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Indicators of geomorphological connectivity facing management fragmentation in coastal protected areas: the case of Guguy (Canary Islands)

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ABSTRACT

The coastal strip is the area where the marine and terrestrial environments meet, and there is a continuous exchange of matter and energy between them. From a natural perspective, coasts are functional units, although they may be subject to administrative divisions. This paper presents an example of the conflict between ecological processes and administrative boundaries in the coastal environment. The proposal for the declaration of the Guguy Maritime-Terrestrial National Park, located on the island of Gran Canaria (Canary Islands, Spain), illustrates this conflict. In contrast to the jurisdictional boundary established by law along the coastline between the regional administration (land area) and the state administration (marine area), this work presents theoretical and experimental indicators that demonstrate the existence of land-sea ecological connectivity in the beach-dune system. The sedimentary analyses and wind and marine dynamics indicate the presence of a single geodynamic functional unit on the Guguy coast, where marine, wind, fluvial and slope processes are interconnected. Based on this evidence, it is recommended to avoid administrative fragmentation of this area to promote an integrated, holistic and sustainable coastal management.

1. Introduction

The concept of ecological connectivity includes the movement among ecosystems of fluxes of energy, organisms and materials (Liczner et al., 2024). This connectivity, in land-sea environments, implies interrelationship between terrestrial and marine ecosystems via several processes (Fang et al., 2018; Harris et al., 2025). These processes represent complex mechanisms in which various geomorphological, biological, chemical and physical factors intervene and interact (Beger et al., 2010; Ward et al., 2020; Waterhouse et al., 2016), so connectivity is a ubiquitous feature of coastal ecosystem functioning (Martínez et al., 2020; Sheaves, 2009).

Coastal morphodynamic are intricate processes that involve the interaction between land and sea and play a pivotal role in the formation and evolution of coastal zones (Cowell and Thom, 1995; Davidson-Arnott et al., 2019; Short and Jackson, 2013). The interconnection of the marine and terrestrial parts of the coastal zone can be observed through the sediment flow resulting from morphodynamic processes (Rozzi et al., 2023). Marine ecosystems, such as coral reefs and mangroves, exert a stabilising influence on coastal morphodynamics through the stabilisation of sediments and the reduction of wave energy (Martínez et al., 2020). Consequently, they act as a source of biogenic sediment, derived from the organisms that inhabit them. In inland ecosystems, fluvial dynamics erode rock masses and generate terrigenous sediment, which is transported by rivers and ravines from inland to the sea (Fang et al., 2018; Sheaves, 2009). During periods of high discharge, such as during storms, the quantity of sediment reaching the coast is significantly increased. Terrigenous sediment can also be derived from the erosion of cliffs and beaches by waves. The force of the waves can disintegrate and transport terrestrial sediments out to sea (Yun et al., 2023). Once the sediment has been formed and is located on the coastline, it can be transported by tidal currents along the coast and

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into the sea. Additionally, wave action at an oblique angle can move the sediment longitudinally towards the coast, redistributing the eroded materials (Saengsupavanich et al., 2022). In the emerged zone, small, loose, dry sediment is readily lifted and transported by wind action, resulting in the formation of sedimentary features landwards, such as dunes and sand bars (Ueno et al., 2024). The intensity and direction of the wind exert a determining influence on the quantity of sand transport and accumulation (Cohn et al., 2018; McLachlan and Defeo, 2018).

As coastal areas also provide a wide range of ecosystem services for society (Barbier et al., 2011; Harris and Defeo, 2022; Mitchell et al., 2013), they are areas of population agglomeration and resource exploitation (Martínez et al., 2007; Susiloningtyas et al., 2024). Consequently, anthropogenic disturbances have gained influence on morphodynamic processes in land-sea interface environments (Deng and Yu, 2023; El Mrini et al., 2012; Saengsupavanich et al., 2022), altering natural dynamics, threatening ecological connectivity (Crook et al., 2015), and making it imperative to implement management measures for the effective protection and conservation of these areas (Fang et al., 2018; King et al., 2024). Therefore, integrated coastal management is essential in coastal areas to effectively address and manage the complexities of sea-land morphodynamic equilibriums (Christophe et al., 2025; Harris et al., 2025; Rozzi et al., 2023).

The interplay of coastal processes is complex in both physical and administrative terms. This complexity is further compounded by the management of sea-land protected areas, where administrative conflicts frequently arise due to challenges in handling various territorial competences (Schütz and Slater, 2019). This is particularly evident in areas where different public administrations intervene in management and decision-making, as it is often the case with shorelines (Crawford, 2019; O'Hagan et al., 2020; Walsh and Kannen, 2019). These conflicts can arise between different government agencies, local communities, and other stakeholders involved in coastal management (Khakzad et al., 2015). The conflicts arise due to differences in their understanding and interpretation of management competences, as well as competing interests and priorities (Martínez et al., 2024), and can hinder effective and efficient management of sea-land protected areas, leading to negative impacts on biodiversity conservation and sustainable use of resources (Uda, 2022). To avoid potential conflicts of competence between separate administrations, which may have different objectives and interests in the management of the site and its resources, it is essential to ensure its integrated governance (Shipman and Stojanovic, 2007; Yue et al., 2023). The lack of clearly defined management boundaries in coastal areas is likely to lead to conflicts between administrations and even between users, making it difficult to reconcile the use of these areas for both development and conservation (Harris et al., 2025; Jay et al., 2016; Kerr et al., 2014). The existence of disparate uses and activities within the marine protected areas, some of which have been identified as exerting a high degree of pressure on the environment, such as fishing and tourism, has been demonstrated to be a source of conflict with the potential to compromise the achievement of conservation objectives (Molina-Urruela et al., 2024).

In Spain, competences over coastal protected areas are very distributed between different government scales. The Spanish State holds responsibilities for environmental protection and nature conservation through various laws and institutions, mainly the Ministry for Ecological Transition and the Demographic Challenge. However, important legal competences are transferred to the Autonomous Communities, which have their own legislation and governing institutions concerning the protecting natural areas and coastal policies. In addition, but subject to regulations and guidelines established by the autonomous community and national government, some municipalities also have responsibilities for managing relevant aspects of local spatial planning and coastal management. The fragmentation of management responsibilities is already having a negative impact on other coastal protected natural areas in the Canary Islands (Pinardo-Barco et al., 2023; Sanromualdo-Collado et al., 2021). From a management point of view, the existence of this partitioning competence areas and overlapping administrations could be incompatible with the land-sea continuity of the natural environment and with the functional marine-terrestrial connection of the existing ecosystems and habitats.

In the case of National Parks, Spanish legislation establishes that the management and organisation correspond directly to the autonomous communities in terrestrial areas, while in the case of marine areas correspond to the Spanish State administration (*Ley 30/2014, de 3* de diciembre, de Parques Nacionales, 2014), which stablish a jurisdictional border and conflict at coastline in the case of maritime-terrestrial protected areas, such as the proposed National Parks. However, the legislation provides for "the full management and organisation of maritime-terrestrial National Parks by the autonomous communities where there is evidence of ecological continuity between the terrestrial ecosystem and the marine ecosystem", as is the case of the two national maritime-terrestrial parks currently declared in Spain (Ferreiro da Costa et al., 2022).

This work presents a relevant example of discordance between ecological coastal processes and administrative boundaries in the proposed Guguy National Park (Gran Canaria, Canary Islands). The Cabildo of Gran Canaria and the Department of Ecological Transition of the Canary Islands Government presented a proposal to the Ministry for Ecological Transition and the Demographic Challenge of the Spanish Government in September 2021. The proposal currently under consideration entails the designation of Guguy as a maritime-terrestrial National Park, which would establish a potential administrative boundary in the area in the event that the ecological continuity between terrestrial and marine ecosystems cannot be demonstrated.

In this context, the main objective of this work is to illustrate the conflict that occurs between the legal and administrative fragmentation and the continuity of natural dynamics in many coastal areas, taking the Guguy National Park proposal (Canary Islands) as a case study. The provision of a tool to assist managers of marine-coastal protected areas in defending the need for integrated management by a single administration is the purpose of this endeavour. The prevention of further conflicts arising from the division of competences and responsibilities is the overarching goal. For this purpose, we aim to determine, firstly, the functional marine-terrestrial connection on the Guguy coast, using geomorphological processes as indicator to highlight the interconnection of ecological processes, and secondly, to compare them with the hypothetical administrative borders to detect management inconsistencies. To establish the functional connection between the marine and terrestrial environments, we have focused on the analyses of i) the topographic evolution of sedimentary landforms; ii) the marine-terrestrial origin of sediments; iii) the aeolian sedimentary dynamics; and iv) the extension of marine sedimentary nearshore activity.

2. Study area

2.1. The protected site of Guguy

The Guguy National Park proposal focuses on the Guguy massif, located in La Aldea de San Nicolás, at the west of the island of Gran Canaria (Canary Islands, Spain), a natural area of great value and uniqueness (Fig. 1). It forms part of the oldest known relief of the island of Gran Canaria and represents a unique sample of the lava pile of the first island volcanic cycle (Hoernle and Carracedo, 2009). The Miocene geological complex of Guguy is of exceptional antiquity in the context of the world's intraplate oceanic islands, a context to which only 0.05 % of the planet's emerged masses belong (Ferrer et al., 2024). Geomorphologically, it shows a unique fan-shaped structure, marked by deep ravines, knife-edge interfluves and large coastal cliffs. The study area is limited to the coastal sedimentary system that develops on the central coast of the massif, where the dynamics of energy and matter exchange between the marine and terrestrial systems could be particularly evident.

