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THE COMPLEXITY OF STUDYING COASTS: FROM FORMS AND PROCESSES TO MANAGEMENT

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ABSTRACT. Coastal environments are characterized by their high dynamism, related to the interaction between marine agents (winds, waves, currents, sea level changes) and continental forms and processes. The present article summarizes the main morphodynamic characteristics of coasts and the resulting environments. Different oscillations of the sea level are considered, depending on their amplitude and frequency: rapid eustatic fluctuations, energetic tsunamis, storm waves and surges, tides and good weather wind waves. Coastal environments are classified in low, sedimentary coasts, including beaches, dunes, barrier islands, lagoons, salt marshes and river mouths, and high, rocky coasts. Management of coastal zones needs a deep knowledge of all the processes involved at the littoral, especially at the local scale, since coastal processes vary rapidly alongshore. At present the integrated coastal management intends to involve different socioeconomic sectors interested in the occupation and use of coasts. Coastal management must include the adaptation of human activities to the natural processes and associated coastal hazards and the protection of coastal values, both of natural and historical-cultural character. Public administrations at different levels should consider the knowledge of the coastal processes at different scales and their potential interaction with human activities in order to design laws and regulations accordingly.

La complejidad de estudiar las costas: de las formas y procesos a la gestión

RESUMEN. Los ambientes costeros se caracterizan por su gran dinamismo, relacionado con la interacción entre agentes marinos (viento, oleaje, corrientes, variaciones del nivel del mar) y formas y procesos continentales. El presente artículo resume las principales características morfodinámicas de las costas y los ambientes resultantes. Se han considerado las diferentes oscilaciones del nivel del mar, dependiendo de su amplitud y frecuencia: fluctuaciones eustáticas rápidas, tsunamis enérgicos, olas de temporal e inundaciones de marejada, mareas y oleaje de viento de buen tiempo. Los ambientes costeros se han clasificado en costas bajas, sedimentarias, que incluyen playas, dunas, islas-barrera, albuferas, marismas y desembocaduras fluviales, y costas altas, rocosas. La gestión de zonas costeras necesita de un conocimiento profundo de todos los procesos involucrados en el litoral, especialmente a escala local, ya que los procesos costeros varían rápidamente a lo largo de la línea de costa. En la actualidad la gestión integrada de zonas costeras pretende involucrar a diferentes sectores socioeconómicos interesados en la ocupación y uso de la costa. La gestión costera debe incluir la adaptación de las actividades humanas a los procesos naturales y a los riesgos naturales asociados, así como la protección de los valores de la costa, tanto naturales como histórico-culturales. Las administraciones públicas a distintos niveles deberían considerar el conocimiento de los procesos costeros a diferentes escalas y su interacción potencial con las actividades humanas, de cara a diseñar leyes y normativas de acuerdo con ellas.

Key words: Coastal environments, morphodynamic processes, natural hazards, integrated coastal zone management.

Palabras clave: Ambientes costeros, procesos morfodinámicos, riesgos naturales, gestión integrada de zonas costeras.

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1. Introduction

As in any other natural morphogenetic system, the coast is the result of the action of a number of processes acting on a given space, in this case of azonal nature, not strictly controlled by climate. The main difference between coastal zones and other morphogenetic systems is the high energetic gradient existing in a narrow band, where land and sea meet. Oceans spread out along all latitudes, climates and geological situations, and this adds an additional level of complexity to coasts, since marine processes can affect any kind of morphogenetic system reaching the coast. We can find rivers or glaciers arriving to the coast, coastal karst, active oceanic volcanism, coastal deserts, etc. Any of all those systems, with their specific processes, can interact with specific marine processes, a situation exclusive of coastal environments. The result is a high casuistry, which produces great variability and multiplicity of coastal types (Bird, 2010). Another typical characteristic of coasts is their high dynamism: different marine agents (winds, waves, currents, sea level changes) interact with coastal materials to produce erosion, transport and sedimentation of particles, dealing to rapid changes, perfectly perceptible by humans. A corollary of this is the frequency of situations where natural coastal processes interact with human occupations to produce damage (Morales, 2022).

All this complexity makes it difficult to classify coasts, especially when different spatial and temporal scales are involved (Huggett, 2011; French *et al.*, 2016). Following Fairbridge (2004), a given coast can be described by considering three main terms: coastal material exposed to marine agents, coastal agents and their nature (erosive, constructive, physical, chemical, biological and their geographical conditioning factors), and history (geological, climatic, eustatic, occupational evolution). However, not always it is so simple, because sometimes it is very difficult to define where the continent ends and where ocean begins. This is the case of low coasts and coastal wetlands periodically affected by marine flooding, where sometimes they are clearly continental, while others they turn to be marine. A number of classifications have been proposed to cope with this problem, but many of them are useless when applied at a regional/local scale. Pérez Alberti (this issue) presents a new proposal of coastal classification methodology, designed to be applied to any coastal type, based on the quantification of a number of morphometric, topographic and morphodynamic variables. The method, applied to the Galicia coast, results in a detailed inventory and mapping of that region, including different numeric data, which allows grouping the high diversity of coasts into a number of types in a hierarchical manner.

An additional complication is the increasing concentration of human occupations and activities at coastal zones. Only considering coastal zones of low elevation (< 10 m high), more than 600 million people lived at the coast by 2000, and present trends indicate a growth of more than 50% in the following 30 years, to reach almost 900 million by 2030, especially on the less developed countries (Neumann *et al.*, 2015). This situation considerably increases the exposition of people, settlements and social and economic activities to potentially dangerous marine processes, like flooding linked to the ongoing sea level rise, storm surges, high energy waves, coastal erosion, etc. (Elko *et al.*, 2014).

The sustainability of coastal human occupations and activities is only possible with an adequate adaptation to present natural processes acting on the coast and their future trends. This requires a deep knowledge of the coastal environments, the natural agents and processes acting on them, their future trends, the interaction between human activity and coastal processes, and the extreme potentially dangerous events expected to occur in the future. All these complex topics constitute the aims of the present research carried out in coasts, involving a high number of disciplines such as climate and weather forecast, oceanography, coastal geology and geomorphology, coastal engineering, physical and human geography at the coast, economy and population, urban and social sciences, among others.

The present contribution aims to present a succinct state-of-the-art of all those topics, mainly under a morphodynamic scope applied to management. The exposition firstly presents the main agents and processes acting on coasts, secondly the coastal environments and the most common techniques used in their study, and finally a brief discussion about how all this information can strongly condition future trends in coastal management.

2. Coastal processes

Coastal processes are mostly related to oscillations and changes of sea level, which fluctuates on very different time scales. Fairbridge (1983) distinguished three-time scales of sea level change: 10^6-10^9 years (broad eustatic cycles), 10^3-10^6 years (tectonoeustatic changes, Quaternary glaciations) and short-term changes, from hours to 10^3 years, controlled by astronomical, meteorological, oceanographic and climatic factors. The interest of sea level changes for coastal management is restricted to this third set of scales ($\leq$1000 years of periodicity), and can be detailed into more specific processes, like those presented in Figure 1. Obviously, there exist numerous superimpositions between different processes, which produce interactions, counteractions and synergies. The following sections summarize the main aspects of this set of processes.

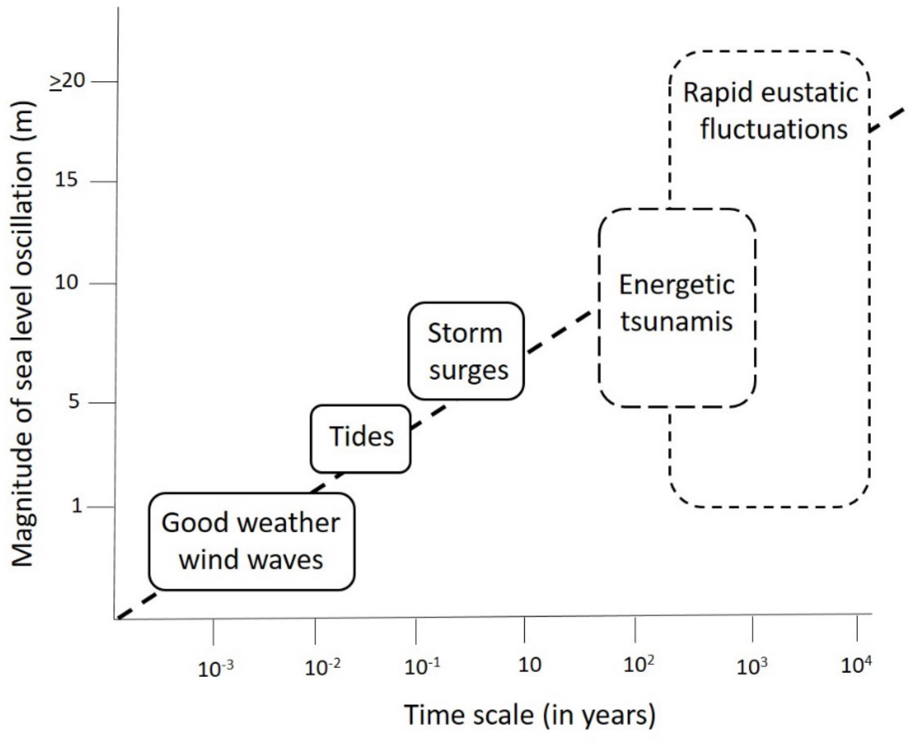

Figure 1. An example of relationships between sea level fluctuations and time scale of their actuation.

2.1. *Rapid eustatic fluctuations*

They are commonly triggered by climate oscillations (like those related to the Little Ice Age; Jevrejeva *et al*., 2014), or by rapid vertical movements mostly related to glacio-eustacy, isostacy and tectonism in general (Morhange *et al.,* 2012). Markers of past sea levels can be recognized both as erosional forms on rocky coasts, or through sedimentary records (staircase marine terraces, sedimentary infilling of coastal plains and salt marshes). The first case can be represented by terraced planation surfaces, perched (Kelsey, 2015) or submerged tidal notches (Evelpidou *et al.*, 2012), or more complex cliff profiles, with alternating bevelled and vertical stretches (Trenhaile, 1987), like those studied by Rodríguez-Vidal *et al*. (2004) in the Gibraltar Rock and showed in Figure 2A; these authors sampled and dated the different deposits associated with stepped erosive levels identified in the cliff, to obtain the Late Quaternary relative sea level evolution of that coast; it consisted in a decreasing rate of sea level fall as a consequence of the apparent reduction of tectonic rise of this portion of the Betic Orogen. According to those authors, in recent times sea level trends seem to be lower than -0.005±0.01 mm/yr. Figure 2B includes another example of cliff exhibiting a complex profile as a result of alternating episodes of relative sea-level fall and cliff erosion/retreat in southern Spain.

Figure 2. Examples of past sea levels indicators. A and B: composite profiles in rocky cliffs including stepped erosion elements due to relative sea level fluctuations; A, eastern side of the Gibraltar Rock; B, western side of the Herradura Bay (Granada, South Spain). C: uplifted Holocene beach deposit (> 90 m above present sea level, a.s.l.), due to glacio isostatic rebound; eastern Baltic coast of Sweden. D: Molluscs accumulations as indicators of former positions of relative sea level (+ 7 m a.s.l.) during historical times; Roman remains at Pozzuoli, SW Italy.

Tectonic uplifting trends during the Quaternary favoured the generation of terraced coastal landscapes, including stepped erosion surfaces and raised beaches, often forming complex systems with numerous staircase levels, like those of the southern Italian and Sicily coasts (Antonioli *et al*., 2006), or the *rasas* and raised beaches developed along the northern Iberian coast (Flor and Flor-Blanco, 2014; López-Fernández *et al.*, 2020). In high-latitude regions, vertical movements are associated with isostatic readjustments due to the retreat of the great ice caps after the last glaciation. Glacio-isostatic uplift in such regions has produced numerous examples of Holocene raised beaches (Fig. 2C). The process is still active and is responsible for the coastal progradation of sedimentary bodies (commonly beach ridges) in many places of the northern regions (Hansen *et al*., 2011; Nunn *et al*., 2021).

In mid and low latitudes recent (Holocene and historical) sea level fluctuations are mostly recorded in low, sedimentary coasts, where historical beach ridges, and boreholes excavated on sedimentary aggradational plains and wetlands (lagoons, salt marshes), are used to reconstruct vertical relative sea level changes. The ridge systems are studied by means of cartography, high-resolution altimetry and dating (Hansen *et al*., 2011), while the latter are explored through boreholes where different sources of palaeoenvironmental information (pollen, foraminifera, geochemistry, mineralogy) are combined to reconstruct palaeogeographical coastal changes due to relative sea level oscillations. Examples of combination of different sources of data for reconstructing recent sea level trends for the western Mediterranean and the Gulf of Cádiz can be seen in Vacchi *et al*. (2016) and Caporizzo *et al*. (2021).

Apart from erosional forms, like notches (Marriner *et al*., 2014), in recent, historical times, past relative sea levels can be established through the analysis of markers on coastal archaeological remains (Orrú *et al*., 2014). Many examples exist along the Mediterranean coasts, due to the recent to present tectonic vertical movements associated with the active collision between the Eurasian-African plates, and also to a long history of coastal human occupation and urbanization all along the Mediterranean shores, which produced an endless number of coastal archaeological sites. Perhaps the most famous and spectacular markers of historical relative sea level oscillations are those of the coastal Roman ruins of Pozzuoli, located in the Bay of Naples, Italy; the markers are represented by the accumulation of *Lithophaga* burrows and marine organisms fixed on the Roman columns and other remains, presently located several meters above mean sea level (Fig. 2D), and also by submerged Roman constructions (Aucelli *et al*., 2019). The relative sea level rapid oscillations during Antiquity and Middle Ages are in this case produced by the volcanic deformational activity of an underlying caldera (Morhange *et al*., 2006).

If sea level fluctuations during the last millennia were usually lower than a few meters (Kemp *et al*., 2011), at minor time scale climatic oscillations during the last centuries gave rise to subtle sea level variations that can be reconstructed through geo-archaeological and historical techniques (Losada *et al*., 2008), and quantified through the analysis of tide gauges, a method not exempt of uncertainties (Marcos *et al*., 2003; Tsimplis *et al.,* 2011). Historical tide gauge records are mainly available on the northern hemisphere, due to the historical concentration and development of human settlements on the coasts of Europe and North America. This situation gives valuable and detailed data about sea level trends in that region of the Earth, but neglects other world regions, where existing data are very limited. Tidal data are combined with geodetic data for the elaboration of sea level projections, usually by the year 2100 (Vecchio *et al*., 2019). At a global scale, present rates of sea-level change are estimated after applying different climate warming scenarios and geodetical models, always considering that sea level trends are mostly controlled by ice sheet fluctuations (IPCC, 2013). However, this procedure introduces important uncertainties and has been questioned by some researchers (Mörner, 2019). Far for seeking after a global sea level curve and trend, which is by no means non-representative, present research aims to establish local/regional sea level trends (Cronin, 2012), in order to predict the associated coastal changes and their consequences to human occupations and activities at the coast.

Traditionally, it is considered that during a period of sea level rise, like the one presently prevailing in most world coasts due to global warming, sandy beaches will erode and retreat: The increase in the accommodation space prevents sediment return after storm erosion episodes, leading to sedimentary deficit at the shoreface. This relation was expressed mathematically by the Danish civil engineer P.M. Bruun, who proposed a quite simple rule to predict shoreline erosion due to sea level rise (Bruun, 1962), although it received numerous criticism due to a number of arguments, like the absence of geological or oceanographic basis (Cooper and Pilkey, 2004); however, it is still applied due to its simplicity and the absence of an alternative approach.

Cooper (this issue) analyses the response of sandy beaches to sea-level rise, concluding the necessity of enough space behind beaches in order to let them migrate inland. If this possibility exists, then beaches can adapt and face sea level rise maintaining their natural properties. Obviously, human-transformed and artificial beaches usually lack such characteristics, especially those landward limited by rigid structures, which cannot migrate and are condemned to erosion and extinction.

Other coastal sedimentary environments, like salt marshes, can present a comparable behaviour, although bearing a higher vulnerability. If they receive enough sediment supply and include sufficient space inland to migrate, usually inside wide estuaries and bays, they can face a sea level rise if it occurs at not very high rates (Sampath *et al*., 2011; Best *et al*., 2018). Other conditions, like accelerated sea level rise, or decrease in the sedimentary supply to estuaries, however, may progressively submerge salt marshes until their permanent flooding (Hofstede *et al*., 2018; Aranda *et al*., 2020). These environments, and coastal wetlands in general are highly vulnerable systems to rapid sea level rise (Fernández-Núñez *et al*., 2019). Nevertheless, projections of future sea level flooding should consider the possible inland migration of beaches, barrier islands, sand spits, dunes, salt marshes and deltas. This vision requires a dynamic analysis of coastal responses to sea level rise, avoiding any rigid consideration of the present coastal topography; flooding projections uniquely based on a simple, passive, uprising of sea level (Fraile *et al*., 2018) are mostly unreal.

2.2. Energetic tsunamis

The recent catastrophic tsunami events of 2004 in the Indian Ocean and 2011 in Japan have encouraged the study of this type of phenomena that suddenly hit the coasts producing severe damage and casualties. Tsunamis represent the most energetic natural process acting on coasts, capable of producing intense destruction, deep erosion and transport inland huge rock boulders (Figs. 3A, B and C). However, their study is not easy because, fortunately, this is not a frequent process. Prediction of future events, based on a given recurrent period, needs enough historical records for establishing believable trends.

Tsunamis are capable to generate a number of coastal landscapes, both of erosional and sedimentary nature (Bryant, 2008). Historical sedimentary records of past tsunamis are scarce and often difficult to interpret due to the numerous similitudes with coastal storm deposits (Dawson and Shi, 2000; Morales *et al*., 2011; Shanmugam, 2012). In recent times attention is increasingly paid on the diagnostic characteristics of the offshore deposits produced by tsunamis (Costa *et al*., 2021).

Regarding coastal forms and deposits, many places have been reported around the world with outstanding records of historical tsunamis (Scheffers and Kelletat, 2003). Some of them are constituted by boulder accumulations, at places never reached by sea storms; an example of this can be found at Trafalgar Cape, South Spain, where more than 80 large boulders, many of them exceeding 10 tons, lie upon a rocky shore platform; other set of more than 100 rounded cobbles, weighting several hundreds of kg, appear at heights between 8 and 16 m a.s.l. (Fig. 3A). The event responsible for their emplacement is thought to be the tsunami generated by the Lisbon earthquake of 1755 (Whelan and Kelletat, 2005); the presence of mill wheels imbricated within the boulders (Fig. 3B) and other indirect markers would be arguments in favour of this ascription (Gracia *et al*., 2006). Usually big boulders located at high positions and distant from the very shoreline are interpreted as the most typical example of deposit generated by a tsunami, like the case showed in Figure 3C; however, even in such cases, theoretical studies and specific examples demonstrate that big storms can produce the same effect (Barbano *et al*., 2010), like the case showed in Figure 3D, where, according to witnesses, a large boulder was suddenly deposited by energetic storm waves inside the Bay of Sydney (Australia) in the early 20th century (W. Stephenson, pers. com.). Very detailed morphometric determinations are then needed to discriminate the origin of such type of high-energy deposits (Goto *et al*., 2010).

Figure 3. Examples of boulder accumulations due to high-energy events. A and B, boulders supposedly accumulated by the 1755 tsunami at Trafalgar Cape, South Spain; A, Imbricated boulders at + 8 m a.s.l.; B, historical mill wheel imbricated within the rest of the boulders; C, big boulder deposited by a historical tsunami on a platform more than + 5 m a.s.l. at Bonaire Island (Netherland Antilles); D, the "Mermaid Rock", boulder deposited by a strong storm in the Bay of Sydney, Australia (photo: Wayne Stephenson).

Much research is still needed for correctly interpreting palaeotsunami markers, both erosional and depositional, related or not to archaeological remains (Goff *et al*., 2012; Röth *et al*., 2015). Although some recent progress has been made in the reconstruction of historical tsunamis in the Atlantic coast, especially along the western European coasts (Scardino *et al*., 2020; Costa *et al*., 2021, Álvarez and Machuca, 2022), one of the best known in the world regarding this topic, the establishment of a credible return period is difficult and proposals in this sense are still controversial (Lario *et al*., 2011; Ruiz *et al*., 2013). The recent catastrophic events that occurred in the Indian and Pacific coasts served as reference for analysing the coastal effects of such phenomenon (Lavigne *et al*., 2009; Ikehara *et al*., 2021), which can be used as a model to a better interpretation of past, historical, events and also to understand how coastal morphology controls the propagation of tsunami waves and the resulting maximum wave height (Umitsu *et al*., 2007).

Taken all these considerations into account, and after combining data from records of historical events, detailed coastal topography and mathematical models for wave propagation, interesting and useful vulnerability analysis can be obtained, with maps of tsunami-flooding hazard that can be used for coastal management in areas exposed to this type of energetic phenomenon (Izquierdo *et al*., 2019). Mathematical models can also be used for theoretically reconstructing the propagation and effects of past tsunamis, in order to compare such results with the real markers and indicators identified in the historical remains (Abril *et al*., 2013). Recent efforts are being made by marine geologists on the specific location and analysis of the submarine faults responsible for the generation of past, historical tsunamis, with present potential activity, in order to refine the existing mathematical models and obtain better flooding maps (Estrada *et al*., 2021; Martínez-Loriente *et al*., 2021).

2.3. Storm surges

Storms are one of the most important natural coastal threats in terms of property damage and lives lost; they produce coastal erosion, coastal flooding and damage to infrastructures (Fig. 4). They are originated by low pressure cells on the ocean and typically produce strong winds; both factors make sea level to rise up (storm surge or set-up). Waves associated with such perturbations are high, steep and with short period. During energetic storms, increasing water level, in coincidence with spring tides, produces coastal surges and flooding of areas which are usually sheltered from water (Vousdoukas *et al*., 2016). Storm effects can vary considerably alongshore, depending on a number of factors (Guisado-Pintado and Jackson, 2019), including both physical/energetic ones (direction of movement of the storm, occurrence of storm-groups and clusters; Ferreira, 2006, Dissanayake *et al*., 2015), and local/geomorphological ones (coastal outline, soil development, slope changes, beach and dune development and elevation, presence of subaqueous sandbars, etc.). The highest storm surges occur in shallow, gently sloping coastal areas and in semi-enclosed bays and estuaries (Davidson-Arnott, 2010).

Figure 4. Coastal effects of sea storms in beaches and dunes of SW Spain. A, outcropping of sewage infrastructures after deep beach erosion during a coastal storm in 1996 at El Puerto de Santa María; B, beach flooding and dune undermining at Camposoto Beach (San Fernando) during Emma storm, in 2018 (photo: L. Del Río); C, dune front erosion at Point Candor Beach, Rota.

Wave energy developed by storms is analysed through statistical approaches, commonly by calculating energetic parameters like significant wave height, storm duration, wave storm direction and energy flux probability of exceedance (Molina *et al.*, 2019), which helps storms to be classified (Anfuso *et al.*, 2015). Wave hindcast can be achieved by applying mathematical models like SWAN (Booij *et al.*, 1999).

All those data are very useful for establishing storm thresholds for a given coast, which represent the minimum wave and tide conditions necessary to produce significant morphological changes and/or damage on beaches, dunes and coastal human occupation (Del Río *et al.*, 2012), which are fundamental for an effective coastal management on exposed coasts. Coastal response to storm impact depends on the natural resilience of the coast: if this can behave without exceeding its system's thresholds, it will maintain its natural dynamics and resist through time; this is quite difficult to be achieved on highly occupied, "developed" coasts (Malvarez *et al.*, 2021).

Storms and hurricanes show a typical seasonal periodicity, although their energy can vary significantly through the years, and extreme wave episodes can hit a given coast unexpectedly (Masselink *et al.*, 2016). Changes in storm frequency and energy should be related to climate trends. However, those relationships are far from simple. In Europe statistical assessment of storminess over the last 30 years evidences an increase in energy variability, although recorded changes are not always directly related to global climate changes (Ciavola and Jiménez, 2013). Only in some specific cases, like the Gulf of Cádiz, a good correlation is obtained between large-scale atmospheric indices (such as the North Atlantic Oscillation, NAO), with a certain increase in the frequency of storms along the 20^{th} century and during the last decades (Ribera *et al.*, 2011). Other regions, like the NW Iberian coast, also record an increased frequency in powerful storm events, and even an alteration in storm approaching directions, which are enhancing erosion of beaches and dunes (Flor-Blanco *et al.*, 2021). In the western Mediterranean coasts, records of the last 40 years show an increase in wave storm durations and direction of approach (Amarouche *et al.*, 2022).

At present, prediction and management of the arrival of storms and their expected energy is assessed through the development of storm early warning systems, an operational oceanography system developed at several coastal sites in Europe (Plomaritis *et al.*, 2012). Apart from hydrodynamic considerations, it is important to evaluate damage and understand the processes responsible for the coastal effects of storms. This can be assessed by post-storm field measurement of changes produced by an energetic event, using high-resolution topographic methods (Almeida *et al.*, 2012; Benavente *et al.*, 2013; Schubert *et al.*, 2015).

More recently, the use of unmanned aerial vehicles (UAV), combined with Structure-From-Motion algorithms, allows detecting and mapping coastal changes through digital elevation models. This method can be used for analysing the response of beaches and dunes to different storm-induced processes, like swash, collision, boulder movement, overwash, beach surface downwearing, dune front retreat, etc. (Pérez-Alberti and Trenhaile, 2015; Talavera *et al.*, 2018; Nagle-McNaughton and Cox, 2020).

2.4. Tides

Tides are periodical metric fluctuations of the sea level mainly produced by the gravitational force of the moon and the sun, with daily vertical sea level variations ranging between low/negligible values (microtidal coasts, average range < 2 m), intermediate values (mesotidal, 2<range<4 m) and high to very high ranges (macrotidal coasts, range> 4 m). In meso and macro tidal regimes tides translate waves and associated currents up and down the nearshore zone, hence modelling their effects (Dey and Shukla, 2019; Héquette *et al.*, 2021).

Tidal currents under macrotidal regimes are strong enough to control beach morphodynamics (Bennett *et al.*, 2019), especially around capes or inside straits, where bottom morphology is the main factor controlling the speed and lateral variations in energy flux (Sánchez Román *et al.*, 2012). Nevertheless, tides can also influence beach dynamics in microtidal coasts under specific morphological circumstances (Chee *et al.*, 2014). Beach and nearshore topography can be used to make computations about direction and speed of tidal currents by applying mathematical models and simulations (Reeve *et al.*, 2019).

In macro and mesotidal environments tidal currents favour the transport and deposition of fine sediments on sheltered coastal areas, commonly bays and estuaries, producing extensive salt marshes (Davidson-Arnott, 2010). In macrotidal coasts human settlements are usually adapted to important sea level fluctuations and are located on places high enough to face such risk. However, in many mesotidal coasts cities, harbour facilities and infrastructures are often located slightly above the high tide level. This situation makes such coasts especially vulnerable to sea level rise. Some approaches to the quantification and mapping of vulnerable tidal coasts and salt marshes to sea level rise emphasize the high exposition of ecosystems, human settlements and activities to the increasing sea level rise (Martínez-Graña *et al.*, 2016; Vázquez Pinillos and Marchena Gómez, 2021). In this sense, larger tidal ranges seem to improve the capacity of coasts to balance sea level rise, due to the role of subtidal gullies as sediment traps, and hence macrotidal coastal flats are considered to be resilient against high rates of sea level rise (Hofstede *et al.*, 2018).

2.5. Good weather wind waves

Determination of wave heights, both modal and energetic, is of prime interest in coastal dynamics. Wave height is usually represented by the significant wave height (average value of the highest third part of a population of data), and is very useful for many purposes related to coastal processes: wave setup, wave-related coastal currents and sediment transport, wave forecasting, atmospheric modelling, ocean circulation, etc.

Measurements of wave heights can be done through a number of methods, although at present satellite radar altimetry is the most accurate source of information about sea surface height, significant wave height and wind speed (López-García *et al.*, 2019). More locally, topo-bathymetric surveys, combined with remote-sensing imagery, can help to understand wave and current dynamics around complex morphologies or bypass processes between adjacent beaches (Da Silva *et al.*, 2021).

When approaching the coast, waves experience a number of processes related to the interaction between the wave base and the sea bottom. From the moment at which the wave base contacts the bottom until the final wave breaking, the wave passes through shoaling processes, which mainly include reduction of wave velocity, increase in wave height, modification of the wave form, and refraction processes that may lead to changes in the approaching direction. All these processes are strongly controlled by the initial wave conditions before reaching the nearshore zone, and especially by the submerged morphology of the sea bottom, mainly slope.

All these physical processes can be predicted with considerable precision through different mathematical equations, which have promoted the generation of mathematic models of wave propagation, very used in coastal studies, like SWAN (Simulating Waves Nearshore; Ris *et al.*, 1999). The accuracy of the results and their correct fitting with natural processes usually depends on the quality of the data feeding the model.

3. Coastal environments and their evolution

A quite common, initial and simple classification of coastal environments starts from the division between low, sedimentary coasts and high, rocky coasts. The former ones are constituted by coastal plains or with very low relief, characterized by the accumulation of sediments of varying nature: pebbles, sands and clays, depending on the processes responsible for their sedimentation and their associated energy. They are usually represented by beaches, dunes, lagoons and salt marshes, and also include river mouth systems (estuaries, deltas). The latter are represented by rocky outcrops directly entering the sea through rough relieves, high slopes and cliffs, and also include coastal rocks generated by biochemical processes, like coral reefs. Of course, there exist intermediate cases, like low cliffs modelled on soft rocks, or coastal plains formed by Quaternary deposits (like stepped marine terraces, or beachrocks) that end to the sea through gentle slopes or microcliffs.

3.1. Low, sedimentary coasts: beaches and dunes

Waves and associated currents accumulate particles in favourable places, creating beaches. These sedimentary units can be formed by elements of varied size depending on the average energy of the incoming waves and their competence in the transport of debris. As a consequence, beaches can be formed by boulders and pebbles (named *coídos* in Galicia), or sands, or even very fine sands and silts. One common characteristic of beaches is their high dynamism: they usually respond very rapidly to any change in the energy level of the incoming waves (Pilkey *et al.*, 2011). If storm episodes prevail, boulder and mixed beaches experience micro and mesoscale morphological changes due to the slight movement of boulders and pebbles by energetic waves (Pérez-Alberti and Trenhaile, 2015; Nagle-McNaughton and Cox, 2020; Casamayor *et al.*, 2022). Sandy beaches experience erosion through shoreline retreat, dune front escarpment, overwashing, inland migration of barrier islands, or even erosive planation and dismantling (Carter, 1990; Jiménez *et al.*, 2007; Crowell *et al.*, 2018; Barrantes-Castillo *et al.*, 2020; Ruiz de Alegría-Arzaburu *et al.*, 2022).

In this sense, some recent proposals of mathematical models focus on the energy developed by waves on sandy beaches, and calculate beach profile modifications associated with the different type of waves approaching the coast. There is an interrelationship and feedback between wave type and energy dissipated on the beach, and beach slope resulting from the sediment erosion/deposition by such waves. Some modern mathematic models combine wave physical processes (including surf and breaking processes, runup and overwashing) with continuous beach adaptation to the incoming wave types. One of the most used models is X-BEACH, developed by the Dutch company Deltares (Roelvink *et al.*, 2009). Recent, more advanced versions of this model include interaction between beaches and dunes (Roelvink and Costas, 2019). In a later phase, understanding coastal processes responsible for the changes detected in sandy shores is being recently assessed through the application of sophisticated theoretical models which include multiple response pathways and outcomes (Van Rijn *et al.*, 2007; Payo *et al.*, 2016).

Although the high energy applied on coasts during storm episodes produces rapid changes in beaches (Beckman *et al.*, 2021), beach erosion also occurs at longer, slower rates. Beaches continuously receive and lose sediments, and the volume of sand at a given moment is the result of the balance existing between sediment supply and sediment loss. Sources of sediments to the coast are mainly represented by rivers, and in a much lesser extent by submarine supply and erosion of soft cliffs. Once arrived to the coastal system, fluvial sediments are then transported alongshore by wave-induced currents. Human activities can alter this chain by retaining sediment within the river catchment through dams and reservoirs, and by blocking longshore currents through groynes, jetties and piers (Rodríguez-Ramírez *et al.*, 2008; Hapke *et al.*, 2013). The proliferation of reservoirs in river basins has produced a dramatic reduction of sediment supplied to coastal areas producing a chronic sedimentary deficit in many coasts. This is especially the case of deltas, where the subtle equilibrium between fluvial sediment supply and coastal erosion due to wave action can be rapidly broken in favour of shoreline retreat. Several deltas along the Mediterranean shores exhibit a present trend toward destruction, due to anthropogenic modification of the river catchments (Anthony *et al*., 2014). Historical trends of sandy beaches in river deltas allow predicting the future of their shorelines with significant precision. This is the case of the Ebro River delta (Aranda *et al.,* this issue), where sediment retention on dams threatens the survival of its most valuable ecosystems in the short term.

Urban growth has destroyed many coastal landforms and often has altered the cross-shore sedimentary equilibrium of beaches by dismantling dune ridges, dredging, etc. According to data obtained by Luijendijk *et al.* (2918), about one third of the world coasts are eroding at rates exceeding 0.5 m/yr, and in many places this trend has been maintained for decades (Lira *et al.*, 2016; Pérez-Hernández *et al.*, 2020). The high vulnerability of sand beaches and the important economic income related to their tourist exploitation has made the study of beaches the most important research topic in coastal studies during the last decades. A historical summary of the main advances in this research line during the last 50 years can be found in Jackson and Nordstrom (2020).

Beach processes and trends can be studied under very different spatial and temporal scales (Gracia *et al.*, 2005). At the short term (hours, days) the amount of daily sand erosion and renovation can be assessed in the field by measuring the depth of disturbance (King, 1951) and determining the thickness of the activation layer. This information is of prime interest before facing any artificial beach nourishment work (López *et al.*, 2019). At a medium term (weeks, months), field work is required, although the introduction of RTK-GPS devices (Schubert *et al.*, 2015) and the use of UAV's have greatly simplified procedures, introducing very high resolution outcomes in the topographic assessment of beaches an dunes (Mancini *et al.*, 2013).

Coastal studies on a longer term (years) are very common, since wave energy and storm frequencies fluctuate around multi-monthly to pluri-annual scales. In this case coastal assessment mainly consists on the comparison of vertical images taken at different moments. If the number of images is high enough, projections of future shoreline trends can be established. Traditionally images used for such purpose are vertical aerial photographs, which in some cases can be available for the last 70 years, and allow a first quantification of coastal changes and trends during the last decades (Fig. 5). However, the problem with this method lies in the correct definition of the shoreline, especially on tidal coasts (Boak and Turner, 2005). Another question is the error inherent to the use of such photographs, all of them including image deformations and several sources of uncertainties (Del Río and Gracia, 2013).

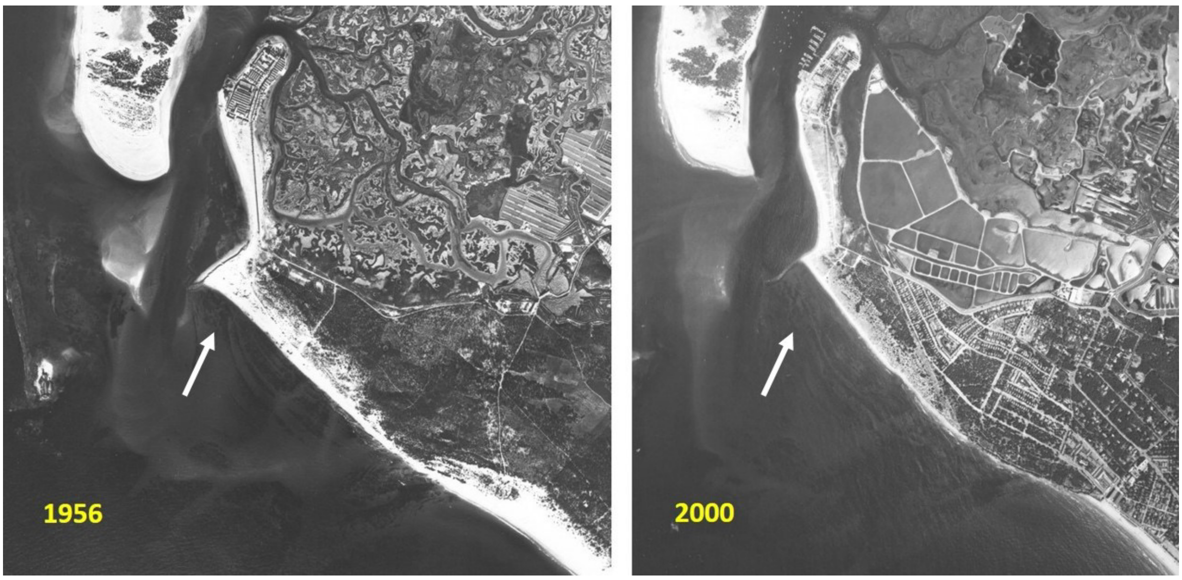

Figure 5. Aerial photographs showing beach deficit and shoreline erosion at Sancti Petri Beach (Chiclana de la Frontera, SW Spain).

In recent years a regular monitoring of shoreline changes can be assessed through the high-frequency/high-resolution satellite data displayed by Quickbird and Sentinel-2 imagery (Mitri *et al.*, 2020). The development of sophisticated tools for the pre-processing of images, like the SHOREX system (Sánchez-García *et al.*, 2020) has allowed the improvement of satellite-derived shorelines and the assessment of high-resolution spatial-temporal models. Pardo-Pascual *et al.* (this issue) apply such technique to analyse the morphological changes experienced by a sector of the eastern Spanish coast, between 1985 and 2020. Results, estimated at the sub-pixel scale, show a general erosional trend for all the area, with a sequence of narrow portions with alternating high and low erosion rates. The comparison of coastal trends with the record of wave energy along the last decades indicates a high influence of strong storms on the recent evolution of this coast, although the grouping of minor storms also produces severe damage and coastal retreat (a relation already analysed by Ferreira, 2006). Recent trends on the increasing energy displayed by storms in the Valencia coast are also evidenced, which could be interpreted as another consequence of the ongoing climate change.

Dunes constitute a buffer to coastal erosion since they represent an extra amount of sediment that can be mobilized during energetic events. The erosion of coastal dunes and their vulnerability has focused the attention of research in the last decades (Carter *et al*., 1990; Peña-Alonso *et al*., 2018).

