95	1.43
	Storm wave	3.57	9.57	4.21	0.86	4.87

aforementioned plain (green ellipse in Fig. 8).

With respect to the El Matorral headland (values of the SIMAR 09 node, see Table 4), in normal conditions the breaking depth is 1.5 m, a value which rises to 4.9 m in storm conditions. Given that, in this case, the head of the canyons is found just a few metres from the shoreline, it could be argued that sediment will be lost even in mean wave conditions and a lot more in storm conditions. Only in conditions of a totally calm sea is it possible to imagine longshore drift restricted to such a narrow strip that no loss of material to the canyons would occur. Of the wave data in this area, 12% correspond to values of $H_s < 0.5$ m, circumstances in which longshore drift is very slight, but the small amount that would occur would accumulate on the El Matorral beach (Zone 6, Fig. 7). However, when there is a slight increase and $H_s \geq 1$ m (which occurs 30% of the hours of the year), the strip where longshore drift takes place would be sufficiently wide for sediment to be lost to the submarine canyons.

That is, the El Matorral beach acts as an area of deposition in calm sea situations, when the sediment accumulates in the headland area and preferentially in the strip closest to the shoreline. In contrast, in mean wave and storm wave situations, the accumulated sediment and the sediment transported in these conditions by longshore drift is lost to the submarine canyons.

Fig. 9 shows an outline of sediment transport in these three conditions: practically calm sea (Fig. 9A), mean wave (Fig. 9B) and storm wave (Fig. 9C) conditions. Each image shows where the losses of material, remobilized as the result of longshore drift, would take place: In the first case, transport is weak and the sediment accumulates on the El Matorral beach. In the second, sediment transport is more intense and sediment is lost to the submarine canyons at the El Matorral headland. In the third, sediment transport is considerably more intense. The longshore drift branches off at the apex of the cuspate foreland, with part of the material lost in this area deposited on the plain shown in green in Fig. 8. The rest of the material continues its journey southwards before finally being lost to the submarine canyons (red ellipses in Fig. 8a).

5. Discussion of management proposals

There is no easy solution in terms of mitigating the changes that coastal areas undergo as the result of inappropriate human interventions (García-Romero et al., 2016; San Romualdo-Collado et al., 2021a) or the changes in environmental conditions (Petit and Prudent, 2010; Pye and Blott, 2012; Sauter et al., 2013). In this case, beach erosion is resulting in the loss of a basic natural resource for the development of the tourist activity. Consequently, conservation of this tourism resource has become a priority for management bodies. However, in many cases, the solution to erosion problems requires major interventions that can entail the loss of other sectors of the ecosystem, generate visual impacts that can negatively modify the perception users hold of that space, fall foul of the prevailing legislation, and/or represent significant economic investments (Edmondson and Velmans, 2001; Alexandrakis et al., 2015).

This is exemplified in Jandía by the fact that protection of the ecosystem and the Use and Management Master Plan established for it do not allow interventions that would minimize erosion of the saltmarsh and beaches. Therefore, the protection does not contemplate the necessary tools to guarantee the conservation of the ecological processes that characterize the functioning of the ecosystem, but only manages the land uses without taking into account that it is a dynamic environment that is currently responding to historical human alterations; as the erosive processes appear to be related to the abandonment of traditional uses (grazing and the gathering of vegetation for fuel), the appearance of barriers to aeolian transport and the spontaneous recovery of vegetation (Alcántara-Carrió et al., 1996; Marrero-Rodríguez et al., 2020a). Erosion of these beaches today is damaging certain infrastructures as well as causing the disappearance of an environmental resource that constitutes the basis of a tourist industry of great local socioeconomic importance. All of which has given rise to a search for possible alternatives to stop or at least slow down the loss of sediments.

For the purposes of this study, a review was undertaken of possible soft management measures along with an evaluation of their usefulness and potential application in the study area in view of the information and results given in the preceding section of this paper. On the basis of this review, four possible forms of action were determined; passive management, sediment remobilization, beach nourishment, and mechanical sand recirculation.