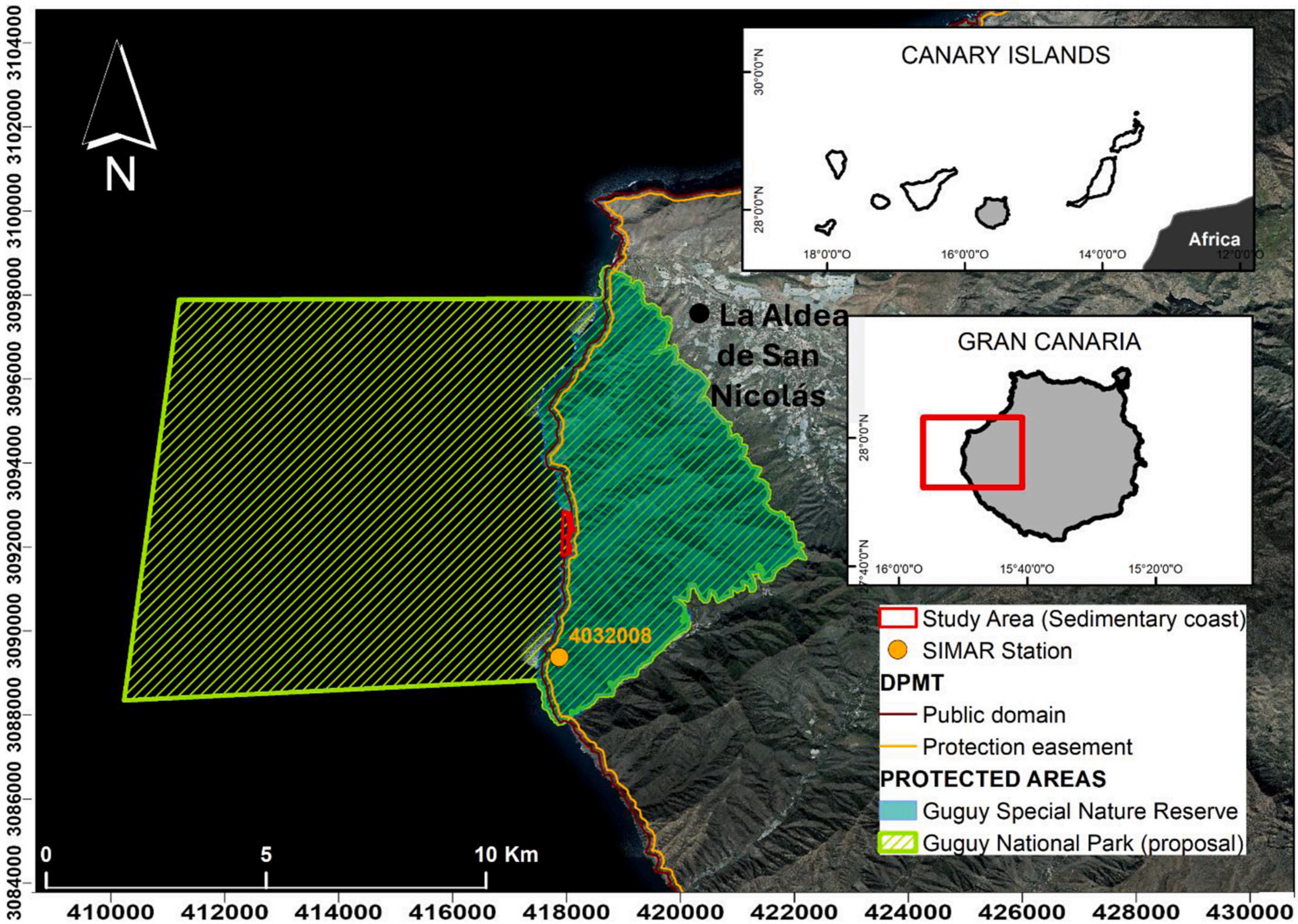

Fig. 1. Location of the study area and zoning map of the proposed National Park and the current environmental protection statuses.

The Guguy massif, with an altitude of over 1000 m, encompasses several of Gran Canaria's primary ecosystems, including the coastal halophilic belt, sweet spurge (Euphorbia balsamifera), cardonal *(Euphorbia canariensis),* palm grove (*Phoenix canariensis),* and thermophilic forest. The terrestrial area boasts a remarkable biological diversity, characterized by the presence of numerous endemic plant and animal species of special interest, particularly birds. The shallow, seabed surrounding the massif is home to extensive seagrass meadows of *Cymodocea nodosa* (Barbera et al., 2005; Tuya et al., 2014), an endangered species that is the only one in the Canary Islands capable of forming extensive subtidal meadows that provide a habitat for a wide range of fish and cetacean species (Reyes et al., 1995). Additionally, the area contains significant archaeological and ethnographic resources that attest to human presence since pre-European times (Martín Rodríguez et al., 2001).

At present time, the Guguy massif is one of the largest areas on the island of Gran Canaria, devoid of human habitation, infrastructure, and facilities. There is no road access by land, and agriculture is of low intensity. The coastline lacks any facilities, buildings, or equipment for navigation or mooring.

The singularities of the Guguy massif and its good preservation have marked a history of protection of almost half a century. The first protection initiative dates to 1975, when the Güigüi region was proposed by the Institute for the Conservation of Nature (ICONA) as a protected natural area in the Inventory of Special Protection Natural Spaces in the province of Las Palmas. Subsequently, in 1987, the Guguy massif was proposed for designation as an Integral Reserve in the Special Plan for the Protection of the Natural Areas of the Canary Islands (PEPEN) of the Cabildo of Gran Canaria. Subsequently, Law 12/1987, on the Declaration of Natural Areas of the Canary Islands, classified this area under the protection of the Parque Natural del Macizo del Suroeste (Southwest Massif Natural Park). The Güigüi Special Nature Reserve was finally established following the enactment of Law 12/1994, of December 19, 1994, on Natural Areas of the Canary Islands. In 1999, the Government of the Canary Islands also designated the entire terrestrial area that coincides with the Special Nature Reserve as a Site of Community Interest. Finally, both the terrestrial and marine areas were designated as Special Area of Conservation of Güigüí (terrestrial) and as Special Area of the Sebadales of Güigüí (marine). Consequently, the Guguy massif is now designated as a Special Nature Reserve of the Canary Islands Network of Protected Natural Spaces and a Special Area of Conservation. It comprises a marine part (SAC ES7011005) and a terrestrial part (SAC ES7010008) of the Natura 2000 Network.

To advance the conservation of Guguy, the proposal, currently under consideration, sought the declaration of Guguy as a National Park, recommending the designation of an area of 10,119 ha, bringing together the 2899 ha of terrestrial ecosystems included in the current Special Nature Reserve and the 7219 ha of marine ecosystems included in the current Special Area of the Sebadales of Güigüi (Fig. 1).

2.2. Geomorphological units

Six main geomorphological units have been identified in the study area: coastal cliffs, rocky shore platforms, debris slopes, ravine basins, beaches and climbing dunes (Fig. 2).

2.2.1. Coastal cliffs, rocky shore platforms and debris slopes

The coastline of the Guguy massif is characterised by a rocky landscape and high cliffs, with narrow ravine mouths that sporadically intersect the rocky terrain. On the promontories comprising the Guguy sedimentary coast to the north and south, the escarpments reach heights of over 400 m. The cliffs supporting the sedimentary systems exhibit a double-slope morphology. At the base, there are almost vertical escarpments up to 80 m high, above which slopes extend, dissected by the effect of the ravines, up to 400 m in height. The base of the rocky cliffs of the sedimentary coast of Guguy is covered by debris slopes of approximately 20°, which are the result of successive landslides and gravitational movements. Some of these slopes reach heights of up to 25 m in the central section, protecting the base of the cliffs from marine erosion.

2.2.2. Ravine basins and water network

The Guguy massif is structured by a main ridge in the form of an open arc to the west, from which a network of short, deep, parallel ravines develops. These are separated by a series of narrow interfluves, which lead to the coast, less than 3 km away. The massif comprises 40 ravine basins, of which only three, the largest in the entire rock massif, flow westwards and empty into the sedimentary coast of Guguy. The *Güigüi Grande* ravine basin, which flows southwards to the beach of the same name, is the largest, covering more than 550 ha. It has a slope of 1050 m and a main channel 3060 m long. The *Güigüi Chico* ravine basin, situated to the north, also flows into the beach of the same name, extending over 230 ha. The gradient of the river is approximately 1.000 m, with a main channel length of 2248 m. Both the *Güigüi Grande* and *Güigüi Chico* ravines discharge into the beaches of the same name via outlets situated approximately 10 m above mean sea level, forming escarpment interfaces between the ravine and the beach.

2.2.3. Beaches

The sedimentary coast of Güigüi is bordered by rocky cliffs and slopes of landslides that restrict its development inland, resulting in the formation of long, narrow beaches. This is characterised by three beaches, namely beach of *Güigüi Grande*, *Playa de Enmedio* and beach of *Güigüi Chico*. In plan view, they form three small arches or concavities open to the west and separated at high tide by small promontories with intertidal rocky platforms. Conversely, at low tide, the three beaches are united to form a single subtidal-supratidal sedimentary body, approximately 1 km in length, situated between two promontories of cliffs to the north and south.

The physical continuity of the beach allows for the identification of three distinct sub-sectors. To the north, the beach of *Güigüi Chico* has an area of over 18,000 m^2 and a length of 360 m. It is composed of a sandy intertidal zone and a supratidal area formed by strands of stones. To the south, *Güigüi Grande* beach has a surface area of approximately 6000 m^2 and a length of 350 m, comprising a sandy intertidal zone and a supratidal zone of pebbles. In both cases, the width of the beach does not exceed 25 m at low tide.

The *Playa de Enmedio* beach, with an area of over 11,000 m^2 and a length of 300 m, is situated between the two aforementioned beaches. The beach is distinguished by a sandy continuum between the intertidal and supratidal areas, with the development of beach cusps and accumulation berms on the beach face and the formation of a large dune on the backshore.

2.2.4. Dune formations

Two well-developed and stable dune formations have been identified on the sedimentary coast of Guguy. The first is located on the beach of *Playa de Enmedio* and is by far the largest, with more than 18 m high and covering an area of 1850 m^2. The dune is situated in a wedge-shaped position on the backshore cliff, thus classifying it as a climbing type of dune (Pye and Tsoar, 2009). The base of the dune is the debris slope at the base of the cliff, on which the sand rises due to wind pressure. The second dune formation identified on the sedimentary coast of Guguy is located at the southern end of *Playa de Güigüi Grande* beach. The dune is a small climbing dune of 50 m^2, which rests on the coastal escarpment and penetrates approximately 35 m in the form of an aeolian mantle on the slopes of the mouth of the *Güigüi Grande* ravine.

