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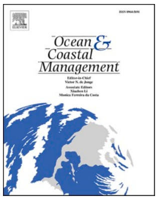

Using multi-scale spatio-temporal shoreline analysis of an urban beach adjacent to a basin system on an oceanic island for its integrated planning

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ABSTRACT

The increasing littoralization process of coastal areas in recent decades to adapt them to user needs has generated important changes in ecosystems. This is the case of the coast of Tazacorte (Canary Islands, Spain) where the construction of a port in the 1970s caused changes to the coastal dynamics that allowed the appearance of a sandy beach as a result of contributions made by ravines and beach nourishment actions. In this context, the aim of this article is to carry out an analysis of the current situation of the beach and better understand its relationship with local ravines and the effects of recently constructed infrastructure. The management measures that have been executed to date are discussed and new measures are proposed. The methodology combines field work, variation of shorelines, LiDAR analysis and marine and atmospheric climate characterization. The results show a clear difference between the processes analysed in the long term where the variation in shoreline, beach area and volume indicate a positive trend (between 17.64 and 151.05 m, from 15,060 to 67,096 m2 and from 141,564 to 630,674m3 respectively), and which is mainly explained by the role of infrastructures (breakwaters and port), however, a short-term analysis from 2009 to 2020, the results show that the beach and the seafront continue to flood as a consequence of marine storms and runoff from the gullies, despite the inputs made the negative trend and an irregular behaviour, that is, years with a volume of 689.966 m3 in 2010 and years with 604,096 m3 in 2014. In this sense, the natural dynamics of the beach are discussed against a beach management that costs approximately 45,000 euros per year and requires continuous work during the winter and spring. Therefore, this research, through the management measures it proposes, aims to increase its natural resilience to extreme events from a long-term point of view.

1. Introduction

Beaches are an important tourism resource for many coastal economies (Klein et al., 2004). This has caused an increasing concentration of human activity on the coast, especially on sandy shores (Caffyn and Jobbins, 2003) where sandy beaches are frequently altered to satisfy the growing demand for this landform (Polnyotee and Thadaniti, 2015; Liu et al., 2019; Yang et al., 2021). Sandy shorelines are fragile environments that undergo rapid transformations when changes occur in their natural components. Modifications to the natural processes affecting these coastal environments are often carried out to adapt them to the needs of users (Peña-Alonso et al., 2018; Sanromualdo-Collado et al., 2021), with many beaches experiencing erosion as a result (Sajinkumar et al., 2021; Bitan et al., 2020; Hasiotis et al., 2021). The erosion processes are associated with the construction of infrastructure (Phillips and Jones, 2006), urban development (Alcántara-Carrió et al., 1996; Alonso et al., 2002), changes in land use (Marrero-Rodríguez et al., 2020, 2021a) and sand mining (Rangel-Buitrago et al., 2023), among other causes. The changes that occur include, as well as erosion (Bird and Lewis, 2015), progradation (Guillén and Palanques, 1997; Anthony et al., 2014; Moussa et al., 2019), modification of the type of sediment (Pezzuto et al., 2006; Bird and Lewis, 2015; Marrero et al., 2017) and even the total disappearance of the beach (Pérez-Hernández et al., 2020). Also, the natural factors including different incident wave environments (Zhenpeng Ge et al., 2017), storms (Pang et al., 2021) and the reduction on sediment input (Marrero-Rodríguez et al., 2021a) also

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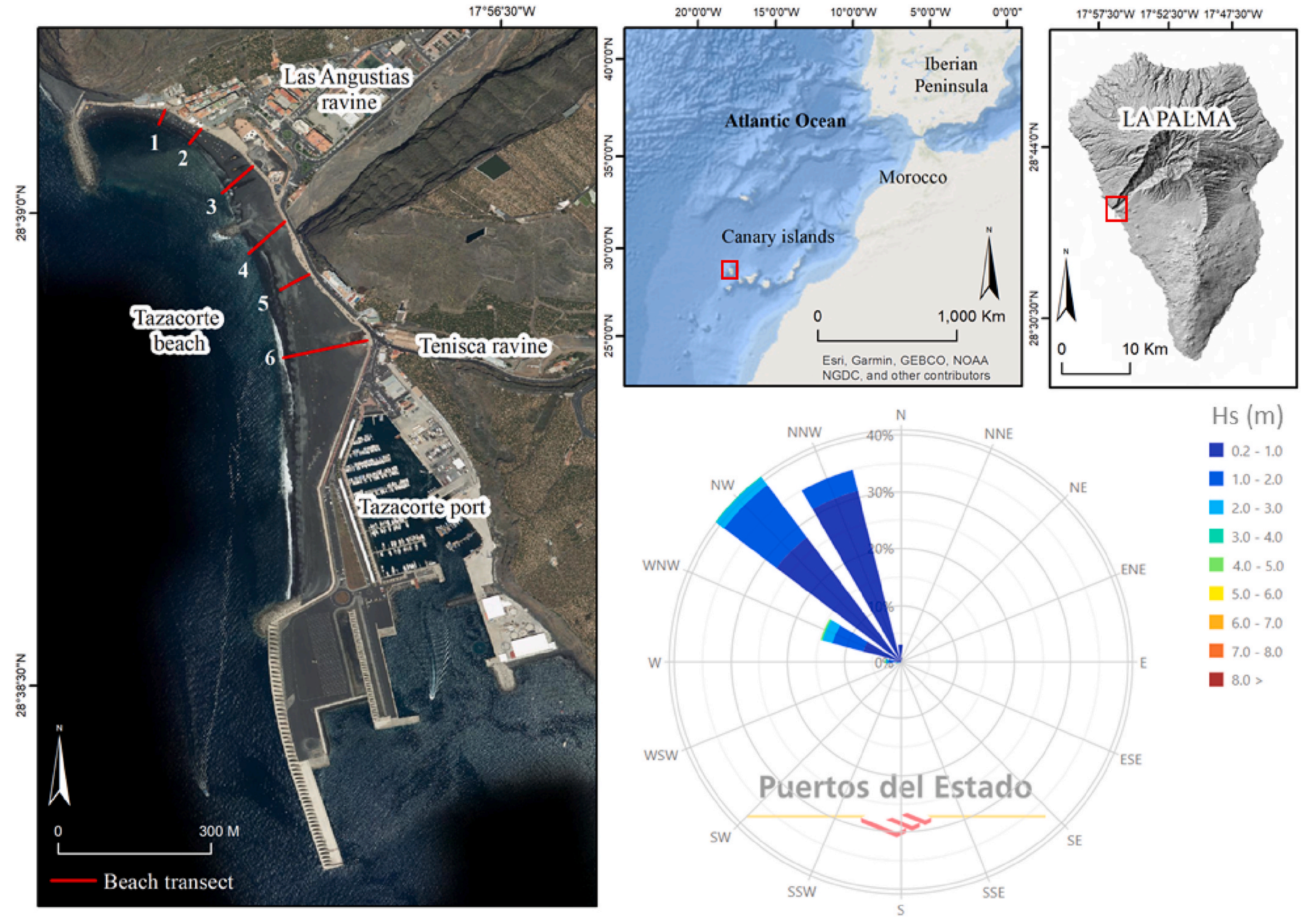

Fig. 1. Location of study area. Wave rose corresponding to node SIMAR 4006017 for the period 1964–2022 (18.00° W and 28.67° N). Red transects were used for topographical changes through profiles.

played important roles on shoreline temporal retreats and erosion.

Even though beaches provide an important variety of ecosystem services, such as providing habitats, foraging and nesting areas for many species or acting as a highly efficient buffer against storms (shoreline protection), in many places they have been mostly used for recreational activities (Beck et al., 2001; Defeo et al., 2009; Barbier et al., 2011; Amaral et al., 2016; Escánez-Pérez et al., 2016). However, the conservation of the landform and its dynamic processes have been relegated to a place of secondary importance, with prioritization given to adaptation of the coastline to user needs and preferences (Peña-Alonso et al., 2018) even when users are willing to pay for the services that the beaches provide (Enriquez-Acevedo et al., 2018).

In this context, a research gap exists regarding enclosed beaches associated to ravine mouths whose sediment supply is limited to occasional ravine runoff during heavy rainfall episodes. The combination of beach sediment loss, the sea level rise (SLR), the increasing number of sea storms, and the urbanization surrounding these systems means that beach retreat inland is impossible and that their disappearance is a strong possibility (De Santiago et al., 2021; Yanes-Luque et al., 2021; García-Romero et al., 2023).

In the case of Tazacorte beach (Canary Islands, Spain), there have been significant changes associated with the construction of a port. This beach, made up of pebbles and cobbles until the 1970s, was transformed into a gravel-sandy beach as a consequence of the presence of the port infrastructure, the contributions of local ravines and beach nourishment carried out by the local authorities. Also, it has been necessary to create breakwaters to reduce wave energy. However, the significant marine dynamics and the important runoff of the ravines during winter causes numerous problems such as flooding, erosion, infrastructure damage and rockfalls from paleocliffs, among others. In consequence, the beach, initially conceived as a tourist and recreational attraction, has become an essential element to prevent the flooding of the seafront and the adjacent town. In this context, the aims of this article are:

i) To carry out a multi-scale spatio-temporal shoreline analysis of the beach, considering the topography, the coastal dynamics, the influence of local ravines and the effects of the infrastructure built around the beach.
ii) To discuss the environmental management actions executed so far, including remobilisation and nourishment projects, and to propose new management measures that take into account all the complex processes that occur on the coast of Tazacorte.

2. Study area

The municipality of Tazacorte is located in the western area of the island of La Palma. Tazacorte beach (Fig. 1) constitutes an anomaly with respect to the general characteristics of the coast, which is generally steep, with the mouths of Las Angustias and Tenisca ravines being the only areas where the cliffs are replaced by a smoother topography. The beach is enclosed by a breakwater to the north and port infrastructures to the south (Sanchez, 2002).