Dune systems can grow significantly if sediment supply is maintained during decades. Strong winds make the dunes active and mobile, producing a net transport inland. These systems, called transgressive dunes, can present different modes of generation and behaviour (Hesp, 2013). Local limiting factors, like the sediment available and its characteristics, control the development of active, mobile dunes. Strong winds associated with storms can favour the generation of transgressive dune systems, rapidly moving, which can interact with human occupation and infrastructures located near the coast. An outstanding example of this situation is the Ria Formosa barrier island, in southern Portugal (Costas *et al*., 2020), where dune invasion of houses and park places is common during wind storms (Fig. 6A).

Coastal dunes are very valuable morphological units to be preserved, not only because of their role in protecting beaches and coastal properties against storms and sea-level rise (Houser *et al*., 2018), or their intrinsic morphological variety and dynamics, but especially because they constitute the base for a number of ecosystems and habitats of great importance. *Psammophytes* are plants adapted to grow upon a sandy substratum affected by wind action. Those plants, of high ecological value, are the main responsible for the partial or total fixation of dunes on coastal environments (Fig. 6B). A subtle equilibrium is established between shoreline progradation/retreat and dune growth, anastomosis of embryo dunes and generation of continuous dune ridges or foredunes (Konlechner *et al*., 2019). Up to 11 different coastal dune habitats are included in the European Directive 92/43, by which states members are committed to establish measures for their preservation (García de Lomas *et al*., 2011).

Dune dynamics is complex due to their sensitivity to different natural and anthropogenic factors. In highly occupied and transformed coasts, dunes develop on specific favourable sites characterized by stability or coastal progradation. Usually coastal erosion produces dune retreat, fragmentation and finally destruction. An outstanding example of the role of different factors in the preservation and trends of beach-dune systems is the Mediterranean coast of Andalucía, studied by Molina *et al*. (this issue). These authors analyse five different photogrammetric flights to quantify recent shoreline trends, and combine those results with the inherent importance of each dune system, taking into account the development of dune habitats. Their results constitute an essential information before facing any management plan on a given low coast.

Present trends in the study of coastal dunes include both field and indirect methods. The former ones are mainly represented by topographic devices: theodolits, electronic levellers, GPS measurements, terrestrial laser scanner, etc. (Labuz, 2016). Wind dynamics and sand transport processes are also investigated through tracers (Wang *et al*., 2017), anemometers and sand traps (Navarro *et al*., 2015). Indirect methods include remote sensed techniques for the acquisition of topographic data and images, and dune mapping (Gonçalves *et al*., 2018; Grottoli *et al*., 2021). Holocene and recent historical trends of dune fields can be deduced from historical maps and the analysis of the inner structure through ground penetrating radar surveys (Flor-Blanco *et al*., 2016).

The status of coastal foredunes is a good indicator of the morphosedimentary health of a given coast. In fact, foredune degradation by sand trampling and urbanization is one of the most important problems in coasts exploited for tourism. Protection and recuperation of dunes can be made through different procedures, like peripheral closures (Fig. 6C) or sand fences (Fig. 6D). A synthesis of dune regeneration methods can be found in Ley *et al*. (2007).

Figure 6. Coastal dune dynamics. A, dune migration upon coastal buildings and properties at Praia de Faro (South Portugal); B, plant succession on embryo dunes (Bolonia Beach, South Spain); C, dune enclosure for preventing trampling at El Puerto de Santa María (SW Spain); D, wooden dune fences at Tarifa Beach, South Spain.

3.2. Low, sedimentary coasts: barrier islands, lagoons, salt marshes and river mouths

Active sand sedimentation on low coasts produces accumulations that grow until generating mesoscale sedimentary bodies, often reaching several kilometres long. Beach progradation normal to the shoreline occurs when an abundance of sediment exists. In such a case, slight oscillations in the sediment supply, storminess and sea level changes combine to produce parallel ridges advancing seawards (Taylor and Stone, 1996; Otvos, 2000). Radiocarbon dating of beach ridges gives clues about the Holocene and historical evolution of shorelines, and help to separate local from regional or even global factors controlling coastal evolution (Rodríguez-Ramírez and Yáñez-Camacho, 2008; Rodríguez-Polo *et al*., 2009).

On a different situation, if longshore currents prevail, they transport and accumulate sands forming elongated systems. They can be anchored at one given point of the coast, typically a headland,

and then the longitudinally growing sand body forms a littoral spit whose free limit is usually very unstable and dynamic (Kraus, 1999; Randazzo *et al*., 2015). If the longitudinal body forms at a certain distance from the shoreline, then a barrier island is generated. About 10% of the open-ocean shorelines in the world are represented by barrier islands, especially abundant in the North America coasts. They are very diverse in size, morphology, geological and geomorphological setting, and also in morphodynamic behaviour (Pilkey, 2003). Such systems change in a temporal scale ranging between 10 to 10^2 years and are very sensitive to changes in external forcing, like sea level, storminess, or climate changes (Cooper *et al*., 2018), and also to human interventions (Paris and Mitasova, 2018; Kombiadou *et al*., 2019).

In microtidal environments the outer sandy barriers can grow enough to close former bays and embayments. As a result, a coastal lake or lagoon is formed (*albufera* in Spanish), characterized by sediment aggradation occasionally affected by storm waves and coastal flooding by sea storms (Adlam, 2014). Sedimentary records in lagoons represent very valuable archives of the recent climate and coastal environmental evolution of the zone, including historical sea level fluctuations (Carrasco *et al*., 2016), and are usually analysed through sedimentological and palynological methods in cores (Ruiz-Pérez and Carmona, 2019). A complete information on the Holocene-historical evolution of a given low coast would be obtained by combining beach ridge data and sedimentary record of coastal lagoons (Sander *et al*., 2015).

In tidal environments, tidal currents usually prevent the closure of inlets and typical tidal deltas form at both sides of the breachings. Tidal currents are usually low and can only transport medium to fine sediments, except at local places where the oceanographic and coastal configurations (macrotidal regime, gently sloping continental shelf, back-barrier plains, straits, channels, etc.) accelerate the tidal flux. As a consequence, the normal result of the tidal dynamics is the accumulation of fine sands, silts and clays at favourable, sheltered places inside bays, estuaries, etc., forming salt marshes (Rahman and Plater, 2014; McLachlan *et al*., 2020). Plants exert a determinant role in the tidal sedimentation process through particle trampling and sediment compaction. The existing interdependences between plant dynamics and morphological evolution of salt marshes are complex and depend on a number of concurrent factors, not always easy to differentiate. As in the case of dune systems, salt marshes are considered as typical cases of biogeomorphological systems, especially under tropical climates (Li *et al*., 2021). In fact, salt marsh reclamation or the removal of vegetation from marshes usually has the same consequence as the effects of strong currents and waves: shoreline erosion and retreat (Brunier *et al*., 2019; Zhang *et al*., 2021; Evans *et al*., 2022).

Sedimentary evolution of salt marshes usually consists in a progressive aggradation, coupled with subsidence due to sediment compaction. The maintenance of this trend in certain areas since the last Holocene eustatic maximum has produced tens of meters of sedimentary record, very useful as geoarchives for palaeoenvironmental and sea-level reconstructions (Zazo *et al*., 2008; Brain *et al*., 2015; Caporizzo *et al*., 2021). Holocene palaeogeographical reconstructions of salt marshes can also be made through detailed geomorphological mapping and dating of inactive elements, like supratidal sedimentary plains, abandoned channels, etc. (Pierik *et al.,* 2016). Historical tidal silting of bays and harbours, sometimes favoured by vertical tectonic movements, can be reconstructed through geoarchaeological techniques (Morhange *et al*., 2012).

The morphological and ecological evolution of salt marshes in the last decades can be analysed through aerial photographs (Aranda *et al*., 2020). Monitoring of salt marsh dynamics and their bio-geomorphological trends are analysed through satellite imagery, LiDAR and high-resolution mapping (Haynes *et al*., 2017) combined with sediment sampling and textural analysis (Chen *et al*., 2018). At present sediment starvation and sea level rise are the most important threats to salt marshes (Fernández-Núñez *et al*., 2017). Most recent research on the topic focus on the resilience of these environments and their role as a natural defence against marine flooding (Day *et al*., 2011; Hofstede *et al*., 2018; Reed *et al*., 2018).

Salt marshes and coastal lagoons are very often related to river mouths, totally or partially closed by outer sand spits or barriers. The palaeoenvironmental reconstruction of such coastal systems is then complicated by the usually complex interaction between tidal and fluvial dynamics (Dabrio *et al*., 2000; Ciavola and Collins, 2004). Tidal currents and fluvial fluctuations control the main paths of sediment transport and accumulations, and the generation of beaches, beach ridges and spits inside these systems (Fortunato *et al.,* 2021). Multi-temporal maps and images help to understand the evolutionary trends of the different environments forming the estuary (Ghosh, 2019; Aranda *et al*., 2020).

River deltas form when fluvial sediment supply is high enough to counteract the erosive action of waves, and sedimentary balance inclines toward sedimentation and coastal progradation. Delta growth usually includes channel migration and capture, closing of embayments by sandy barriers, and rapid shoreline changes, very sensitive to any fluctuation of the energetic forcing (both fluvial and marine). All these processes favour the formation of different fluvial, coastal and mixed environments, including coastal lagoons and wetlands, often of high ecological value (Schmidt, 2011). Apart from accelerated shoreline erosion due to sedimentary deficit, river deltas also present an important issue to take into account: land-surface subsidence, due to sediment compaction and dewatering. This process, active in most deltas during the last millennia, affects the uppermost 5-10 m of sediments, and despite its low rate the associated deformation and faulting produces damage on coastal settlements and increases the zones exposed to marine flooding due to sea level rise (Jankowski *et al*., 2017; Gómez *et al*., 2021).

3.3. High, rocky coasts

Coastal cliffs are typical erosional forms, commonly associated with rocky escarpments subject to different erosive processes, both continental and marine, and represent about 80% of the world coasts (Emery and Kuhn, 1982). As in sedimentary coasts, most part of the marine cliffs in the world has generated and evolved along the last 6000 years, moment at which sea level reached a height broadly similar to the present one (Bird, 2016). Cliff evolution is controlled by a number of factors, like wave energy, sea level trends, and especially their geological characteristics (Trenhaile, 1987; Sunamura, 1992). The geometry of rocky coasts is highly influenced by geological and tectonic processes. Although such relationships are not always evident, mathematical approaches sometimes shed light on this dependency (De Pippo *et al.*, 2004).

A simple subdivision of cliff types could differentiate between those formed by hard or resistant rocks and those constituted by soft rocks (Sunamura, 2005; Carpenter *et al*., 2014). The former ones are affected mainly by erosive processes related to wave breaking at their toe, which produces vibrations and fracturing, undercutting and notch excavation, and falling of unstable elements (Neves, 2008). Mass movements, mostly intermittent due to the seasonality of storminess, affect most cliffs; the material accumulated at the cliff toe is afterwards removed by waves and currents (Granger and Kalaugher, 1987; Del Río and Gracia, 2009; Montoya *et al*., 2012). Only 5% of the world cliffs modelled upon hard rocks experience significant erosion. A common result of cliff retreat is the generation of rock platforms, usually less than 100 m wide due to the rapid wave energy dissipation, that prevents the progression of wave erosion and hence limits the extent of such erosional forms (Trenhaile, 1987). Rock weathering and bio-erosive processes are the main mechanisms of rock downwearing (Trenhaile and Porter, 2007; Moura *et al*., 2011); waves export the resulting products and flatten the surface to the medium sea level through abrasion (Gómez-Pujol *et al*., 2006; Blanco-Chao *et al*., 2007).

In contrast, more than 30% of the cliffs on soft rocks are subject to different erosive processes, and this situation affects to more than 50% of the European cliffs (EUROSION, 2004). As in any other slope, erosive processes are related to gravity (rock falls) and fresh water processes (mainly sheetwash erosion, rilling, gullying and piping). Rock weathering, especially salt weathering (Welman and Wilson, 1965), softens the rocks and make them more vulnerable to such processes. Waves can erode the possible beaches existing at the cliff toe, or directly attack the cliff base (Sallenger *et al*., 2002; Lee, 2008; Limber and Murray, 2011). Winds can produce both erosion and sand deposition. All those processes present variations along the year, with a typical seasonal behaviour (Fig. 7). At the end, cliffs erode both vertically (downwearing) and horizontally (cliff retreat), the latter reaching very often values higher than 1 m/year (Tsujimoto, 1987).

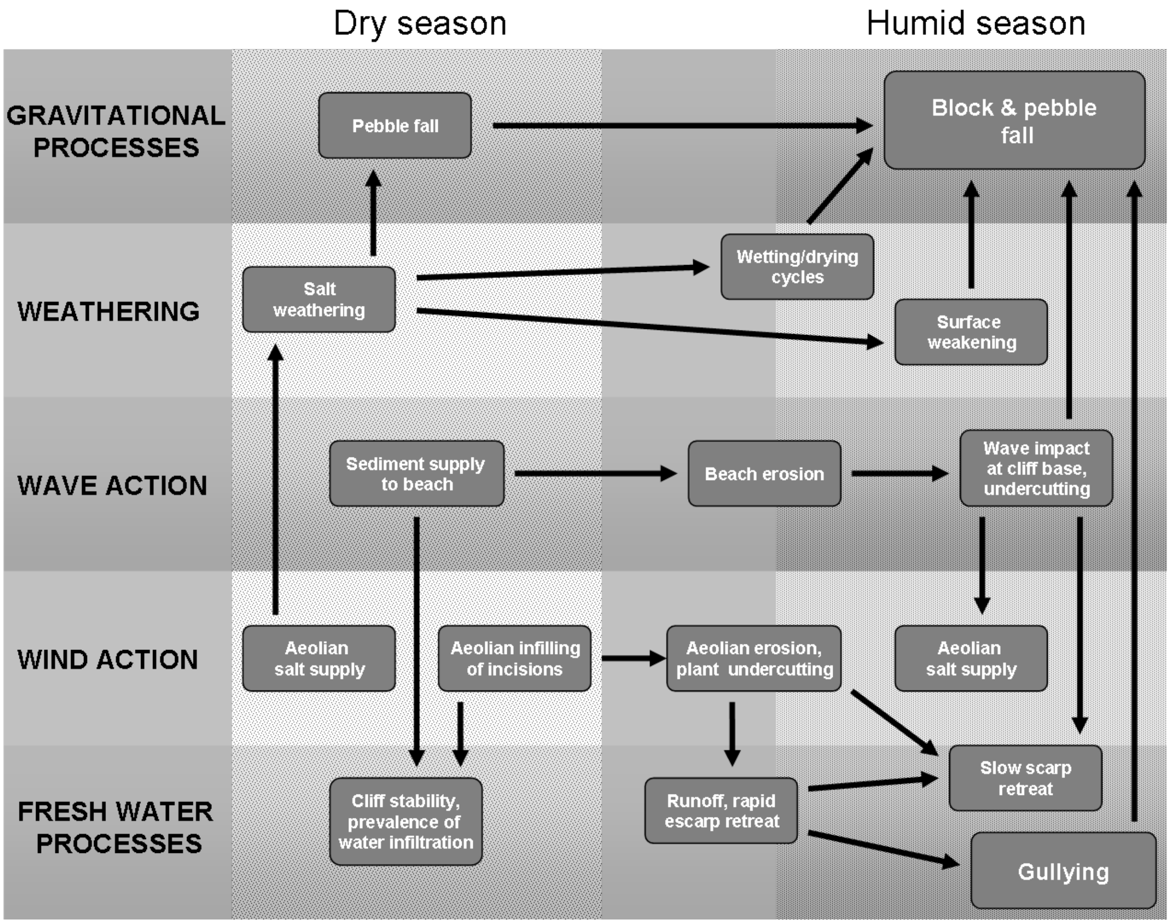

Figure 7. Seasonality of the main processes dealing to the erosional evolution of coastal cliffs under temperate climates.

All those processes generate a number of forms that control the final cliff profile morphology and slope. Field indicators/markers of erosive processes on cliffs are numerous and include local gully incisions and generation of small alluvial fans at the cliff toe (Fig. 8A), cracking at the cliff top (Fig. 8B), notching at the cliff toe in the case of resistant rocks, etc. Markers of cliff instability are similar to those recognizable on inland slopes. Such indicators can be used to identify problematic points and subsequently decide to apply protective measures if appropriate (Brampton, 1998). Figures 8C and 8D include examples of defence measures taken in active cliffs of south Spain, like persuasive fences and sign posts of danger.

From a methodological point of view, since middle 20th century a wide variety of techniques have been developed for assessing erosive processes on marine cliffs (Zively and Klein, 2004; Del Río and Gracia, 2009). They include aerial photogrammetry, analysis of historical maps, field measurement and photography, etc. (Young *et al.*, 2009). In the last decades the introduction of a group of advanced techniques has allowed generating high resolution 3D models very rapidly (Wilkinson *et al.*, 2016). One of the most used is the LiDAR sensor (Laser Imaging Detection and Ranging), installed both terrestrial (placed upon the ground) or airborne (on a plane or, preferably nowadays, on a UAV). The terrestrial laser scanner (TLS) is frequently used for assessing rocky escarpments and other coastal forms (Rosser *et al.*, 2005; Sanjosé *et al.*, 2016). A synthesis of the application of this technique to coastal environments can be found in Fairley *et al.* (2016). An alternative technique is the Structure-from-Motion Photogrammetry (SfM), much more economic and giving digital topographic models with a reasonable resolution (Westoby *et al.*, 2012; Del Río *et al.*, 2020). As with LiDAR, image acquisition can be made on the ground or airborne (Gonçalves and Henriques, 2015), and is especially useful in the assessment of coastal cliffs (Warrick *et al.*, 2017).

Figure 8. Examples of eroding cliffs. A, gully erosion and alluvial fan generation on compacted sands, El Asperillo cliffs (Huelva, SW Spain); B, C and D, unstable cliffs at Conil de la Frontera, Cádiz, affected by mass movements; B, development of fractures at the cliff top; C and D, danger sings and indications at the cliff foot.

4. Towards an efficient management of coastal zones

The growing concentration of human population at coasts and adjacent areas has made these zones be populated with densities nearly 3 times higher than the global average density (Small and Nicholls, 2003). Under this situation, human activities on coasts can directly modify coastal dynamics, both directly and indirectly. Direct interaction with coastal processes includes the modification of the coastal morphology by means of dredging, construction of jetties, docks, harbours, promenades, etc. Those artificial structures modify wave refraction patterns and shoreline currents, block sediment circulation producing sand accumulation at some places and sedimentary deficit in others especially during storm episodes, while changes in the geometry of tidal channels alter the tide dynamics (Rodríguez-Ramírez *et al*., 2008; Manno *et al*., 2016).

Indirect effects include the modification of the quantities and qualities of sediments supplied to the coast through rivers; fluvial basin deforestation increases soil exposure to water erosion processes, increasing the amount of sediment yielded by rivers to the coastal systems; some historical cases of rapid delta progradation are related to this kind of interventions (Anthony *et al.,* 2014). In the opposite situation, regulation of river flows by dam construction, revegetation, irrigation practices, etc., produce sediment trapping and a starvation of sediments to the coast, especially if the reservoir is sufficiently close to the river mouth (less than 50 km). In such a case, sands and gravels are dramatically reduced in the river solid flow, but the suspension fraction (silts, clays) can bypass the barriers and reach the coast, finning the beach sediments and making coastal deposits more erodible (Donadio, 2017).

A common consequence of all these activities is coastal erosion, exacerbated by the ongoing sea level rise. According to EUROSION (2004), 15% of the more than 100 000 km of the European coasts are eroding. In some countries the negative beach sediment budget is being opposed through artificial nourishment, mostly dredged from the nearshore zone, although other alternative methods have been tested and adopted in several countries to protect beaches (Orombelli and Pranzini, 2020). Beach nourishment introduces additional problems, like the burial of shallow reefs and other beach habitats, or the reduction of densities of invertebrates, which represent essential preys for shorebirds, surf fishes, and crabs (Peterson and Bishop, 2005). Additionally, if nourished profile is not strictly controlled, artificial beaches become more susceptible to develop erosive scarps (Van Bemmelen *et al*., 2020). Very specific and exigent requisites must be followed in order to achieve an ecologically sound result (Speybroeck *et al*., 2006).

Dunes are often very active and vulnerable. A simple re-profiling of dunes can derive in a rapid and unexpected change of the dune system, with non-desired results (Gangaiya *et al*., 2017). Dunes are very sensitive to coastal occupation and their naturality is an indicator of the environmental health of the coastal system. Besides, dunes can grow rapidly if the natural conditions are favourable. Unfortunately, many urbanised areas do not allow the development of embryo dunes, due to the seasonal, sometimes daily practices of beach cleaning by mechanical methods, which very often destroy pioneer plants and small aeolian accumulations in the backshore (Fig. 9A). Dune restoration has been addressed in many degraded coasts, by following different methods of sand trampling (Fig. 6C, D), dune coring (Nordstrom, 2019) and replanting (Ley *et al*., 2007). However, as in beaches, dune recuperation must be very carefully performed, always taking into account the subtle equilibrium between plant ecology and sediment accumulation (Houston *et al*., 2001; Jenks, 2018). In this sense, García-Lozano *et al*. (this issue) make an analysis of the response of different types of dunes, both natural and restored, along the Catalan and Valencian shores. These authors show how only sustainable management methods ensure the effective recovering and maintenance of the system.

Another source of coastal degradation is the growing presence of waste materials and litter in beaches and dunes (Fig. 9B). The study of the sources, distribution and consequences of beach debris is a line only very recently addressed in coastal management research (Williams *et al*., 2016), especially due to its possible influence on tourism quality of beaches (Krelling *et al*., 2017; Asensio-Montesinos *et al*., 2019). Regarding impacts on salt marshes and estuaries, urban and industrial settlements eliminate valuable habitats (Fig. 9C), while salt harvesting modifies the geometry of natural tidal channels, altering tide dynamics and sedimentation rates (Gracia *et al*., 2017; Brunetta *et al*., 2019). Nevertheless, the abandonment of traditional salinas maintaining sluice gates open allows the system to rapidly recover its naturalness through plant colonization (Fig. 9D), which favours seabirds nesting (Aguilera and Gracia, 2004).

Figure 9. Coastal transformations and impacts by human activities. A, destruction of pioneer plants in the upper beach by "beach cleaning" at La Atunara beach (La Línea de la Concepción, South Spain); B, litter accumulation at a stream mouth (Catania, Sicily); C, industrial complex installed upon former vegetated salt marshes (Huelva, SW Spain); D, industrial facilities near abandoned salinas (Cádiz, SW Spain).

The high dynamism of coastal environments briefly described in previous sections, combined with the dense human occupation and activities on coastal areas, produce numerous situations of hazards. Sea level rise accelerates coastal erosion and increases the risk of flooding on low coasts, like deltas (Fig. 10A), where sometimes drastic measures must be applied in order to protect properties and activities that originally were not threatened by marine processes but at present they are (Fig. 10C). The illogical urban occupation of unstable cliffs also increases the situation of imminent hazard (Fig. 10B). Dense urbanization of low coasts and barrier islands (Fig. 10D) strongly increases the exposition to potentially risky natural processes, like storm waves, overwashing and shoreline retreat.

Coastal hazards must be included in any coastal management plan, through vulnerability analysis of exposed areas and activities and improvement of the coastal resilience. In the last decades this approach is being assessed by means of Coastal Zone Integrated Management, which consists in the articulation of different sectors, communities and agencies involved in the exploitation of spaces and resources at the coast or its vicinity (Quevauviller *et al*., 2017; Puertas and Aparicio, 2020). This strategy is being developed especially in European and South American countries (Barragán, 2005; Rodríguez-Perea *et al*., 2013). Some Spanish regional administrations have included this scheme in their territorial regulations (Oliveros *et al*., 2008; Mas-Pla and Zuppi, 2009).

Figure 10. Human infrastructures threatened by erosional coastal processes. A, abandoned agricultural facilities affected by shoreline retreat at the Ebro River delta (aerial photo: 2008, Institut Cartografic de Catalunya); B, tourist urban complex on a cliff affected by gullying and mass movements at Santiago de Teide (Tenerife, Canary Islands); C, protecting crops and houses from energetic waves by an artificial earth barrier at the Ebro River delta; D, tourist urban settlement affected by severe beach erosion at Murcia coast (Manga del Mar Menor).

Coastal protection by stakeholders and policy makers needs to assess the degree of vulnerability and mitigation efforts must be focused in that sense (Wolters and Kuenzer, 2015). Coastal hazards have become an essential element in any approach to coastal management (Rangel-Buitrago *et al*., 2020). Coastal vulnerability is commonly assessed through the application of indices that combine different variables involved in the degree of coastal exposition to risky processes, human impacts on coasts, socioeconomic activities developed on them, etc. (Alberico *et al*., 2017; Bagdanaviciute *et al*., 2019; Alcérreca-Huerta *et al*., 2020). Coastal vulnerability assessment is applied to both natural and historical-cultural heritage elements (Peña-Alonso *et al*., 2018; Mattei *et al*., 2019; Rodríguez-Rosales *et al*., 2021).

As indicated in previous sections, sea level rise produces beach erosion and salt marsh degradation, leading to the deterioration of valuable ecological spaces and the loss of economically profitable beaches, an important source of money in tourist coasts. As a consequence, an important issue in coastal planning must be adaptation to sea level trends and its consequences. Since the latter vary laterally, an analysis of the hazards associated with this phenomenon and its trends is required through the development of coastal response models and databases for assessing the multiple impacts to the socio-economic systems, to the coastal settlements and uses (Wolff *et al*., 2018). In the case of beaches, as Cooper (2022, this issue) points out, policies must prioritise the preservation of their natural features over urbanization and protection of coastal properties; otherwise, many beaches presently considered as important economical sources for coastal communities may degrade severely or even disappear. In the case of coastal wetlands, lagoons and salt marshes, local effects of sea level rise must be specified in order to correctly predict future evolution of the system, including the dynamics and possible impacts on ecosystems (Carrasco *et al*., 2016).

Finally, coastal management must also include the especial protection of the main natural and human values of the coasts. An important component of the coastal value is the historical-cultural heritage, sometimes exposed to hazards like shoreline retreat (Fig. 11A) or erosion due to storm wave impact (Fernández-Montblanc *et al*., 2018; Pourkerman *et al*., 2018; Mattei *et al*., 2019). Another essential aspect of coastal management is the protection of natural areas with environmental interest, a practice that must be compatible with a rational exploitation of coastal resources (Barragán, 2005). Protected habitats (Fig. 11B) must receive an especial attention in laws and coastal regulations (Bartolomé *et al*., 2005). At the same time, coastal active processes can be used to illustrate visitors the dynamism of the coast and the importance of its protection (Fig. 11C). In that sense, the geological and geomorphological aspects of the coast should serve not only for a proper zonation of uses of coastal zones (Flor, 2007), but also for disseminating the heritage value of the abiotic aspects of coasts and their interest as living landscapes (Gracia, 2008). The scenic value of many coasts, combined with their inherent natural values (Fig. 11D) also constitutes an additional task to be included within the integrated coastal management (Mooser and Anfuso, 2018). Protection measures should include the preservation of all these values (Hooke, 1998).

Figure 11. Four examples of different environmental values taken from the SW Spanish coast. A, historical-archaeological value: remains of a Roman fishery at Cape Trafalgar; B, ecological value: natural salt marshes at the Bay of Cádiz Natural Park; C, geomorphological value: dune ridge affected by a washover fan which lies upon salt marshes, near the Guadiana River estuary; D, faunal and scenic value: a deer walking along the beach in the Guadalquivir estuary, in front of Sanlúcar de Barrameda village (Doñana National Park).

5. Concluding remarks

At a human scale, coastal processes act at very different time scales. The interaction among continental and different marine phenomena produces a quite complex system, sometimes affected by severe risky processes. The combination of dangerous agents (storms, tsunamis, coastal flooding, sea level rise, aeolian sedimentation, accelerated shoreline erosion and retreat, mass movements and water erosion on cliffs, etc.) with an increasing human occupation and transformation of coasts gives as a result a complex casuistry of natural hazard situations. The main consequence of this interaction is the great difficulty to correctly adapt and manage human settlements and activities on the coast and make them compatible with its natural dynamics. This problem converges with the additional uncertainty associated with the political and economic lines followed by governments and stakeholders, which can strongly fluctuate through time.

As Malvarez *et al.* (2021) suggest, another important issue in a correct coastal management is the perception of coastal safety once the administration has dealt with shoreline protection measures against hazardous processes. The false sensation that no more problems will affect the coast once users identify apparently strong and consistent protective structures can deal to encourage more occupation and urban development, increasing exposition of users to future high-energy events.

Education and information seem to be a good tool for making people aware of the real importance of observing and respecting the complex natural processes acting on coasts. Due to the rapidly alongshore changing conditions of coastal processes, more local studies are needed for identifying and understanding them in detail, and all the possible interactions with all types of settlements and human activities at different scales. All the administrative levels (municipal, regional and national governments, supranational associations) should include the study, prediction and prevention of coastal hazards into their regulations, and also the protection and future preservation measures of all valuable components existing at the coastal zone, both natural and historical-cultural.

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RESPONSE OF NATURAL, MODIFIED AND ARTIFICIAL SANDY BEACHES TO SEA-LEVEL RISE

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ABSTRACT. Sandy beaches occur in a wide variety of environmental settings and as components of a diverse range of coastal system types. These variations among beaches lead to significant differences in their mesoscale (multi-decadal, km length scale) behaviour, including their response to sea-level rise. In addition to this natural variability, the degree to which the sandy beach system has been or will be modified by humans is a major influence on how it responds to sea-level change. From a spectrum of beach types based on the degree of human modification, three situations (Natural, Modified and Artificial beaches) are considered in order to demonstrate the role of humans as geomorphic agents as sandy beaches respond to rising sea level. The potential trajectories of change are assessed, and future scenarios are presented and discussed. Natural beaches are most likely to survive sea-level rise, while the fate of artificial beaches depends almost entirely on the politics and economics of what lies immediately landward. In all categories of beach, human decision-making is the most important determinant of sandy beach response to sea-level rise.

Respuesta de las playas de arena naturales, modificadas y artificiales a la elevación del nivel del mar

RESUMEN. Las playas de arena se encuentran en una amplia variedad de entornos ambientales y como componentes de una amplia gama de tipos de sistemas costeros. Estas variaciones entre playas implican diferencias significativas en su comportamiento a mesoescala (escala de longitud de multi-década a kilómetros), incluyendo su respuesta al aumento del nivel del mar. Además de esta variabilidad natural, el grado en el que el sistema de playa de arena ha sido o será modificado por los seres humanos es importante en la respuesta al cambio del nivel del mar. A partir de un espectro de tipos de playa, basado en el grado de modificación humana, se consideran tres situaciones (playas naturales, modificadas y artificiales) para demostrar el papel de los humanos como agentes geomórficos a medida que las playas de arena responden al aumento del nivel del mar. Se evalúan las posibles trayectorias de cambio y se presentan y discuten escenarios futuros. Las playas naturales tienen más probabilidades de sobrevivir al aumento del nivel del mar, mientras que el destino de las playas artificiales depende casi por completo de la política y la economía. En todas las categorías de playa, la toma de decisiones humana es el determinante más importante en la respuesta de la playa de arena al aumento del nivel del mar.

Key words: Sandy beach, sea-level rise, human impact.

Palabras clave: Playas de arena, elevación del nivel del mar, impacto antrópico.

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1. Introduction

Sandy beaches take a wide variety of geomorphic forms and exhibit various morphological behaviours according to their environmental setting (Carter, 1989; Woodroffe, 2002; Davis and FitzGerald, 2009). Empirical data show that their instantaneous and seasonal variation in morphology reflects the interaction between sediment texture and the associated wave and tidal regime (Jackson and Short, 2020) but at longer-terms (decades to centuries) and larger spatial scales (> 1 km alongshore distance) beach behaviour is strongly influenced by aspects of the geological framework and geomorphological system in which they occur (Cooper and Pilkey, 2004; Anthony, 2013; Cooper *et al.,* 2018). These include the volume of sediment and rate of sediment supply, as well as the surrounding geological framework that may comprise erodible or unerodable materials in various configurations (headlands, Commonly, for example, distinction is made between uninterrupted linear sandy beaches, on which longshore transport is a dominant process (e.g. Abadie *et al.,* 2006; Laïbi *et al.,* 2014; Balouin *et al.,* 2005), and embayed beaches in which cross-shore transport is dominant (Bowman *et al.,* 2009; Pinto *et al.,* 2009; Loureiro *et al.,* 2012). Beaches are often part of a wider sedimentary system involving exchanges of material and energy between beach, dune, lagoon, mainland, tidal inlet sand bodies, shoreface, alongshore environments etc. and their behaviour is strongly determined by the nature of the sedimentary system of which they form a part. At a smaller spatial scale, beaches and parts of beaches have also been classified in terms of their profile and plan morphology into a spectrum of beach states (Jackson and Short 2021).

Sandy beaches are widespread and important environments as far as humans are concerned. They deliver a range of ecosystem services inasmuch as they support foodwebs, act as buffers against storms, and perhaps most importantly in the Mediterranean and other warm water locations, they are associated with high levels of economic activity via their high recreation and tourism value (Jacob *et al.,* 2021). Consequently, their response to near-future sea-level rise is an important societal issue.

Aside from the natural variability in sandy beach form, sandy beaches also exist in a range of states according to the degree to which they have been modified by human activities (Cooper and Alonso, 2006; Palazón *et al.,* 2016; Cooper and Jackson, 2020) (Fig. 1). Some remain in essentially natural conditions in which sediment supply to and within the beach sedimentary system has not been altered. These are becoming increasingly rare as the global population increase and increased wealth has increased the pressures to which beaches are subjected, but they are often associated with sparely populated, remote and inaccessible locations.

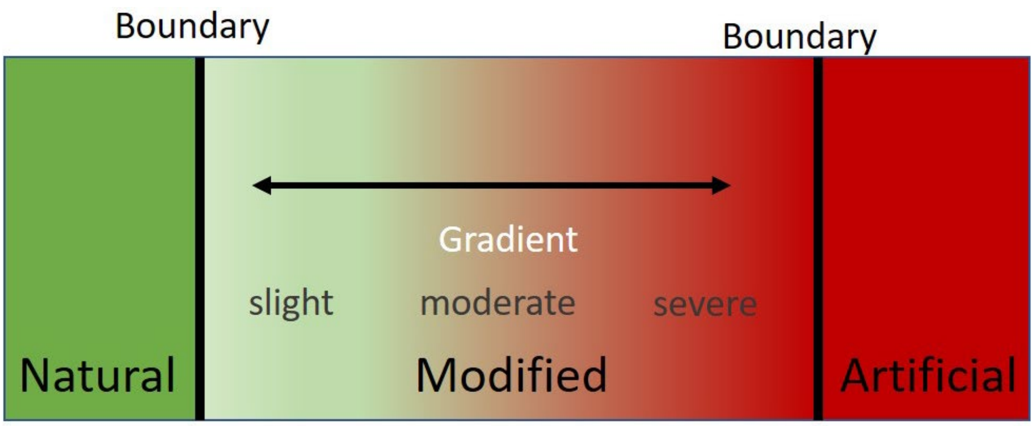

Figure 1. Conceptualisation of the degree to which human activity modifies sandy beaches. Totally natural and artificial states are separated by clear boundaries or thresholds whereas modified beaches exist on a gradient ranging from minor to major modifications of the natural dynamics and/or boundary conditions.

Many other beaches have been modified by human activity to varying degrees and this modification in turn can affect their medium-term behaviour. Ephemeral human impacts related to, for example, driving on a beach, high-density summer tourism use or the effects of a pollution incident, tend to be short-lived and have little lasting impact. More long-lasting and/or widespread impacts are reflected in the medium-term behaviour of beaches (e.g. del Rio Rodriguez *et al.,* 2015; Garel *et al.,* 2015). These human impacts include reduction in beach sediment volume through sand mining (e.g. Alonso *et al.,* 2002; Costas and Alejo, 2007); reduction of external supply (Malvárez, 2012) increases in volume or changes in texture due to sediment input, often via beach nourishment (e.g. Anfuso *et al.,* 2001), changes in boundary conditions through emplacement of coastal engineering structures (e.g. Malvárez, 2012; del Rio *et al.,* 2015) and direct construction on the beach or dune surface (Roig-Munar *et al.,* 2006) to name but a few. These interventions damage the beach and cause changes that occasionally cause further interventions or beach destruction (Pilkey and Cooper, 2014).

Artificial beaches are those that were created or are maintained entirely through ongoing human intervention (Malvárez *et al.,* 2021). They can arise through progressive human alteration of natural beaches to the point that the natural aspects are lost.

The best examples are artificially nourished beaches whose existence relies on continued input of sand by human means. Other artificial beaches are created where previously no beach existed. When accommodation space is available in the geological framework, the addition of sand can lead to development of an artificial beach that may or may not require ongoing human intervention to maintain it.

Ongoing and near-future sea-level rise is often cited as a threat to sandy beaches (e.g. Vousdoukas *et al.,* 2020), but rather than being a ubiquitous threat, the ability of beaches to survive sea-level rise is related partly to the natural geological setting and to human interventions (Cooper *et al.,* 2020). Currently, the rate of sea-level rise is accelerating (Dagendorf *et al.,* 2019) and future sea levels have been estimated for various emissions scenarios (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool). There is much uncertainty regarding future sea-level projections, related mainly to the poorly understood rate of ice sheet decay (Golledge, 2020), however, IPCC AR6 scenarios suggest a rise of between 0.6 and 0.75 m by 2100 relative to a 1995-2014 baseline at sites around the Spanish coast.

Just as beaches have previously been categorized from a coastal management perspective according to their degree of urbanization (Natural, Semi-Urbanized and Urbanized; Palazón *et al.,* 2016), in this paper, three categories of sandy beach are presented (Natural, Modified and Artificial) in terms of the degree to which they have been modified by humans. The likely response of each category of beach to near-future sea-level rise is then considered. The boundaries between the categories are gradational and reflect the progressive and incremental impact of human actions on beaches. The perspective of the paper, based on geomorphological observations and geological principles, is that natural (or lightly impacted) beaches can evolve and persist within the changing boundary conditions imposed by sea-level rise, whereas human intervention, driven by a desire to protect coastal property and human interests through shoreline stabilization, hampers the ability of beaches to adapt. Human responses to beach changes that threaten or are perceived to threaten human interests often involve interventions to stabilize the beach (Cooper and Pilkey 2012). These interventions transform natural beaches into modified beaches and these interventions may proceed to the stage that the beach is transformed into an artificial system whose continued existence depends on beach nourishment (Fig. 2). It is likely that sea-level rise-related changes will be perceived in the same way and further human interventions on natural beaches are likely to occur. In efforts to stabilize the shoreline. The presence of infrastructure landward of a natural beach is the most likely driver of such interventions and in very few cases has the alternative strategy (remove or modify the infrastructure) been adopted (Creach *et al.,* 2020).