3. Methods

3.1. General approach

Connectivity between marine and terrestrial ecosystems involves the dynamics of matter and energy exchange between the two environments. In a coastal sediment system, this is evidenced by the dynamics of sediment exchange between the different sub-environments from the subtidal to the backshore. The methodology has therefore focused on identifying and assessing the dynamics responsible for the interaction and sediment exchange between adjacent sub-environments.

Based on the identified geomorphological units, a methodology has been developed to use the geomorphological processes involved in the development of these units as indicators of the existence of continuous sedimentary dynamics between the submerged and emerged parts. The methodology focusses on four fundamental aspects: (i) the existence and extent of nearshore transport of sediments, (ii) the existence and magnitude of topographic changes on intertidal and supratidal zones, (iii) the granulometric characteristics and provenience of sediments, and (iv) the existence and dynamic patterns of aeolian sediment transport landward. The procedures used combine the analysis and integration of external sources, field surveys (September 3, 2023), laboratory sedimentological analysis and application of theoretical models. These have allowed the development of a dynamic model of the interaction between the processes that continuously link the sub-environments from the subtidal to the backshore (Fig. 3).

3.2. Subtidal sediment transport

The underwater sediment transport in Guguy was calculated theoretically by analysing the wave series and determining the closure depth. The wave series has been used as an initial approximation to the maritime regime on the sedimentary coast of Guguy. Specifically, it helps determine the possible direction and intensity of sediment transport by coastal drift. The depth of closure or depth of the active beach profile (Hc) was calculated using the equation proposed by Hallermeier (1980):

$$H_c = 2.28H_s\text{-}68.5\ (H_s^2 / gT_{s)}^2$$

where Hs and Ts 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, the characteristic wave is associated to a probability not exceeding 12 times/year. Both Hs (with a value of 4.72 m) and Ts (with a value of 10.77 s) were obtained from the wave dataset corresponding to SIMAR node closest to the beach for the complete available data period. The data period was 65 years (from January 01, 1958 to October 17, 2023), with a sampling frequency of 1 year out of 5. The time series of waves and climatic conditions between 1958 and 2023 were used, respectively, to estimate the depth of closure, and to contextualise the wind conditions recorded during the field campaign. The resulting closure depth and the extension of the active profile was mapped thanks to the bathymetric chart of the Ecocartography Plan of the Spanish Coast Line (MAGRAMA, 2000) (Table 1).

3.3. Intertidal and supratidal volumetry changes

In order to ascertain the sedimentary dynamics between marine and terrestrial ecosystems, topographical changes were utilised as an

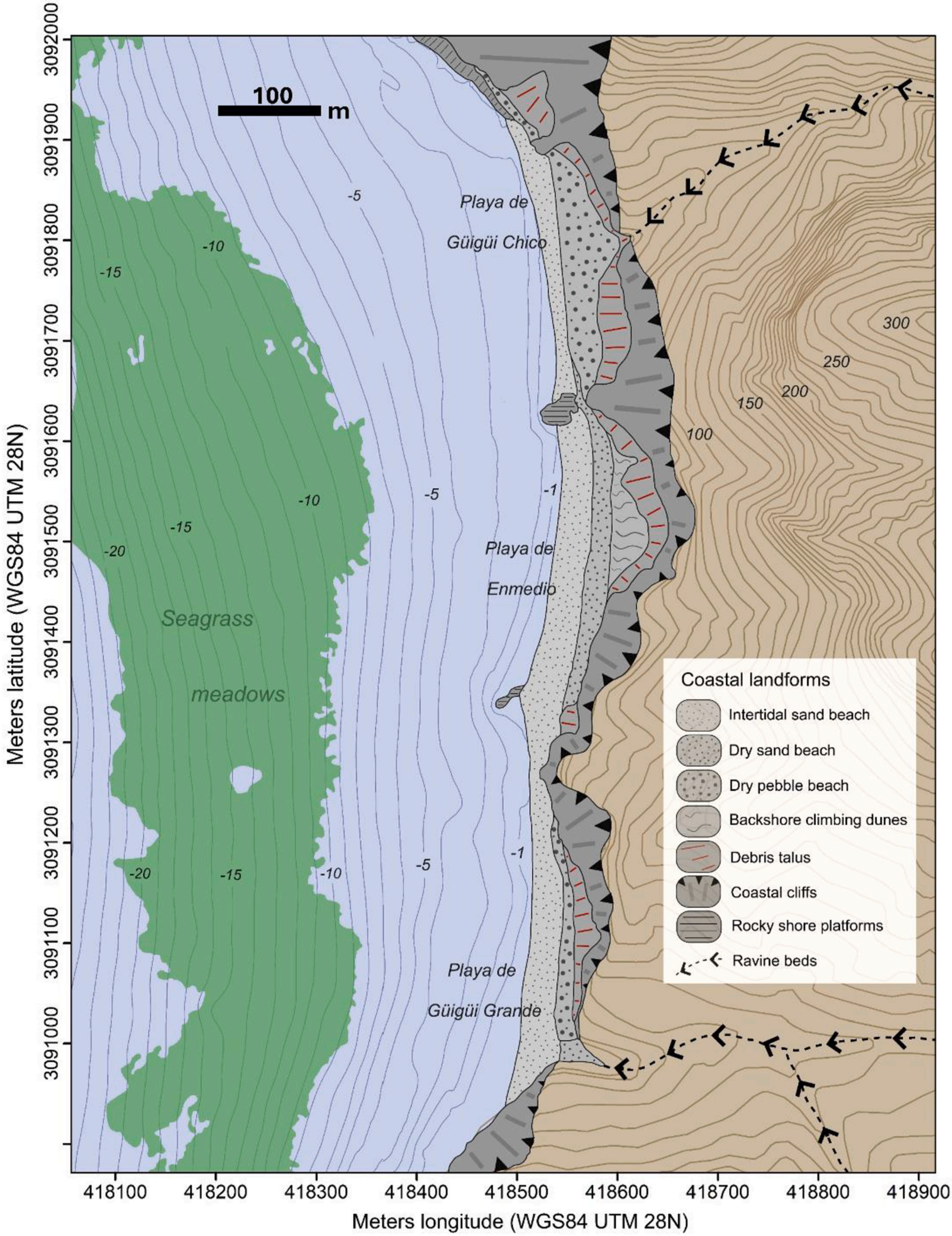

Fig. 2. Geomorphological units identified on the sedimentary coast of Guguy.

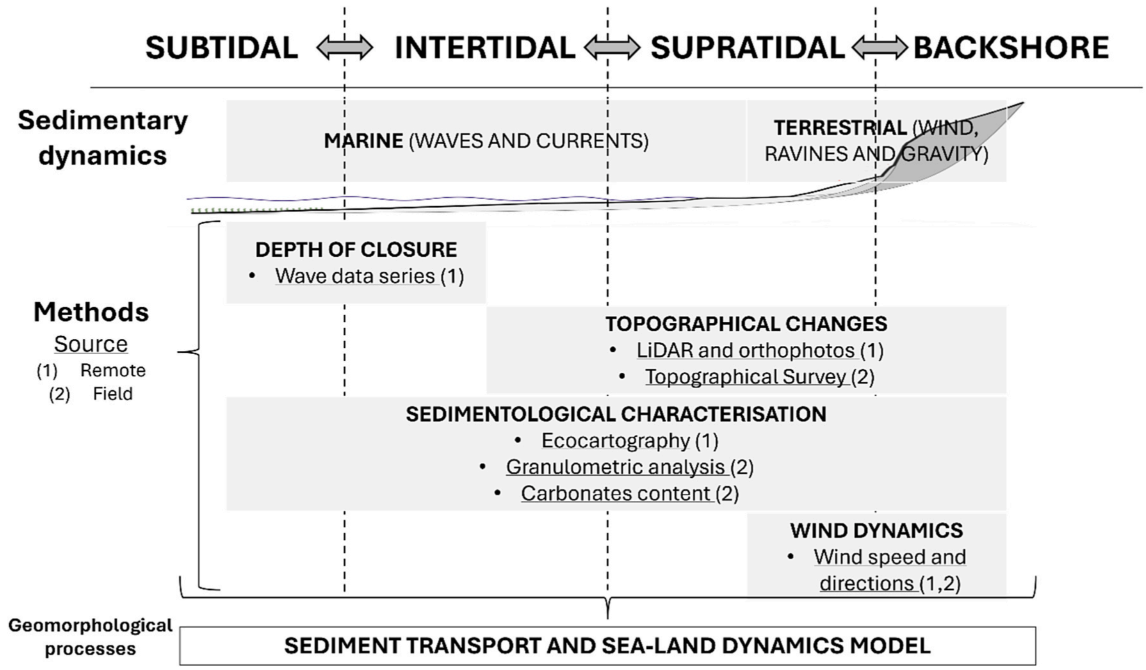

Fig. 3. Methodological scheme.

Table 1
List of remote data used, including periods, resolutions and sources.

	Period	Resolution	Source
Ortophoto	2002–2020 (yearly)	<25 cm/ pixel	GRAFCAN, Gobierno de Canarias
DEMs (LiDAR)	2009	2m	PNOA-IGN, Gobierno de España
	2015		
Ecocartography	2000		MAGRAMA, Gobierno de España
Wave data series	1958–2023		Puertos del Estado, Gobierno de España
Climatic data series	1958–2023		Puertos del Estado, Gobierno de España

indicator (Delgado-Fernández et al., 2018). The utilisation of geophysical technology, which facilitates the estimation of sediment budgets with enhanced spatial resolution and detail, was ultimately deemed unfeasible due to the temporal and financial constraints imposed, in addition to the logistical challenges associated with inaccessibility of the study area. Nevertheless, the employment of these techniques is consistently advocated. To this end, Digital Elevation Models (DEMs) from 2009, 2015 and 2023 were constructed and compared altimetrically. DEMs from 2009 to 2015 were obtained by LiDAR flights and used to detect and calculate topographical variations through DEMs of difference (DoDs). These flights are from PNOA (National Aerial Orthophoto Plan-acronym in Spanish) and available in the Spanish Geographical Institute (acronym in Spanish: IGN) of the Spanish Government (Table 1).