In terms of its climate, data from the Tazacorte weather station (100 m above sea level (m.a.s.l)) show rainfall is very low throughout the year

Table 1
Information related to aerial sources used in this research.

Date	Point density (points/m^2)	Spatial resolution (m)	RMS (m)	Scale	Source
LiDAR					
2009	0.5	2	–	–	IGN
2010	1.2	1	–	–	GRAFCAN S.A.
2011	1.2	1	–	–	GRAFCAN S.A.
2014	1.2	1	–	–	GRAFCAN S.A.
2016	1.2	1	–	–	GRAFCAN S.A.
2020	1.2	1	–	–	GRAFCAN S.A.
Aerial photograph1 and orthophotos[2]					
19,64[1]	–	0.80 m/píxel	–	1:30,000	GRAFCAN S.A.
19,83[1]	–	–	–	1:30,000	IGN
19,89[1]	–	0.12 m/pixel	–	1:5000	IGN
20,02[2]	–	1 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,09[2]	–	0.40 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,10[2]	–	0.40 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,11[2]	–	0.50 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,13[2]	–	0.25 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,15[2]	–	0.25 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,17[2]	–	0.25 m/píxel	<1,5 m	–	GRAFCAN S.A.
20,20[2]	–	0.20 m/píxel	<1,5 m	–	GRAFCAN S.A.
2022	–	0.20 m/píxel	<1,5 m	–	GRAFCAN S.A.

(below 300 mm) and is mainly concentrated in the winter months. However, the location of the study area makes it necessary to consider the precipitation in the entire Las Angustias basin (55.91 km^2). The head of this ravine is in Roque de Los Muchachos at a height of 2426 m.a.s.l., where rainfall is over 1000 mm/year and has been known to exceed 200 mm in 24 h (Máyer et al., 2016). The ravine has a funnel morphology characterized by a very wide head with a channel that gradually narrows towards the mouth. Heavy rainfall concentrated in a few hours and associated to polar front storms (Máyer and Marzol, 2014), combined with the ravine's steep slopes and morphology, can cause sudden floods at the mouth in the winter months (Díez-Herrero et al., 2012; Génova et al., 2015). The other basin that flows into the study area is the Tenisca ravine (42.76 km^2). However, this ravine has gentler slopes and its sediment contribution to the beach is more limited. Nevertheless, after heavy rainfall channels can be opened on the beach by its runoff.

In reference to the maritime climate, the dominant swell is from the fourth quadrant (Fig. 1) with wave heights that exceed 2 m and periods of less than 14 s. However, the impact on the beach of the dominant waves is reduced by the constructed breakwaters.

3. Methodology

The methodology comprises four stages: i) to understand the planimetric evolution of the beach, shoreline and surface area changes over time were mapped using different historical aerial photographs and orthophotos; ii) for the topographical characterization of the beach, its closure depth was calculated to establish an approximate value for the volume of sediment accumulated on the beach (long-term), and digital elevation models (DEMs) were generated on the basis of LiDAR flights (short-term); iii) climate data were obtained to characterize the ravines and a search performed of press publications to find specific information on events leading to damages and changes to the beach and the coastal infrastructure; and iv) wave data were used to characterize coastal storms. The information and data that were gathered were then used to discuss the management of the beach and future perspectives.

3.1. *Shoreline evolution*

Two different temporal scales were used to assess the shoreline evolution. A long-term perspective was used to analyse the changes from an historical point of view, and a short-term perspective to detect the most recent changes according to the available information. The shoreline was mapped and the beach polygons established in a simple manner between the line of wet sand and the coastal seafront. Digitalization was carried out through photointerpretation and using the highest spatial resolution of the orthophotos and the historical aerial photographs used.

3.1.1. *Shoreline digitalization*

For the long-term analysis, the aerial photographs and orthophotos were selected based on observations of relevant changes in the volume of sediment accumulated and changes in the infrastructure responsible for retaining sediments. Aerial photographs and orthophotos taken between 1964 and 2022 were used (1964 from GRAFCAN S.A.; 1983 and 1989 from the Spanish National Geographic Institute and orthophotos 2015, 2002 and 2022 from GRAFCAN S.A.) with different spatial resolutions of between 10 and 50 cm. For the short-term approach, orthophotos from 2009, 2010, 2011, 2013, 2015, 2017 and 2020 from GRAFCAN S.A. were used since they correspond to low tide hours and high spatial resolution (12.5–50 cm) (Table 1).

3.1.2. *Digital shoreline analysis system (DSAS)*

The Digital Shoreline Analysis System (DSAS) software application was used for both scales to calculate rate-of-change statistics from multiple historical shoreline positions. This tool provides an automated method for establishing measurement locations, performs rate calculations, provides the statistical data necessary to assess rate robustness, and includes a beta model of shoreline forecasting with the option to generate shoreline horizons and uncertainty bands (Thieler et al., 2009; Douglas and y Crowell, 2000). Three variables were used: i) the Shoreline Change Envelope (SCE), which shows the distance between the furthest apart lines for each transect, indicates the dynamism of the shoreline regardless of dates, and represents a cross-shore distance (m) (Thieler et al., 2009); ii) the Net Shoreline Movement (NSM), which shows the distance between the oldest and most recent shorelines regardless of whether they coincide with the most distant lines from each other like the SCE. It also represents a cross-shore distance (m); and iii) the End Point Rate (EPR), which is simply the NSM value divided by the number of years elapsed in the time interval. It corresponds to an annual rate of movement (m/y).

3.1.3. *Beach volume (long-term)*

The beach surface was multiplied by the depth of closure to establish an approximate value for the volume of sediment accumulated on the beach, as also performed by other authors (Marrero-Rodríguez et al., 2021a). 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 (Nicholls et al., 1996). Its determination is essential to estimate the volume of sediment that has been gained or lost in the coastal zone. The equation used was proposed by Hallermeier (1981):

$$d_c = 2.28\, H_S - 68.5\left(H_S^2 \,/\, gT_S^2\right) \tag{1}$$

where Hs and Ts are, respectively, the values of the significant wave height and associated period, representing high energy conditions (storms) in which contour modification can attain higher depths. In the

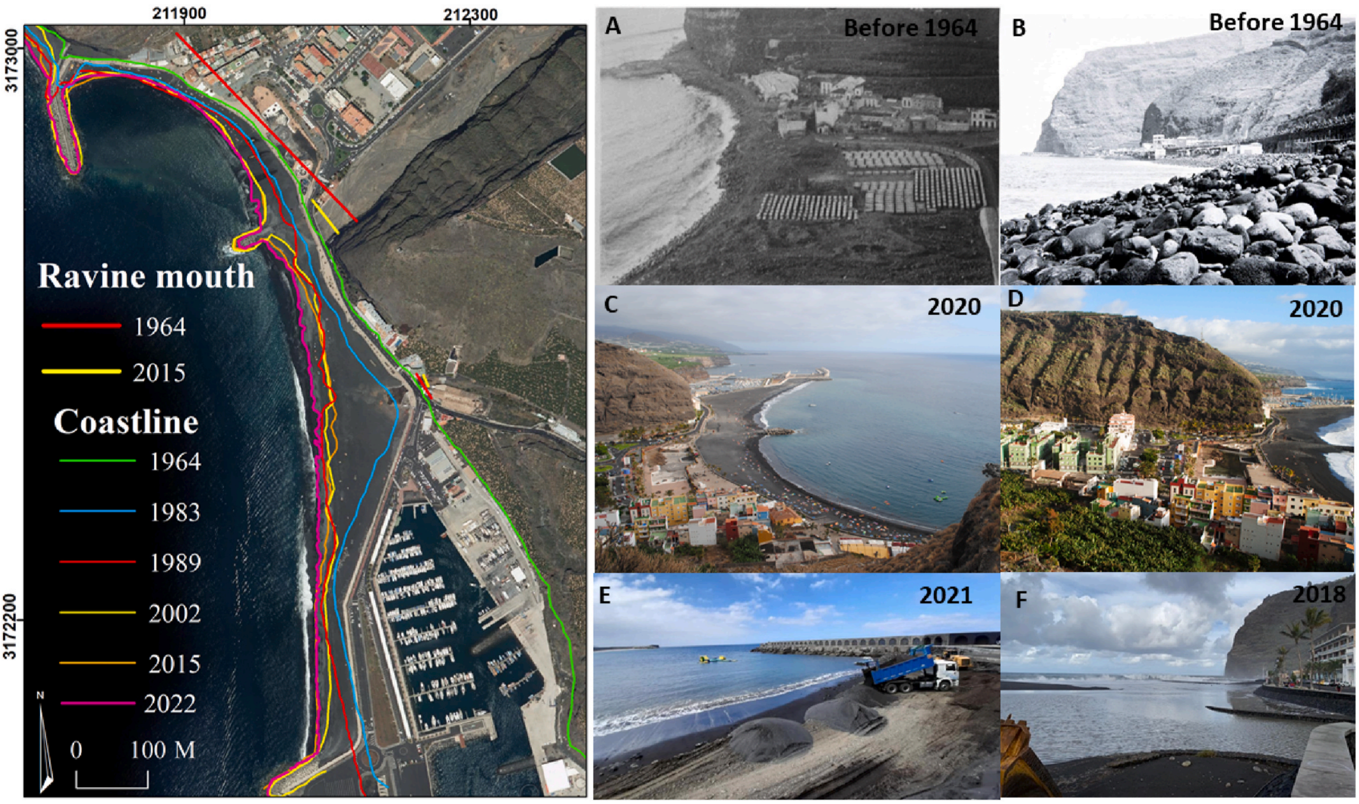

Fig. 2. Evolution of the coastline and the mouth of the ravines between 1964 and 2022. Photograph: A) and B) Coast of Tazacorte before human interventions on the coastline (author unknown; obtained from a Facebook group of old photographs of the Canary Islands); C) current morphology of the sand beach in 2020; D) Current occupation of the mouth of the ravine; E) Beach nourishment performed in 2021 (source: eldiario.es/canariasahora/); F) beach flooded by marine storm (source: eltime.es).

original formulation of Hallermeier (1981), the characteristic wave is associated with a probability of exceeding 12 times/year. *Hs* (4.71 m) and *Ts* (10.75 s) were obtained from the wave dataset corresponding to SIMAR node 4006017 for the complete available data period (January 1964 to December 2022). The estimated depth of closure is 9.4 m.