5.1. Passive management

Passive problem management means taking no action and allowing the system to evolve naturally. The paradox arises that this is the only measure allowed by current legislation but, if current trends continue, it

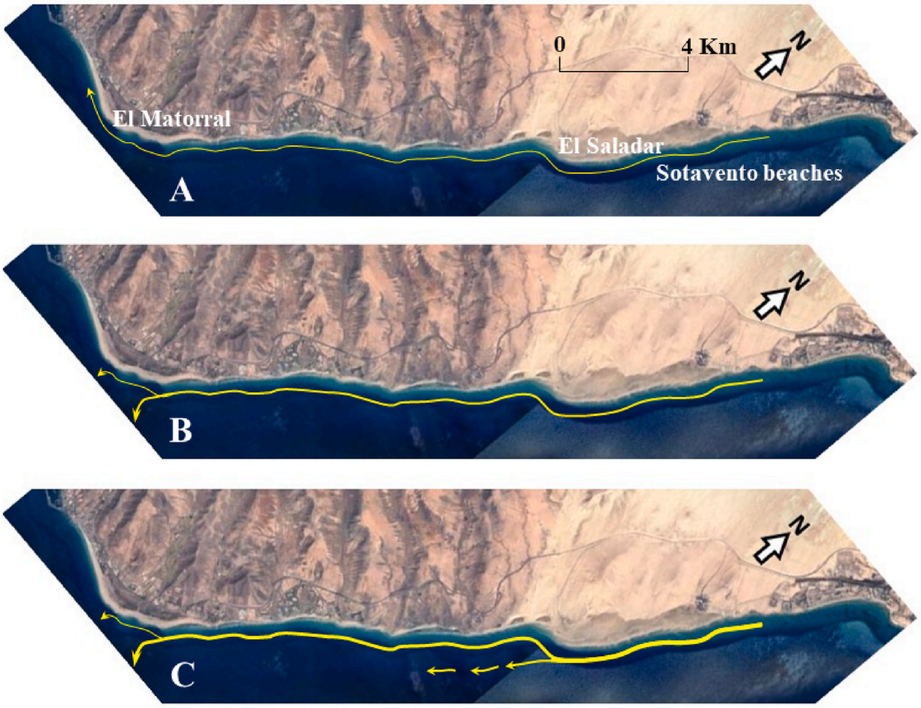

Fig. 9. Conceptual diagram of longshore drift in the study area. A) calm sea conditions. B) Mean wave conditions. C) Storm wave conditions. The thickness of the yellow lines indicates sediment transport intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

would mean the disappearance of the Sotavento beaches and Saladar, the saltmarsh sector (Fig. 1), at least in the areas where the beaches do not reach equilibrium situations as they are protected by natural projections. In this respect, the study area has a basement of alkaline basaltic lava and pyroclastic material (Coello et al., 1992) which, by reaching it, would slow down the erosion processes. In this case, the beach area would be significantly reduced in many sectors but the impacts derived from other management measures on the ecosystem would be avoided. It is possible that, as Marrero-Rodríguez et al. (2020a) pointed out, the Sotavento beaches would have undergone a process of progradation between approximately 1850 and 1960 due to the gathering and use of vegetation as fuel which would have caused aeolian erosion of the isthmus. Beach erosion would be a natural response to the cessation of this land use, accelerated by the extraction of aggregates and the construction of barriers to sediment transport (roads and urbanizations). Furthermore, ecosystems do not always return to their original state prior to human intervention, but rather reorganize themselves based on the new environmental conditions (Kombiadou et al., 2019; Marrero-Rodríguez et al., 2020b) including, among others, sediment availability, topography and vegetation cover. Passive management would therefore allow the ecosystem to continue with its natural evolution or its response to human interventions, whether it is natural erosion processes (depletion of sediment inputs from the isthmus of Jandía), anthropic processes (creation of barriers to sediment transport) or a combination of both. This form of management has been proposed for other systems such as the small island of La Graciosa (Canary Islands, Spain) (Pérez-Chacón et al., 2010, 2012), which received a total of 250, 000 tourist visits between 2011 and 2019 (ISTAC, 2020). The analysis of the aerial photographs shows that the beaches of Costa Calma, in front of the urbanized sector, are stabilized and that the buildings only suffer damage during storms, since they are not in the protected area, interventions to protect the buildings are allowed and could be carried out easily.