The DEM of 2023 was obtained through a topographic survey carried out during the field campaign (Fig. 4). The topographical survey was carried out using two TOPCON Hiper SR GNSS antennas and a TOPCON FC6000 wireless storage device connected via Bluetooth. The differential method used is based on the use of a fixed antenna (base), and a mobile antenna (rover). The base antenna remains at a known fixed point and is used to make real-time corrections to the errors in the topographic points taken by the mobile antenna. To cover the entire study area, it was necessary to install two base antennas with known coordinates at different times. The first base antenna was installed at a clear point, at an altitude of 4.51 m (UTM coordinates X.418,556.5m, Y.3,091,637.55m), and the second base antenna was installed at an altitude of 29.99 m (UTM coordinates X. 418,535.91m, Y. 3,090,964.95m). The mobile antenna was used to record more than 1900 topographic coordinates along the intertidal and supratidal zones of the beaches of Guguy, in a coastal strip between 0 and 22 m above mean sea level. GPS positions received real-time kinematic (RTK) corrections, via internet (mobile telephony), through NTRIP protocol from the GRAFCAN Permanent Stations service.

Topographical DEMs and DEMs of Differences (DoDs) were cleaned, corrected and calculated using geomorphic change detection (GCD) software, including the calculation between raw and threshold error (Wheaton et al., 2010).

3.4. *Sedimentological characteristics and provenience*

Forty-two sediment samples were collected from 10 transects along the beaches of Guguy. (Fig. 2). Sampling was planned according to the different sedimentary sub-environments: (i) beach subtidal (<1.5 m above mean sea level (AMSL)), (ii) beach intertidal (−1.5, 1.5 m AMSL), (iii) beach supratidal (1.5, 3.0 m AMSL) and (iv) backshore formations (>3.0 m AMSL). Based on these sedimentary sub-environments, each of the transects includes one sample for the beach subtidal (cod. INF), one sample for the beach intertidal (cod. INT), one sample for the beach supratidal (cod. SUP) and one sample for the backshore formations (cod. TRP) (Fig. 2). In addition, two sediment samples were taken from the *Güigüi Grande* ravine (Cod. BCO) to determine the origin of the beach sands. Using a shovel, 400 g of surface sand were collected at each point and placed in duly labelled plastic bags. The location of the sampling points was determined by GPS.

The samples were then taken to the University of Las Palmas de Gran Canaria (ULPGC) laboratories for chemical and granulometric analysis. The samples were first washed to remove organic matter and salts that could interfere with the particle size and calcimetry results. The samples were washed in triplicate with distilled water, allowing the sediment to settle and removing the water with a suction tube to avoid losing the finest fractions. After washing, the samples were dried in an oven at 60 °C for the required time.

Sieving of samples for particle size analysis requires 100 ± 20 g of

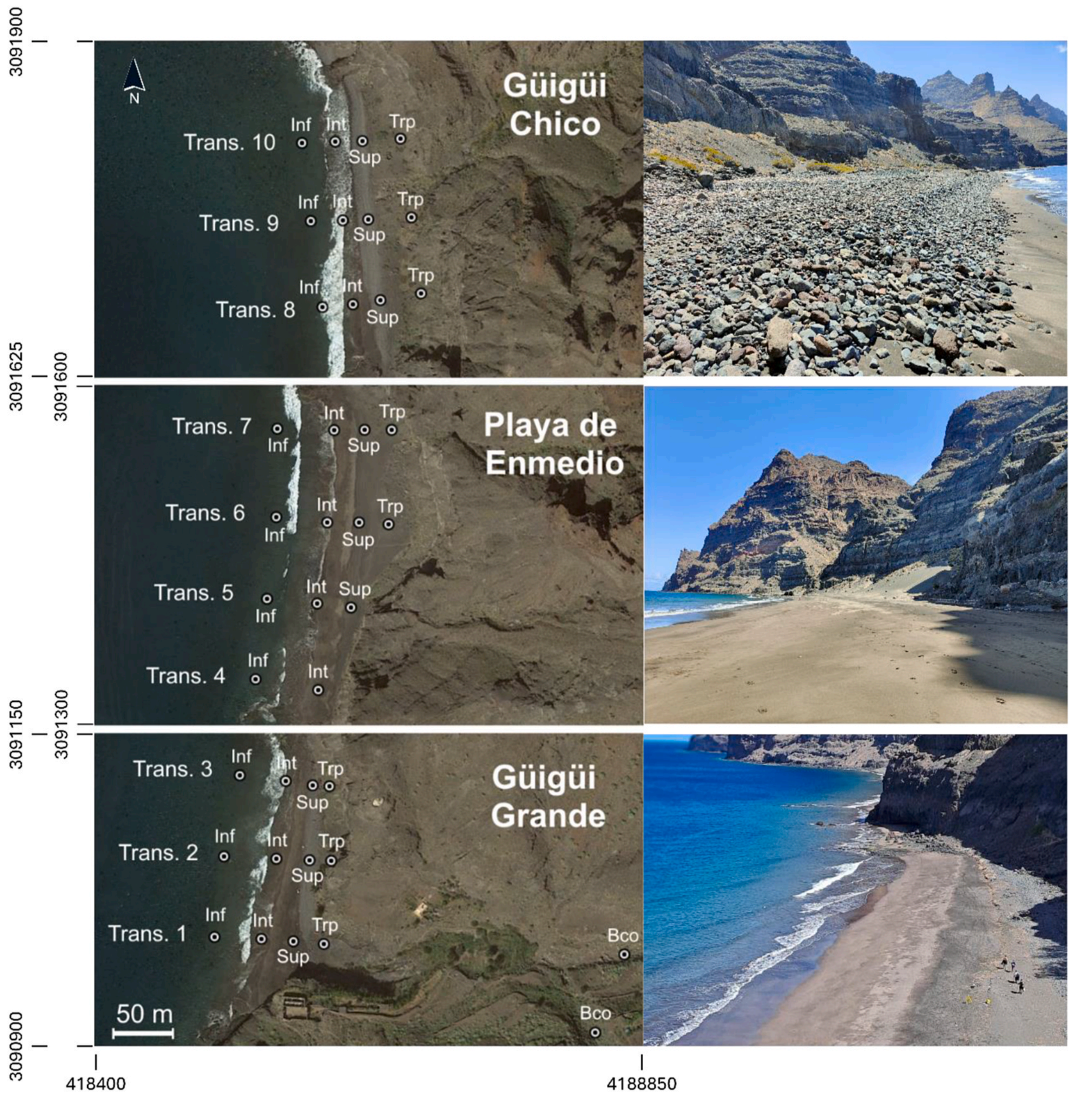

Fig. 4. Location of sediment sampling points along 10 transects and general view of the beaches. (Inf: subtidal; Int: intertidal; Sup: supratidal; Trp: backshore; Bco: ravine). Wind stations were in "Int" and "Sup" points. As illustrated on the right, the geomorphological units under consideration can be identified as follows: dry pebble beach and debris talus (top); backshore climbing dunes (centre); and sandy beaches (bottom).

sediment, previously quartered to ensure representativeness. The weight of the initial amount of sediment was recorded using a precision balance. It was then placed in a Filtra dry sieve shaker, consisting of a column of 8 sieves plus the bottom, with mesh sizes Φ from 8 mm to 0.063 mm. Sieving was carried out for 10 min, with cycles of 5 s. After sieving, the sediment retained on each sieve was weighed on a precision balance. The results were then analysed using the GRADISTAT programme (Blott and Pye, 2001) to obtain the most relevant parameters. The characteristics of these parameters are based on the geometric method of (Folk and Ward, 1957). Data from the Ecocartography Plan of the Spanish Coast Line (MAGRAMA, 2000) were used to contrast with the sedimentological analysis of submerged samples obtained in field.

The carbonates present in each sample were determined using the Bernard calcimeter (Guitián Ojea and Carballas, 1976). This method is based on the determination of the amount of carbonate present in the sample by means of the release of CO_2 resulting from the reaction between $CaCO_3$ and HCL. The quantification of the carbonate present in each sample is obtained from small, quartered samples that are representative of the total sample. The initial value of the volume marked on the burette is recorded, then the acid is poured in to start the reaction on contact with the sample, shaking the Erlenmeyer flask to ensure that the reaction is complete. Finally, the value of the volume marked on the burette is recorded again, giving the amount of CO2 released by the reaction and therefore the amount of carbonate in the sample.

3.5. Supratidal wind dynamics and aeolian transport

Seven data collection stations were used simultaneously to collect wind speed and direction data at 18 sampling points. The wind vane and anemometer stations were located 0.4 m above the ground, and a data logger with wireless communication was used to record data every 2 s (Domínguez-Brito et al., 2020). The stations were installed at the upper intertidal and upper beach points, coinciding with the INT and SUP code points of the sampling (Fig. 2). During data recording, one station was fixed in the upper intertidal and remained unobstructed throughout data collection, serving as a control element. Data was collected in three periods, each lasting over 30 min, at different positions. The data collected was then averaged every 30 s to obtain representative means that could be spatially compared for each period. The means obtained at the control station for the corresponding period were used to normalise these means. Normalisation allowed for comparisons to be made throughout the study area between the different times of data collection during the campaign (Delgado-Fernández et al., 2013). The system's operation requires synchronous data recording for all stations, resulting in three series of records covering the entire beach throughout the day.

To contextualise the wind speed and direction data collected in the field and determine their representativeness, the wind time series between 1958 and 2023 of the nearest SIMAR station (Puertos del Estado) were consulted (SIMAR 4032008 Long: 15.83° O - Lat: 27.92° N) (Fig. 1). The winds recorded at the control station during the data acquisition were 8.5 m/s of a NNE component, which represents near 80 % of the complete wind series between 1959 and 2023 at the SIMAR station. Therefore, the 30-min data collected in the field correspond to the local downscale behaviour of the incident prevailing winds as they are influenced by local factors on the coast of Guguy, mainly the coastal relief.

4. Results

The use of geomorphological processes as indicators in the coastal sedimentary system studied has made it possible to identify the dynamics of sediment flow exchange between the submerged, intertidal and emergent zones.