3.1.4. *Digital elevation models (DEMs, short-term analysis)*

Sedimentary changes of the beach were characterized using digital elevation models (DEMs) with 1-m spatial resolution and shown through six profiles along the beach over eleven years (2009–2020). The DEMs were derived from LiDAR data. The 2009 DEM was calculated using digital files with altimetric information from the LiDAR point cloud with a density of 0.5 points/m^2 (Spanish National Geographic Institute – IGN by its initials in Spanish). The 2010, 2011, 2014, 2016 and 2020 versions were generated through LIDAR flights with a mean density of 1.20 points/m^2 (Spatial Data Infrastructure (SDI) of the Canary Islands Government developed by GRAFCAN S.A.) (Table 1).

3.2. *Wave data*

The wave analysis covers the period from 1958 to 2022. The raw data was obtained from the Spanish States Port Authority for SIMAR node 4006017 (longitude: 18.00° W - latitude: 28.67° N), located in deep water 4 km NW of the study area. The SIMAR dataset comes from a numerical simulation of hourly values of different wave parameters. It has been validated against direct measurements from oceanographic buoys showing good correlation (Pilar et al., 2008). For the analysis of coastal storms, events with significant wave height (Hs) values that exceeded the P_{99} (Yang et al., 2021) were selected for the period 2015 to 2022, since in 2015 the building process of the port had finished and no additional infrastructures have been built since. The variables analysed for the coastal storms were the daily mean and maximum Hs, the daily mean peak period (Tp) and the daily mean wave direction.

3.3. *Climate data*

For climate characterization and to establish relations with beach evolution and the torrential dynamics of the ravines, data from the weather station of the Spanish Meteorological Agency (AEMET) at Santa Cruz de La Palma airport, located 18 km from Tazacorte beach, were used (annual rainfall (mm), maximum rainfall in a day (mm), number of days with rain and number of days with storms). Data on heavy rainfalls and wave storm events were used to carry out a search of press publications, using the Jable tool of the University of Las Palmas de Gran Canaria, in order to obtain further information about the consequences of extreme precipitation events on the beach and the infrastructures located in its immediate surroundings. The station was selected for its long-term record (1983–2021) with no gaps, while stations located inside the head of the Las Angustias ravine provided rainfall records but with important data gaps. In addition, a precipitation model from the Canary Islands Climate Atlas (GRAFCAN S.A., Canary Islands Government) for the period 1975–2020 was used.

4. Results and discussion

The results are organized in three parts: i) long-term evolution of the shoreline (1964–2022); ii) short-term characterization of the beach (2009–2020), including beach volume and its interaction with local runoff; iii) characterization of the sea storms on the coast.

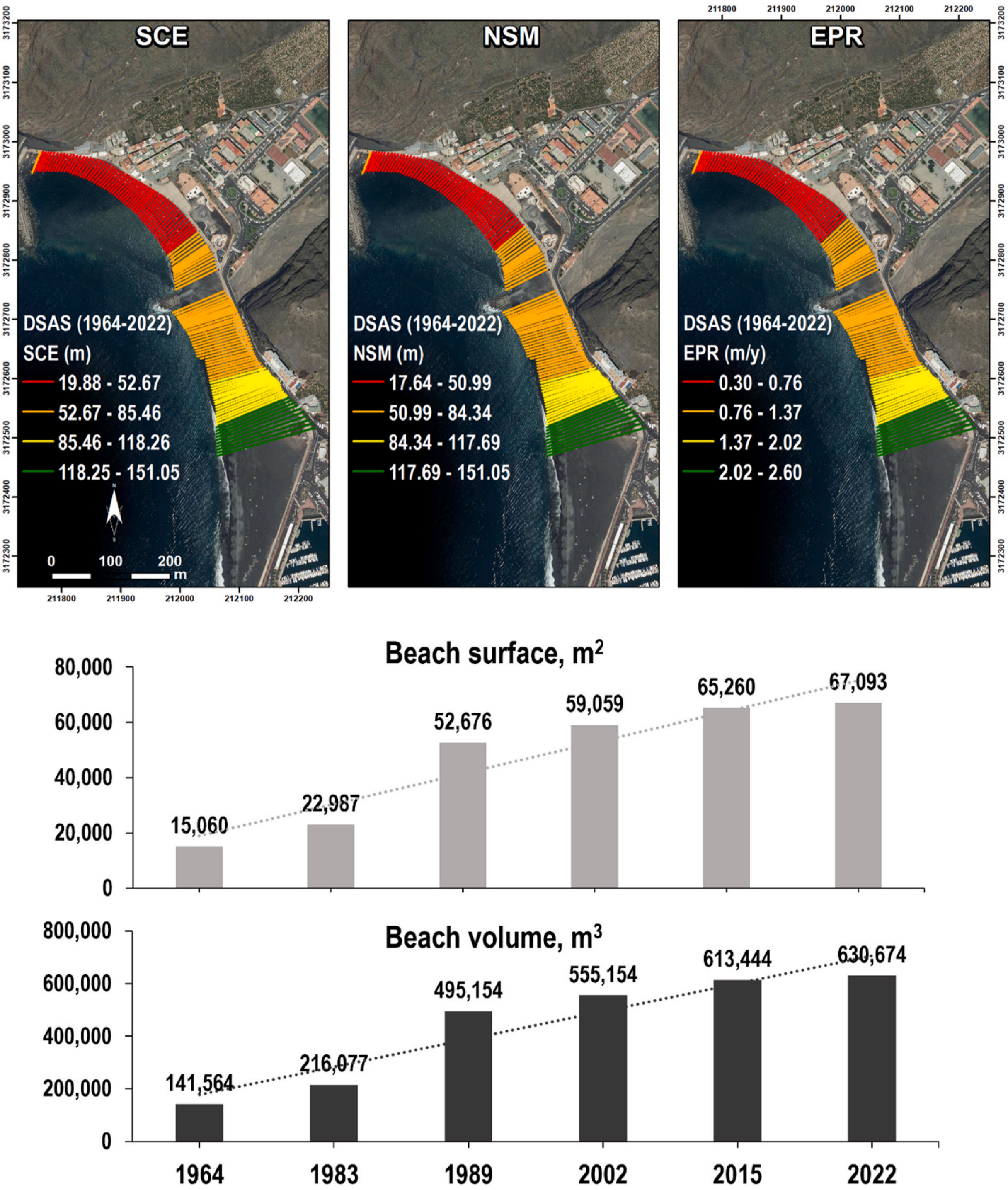

Fig. 3. Long-term DSAS (SCE, NSM and EPR), evolution of beach surface and accumulated sediment volume for each year in Tazacorte.

4.1. *Long-term evolution (1964–2022)*

Both aerial and field photographs show the numerous changes that the coast of Tazacorte has undergone. The aerial photograph of 1964 shows a coast in which heterometric pebbles, cobbles and boulders predominate at the base of paleocliffs and with reduced human interventions (Fig. 2 A and B). The fine materials contributed by the ravines are redistributed by marine dynamics to the south. At that time, the beach had an area of 15,060 m^2. However, in the 70s, the construction of the road and the wall limiting the bed of the Las Angustias ravine was carried out. In the 1970s the construction of the main dock of the port began and part of the previously existing beach disappeared under the port infrastructure and as a result of the subsequent construction of the road and coastal seafront. In the aerial photography of 1983 coastline progradation is observed, although the change that occurred in the period 1983–1989 has greater importance. The biggest growth occurs between these two years, with a beach area in 1983 of 23,000 m^2 and in 1989 of 52,700 m^2, showing a net increment of 29,700 m^2 (Fig. 3). At the end of the 1990s, new infrastructure was created associated with the construction of a parking area located at the southern end of the main pier, expanding the space where sediments could be retained. In addition, two new breakwaters were built. The first