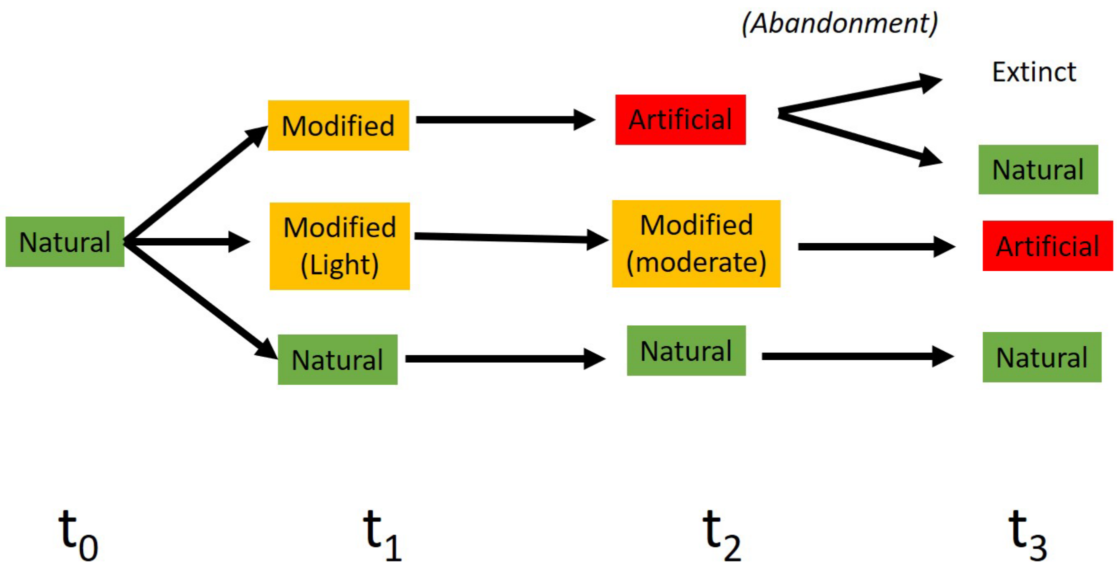

Figure 2. Trajectories of change for natural beaches as sea-level rise continues (t_0 to t_3 denotes time). Natural beaches can remain in a natural state or be modified by human activity to greater or lesser extents. Over time, the degree of modification usually increases until artificial beaches are created.

2. Natural sandy beaches and sea-level rise

Sandy beaches that are in a natural state are free to change morphology in response to external forcing within the confines of the surrounding geology. These changes take place at various timescales and are often difficult to recognise and interpret because of inadequate data (Woodroffe, 2002). Temporal morphological changes on beaches are complex and occur as a result of seasonal or longer-term variations in hydrodynamics or sediment supply (Anfuso *et al.,* 2016) and episodic events such as storms (Loureiro *et al.,* 2009) after which recovery can last for years or even decades (Orford *et al.,* 1999). Beach behaviour can also be decoupled from hydrodynamic forcing and is then characterised by "emergent behaviour" (Hird *et al.,* 2021). There are also feedbacks between beach morphology and dynamics (Sénéchal *et al.,* 2009, Anthony, 2012). Sandy beaches, being composed of uncohesive sediment are, however, able to adjust their morphology as a result.

Beach response to sea-level rise is difficult to detect in the face of the multiplicity of temporal morphological changes attributable to other sources. In broad terms, sea-level rise causes changes in the surrounding geological framework and the plane on which hydrodynamic forces operate. The precise nature of a beach's response to sea-level rise depends to a very great extent on local geological factors (initial morphology, surrounding geological framework and sediment supply; Cooper e*t al.,* 2018) and the rate (not just amount) of sea-level rise (Green *et al.,* 2014) and no generic approach can predict the extent of beach response and future shoreline position (Cooper and Pilkey, 2004). Local factors of a geological nature must be quantified if the future behaviour of a sandy beach is to be envisaged. Among these, the existing morphology and sediment volume, plus the presence or absence of uncohesive, erodible sediment either landward or seaward of a beach are among the most important elements in its future behaviour.

Nonetheless, free from human interference, most natural beaches are likely to adjust and therefore survive sea-level rise by migrating landward as part of an evolving coastal sedimentary system (Cooper *et al.,* 2020). The preservation of littoral deposits on the continental shelves of the world (e.g. Green *et al.,* 2014), testify to the ability of beaches to survive sea-level rise and to adjust to major changes in sea level. The coastal morphology may change according to the geological framework over which transgression takes place, but, free of human interference, a coastal system will be sustained in dynamic equilibrium with the ambient conditions dictated by geological framework, sediment supply and coastal dynamics. Although natural coastal systems will survive, these evolving systems may involve changes in coastal character, including local extinction of beaches in areas of steep topography (e.g. Peterson *et al.,* 2021) and coastal progradation in areas of abundant sediment supply (e.g. Goy *et al.,* 2003).

3. Human-modified sandy beaches and sea-level rise

Sandy beaches can be modified in many ways through human activity. Some of these cause alteration of the beach boundary conditions (e.g. by construction of engineered structures), changes in sediment volume (e.g. reduction by sand mining or augmentation by beach nourishment), or modification of patterns of sediment movement and storage (e.g. by groyne construction or creation of artificial dunes). These interventions are often (but not always) emplaced to adapt the beach to human requirements by stabilizing or altering its position to protect developments to landward. As sea-level rises, it is likely that existing installations on such shorelines will be maintained as long as adequate financial and technological resources are available. The critical issue is that on shorelines adjacent to fixed human infrastructure and property, landward migration of the shoreline is generally perceived primarily as a threat, rather than a natural process. Consequently, the landward migration in response to sea-level rise characteristic of natural beaches, is likely to be resisted (Malvárez *et al.,* 2021). One manifestation of this situation is the presence of seawalls on the landward side of many beaches. As in the case of beaches backed by steep topography, the lack of accommodation space created by seawalls will lead to beach narrowing and ultimately beach extinction.

In response to sea-level rise, early "adaptation" strategies are likely to involve the emplacement of more defences in a kind of "domino effect" as the impacts of earlier interventions are addressed by still more human modification. This is well illustrated on coasts where groyne fields extend alongshore in response to the longshore impact of the initial groynes. Early "adaptation" can also involve raising or strengthening of sea defences (especially seawalls, but also artificial dunes) and is often followed by beach nourishment. The temporal evolution of this sequence of stabilization approaches is well-illustrated on the Costa del Sol (Malvárez, 2012).

These kinds of intervention incur increasing costs over time as more sand or higher walls are required to hold stabilized shorelines in place as sea levels rise (Cooper and Lemckert, 2012). These responses amount to resisting (rather than adapting to) the natural change driven by sea-level rise (Cooper and Pile, 2014), and at meaningful timescales such responses can be regarded as maladaptation (Magnan *et al.,* 2016). Efforts to hold the shoreline and sustain beaches in the face of sea-level rise by beach nourishment have increased in extent and volume of nourishment and the volumes of sand involved in recent years (de Schipper *et al.,* 2021). This practice leads to beaches crossing a threshold and becoming artificial beaches that cannot survive without continued human intervention.

As sea-level rises and the extent of currently stabilized shoreline is recognised, the financial and technical resources necessary to maintain all such beaches may not be available (Pilkey and Cooper, 2014b). In circumstances where resources do not permit continued maintenance of human structures it is possible that modified sandy beaches could then revert to a more natural state (Fig. 3). In a few localities worldwide, the decision has already been made to permit beaches to migrate in spite of the presence of adjacent human structures and property (Berry *et al.,* 2013; Siders, 2019). In such locations as structures are removed or allowed to decay, the natural beach dynamics may be restored and the beach could therefore survive sea level rise.

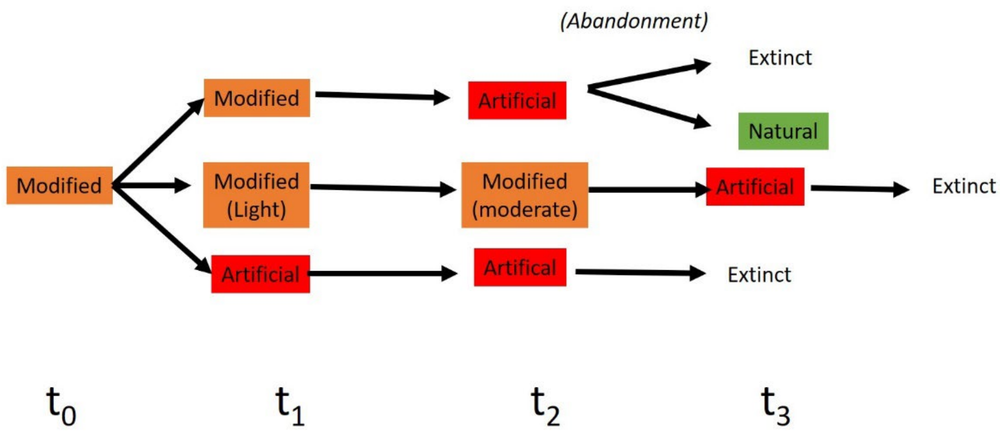

Figure 3. Trajectories of change for modified beaches as sea-level rise continues (t_0 to t_3 denotes time). The degree of modification usually increases, leading to transformation into artificial beaches.

4. Artificial sandy beaches and sea-level rise

Artificial sandy beaches arise mainly through continued efforts at stabilization that ultimately involve repeated phases of beach nourishment. Often this situation arises after the failure of several types of engineered structure to maintain the beach position. On the Costa del Sol, for example, a succession of hard structures of varying design were emplaced before beach nourishment was adopted as the shoreline stabilization method (Malvárez, 2012). On such beaches, ultimately, the beach is maintained against erosion only by ongoing nourishment and long-term plans are developed to maintain the shoreline. The entire mainland shoreline of the Netherlands is one such example, but large areas of the eastern United States (Armstrong and Lazarus, 2019) and individual beaches around the Mediterranean are now in this category. The Netherlands "dynamic preservation" strategy (Borsje *et al.,* 2017), for example, aims to maintain the 1991 shoreline in the face of rising sea level. Perversely, the strategy has been labelled by its proponents as "working with nature", whereas it is actually resisting the forces of nature that would otherwise cause the shoreline to shift landwards. Some authors have recognised that the approach is not sustainable in the long term (Parkinson and Ogurcak, 2018).

Some artificial beaches, however, have been constructed where no beach previously existed. Examples include Sentosa Island, Singapore (Lai *et al.,* 2015), the engineered shorelines of Dubai (Spurrier, 2008) and many sites in the Canary Islands (Alonso *et al.,* 2019) including the Playa de Las Teresitas in Tenerife (Pranzini *et al.,* 2010).

On artificially nourished beaches the management strategy is to maintain the beach position and in the face of sea-level rise this can only happen through more frequent additions of larger volumes of sand to enable the beach to keep pace with rising sea-level over time. Because the beach system also includes the submerged surf zone and shoreface, this can be a much larger volume of sand than is visible on the intertidal beach (Cooper and Lemckert, 2012). On beach systems that comprise part of a longshore drift system, those adjacent beaches also need to stabilized, thus spreading the need for nourishment alongshore (Armstrong and Lazarus, 2019).

Several factors combine to threaten future beach nourishment practice on a continental or global scale (de Schipper *et al.*, 2021). One important constraint is the availability and cost of sand. Sand is in high demand for construction and as supplies are depleted the costs increase and new sources must be found. A second factor is the increasing volume of sand required for beach stabilization as sea levels rise. In addition, infrastructure behind nourished beaches will be at ever lower elevation compared to future sea-level and the need for additional back-beach defences is therefore likely to increase. Ultimately, stabilization by nourishment could lead to artificial beaches that are much higher in elevation than the adjacent coastal infrastructure.

The fate of artificial sandy beaches lies entirely in the hands of human decisions regarding beach maintenance. If resources permit, the beaches can be maintained against sea-level rise (Fig. 4), although in the case of nourishment becoming unfeasible, seawalls are the last resort to protect landward developments. Sea wall construction would lead to the extinction of beaches as there is no opportunity to migrate (Pilkey and Cooper, 2014a). If political and economic conditions mean that seawalls are not constructed and infrastructure is abandoned or relocated, the possibility exists for re-establishment of natural sedimentary systems (Fig. 4). A Neolithic example has been documented from the coast of Israel (Galili *et al.,* 2019) where, after abandonment of a 7000 year-old seawall, a natural coastal system with a sandy beach was re-established landward of the former sea defence.

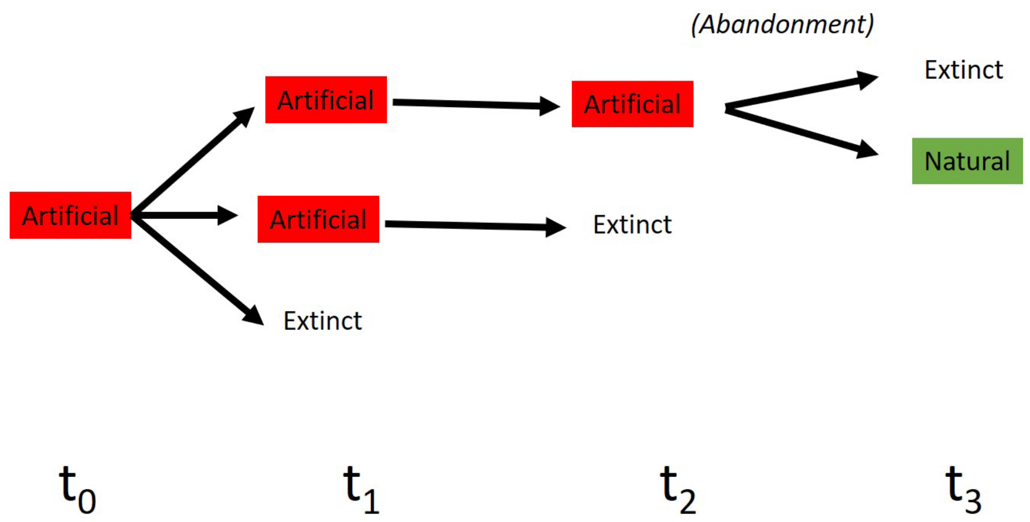

Figure 4. Trajectories of change for artificial beaches as sea-level rise continues (t_0 to t_3 denotes time). At some point controlled by the rate of sea-level rise and socio-political conditions, maintenance of artificial beaches may become unfeasible and the beach is then destroyed. At that point, natural conditions might be re-established, causing a reversion to a natural state, or the shoreline might be stabilized without the presence of a beach.

5. Discussion

The prospect of a general landward migration of beaches as a result of sea-level rise is only partly appreciated by decision-makers and beach nourishment has been widely regarded as an "easy solution". This has created the misperception that beach loss can be avoided or easily rectified. To date, beach nourishment has been effective in stabilizing some sandy shorelines to the extent that the background rate of beach recession has been masked (Armstrong and Lazarus, 2019) but as volumes of sand for nourishment increase, and the extent of nourished beaches increases, the costs and logistics will put pressure on nourishment as a stabilization technique (Pilkey and Cooper, 2014b).

Sea level rise does not pose a threat to most natural beaches. Beaches have survived many metres of sea-level rise during the Holocene and overstepping of sandy shorelines appears to be associated with much higher rates of sea-level rise than are envisaged for the near future. Widespread overstepping has been noted during glacial meltwater pulses when rates of sea-level rise reached 20-30 mm per year (Green *et al.,* 2014; Cooper *et al.,* 2016), an order of magnitude greater than envisaged in current IPCC projections (IPCC, 2021). Natural beaches can therefore be generally expected to migrate and adjust their morphology as sea levels rise. A risk is posed to natural beaches, however, if there is development in close proximity that might create pressure for future shoreline stabilization. Such shorelines were classified as "at risk" by Cooper and Jackson (2019).

On highly developed back-beach areas, such as those with high-rise commercial and residential development, defence of property is likely to be maintained by continued nourishment to stabilize the shoreline and maintain the artificial beach. On less developed areas, the cost of nourishment may become prohibitive, at which stage seawalls are likely to be emplaced to protect property and the beach will be eroded due to a lack of accommodation space. On the least developed shorelines a cessation of nourishment without alternative hard defences could lead to the re-establishment of natural beach conditions. If beach nourishment stops, then such beaches are likely to narrow and disappear as sea-level rise.

Consistent with current views on global dynamics in the Anthropocene (e.g. Zalasiewicz *et al.,* 2008) on all beaches, whether natural, modified or artificial, decisions made by humans are the single most important determinant of their future status and trajectory of change. This highlights the importance of adaptation planning for beach preservation. The adoption of policies that prioritise the preservation of beaches (long-lasting, natural features) over buildings (ephemeral artificial structures) is an urgent priority because at present, human interventions continue to damage beaches in order to protect property. These conditions stimulate ongoing property development in back-beach areas and increase the future threats to the survival of beaches. Adoption of alternative strategies is politically difficult but in the current climate emergency, increased attention on the importance of natural ecosystems might create conditions in which beach survival is prioritised. Some authors (e.g. Anderson *et al.,* 2020) consider retreat of beachfront communities (and infrastructure) to be unavoidable in the future engineered responses to shoreline stabilization become less feasible both technically and economically.

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PROPUESTA METODOLÓGICA PARA LA CARACTERIZACIÓN Y TIPIFICACIÓN DE LAS COSTAS ESPAÑOLAS. APLICACIÓN A LAS COSTAS DE GALICIA

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RESUMEN. Hay varias clasificaciones costeras. La mayoría de ellas han sido elaboradas a nivel mundial utilizando criterios tectónicos, climáticos, topográficos u oceanográficos. Otras clasificaciones han sido elaboradas a mayor escala y han sido enfocadas a catalogar las formas costeras: acantilados, playas, estuarios, lagunas o complejos dunares.

Este trabajo analiza los tipos de litoral, entendiendo como tal cada sector que presenta determinadas condiciones topográficas marcadas por la elevación y pendiente, y que se modeló sobre un tipo concreto de roca en un entorno climático y marino específico. Se describe un enfoque metodológico para una clasificación a escala detallada. Este enfoque se basa en la delimitación de los diferentes sistemas costeros, ejemplificados en acantilados y playas de bloques, playas de arena y dunas. En este caso las plataformas costeras, marismas y lagunas no han sido consideradas por los problemas técnicos derivados de la fuente de datos LiDAR, de la cual se derivan los modelos digitales del terreno (MDT) de resolución espacial de 2 m.

El primer paso en la clasificación fue una delimitación manual que combinaba MDT y ortofotografías. Posteriormente, se realizó otra tipificación mediante la creación automática de Unidades Topográficas Litorales (UTC). Este índice es la combinación de dos variables: elevación costera y pendiente. La posible integración de otras, como la orientación o la litología, es posible, pero generan un número muy elevado de unidades y dificultan su interpretación. Por esta razón, este estudio no consideró más variables.

En este proyecto se generaron 30 UTC, y luego se seleccionaron solo aquellas que aparecen en los sectores de acantilados, playas de cantos rodados, playas de arena y dunas costeras. La posibilidad de visualizar una o varias UTC en cualquier sector de la costa permite conocer con mayor precisión las condiciones de cada sector y estas categorías podrían mejorar los planes de gestión costera.

Methodological proposal for the characterization and typification of the Spanish coasts. Application to the coast of Galicia

ABSTRACT. There are several coastal classifications. Most of them have been elaborated worldwide using tectonic, climatic, topographic, or oceanographic criteria. Other classifications have been generated on a larger scale and focused on classifying the coastal forms, as cliffs, beaches, estuaries, lagoons, or dune complexes in different places.

This project analyzes the types of coastlines, understanding as such each sector that presents certain topographic conditions marked by the elevation and slope, and that was modeled on a concrete type of rock in a specific climatic and marine environment. This paper describes a methodological approach for a detailed scale classification. This approach based on the delimitation of the different coastal systems, exemplified in cliffs and boulder beaches, sandy beaches, and dunes. In this case the shore platforms, marshes and lagoons have not been considered for the technical problems derived from the LiDAR data source, from which the 2 m spatial resolution digital terrain models (DTM) are derived.

The first step in the classification was a manual delimitation combining DTMs and orthophotographs. Subsequently, other typification has been carried out through the automatic creation of Coastal Topographic Units (CTU). This index is the combination of two variables: coastal elevation and slope. The possible integration of others, such as orientation or lithology, is possible, but generate a very high number of units and make it difficult to interpret. For this reason, this study did not consider more variables.

In this project 30 CTUs was generated, and then selecting only those that appear in the cliffs, boulder beaches, sandy beaches, and coastal dunes sectors. The possibility of viewing one or several CTUs in any sector of the coast allows to know more accurately the conditions of each sector and these categories could be improve the coastal management plans.

Palabras clave: Geomorfología, UTC (Unidades Topográficas Litorales), Tipos de costa, España, Galicia.

Key words: Geomorphology, CTU (Coastal Topographic Units), Coastal types, Spain, Galicia.

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1. Introducción

La costa es una franja de ancho variable en donde entran en contacto la tierra y el mar. Sin embargo, no siempre es fácil delimitar con exactitud dónde termina el continente y dónde empieza el mar. Esto es particularmente complicado en las costas bajas, en el entorno de los humedales costeros, que unas veces pueden estar dentro de un ambiente terrestre, pero otras se encuentran sumergidas bajo el agua durante la marea alta. Por ello, parece más conveniente hablar de regiones costeras, áreas de contacto entre el mar y la tierra, es decir, el límite hacia la tierra de la influencia marina y el límite hacia el mar de influencia terrestre (Carter, 1988).

Delimitar, clasificar o tipificar las costas tampoco es tarea fácil. Ello se observa en el artículo de síntesis de Finkl (2004) en el que se analizan las diferentes clasificaciones que se han hecho de las costas a nivel mundial o, a modo de ejemplo, en las diferentes entradas de la *Encyclopedia of Geomorphology* dirigida por Goudie (2004).

De su lectura se deduce que una primera cuestión a plantear es la de la escala de análisis. Si se diferencian las costas a una escala global, la clasificación es relativamente fácil. Es el caso de la propuesta de Suess (1906) que diferenció las costas atlánticas, que, según él, cortan las estructuras geológicas, de las del Pacífico, que corren paralelas a ellas. Inman y Nordstrom (1971) elaboraron una clasificación con relación a la tectónica de placas diferenciando entre costas de subducción, de margen de placa divergente y costas marinas marginales. En esta misma línea global, Aufrere (1936) propuso una clasificación costera basada en el clima diferenciando entre costas con cubierta de hielo permanente, costas con capa de hielo estacional, costas templadas húmedas, costas tropicales húmedas, costas áridas y costas semiáridas.

Usando el mismo rango de análisis, Davies (1980) centró su clasificación en los procesos costeros diferenciando costas afectadas por olas de tormenta, costas sujetas a vientos alisios, monzones y ciclones tropicales, es decir costas de energía alta, moderada y baja, así como por el tipo de marea (semidiurna, mixta y diurna) y rangos medios o máximos de marea diferenciando micromareal (<2 m), mesomareal (2-4 m) y macromareal (>4 m), al que se le puede añadir megatidal (>6 m). Por su parte, Cotton (1952) hizo una distinción entre costas de regiones estables y móviles, siendo las primeras las que escaparon a los movimientos tectónicos del Cuaternario que han afectado a las regiones inestables, especialmente en el entorno del borde del Pacífico, donde todavía continúan. En las costas de las regiones estables diferenció entre las dominadas por procesos generados por el levantamiento marino del Cuaternario tardío de las dominadas por características heredadas, especialmente del Pleistoceno, conservadas por un levantamiento anterior.

Un análisis diferente lo había propuesto años antes de Martonne (1909) con una clasificación morfológica diferenciando entre costas escarpadas y planas, proponiendo una serie de subtipos, algunos descriptivos, por ejemplo, costas de estuarios; otros genéticos, costas de falla o modeladas por glaciares. Un enfoque similar siguió Ottmann (1965) que propuso tres categorías de costa acantilada (acantilados que se hunden en las profundidades oceánicas, acantilados con plataformas costeras y acantilados que se precipitan sobre plataformas sumergidas), costas parcialmente sumergidas, costas no acantiladas y costas bajas. Zenkovich (1967) clasificó los rasgos costeros deposicionales en cinco categorías: formas adosadas (incluyendo playas y promontorios), formas libres (incluyendo flechas), barreras, formas en bucle (incluidos los tómbolos) y formas separadas (incluidas las islas-barrera).

Valentin (1952), partiendo de la base de que una línea de costa puede avanzar o retroceder, clasificó las costas entre las que surgieron por emergencia, por deposición orgánica, caso de los manglares o los corales, y por deposición inorgánica, marina o fluvial, mientras que las costas que retrocedieron las dividió entre las que se formaron por inmersión de formas terrestres erosionadas por procesos glaciares o fluviales y las formadas por erosión marina.

Otro autor, Russell (1967) propuso una clasificación de las costas rocosas, sobre la base de la geología y de la estructura, teniendo en cuenta la similitud de formas desarrolladas sobre rocas cristalinas, independientemente del ambiente climático y ecológico. Los granitos que afloran en diferentes lugares de las costas de Escandinavia, en el suroeste Australia, en Sudáfrica o Brasil muestran superficies abovedadas similares. Las calizas, los basaltos y las areniscas también muestran formas costeras originales. Por su parte Haslett (2009) analizó las costas como sistemas dinámicos diferenciando los sistemas costeros dominados por el oleaje, que engloban a las playas, acantilados, plataformas y costas coralinas; sistemas costeros dominados por las mareas, caso de las llanuras intermareales, estuarios, marismas y manglares; y sistemas costeros dominados por los ríos, en los que engloba a los estuarios.

Visto lo anterior, parece evidente que las diferentes clasificaciones sirven en gran medida para obtener una visión global de las costas a nivel mundial pero no para ser empleadas a nivel local. Sin embargo, existen diferentes publicaciones a nivel internacional que se centran en clasificaciones regionales. A este respecto se pueden mencionar algunas como las siguientes: Benedet *et al.* (2006) realizaron una clasificación morfodinámica de las playas de Florida diferenciando cinco compartimentos morfológicos y 24 subsegmentos con distintos niveles de peligro; Del Río *et al.* (2013) propusieron una clasificación basada en la morfología y dinámica de las playas para poder comprender la forma en que las características morfológicas costeras influyen en las tendencias de erosión-acreción; Ward y Roberts (2020) caracterizaron los estuarios de Southland (Nueva Zelanda) dentro de una clasificación relativamente compleja de doce tipos principales y subtipos basados en amplias características físicas. En el caso de Galicia, en el Plan de Ordenación de Litoral de Galicia (POLGalicia, 2011) se diferencian ocho tipos de acantilados, once tipos de playas junto con marismas, estuarios y llanuras intermareales.

El objetivo del presente artículo es proponer una nueva metodología que permita caracterizar mejor los diferentes tipos de costa existentes en cualquier lugar del mundo combinando las distintas variables asociadas al relieve costero, es decir la altura, la pendiente y la orientación. Su combinación junto con los variados tipos de rocas permite entender mejor las diferencias existentes tanto en el diseño de la costa como en su comportamiento dinámico en relación con las variables atmosféricas y oceanográficas.

2. Fuentes y metodología

Caracterizar y tipificar cualquier espacio geográfico requiere el uso de diferentes fuentes y de una metodología clara. En este caso se ha optado por trabajar a dos escalas. Una primera, a escala general de España, que permitiese caracterizar los grandes rasgos de las costas españolas y, una segunda, a mayor escala. A modo de ejemplo, en este caso, se optó por estudiar la costa gallega con el objeto de poder diferenciar mejor los distintos tipos de costa. Para el primer objetivo se creó un Modelo Digital de Elevación (MDE) de 5 m de resolución espacial de una franja de 1000 m de ancho desde la costa. Para el segundo se elaboró MDE de 2 m al que se le superpusieron la ortofotografía del PNOA de los años 2010 y 2017 (IGN, 2021). Los archivos se procesaron usando ArcGIS 10.7 (licencia USC). El análisis litológico se ha llevado a cabo a partir de las capas a escala 1:50.000 y 1: 1.000.000 del IGME (2021), mientras que los datos oceanográficos se han obtenido de Puertos del Estado (2021).

Con los MDEs se han construido los mapas de altitud, pendiente y orientaciones. En el caso de Galicia, se han elaborado mapas de unidades topográficas a partir de la unión de altitud y pendiente. Por otra parte, se ha creado una cartografía detallada de acantilados, playas de bloques, playas de arena y dunas, a partir de la construida durante la elaboración del Plan de Ordenación del Litoral de Galicia (POLGalicia, 2011) bajo la dirección del autor.

3. Resultados

3.1. Caracterización general de las costas españolas

Sin duda se puede afirmar que la diversidad es la principal característica de las costas españolas. A lo largo de los más de 9000 km de longitud (Pérez-Alberti *et al.,* 2019) se encadenan dominios climáticos diferentes, tipos de rocas variados, condiciones oceanográficas distintas y una gran diversidad de acantilados y plataformas rocosas, playas y dunas, marismas, albuferas o lagunas. También se localizan Regiones Biogeográficas (Atlántica, Mediterránea y Macaronésica), Demarcaciones Marinas (Noratlántica, Suratlántica, Estrecho y Alborán, Levantino Balear y Canarias) y diferentes Hábitats de Interés Comunitario (Acantilados, Dunas, Lagunas, Marismas, etc.). Incluso existe una distribución turística de las costas. A lo anterior hay que añadirle que, dado que existen marcadas diferencias desde el punto de vista topográfico, geomorfológico u oceanográfico, se pueden individualizar ocho sectores distintos (Aranda *et al.,* 2019): Costa Cantábrica, Costa de Galicia, Costa del Golfo de Cádiz, Costa del Estrecho, Costa de Alborán, Costa Levantina-Balear, Costa Brava y Costa Canaria.

3.1.1. Longitud de la línea de costa

El cálculo de la longitud de la costa se ha hecho combinando los límites marinos de las diferentes comunidades autónomas a partir de la cartografía del IGN, a escala 1:25.000. Esto ha permitido obtener datos más precisos que los conocidos anteriormente. Así frente a los 6885 km citados en el IGN, la cifra obtenida alcanza los 9265,88 km (Tabla 1). En el 1985 el INE estimaba la longitud de la costa en 5937 km.

Tabla 1. Longitud de los diferentes sectores de la costa española.

Zona	**Longitud (km)**
Cantábrica	1108,54
Costa Brava	610,74
Costa Canaria	1765,78
Costa de Alborán	758,27
Costa del Estrecho	156,23
Galicia	2021,49
Golfo de Cádiz	347,42
Costa Levantina-Balear	2092,55
Total	9265,88

3.1.2. Diversidad topográfica

Los datos de elevación y pendiente (Tabla 2), permiten saber que el 99,86% de las costas españolas tienen menos de 50 m de elevación y de ese porcentaje el 96,66% se encuentra dentro del rango de menos de 4º de pendiente. Esto indica que dominan las costas bajas y de escasa pendiente, a excepción de lugares muy concretos del territorio. De lo anterior de deduce que las costas acantiladas suponen un porcentaje muy bajo en el total. Sin embargo, ello no quiere decir que su importancia no sea grande en distintos lugares de las costas españolas, caso de la costa cantábrica, Costa de Galicia, Costa Brava o Canarias.

Tabla 2. Distribución por pendiente y elevaciones de las costas españolas.

Pendientes	**50m**	**100m**	**150m**	**200m**	**250m**	**300m**	**>300m**	**Total**
0º	99,86%	0,09%	0,05%	0,00%	0,00%	0,00%	0,00%	100,00%
4º	95,66%	2,45%	1,23%	0,58%	0,06%	0,03%	0,00%	100,00%
8º	76,57%	14,31%	6,25%	2,20%	0,42%	0,25%	0,00%	100,00%
16º	52,10%	30,65%	11,11%	4,04%	1,66%	0,43%	0,01%	100,00%
32º	30,85%	37,02%	19,47%	9,13%	2,99%	0,51%	0,04%	100,00%
64º	40,62%	27,69%	20,14%	8,55%	2,67%	0,33%	0,00%	100,00%
>64º	43,09%	50,34%	5,97%	0,60%	0,00%	0,00%	0,00%	100,00%
Total	**76,06%**	**13,70%**	**6,44%**	**2,74%**	**0,85%**	**0,19%**	**0,01%**	**100,00%**

3.1.3. Orientaciones

La orientación es otro factor clave a la hora de entender el comportamiento dinámico de las costas. Por supuesto, los contrastes entre el Cantábrico, Atlántico y Mediterráneo son un primer rasgo diferenciador, pero, ampliando la escala, se puede observar como las orientaciones son diversas en buena parte de la fachada marítima española (Tabla 3) lo que motiva cambios importantes en su dinámica en sectores próximos.

Tabla 3. Relación entre la elevación y la orientación de las costas españolas.

Orientación	**Elevación**								
	0	**50**	**100**	**150**	**200**	**250**	**300**	**> 300**	**Total**
Este	4,92%	11,78%	12,89%	12,49%	12,23%	11,55%	10,02%	8,65%	11,88%
Noreste	4,31%	10,17%	11,59%	12,33%	11,90%	11,06%	10,51%	9,99%	10,59%
Noroeste	5,86%	10,13%	13,42%	14,31%	14,33%	14,83%	16,51%	18,72%	11,45%
Norte	5,01%	9,43%	12,51%	13,26%	13,35%	13,76%	14,25%	14,99%	10,58%
Oeste	4,95%	9,91%	12,49%	12,52%	12,36%	12,40%	13,85%	15,22%	10,79%
Plano	61,53%	10,88%	0,14%	0,15%	0,15%	0,15%	0,16%	0,17%	7,67%
Sur	4,11%	12,49%	11,81%	11,50%	11,67%	11,93%	10,95%	10,14%	12,17%
Sureste	4,75%	13,76%	13,30%	12,60%	13,17%	13,30%	12,38%	10,81%	13,46%
Suroeste	4,56%	11,44%	11,84%	10,84%	10,84%	11,01%	11,37%	11,32%	11,41%
Total	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**	**100,00%**

3.1.4. Diversidad litológica

Litológicamente las costas españolas se pueden englobar en cinco grandes unidades: graníticas, metamórficas, calizas, sedimentarias y volcánicas. Su composición mineralógica y su grado de fracturación condicionan los rasgos esenciales de los diferentes sectores, pudiéndose decir que existe un control estructural y litológico de las formas. El primero marca el diseño general y el segundo el modelado de detalle.

3.1.5. Rango mareal

Las diferencias en el rango mareal entre los ambientes atlánticos y mediterráneos es otro aspecto para tener en cuenta. Los ciclos mareales de ascenso y descenso a lo largo del día provocan cambios en la humedad que influyen tanto en la fauna y flora como en los procesos de alteración química y física de los materiales rocosos. No se debe dejar de lado el hecho de que en el Noroeste existe un rango mareal de 4 m y en el Sudeste no supera los 0,5 m.

3.1.6. Oleaje

Sin duda, uno de los aspectos más importantes a la hora de entender la dinámica litoral es el oleaje. El análisis de los datos obtenidos indica las grandes diferencias que hay entre regiones. En las costas del norte y del noroeste no son infrecuentes las olas que superan los 10 m e, incluso los 12 m destacando Estaca de Bares o el Cabo Vilán (Tabla 4). Por el contrario, en el Mediterráneo se superan los 6 m en Alborán o Cabo de Gata (Tabla 5), Cabo de Palos y en Dragonera y los 8 m en Mahón. En Canarias las olas máximas registradas en Gran Canaria y Tenerife Sur no alcanzan los 6 m.

Tabla 4. Datos de oleaje en Estaca de Bares (Galicia). Boya de Vilán-Sisargas en el período 1998-2017 (Puertos del Estado, 2021).

Mes	Máxima. Hs	Tp	Dirección	Año	Día	Hora
Enero	13,5	14,3	296	2009	24	1
Febrero	11,7	18,2	275	2017	2	15
Marzo	12,6	14,3	323	2008	10	19
Abril	8,3	14,3	320	2012	18	17
Mayo	8,8	13,4	290	2006	21	21
Junio	6,3	12,5	319	2013	23	5
Julio	5,5	12,5	292	2007	1	2
Agosto	6,3	14,3	313	2008	18	16
Septiembre	7,0	10,0	249	2015	16	8
Octubre	10,2	14,3	309	2003	31	20
Noviembre	11,7	14,3	324	2010	9	3
Diciembre	10,9	12,5	309	2006	8	16

Tabla 5. Datos de oleaje en el Cabo de Gata en el período 1998-2017 (Puertos del Estado, 2021).

Mes	Máxima. Hs	Tp	Dirección	Año	Día	Hora
Enero	6,6	9,5	258	2015	31	9
Febrero	4,8	8,3	248	2016	14	5
Marzo	5,3	9,1	238	2009	5	12
Abril	4,5	8,7	83	2015	8	11
Mayo	4,9	8,3	251	2004	5	23
Junio	3,6	7,7	256	2016	15	22
Julio	3,3	8,7	93	2016	4	3
Agosto	3,9	8,4	60	2007	25	21
Septiembre	3,6	8,5	-	1998	19	0
Octubre	4,2	8,0	253	2009	22	12
Noviembre	5,6	8,7	244	2010	8	19
Diciembre	5,3	9,1	249	2010	23	13

3.2. Delimitación y tipificación de las costas de Galicia

La costa de Galicia tiene una longitud de 2100 km (POLGalicia, 2011). El estudio llevado a cabo para poder conocer la elevación y pendiente de las costas españolas permitió saber que en el caso gallego (Tabla 6) el 68,29% tenían menos de 50 m de elevación y únicamente el 3,15% superaban los 300 m. Por otra parte, el grado de pendiente es muy variable en cualquier intervalo de elevación como se puede ver en la Tabla 6. A lo anterior hay que unirle la diversidad litológica, así como la diversidad de orientaciones. A nivel general dominan las rocas pizarroso-esquistosas y graníticas ricas en cuarzo.

Tabla 6. Distribución por elevación y pendiente de las costas de Galicia

	50m	100m	150m	200m	250m	300m	Resto	Total
0º	99,67%	0,25%	0,05%	0,01%	0,01%	0,00%	0,00%	100,00%
4º	88,39%	8,32%	2,16%	0,69%	0,29%	0,06%	0,10%	100,00%
8º	70,09%	20,16%	6,05%	2,12%	0,66%	0,29%	0,63%	100,00%
16º	47,15%	31,29%	13,24%	4,84%	1,80%	0,76%	0,92%	100,00%
32º	31,25%	30,39%	20,30%	9,86%	4,43%	2,09%	1,69%	100,00%
64º	61,06%	20,22%	10,79%	7,26%	5,56%	4,73%	8,38%	100,00%
>64º	18,73%	37,48%	19,78%	9,89%	4,24%	1,77%	8,12%	100,00%
Total	**68,29%**	**18,04%**	**7,78%**	**3,19%**	**1,32%**	**0,62%**	**0,76%**	**100,00%**

Morfológicamente destacan las rías, brazos de mar que penetran en el continente separadas por estrechos sectores rectilíneos observándose una intensa relación entre la red de entrantes y salientes con la litología y la fracturación.