4.1. Nearshore interaction

The depth at which the waves are capable of mobilizing sediment from the seabed is referred to as the depth of closure (Hc), which defines the zone of active sediment transport on the beach (active profile). The methodology employed yielded Hc values that ranged from 5.67 m to 8.54 (Table 2), with an average value of Hc = 6.9 m. When applied to the entire data set (all 65 years), Hc = 9.42 m was obtained (Table 2), but this value is an overestimation. Consequently, the sediment that can migrate towards the intertidal and emerged beach, on average, would be that down to a depth of 8.54 m. However, using the complete range of wave heights likely overestimates the actual depth at which sediment is mobilized during a typical storm event in the study area. Therefore, it is more realistic to expect sediment movement down to a maximum depth of 8.54 m during common storm events, rather than 9.42 m. While it is theoretically possible for sediment to be mobilized at 9.42 m during an extreme event, such a condition has not occurred in any single year within the time series analysed. In other words, the 9.42 m value results from aggregating the highest waves from different storm events across the time series, not from a single storm capable of mobilizing sediment to that depth. The depth of closure (8.54 m) is situated approximately 300 m from the coast in front of *Güigüi Chico* beach and 200 m in front of *Playa de Enmedio* and *Güigüi Grande* beach. The slope is characterised by a gentle to steep gradient, with a range of 2.5 %–4 %. The northern area exhibits a lower gradient, while the southern area exhibits a higher gradient (Fig. 2).

4.2. Topographical evolution

The study and use of the altimetric and surface volumetric variability of the sediment in the study area and the different morphodynamical strips as an indicator of marine and terrestrial dynamics has enabled, at least, the observation of surface sea-land sediment exchanges produced by waves and currents. In the case of the Guguy beaches, the comparison of interannual altimetry between the MDTs from LiDAR (2009 and 2015) and the altimetric data collected by differential GPS on September 2, 2023 provided corroboration of this hypothesis. The topographic techniques have revealed a range of interannual oscillation in the intertidal and supratidal zones of up to 3 m in elevation, with interannual losses and gains of up to approximately 1.5 m (Fig. 5), which provides evidence of the dynamics of sedimentary land-sea exchange on the Guguy coast.

Table 2
Depths of closure (Hc) according Hallermeier (1981).

Year	Hs	Tp	Hc
1963 (min)	3,07	7,04	5,67
1973 (max)	3,91	16,95	8,54
1958–2023 (aggregated)	4,72	10,77	9,42

The study area, in general shows an evolution of its sediment budgets from 117,462.650 m^3 in 2009; 111,989.950 m^3 in 2015; and to 106,914.276 m^3 in 2023, that is a negative trend in sediment budgets is detected, although these results should be checked taking into account the sediment seasonality factor inherent to coastal sediment dynamics. This factor could not be analysed in this research due to the time and funding given to the research team to carry out this study by the contracting entity (5 months). In addition, in Table 3 the net volumetric differences are exhibited. These differences have been classified according to erosion (negative values) and accumulation processes (positive values). In this sense, a trend of erosion is also observed in the different morphodynamical zones, except for the sandy intertidal zone of *Güigüi Chico*, where erosion attenuates by almost 18 % between 2009 and 2015, and by 49 % between 2009 and 2023. However, the observed errors ($\pm m^3$) indicate that the morphodynamical zones of the sandy intertidal (*Güigüi Grande-Enmedio*) and the sandy backshore of *Playa de Enmedio* may also exhibit a decreasing trend in erosion between 2009 and 2023. Regarding total accumulation volumes, certain areas exhibit a positive trend, including the sandy backshore of *Güigüi Grande*, the dune formation of *Playa de Enmedio* and the sandy intertidal of *Güigüi Chico*, which have experienced an increase of approximately 30 % and 70 % between 2009 and 2023. As previously observed, the cumulative trends of the different morphodynamical zones may be affected by the inclusion of error values (in m^3). This is particularly evident in the case of the pebble backshores of *Güigüi Grande* and *Güigüi Chico*, which have decreased by approximately 96–99 % between 2009 and 2023. Finally, the total net balance of the differences obtained in the study area as a whole and those obtained in each zone indicates that the only morphodynamical strips with a positive sedimentary trend were the sandy intertidal areas of *Güigüi Chico* and *Güigüi Grande* and of *Playa de Enmedio*, where increases of more than 300 % were detected.

4.3. Sedimentological characteristics and provenience

The beaches in the sedimentary system of Guguy constitute a continuous sandy area between the subtidal and intertidal zones, although they are separated at high tide, while the granulometry of the supratidal beach is more heterogeneous (Fig. 6, A). The sedimentary composition of the beaches is characterised by the presence of fine sands on the *Playa de Enmedio*, while the backshore of *Güigüi Grande* and *Güigüi Chico* is formed by pebbles larger than 8 mm.

The spatial distributions of sediment sorting (Fig. 6, B) and skewness (Fig. 6, C) provide further corroboration of these observations. In accordance with the grain size distribution, the skewness of the supratidal beach samples exhibits a deviation towards fine fractions in the *Playa de Enmedio* transects, which evolves to coarse fraction skewness in the northern and southern sectors. Concurrently, it is observed that, although the sediment is well sorted in all sectors of the beach, the level of sorting is higher on the beaches of *Güigüi Grande* and *Güigüi Chico*, and slightly lower on the *Playa de Enmedio*. Transect 5 of this beach exhibits a pronounced sorting peak associated with the penetration of seawater into the dry beach, where it forms a small lagoon.

The grain size distributions of the samples exhibit a discernible and continuous pattern from the subtidal to the supratidal. With a few exceptions, there is a bell-shaped pattern between the values of medium and very fine sands, with a pronounced peak in the proportion corresponding to the fine sands (Fig. 7). The sediment classification exhibits a notable increase in the *Playa de Enmedio*, in proximity to the dune. This increase in classification is comparable to that observed in the subtidal and intertidal zones. The absence of pebbles or debris from the intertidal zone to the dune allows the sediment to be classified by wind action. The skewness of the sediment distribution is also continuous from the

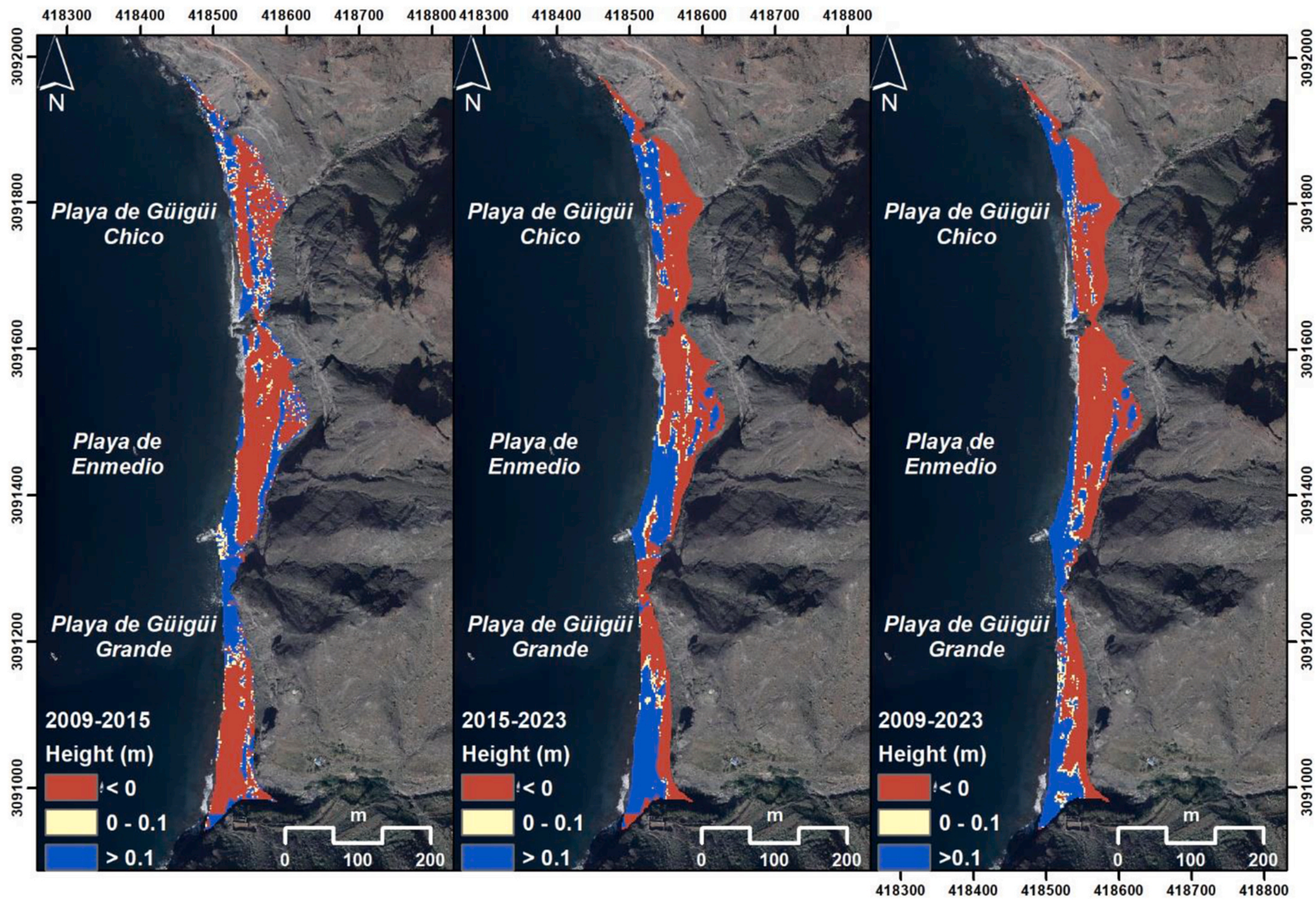

Fig. 5. Altimetric differences (gains - blue, stability - yellow and losses - red) in sandy substrates in the study area over the interannual periods of 2009–2015, 2015–2023 and 2009–2023. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Total net volume and errors associated of the DEMs of Differences (DoDs).