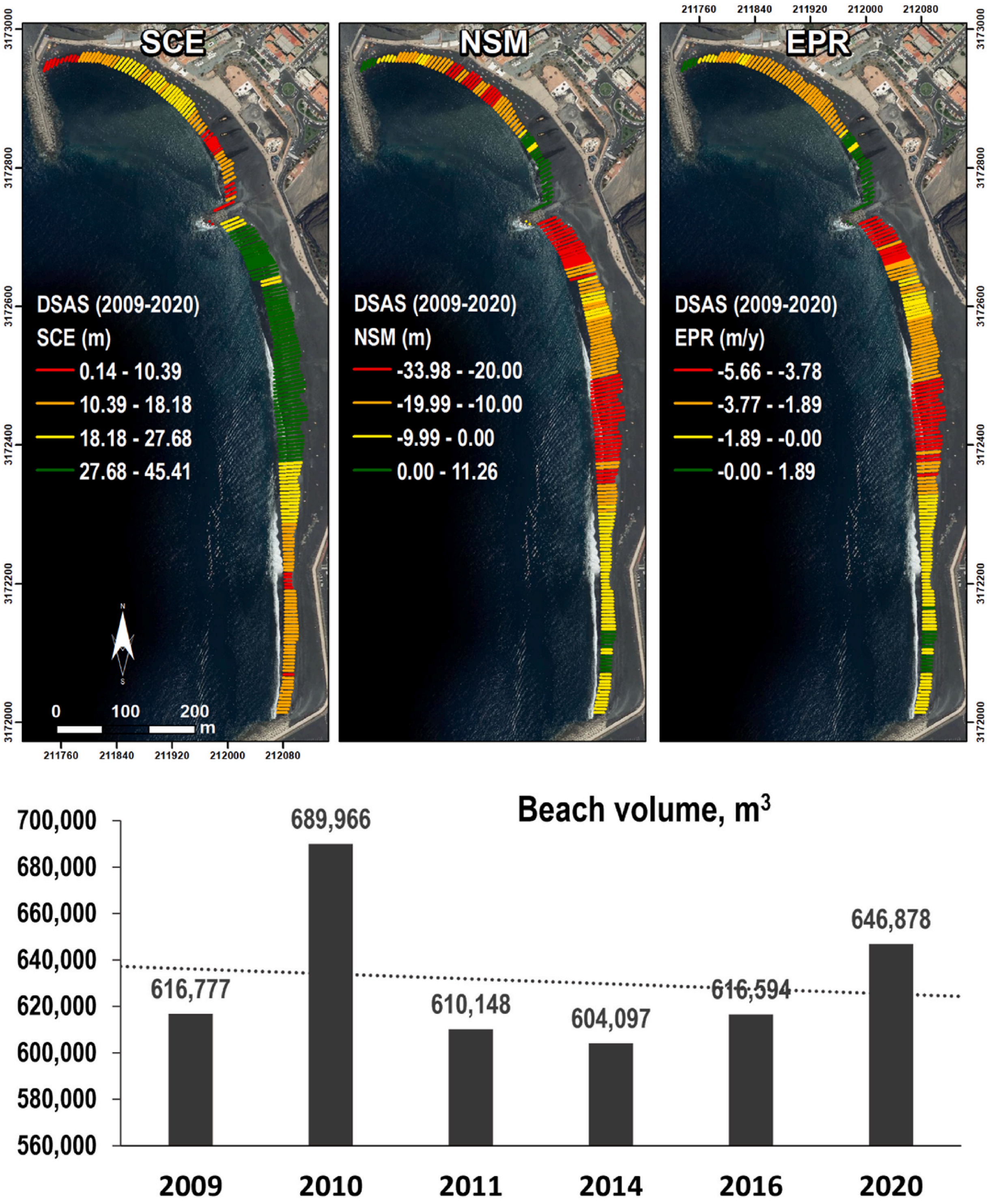

Fig. 4. Short-term DSAS (SCE, NSM and EPR) and evolution of beach volume.

of them to the north and the second in the central sector, representing a fixed element that contributes to stabilizing the sediments delivered by the ravine and to protecting the beach from the prevailing NW waves. Beach growth for the period 1989–2002 was calculated to be approximately 6400 m^2, resulting not only from the contributions of the ravine but also from the beach nourishments performed by the local authorities. In 2015, the works on the port of Tazacorte were completed and the beach reached an area of 65,260 m^2. Since the closure depth obtained after applying the Hallermeier (1981) expression is 9.4 m, a total volume of 613,444 m^3 was accumulated on the beach of Tazacorte in 2015. The area with the greatest growth is located at the mouth of the Tenisca ravine, coinciding with the location of the main breakwater. From then on, the beach shows a certain stability until recently when southerly wave storms have generated sand losses that had to be replaced by the local authorities. In 2021, an additional contribution of 10,000 m^3 of sand was made (eldiario.es/canariasahora editon of May 31, 2021) and, due to the continuous flooding suffered by the coastal seafront and the beach itself during storm surges, the possibility of building a groin or detached submerged reef has been raised to reduce the wave effects on the beach and the town. The proposed infrastructure

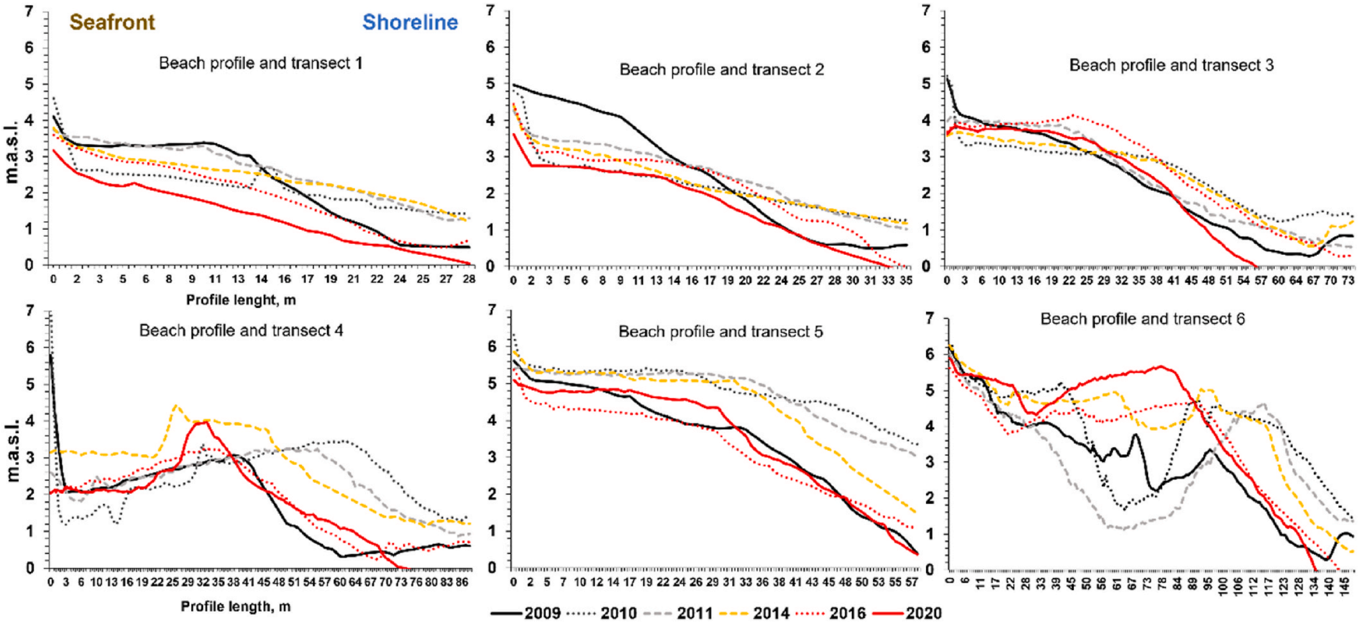

Fig. 5. Beach profiles and transects used to characterize and analyse the morphological evolution of the Tazacorte beach. The y-axes change according to transect length and font size. The transect lengths are: transect 1 (28.41 m), transect 2 (34.56 m), transect 3 (74.03 m), transect 4 (87.51 m), transect 5 (58.21 m), transect 6 (148.32 m).

would be located between the northern groin, and the one located in the central sector of the beach. In 2022, the beach had an area of 67,100 m^2 and an accumulated volume of 630,700 m^3 (Fig. 3).

In general, the long-term DSAS analysis of the three variables explained in the methodology shows a prograding pattern increasing from the north to the south of the beach (Fig. 3). Even the lowest values (to the north) of SCE (19.88–52.67 m), NSM (17.64–50.99 m) and EPR (0.30–0.76 m/y) correspond to positive values, indicating that accretion processes are detected in the most sheltered areas close to the northern breakwater. As we move southwards closer to the port the progradation increases, with higher values of SCE (118.25–151.05 m), NSM (117.69–151.05 m) and EPR (2.02–2.60 m/y). This long-term behaviour can be mainly attributed to the role of the infrastructures (breakwaters and port) and their effect in stabilizing new inputs of sediments, which proceed either through the ravines or through beach nourishments.

4.2. Short-term evolution (2009–2020)

The short-term analysis (2009–2020) represented in Fig. 4 indicates a different behaviour to that detected in the long-term analysis. Firstly, the progradation pattern from north to south is broken, with different beach environments detected. Secondly, the area that coincides with the two ravine mouths is the most progradated (green transects, SCE: 27.68–45.41 m), shows the greatest dynamism (red transects, NSM: −33.98 to −20.00 m) and the greatest erosion processes, (red transects, EPR: −5.66 to −3.78 m/y). The least progradation is detected in the sheltered area of the northern breakwater and the section closest to the port of Tazacorte, with the first area being more dynamic (NSM between −33.98 and −10.00 m) than the second. These two sectors also show two different behaviours in EPR, with the northern sector more erosive (−3.77 to −1.89 m/y), and the southern more stable (−1.89 to −0.00 m/y). Finally, beach volume shows a slightly negative trend and irregular behaviour, with a maximum value of 689,966 m^3 (2010) and a minimum of 604,096 m^3 (2014).

Fig. 5 shows the behaviour and evolution of the beach profiles obtained through the transects shown in Fig. 1 (red lines associated to beach transects 1–6). Firstly, in terms of beach morphology (profile shape), the first group (or beach environment) is formed by profiles 1, 2 and 3 (to the north and sheltered from the northern breakwater), showing a regular slope from shoreline (between 0 and 1.8 m.a.s.l.) to seafront (between 3.2 and 4.6 m.a.s.l.), and also showing erosion, with differences of between 1 and 1.80 m (see the black and red lines in the graphs of Fig. 5 corresponding to 2009 and 2020). The second beach environment s formed by profiles 4, 5 and 6, which are located around the mouths of ravines and are characterised by a steeper slope in the first section from the shoreline (between 0 and 3.2 m.a.s.l.) to the seafront where in some cases they practically exceed it (between 1.2 and 7 m.a.s.l.). In morphological terms, all the profiles (but most clearly 4 and 6, the longest profiles) show a well-defined berm whose crest is at 3–4 m in profile 4, at 4–5.2 m.a.s.l. in profile 5, and 4.5–5.5 m.a.s.l. in profile 6. This gradual increase in crest berm height from N to S is related to the higher wave energy in the southern profiles compared to the northern ones. Moreover, a trend of gain is detected, especially in the centre of the profile, with two groups observed; one formed by transects 3 and 5 with a not very significant accumulation and the other by transects 4 and 6 with gains of between 0.5 and 3.2 m in height. Except for profile/transect 5, the second group, although showing sediment gains, is nevertheless comprised of profiles with a steep slope in the first section closest to the shoreline, which is also associated with the 14–30 m retreat of the beach, previously detected in Fig. 4.