El diseño de las formas litorales está íntimamente relacionado con la evolución geotectónica de Galicia y se puede ver desde varias perspectivas; desde la de las megaformas, que marcan los rasgos generales de la costa, hasta el de las microformas, que introducen matices de diferenciación a escala de detalle. En ello los movimientos tectónicos han jugado un papel fundamental tanto a nivel general como en la costa, en particular. La parte final de la orogenia Varisca, estudiada por diferentes autores ha sido la más importante desde el punto de vista geomorfológico. En aquel momento el territorio gallego se fragmentó en numerosas parcelas siguiendo una serie de fracturas conjugadas NE-SW, con direcciones que oscilan alrededor de los 50º N con desplazamiento horizontal del bloque sudoeste hacia el nordeste. También se debe tener en cuenta que, aunque actualmente Galicia forma parte de un margen continental estable, en el pasado ha sido un límite de placas. A cualquier escala, la disposición de los distintos afloramientos rocosos establece las líneas del trazado en planta de la costa, mientras que en el perfil vertical sus características se relacionan con la disposición estructural de los materiales. La efectividad y los modos de operación de los procesos erosivos no dependen tan solo del tipo de roca, sino de la geometría (densidad, dirección e inclinación) o del patrón de discontinuidades, que son las que establecen las líneas de debilidad en las que se produce preferentemente la erosión (Trenhaile 1987).

La fachada marítima de Galicia se encuentra, de acuerdo con Davies (1972), en un ambiente mesomareal, con un rango medio de marea de 2,5 m y un rango máximo de alrededor de 4 m. Respecto al régimen de oleaje, Galicia se localiza en la zona de transición entre las áreas afectadas principalmente por el oleaje tipo *swell* y las afectadas por oleaje tormentoso. Las olas de mar de fondo tienen una dirección de aproximación predominantemente del NW, y con menor frecuencia del W y el SW. Las olas de mayor tamaño (>3 m) tienen una mayor frecuencia durante el invierno y generalmente con direcciones NW y W, generadas por las borrascas que se desplazan desde estas direcciones.

3.2.1. La cartografía manual de los tipos de costa

Tanto durante la elaboración del POL de Galicia (POLGalicia, 2011) como en trabajos posteriores se ha tratado de crear una metodología útil en el seguimiento del estado de conservación de los tipos de hábitat costeros en España (Pérez-Alberti *et al.,* 2019) probando diferentes opciones para llevar a cabo una clasificación automática usando imágenes de satélite y los SIG. Los resultados no fueron plenamente satisfactorios por lo que se ha optado por, en primer lugar, llevar a cabo una cartografía manual de los diferentes ambientes y, posteriormente, engarzarlos con diversos análisis SIG.

Para ello, en primer lugar, se ha creado el SIG Costa-Galicia en el que se ha cargado un modelo digital del terreno (MDT) y otro de superficie (MDS), ambos de 2 m de resolución espacial, y las ortofotografías del PNOA de los años 2010, 2011 y 2017. El uso de un MDT y MDS responde a la mejor caracterización de la costa granítica, donde en los MDT quedan truncadas las formas de modelado, posiblemente debido a que en los procesos de clasificación los grandes bolos o domos fueron interpretados como elementos antrópicos y eliminados. En cambio, en el MDS, con la presencia de estas geoformas permiten una mejor cartografía. En segundo lugar, se han creado las capas de acantilados, playas de bloques, playas, dunas, lagunas costeras y marismas. En el caso de los acantilados, playas, dunas y marismas, se han utilizado como punto de partida las capas del POL (POLGalicia, 2011).

Una vez creado el SIG se pulieron con mayor exactitud las capas citadas y se crearon otras nuevas, concretamente las de playas de bloques y lagunas costeras. En el primer caso se utilizó la escala 1:5000 para dibujar los contornos de cada sector. En las lagunas y playas de bloques que tienen una extensión menor se usó la escala 1:500. Para la cartografía de las plataformas costeras, de pequeña extensión, se han usado ortofotografías y modelos digitales elaborados mediante el uso de UAVs (Pérez Alberti y Trenhaile, 2015; Gómez Pazo *et al.,* 2021). Por último, con el objeto de poder hacer visibles los diferentes tipos de costa cartografiados en las figuras se ha creado una malla con cuadrículas de 10 km de lado. Ello permite mostrar con mayor precisión cualquier sector de la costa como se puede ver, a modo de ejemplo, en la Figura 1.

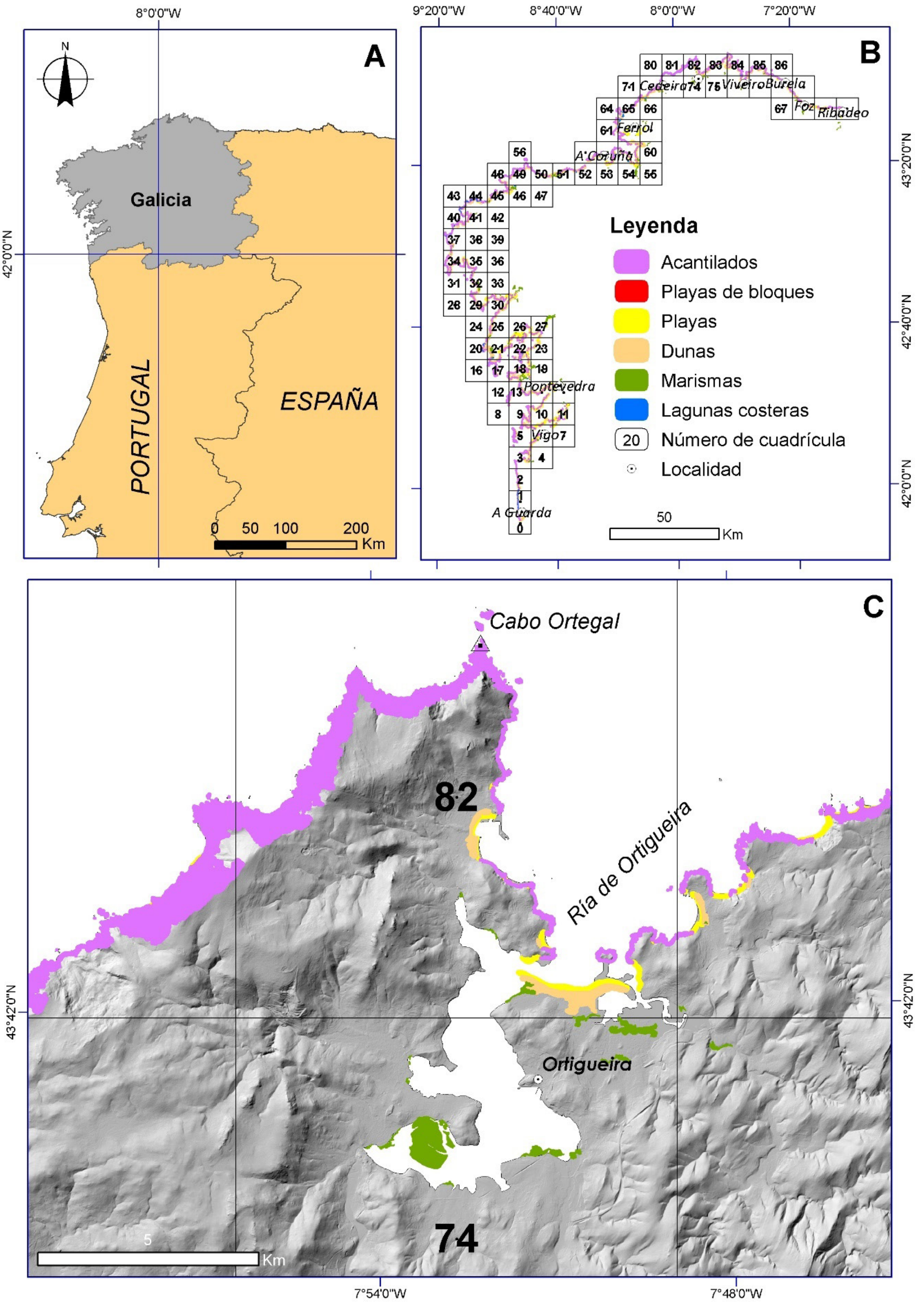

Figura 1. A) Situación del área de estudio: B) Cuadrículas de los acantilados, playas, dunas, playas de bloques, lagunas y marismas de Galicia, modificado de (POLGalicia, 2011); C) Detalle de la Ría de Ortigueira (A Coruña).

3.2.2. Cartografía mediante SIG de la costa

Se ha considerado que las formas costeras son laderas que tienen una elevación, pendiente y orientación determinadas. Como tal puede ser homogénea o no, es decir que toda la fachada costera es uniforme o está compuesta por diferentes segmentos escalonados, emplazados a una elevación determinada y con pendientes diferentes. Por ello, con el objetivo de poder conocer con mayor exactitud el encadenamiento en altitud de los diferentes segmentos y sus relaciones que, a la postre, caracterizan y tipifican la costa, se creó el SIG Unidades Topográficas Costeras (UTC). En este caso se cargó el MDT de 2 m y las capas citadas anteriormente, es decir acantilados, playas, dunas y playas de bloques. Las plataformas costeras fueron descartadas dado que al estar afectadas por las mareas no aparecen bien reflejadas en el MDT; esto también se aplica a las lagunas y marismas que no fueron consideradas por ser formas planas y con presencia de agua, lo que genera problemas en el uso de información LiDAR. También se empleó la capa del ámbito del POL (POLGalicia, 2011) dado que, aunque abarca una amplia franja costera que supera el espacio objeto de estudio, permite poder analizar la costa de una manera más integrada y muy especialmente poder ver la relación que existe entre las UTC de la fachada costera y el engarce con el continente lo que ayuda a diferenciar tipos de costa.

A partir de la mencionada información, se han generado en formato ráster: a) un MDT del ámbito del POL; b) el mapa de elevaciones; c) el mapa de pendientes; d) el mapa de UTCs y e) la extracción de las UTC enmarcadas dentro de las capas de acantilados, playas, dunas y playas de bloques. Posteriormente, los mapas se han convertido a formato vectorial para extraer cada una de las UTC, analizarlas por separado y ver su combinación en los diferentes sectores de costa.

3.2.2.1. Mapa de elevaciones

Se generó a partir del MDT de 2 m derivado de los datos LiDAR del año 2015. Posteriormente se han reclasificado las elevaciones en cinco niveles: 0-25, 25-50, 50-100, 100-300 y >300 m. Esta clasificación se hizo teniendo en cuenta que la mayor parte de las costas de Galicia no superan los 50 m de elevación pero que, por encima de esta, aparecen sectores de gran interés geomorfológico. Finalmente se han renombrado los niveles como 10, 20, 30, 40 y 50 (Figura 2, parte superior). Esto supone que a la hora de observar las UTC las decenas indiquen la elevación de la costa.

3.2.2.2. Mapa de pendientes

Se ha elaborado a partir del mismo MDT del caso anterior. Como para las elevaciones, se ha creado un número reducido de grupos pero que fueran representativos: 0-4º, 4-8º, 8-16º, 16-32º, 32-64º y >64º que se renombraron como 1, 2, 3, 4, 5 y 6 (Figura 2, parte inferior). Esto quiere decir que las unidades reflejan la pendiente.

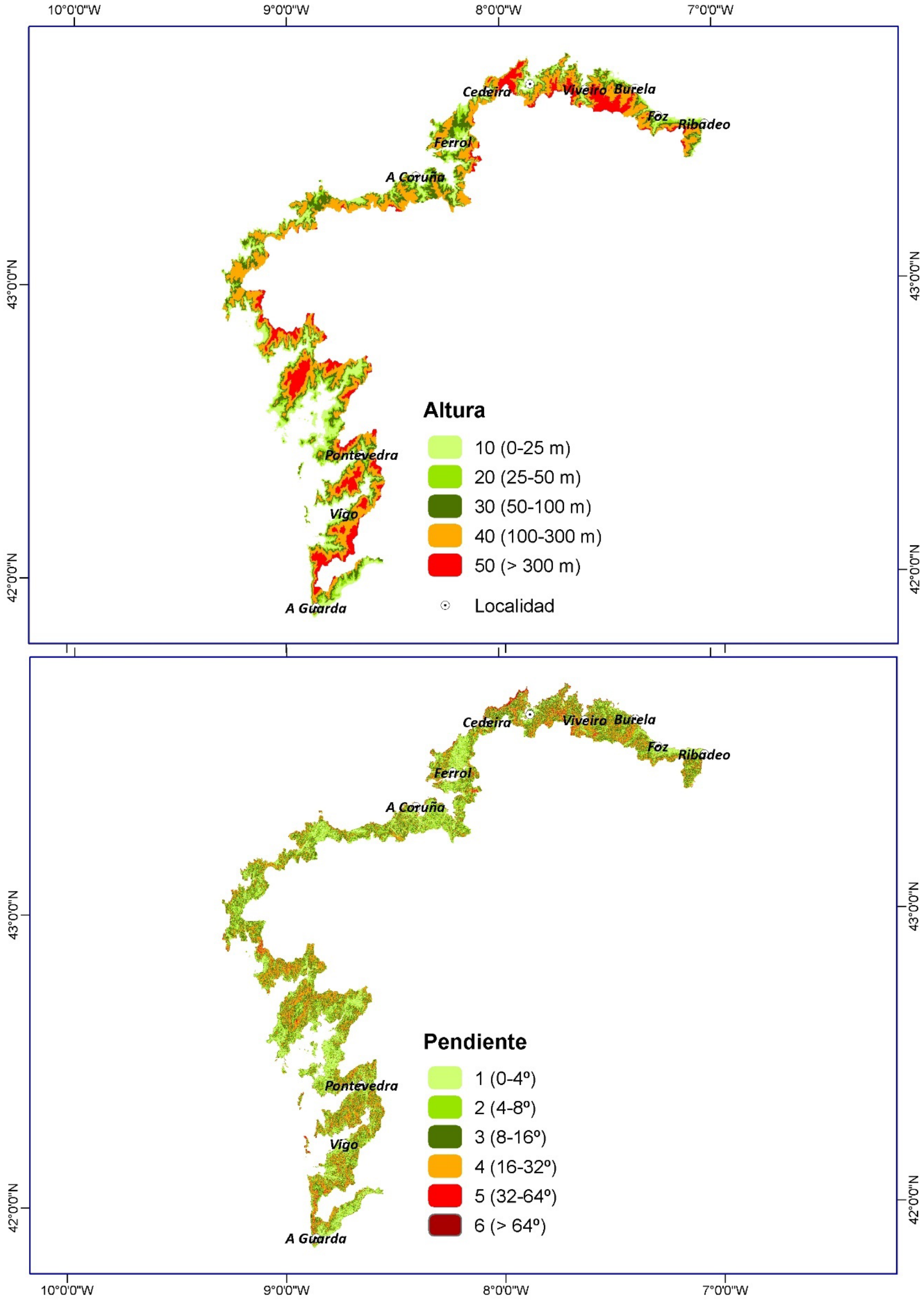

Figura 2. Mapa de elevación de la costa (superior) y pendiente (inferior) reclasificadas.

3.2.2.3. Mapa de Unidades Topográficas Costeras (UTC)

Hay que tener presente que cualquier forma topográfica lleva asociada las variables elevación, pendiente y orientación lo que supone que un cambio en cualquiera de ellas provoca una modificación en el resto. Por ello, en los primeros ensayos llevados a cabo para elaborar las UTC, aparte de los mapas de elevación y pendiente, se creó el de orientaciones y el litológico. Sin embargo, a pesar de introducir un número pequeño clases, al combinarlas con las otras once, el número de UTC resultantes era tan amplio que dificultaba su interpretación. No se debe de olvidar que la creación de cualquier clasificación costera debe de buscar el poder ser útil en la gestión. Por ello se ha optado por combinar solamente las dos primeras. En total han resultado 30 UTC que aparecen reflejadas en la Figura 3.

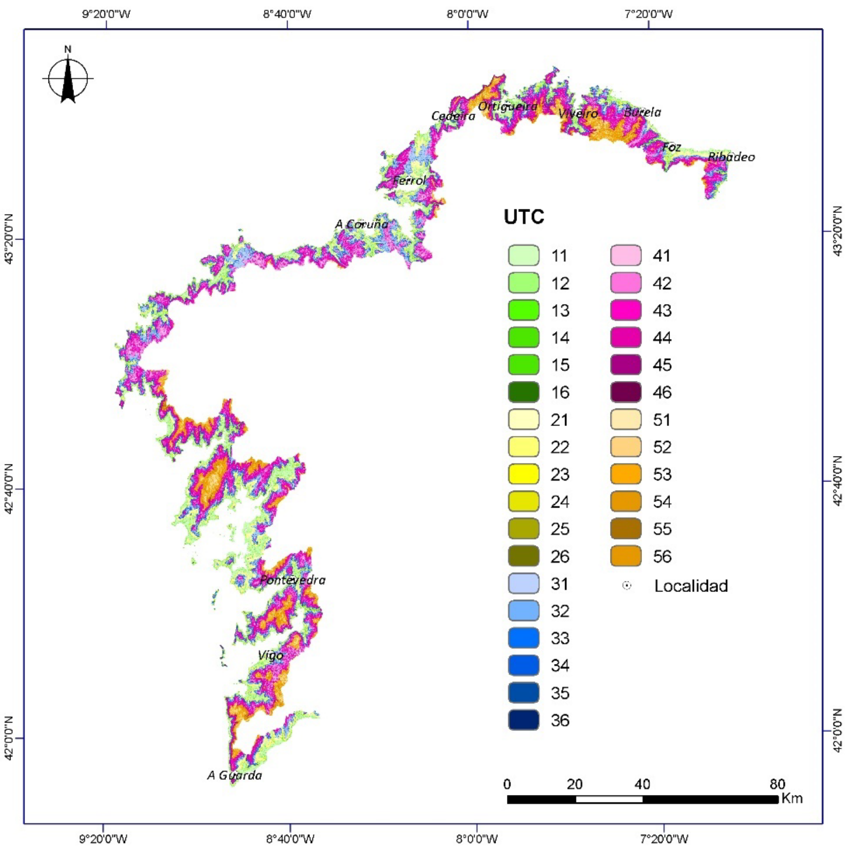

Figura 3. Mapa de UTC de la costa de Galicia.

3.2.2.4. Extracción de las UTC de los acantilados, playas, dunas y playas de bloques

La extracción de las UTC de forma individualizada permite ver con claridad como se combinan en cada ambiente concreto. Una UTC puede englobar totalmente la fachada marítima o combinarse con otras caracterizando los distintos tipos de costa. En el primer caso hay una uniformidad en la forma; en el segundo existen diferentes segmentos que, en función de las UTC, indican cambios en la elevación, lo que pueden provocar cambios en la dinámica y/o diferencias en un hábitat costero. En la Tabla 7 aparecen remarcadas las UTC existentes en los acantilados, playas de bloques, playas y dunas.

Tabla 7. UTC existentes en las áreas de acantilados, playas de bloques, playas y dunas.

UTC	Elevación (m)	Pendiente (º)	Acantilados	Playas de bloques	Playas	Dunas
11	0-25	0-4	X	X	X	X
12	0-25	4-8	X	X	X	X
13	0-25	8-16	X	X	X	X
14	0-25	16-32	X	X	X	X
15	0-25	32-64	X	X	X	X
16	0-25	>64	X	X	X	X
21	25-50	0-4	X			X
22	25-50	4-8	X			X
23	25-50	8-16	X			X
24	25-50	16-32	X			X
25	25-50	32-64	X			X
26	25-50	>64	X			X
31	50-100	0-4	X			X
32	50-100	4-8	X			X
33	50-100	8-16	X			X
34	50-100	16-32	X			X
35	50-100	32-64	X			
36	50-100	>64	X			
41	100-300	0-4	X			
42	100-300	4-8	X			
43	100-300	8-16	X			
44	100-300	16-32	X			
45	100-300	32-64	X			
46	100-300	>64	X			
51	>300	0-4	X			
52	>300	4-8	X			
53	>300	8-16	X			
54	>300	16-32	X			
55	>300	32-64	X			
56	>300	>64	X			

3.2.2.5. Análisis de la combinación de UTC y tipos de acantilados

La combinación de las distintas unidades que se encadenan en la costa de Galicia y de las existentes en su entorno continental ha permitido diferenciar los tipos de acantilados más comunes (Figura 4): acantilados con planicie anexa, acantilados con remate plano y amplia planicie anexa, acantilados vertiente, acantilados convexos y grandes acantilados.

a) Acantilados con estrecha planicie anexa. Se trata de acantilados que aparecen flanqueados hacia el continente por estrechas planicies litorales suavemente onduladas. Se encuentran modelados tanto sobre rocas graníticas como esquistosas. Son de baja elevación y en ellos dominan las UTC 13, 14, 15, es decir formas por debajo de 25 m y con pendientes entre los 8º y los 64º. Los mejores ejemplos aparecen en el entorno de la Ría de Arousa y en el margen meridional de las de Muros e Noia, Costa de Dexo, así como en la Ría de Ares y Betanzos (Figura 5A).

b) Acantilados de remate plano con amplias planicies anexas. Se diferencian de los anteriores porque presentan un perfil muy vertical y por detrás la horizontalidad y amplitud es mayor. Entre la base y la parte superior se encadenan las UTC 15, 24, 25, 35 o 45 según los sectores. Se trata pues de formas que no alcanzan los 25 m hasta otros que pueden alcanzar los 300 m. Su fisonomía aparece claramente condicionada por la estructura, bien por los planos de estratificación verticales; bien por la existencia de líneas de fractura que de manera nítida señalan el límite entre el mar y la tierra. Ejemplos de este tipo de acantilados son los de Picón (Ortigueira, A Coruña) y Augasantas (Ribadeo, Lugo). Litológicamente dominan las pizarras con buzamientos prácticamente horizontales o subhorizontales (Figura 5B)

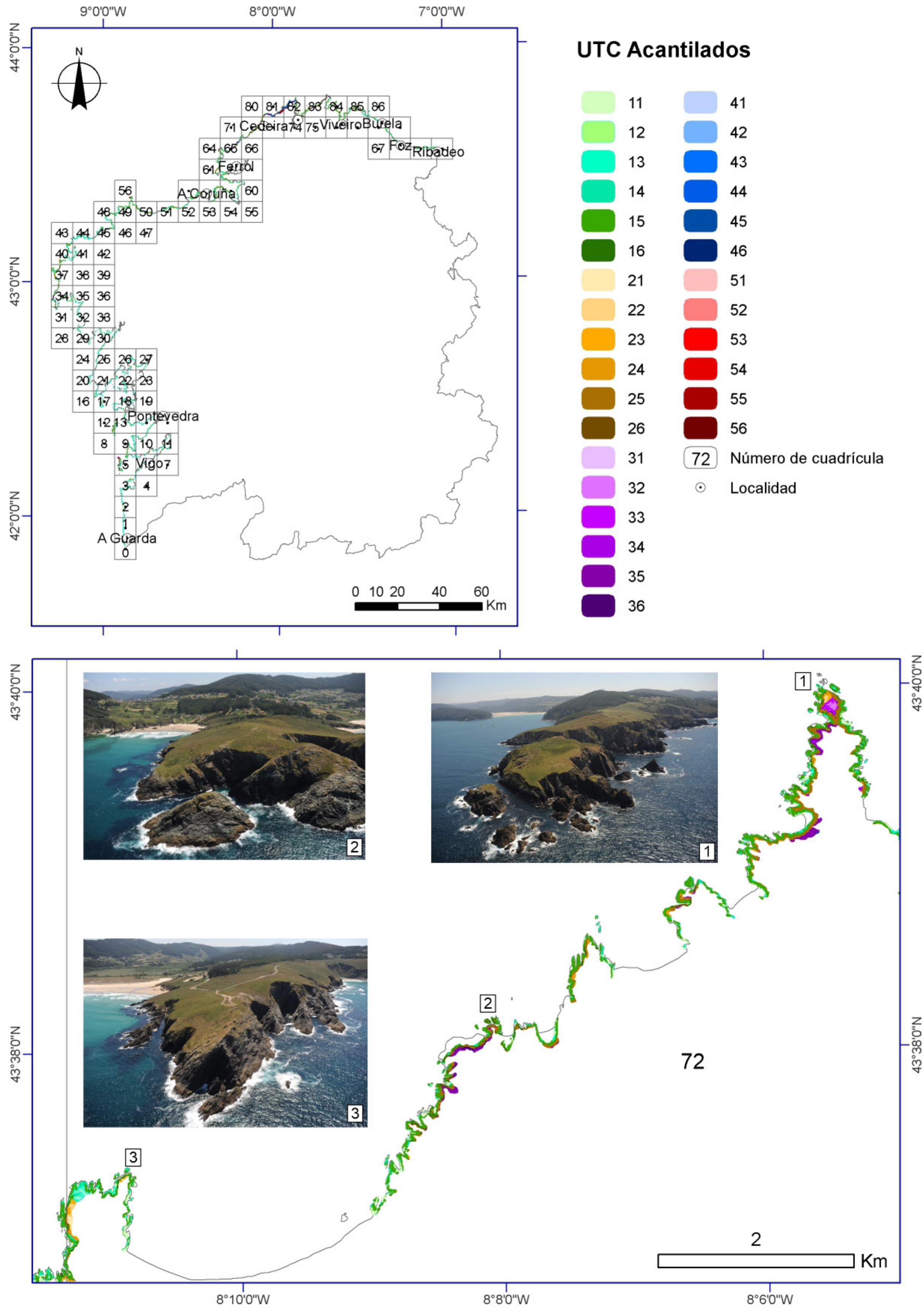

Figura 4. Tipos de acantilados (superior) y detalle de los acantilados de la cuadrícula 72 (inferior) con la localización de las imágenes, Fotos: POLGalicia (2011).

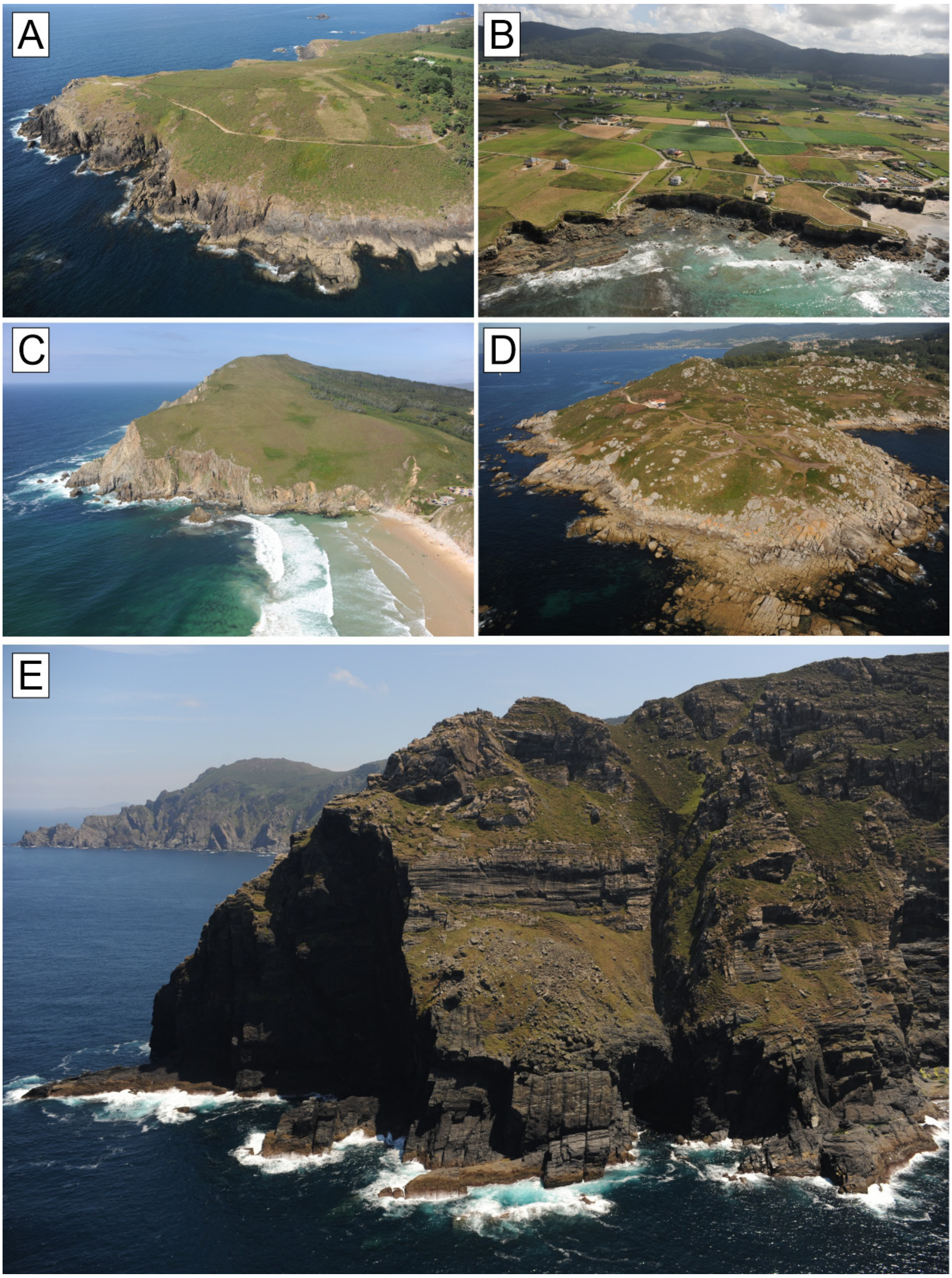

Figura 5. Ejemplos de tipos de costa en Galicia, A) Costa de Dexo (A Coruña); B) Augasantas (Lugo); C), Valdoviño (A Coruña); D) Bueu (Pontevedra); E) A Capelada (A Coruña), Fotos: POLGalicia (2011).

c) Acantilados vertiente. Este tipo de acantilados dibujan una línea continua desde la orilla del mar hasta parte alta de la vertiente. En ella se encadenan, según los sectores, las UTC 13, 14, 15, 24, 25 o 34 y no están asociados a planicies. Se podría diferenciar a su vez entre acantilados de vertiente suave o fuerte. Se han modelado fundamentalmente sobre rocas graníticas y son los más abundantes en las costas de Galicia (Figura 5C).

- **d) Acantilados convexos.** Son acantilados que dibujan un perfil convexo, generalmente compuesto por segmentos bien diferenciados en los que se combinan las UTC 13 y 14. Se trata de formas asociadas a las rocas graníticas como las que se puede observar en el entorno del Cabo Udra (Pontevedra) (Figura 5 D).
- **e) Grandes acantilados.** En este grupo se encuentran formas relacionadas más con la dinámica tectónica que con la acción del mar que únicamente les afecta en su base. Los mejores ejemplos se pueden ver en el sector costero que se prolonga desde Cabo Ortegal hasta la Ría de Cedeira, así como en los Montes das Lagoas (Narón-Ferrol), en la Costa da Vela (Cangas) o en las Illas Cíes. Las UTC se escalonan, con cambios importantes en la elevación lo que da lugar a segmentos en los que dominan las UTC 12 o 13, con otros en las que domina la 33 o 34 o incluso, como es el caso de los acantilados de A Capelada, las 44 o 56 (Figura 5E).

3.2.2.6. Las UTC en las playas de bloques (*coidos*)

Las UTC 12, 13, 14, 15 y 16 son las dominantes en las playas de bloques, que son formas muy singulares de las costas graníticas, caso del sector del Cabo Vilán (Camariñas, A Coruña), en el de Corrubedo (Ribeira, A Coruña) o en el tramo de costa que se alarga entre el Cabo Silleiro y A Guarda (Pontevedra) (Figura 6). La existencia de las UTC 14, 15 y 16 son indicativas de su carácter reflectivo que hace que a mayor tamaño de los bloques mayor es su pendiente. La tipificación de las playas de bloques se ha hecho por su diseño en planta diferenciando *coidos* longitudinales, en saliente simple, en doble saliente, en arco y en canal (Pérez Alberti y Gómez Pazo, 2019).

3.2.2.7. Las UTC en las playas

Las UTC que son dominante sen las playas son las 11, 12, 13, 14, 15 y 16, de manera especial las tres primeras mientras que las otras tres están asociadas a bermas, cúspides de playa o a zonas de contacto con sistemas de dunas (Figura 7). Y, como en el caso de las playas de bloques, la tipología hay que ponerla en relación con su diseño en planta. Se trata por lo general de arenales de pequeña extensión a excepción de los existentes en lugares muy concretos de la costa, caso de Corrubedo (Ribeira, A Coruña) o Carnota (A Coruña). El tratamiento mediante las UTC ha permitido diferenciar con claridad 8 tipos de playas (Figura 8): sobre tómbolo (1), de fondo de bahía (2), sobre flecha simple (3), sobre flecha doble (4), anclada en dos salientes rocosos (5), de desembocadura fluvial (6), sobre plataforma rocosa (7) y de fondo de saco (8).

3.2.2.8. Las UTC en las dunas

Las UTC 11, 12 y 13 son las más abundantes en los sistemas dunares, marcando con claridad el cambio en las ondulaciones existentes. Las UTC de los grupos 20, 30 y 40, se corresponden con dunas rampantes, caso del arenal de O Trece (Camariñas, A Coruña), Monte Branco (Ponteceso, A Coruña) o A Frouxeira (Valdoviño, A Coruña). En Galicia se han diferenciado 10 tipos de dunas (Pérez-Alberti y Vázquez Paz, 2011): dunas embrionarias o incipientes, colas de arena, lingüiformes, antedunas o primarias, piramidales, parabólicas, barjanoides, rampantes o remontantes, transversales y grises. La mayor parte de estas tipologías están muy degradadas (Figura 9). Las UTC costeras no permiten diferenciar todas las formas dunares, únicamente las de mayor tamaño, caso de las dunas incipientes, pinaculares, rampantes o parabólicas. Sin embargo, la combinación del sombreado, junto con las UTC y las curvas de nivel de 2 m ayuda a diferenciar no sólo el tipo de duna sino aspectos importantes de su topografía, caso de la existencia de corredores de deflación o de frentes de avance dunar (Figura 10A y B). Por otra parte, ayuda a visibilizar muy bien la existencia de distintos cordones separados por campos eólicos. Esto es visible, entre otros, en el caso del campo dunar de Valdoviño (Figura 10A).

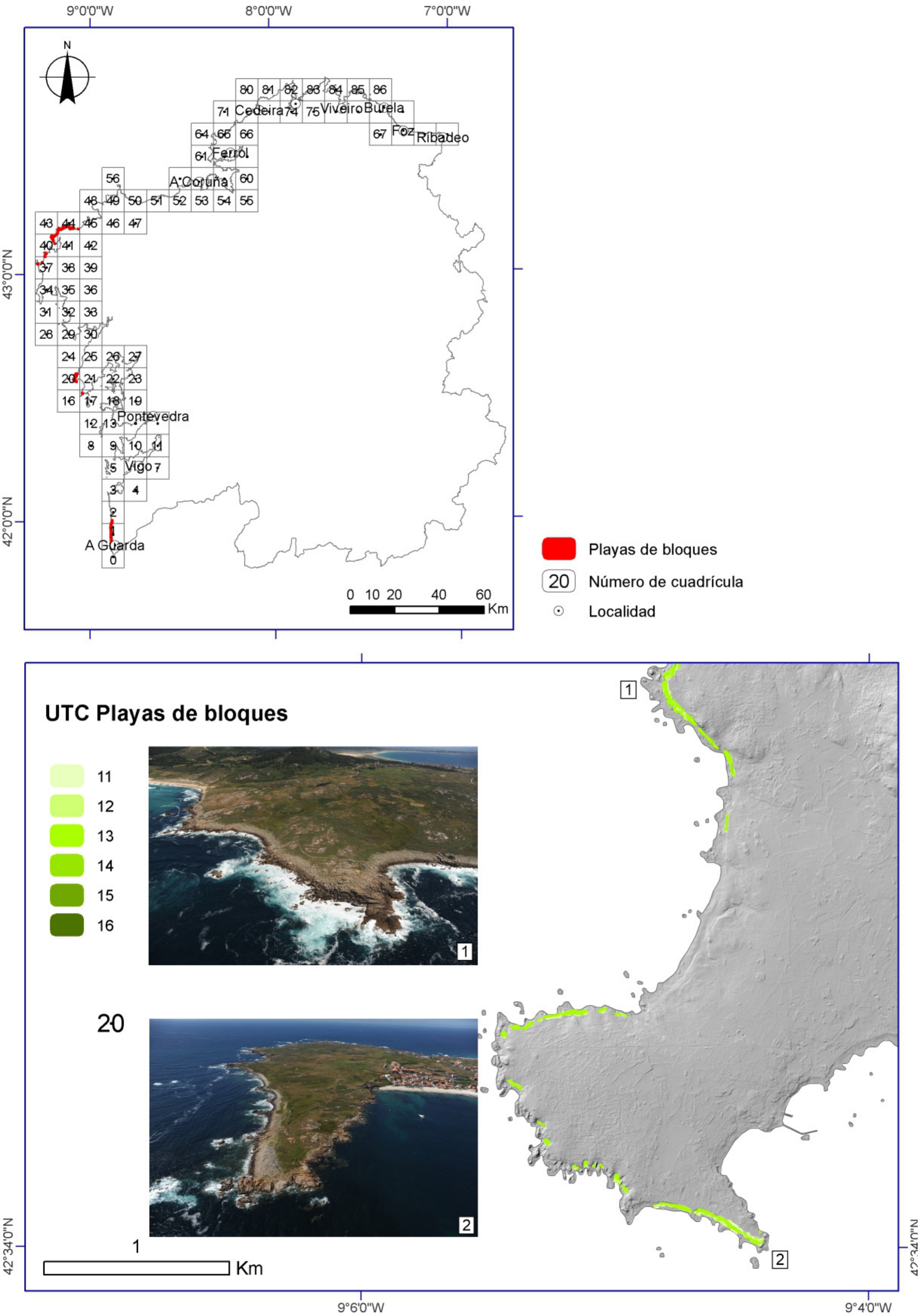

Figura 6. Distribución de las playas de bloques (superior) y UTCs en la cuadrícula 20, en el sector de Corrubedo (A Coruña) (inferior), Fotos: POLGalicia (2011)

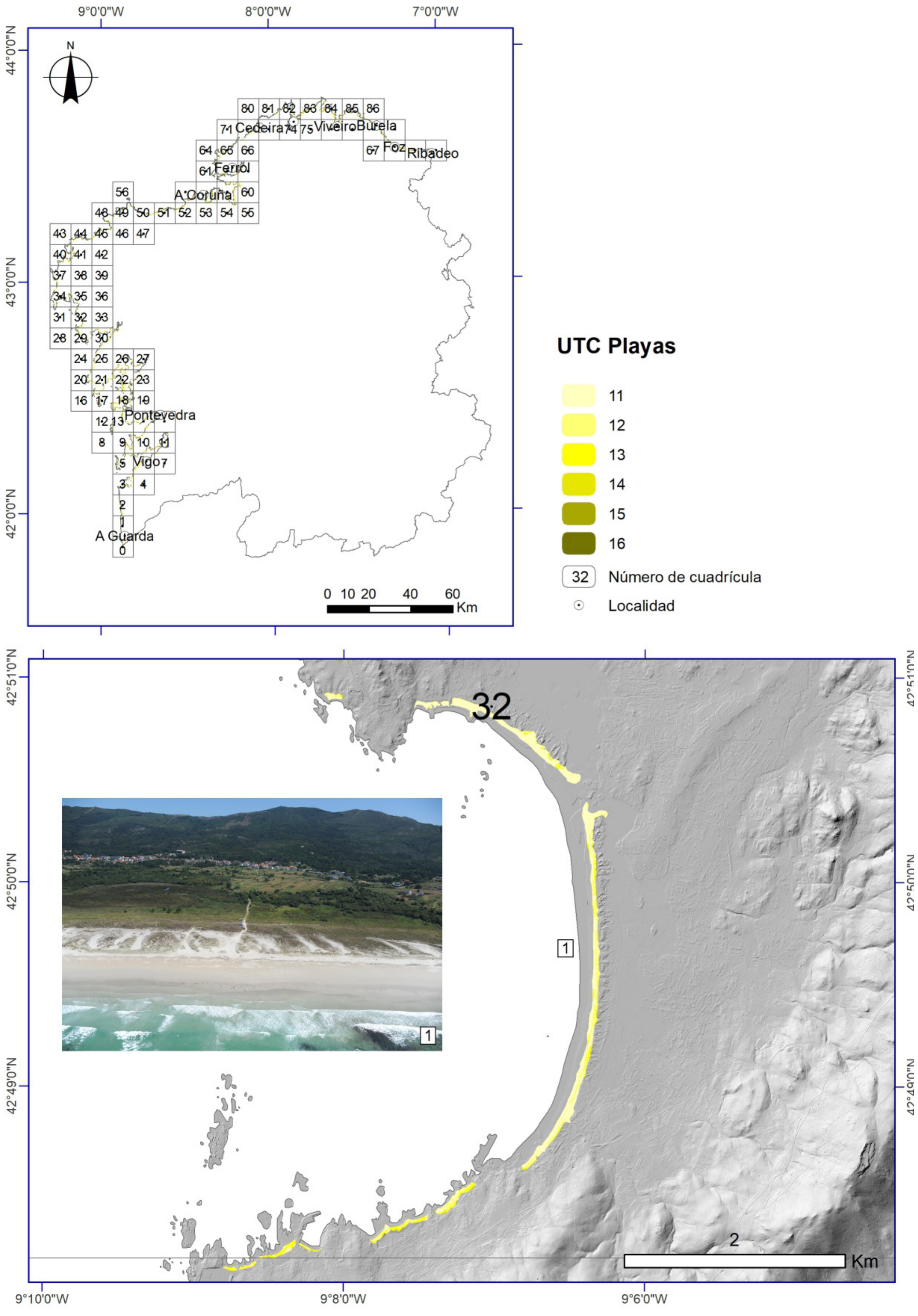

Figura 7. Distribución de las UTCs de las playas en la costa de Galicia (superior); detalle de la cuadrícula 32 (Carnota, A Coruña) (inferior), Foto: POLGalicia (2011).