Morphodynamical areas	Total net volume of difference (m^3)		
	2009–2015	2015–2023	2009–2023
	m^3 (±error)	m^3 (±error)	m^3 (±error)
Study area (Total)	**−191.16 (± 39)**	**−14307.72 ± 4610.15**	**−14584.8 ± 4682.32**
Sandy intertidal (Güigüi Grande-Enmedio)	**1066.04 ± 21.37**	**−793.17 ± 283.69**	**1816.33 ± 215.91**
Sandy backshore (Güigüi Grande)	−56.83 ± 32.64	−217.76 ± 56.94	−270.79 ± 60.12
Pebbles backshore (Güigüi Grande)	144.31 ± 19.91	−2265.86 ± 358.44	−2082.8 ± 370.4
Sandy backshore (Enmedio)	−533.45 ± 45.54	−1241.47 ± 392.94	−1737.16 ± 608.45
Dune formation (Enmedio)	−344.24 ± 229.09	−2390.09 ± 353.17	−2759.91 ± 365.36
Sandy intertidal (Güigüi Chico)	**223.04 ± 54.5**	**742.53 ± 504.5**	**941.78 ± 487.65**
Pebbles backshore (Güigüi Chico I)	−315.85 ± 46.96	−7593.58 ± 1145.13	−7883.71 ± 1177.4
Pebbles backshore (Güigüi Chico II)	39.81 ± 21.97	−248.59 ± 60	−222.66 ± 58.4

subtidal to the dune at *Playa de Enmedio*, with values shifted towards the fine fraction of the sediment, which is the most susceptible to wind transport.

Conversely, the two samples collected in the ravine exhibit a markedly disparate pattern, exhibiting a less pronounced bell curve that encompasses the fractions corresponding to gravels and medium sands, with their respective maximums observed in the coarse or very coarse sands.

The proportion of carbonates found in the beach samples (Fig. 6, D) was consistently low, with a mean value of less than 4.5 %. It can therefore be concluded that the primary mechanism responsible for the supply of sediment to the Guguy beaches is the erosion of the massif, with a contribution from organogenic sand derived from the marine environment. Furthermore, the carbonate content of the two samples collected in the ravine is found to be zero. As anticipated, the organic (marine) fraction was observed to be higher in the subtidal and intertidal zones, in direct contact with the sea, and to a lesser extent in the upper beach strips. Within these zones, there was a greater presence of carbonate sands in the areas corresponding to the *Güigüi Grande* beach, to the south of the study area, and secondarily in the supratidal and the backshore of the *Playa de Enmedio* beach, where the dune is located, with values of between 1 % and 2 %. Despite the low proportion of carbonates, the presence of at least a significant portion of bioclasts, formed in the surrounding shallow bottoms, provides evidence of effective sediment transport processes from the submarine environment to the upper beach and backshore areas.

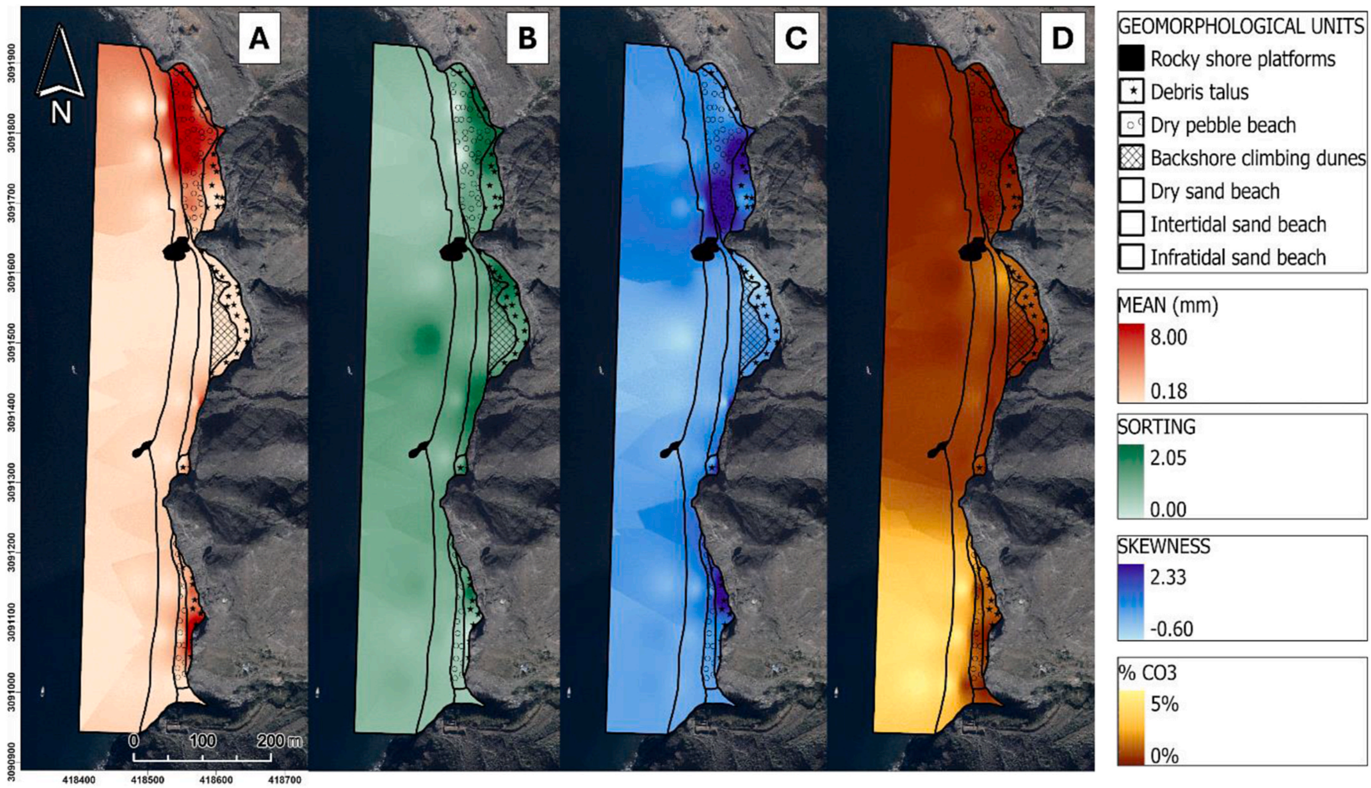

Fig. 6. Spatial distributions of mean grain size (A), sorting (B), skewness (C) and percentage of carbonates (D) in the sedimentary coast of Guguy, in relation to the main geomorphological units.

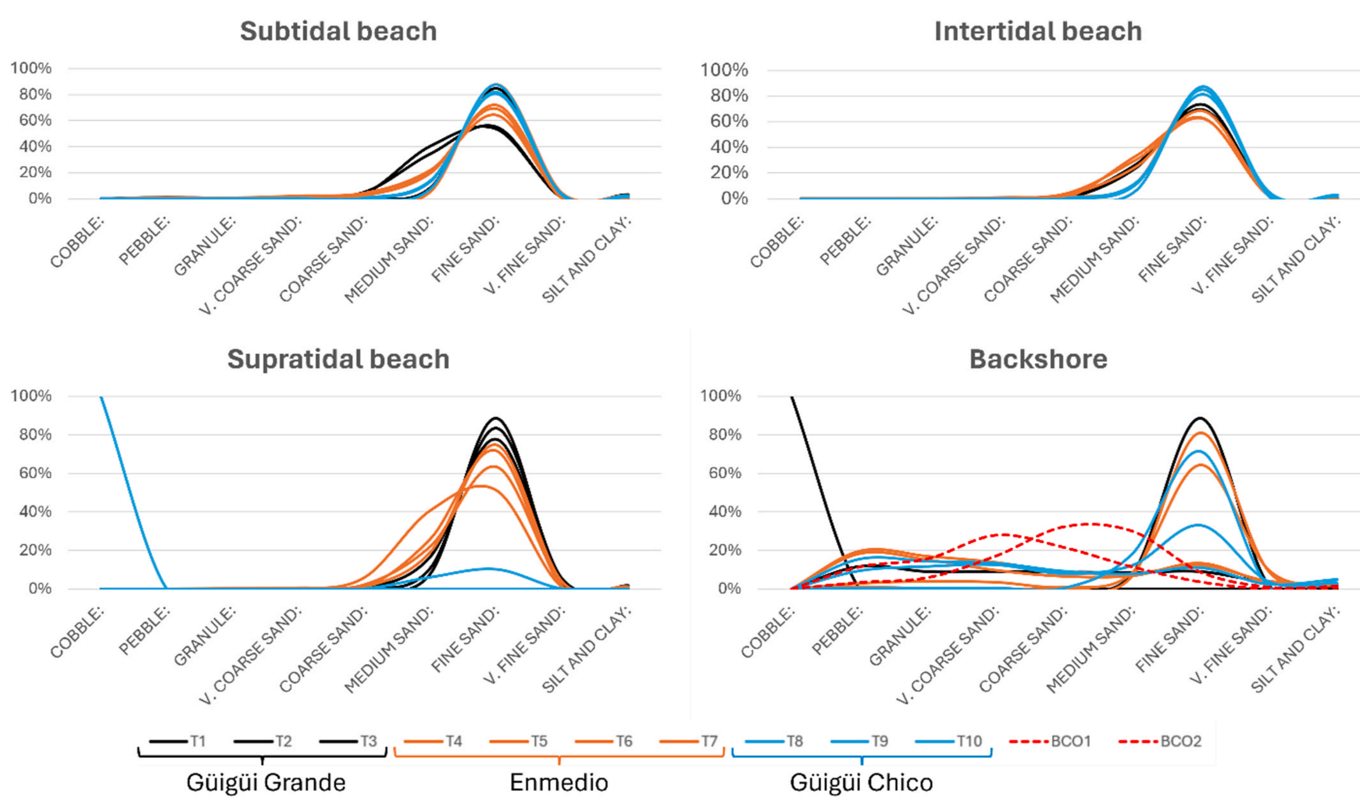

Fig. 7. Grain size distributions for each of the beach sub-environments.

4.4. Wind flow dynamics

The spatial distribution of wind speed and direction (Fig. 8) under the general conditions demonstrates the influence of local topography on wind dynamics. The inflow wind speeds of 8.5 m/s from the N-NE are representative of the prevailing conditions observed at the SIMAR station between 1958 and 2023 (Fig. 8, A). At *Güigüi Chico*, northerly winds sweep the beach from north to south. In the absence of dry sand on the upper beach of *Güigüi Chico*, the intertidal sand (the most stable morphodynamical zone, which shows a tendency to sedimentary accumulation) is transported and accumulated by the coastal drift at the southern end of the beach. This process continues until dry sand accumulations of a certain volume are generated, which in turn are transported by wind action towards the *Playa de Enmedio* through the rocky outcrop that separates them. In accordance with the prevailing wind conditions, this rocky outcrop exerts a forceful acceleration on the leeward wind, which, when combined with a turn to the east, facilitates the transport of sediment in a northerly direction towards the *Playa de Enmedio* and the accumulation of sand on the debris talus.