This incongruence between sediment gain and beach retreat could be attributable to 3 factors: (i) the sediment accompanied by water that is produced in a concentrated form through the new ravine channels (the new and artificial ravine mouths) towards the beach contributes large quantities (sediment gain); (ii) these inputs behave aggressively because of the channelling of the fluid (sediment and water) which results in an increase in velocity; (iii) the aggressiveness of the sediment and water arrival destabilises and weakens the beach (especially at the arrival points which coincide with the ravine mouths) against marine impacts (especially in the event of storms).

4.3. Role of the ravines

The natural dynamics along the Tazacorte coast have changed over the study period. Until the beginning of the port construction, extreme runoff generated by heavy rains in either of the catchment basins (Las

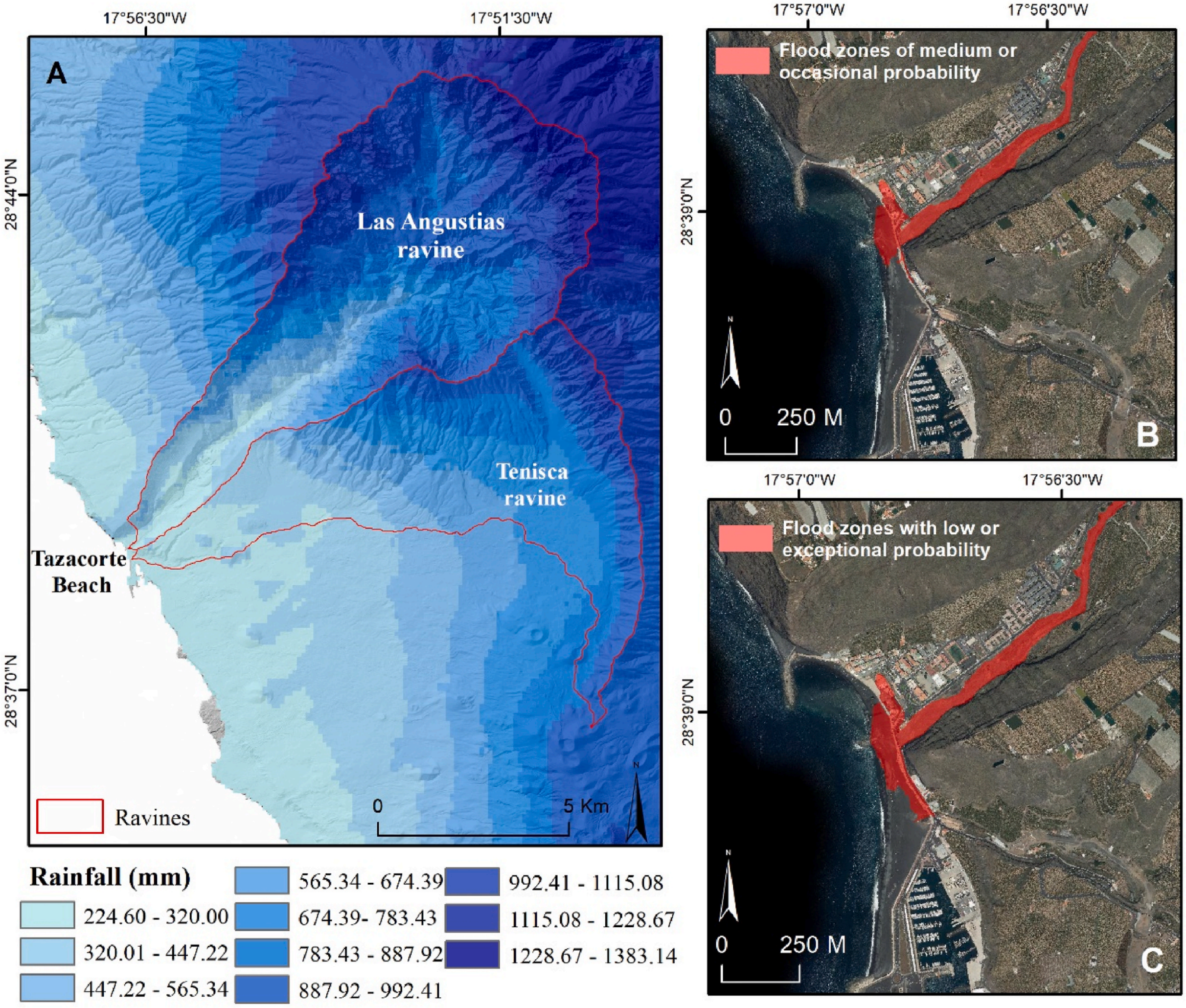

Fig. 6. A: Precipitation model for the period 1975–2020 (mm). Source: Climate Atlas of the Canary Islands (GRAFCAN S.A., Canary Islands Government); B & C: Flood zones for the study area (Ministry for the Ecological Transition and Demographic Challenge - MITECO).

Angustias and Tenisca) would have contributed to feeding the beach, playing a decisive role in the natural dynamics of the coast. The presence of the Las Angustias and Tenisca basins are therefore decisive in the formation of the beach. They are large basins (55.55 km^2 in the case of Las Angustias and 42.76 km^2 in the case of Tenisca), both starting from the summit line located at 2428 and 2050 m.a.s.l. respectively. The accumulated annual precipitation recorded at the airport weather station is much lower than that recorded at the summits of the island of La Palma, where rainfall exceeding 1350 mm/y has been measured (Fig. 6A) (Génova et al., 2015).

Although there are numerous rainy days per year, most of the annual rainfall occurs on one (12 years) or two (8 years) days (Fig. 7) (Marzol et al., 2006). Only in 1998 and 2000 were there six days of rainstorms (rainstorm days refer to the arrival of storms from the polar front). In six years there were no rainstorms. The maximum precipitation exceeded 100 mm/d in seven years of the series. It is in those years that the most press publication references to damages to the beach and coastal infrastructure were found. In 1989, with a maximum daily rainfall of 150 mm and 3 stormy days, there was an important runoff that filled the beach with plant debris. In 1990, with a maximum rainfall of 129.6 mm and a single stormy day, plant debris and beach flooding occurred. In 1998, after the winter storms that amounted to 6 days and 103.6 mm, the need arose to feed the beach due to the erosion produced. Finally, in 2008 there were no storm days but 113.3 mm accumulated precipitation that caused flooding of the road, the beach and the town (Fig. 6B and C) and numerous landslides (Table 2).

Since 2005 the number of stormy days per year has appeared to show a tendency to decrease, with 2013 being the only year that exceeded two stormy days, and in no case have there been extreme precipitation events exceeding 100 mm/y. However, a significant number of storms took place between 1998 and 2004, with the press reporting several episodes of damage to the coastal area. The rainfall accumulated inside Las Angustias basin generates significant runoff that causes damage, as shown by the press reports for that period. According to the reports, the main damages produced by the runoff from the ravine on the beach are: appearance of plant debris on the beach (Fig. 7E), damage to coastal infrastructures (Fig. 7F), damage to the access road (Fig. 7G), erosion and flooding of the beach (Fig. 1F); appearance of rough material on the beach such as boulders and blocks; and the formation of discharge channels on the beach.

One of the problems in the contribution of sediments through Las Angustias ravine runoff is the continued extraction of aggregates that has been carried out in the deeper part of the ravine around 1 km landward of the road. Despite the fact that there are no extraction records, oral sources indicate that trucks filled with aggregates could be observed daily coming out from the ravine. The quarry was regularly mined between 2004 and 2011, although there are references to extractions since 1988. The only reference to a licence for the extraction of aggregates is a request by Tazacorte Council in 2001 to extract a volume of 30,000 m^3 per year in an area of 61,500 m^2 with a term of 10 years for