Figura 8. Ejemplos de los tipos de playas diferenciadas en Galicia. 1) A Lanzada (Sanxenxo-O Grove, Pontevedra); 2) Corrubedo (Ribeira, A Coruña); 3) Ladeira (Baiona, Pontevedra); 4) Morouzos (Ortigueira, A Coruña); 5) Traba (Laxe, A Coruña); 6) Esteiro (Mañón, A Coruña); 7) Lariño (Carnota, A Coruña); 8) Arnela (Muxía, A Coruña). Fuente: PNOA (2011), IGN (2021).

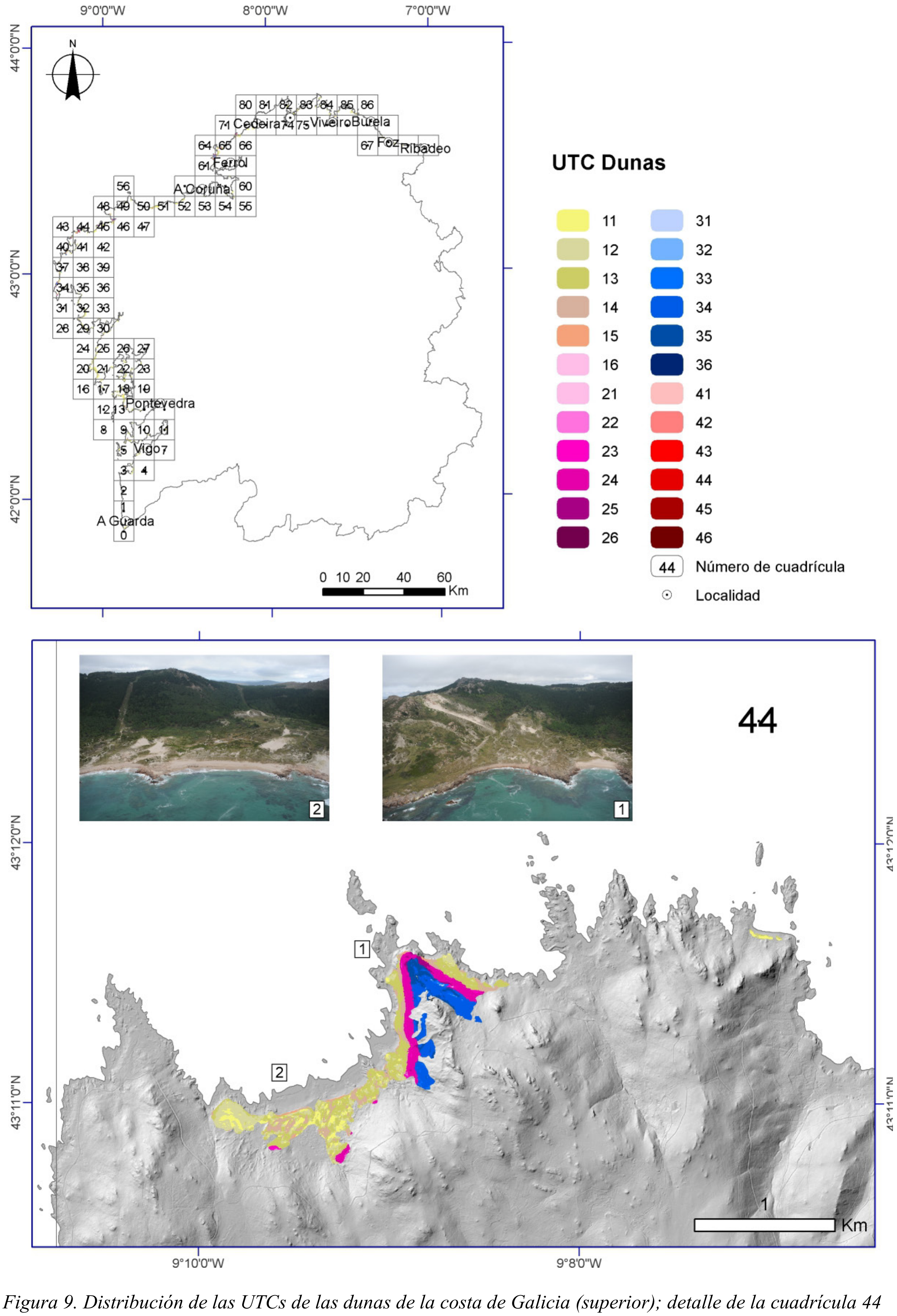

Figura 9. Distribución de las UTCs de las dunas de la costa de Galicia (superior); detalle de la cuadrícula 44 (Camariñas, A Coruña) (inferior), Fotos: POLGalicia (2011).

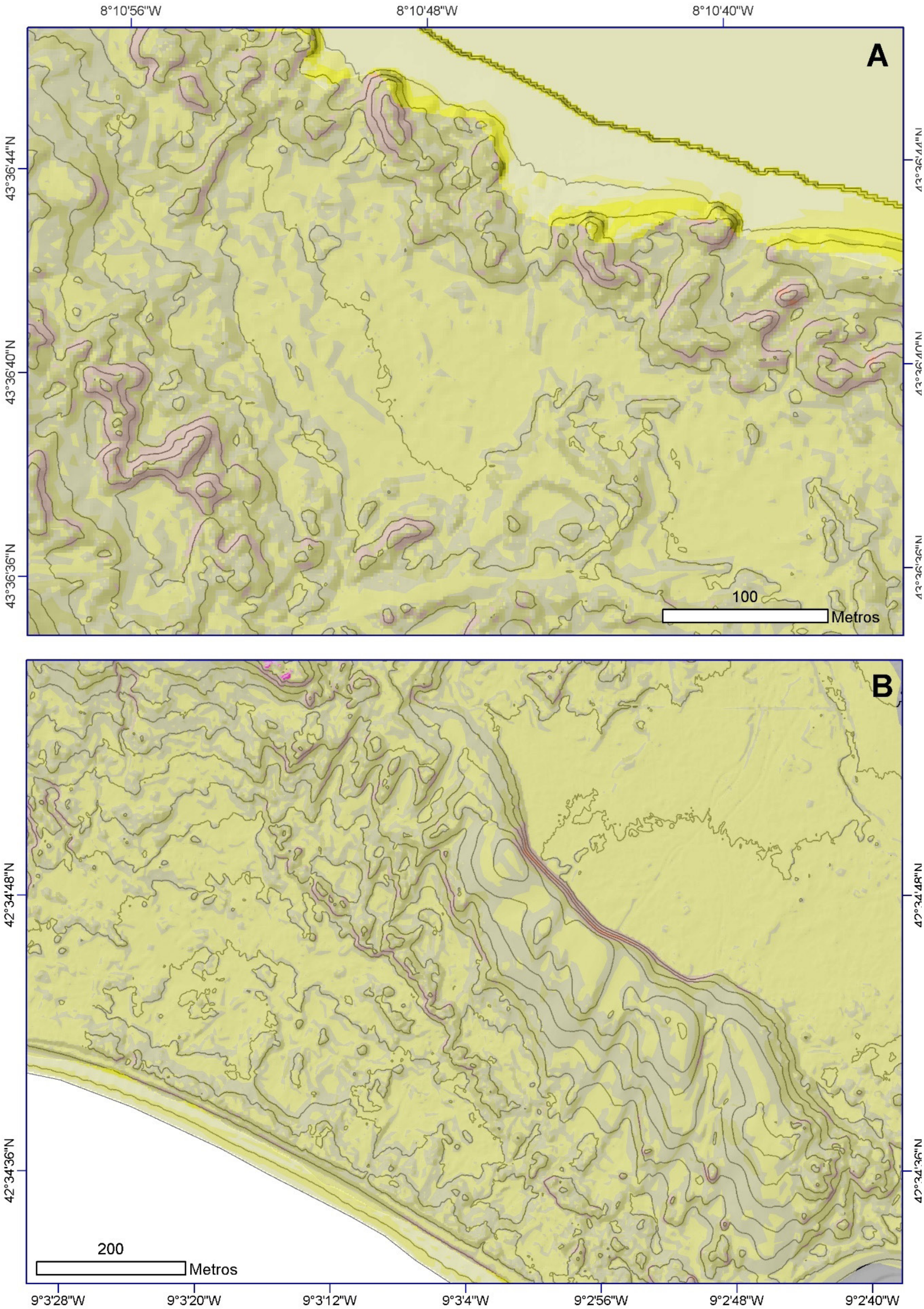

Figura 10. Combinación del sombreado, las curvas de nivel con 2 m de intervalo y UTCs, A) Campo dunar de Valdoviño (A Coruña); B) Duna de Corrubedo (A Coruña).

4. Conclusiones

1. Hay que partir de la idea de que cualquier tipo de clasificación de tipos de costa presenta problemas y es discutible.
2. La combinación de múltiples variables (elevación, pendiente, orientación, litología o grado de estabilidad) dificulta llevar a cabo una clasificación simplificada lo que motiva la necesidad de seleccionar variables.
3. En la presente investigación se ha optado por una cartografía manual que delimitase las áreas ocupadas por los diferentes sistemas costeros (acantilados, playas de bloques, playas y dunas) combinada con un análisis mediante SIG para diferenciar los distintos tipos existentes en cada uno de ellos.
4. La creación de 30 Unidades Topográficas Costeras (UTC) ha permitido caracterizar los tipos de costa proporcionando un análisis más objetivo de la realidad existente en cualquier sector de las costas españolas en general o en las gallegas en particular.

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HISTORICAL MORPHOLOGICAL CHANGES (1956-2017) AND FUTURE TRENDS AT THE MOUTH OF THE EBRO RIVER DELTA (NE SPAIN)

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ABSTRACT. The present work focuses on the recent morphological changes recorded in the Ebro River delta, by using aerial photographs in the last six decades and by analyzing changes in the main constitutive features through geomorphological maps. Geomorphological maps of the years 1956 and 2017 are here presented. The results obtained give very valuable clues about the recent trends of the river delta mouth, which can be used to predict future coastal changes to be expected in the following decades. In this sense, by analysing changes in the surface by means of the geomorphological maps together with a shoreline analysis, a differential behavior has been described at both sides of the river mouth: the left side, El Garxal wetland, shows an accretionary trend with rates reaching +40 m/year, while the right side, San Antonio Island, shows erosive trends of more than -20 m/year. This last side also presents a surface reduction of more than 50 ha in the last 60 years. These results suggest that, approximately by the year 2050, the emerged San Antonio Island may disappear if shoreline retreat trends are maintained, making El Garxal exposed to easterly storms, the main erosive dynamic processes in this zone and, therefore changing the entire configuration of the Ebro River delta mouth in the upcoming years. Despite possible solutions have been described in recent works, they may not contribute to a total recovery of the most natural part of the Ebro Delta. Urgent management plans are required to attempting to slow or reverse these trends, otherwise one of the most valuable ecosystems of the delta could disappear.

Cambios morfológicos históricos (1956-2017) y tendencias de futuro en la desembocadura del delta del río Ebro (NE de España)

RESUMEN. El presente trabajo analiza los cambios morfológicos registrados recientemente en el delta del río Ebro, utilizando fotografías aéreas de las últimas seis décadas y examinando los cambios principales a través de mapas geomorfológicos. Se presentan mapas geomorfológicos de los años 1956 y 2017. Los resultados obtenidos dan pistas muy valiosas sobre las tendencias recientes de la desembocadura del río, que pueden utilizarse para predecir los futuros cambios costeros que se esperan en las próximas décadas. En este sentido, mediante el análisis de los cambios en los mapas geomorfológicos junto con un análisis de la línea de costa, se ha descrito un comportamiento diferencial a ambos lados de la desembocadura: el lado izquierdo, el humedal de El Garxal, muestra una tendencia a la acreción con tasas que alcanzan +40 m/año, mientras que el lado derecho, Isla San Antonio, muestra tendencias erosivas de más de -20 m/año. Este último sector también presenta una reducción de superficie de más de 50 ha en los últimos 60 años. Estos resultados sugieren que, aproximadamente para el año 2050, la isla San Antonio actualmente emergida podría desaparecer si se mantienen las tendencias de retroceso de la línea de costa, dejando a El Garxal expuesto a las tormentas del este, los principales procesos dinámicos erosivos en esta zona. Se cambiaría, de esta forma, toda la configuración de la desembocadura del delta del río Ebro en los próximos años. A pesar de que se han descrito posibles soluciones en trabajos recientes, es posible que no contribuyan a una recuperación total de la parte más natural del Delta del Ebro. Se requieren planes de manejo urgentes para intentar frenar o revertir estas tendencias, de lo contrario uno de los ecosistemas más valiosos del delta podría desaparecer.

Key words: Ebro River delta, Coastal retreat, Cartography, Geomorphology, Coastal management.

Palabras clave: Delta del río Ebro, Retroceso de costa, Cartografía, Geomorfología, Gestión de costas.

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1. Introduction

Present trends and rates of shoreline change are commonly associated to a combination of geological factors, variations in sediment supply and fluctuating climate (Hapke *et al.,* 2013). Sea level trends also play a determinant role in shoreline evolution, especially on low, sedimentary coasts (Dyer *et al.,* 2021). In this sense, it is broadly accepted that a medium to long-term sea-level rise will increase long-term erosion rates (Zhang *et al.,* 2004). Most of the European sandy shores are presently affected by erosion. Although coastal erosion is a natural process, very often it is triggered or intensified by human practices (Pranzini and Williams, 2013). A very common cause of beach erosion is the disruption of sediment fluxes from rivers to the sea (Abeyta *et al.,* 2017), due to sediment retention in reservoirs, land reclamation, agricultural practices, coastal urbanization and coastal engineering works (Sherman *et al.,* 2002).

In the case of Spain, 35% of the Mediterranean coast of the Iberian Peninsula is protected and adapted to climate change (European Commission, 2009). However, a number of places along this coast are very vulnerable to sea level rise and sediment retention in the fluvial catchments, which historically has produced shoreline erosion (Semeoshenkova and Newton, 2015). This problem is particularly remarkable the case of deltas, which very often are densely populated and highly vulnerable areas (Wolters and Kuenzer, 2015).

The Mediterranean deltas constitute a particular case, where historical human practices have transformed estuaries into deltas over the past 2000 years and have conditioned their morphological evolution from initial progradation to later erosion along this period (Cooper and Alonso, 2006). This trend has been recorded by deltas like the Po and Nile cases, where human perturbation of catchments during Roman times triggered erosion. After a short progradation period during the Little Ice Age, the last two centuries have been characterized by sediment flux reduction due to catchment reforestation, sediment retention in reservoirs, fluvial regulation and dredging. This situation of progressive delta degradation will be exacerbated by sea level rise, which can lead to delta destruction (Anthony *et al.,* 2014).

Different previous approaches have been made on the recent Ebro Delta morphological evolution (Jiménez and Sánchez-Arcilla, 1993; Ibáñez *et al.,* 1997; Rodríguez-Santalla *et al.,* 2011b; Somoza and Rodríguez-Santalla, 2014; Ramírez-Cuesta *et al.,* 2016). However, most of them do not present any consistent proposal of present trends of morphological change and modifications expected to occur in the near future. Only a very recent study ordered by the Spanish Government analyses such a problem with certain detail (CEDEX, 2021), although without considering any possible sediment by-pass processes within the deltaic system, despite the fact that this process had been already evidenced by Ramírez-Cuesta *et al.* (2016). Obviously, the possible trends will also be conditioned by the climatic and sea level behavior, an aspect already considered by Romagosa and Pons (2017).

The present work focuses on the recent morphological changes recorded by the Ebro River delta, by using aerial photographs taken in the last six decades. The geomorphological maps obtained after them give very valuable clues about the recent shoreline trends of the delta, which can be used to predict future coastal changes to be expected in the following decades. The results are fundamental for facing any kind of recuperation plan and/or management program along the river delta coast.

2. Study zone

2.1. Geographical background

The Ebro River delta mouth (Fig. 1) is located on the Mediterranean coast of the Iberian Peninsula and is one of the most important deltas in the western Mediterranean (Ibáñez *et al.,* 1997). It is also one of the six greatest rivers of the Iberian Peninsula and the only one of them draining to the Mediterranean Sea. The extension of the emerged area is 325 km^2, which represents only a 15% of the total area of the delta (Rodríguez-Santalla and Somoza, 2019). The elevations do not exceed 5-6 m and approx. 50% of the total surface lies below 0.5 m above Mean Sea Level (MSL; Genua-Olmedo, 2017). The current shape of the Ebro Delta can be described as two hemideltas separated by the main river channel (Fig. 1). In the left side of the main channel, the development of the beach and dune ridges led to the formation of a submerged meadow (Garxal), sheltered by the sandy barrier.

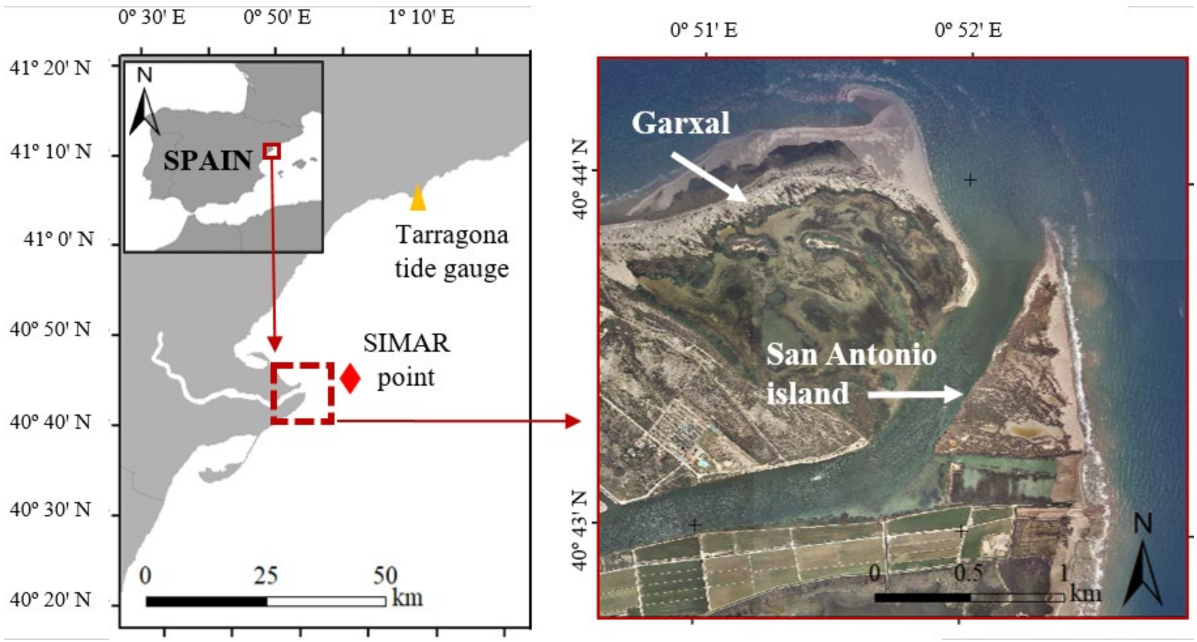


Figure 1. Location of the study area. The SIMAR point and the tide gauge's positions from which the hydrodynamic data have been extracted are indicated.

Additionally, the average subsidence of the delta was estimated in 1 to 3.2 mm/year in recent decades (Ibáñez *et al.,* 1997). The medium-long term effects of this subsidence together with the relative sea level rise (RSLR) estimated for this area (1-2 mm/y), result in an effective RSLR between 3 and 6 mm/y in the areas close to the mouth (Barnolas, 1995; Day *et al.,* 1995; Ibáñez *et al.,* 1995; Verdaguer, 1983). Ibáñez *et al.* (2010) described that floods and river overflowing enhance vertical accretion, minimizing the effects of the RSLR in the mouth complex. However, recent strong storm episodes, like Gloria Storm in January 2020, produced severe damage and intense erosion. The increasing frequency of such energetic events could accelerate the rate of shoreline retreat (Vousdoukas *et al.,* 2016), which could lead to a severe delta modification (Fig. 2).

Apart from this, the ecological values of the habitat diversity on the Ebro River estuary (beaches, dunes, wetlands, coastal lagoons, etc.) coexist with an intensive economic activity mainly focused on rice crops. The singularity and relevance of the Ebro delta led to the declaration as Natural Park in 1983. Besides, some zones are protected as Biosphere Reserve, Site of Community Interest and Special Protection Areas for Birds zones due to the great biodiversity of species and ecosystems, as well as Natura 2000 Network area. All these ecological aspects significantly increase the vulnerability and interest in studying the recent evolution and possible future trends of the delta shores.

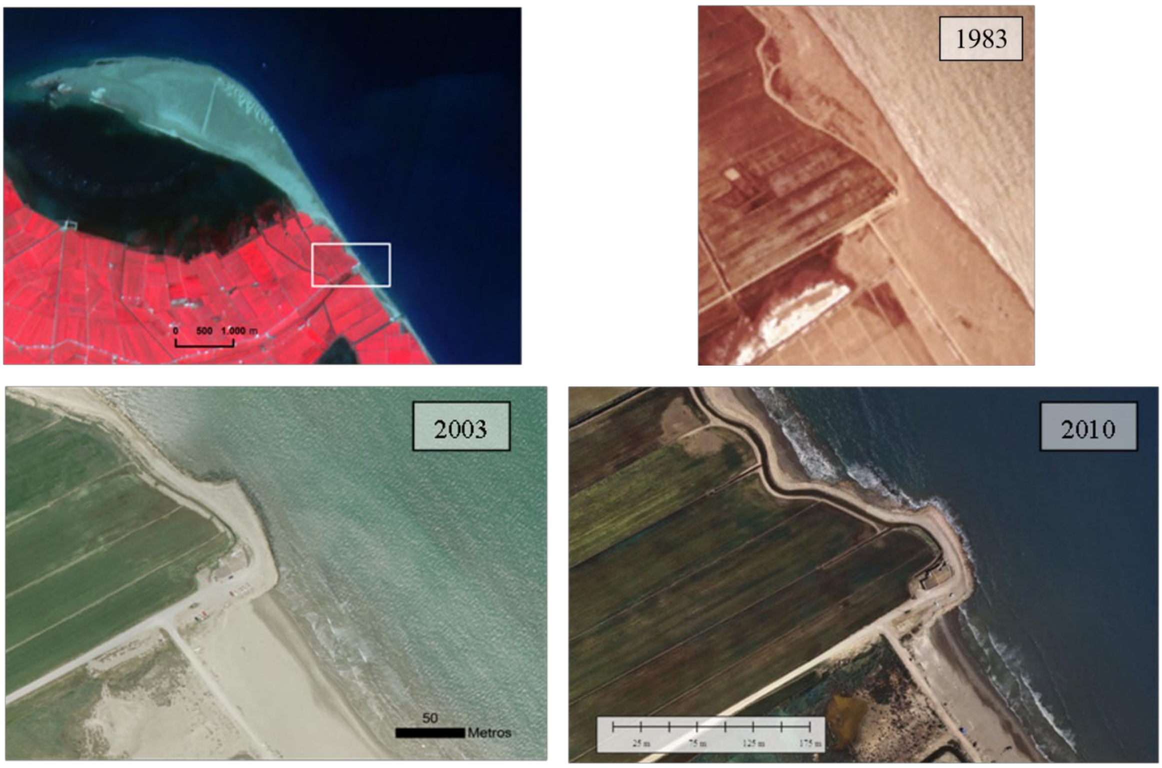


Figure 2. Examples of a strong erosion in a coastal point where a restaurant facility (Los Vascos) is located.

2.2. Historical background

The Ebro Delta began to develop at the end of the sea level post-glacial eustatic rise (Maldonado, 1986, 1977), and its shape is the results of the advance of successive deltaic lobes that have progressed radially (see Rodríguez-Santalla *et al.,* 2011a, for more information about Ebro river Delta formation). In accordance to previous conclusions achieved by Canicio and Ibañez (1999), and after applying a number of mathematic models to the morphological evolution of the delta, Nienhuis *et al.* (2017) concluded that the main recent historical progradation occurred 2100 years ago. This process was followed by river avulsions that favoured the development of the Northern (El Fangar) and Southern

(La Banya) spits between 900 and 300 years BP. The current shape of the mouth is linked to a change on the river flow in 1947 (Fig. 3). Consequently, the northern inlet or Gola Norte (Garxal) developed, which constitutes the study area of the present work. The two mouths coexisted until 1956, when the eastern mouth, named Gola Este, or Cap Tortosa, was naturally closed (Guerrero *et al.,* 2018).

The Ebro River presents the largest discharges in Spain (426 m^3/s), with a marked variability between dry and wet years (Movellán, 2004; Rodríguez-Santalla *et al.,* 2011a; Genua-Olmedo, 2017). Nevertheless, the river input of sediment has been drastically reduced by the construction of dams (e.g. Flix [1948], Mequinenza [1966] and Ribarroja [1967] dams, particularly) (Rodríguez-Santalla and Somoza, 2019). The direct effect of dam constructions in the Ebro Delta is the interruption of the sediment transport, causing morphological changes downstream, as well as modifications in the associated habitats (Guillén and Palanques, 1997; Kondolf, 1997).

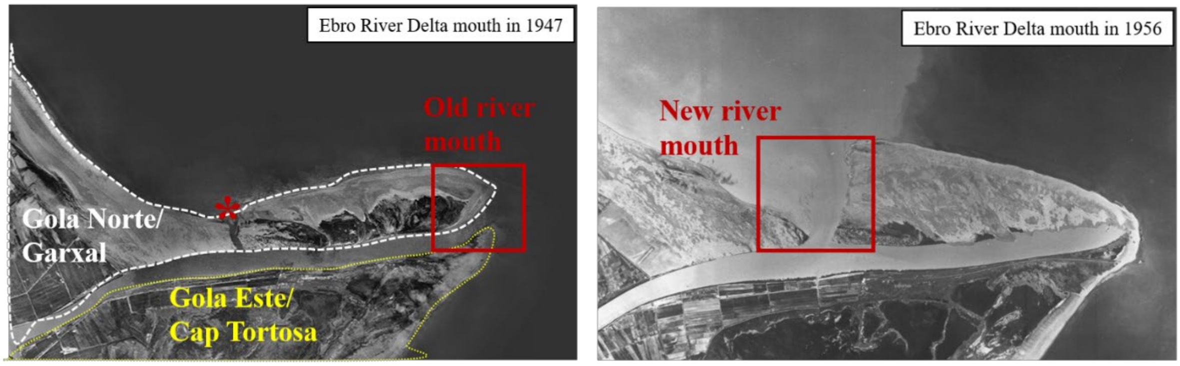


Figure 3. Aerial photographs showing the major changes recorded by the Ebro River Delta mouth between 1947 and 1956. Old and new opened river mouths are indicated (red boxes).

2.3. Sea climate, hydrodynamics and sea level fluctuations

The Ebro Delta has a microtidal regime with a Mean Spring Tidal Range (MSTR) of about 0.20 m (Franquet Bernis *et al.,* 2017), what gives a greater importance to the meteorological tide component (surges). The combined effect of meteorological and storm surges has a strong erosive effect both on the coast and on the dune fields of this area (Sánchez, *et al.,* 2011a). Originally, the Ebro Delta was dominated by fluvial sediment deposition remodelled by waves (Sánchez-Arcilla and Jiménez, 1997). Currently, it is a wave-dominated system (Rodríguez-Santalla and Somoza, 2019) where waves come mainly from three directions: E, S and NW (Fig. 4a). The East component is the dominant direction due to its frequency and energy, and in fact it is the responsible for the main transport of sediments in the mouth of the Ebro River. Waves and currents are strongly controlled by wind dynamics in this area. The wind is an important component within this area, with strong events during spring, matching with E wave events (Fig. 4b; Cateura *et al.,* 2004). Nevertheless, the strongest winds come from NW (Mestral winds), corresponding to wave calm periods (Jiménez *et al.,* 1997). Lastly, prevailing littoral drift in the N hemidelta follows a NW direction, while in the S hemidelta it follows a N-S direction, highlighting the differential behaviour of these too close areas.

Climatically, this zone has a littoral Mediterranean climate, with moderate temperatures during winter and sub-arid weather in summer, because of high temperatures and low precipitations. The thermoregulatory effect of the sea softens the temperatures in the coastal strip throughout the year, with average values between 15.5ºC and 17ºC, and an average rainfall between 500-600 mm/year (Sánchez *et al.,* 2011a).

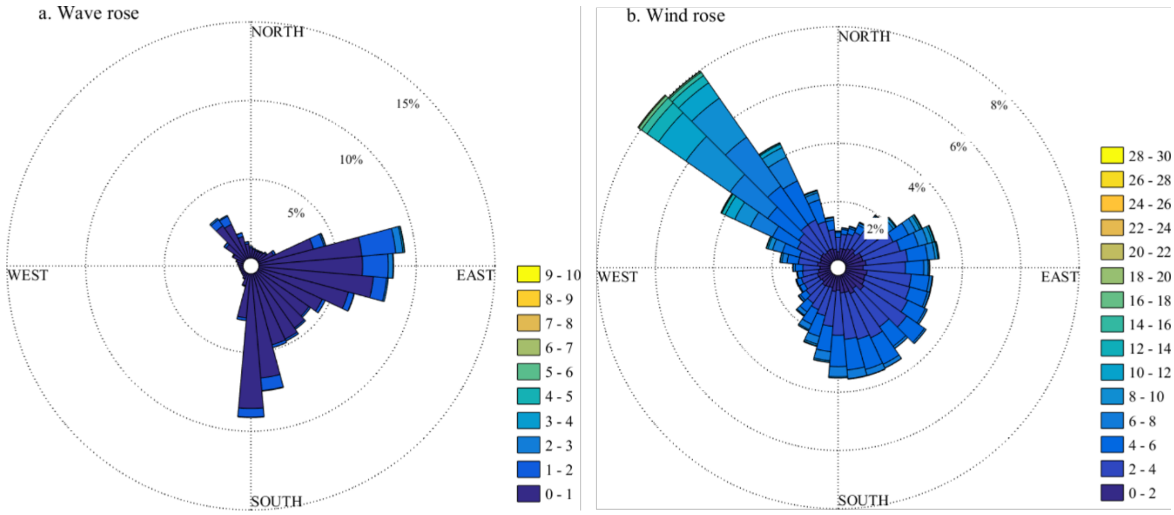


Figure 4. (a) Wave and (b) wind roses extracted from the SIMAR point (SIMAR 2095129; 0.92ºE, 40.75ºN). See Figure 1 for location of the SIMAR point. Data provided by the National Port Authority (2019).

3. Methodology

To cope with the main objective of the present work, the Ebro Delta river mouth has been mapped by means of orthophotographs of the years 1956 and 2017, obtained from the Spanish National Plan of Aerial Orthophotography (PNOA). Besides, data from a previous work (Aranda *et al.,* 2020) have been used to obtain a more extended database about the evolution of this system.

Stereoscopic photo-interpretation techniques were carried out for the 1956 images and then scanned and georeferenced in ArcGIS 10.2, through a second-order polynomial function, using at least 15 well distributed control points on every image. The accuracy of the georeference process was determined by calculating the total Root Mean Square Error (RMSE), less than 0.5 m in all cases. The 2017 cartography was developed on-screen digitization using visual image interpretation of different elements, i.e. colour, texture and plant association (Arveti *et al.,* 2016). The geodetic reference system used was the European Terrestrial Reference System 1989 (ETRS89-H30). Every feature was mapped by using the Habitat Digitizer Tool (NCCOS, 2003) extension to ArcGIS (ESRI©). Each feature was recorded with a unique ID, according to the hierarchical scheme previously mentioned. The maps were developed with a minimum scale of 1:2500, to outline small features with enough relevance to have a role in the coastal dynamics. In addition, a minimum mapping unit (MMU, Stehman and Czaplewski, 1998) was set, so areas lower than 100 m2 were not mapped. The main active processes were also mapped based on reviewed literature. Thus, the main ebb and flow directions responsible for the development of the main features were identified.

Once defined and mapped every unit together with the main hydrodynamic processes, the changes in the total surface (ha) of each year were calculated, supplementing the data with the results from the previous work abovementioned, in which the years 1984, 1994, 2003 and 2012 were also mapped, to obtain a larger temporal data series.

Besides, due to the strong changes recorded in the coastal configuration during recent years and reflected in the evolutionary maps of San Antonio Island, the shoreline evolution was calculated for two different periods: long term (1983-2019; 1956 was not used as first year of the shoreline evolution study period as the shape was completely different between this year and 1983 and the calculations could not be made), and short-term (2009-2019), to quantify if the system trends accelerated in these last years. The years selected differs from the orthophotograph analysis. The shoreline evolution also included the shoreline position in 2019, as it is the last available orthophotograph. The dune foot was selected as a proxy for the identification of the shoreline. It was based on slope differences, changes in the colour of the image and the onset of vegetation colonisation in embryo dunes (Del Río, 2007; Ojeda-Zújar, 2000). Once extracted the shorelines of the different years, the quantification of change rates was performed in ArcGIS extension Digital Shoreline Analysis System (DSAS 4.3; Thieler *et al.,* 2009). The process consists on defining a baseline, as parallel as possible to the digitized coastlines and as straight as possible in order to avoid irregularities. Both the coastlines and the baseline were used as input data in the DSAS extension. Then, the statistical output was represented in transects projected perpendicular to the baseline and evenly spaced (Fig. 5). The distance between transects was set at 25 m. The evolution of the shoreline was defined using the Lineal Regression Rate (LRR; m/year). Finally, four sectors (shaded areas in Fig. 5) regularly spaced were used to quantify the shoreline evolution. Three profiles were selected before and after the central profile in order to evaluate the evolution by sectors and not at fixed points, thus being more representative of the trend of the system. In a later phase, these data were represented and projected in order to quantify, from a simple linear regression, future trends and the possible reduction, increase or disappearance of San Antonio Island.

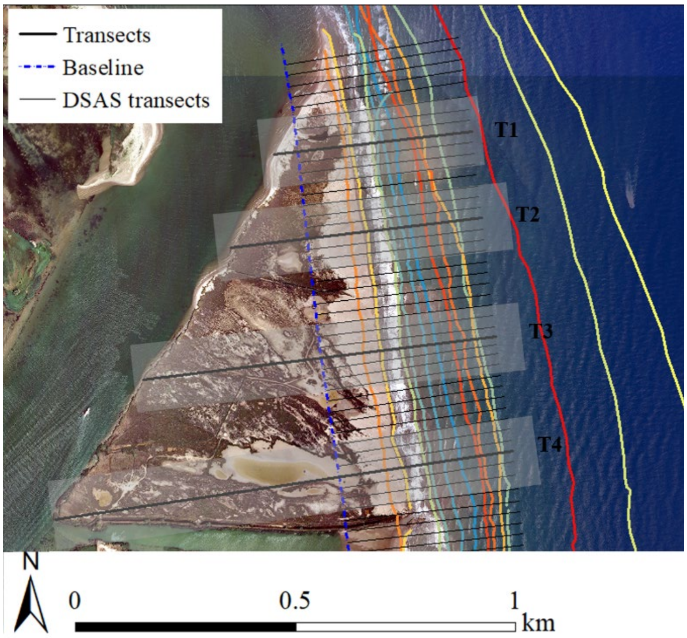


Figure 5. Example of the transects used to calculate the LRR (DSAS transects), the baseline and all the digitized shorelines for the San Antonio island changes quantification (coloured lines).