In the southern region of *Playa de Enmedio*, the presence of another intertidal rocky body (El Pasillo) and the abrupt topography generate wind accelerations and vortices, whose behaviour is difficult to predict. It is to be expected that the transfer of sediment from *Playa de Enmedio* to *Güigüi Grande* beach is already minimal, given the lack of dry sand in this area. The topography that separates the beaches of *Playa de Enmedio* and *Güigüi Grande* also means that the latter is more sheltered from the predominantly northerly winds. The data indicate that at *Güigüi Chico* beach, wind speeds decrease in general, even below the effective transport threshold. This reduction in velocity is more pronounced in the southern part of the beach, where a small, active dune is observed. The accumulation of dry sand in this sector of the beach must be attributed once more to the effect of sediment transport and accumulation by the north-south coastal drift. Furthermore, the wind conditions that subsequently form the dune probably correspond to non-dominant wind conditions that were not recorded during the campaign.

5. Discussion

5.1. Geomorphological processes defining ecological connectivity

The continuity of sediment flow between the subtidal, intertidal and supratidal areas of the Guguy coastal sedimentary system provides evidence of the existence of morphodynamic processes linking submerged and emerged ecosystems. The sediment dynamics, including stabilisation by seagrass, wave, wind and fluvial transport, as well as gravitational mobilisation, link sub-environments and traverse the administrative boundary that separates maritime-terrestrial management (Fig. 9). This underscores the inherent inconsistency in the proposed approach of establishing state-level management of the maritime zone, while concurrently implementing regional-level management of the terrestrial zone. This discordance poses a significant threat to ecosystem connectivity.

The sedimentological analysis has confirmed the constant predominance of sands in the intertidal zone, as well as at subtidal depths of approximately 2 m. The results obtained are also in agreement with the Ecocartography of the Coastline of the Southern Area of Gran Canaria (MAGRAMA, 2000), which determines that the island platform off the coast of Guguy is several kilometres wide, has a shallow average depth and a predominance of sandy sediments. Furthermore, the composition of the sediment has enabled the determination of its origin. As carbonate production in the Canary Islands is exclusively of marine origin, a higher proportion of carbonates is related to shelf sediments (Montoya Montes et al., 2017). Conversely, low carbonate concentrations are associated with terrestrial sources. The absence of carbonates in the sediment samples collected in the ravine (0 %) has enabled us to corroborate this assertion and to associate the presence of calcium carbonate in the sedimentary coast of Guguy with the natural contribution of bioclasts from the submarine shelf environments. Nevertheless, the proportion of carbonates found in the beach samples has been consistently low, with values below 4.5 %. It can therefore be concluded that the primary mechanism of sediment input to the Guguy beaches is the erosion of the massif and, potentially, coastal drift from ravines to the north, with an additional contribution from organogenic sand input from the marine environment. The transport of lithoclastic sediments is channelled through the ravines network, and they are ultimately deposited both on the beaches and in the immediate marine strip. Despite the low proportion of carbonates, the existence of at least a significant portion of bioclasts, formed in the surrounding shallow bottoms, provides evidence of effective sediment transport processes from the submarine environment to the beaches and backshore areas.

The dominant swell in the study area originates from the first and fourth quadrants (Fig. 8, B), because of the refraction effect generated by the island on the beaches. This provides evidence of the existence of a longshore current that transports sediments from the north to the south. The waves can remobilise the sediment from the bottom to the depth of closure. It is in this zone of active waves that part of the *Cymodocea nodosa* meadows develop. Seagrass meadows represent a crucial component in the conservation of coastal sediment bodies and participate in the flow of sediment. In this context, *Cymodocea nodosa* meadows facilitate the stabilisation and retention of sediments, thereby contributing to the protection of coastal areas from erosion during marine storms. They also reduce water turbidity, act as a natural barrier to dampen waves, and, over a longer timescale, can contribute to the generation of organogenic sediments due to the large number of marine organisms that inhabit them (De Boer, 2007; Infantes et al., 2022). In certain circumstances, the sediment retained and generated in the seagrass meadows of the active part of the subtidal zone is transported towards the beach by waves and currents. In the intertidal zone and on the emerged beach, the drift sediment is mixed with the sediment from the ravine network. A portion of the sandy fraction of this sediment is returned to the active wave profile, where it is remobilised by waves and currents. Another portion dries out on the upper part of the beach and is subject to wind dynamics, eventually feeding the dune formations.

Consequently, the existence of active dynamics that contribute to the prevalence of a continuous body of sand from the subtidal beach to terrestrial environments in the study area has been corroborated. It is therefore of the utmost importance to implement integrated management measures that safeguard not only the geomorphic features that support ecosystems (Corenblit et al., 2011), but also the sediment flow described in order to guarantee the natural dynamics that determine their formation and the natural values of the area. Nevertheless, it should be acknowledged that, while the findings are indicative and adequate to formulate preliminary management recommendations, it would be prudent to augment the number of data collection initiatives to ascertain the seasonal fluctuations of the physical processes identified along the coastline. This would necessitate increased financial and temporal resources to overcome the challenges associated with conducting research in a remote location, such as the study area.

5.2. Integrated management to avoid jurisdictional boundaries

As the marine and the terrestrial ecosystems are connected by sea-land processes, threats originating in one realm can affect the other, so links between the two need to be incorporated into management and conservation plans. Similarly, conservation measures taken in one realm affect the other (Harris et al., 2025). On the other hand, the creation of administrative management boundaries between the two environments and the division of responsibilities between the terrestrial and marine domains may neglect the linkages between land and sea, jeopardising the conservation of the system.

The socio-economic importance of coastal areas makes human activities a link between land and sea, so management decisions with

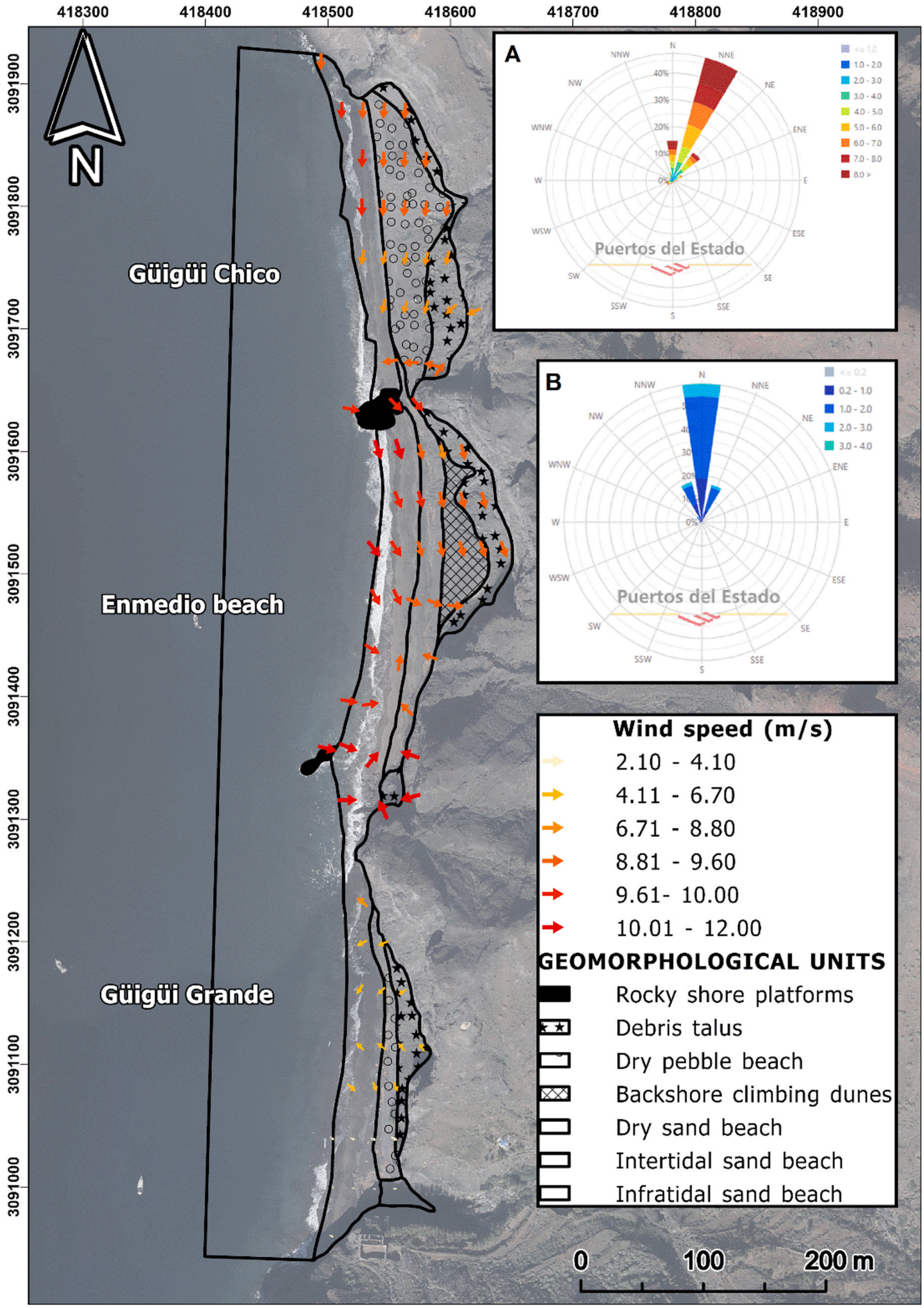

Fig. 8. Spatial distribution of wind flow dynamics with an inflow wind of 8.5 m/s from the N-NE. Inserts: Wind rose (A), and wave rose (B) at the SIMAR station 4032008 for the period 1958–2024 (Puertos del Estado, Spain).