5.2. *Reestablishment of sediment transport*

This measure consists of restoring the flow of aeolian transport that once fed the Sotavento beaches. Remobilization of the sand by removing the vegetation, a measure used in other dune systems (Burton, 2001; Plassmann et al., 2010; Millett and Edmondson, 2013) is prohibited in the Use and Management Master Plan. In any case, for various reasons it is not recommended as a solution to the erosion problems of the Sotavento beaches. On the one hand, because the elimination of vegetation without damaging the plant communities and protected species is complex due to their extensive distribution in the study area. In this regard, the only viable way is to hire crews that perform manual species discrimination, thus avoiding the numerous negative effects of the removal of vegetation through mechanical means or by encouraging increasing livestock grazing. In the latter case, such negative effects include the creation of monospecific scrub and damage to the landforms due to the establishment of, for example, burrows, wallows and trails (Zunzunegui et al., 2012). Furthermore, the strong arid conditions of Jandía have traditionally only allowed goats, rabbits and camels to graze. However, given the transit of walkers, camel grazing is not recommended due to the aggressive behaviour they exhibit, especially in the reproductive season (Yagil and Etzion, 1980). The traditional grazing model in Jandía does not allow control over the animals and has therefore resulted in a considerable impact on the flora and substrates of the protected area (Gangoso et al., 2006; Rodríguez et al., 2005). With respect to the use of machinery, this would have a major impact on the aeolian system due to the need to create tracks for the machines to access the areas with the greatest sediment thicknesses. In addition, when machinery is used to eliminate vegetation it is difficult to select between, for example, protected and unprotected species.

Likewise, even if the sand sheets were remobilized, it would require a very large volume of sand to alleviate the long-term erosion of the Sotavento coast, which has been estimated at 96,000 m^3 per year (see section 4.4). In this sense, there are few sectors in which the free movement of the sand can occur due to the constructions and the highway. In addition, this measure would induce an intense process of erosion of the biogenic deposits of the isthmus of Jandía. According to Marrero-Rodríguez et al. (2020a), something similar occurred between approximately 1850 and 1960, on that occasion until their exhaustion as there are no current contributions from the beaches and cliffs of Barlovento (Alcántara-Carrió, 2003; Alcántara-Carrió et al., 2010). It is also important to pay attention to the fact that sediment losses, once the sediment has been deposited on the beach, will continue over time.

5.3. *Beach nourishment*

Beach nourishment is a method that has been used in Spain since 1983, mostly along the Mediterranean coast (Hanson et al., 2002). It is a preferred method because of its economic advantages (Finkl and Walker, 2005), but can cause important ecological damage to beach habitats (Peterson and Bishop, 2005; Speybroeck et al., 2006). The factors that influence beach nourishment include the mechanical process employed, the time required, the amount of sediment contribution and the characteristics of that sediment (Speybroeck et al., 2006). Beach nourishment has also been found to have impacts on micro and macro fauna (Bishop et al., 2006; Beach, 2000; Speybroeck et al., 2006; Peterson et al., 2000; Menn et al., 2003; Bilodeau and Bourgeois, 2004). It often only functions as a temporary solution, with beaches likely to maintain their erosive tendency (Peterson and Bishop, 2005) and their recovery may be only for short periods of time (Defeo et al., 2009). Good long-term results are related to sediment quality and whether its characteristics are suitable for the beach conditions (Peterson et al., 2000, 2006). For this reason, in many areas such interventions are accompanied by the construction of seawalls, breakwaters or groynes (Pilkey and Wright, 1988; Hsu et al., 2007).