4. Results and discussion

Retrospective studies are necessary to understand processes controlling coastal systems dynamics. For that, aerial orthophotographs libraries are needed. The quality of the aerial orthophotos is an important issue as it may limit the accuracy on the identification of the features limits when mapping. The main errors come from the quality of the image and the bias of the analyst (Olofsson *et al.,* 2014). Despite that, it is not possible to make an accuracy assessment of historical orthophotographs, so that it results compulsory to accept sources of errors greater than those obtained with current methods. The data obtained from orthophotographs such as that of 1956 proportionate valuable information about the evolution of the system that, without doubt, must be taken into account when defining current and future trends, but results must be interpreted with caution.

The Ebro River Delta mouth recorded great changes between 1956 and 2017 (Fig. 6). The first available aerial photo of the zone (1947; Fig. 3) shows the old mouth of the river, presently located in the Southern part of the San Antonio Island (old channel in Fig. 6). The current active mouth derives from the breakage of the old channel on its left side, as a consequence of a river flooding episode in 1937 (Rodríguez-Santalla *et al.,* 2011b). In 1956, the original mouth was already closed and the active mouth opened very widely, initiating the shifting toward the present shape (Fig. 6). Huge sand sheets covered San Antonio Island in 1956, which could be considered as a complex sandy system with a virtual absence of muddy features, except for the proper deltaic plain. As it can be observed in the comparison between both geomorphological maps, this zone underwent important eco-geomorphological changes during the last 60 years. The most evident one is the development of beach and dune ridges forming a sandy barrier in the left part of the river mouth, and El Garxal wetland, a submerged meadow sheltered by the sandy barrier and open to the main channel (Fig. 6). During the study period, the main littoral drift transported important inputs of sediment into El Garxal wetland (main changes in the 80's according to Aranda *et al.,* 2020), enabling the formation of new recurved spits (black dotted arrows in Fig. 6). These spits have slowly connected to land with the consequent formation of a new coastal lagoon in recent years. Regarding the right side of the river mouth, i.e. the San Antonio Island, the main changes are related to a reduction in the surface of this sandy system since it has been strongly eroded in the last 60 years on its eastern side.

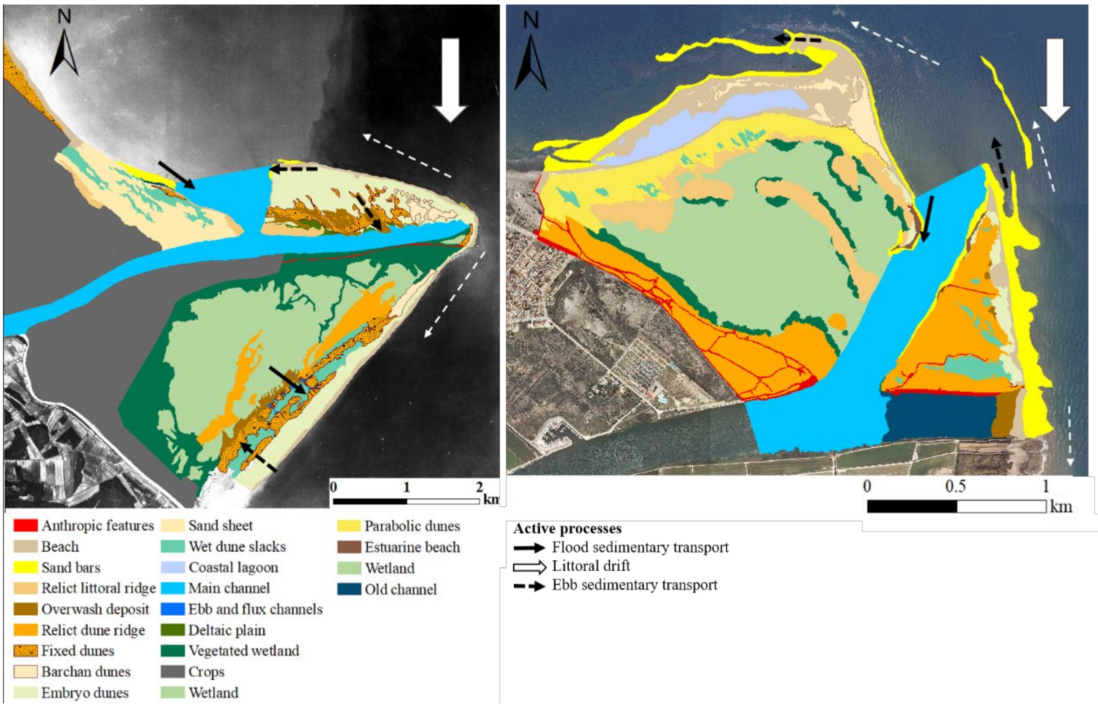


Figure 6. Geomorphological maps of the Ebro River Delta mouth in 1956 (left image) and 2017 (right image), with indication of the main prevailing processes. Dotted white arrows indicate local littoral drifts.

The total Ebro River delta mouth shows a decrease of a 10 % on its surface compared to 1984 (Aranda, 2021). This trend has been fuelled by the strong changes associated with the abovementioned erosion of San Antonio Island, which shows a decrease in the surface of more than 50 ha (Fig. 7). This process equates to erosion rates reaching almost 20 m/year (Fig. 8), which has been only partly counterbalanced by the growth of the sandy barrier on the left side of the estuary (Fig. 9). In this sense, the evolutional geomorphological maps reveal that part of the sediment forming new sandy hooks on the left side could come from the breakage of the sandy intertidal spits of the north part of San Antonio Island. This means that an active bypassing of sediment is occurring between both sides of the river mouth. In any case, other processes not included in the present work complicate the overall scheme here presented (i.e. the limitation and increasing scarcity of sediment inputs from the river, its intermittency, and the action of the NW winds, which generate currents that can redistribute part of the sediment input; Rodríguez-Santalla *et al.,* 2021). These results must be carefully interpreted, and a deeper study focusing on external factors (i.e. waves, winds, storms, river discharges…) is also needed. Furthermore, the huge erosion of this part of the river mouth is subject to temporary variations, so the trend may be accelerated or even decelerated in the future, depending on those external factors.

The erosive trend of San Antonio Island has increased in recent years, which is clearly noted in its short-term evolution (Fig. 10), with constant erosion in the northern part that becomes more differential than the long-term towards the south, where the old mouth was located. Besides, it can be noted an increasing erosional trend at the south of the former river mouth, and a decrease in the erosional behaviour in the northern part in the last 10 years. If this trend continues, approximately in 2050 the San Antonio Island could disappear (according to Fig. 7). In such a case, El Garxal wetland (left side) would be exposed to energetic wave events arriving from the East, which would most likely cause its retreat and that of the associated features. As a consequence, the current hemi-deltas of the river mouth complex would change their shape completely.

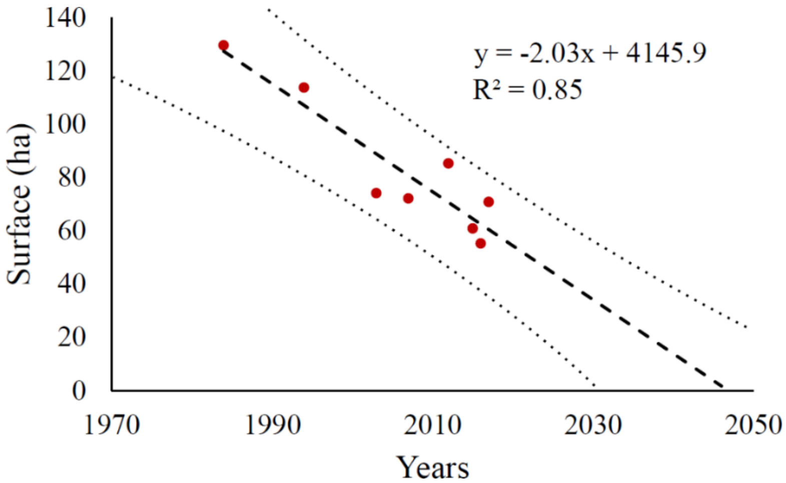
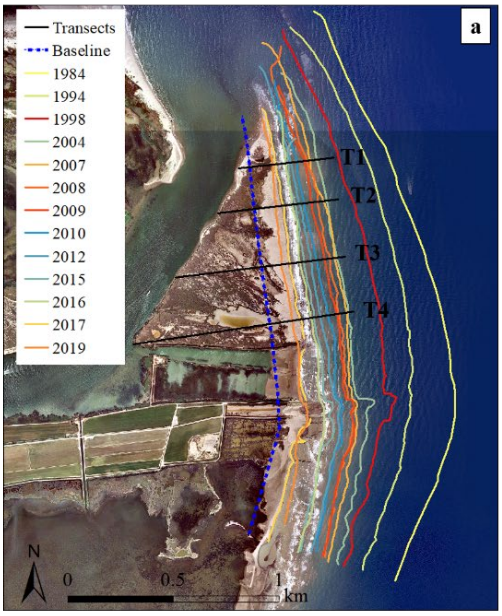
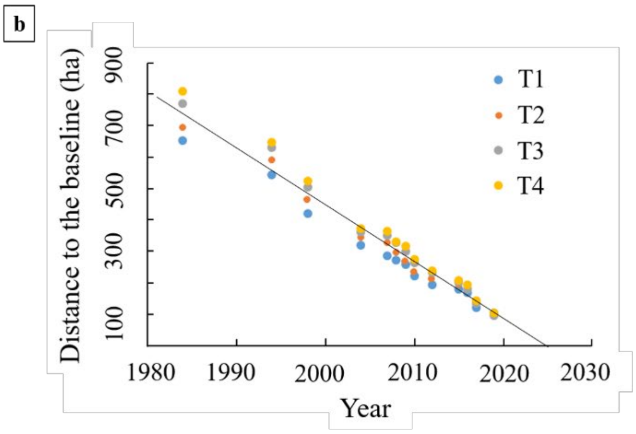


Figure 7. Evolution of the surface (ha) of the San Antonio Island during the period 1984-2017, showing a virtual disappearance (0 ha) around 2050 according to linear regression equation (R^2=0.84). Dotted lines show the 95% confidence intervals.





c

	Distance (m)	LRR_1 (m/y)	t_1 (y)	LRR_2 (m/y)	t_2 (y)
T1	160.514	-13.4271	11.95 (2032)	-15.6785	10.23 (2031)
T2	278.2197	-15.0385	18.50 (2039)	-17.0543	16.31 (2037)
T3	504.489	-18.4914	27.28 (2048)	-18.8728	26.73 (2047)
T4	760.772	-19.4057	39.20 (2060)	-19.6171	38.78 (2059)

Figure 8. (a) Image of the 4 selected transects to evaluate the LRR and the digitized coastlines. (b) Distance from the digitized coastlines to the baseline, measured along each selected transect. y = -17.36x + 35155 (R^2= 0.98). (c) Distance of every transect (m) from the baseline to the western part of San Antonio Island; LRR_1: short-term evolution for every transect; t_1: expected time in which the width of the transect will disappear according to short-term rates (calendar years in brackets); LRR_2: long-term evolution for every transect; t_2: expected time in which the width of the transects will disappear according to long-term rates (calendar years in brackets).

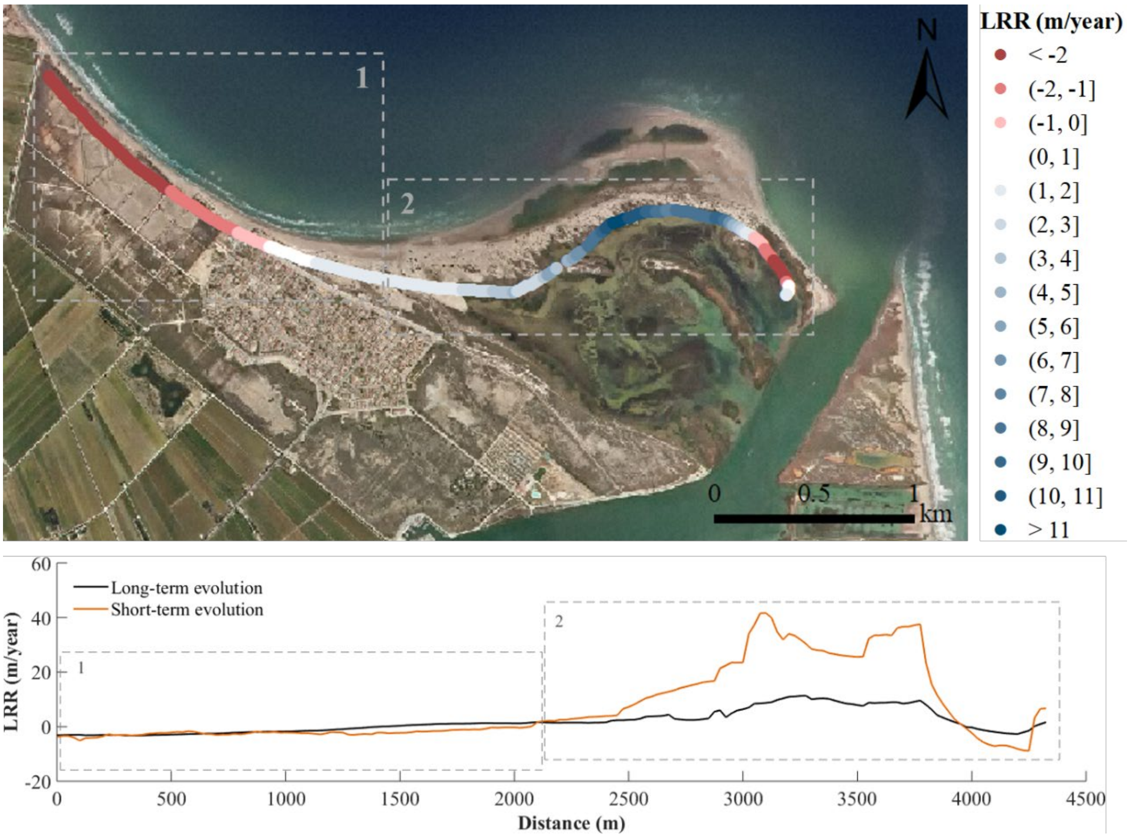


Figure 9. (a) Long term evolution (LTE) based on Linear Regression Rate (LRR) of the shoreline in Ebro River Delta mouth. Grey boxes differentiate the (1) anthropic zone from the (2) natural one. (b) Erosion rates as a function of the alongshore coordinates, being 0 the western side. Black line corresponds to long-term evolution of LRR (1983-2019) and the orange line represents short-term evolution of LRR (2009-2019).

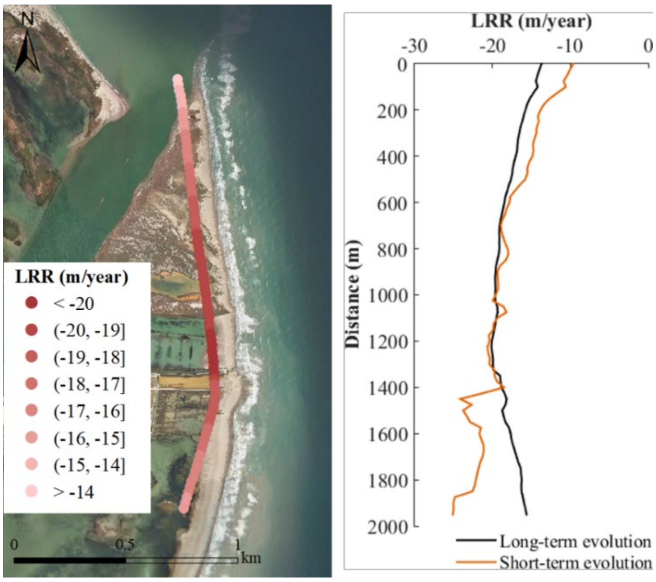


Figure 10. Left: Long term evolution based on Linear Regression Rate (LRR) of the shoreline in San Antonio Island from 1983 to 2019. Right: A comparison of the LRR as a function of the alongshore coordinates for two different time periods: black line corresponds to long-term evolution of LRR (1984-2019) and the orange line corresponds to short-term evolution of LRR (2009-2019).

The deterioration of this part of the Ebro Delta mouth, understood as coastal erosion and loss of associated habitats, could be associated with the increase in frequency and intensity of storms coming from the East (the most energetic component in this area; Cateura *et al.,* 2004), together with the effects of the SLR (which is aggravated in this zone due to subsidence; Genua-Olmedo, 2017). Nevertheless, a deep study on the functioning of river mouth marine dynamics within this system is needed. However, it is also a consequence of the lack of social and political awareness about the importance and vulnerability of coastal systems (Romagosa and Pons, 2017). An example of this vulnerability was the effects of the storm Gloria, which flooded a large part of the delta in January 2020 and washed away large coastal features. This storm was not extreme in terms of atmospheric conditions, but intense (Alonso *et al.,* 2020). Almost all the dune fields were above the sea level during the storm, especially in the left part (dune heights around 6 m at some points), proving its protective role against such erosive event. Nevertheless, to increase the reliability of the predictions additional studies combining hydrodynamic models in this zone are still needed. The process of erosion on this side is also due to the reduction of the river sediment input, as the discharges have been intensively regulated since the beginning of the 20th century (Guillén and Palanques, 1992; Rodríguez-Santalla and Somoza, 2019), causing strong negatives rates (Fig. 8).

Ibáñez *et al.* (2014) proposed three possible self-reinforcing mechanisms to cope with SLR and erosive trends in this zone: (1) increase in the frequency of delta lobe switching leading to the formation of new lobes, (2) an increase in the frequency and magnitude of flood events through natural river levees, and (3) an increase in the frequency and magnitude of overwash events, enhancing the ability of sandy beaches to adapt to sea level rise. First of all, there is not enough time to lobe switching to occur. The retreat rate of the San Antonio Island is too fast for the delta mouth to migrate and adapt. Secondly, the increase of flood events could be an option but their management through dam regulation is difficult and depends on a number of external factors (technical, hydrological, and socio-economic, among others). Additionally, the lowest reservoirs built in the Ebro river basin are too close to the delta, so there is not sufficient river catchment to produce natural flood flows that generate sediment. It is an over-regulated river, where flooding in the final parts of the river are virtually ruled out. Lastly, the overwash process is the most active one in the delta mouth, which is effectively making beaches retreat inland but, in the case of San Antonio Island, there is a physical limit, imposed by the river channel itself.

Nevertheless, most of the proposed solutions may not solve the erosion problem in San Antonio Island, so a possible solution could be to let the system act naturally and reach a new state of equilibrium, even if this entails the loss of one of the most emblematic natural parts of the Ebro River Delta. This possible evolution may consist in a westward shifting of the entire mouth complex, maintaining a certain sandy barrier in its eastern side while the Garxal wetland is being eroded. The rollover model of coastal evolution, typical of sand coasts subject to slow sea level rise trends, could be the solution to maintain the diversity of subsystems and habitats in this part of the delta. It will be necessary to assess any subtle change in the delta shoreline, especially when affected by strong easterly sea storms, that represent the main trigger of rapid coastal changes in the zone. The detailed analysis of the evolution and changes recorded by the delta during past storm episodes, together with the application of wave propagation models referred to such energetic situations could be another step that would help to predict the immediate future of this emblematic portion of the Iberian coast.

5. Conclusions

The development of sequential eco-geomorphological maps from historical images has proved to be a useful tool to assess the resilience of coastal systems under present and future pressures. In future works, the combination of aerial orthophotos, which provide the historical data for the study of landscapes, with other methods, as wave propagation models or hyperspectral or surface elevation information derived from airborne and satellite sensors, will facilitate the reconstruction and monitoring of coastal changes at landscape level, reducing time and efforts.

The Ebro River Delta mouth is exhibiting a strong positive trend on sandy features on the left side of the main river channel, but a huge negative trend on the other side. From the obtained results, it can be inferred that in between 2040 and 2050 the San Antonio Island could disappear if this trend continues. It is important to read these results with caution, since they were obtained from a simple linear regression applied to surface changes and shoreline migration. As it is eroded, other processes will occur that will either increase or decrease the dynamics of the process. That is, these results are related to the recent evolution of the system but it can change depending on external factors in the future. This assumption reinforces the need of the application of hydrodynamic and geomorphological models that could better explain future trends of this part of the Ebro Delta mouth.

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ANALYSIS OF THE MORPHOLOGICAL CHANGES OF THE BEACHES ALONG THE SEGMENT VALÈNCIA - CULLERA (E SPAIN) FROM SATELLITE-DERIVED SHORELINES

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ABSTRACT. Beaches are spaces of paramount importance for coastal societies currently threatened by coastal erosion. Their preservation requires accurate quantification of their changes in order to understand their behavior and to propose efficient solutions. Landsat 8 and Sentinel 2 mid-resolution satellites offer free-of-charge images with great potential for coastal monitoring. From them, it is possible to automatically extract the shoreline position as a quantitative indicator of the beach morphology over large territories and with high temporal frequency.

Beach changes take place at different spatial and temporal scales, typically responding to coastal storms and human interventions on the coast. The collection of large packages of satellite-derived shorelines (SDS) at the coastal sector València-Cullera (W Mediterranean) covering the period 2013-2020 makes it possible to characterize the state of its beaches and their width changes over space and time.

Results reveal a widespread erosional trend, most likely caused by a shortage of sediment in the coastal system. Thus, the majority of the beaches are not capable of restoring their previous conditions after storm-driven retreats. The information provided by the SDS also shows the ineffectiveness of the nourishment actions, at least in the way they have been carried out, and the urgent need for a strategy to address the erosion problem.

Análisis de los cambios geomorfológicos de las playas en el tramo Valencia-Cullera (Este de España) a partir de líneas de costa derivadas de satélite

RESUMEN. Las playas, espacios de suma importancia para las sociedades costeras, actualmente están amenazadas por la erosión costera. Su preservación requiere una cuantificación precisa de sus cambios para comprender su comportamiento y proponer soluciones eficientes. Los satélites Landsat 8 y Sentinel 2, de resolución media, ofrecen imágenes gratuitas con un gran potencial para la monitorización de costas. De ellos, es posible extraer automáticamente la posición de la línea de costa como indicador cuantitativo de la morfología de la playa en grandes territorios y con alta frecuencia temporal.

Los cambios en las playas tienen lugar a diferentes escalas espaciales y temporales, respondiendo normalmente a tormentas costeras e intervenciones humanas en la costa. La recopilación de grandes paquetes de líneas de costa obtenidas a partir de imágenes de satélite (SDS) del sector costero València-Cullera (Mediterráneo occidental) (período 2013-2020) permite caracterizar el estado de sus playas y sus cambios en el espacio y el tiempo.

Los resultados revelan una tendencia erosiva generalizada, probablemente causada por la escasez de sedimentos en el sistema costero. Por lo tanto, la mayoría de las playas no son capaces de restaurar las condiciones anteriores al retroceso causado por las tormentas. La información aportada por las SDS también muestra la ineficacia de las acciones de realimentación de arena, al menos en la forma en que se han llevado a cabo, y la urgente necesidad de una estrategia para abordar el problema de la erosión.

Key words: Shoreline dynamics, Monitoring beach variability, Remote sensing, Coastal management, Coastal storms, Western Mediterranean.

Palabras clave: Dinámica de la línea de costa, Monitorización de la variabilidad de las playas, Gestión costera, Tormentas costeras, Mediterráneo occidental.

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1. Introduction

Beaches represent natural spaces with a vital role in coastal societies for different reasons: they shelter inland territories from marine storms, serve as a habitat for valuable ecosystems, and, undoubtedly, are an indispensable resource for sustaining the economy of coastal regions (Prodger *et al.,* 2016). "Nowadays, a large part of the world's beaches are subject to severe erosive problems. These processes are mostly induced by human actions by altering sediment transport, limiting its entry into the system, or by constructing on the beach-dune system and immobilizing the sediment (Sanjaume and Pardo Pascual, 2019). Additionally, the erosive processes are aggravated due to the climate change (Sutherland and Gouldby, 2003) associated with rising sea levels and increased frequency and magnitude of coastal storms. The erosive process is especially noteworthy in the Gulf of València (Pardo-Pascual, 1991; Sanjaume and Pardo-Pascual, 2005), where about one-quarter of the beaches present this kind of problem (European Commission, 2009).

In this context, beaches undergo morphological changes of different dimensions and causes. Having updated information regarding the state of the beaches, their dynamism, and the real risk of their disappearance is of strategic interest as this information is essential for coastal managers to make appropriate decisions. Therefore, the systematic monitoring of beaches is a helpful strategy to comprehend how and why beaches change, thus enabling a correct diagnosis of their condition.

In the last few years, it has been possible to use the successive multispectral images acquired from artificial satellites as a source of environmental information. Among them, two series of satellite images stand out: Landsat images acquired by NASA and managed by the United States Geological Survey, and Sentinel 2 images acquired and managed by the European Space Agency. Their main advantages are the high frequency of acquiring images (every 2 to 5 days when combining images from different satellites) of the whole planet since the mid-eighties of the last century, and the fact that since 2008 they are available free of charge. These images present a great opportunity to deduce indicators capable of characterizing the morphology of the beach. Among them, the position of the shoreline (Satellite-Derived Shoreline, SDS) stands out as an intuitive and clear descriptor of the physical dimensions of the subaerial beach. The essential limitation in defining the shoreline with sufficient precision for coastal monitoring purposes comes from the spatial resolution of the satellite images. Thus, while Landsat offers 30 m of pixel size, Sentinel 2 offers 10 m and 20 m. This limitation has been overcome by different algorithmic solutions (e.g. Pardo-Pascual *et al.,* 2012, 2018; Vos *et al.,* 2019; Bishop-Taylor *et al.,* 2019, Sánchez-García *et al.,* 2019) that extract the position of the shoreline with sub-pixel accuracy. Thus, the integration of the extraction algorithm originally proposed by Pardo-Pascual *et al.* (2012) and Almonacid-Caballer (2014) with other necessary tools for the download and pre-processing of the images has led to the creation of SHOREX (Sánchez-García *et al.,* 2020; Cabezas-Rabadán *et al.,* 2021). This extraction system follows an efficient workflow to obtain the SDSs from the image servers. In turn, the extracted SDSs constitute the input data for the creation of Spatial-Temporal Models (STMs) that characterize the morphological changes at different temporal and spatial scales (Cabezas-Rabadán *et al.,* 2019a).

The present study aims to use the SDSs extracted with SHOREX and the derived STMs to analyze the recent morphological changes of the beaches between València and Cullera, a coastal stretch of the Gulf of València with a pronounced erosive trend, in an attempt to provide information on their behavior and causes.

2. Study area

The study focuses on the 28 km of sandy beaches located between the Port of València and the Cape of Cullera (Fig. 1).

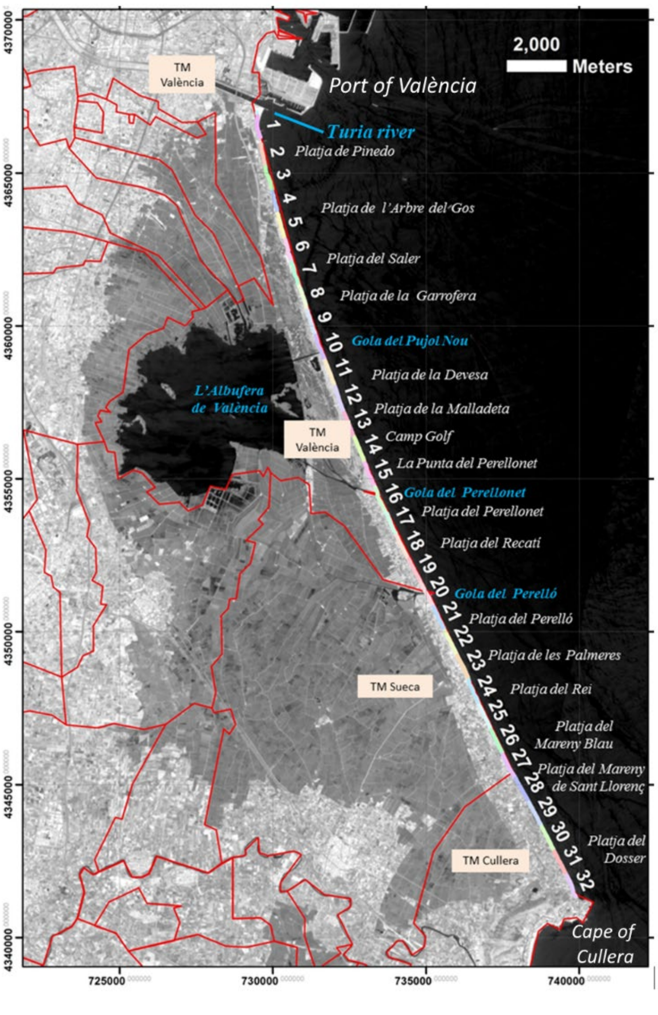

Figure 1. Study area divided into 32 sections of 900 m to facilitate subsequent analyses. It comprises beaches of the coastal front of the municipalities of València, Sueca, and Cullera.

The study area is located along a micro-tidal coast (the maximum astronomical oscillation is 0.39 cm, but it may exceed 1.32 m when adding the meteorological oscillation). The waves show low energy, with only 24% of them exceeding 1.5 m (Pardo-Pascual and Sanjaume, 2019). The waves with the highest energy come from the ENE. The orientation of the dominant waves in combination with the coast led to a dominant longitudinal transport towards the south. Nevertheless, E and ESE waves of lower magnitude are also frequent (about 1/3 of the time).

This is a sandy coastal segment that historically has followed a well-defined accretionary trend. This is evidenced by the creation of the barrier beach enclosing l'Albufera de València lagoon, and by the development of a large dune field (Sanjaume *et al.,* 2019; Sanjaume and Pardo-Pascual, 2019). The present beach barrier has Holocene origin, although there are multiple signs of the existence of ancient Pleistocene beach barriers currently submerged at different levels due to tectonic influence (Rosselló, 1979; Rey and Diaz del Río, 1983; Sanjaume and Carmona, 1995; Albarracin *et al.,* 2013; Alcántara-Carrió *et al.,* 2013). The genesis of the current beach barrier began with the formation of a sandspit that developed in different hooks that started from the main source of sedimentary inputs, the Túria River. The development of this spit ended when it trapped the sand accumulated at the Cape of Cullera (Sanjaume, 1985; Sanjaume *et al.,* 2019). The beach barrier shows three inlets (which the local toponymy calls 'Gola', Fig. 1): the Pujol Nou, the Perellonet, and the Perelló. The first of these is completely artificial (opened in 1953), while the other two have been artificially altered at least during the nineteenth century (Rosselló, 1995). Previously, a large inlet was open in the southern area at least between the middle age and the eighteenth century (Sánchis, 1998). All these inlets maintain the water communication between the sea and the current lagoon, which is artificially regulated to ensure fishing and agricultural activities.

The historical human action on the beach barrier presents some differences between the northern part (within the municipality of València, see Fig. 1), and the rest of it. This is because the northern part (known as Devesa del Saler) was, for centuries, a royal property protected for hunting purposes until a century ago when it was ceded to the municipality (Benavent *et al.,* 2004). For this reason, this sector was not heavily-altered during a long historical period. On the contrary, the rest of the barrier experienced a strong demographic pressure, the landscape was strongly modified by agricultural use, and the dune morphology was largely destroyed (Sanjaume and Pardo, 2011a). The Devesa del Saler dunes were partially destroyed due to the implementation of a large urbanization plan at the end of the 1960s. This provoked an important social reaction that led to the suspension of the urbanization plan in 1979. Since then, several actions have been aimed at progressively recovering the naturalness of the area and the dunes (Sanjaume and Pardo, 2011b).

Focusing on the beaches, the most important human intervention by far is the port of València, which began its construction at the end of the eighteenth century. The port is located just north of the Túria River mouth, and its main impact is caused by its dikes interrupting the transport of sand towards the south associated with the coastal drift. This effect reached its peak during the second half of the 20th century when the dikes were extended beyond the closing depth, becoming a complete trap for the longitudinal transport of sediments. It caused the division in two parts of the sedimentary cell that historically extended throughout the Gulf of Valencia. All this has led to a decrease in sediment inputs towards the study area (Sanjaume and Pardo, 2005; Pardo-Pascual and Sanjaume, 2019). On a smaller scale, other human interventions have also conditioned the beach trends. At the northernmost part of the study area, just south of the Túria River mouth and the port (Pinedo beach), up to 16 breakwaters have come to coexist, and since 1985 more than 300,000 m^3 of sand have been nourished. Currently, there are still four fixed structures of significant dimensions: the jetty of the Túria river that generates a shadow effect protecting the adjacent beach, two perpendicular groins, and between them, a breakwater that protects the promenade at the point where there is no beach left. The next section to the south has never shown rigid elements over the shore, although constructions have been eliminated on the dune ridge, and subsequently, it has been regenerated. Further south we find a sector that, despite remaining intact until the 1960s, the urbanization process seriously altered its ecosystems (Sanjaume and Pardo-Pascual, 2011a).

Concerning sediment availability, the Administration has carried out different nourishment actions along the study area in an attempt to favor the maintenance of the subaerial beach surface. Thus, in the mid-1990s large inputs were carried out in this coast, progressively repeated over time (Fig. 2). The majority of these nourishments occurred in the northern part (Devesa del Saler) although in 2010 there were also actions to recover the dunes on El Dosser Beach.

In addition to the impact of the port, the study area is also affected by the lack of sediment arrival from the fluvial system. This is the case of the Túria River, which only discharges water into the sea during stormy episodes through its newly artificial channel. The Benagéber and Loriguilla reservoirs (located in the last hundred kilometers upstream of the river mouth) act as obstacles to sediment transport preventing the arrival of sediment to the coast.

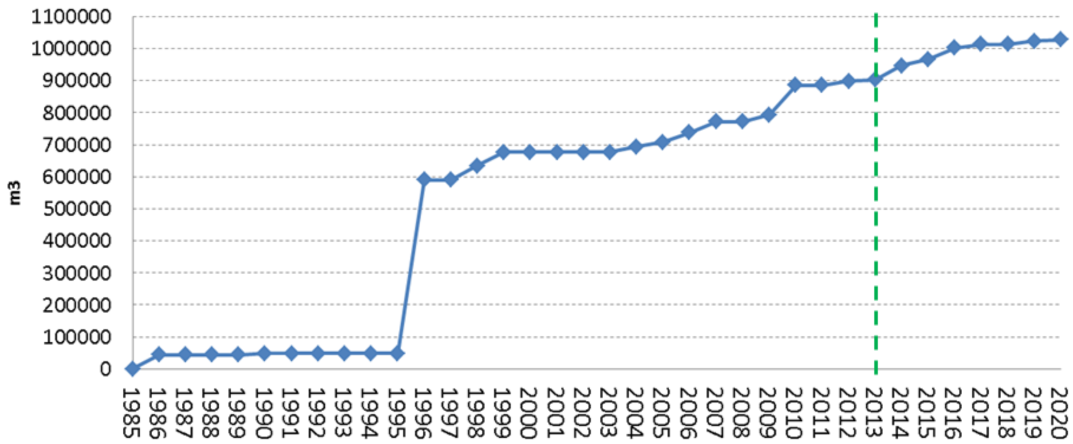

Figure 2. Volume of sand nourishments accumulated along the period 1985-2020 carried out in the study area. Data provided by the Coastal Demarcation of the General Directorate for Sustainability of the Coast and the Sea (DGSCM). The vertical line highlights the start of the study period.

3. Methods

3.1. Shoreline extraction

This study is based on the information provided by Landsat 8 (OLI) and Sentinel 2 (sensor MSI) imagery available between 2013 and November 2020 to automatically define the shoreline position (SDS) using the SHOREX extraction system (Fig. 3). Both satellites offer mid-resolution images that may be obtained free of charge from the Copernicus Open Access Hub (https://scihub.copernicus.eu/) and the Earth Explorer of the U.S. Geological Survey (USGS) (https://earthexplorer.usgs.gov/). The images include the bands RGB, NIR, SWIR1, and SWIR2, employed within the extraction process. Their similar spatial resolution and radiometric characteristics allow the extraction of comparable SDSs, as discussed in Pardo-Pascual *et al.,* 2018 and Sánchez-García *et al.,* 2020.

The images were downloaded and pre-processed using the system SHOREX (Cabezas-Rabadán *et al*., 2021). A manual cloud-checking was carried out, and the resulting images were georeferenced using orthorectified aerial photography. From the resulting images, SDSs were automatically defined as the water/land intersection at the acquisition time applying the sub-pixel algorithm proposed by Pardo-Pascual *et al.* (2012) operating over the Short-Wave Infrared bands (SWIR1) using a third-degree polynomial, and 3x3 analysis kernel. As a result, 236 SDS were obtained, and they are expected to offer an accuracy of 3-4 m RMSE according to previous assessments at micro-tidal beaches (Sánchez-García *et al*., 2020).

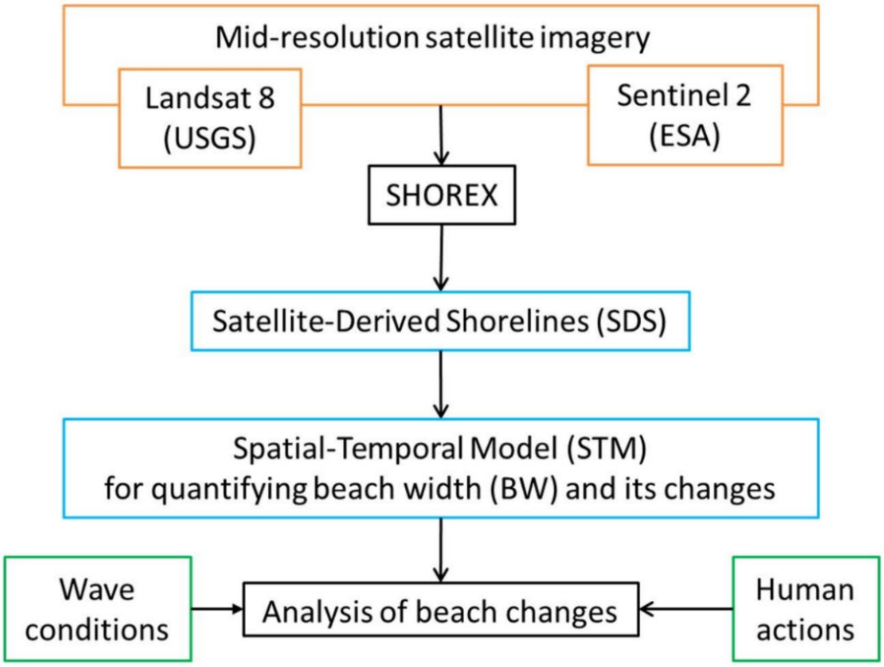

Figure 3. Diagram with the methodology followed in this work. The satellite imagery (orange) constitutes the input data. They are used by the SHOREX system for extracting the satellite-derived shorelines (SDS) and the spatial-temporal model (STM) of beach width (BW) as products for characterizing the beach morphology (light blue). These products, together with the external information (green) regarding the wave conditions (wave height and peak) and human actions (nourishments, dredgings, and coastal constructions) will make it possible for the analysis of beach changes.