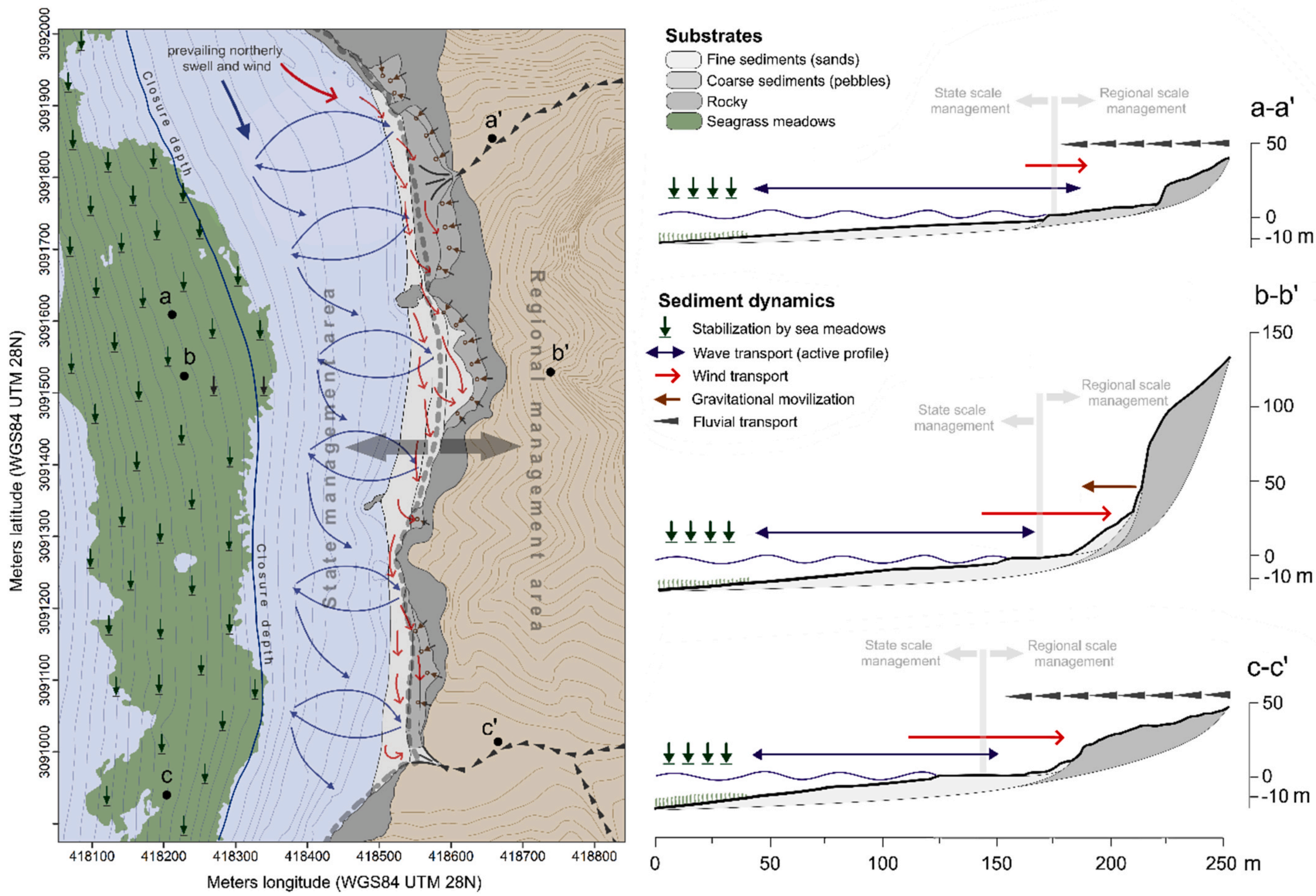

Fig. 9. Sediment transport and land-sea dynamics model in the coastal system of the Guguy National Park proposal. Cross-sectional profiles at Playa de Güigüi Chico (a-a'), Playa de Enmedio (b-b') and Playa de Güigüi Grande (c-c') are included.

socio-economic implications need to consider the area as a whole and manage human use of the environment along the land-sea continuum (Harris et al., 2025). Increased human activity in the coastal zone threatens biodiversity and ecosystem services at multiple scales (Onyena and Nwaogbe, 2024), as well as the destruction of land-sea ecological connectivity (Fang et al., 2018), including sedimentary connectivity.

Management decisions on the landward side have the potential to affect sediment flux and have consequences in coastal zones that are sometimes managed by different agencies. Pollutants resulting from human activity on land are transported by rivers and ravines to the sea, affecting marine coastal ecosystems (Saengsupavanich et al., 2024). Actions on river basins such as water diversions, channel modifications or water body renting have the capacity to impact sediment fluxes that feed coastal systems (Rozzi et al., 2023), as evidenced by the cases of the Ebro river (Guillén and Palanques, 1997) or the Bay of Marbella (del Río et al., 2020). Similarly, in coastal sedimentary systems, management actions on the marine side that interrupt or modify the sedimentary continuum (Saengsupavanich et al., 2022), which encompasses a succession of environments from submerged sand flats to possible dune formations, through submerged and emerged beaches, have direct consequences on the terrestrial side (Molina et al., 2025). These consequences are related to problems of coastal erosion, changes in species richness and dominance, and possible loss of habitats.

In the specific case of insular coastal environments, such as the coastal sedimentary system of Guguy, the limited surface area serves to further narrow the relationship between terrestrial and marine environments (Quesada-Ruiz and Peña-Alonso, 2023). Consequently, the sites of reciprocal interaction between natural and anthropogenic processes are readily identifiable. However, in the context of the Canaries, oceanic islands exhibit a rapid and significant sediment flux between the summit areas and the coasts, driven by the shorter distances, steep slopes, and torrential rainfall characteristics. Given that the precipitation is scarce and concentrated (Hernández-Cordero et al., 2019), it generates significant sediment flows in a relatively short period of time (Génova et al., 2015). The seasonal and highly dynamic sediment flux may present a challenge in determining the area of interaction between geomorphological processes (Marrero-Rodríguez et al., 2024). This is because there may be important inputs of sediment by coastal drift that have not been considered, depending on the scale. It is therefore crucial to make management decisions based on a broad spatial and temporal scale. This enables the identification of inputs from areas outside the boundaries of the protected area or large inputs made long ago, whose effects are noticeable despite the cessation of sediment input (Guillén and Palanques, 1997; Marrero-Rodríguez et al., 2020b). Similarly, once the sediment flow has been delineated, it is essential to continue monitoring it to evaluate potential changes and make modifications to the boundaries of the protected area to conserve the dynamics involved in a comprehensive manner.

In other coastal protected areas in the Canary Islands, some management decisions have been taken based on the protection or conservation of specific natural elements, despite the potential for these measures to prevent the interruption of geomorphological processes. Despite the designation of some areas as protected natural areas, the continuity of sediment flow in coastal sedimentary systems located in other areas of the Canary Islands has been compromised. The quantity of sediment reaching the coastline in the Canary Islands has been diminished as a consequence of alterations in precipitation patterns and human activities (Marrero-Rodríguez et al., 2024). Furthermore, the continuity of the active transport of sediment reaching the coast and supporting important coastal ecosystems is also modified or directly disrupted by human activity at different spatiotemporal scales. The utilisation of historical (Marrero-Rodríguez et al., 2020a, 2021) and contemporary practices in and around aeolian sedimentary systems is causing concern regarding the stability of sedimentary dynamics and biogeomorphological processes. Anthropogenic activities, such as urbanisation (García-Romero et al., 2016; Hernández-Calvento et al., 2014), the presence of structures and services on the beaches (Pinardo-Barco et al., 2023; Sanromualdo-Collado et al., 2021), the construction of stone windbreak structures (Sanromualdo-Collado et al., 2023) or the extraction of aggregates (Marrero-Rodríguez et al., 2020a; Sanromualdo-Collado et al., 2022), have been found to have repercussions on the systems in terms of species richness and distribution (García-Romero et al., 2021; Hernández-Cordero et al., 2017; Peña-Alonso et al., 2019), the development of landforms (Hernández-Cordero et al., 2018; Hesp et al., 2021) and the erosion of beaches and dunes (Marrero-Rodríguez et al., 2022). These activities are the consequence, in one way or another, of management decisions that have not been aware of the importance of preserving the continuity of geomorphological processes. Consequently, the most efficacious method of circumventing management decisions that could have a deleterious effect is to implement an integrated management approach to coastal areas that safeguards not only the geomorphological elements but also the dynamic processes and interactions that give rise to and perpetuate them.

6. Conclusions

Despite the trend towards integrated management of sea-land areas, conflicts of decision-making powers persist due to the division of marine and terrestrial jurisdictions. In certain instances, it is necessary to demonstrate the ecological connectivity between the marine and terrestrial environments is necessary to transfer spatial management competences to a single administration for integrated management. In such instances, the identification of interconnected sedimentary systems through geomorphological processes can be of significant importance in determining the area that requires integrated protection and management. This is particularly pertinent to the proposed Guguy National Park on the island of Gran Canaria (Spain), where the connectivity of the sedimentary systems has been demonstrated through four key elements: recent topographic evolution, sediment provenance, wind circulation, and nearshore interaction.

It is evident that the contributions from the ravines play a crucial role in the formation of the described geomorphological units. Furthermore, the marine contributions, although less significant, are also important. The continuous flow of sediments between the interior of the island, the coastal zone and the nearshore necessitates the establishment of protection measures that not only safeguard the landforms that form part of the study area, but also the integrity of the dynamic processes that originate and maintain the sedimentary coast of Guguy, avoiding human activities that could interfere with these processes.

The utilisation of specific geomorphological processes as indicators has enabled the corroboration of the ecological connectivity between the marine and terrestrial environments within the national park proposal. The establishment of a jurisdictional boundary along the coastline for the management of these environments would result in the fragmentation of management responsibilities for the area, which would in turn threaten the continuity of the natural dynamics that guarantee the interconnection and functionality of the marine and terrestrial ecosystems and habitats present. In light of the aforementioned considerations, it is advised that the competences of the site be transferred to a single administration, or that a managing body be established to assume all responsibilities for the site, in order to avoid such fragmentation of responsibilities and to promote sustainable, integrated and holistic management of the coastal protected area.

CRediT authorship contribution statement

Abel Sanromualdo-Collado: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicolás Ferrer:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Néstor Marrero-Rodríguez:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio I. Hernández-Cordero:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leví García-Romero:** Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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