In addition, beach nourishment is only allowed where beaches are not situated in a protected space and where longshore drift is limited (for example the Costa Calma beaches). However, in Jandía the whole coastal strip is a protected space (Fig. 1). This protection is fundamentally due to the presence of *C. nodosa* meadows which would be severely affected by the turbidity that beach regeneration would cause (Tuya et al., 2014; Fabbri et al., 2015). Nonetheless, four beach nourishment options are described below which differ in terms of the source of the sediment:

i) *Purchase of sediment from abroad*. There are numerous artificial beaches which have been constructed using sand imported from other countries, including several examples in the Canary Islands where sediment has been acquired from Morocco or the Bahamas. Importantly, in these cases the beaches are artificial in their entirety and the deployment of different coastal engineering works significantly reduces the energy of the incident waves ensuring that the sediment contribution remains relatively stable. It should also be noted that it is very complicated to obtain sediment from elsewhere with similar characteristics to those of the local area that do not have a negative effect on the beach (Goldberg, 1988; Peterson et al., 2000, 2006). It is also difficult to avoid the introduction of exotic invasive species, and so the sand needs to be fumigated.

ii) *Sand extraction from submarine banks*. This option has been employed on various occasions for the regeneration or construction of beaches in the Canary Islands. Examples include the Santa Cruz beach in La Palma, where 740000 m^3 of sand were used from the submarine sandbank in the Nogales area (Puntallana, La Palma) (MITECO, 2020). As in the previous case, regenerated beaches are artificial, with the sediment contribution maintained *in situ* thanks to a series of coastal engineering works. In addition, the area where the material is extracted should be as close as possible to where it is to be used. In the case of Jandía, as reported in section 4.4, 96000 m^3 of sand are lost each year, mainly to the canyons situated opposite El Matorral beach and some along the steep slope opposite the apex of the cuspate foreland (Fig. 8). The shape and depth that these canyons reach make the dredging of sand here an unfeasible option, with the most viable dredging site being the area identified in Fig. 9 where the bathymetry seems to indicate the existence of a submerged sandbank at depths of between 12 and 25 m. Both the depth and distance from the area where the sand would be deposited are ideal for this type of operation. However, given that nearly 100000 m^3 of sediment would be needed each year, it is vital to ensure that the sandbank has a sufficiently appropriate volume of material for extraction to guarantee a periodic contribution to the beaches for various decades. In addition, care needs to be taken with respect to the presence of sea meadows of the phanerogam *C. nodosa*, which could suffer serious damage as a direct result of dredging activities and as an indirect result of the increased turbidity that would be generated and which has been shown to have negative effects on such meadows (Silva et al., 2013).

iii) *Crushed stone* Another alternative to nourish the beaches is to use crushed stone. An example of the results of this method can be seen at Martiánez beach in Puerto de la Cruz (Tenerife, Canary Islands), which was regenerated through the contribution of 132000 m^3 of sand obtained from crushed stone (MITECO, 2020). While technically feasible, the production of sand obtained from crushed stone has some drawbacks, most notably a highly varied granulometry with the usual inclusion of pebbles, gravel and sand despite the sieving that takes place. Moreover, the composition of the material would be basaltic, which would mean a change of colouring given that the present beaches are mostly organogenic in nature. Such a change could affect the perception held of the beach by its users (Pranzini et al., 2010). Finally, it should be noted that the production of large volumes of sand using this technique is very expensive, especially when considering the need to produce some 100000 m^3 of material each year, making it effectively unsustainable over time.