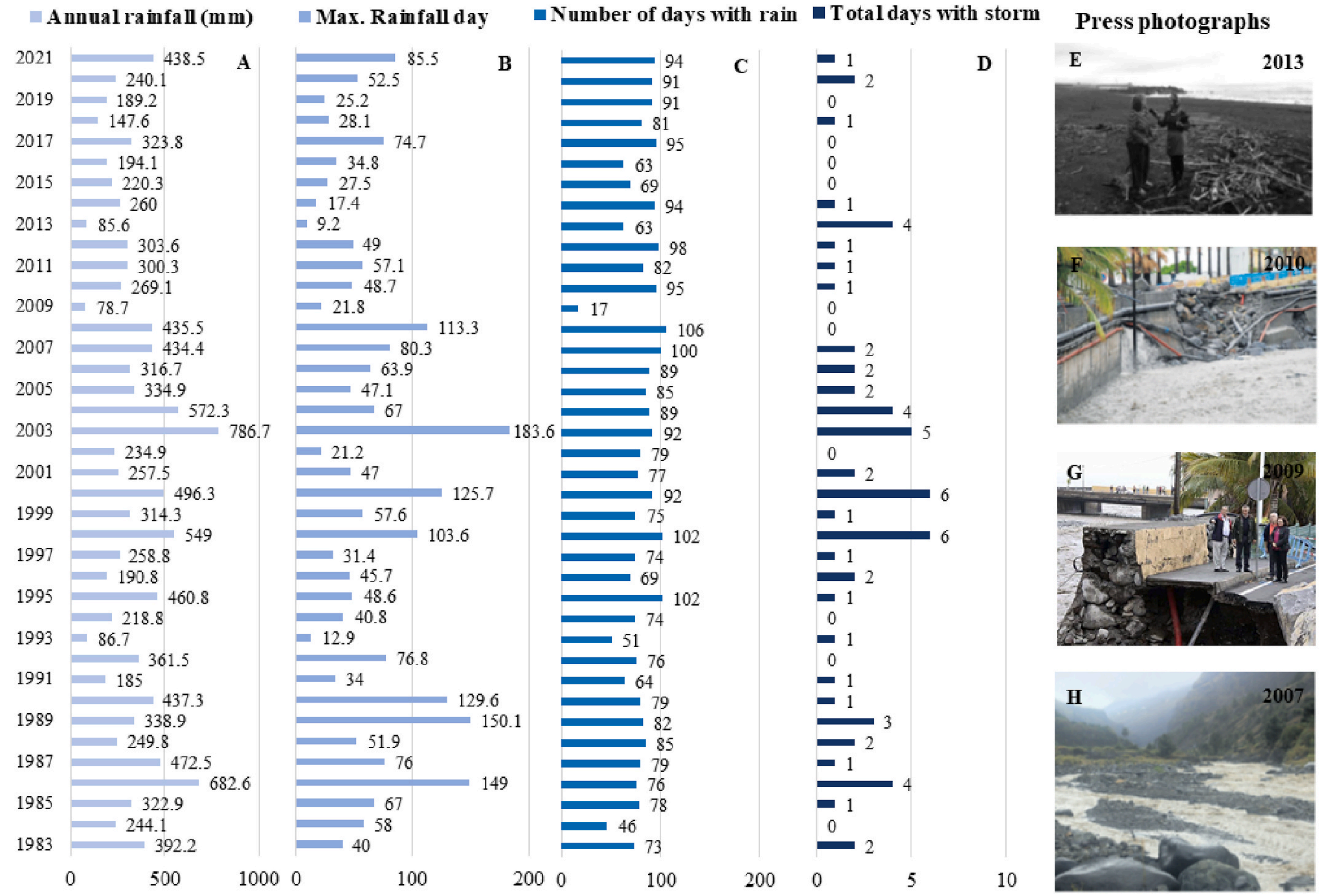

Fig. 7. Data from Santa Cruz de La Palma airport: A) Annual rainfall; B) Maximum rainfall in a day (mm/d); C) Number of days with rain; D) Total days with storm. Press photographs of damages: E) Plant debris on the beach (source: La Opinión, 12/Dec/2013); F) Collapse of the protection wall (source: Canarias 7, 18/Feb/2010); G) Road damaged by the runoff of Las Angustias (source: El Mundo, December 26, 2009); H) Runoff of Las Angustias (source: Canarias 7, 21/Nov/2007).

Table 2
Main references to damages to the beach and the coastal infrastructure in press.

Date	Press report	Source
Nov-1989	Strong runoff damages to the road. Damages associated with coastal storm.	Diario de Avisos
Dec-1990	Strong runoff, plant remains on the beach.	Diario de Avisos
Dec-1991	Strong runoff. Damage to the canal and retaining walls.	La Provincia; Diario de Avisos
Jun-1998	Erosion caused by storms made it necessary to add sand to the beach.	El Día
Nov-2001	Strong runoff on the beach and landslides on the paleocliffs.	Canarias 7; Diario de Avisos; El Día; La Provincia
April-2002	Heavy runoff and power outages.	La Provincia; Diario de Avisos
Dec-2004	Considerable damage to coastal infrastructures due to coastal storms.	El Día
Feb-2008	Road closure due to flooding and landslides due to runoff.	El Día
Dec-2009	Runoff and landslides. Rupture of the riverbed retaining wall.	La Opinión; Canarias 7; Diario de Avisos; El Día
Feb-2010	Breaking of a wall and collapse of the road due to runoff.	Canarias 7; El Día
Nov-2012	Landslides, roads cut off and strong runoff.	La Opinión
Dec-2013	Landslides, collapse of a wall, vegetation remains on the beach due to runoff.	La Opinión; El Día; Diario de Avisos
May-2021	The beach loses sand due to coastal storms in winter.	Diario de Avisos
Dec-2022	Damage to coastal infrastructures due to coastal storms.	El Time

the extraction (Boletín Oficial del Parlamento, 2011). The extraction volumes would have been set according to the existing contributions in the channel and the contributions after the rainy season without being able to dig below 3 m deep. Therefore, it is a surface extraction that is difficult to measure since it varies depending on the existing contributions. The current surface affected by the mining activities carried out in the ravine is approximately 12,500 m^2. However, it is noteworthy that, after runoff from the ravines, the contributions are sometimes redistributed by the local authorities by truck to other nearby beaches to avoid overaccumulation (source: El Time, October 27, 2018).

4.4. Wave storms

Considering the P99 percentile, the Hs threshold for storms is 3.47 m, and taking also into account storm duration and the inter-storm period, a total of 93 wave events meet the defined criteria to be considered wave storms. In the study area, coastal storms follow a well-defined seasonal pattern, with all of them occurring between October and April and especially in February–March (49%) and November–December (36%) (Fig. 8 A). Throughout the considered wave data period (2000–2023), the number of storms per year shows high variability, ranging between 1 and 11 storms/year (Fig. 8 B), with the most common duration for these events ranging between 6 and 10 h and a fewer number of events as storm duration increases (Fig. 8 C).

The prevailing wave direction in the study area is NW, which is due to the shadow effect of La Palma Island (Fig. 9 A). Nevertheless, when only wave data values above the Hs threshold are considered, it can be seen that waves with Hs > 5 m approach both from the NW and the W

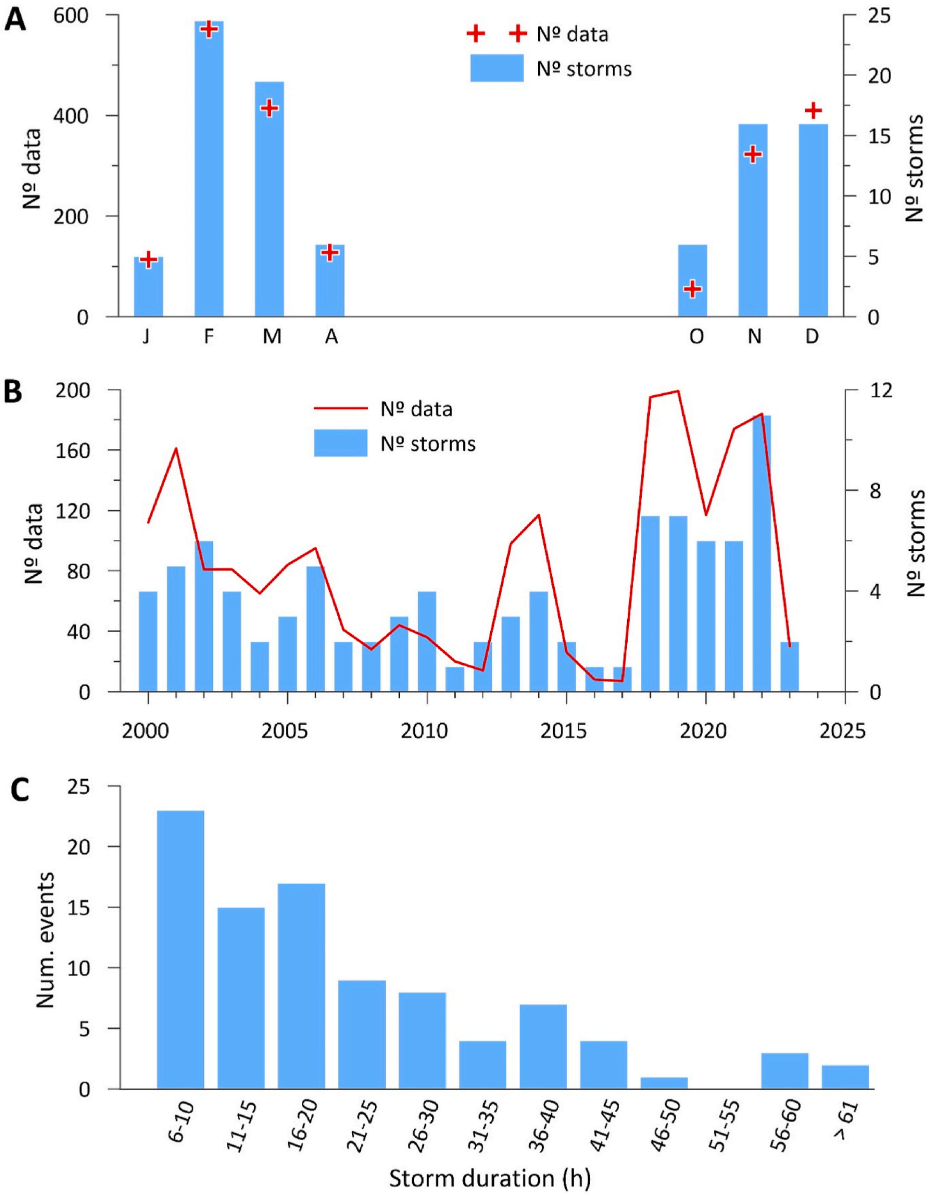

Fig. 8. A) Seasonal distribution of wave storms. B) Inter-annual variability of wave storms. C) Classification of storms according to their duration. Only data above the Hs threshold are considered.

(Fig. 9 B). This was also reported by Alonso et al. (2002), indicating in both cases a fetch of several thousand km.

The maximum Hs recorded during the considered period was 6.2 m recorded on November 17–19, 2018. This storm lasted for 57 h, and therefore this is one of the longest ones recorded (Fig. 10 C). It involved Tp values above 21 s and the direction of approach was from the NW (Fig. 10 A). Unfortunately, we have not found any information about the effects of this storm on the beach, but in February of the same year two consecutive storms hit the area. The first, which arrived on February 25 was a very short storm of 12 h duration from the SW, with Hs up to 3.75 m and Tp values of around 8 s. The second storm, which occurred between February 27 and March 1 and lasted for 61 h, arrived from the NW with Hs values above 6 m and Tp values around 16 s (Fig. 10 B). In the assessment of damage caused by the two wave storms a raising of sand is reported that invades the coastal seafront along with a huge accumulation of sand along the wall that delimits the beach (available in: https://www.miteco.gob.es/es/). A similar situation was observed in 2023 during the coastal storm associated to the passage of the distal part of storm Kamiel (2nd-3rd of March 2023) or in the aerial photograph of 2021 (Fig. 11A). Storm Kamiel was a short event in which the Hs threshold was slightly exceeded for only 6 h, but it was preceded by another storm on February 28. During both events Tp values were round 16 s with waves approaching from the NW (Fig. 10 C). Once again, the effects of these storms included seawall damage and sand accumulation on the promenade (Fig. 11 B, D and E).