3.2. Spatial-temporal models of the beach width

Parallel to the SDS, the inner limit of the beaches was defined by photo-interpretation of recent aerial orthophotography. This inner line was divided into 60 m segments, and the distance to each of the SDS was measured in order to define the average beach width (BW) of each segment. All these measurements were organized within a spatial-temporal model (STM) as described by Cabezas-Rabadán *et al.* (2019a) allowing to quantify the beach width continuously over space and time. The morphological information provided by the STM was combined with data characterizing both wave conditions (significant height and peak period) and anthropogenic actions (sand nourishments, dredgings, and constructions on the shore) to analyze their effect on the beaches. Thus, it was possible to analyze at different levels of spatial and temporal detail the changes registered by each beach segment in response to storm events or anthropic actions. Subsequent analyses were carried out considering as the unit of analysis sections of 900 m length created by grouping the 60 m segments.

3.3. Identifying problematic beach sections

Insufficient beach widths can jeopardize the maintenance of the beach functions. The width may become problematic depending on the characteristics of the beach, the functions that it sustains, and the oceanographic conditions to which it is exposed. Nevertheless, there is a certain consensus that on Mediterranean beaches widths below 30 m negatively affect the recreational function (Alemany, 1984, Lozoya *et al.,* 2011; Yepes, 2002) by conditioning the type of user, increasing the density, or even impeding the access and use of the beach (Valdemoro and Jiménez, 2006; Cabezas-Rabadán *et al.,* 2019b). Accordingly, and following the criteria proposed in Cabezas-Rabadán *et al.* (2019c), coastal segments narrower than 30 m were identified as problematic, while those narrower than 15 m were defined as critical.

The mean beach width is a representative parameter of the beach morphology useful to characterize its state. However, the high sub-annual variability of the beach makes it necessary to use other parameters to characterize the width conditions throughout the year (Cabezas-Rabadán *et al.,* 2019c). Thus, in the present work, the standard deviation was considered together with the annual mean width as a statistic to quantify the annual changes of each beach segment.

4. Results

The analysis of the beaches over the period 2013-2020 shows an average width of 36.9 m ±17.9 m (expressed as annual mean width ± standard deviation). This is a value close to the threshold employed to identify a width as problematic (30 m). According to the average width of the sections that compose the study area (Fig. 4), it may be divided into three large sectors. From north to south:

Sector A. Relatively narrow beaches (its average width is 33.4 m ±9.9 m) extending between sections 1 to 14 (from the beaches of Pinedo to north of la Punta del Perellonet, see Fig. 1)

Sector B. Dominated by wider beaches (average width 50.7±10.9 m) and extending between sections 15 to 20 (from la Punta del Perellonet to Gola del Perelló)

Sector C. The southern sector (sections 21 to 32, from el Perelló beach to El Dosser beach) is also dominated by narrow beaches (the average width is 33.5 ±5.8 m). During the first years of the study period, the beaches of this section were far wider and have progressively reduced their width. Over time, many sections of the beach have reached widths below 30 m (problematic) while in some cases, widths below 15 m (critical) have also been recorded.

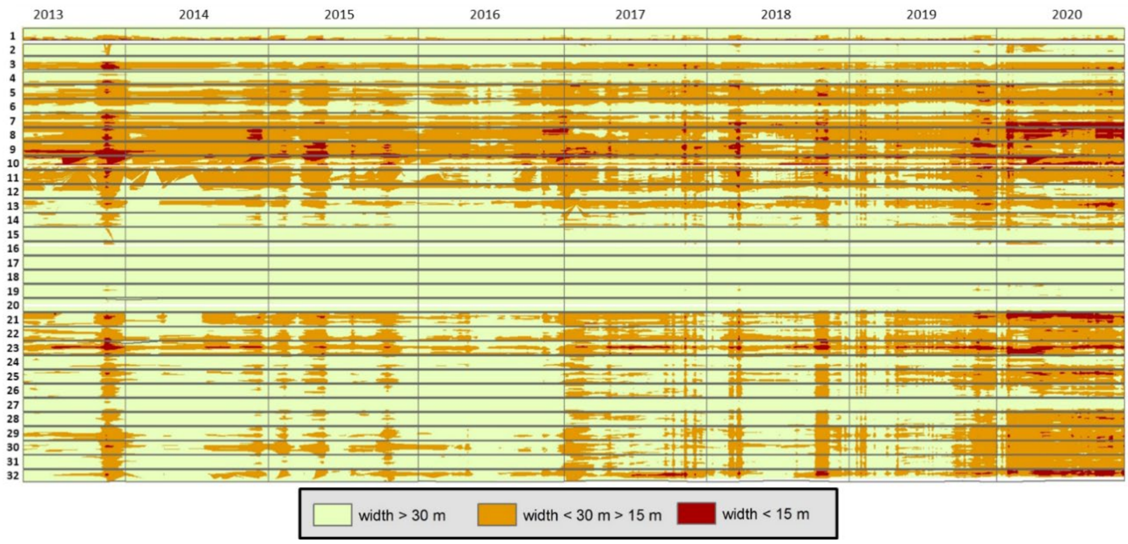

Figure 4. For the period 2013- 2020, characterization of the beach width of the 32 sections into which the study area is divided. Sections with problematic widths (below 30 m, in orange color) and critical widths (below 15 m, red), and those with no problems (green) have been identified.

Problematic widths affect each sector very differently. Figure 5 shows the percentage of time a section shows widths below 30 m, that is experiencing a problematic width. These results allow recognizing more clearly how the northern zone (sector A) has a clear dominance of problematic conditions. This is especially noticeable in sections 5 and 7 to 11, where more than half of the time the width is below 30 m. Moreover, as evidenced by the very low standard deviation values, this is a sector without large variations in width over the study period, so that this problematic situation has remained constant. The intermediate sections (sector B) delimits the area with wider beaches in which a problematic width situation is not reached. This is the segment that extends between La Punta beach and Gola del Perelló. However, south of El Perelló Port begins a stretch of about 2.6 km in length (Les Palmeres beach) in which at least 50% of the time the beach is narrower than 30 m. This happens mostly after storm episodes but becomes constant since mid-2019. To the south (sector C) we find El Rei beach where there are very strong variations in the width of the beach, which often leads to a problematic situation. Section 27 (corresponding to Mareny Blau beach) is maintained with sufficient width practically throughout the entire period studied. However, further south the problematic width conditions -even critical- are repeated on multiple occasions, especially from autumn 2019 when it can be considered constant. The critical condition (width less than 15 m) is practically limited to El Dosser beach (sections 31 and 32) during 2020.

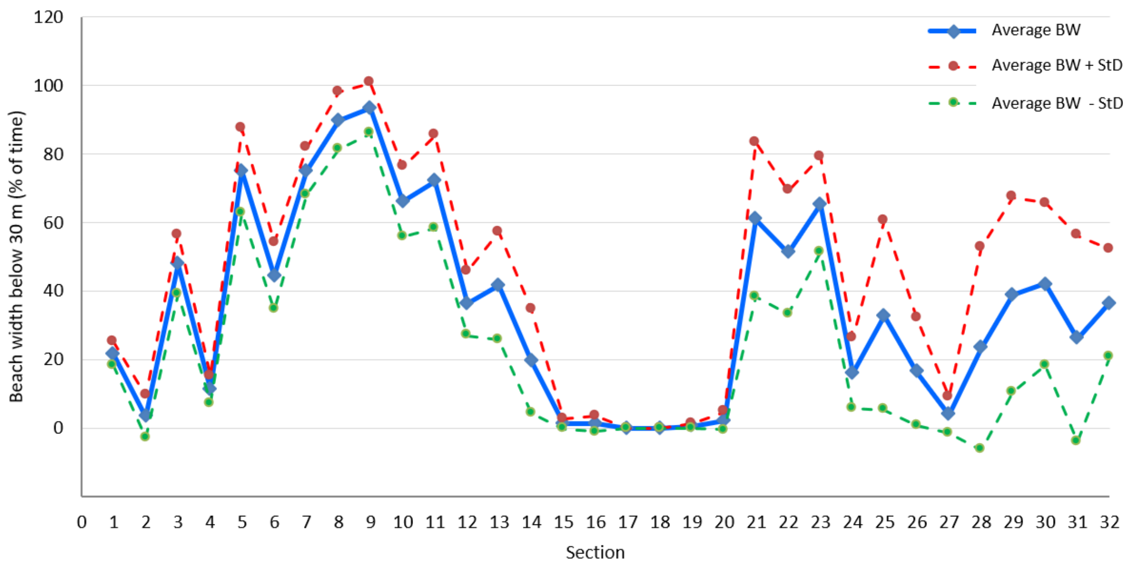

Figure 5. For each of the sections composing the study area, the amount of time (%) for which the beach width is below the 30 m threshold, considering the average beach width (blue color) and adding/substracting the associated standard deviation along the year (red and green respectively).

Regarding the rate of change followed along the study period, practically the entire area has followed a negative trend (Fig. 6). Only the segment corresponding to La Garrofera beach shows a clear positive trend, with rates higher than 2 m/year. However, the general domain is erosive. Important erosive trends (retreats larger than 2 m/year) are experienced in the segment of El Rei beach and, above all, El Dosser beach, reaching -2.9 m/year.

It is very interesting to note the existence of a pattern in which erosive peaks are experienced along segments several hundred meters in length. They appear alternated with others more stable or with less exacerbated erosive rates. The average spacing between peaks is about 2.2 km although it can by no means be considered regular.

Concerning the temporal evolution of beach changes, the STM model shows changes over the study period taking as reference the first recorded date (23/04/2013), and with a scale of colors reflecting the erosion/accretion trend (Fig. 7). This model allows the study of beach behavior at different scales of spatial and temporal detail. This enables analyzing the relation between width changes and oceanographic conditions. A strong correlation appears between episodes with high wave heights and beach width loss phenomena that affect the entire study area in a generalized manner.

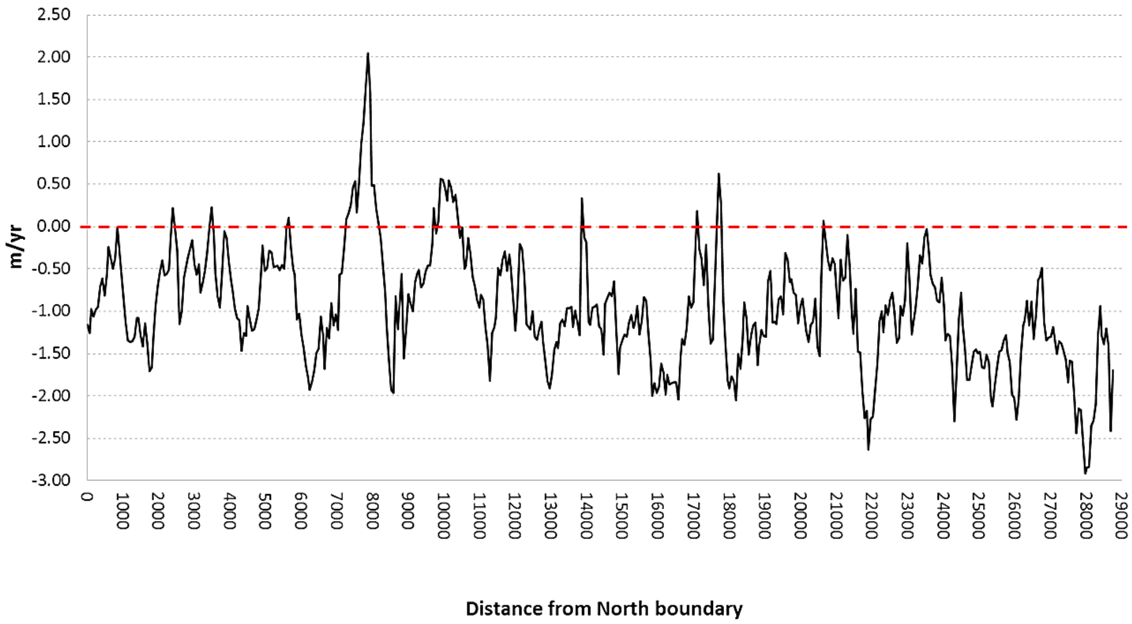

Figure 6. Rate of width change (Y-axis, in m/yr) for the period 2013 – 2020 (X-axis, as distance in m from the Northern limit of the study area).

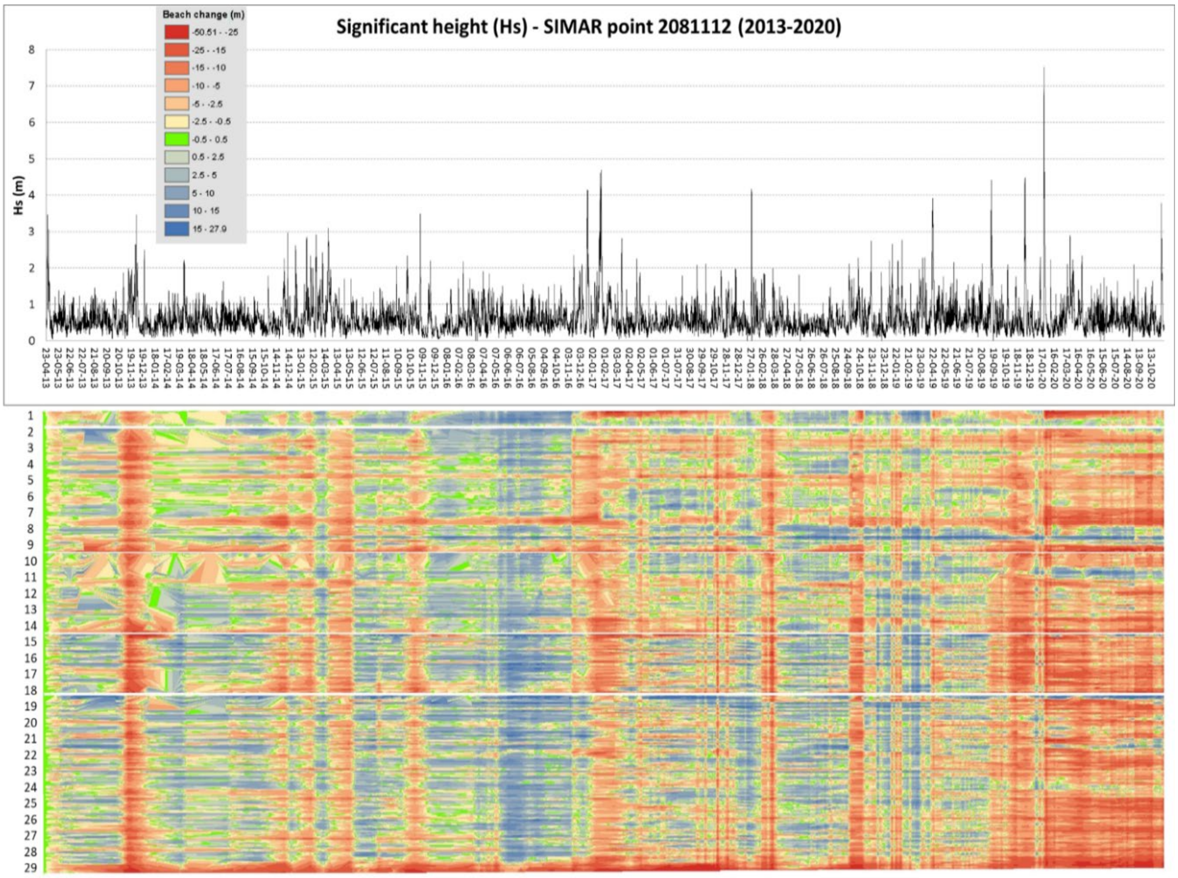

Figure 7. The upper part of the figure shows the significant wave height (Y-axis, in m) obtained from the SIMAR point 2081112 for the period 2013-2020 (X-axis). The lower part shows the associated spatial-temporal model of width changes, taking as reference the first recorded date (23/04/2013), along the study area (Y-axis, as the distance from the North limit, in km).

To facilitate the analysis, all this information can be simplified by taking years as a time unit and averaging the changes recorded in each of the 32 sections that compose the study area (Fig. 8). During the first year (2013) there was a retreat of about 2.4 m. In the following two years (2014 and 2015), although the width increases, it does not exceed the original situation, while in 2016 there is an accretion of 1.5 m from the original position. In 2017 a sharp setback is detected (- 3 m), partially recovered in the following two years but without reaching the initial position. Finally, 2020 experiences the most important retreat of the study period (up to 8 m on average from the original situation).

The analysis shows significant geographic differences. Thus, the most positive trends are experienced by sections 3 and 4 (south of Pinedo beach and north of l'Arbre del Gos beach), section 9 (La Garrofera beach), and section 27 (Mareny Blau beach). On the contrary, sections 1 and 2 (north of Pinedo beach), 5 to 8 (El Saler beach), and the entire southern area, from section 13 (La Malladeta beach) to 32 (El Dosser beach) stand out as more erosive. It is very interesting to note that in the latter beach (fig. 8, D) all the annual mean values of width are lower than in 2013 (including 2016, which in the rest of the places presented significant increases in beach width).

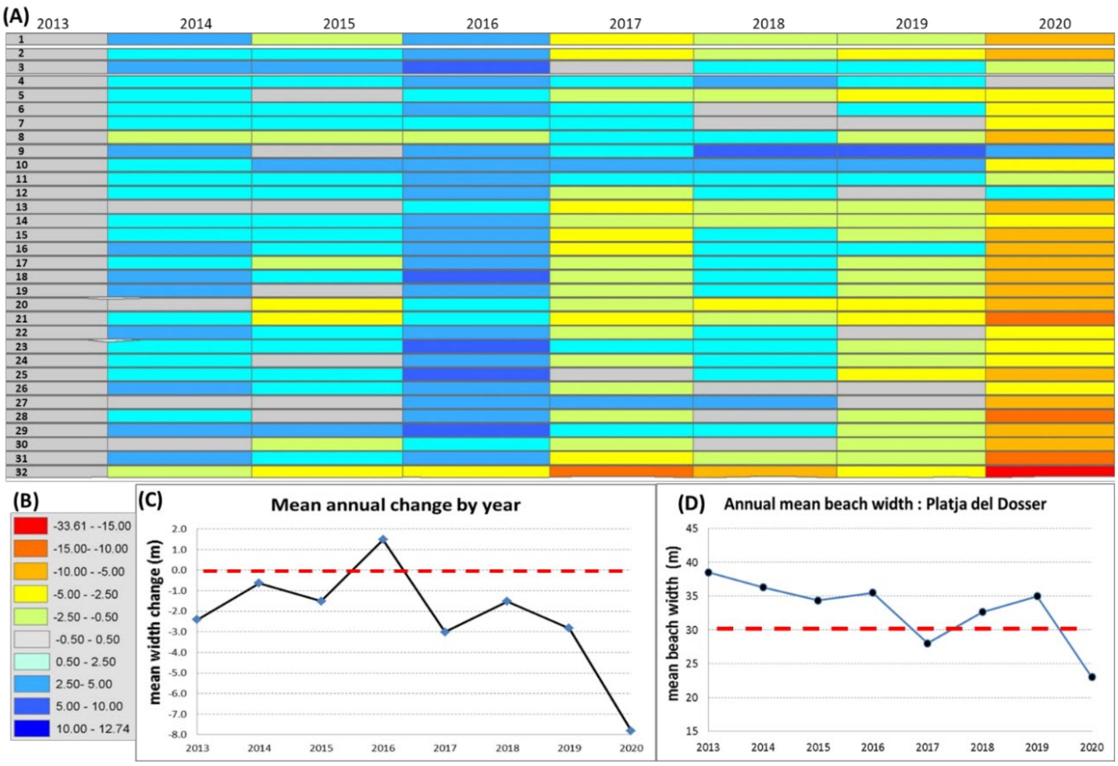

Figure 8. (A) Spatial-temporal model of beach changes for the 32 sections that compose the study area taking 2013 as reference the initial date of the series of records (April 23, 2013). (B) color legend representing the magnitude of the change, (C) graph of the mean annual change by year, and (D) annual mean beach width of El Dosser beach.

5. Discussion

The results presented show that the coastal segment has mostly suffered a strongly recessive trend during the period 2013-2020. Among the results obtained in this work, this is probably the most remarkable, as it breaks with the historical behavior of this coast. The whole sector is deeply affected by the complete interruption of the longitudinal sediment transport caused by the dykes of the port of València for decades. The old coastal sedimentary cell is fragmented and, therefore, the sediment no longer arrives from the north. In addition to this phenomenon, the Túria River is artificialized and with different dams along its course, meaning that it also does not constitute a sedimentary input. All this translates into an erosive trend that for years has been taking place causing a progressive emptying of the submarine profile and a retreat of the shoreline position. These retreats are the most obvious signs of the erosive scenario, and they have been expanding southward over the years. In the 1930s and 1940s, the effects were obvious, especially on Pinedo beach (Vilar, 1934; Yordi, 1943). At the end of the 1980s and based on a systematic analysis of successive series of aerial photographs Pardo-Pascual (1991) detected the end of the effect caused by the port of València on El Saler beach, about 4 km north of Gola del Pujol Nou. Some decades later, in a study based on the analysis of successive images captured from Landsat 5 and 8 between 1984 and 2014 (Pardo-Pascual *et al.,* 2015), the effect had reached La Malladeta beach (1.5 km south of Pujol Nou). Now, after the strong storms of 2017 and 2020, it can be seen how the most accelerated erosive processes cover practically the entire study area.

Particularly remarkable is the erosion along its southern end (El Dosser beach), as well as the strong retreat on El Recatí and El Rei beaches. Throughout the whole period, El Dosser follows an erosive trend quite surprising considering its geographical position at the end of the sedimentary cell. This beach is supported by the rocky promontory of the Cape of Cullera. It is the base of the sedimentation process that has built up the barrier beach enclosing the Albufera de València. For this reason, it is so striking that it is now evolving negatively. When analyzing the phenomenon from a longer time perspective (1956-2021) taking advantage of the series of historical orthophotographs it can be seen how until 2012 the area followed the expected cumulative trend (Fig. 9). It should be noted that from 2000 to 2010 there was a decline that seems to be partly mitigated by sand nourishments of the dune ridges (92,725 m^3) which caused in 2012 a seawards displacement of the shoreline. However, since 2012 it has followed an erosive trend, although with an oscillating behavior.

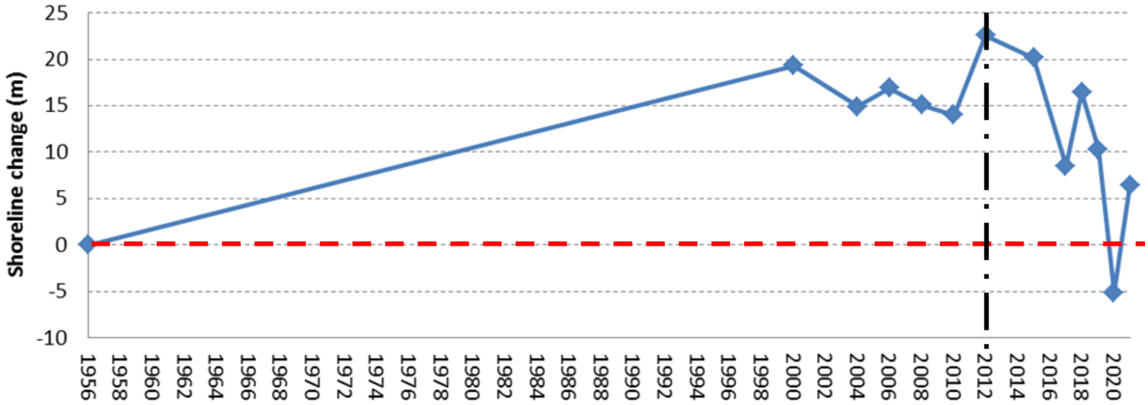

Figure 9. Shoreline change in El Dosser beach for the period 1956-2020. The registers appear as blue points, being the position of 1956 considered as reference. The year 2012 constitutes a turning point in the evolution of the shoreline position. The shoreline position was manually defined using historical orthophotographs (Available in the Generalitat Valenciana viewer; https://visor.gva.es/visor/).

A detailed analysis of the shoreline changes during the last eight years (2013-2020) together with the incident wave conditions and human actions provide some important clues (Fig. 10).

The comparison of the wave conditions and the evolution of the beach width shows how the shoreline systematically retreats linked to storm events. As a clear example of this, after the first available SDS (20/04/13) a storm with Hs of 3.46 m causes a retreat from which the beach widths do not recover. In fact, in late autumn 2013, several weeks with energetic waves (Hs of 3.46 m in December 2013) cause a critical situation with widths below 15 m (on days with significant energetic swell). After that storm, there is a recovery, showing widths about 40 m compared to the 30 m previously observed. When waves reach again Hs of 3 m, critical widths of 15 m appear, from which they tend to recover within a period of about three months. However, when more energetic storms occur in which the Hs exceeds 4 m as in January 2017 and especially in January 2020 (Storm Gloria), the retreat is more aggressive. It results in beach widths of only 5 m, followed by a very slow recovery. In the case of the Storm Gloria, the complete recovery does not occur, leaving a residual beach width (less than 10 m). A similar pattern of retreatment during the largest storm events and the subsequent lack of complete recovery was identified on beaches with similar characteristics at the southern part of the Gulf of València by Cabezas-Rabadán *et al.* (2019d). On the contrary, this behavior does not seem to take place associated with the storm in January 2017. This could be due to the sand nourishments carried out: 2065 m^3 and 5000 m^3 of sand were nourished in February and November 2017 respectively (marked with a blue arrow in Fig. 10). Although of small magnitude, these artificial inputs, seem to have an immediate effect on widening the beach. However, even though the wave conditions are quite calm, the effect is not sustained over time.

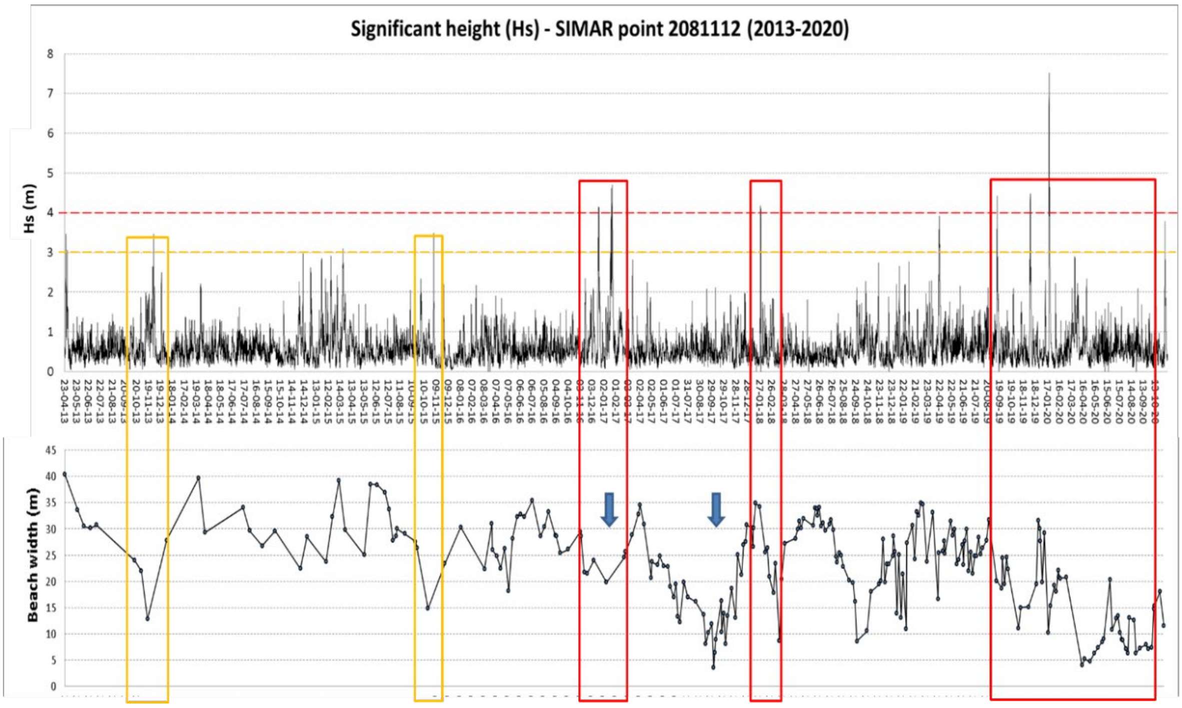

Figure 10. Shoreline changes in El Dosser beach (North of Cullera, section 32), together with wave data (SIMAR point 2081112) highlighting the storm episodes with Hs over 3 m (yellow) and 4 m (red). Blue arrows allow identifying sand nourishments

The underlying question is why a historically cumulative sector has become erosive without the direct human intervention. The explanation could be associated with the gradual emptying that has been occurring in the profile of the majority of the beaches of this sector as a result of the lack of sediment arrival from the north. This emptying has been exacerbated as a result of the storms recorded since autumn 2016 and, particularly in January 2020, when waves of more than 7 m were reached. The emptying must have been particularly aggressive in front of the middle cliffs of the cape of Cullera where the reflection of the large waves has been able to displace the submerged sand offshore. In this context, the E and ESE waves of small dimension (Hs up to 1 m) that occur in this sector about 1/3 of the time together with the coastal orientation may lead to the sand transportation towards the north in the nearshore zone (upper part of the beach profile). At the same time, as the availability of nearshore sand at the Cape of Cullera is very low, the sediment transported northwards cannot be replaced. This would cause a local and well-defined negative sedimentary balance that would explain the change in the evolutionary dynamics highlighted by the STMs.

Until a decade ago, the erosive problem affected practically only the northern part of the Albufera barrier beach. However, it now includes places far away from the harbor dikes. This substantial change in the evolutionary dynamics of El Dosser beach is an example of this. All this raises the need to open the potential range of causes that would explain this erosive behavior, beyond the interruption of the southward drift of sands caused by the dykes of the port of València. Undoubtedly, the decrease in sedimentary inputs from the fluvial systems must also be taken into consideration. Throughout the 20th century, Valencian rivers experienced great anthropic alterations that have been associated with a significant hydro-sedimentary deficit (Segura-Beltrán and Sanchis-Ibor 2013; Sanchis-Ibor *et al.,* 2017). One of the most important impacts has been sediment retention in the reservoirs. It has been estimated that in the Benagéber reservoir alone in its first 37 years of operation 6.66 Hm^3 of sediments were retained (Cobo, 2008). This effect is not only confined to the Túria basin but practically 75% of the area that drains to the Valencian coasts is controlled by the reservoirs (Pardo-Pascual and Sanjaume, 2019) so it is evident that the whole coastal system receives less sediment than it had historically received.

A third key factor, in addition to the effect of the port of València and the decrease in fluvial sediment inputs, is the fact that the magnitude of the storms seems to be increasing. Thus, both wave height and storm intensity expressed as a product of wave height and storm duration (Sénéchal *et al.,* 2015), are increasing in recent decades (Fig. 11). Prior to 2017 only one storm showed intensity values over 250 m^2h, but since then six storms have been recorded. Likewise, prior to 2000 no storm had shown Hs of 4 m. In 2001, one case was recorded, but since 2009 there have been 10. This increase in situations of higher energy is associated with the wash of the beach and the sediment loss (especially of that of smaller caliber) towards deeper waters that cannot always be returned to the coast during calmer wave conditions.

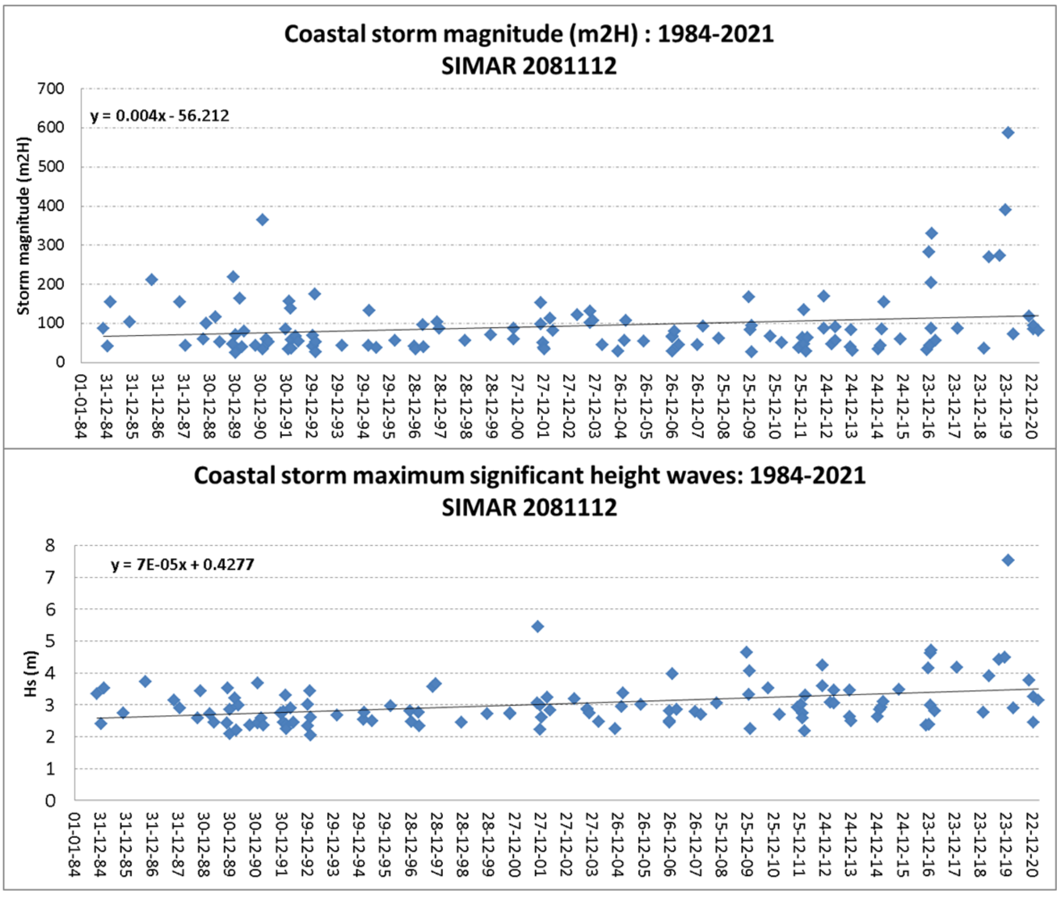

Figure 11. Changes in the magnitude of coastal storms according to two representative parameters: the maximum significant wave height and the intensity (in m2h). The latter one is the result of multiplying the maximum significant height squared by the duration of the storm.

One last factor to take into consideration within this area is that during the study period (2013-2020) the artificial sediment input has been substantially lower than during the previous two decades (Fig. 2). Thus, the large sediment nourishments carried out on this coast during the 1990s could have helped to temporally minimize the erosive impacts in the area. On the other hand, the holistic analysis made possible by this work shows how the numerous rigid interventions carried out in the area in an attempt to offer local solutions have been insubstantial in terms of the sedimentary state of the cell as a whole.

The physical maintenance of the beaches requires the supply of new sediment to the coastal system. This supply must have a magnitude large enough to enable the recovery of beach widths, but also to replenish the submerged profile. It would be convenient to take advantage of all the potential resources of sand of suitable grain size. This is the case of the large submerged deposits of sands linked to the transition between the Pleistocene and the Holocene found off the coast of Cullera (MITECO, 2018) but also those that are being retained in the reservoirs or on beaches artificially, constituting potential sediment reservoirs.

6. Conclusions

The entire coastal segment València- Cullera is affected, on the one hand, by the low availability of sand and, on the other hand, by substantially more energetic wave conditions. It takes places a progressive migration of the finer sediment to deeper areas from which only a small proportion of sands can return to the beach system. These factors favor the progressive increase in the slope of the beach profile, the decrease in the width of the emerged beach, and the increase in sediment size. Therefore, this causes a progressive decrease in the volume of sand that can be transported by longitudinal currents parallel to the coast. This new scenario, conditioned by the scarcity of sediments, would explain a general retreat of the shoreline position, not only in areas immediately affected by the sediment trap effect of the port of València. This scenario urges to counteract the sediment shortage in an attempt to physically maintain the beaches in their current state.

Acknowledgments

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CARACTERIZACIÓN Y EVOLUCIÓN DEL SISTEMA PLAYA-DUNA DE LA COSTA MEDITERRÁNEA DE ANDALUCÍA (ESPAÑA): INFLUENCIA DE PROCESOS NATURALES Y ACTUACIONES ANTRÓPICAS

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RESUMEN. En las últimas décadas, los impactos relacionados con la erosión costera en las costas del mundo han aumentado significativamente debido al actual desarrollo costero y a la ocupación turística, así como a los eventos naturales de erosión/inundación acelerados por el cambio climático. Las costas oceánicas son entornos muy dinámicos y cambiantes, ya que muestran una gran variabilidad temporal y espacial en respuesta a la acción de diferentes y complejos procesos costeros. Esta variabilidad a escala temporal interanual está relacionada con las variaciones climáticas estacionales del oleaje, debido a distribuciones temporales y espaciales de tormentas de alta latitud y tormentas/huracanes tropicales, o son resultado de eventos con un gran período de retorno, como el impacto de tormentas y tsunamis muy energéticos, elevación del nivel del mar y variaciones en el suministro de sedimentos de los ríos. Para prevenir y reducir tales impactos, los gestores deben conocer la sensibilidad de los sectores costeros naturales, que está relacionada con la energía de las olas, las características/evolución de las playas y la tendencia del nivel del mar, así como la vulnerabilidad potencial y el valor económico de los sectores urbanizados.

Este trabajo muestra la evolución costera y los impactos de las estructuras costeras y la caracterización y evolución de los sistemas dunares a lo largo de la costa mediterránea de Andalucía (España). Para ello, se definieron 47 unidades a lo largo de la costa de estudio, y se cuantificó la evolución de las tasas de evolución (erosión/acreción/estabilidad) para el período 1956-2016, mediante el uso de la extensión DSAS del software ArcGIS. Como resultado, 9 unidades registraron acreción, 19 erosión y 19 estabilidad y, en cuanto al balance de superficie de playa, 17 unidades presentaron balance positivo y 28 negativo con un balance neto de -29.738,4 m^2/año. El análisis de la evolución costera evidenció el impacto de las estructuras sólidas: la acreción se observó principalmente aguas arriba de los puertos y espigones y en correspondencia con los rompeolas; la erosión se detectó aguas abajo de los puertos y espigones y en correspondencia con los malecones, revestimientos y deltas de los ríos más largos; la estabilidad se observó en las playas pequeñas y en las áreas costeras estabilizadas localmente por estructuras de protección y obras de sustento. Estos resultados se utilizaron para determinar la distribución de los sectores costeros alineados con la corriente y la deriva y la dirección principal del transporte de sedimentos.