iv) *Sand extraction in the isthmus*. Loose sediments in the interior of the isthmus, as previously mentioned, are of marine origin and their origin is related to sea levels different to those of today. The present relative position of the sea level would seem to suggest that there could not be significant contributions from the Barlovento coast (Alcántara-Carrió et al., 2010). However, there are areas where the thickness of these materials is substantial (Fig. 4). One such area is the head of the Pecenescal ravine, where sand extractions have previously been carried out (Alcántara-Carrió et al., 1996). As far as the presence of protected species is concerned, this would also be a viable option given that, as can be seen in Fig. 5, no such species are found in the areas of greater sediment thickness. However, the effects of sand extraction have been widely studied. Some works have reported evidence of changes in the recovery patterns of vegetation cover and the species that recolonize the area (Fernández-Montoni et al., 2014; Price et al., 2005), while others have reported reactivation of the sand sheets (Garriga-Sintes et al., 2005) or the generation of flooded zones and areas of aeolian deflation (Marrero-Rodríguez et al., 2020b). In addition, isthmus-based extractions would only guarantee beach nourishment for a relatively low number of years as the resource in the area in question is limited. Finally, and very importantly, sediment extraction from the isthmus also happens to be prohibited by law.

5.4. Mechanical sand recirculation

This proposal involves taking sand from areas of accumulation and depositing it in areas of erosion overland through the use of machinery. This option has two main advantages. Firstly, it allows sediment reuse innumerable times, meaning that 100000 m3 of new material each year would not need to be produced. Secondly, the deposited sand comes from the same system, and hence will have the same sedimentological characteristics (grain size, density, composition, etc.). Some drawbacks may also be encountered. These include sand extraction in the intertidal area increasing turbidity in the water and potentially affecting the marine phanerogams that inhabit the subtidal regions of nearby beaches (Silva et al., 2013). In addition, sand extraction can substantially alter the beach slope, which can directly impact beach sediment behaviour and potentially negatively affect the perception of the beach by its users.

The only part of the study area with sand accumulation is found in Zone 6. However, despite its cumulative tendency, its use would have to be discarded as there is sufficient sediment to cover just 2.63% of the current annual deficit of the system.

6. Conclusions

The coastline of the study area on the island of Fuerteventura has shown a clear erosive trend since at least 1956. However, this erosive tendency is not homogenous, and there are significant spatial and temporal differences. The strip with the highest degree of erosion is situated south of the Costa Calma tourist resort, where some 250 m of beach have been lost. This in turn has caused the beginning of the reef to shift 1 km southwards with a consequent decrease in size of the lagoon area. The analysis of longshore drift that was undertaken revealed that some 96000 m^3 of sediment is transported southwards each year, and that most of it is lost to two submarine canyons situated opposite the El Matorral headland.

Proper management of this shoreline is necessary because of the danger of the loss of elements of important natural value and because of the damage that is being caused to the tourist industry that is the main driver of the island's economy. However, the beaches of Costa Calma, in front of the urbanized sector, are stabilized and that the buildings only suffer damage during storms, since they are not in the protected area, interventions to protect the buildings are allowed and could be carried out easily. The rest of the shoreline despite its being declared a protected space with the aim of ensuring the continued existence of an area of exceptional natural values, the regulations that have come into force as a consequence of its protected status do not permit the interventions that are necessary to mitigate the erosion processes that the area has been experiencing for over 60 years. The only measures that could be undertaken in the study area are artificial regeneration and mechanical sand recirculation. Reestablishment of aeolian sediment transport is discarded because the ways available to carry out this task would not allow to keep the protected species undamaged. On the other hand, passive management would force new damage to infrastructure and the disappearance of the salt marsh. However, all the measures would imply a high and continuous economic cost and, therefore, are of doubtful long-term sustainability. Artificial regeneration with local sediment is also discarded because with the current sand volume available in the study area it will also not be sustainable in the long-term; the same problem is related to other ways of nourishment. In this sense, beach nourishment will have very limited succeed because of the high economic cost that will be continuous in time and the impossibility of building infrastructures for the retention of sediment. However, the combination of different measures (artificial regeneration and mechanical sand recirculation) could be the key to stop erosion problems.

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.

Acknowledgments

The authors would like to thank the City Council of Pájara (Fuerteventura) for financing this work and Puertos del Estado for providing the data for wave and transport analysis.

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