5. General discussion

5.1. Beach behaviour

The alterations produced in the coast of Tazacorte due to the construction of the port have generated a sandy beach that is currently the main economic engine of the area. The beach continues to gain surface area thanks to contributions from two ravines and beach nourishment. However, since no new structures have been built to increase sediment retention there are difficulties to maintain the beach surface in the long term and new contributions are redistributed to the south by the prevailing NW swell. If new contributions do not take place the beach will

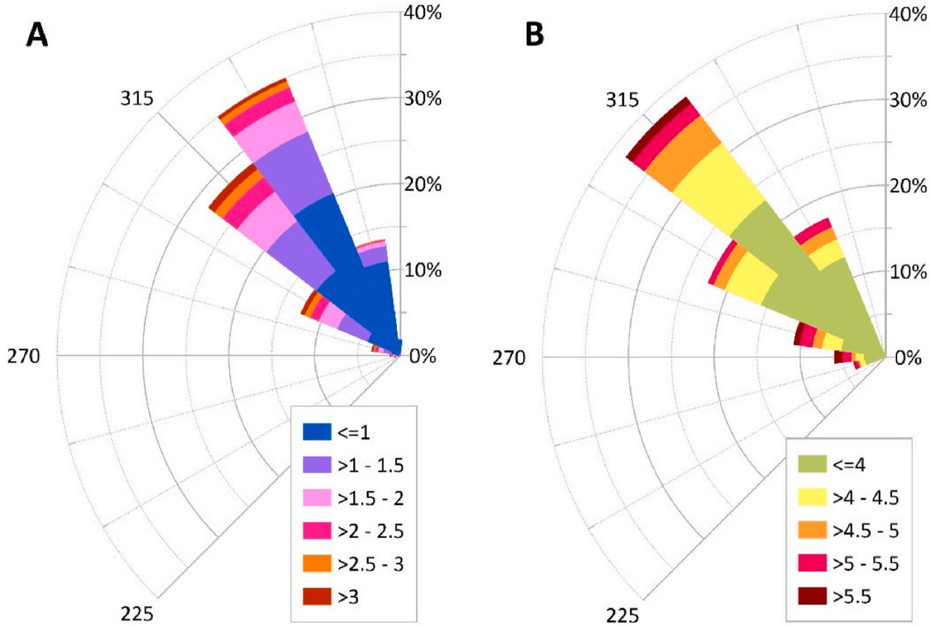

Fig. 9. Wave roses of Hs (m) at the study area considering all data (A) and only data above the Hs threshold (B).

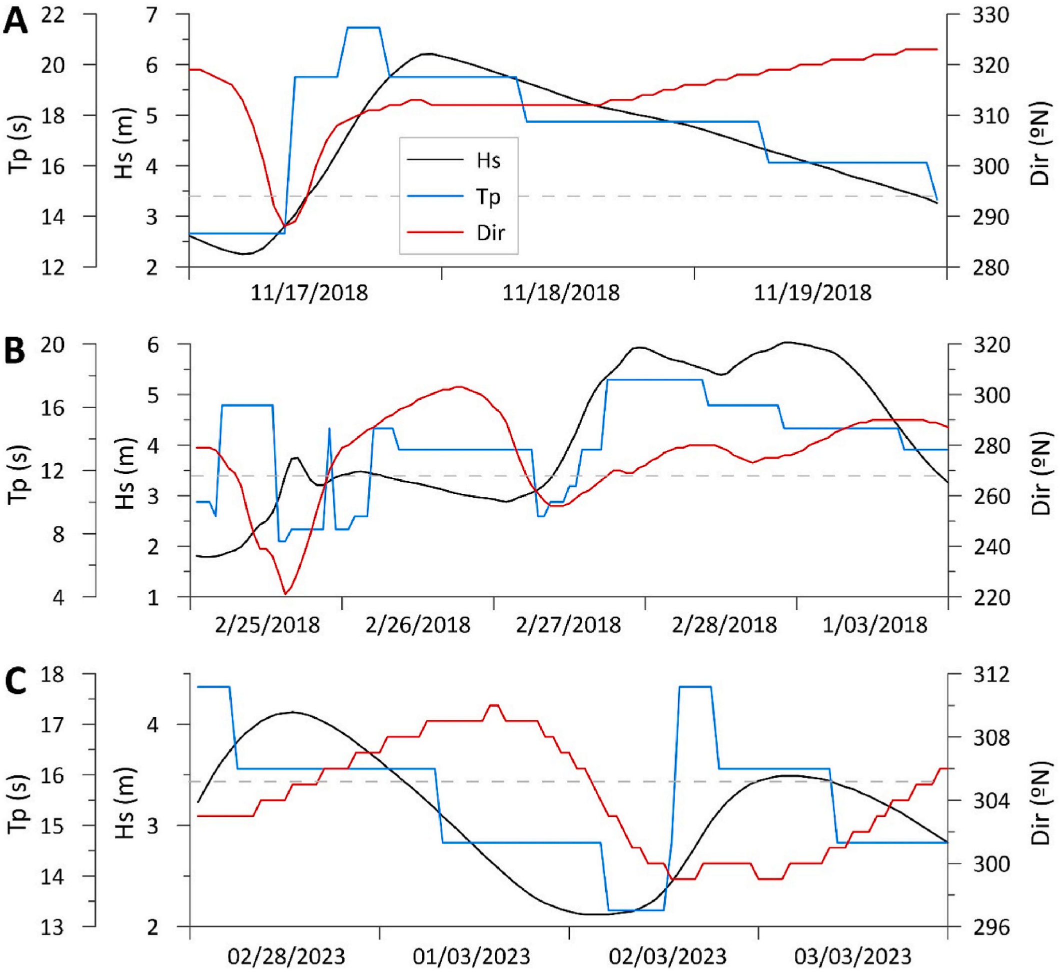

Fig. 10. Characteristics of the two most important (A and B) wave storms and the last wave storm (C) recorded in the area. The grey dashed line indicates the defined Hs threshold.

Fig. 11. Effects of coastal storms on Tazacorte beach and seafront. A) Orthophoto of 2021 showing the area affected by storm Kamiel (source: IDE Canarias. GRAFCAN S.A.). Photos of the effects of storm Kamiel (3rd of March 2023): B) The seafront at Tazacorte beach being affected by waves; C) Access walkways at the backshore before the storm; D) Buried access walkways and sand on the seafront; E) Sand on the beach seafront.

once again have an erosive tendency in certain sectors, such as that observed in the short-term analysis. Likewise, it is possible that the changes in land cover that have been taking place within the basins, due to the abandonment of traditional uses because of their protected status as part of a National Park, have reduced the sediment supply to the beach. However, this must be further analysed in depth for the study area. Similar processes have been studied associated with land use, for example, for the Ebro Delta (Catalonia, Spain) (Guillén and Palanques, 1997), the Dijle catchment (Belgium) (Van Rompaey et al., 2002), and the Sotavento beaches in Jandía (Marrero-Rodríguez et al., 2020, 2021a) or Arrecife (Marrero-Rodríguez et al., 2021b) (Canary Islands, Spain). In these areas, accretion processes have dominated while traditional uses that reduce the vegetation cover have been abandoned, favouring the contribution of sediments to the beaches. In contrast, erosive processes start when the contribution of sediments is reduced, which is associated with the cessation of these traditional land uses and the recovery of the associated vegetation. In addition, the narrowing of the mouth of Las Angustias and Tenisca ravines due to human interventions generates an acceleration of the water flow and, therefore, sediment deposition is ineffective and slow (Sumer et al., 2003). The high runoff velocity could be responsible for the erosive processes observed on the beach and is probably the reason for beach flooding. On the other hand, the reduction in the contribution of sediments may also be associated to a decrease in rainfall and the number of storm days (Zhang et al., 2004), the channelling of water for irrigation and the extraction of aggregates (Marrero-Rodríguez et al., 2020). However, the main problem currently is related to coastal storms. These are more frequent than ravine runoffs and have several effects on the beach, seafront and houses, including flooding of the beach and the seafront and the raising of sand onto the seafront (Fig. 12).

5.2. Beach management

The maintenance of Tazacorte beach costs around 45,000 €/y, including cleaning, flattening and post-storm reconstruction (Table 3). In this regard, the local authorities have proposed a recharge of sand as a solution to the flooding problems of the coastal seafront, something that has shown its effectiveness in other beaches such as Delray Beach or Miami Beach (Hanson et al., 2002; Houston, 2022). The management of the beach has been based on interventions with machinery to recover its flat morphology after marine storms and the effects of runoff from the ravines. Before the rainstorms, draining channels are opened on the beach to facilitate runoff and prevent flooding. In addition, beach nourishment and the construction of infrastructure to prevent erosion have been performed (Table 3).

We make new management proposals that take into account the natural dynamics of the beach: i) setback of the coastal seafront to allow the formation of a double-berm sandy beach (Fig. 13 A); ii) construction of a submerged breakwater (Fig. 13 B); iii) construction of an emerged breakwater (Fig. 13 C); iv) increasing the height of the sea wall (Fig. 13 D); v) allowing the beach to recover its original sediment (Fig. 13 E).

First, it is necessary to attend to the role played by wave storms.

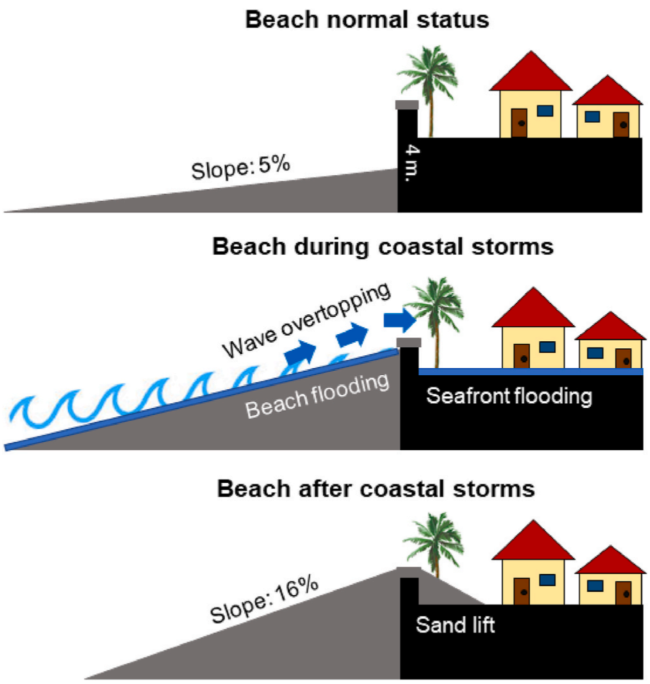

Fig. 12. Diagram of beach normal status, beach during coastal storms and beach after coastal storms.

Table 3
Origin of the beach problems and the management measures executed to solve them.

Beach problems	Origin	Management measures executed
Accumulation of coarse material and plant debris	Runoff	Cleaning with machinery
Opening of channels on the beach by runoff	Runoff Human action	Covered with heavy machinery
Loss of beach profile (berm flattening)	Runoff and surge	Flattening using machinery
Landslides	Gravity processes sometimes influenced by rainfall	Cleaning
Beach flood	Storm surge/wave storm associated to high tide	
	Extreme rainfall that produces runoff	Opening of draining channels on the beach to facilitate runoff reaching the ocean
Seafront flood by runoff and wave storms	Overaccumulation of material from the ravines that is not redistributed by marine dynamics	Opening of channels in the areas of the mouths of the ravines to allow the water to arrive to the sea
	Elimination of berms and flattening of the beach profile combined with wave storms	
Sand occupying the coastal seafront	Wave storms	Manual cleaning
Beach erosion and shoreline retreat	Wave storms	Beach nourishment
Sediment overaccumulation	Ravine runoff	Redistributed by the local authorities to other beaches

During storm surge episodes, the width of Tazacorte beach, in relation to the presence of a coastal seafront behind the beach, does not allow the formation of a storm berm. Instead, the beach acquires a steep slope (16%) that acts as a ramp over which the waves rise, overtopping the seafront and depositing sand on it (Fig. 12). This process has been verified in other areas where similar constructions have been carried out (Villatoro et al., 2014; Leaman et al., 2021). The changes of sediment size, as occurs in many beaches with the aim of adapting them to user preferences (Peña-Alonso et al., 2018), have resulted in an increase in the width necessary for the formation of a berm. Therefore, before human interventions, Tazacorte beach was able to set back during wave storm episodes, but this space no longer exists due to the construction of the seafront. In addition, the space needed to set back is longer for a sandy beach than for a pebble and cobble beach.

Coastal narrowing (Pontee, 2013), which has been gaining prominence in the scientific literature, is one potential solution to this problem. In this case, it is related to a deconstruction of the coastline and the relocation of the current coastal seafront (Fig. 11 A). However, this is only possible in a sector of the seafront where there is enough space to do so, while in other sectors it would imply the elimination of private constructions. This would mean that the beach could gain some 20 m inland. However, according to SLR predictions, the beach will suffer from coastal squeeze processes (Pontee, 2013) associated with the rise in sea level and the significant coastal pressure it will suffer. Therefore, deconstruction of the coastline to give space to the beach is only a temporary solution and is unlikely to be socially accepted. Another option is the construction of a detached breakwater, submerged (Fig. 11 B) or otherwise (Fig. 11 C), designed to reduce the energy of the waves before they reach the shore. This would avoid the problems associated with marine storms. However, the runoff from the ravines would continue to represent a problem for the beach and potentially for such a structure, making it necessary to study this proposal in greater depth. Another option would be simply to increase the height of the seawall protecting the beach seafront in order to avoid wave overtopping (Fig. 11 D). This solution is cost-efficient against wave storms but has no effect against episodic runoffs associated with heavy rains and would change the aesthetics of the seafront.

Finally, a viable and cheaper alternative would be to modify the dominant sediment size, with the central part of the beach (where floods are more frequent (Fig. 5 B and C)) changing from a coarse sand beach to a cobble beach. With this, no new sand nourishments would be needed and the beach would be allowed to retreat, since the erosion consists of the loss of the finer particles by wave action (Fig. 13 E).

Once the situation had naturally evolved, the beach would be narrower and the dominant sediment size would be coarser. The beach would naturally develop a double-berm profile, with a tidal berm at around 2–3 m above mean sea level, and a storm berm located landwards at around 4–5 m (Casamayor et al., 2022). The storm berm would act as a buffer to waves during high energy wave events, while remaining inactive during intervening calm periods (Kennedy and Woods, 2012). Therefore, it is a highly efficient natural barrier in preventing flooding generated after wave storms (Poate et al., 2014). Additionally, a cobble beach presents ç much higher permeability than a sandy beach, which would reduce the negative effects observed on the beach after heavy runoff events. Pebbles from the beach would reach the seafront and the adjacent road only under exceptional high energy waves coupled with high tides. While this would represent a potential risk for users, the frequency of it occurring would be far less.

This solution entails the beach changing from a coarse sand beach to a cobble beach, which would eventually reduce the acceptance of beach users. To minimize that negative perception, two sectors of the beach could be kept as they are: the northern sector attached to the north groin, and the southern sector where the beach is backed by the port. Neither sector has been flooded in the last few decades and they are not considered vulnerable even under exceptional circumstances (Fig. 5 C).

6. Conclusions

The beach under study has shown in recent decades a clear progradation trend as a result of the contributions of ravines and the

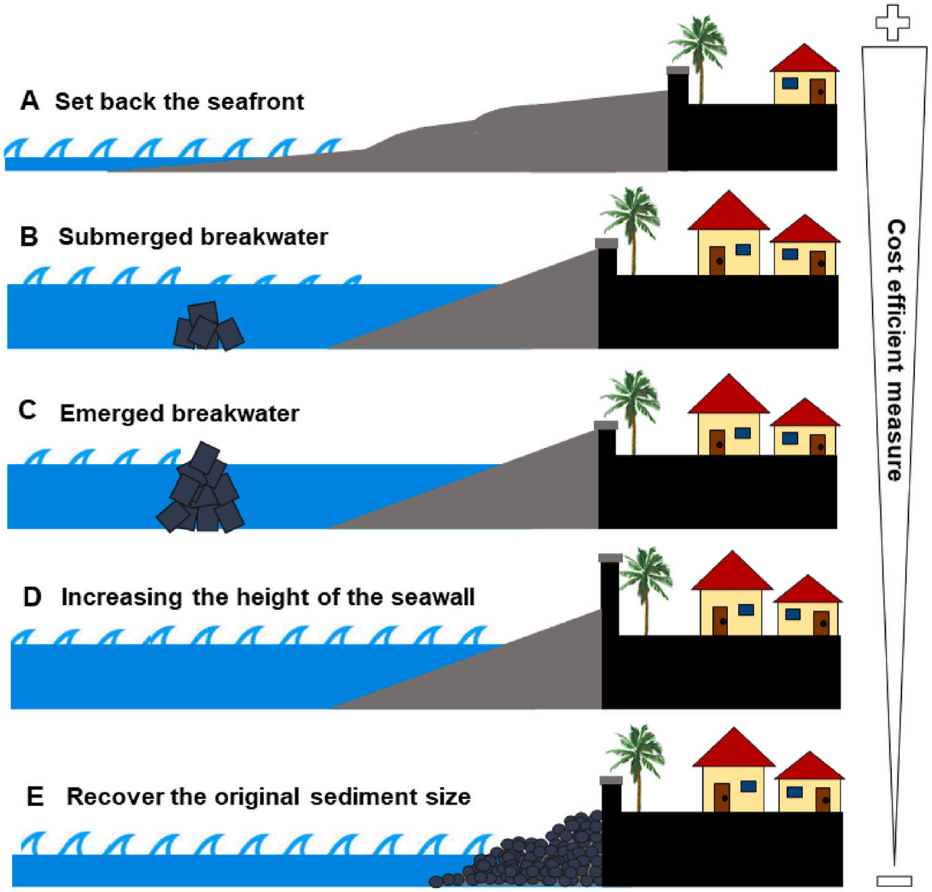

Fig. 13. Diagram of the management proposals for Tazacorte beach.

different sand nourishments carried out by the local authorities. In consequence, the previous pebble and boulder beach evolved into a sandy beach. However, the beach needs continuous management due to the modifications that have been artificially made in the lower section of the ravines, such as the narrowing of their mouths and the extraction of aggregates. These changes may have led to a decrease in sediment inputs, although this requires further study for confirmation. The beach suffers continuous flooding during coastal storms because the width of the beach does not allow the formation of a storm berm.

In this context, the main problem detected in the study area was the transformation of the dominant grain size, since sandy beaches need to be wider than coarse-grain beaches to generate the double-berm profile. Due to the presence of the coastal seafront, the road and the village, the beach is not sufficiently wide to give an effective response to storms. Instead, the beach acquires a steep slope over which the waves ascend, flooding the seafront. Future management of this space should not include continuous sand nourishments, since this new material would be lost due to the non-existence of infrastructures that allow their retention, or deconstruction of the coastline to allow the beach width to increase. Instead, the proposed management options include building a detached breakwater and/or increasing the height of the seawall protecting the seafront. Although both options are designed to reduce the impacts generated by storm waves, they have no effect against runoff impacts. The best management option would be to allow the beach to behave under natural processes. This measure implies beach retreat and erosion but would be facilitated by coarsening of the dominant sediment size. A new cobble-size beach would naturally develop a double-berm profile, which is highly efficient against both wave storms and heavy runoffs.

CRediT authorship contribution statement

Néstor Marrero-Rodríguez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Ignacio Alonso:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Leví García-Romero:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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

Data will be made available on request.

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