En cuanto a la caracterización y evolución de los sistemas dunares, se cartografiaron diferentes tipos de sistemas dunares, así como la posición y fragmentación de la punta de las dunas, y la ocupación y evolución humana desde 1977 hasta 2001 y desde 2001 hasta 2016. En total, se delimitaron 53 sistemas dunares. a lo largo de la costa mediterránea de Andalucía, diferenciando tres tipos: dunas embrionarias y móviles, dunas fijadas por herbáceas y dunas estabilizadas. Se observa un descenso generalizado de la superficie dunar en el periodo 1977-2001 (-7,5 x 106 m^2), ligado al aumento de la ocupación antrópica (+2,3 x 106 m^2), y fragmentación de las dunas, especialmente en las provincias de Málaga y Almería. Durante el período 2001-2016 se observaron cambios menores en el nivel de fragmentación y en la superficie de las dunas. Solo se observó un aumento de la superficie de dunas en playas estables o en acreción (4 de 53 sistemas de dunas), tanto en áreas naturales como antrópicas (generalmente aguas arriba de los puertos).

Characterization and evolution of the beach-dune system of the Mediterranean coast of Andalusia (Spain): influence of natural and anthropic processes

ABSTRACT. In past decades coastal, erosion related impacts on the world's shorelines have been significantly growing due to ongoing coastal development and tourist occupation as well as to natural erosion/flooding events exacerbated by climatic change. Ocean coastlines are highly dynamic and changing environments since they show great temporal and spatial variability in response to the action of different and complex coastal processes: at an inter-annual time scales, related to seasonal wave climate variations due to temporal and spatial distributions of high latitude storms and tropical storms/hurricanes, or as a result of events with a large return period, such as the impact of very energetic storms and tsunamis, sea level rise, and variations in rivers' sediment supplies. In order to prevent and reduce such impacts, coastal managers need to know the sensitivity of natural coastal sectors, which is related to wave energy, beach characteristics/evolution, and sea level trend as well as the potential vulnerability and economic value of the urbanized sectors.

This paper shows coastal evolution and the impacts on it of coastal structures and the characterization and evolution of dune systems along the Mediterranean coast of Andalusia (Spain). For this purpose, an amount of 47 units were defined along the studied coast, and evolution rates (erosion/accretion/stability), for the period 1956-2016, quantified by using the DSAS extension of ArcGIS software. As a result, 9 units recorded accretion, 19 erosion and 19 stability and, concerning the beach surface balance, 17 units presented a positive balance and 28 a negative one and a net balance of -29,738.4 m^2/yr. The analysis of coastal evolution evidenced the impact of hard structures: accretion was essentially observed up-drift of ports and groins and in correspondence of breakwaters; erosion was observed down-drift of ports and groins and in correspondence of seawalls and revetments, and at largest river deltas; and stability was observed at pocket beaches and coastal areas locally stabilized by protection structures and nourishment works. These results were used to determine the distribution of swash- and drift-aligned coastal sectors and main direction of sediment transport.

Concerning the characterization and evolution of dune systems, they were mapped different type dunes' systems as well as dune toe position and fragmentation, and human occupation and evolution from 1977 to 2001 and from 2001 to 2016. In total, they were delimited 53 dune systems along the Mediterranean coast of Andalusia, differentiating three types: Embryo and mobile dunes, grass-fixed dunes and stabilized dunes. It was observed a general decrease in dunes' surfaces in the 1977-2001 period (-7.5 x 106 m^2), linked to the increase of anthropic occupation (+2.3 x 106 m^2), and dunes' fragmentation, especially in Málaga and Almería provinces. During the 2001-2016 period, smaller changes in the level of fragmentation and in dunes' surfaces were observed. An increase of dunes' surfaces was only observed on stable or accreting beaches (4 out of 53 dune systems), both in natural and anthropic areas (usually up-drift of ports).

Palabras clave: Evolución costera, estructuras costeras, caracterización de dunas, ocupación antrópica.

Key words: Coastal evolution, coastal structures, dune characterization, dune evolution, anthropic occupation.

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1. Introducción

A consecuencia del continuo desarrollo del turismo y ocupación de la costa durante las últimas décadas (Silva *et al*., 2014; UNWTO, 2015; Rangel-Buitrago *et al.,* 2018) y de los procesos relacionados con el cambio climático (Jones y Phillips, 2011; Masselink *et al.,* 2020), como son la subida del nivel del mar o los cambios en la frecuencia, intensidad y dirección de las tormentas (Cid *et al.,* 2016; Anfuso *et al.,* 2020; Wolf e*t al.,* 2020), los impactos relacionados con la erosión costera han aumentado considerablemente en todo el mundo.

El desarrollo costero, que está esencialmente unido al turismo, continúa aumentando, encontrándose actualmente alrededor del 50% de las costas mundiales bajo la presión de un desarrollo excesivo (Finkl y Kruempel, 2005; Silva *et al.,* 2014). En Europa, durante el periodo 1990-2000, se ha producido una rápida expansión de las superficies urbanas en las zonas costeras mediterráneas y sur-atlánticas (European Environmental Agency, 2006), emplazando las actividades e infraestructuras humanas relacionadas tanto con el turismo como con la industria y la pesca extremadamente cerca de la orilla de mares y océanos (Silva *et al.,* 2014).

Las costas son ambientes cambiantes muy dinámicos que muestran una gran variabilidad temporal y espacial en respuesta a la acción de diferentes y complejos procesos, esencialmente relacionados con el oleaje y las corrientes (Komar, 1998). La erosión se observa tras eventos de tormenta a altas latitudes registradas durante los meses de invierno, y la recuperación de las playas tiene lugar durante el periodo estival en circunstancias climáticas favorables, lo que se conoce como comportamiento "estacional" de la playa (Rangel-Buitrago y Anfuso, 2013). En este caso, los procesos de erosión representan un peligro ya que pueden amenazar localmente las estructuras y/o actividades humanas en intervalos de tiempo pequeños, mientras que la recuperación natural de la playa ocurre durante intervalos mayores de tiempo, de semanas a meses (Komar, 1998; Sanjaume Saumel y Gracia Prieto, 2011). Esta recuperación garantiza la formación de una playa ancha y la función de protección asociada a ella, además de su uso turístico, pero la respuesta de las dunas a los eventos erosivos es muy diferente, es decir, la erosión es muy rápida y está asociada a eventos puntuales mientras que la acreción es un proceso que normalmente se produce durante un largo periodo de tiempo, de varios meses a años (Sanjaume Saumel y Gracia Prieto, 2011).

Por ello, la determinación de las características, comportamiento y evolución de las dunas costeras necesitan una especial atención con el fin de reducir los impactos de los procesos de erosión/inundación, tanto en costas naturales como urbanizadas.

Diferente es el caso en el que la erosión costera es el resultado de una larga tendencia debido al impacto de grandes tormentas y tsunamis (Cooper *et al.,* 2004; Sánchez-García *et al.,* 2007), subida del nivel del mar, y variaciones en el aporte sedimentario, relacionadas con la contribución de los ríos y las corrientes longitudinales y transversales. Las contribuciones de los ríos están relacionadas con las variaciones de las lluvias, cambios en los usos del suelo y la construcción de presas y canalización de cauces (Jiménez y Sánchez-Arcilla, 1993; Senciales González y Malvárez, 2003; Pranzini, 2007; Prieto *et al.,* 2012; Berguillos *et al.,* 2016, 2017; Pranzini *et al.,* 2020). Las contribuciones longitudinales y transversales registran variaciones debido a los cambios en el clima marítimo y las corrientes (Shand *et al.,* 2001; Orford *et al.,* 2002) o la acumulación aguas arriba de estructuras antrópicas (p. ej., puertos, espigones, etc., Nordstrom, 2000, 2014; Manno *et al.,* 2016; Molina *et al.,* 2019a). En este caso, los procesos de erosión producen un importante retroceso (parcialmente o sin una recuperación asociada) que en áreas naturales se refleja en procesos de *overwash* y/o erosión de las dunas y playas (Rizzo *et al.,* 2018), además de daños a las estructuras y actividades humanas en sectores costeros urbanizados (Cooper *et al.,* 2004; Rangel-Buitrago y Anfuso, 2015).

Los estudios a escala regional sobre tasas de cambios de la línea de costa son escasos a pesar de su gran relevancia. Algunos intentos se han desarrollado en EE.UU. (Fletcher *et al.,* 2012) y Europa (Salman *et al.,* 2004). Sin embargo, la comparación de los datos no es fácil ya que aspectos como la definición de la línea de costa o el formato de las series de datos difieren mucho en los distintos estudios (Ponte Lira *et al.,* 2016). Todavía se necesita mucho trabajo a escala regional/nacional para definir el mejor procedimiento en estudios regionales de erosión costera y para obtener una visión amplia de los factores regionales/locales que afectan a la evolución de la costa a medio plazo. Estos datos ayudarían a identificar las causas principales de la erosión en las últimas décadas.

La costa mediterránea de Andalucía (España) ha registrado una de las mayores tasas de crecimiento urbano a lo largo del litoral español, especialmente en la Costa del Sol (provincia de Málaga) (Malvárez *et al.,* 2000), cuya población alcanzó los 1.136.712 habitantes en 2006 (Malvárez, 2012) y continuó creciendo con una tasa del 9.2% entre 2006 y 2011 – lo que corresponde al 50% del incremento demográfico registrado a lo largo del litoral andaluz durante el mismo periodo (Martínez *et al.,* 2015).

El creciente y significativo interés turístico de las costas andaluzas conlleva a un aumento importante de la ocupación y las actividades humanas y, por tanto, de la presión antrópica cuyo papel se hace cada vez más relevante en los procesos de erosión costera. En este trabajo se pretende realizar un análisis de la evolución y el estado actual de la línea de costa y los sistemas dunares del litoral mediterráneo de Andalucía prestando una especial atención a los efectos de la presión antrópica.

2. Área de estudio

El litoral de Andalucía se extiende a lo largo del océano Atlántico, el estrecho de Gibraltar y el mar Mediterráneo, al sur de España. La costa mediterránea andaluza, de 546 km de longitud, se extiende desde el estrecho de Gibraltar hasta la Región de Murcia e incluye, desde el punto de vista administrativo, las provincias de Cádiz, Málaga, Granada y Almería. La línea de costa tiene una orientación predominantemente E-O, con dos sectores orientados NE-SO situados cerca del estrecho de Gibraltar y en el extremo E de la costa de Almería (Fig. 1).

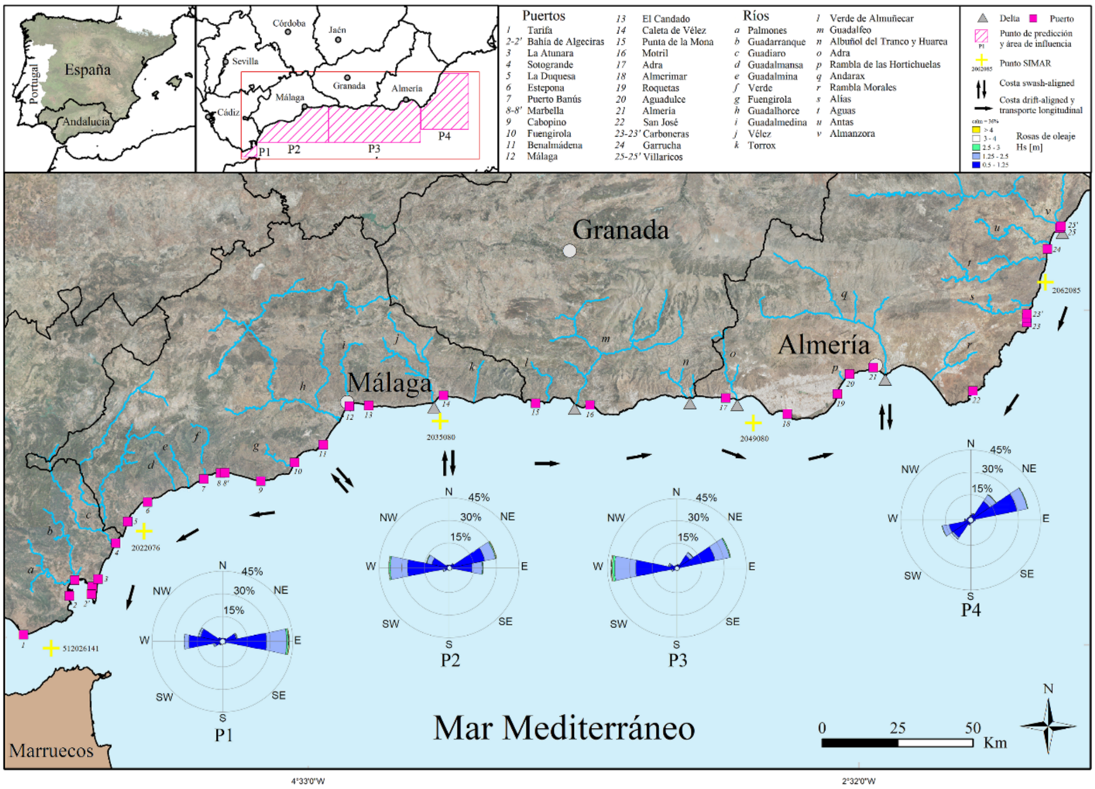

Figura 1. Área de estudio.

La orografía y la morfología costeras las determina la Cordillera Bética, formando una costa muy irregular con acantilados, bahías y promontorios. Al pie de estas montañas se desarrollan numerosas llanuras costeras de pequeño tamaño, principalmente en la desembocadura de ríos de escasa entidad y ramblas que drenan la cadena montañosa, siendo los más importantes los ríos Guadiaro, Guadalhorce, Guadalfeo, Adra y Andarax (Fig. 1). Especialmente, durante episodios de fuertes lluvias asociadas al clima semiárido, las arenas y gravas fluviales constituyen un importante aporte de sedimento al sistema playa-duna.

En las últimas décadas, los planes de regulación de cuencas hidrográficas han promovido la construcción de presas y embalses que han limitado sustancialmente los aportes sedimentarios a la costa, agravando el retroceso costero, especialmente en los principales deltas (Prieto *et al.,* 2012; Guisado *et al.,* 2013).

Las principales formaciones deltaicas de la costa mediterránea de Andalucía están asociadas a algunos de los ríos de mayor importancia: los ríos Vélez, Guadalfeo, Adra, Andarax y Almanzora y las ramblas de Albuñol y Huarea. El delta del río Vélez es un buen ejemplo de comportamiento erosivo: la desembocadura del río presenta materiales no consolidados que son muy susceptibles a la erosión y se depositan en los márgenes del delta debido a la deriva dominante (Prieto *et al.,* 2012). Esto también ocurre en los deltas de los ríos Guadalfeo y Andarax (Prieto *et al.,* 2012), en el delta del río Ebro (Jiménez y Sánchez-Arcilla, 1993) y en el del río Arno (Pranzini, 2007). En muchas de estas áreas se han sucedido numerosos trabajos periódicos de regeneración artificial de playa con el fin de estabilizar la línea de costa (Malvárez *et al.,* 2000; Prieto *et al.,* 2012; Guisado-Pintado y Malvárez, 2015; Berguillos, 2016, 2017).

Respecto a las características de las playas del litoral mediterráneo de Andalucía, se pueden diferenciar dos grandes grupos: las playas de Cádiz, Málaga y Granada, con un ambiente micro-mareal (amplitud mareal < 20 cm), de tipo intermedio a reflectivo que se componen comúnmente por arenas oscuras de medias a gruesas y/o gravas en la desembocadura de ramblas, mientras que las playas de Almería, de tipo disipativo, se componen de arenas finas/medias ricas en cuarzo (Guisado y Malvárez, 2009; Sanjaume Saumel y Gracia Prieto, 2011; Williams *et al.,* 2012; Mooser *et al.,* 2018). A menudo, las playas se ven interrumpidas por sectores rocosos o promontorios que dan lugar a calas o playas en bolsillo (*pocket beaches*) de diferentes tamaños y elevado valor paisajístico (Williams *et al.,* 2012).

En cuanto a ocupación del litoral, las mayores ciudades costeras son Málaga (>500.000 habitantes), Almería (200.000 habitantes) y las ciudades turísticas situadas en la parte oeste de la Costa del Sol, es decir Marbella (150.000 habitantes), Fuengirola (80.000 habitantes) y Torremolinos (70.000 habitantes). Los puertos comerciales más importantes se encuentran en Almería, Cádiz (especialmente en la Bahía de Algeciras), y Málaga donde, además, se encuentran numerosos puertos deportivos, esencialmente en la Costa del Sol (Malvárez *et al.,* 2000, 2003; Manno *et al.,* 2016).

Respecto a las características climáticas, las provincias de Cádiz, Málaga y Granada tienen un clima mediterráneo subhúmedo-húmedo (desde el estrecho de Gibraltar hasta el área occidental de la provincia de Málaga) y seco-subhúmedo temperado (provincias de Málaga y Granada) (Gómez-Zotano *et al.,* 2015). La orientación de la costa y la presencia de la cordillera Bética, que resguarda la zona de los vientos fríos septentrionales, favorecen temperaturas medias anuales de unos 15ºC y de 19ºC. Las precipitaciones anuales son de 600 a 1.000 mm, siendo más abundantes en el área del estrecho de Gibraltar (Gómez-Zotano *et al.,* 2015). La provincia de Almería presenta un clima mediterráneo semiárido-árido, con episodios de lluvias muy escasos (< 200 mm/año en algunos puntos, Gómez-Zotano *et al.,* 2015), y una temperatura media anual de 21ºC y de 26ºC en julio y agosto (Chica Ruiz y Barragán, 2011).

La costa se expone, en general, a vientos provenientes de E a O y de NNE a SO en el área más oriental de Andalucía (Fig. 1 y 2), con velocidades mínimas y máximas que oscilan entre los 0,4 a 9,0 m/s (Molina *et al.,* 2019b). El oleaje y el flujo de energía durante las tormentas es muy variable (Molina *et al.,* 2019b, 2020a), ya que la costa de la provincia de Cádiz y la costa oriental de la provincia de Almería se ven afectadas principalmente por las tormentas que provienen del este, mientras que las provincias de Málaga, Granada y, parcialmente, Almería están expuestas a tormentas provenientes tanto del este como del oeste (Molina *et al.,* 2019b; 2020a). El oleaje muestra un comportamiento claramente estacional, registrando condiciones de tormenta durante los meses de invierno (Noviembre-Marzo) (Pita López, 2003; Guisado *et al.,* 2013; Molina *et al.,* 2019b). Debido a la orientación de la costa, los vientos predominantes del este asociados a condiciones de tormenta dan lugar a condiciones de oleaje que generan una deriva litoral preferente del oeste (Pita López, 2003), aunque en algunos sectores se produce, de forma particular, una deriva opuesta (Guisado *et al.,* 2013; Molina *et al.,* 2019b).

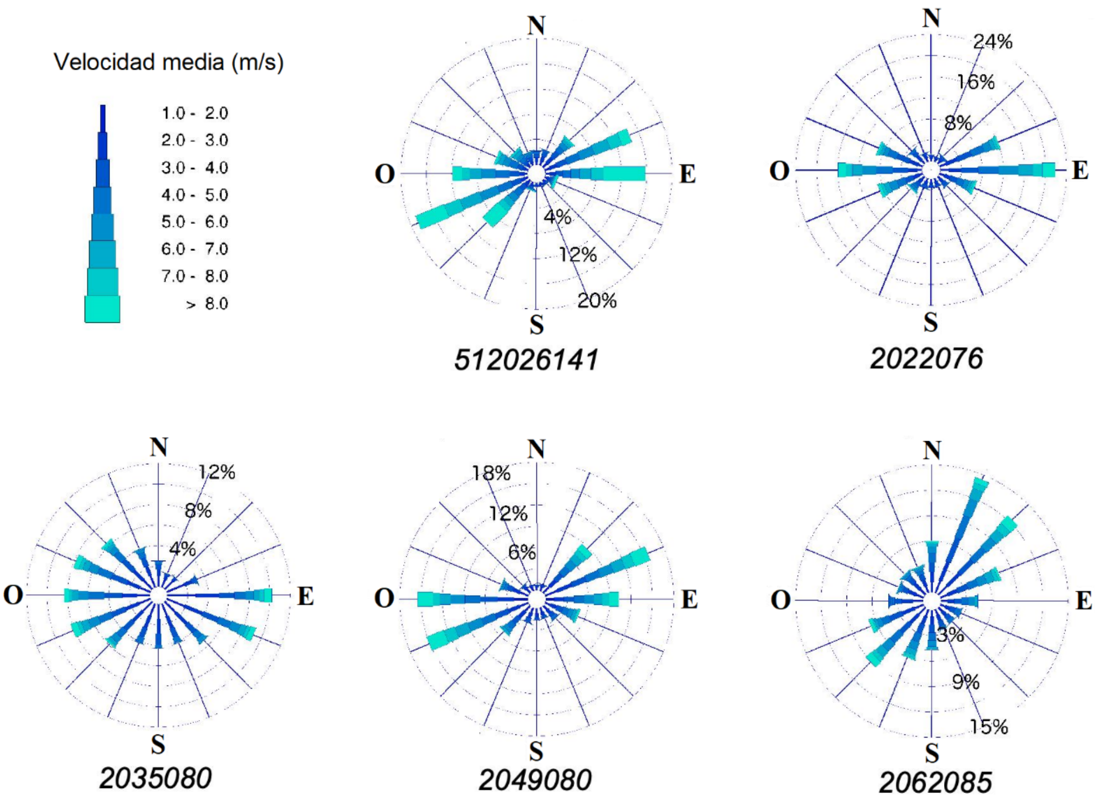

Figura 2. Rosas de viento modificada de Molina et al. *(2019a).*

3. Material y métodos

Para la determinación de la línea de costa y la cartografía de las dunas se han utilizado las ortofotografías aéreas disponibles de los años 1956, 1977, 2001, 2010 y 2016, obtenidas a través de los servicios *Web Map Services* (WMS) pertenecientes a los servicios *Open Geospatial Consortium* (OGC) de la Red de Información Ambiental de Andalucía (REDIAM) de la Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (Junta de Andalucía) y del Centro de Descargas del Centro Nacional de Información Geográfica que, junto a la Dirección General del Instituto Geográfico Nacional (IGN), dirigen el Plan Nacional de Ortofotografía Aérea (PNOA), organismos autónomos adscritos al Ministerio de Fomento (Gobierno de España), (Tabla 1).

Tabla 1. Características de las ortofotografías aéreas utilizadas.

Año	**Vuelo**	**Color**	**Escala**	**Resolución espacial (m)**
1956	1956-57	Blanco y negro	1:10000	1,0
1977	Iryda 1977-83	Blanco y negro	1:5000	0,5
2001	2001-02	Blanco y negro	1:10000	0,5
2010	PNOA 2010-11	Color	1:10000	0,5
2016	PNOA 2016	Color	1:5000	0,25

Las ortofotografías aéreas del año 1956 se han utilizado para el análisis de la evolución de la línea de costa y no para la cartografía de las dunas debido a la baja calidad de las mismas. Las características de estas ortofotografías, es decir, su baja calidad en ciertas áreas de la costa y su color pancromático, dificultan enormemente el reconocimiento y la definición de sistemas dunares poco evolucionados, de poca altura y/o con vegetación herbácea difícil de distinguir en una escala de grises y que, al tratarse en este caso de un estudio regional, se suman a la dificultad de utilizar una escala de trabajo mayor que si se tratara de un estudio a escala de detalle.

Los mapas se han elaborado en un proyecto GIS mediante la aplicación ArcMap del software ArcGIS, utilizando el sistema de referencia WGS84, UTM zonas 29 N y 30 N. Se han cartografiado todos los sistemas dunares con un mínimo de 100 m de longitud de frente de duna, resultando un total de 53 sistemas dunares y diferenciando las unidades que se describen a continuación:

- Línea de costa;
- Línea de pie de duna;
- Dunas embrionarias y móviles (Tipo I);
- Dunas fijas con céspedes (Tipo II);
- Dunas estabilizadas (Tipo III).

Al ser la costa mediterránea andaluza un ambiente micromareal, la posición de la línea de costa se ha establecido en el límite agua-tierra (Pajak y Leatherman, 2002; Boak y Turner, 2005), y las correcciones se han llevado a cabo teniendo en cuenta las condiciones mareales (*σtd*) y de run-up (*σwr*) de acuerdo a Manno *et al.* (2017). La precisión de las medidas depende de la incertidumbre total (*σT*) asociada a la determinación de la posición de cada línea de costa, que a su vez depende de las características propias de las imágenes utilizadas y de los procesos de digitalización, i.e. error de digitalización (*σd*), precisión vinculada al tamaño del píxel (*σp*), error de orto-rectificación (*σr*) y error de co-registro de la imagen (*σco*) (Moore, 2000).

$$\sigma_T = \sqrt{\sigma_d^2 + \sigma_p^2 + \sigma_r^2 + \sigma_{co}^2 + \sigma_{wr}^2 + \sigma_{td}^2} \qquad (1)$$

La línea del pie de duna se ha establecido en el límite entre el frente de duna vegetado y la playa.

La definición de los ambientes dunares, i.e. Dunas embrionarias y móviles (Tipo I), Dunas fijas con céspedes (Tipo II) y Dunas estabilizadas (Tipo III), se ha basado en la clasificación morfo-ecológica descrita en el manual "Las dunas en España" de Sanjaume Saumel y Gracia Prieto (2011) en el que se definen los hábitats dunares costeros más importantes de España. Los hábitats dunares descritos se corresponden con los Lugares de Importancia Comunitaria (LIC) de la Directiva Hábitat de la Comisión Europea, enumerados en la siguiente tabla (Tabla 2).

Tabla 2. Lugares de Importancia Comunitaria (LIC) descritos en el área de estudio y su correspondencia con las tipologías utilizadas en este trabajo (https://ec.europa.eu/environment/nature/natura2000/biogeog_regions/mediterranean/index_en.htm?etrans=es#list_of_sites)

Lugares de Importancia Comunitaria (LIC)	Clasificación
2110 – Dunas móviles embrionarias 2120 – Dunas móviles de litoral con *Ammophila arenaria*	Tipo I – Dunas embrionarias y móviles
2130 – Dunas costeras fijas con vegetación herbácea 2150 – Dunas fijas descalcificadas atlánticas 2210 – Dunas fijas del litoral del *Crucianellion maritimae* 2230 – Dunas con céspedes de *Malcolmietalia* 2240 – Dunas con céspedes del *Brachyopodietalia* y de plantas anuales	Tipo II – Dunas fijas con céspedes
2250 – Dunas litorales con *Juniperus* spp. 2260 – Dunas con vegetación esclerófila de *Cisto-lavanduletalia* 2270 – Dunas con bosques de *Pinus pinea* y/o *Pinus pinaster*	Tipo III – Dunas estabilizadas

Para el análisis de la evolución de la costa se han estudiado los cambios producidos en la línea de costa, la variabilidad del cordón dunar incluyendo su vegetación y fragmentación y el efecto de las construcciones antrópicas sobre el tramo costero analizado. Para ello se ha utilizado la cartografía generada con software GIS con el fin de realizar una descripción detallada de los cambios que se han producido en las distintas unidades geomorfológicas estudiadas.

Para la estimación de las tasas de evolución de la línea de costa, se ha utilizado la extensión DSAS del software ArcGIS (Thieler *et al.,* 2009a) a través de la que se han calculado los parámetros SCE (*Shoreline Change Envelope*), NSM (*Net Shoreline Movement*), WLR (*Weighted Linear Regression*), LRR (*Linear Regression Rate*) y EPR (*End Point Rate*) (Thieler *et al.,* 2009b). El parámetro utilizado para la clasificación de las tasas de evolución fue WLR y la elección de los intervalos para cada clase se basó en el análisis estadístico de los resultados (Tabla 3), descrito en Molina *et al.* (2019a).

Tabla 3. Definición de las clases de evolución.

Clase	Estado de la playa	m/año
1	Acreción muy alta	≥ + 1,5
2	Acreción alta	≥ + 0,5; < + 1,5
3	Acreción moderada	≥ + 0,2; < + 0,5
4	Estabilidad	> – 0,2; < + 0,2
5	Erosión moderada	> – 0,2; ≤ – 0,5
6	Erosión alta	> – 0,5; ≤ – 1,5
7	Erosión muy alta	≤ – 1,5

El área de estudio se dividió en 47 unidades limitadas por estructuras artificiales y/o naturales.

El análisis de la distribución de las clases de evolución de acuerdo a su localización (libres de estructuras, en correspondencia, aguas arriba o abajo de estructuras de protección y puertos) se realizó a través del software estadístico "R" (http://www.rproject.or).

El análisis de la evolución de los sistemas dunares y la ocupación antrópica se realizó a través de cálculos de superficies y de la fragmentación del pie de duna, utilizando los programas ArcGIS y MATLAB. Debido a la heterogeneidad de los sistemas, los valores obtenidos de fragmentación se normalizaron de acuerdo a una distancia constante utilizando un Índice de Fragmentación (*F Index,* Molina *et al.,* 2020b):

$$F = \frac{l}{L} \tag{2}$$

Donde l es la longitud de los espacios entre fragmentos y L es la longitud total del pie de duna. Los resultados se clasificaron en tres clases utilizando la Función de Rupturas Naturales (Jenks y Caspall, 1971), desde la Clase 1 (“Fragmentación nula o muy baja”, 0,00 < F < 0,06), Clase 2 (“Fragmentación media”, 0,06 < F < 0,16) a la Clase 3 (“Fragmentación alta”, 0,16 < F < 0,41).

4. Resultados y discusión

4.1. Evolución de la línea de costa

De las 47 unidades estudiadas, 9 unidades (70,35 km) presentan la prevalencia de clases de acreción, 19 unidades (89,9 km) presentan prevalencia de estabilidad y otras 19 unidades (124,07 km) muestran prevalencia de clases de erosión. Ninguna de ellas muestra acreción muy alta como clase representativa y sólo una unidad muestra erosión muy alta (Fig. 3).

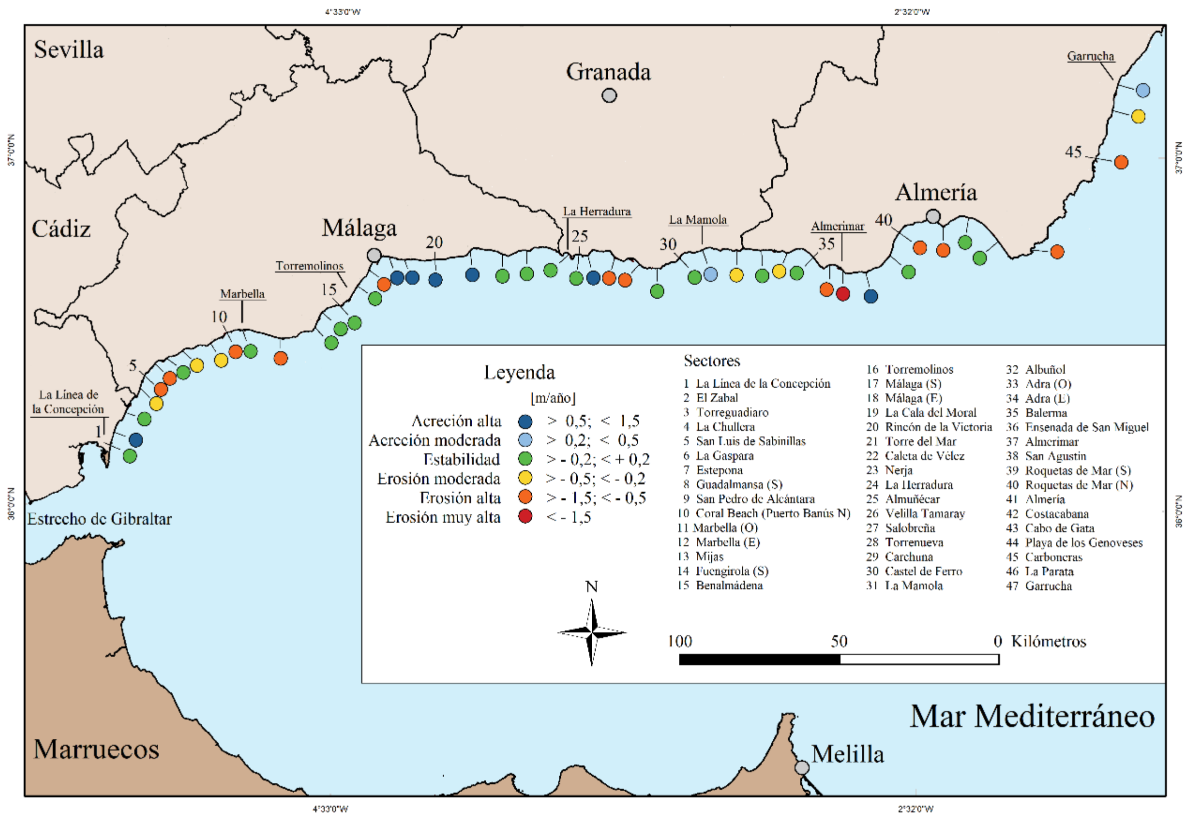

Figura 3. Evolución de la línea de costa.

La distribución de las diferentes clases se muestra en la Fig. 3, en la que se observan dos grandes áreas en erosión a lo largo del SO de la provincia de Málaga y al E de la provincia de Almería y una extensa área constituida por cuatro unidades con acreción muy alta se sitúa al este de la provincia de Málaga. Dentro de esta gran área se intercalan dos áreas estables, una de ellas cerca de Torremolinos (provincia de Málaga) y otra en La Herradura (provincia de Granada). Respecto a las clases de acreción, la más frecuente es la acreción alta (0,5-1,5 m/año), y es resultado del emplazamiento de numerosas estructuras de protección costera y trabajos de regeneración artificial de playa.

Las clases de erosión se observan en áreas cercanas a puertos y estructuras de protección, en deltas y desembocaduras de ríos que han sido intervenidos. Por último, la clase de estabilidad se observa en playas en bolsillo y en algunas zonas que han sido estabilizadas con estructuras de protección costera.

Para determinar con mayor detalle la influencia de las estructuras antrópicas en la evolución de la línea de costa, se ha analizado la distribución de las clases de evolución de acuerdo a la localización de dichas estructuras, en otras palabras, se ha analizado si una zona estaba localizada aguas arriba, aguas abajo o en correspondencia de una estructura, o si se localizaba en áreas “naturales”, es decir tramos del litoral sin estructuras. Además, se han tenido en cuenta las características de las estructuras, la dirección de los frentes de aproximación del oleaje y la dirección prevalente del transporte longitudinal (Molina *et al.,* 2019a).

4.1.1. Sectores naturales

En la costa mediterránea de Andalucía, los sectores costeros naturales estudiados muestran una tasa media de erosión de 0,17 m/año y no se registra acreción en ninguno de ellos (Molina *et al.,* 2019a) (Fig. 4a). Es más, las áreas estudiadas situadas en deltas y desembocaduras de ríos son las que muestran tasas de erosión más elevadas, de 0,62 m/año de media, alcanzando valores de erosión alta y muy alta. Algunos ejemplos son los deltas de los ríos Adra (1,88 m/año) en la provincia de Almería y el delta del río Vélez (3,71 m/año) en la provincia de Málaga (Molina *et al.,* 2019a).

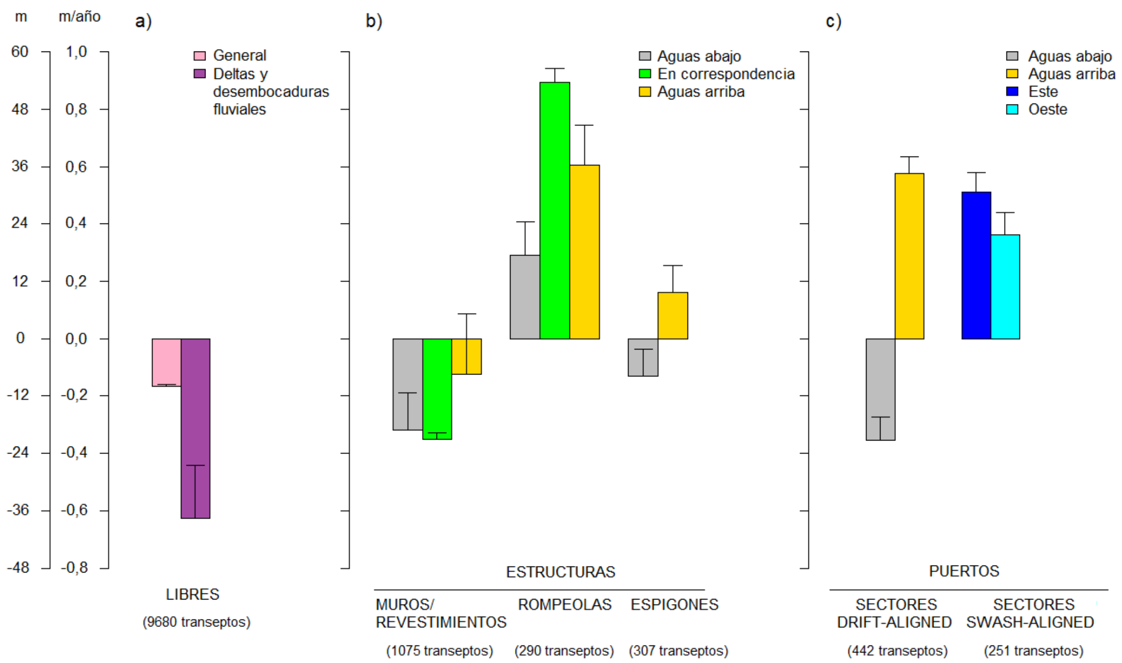

Figura 4. Valores y tendencias de las tasas de evolución según su localización: a) en áreas libre de estructuras, diferenciando entre áreas libres en general y áreas localizadas en correspondencia de desembocaduras fluviales y deltas; b) áreas aguas arriba, aguas abajo o en frente a estructuras (muros/revestimientos, rompeolas y espigones); y c) aguas arriba y abajo de puertos en costas drift-aligned (áreas costeras donde se observa una dirección clara de transporte longitudinal) y lados este y oeste de puertos en costas swash-aligned (áreas costeras donde la dirección de transporte es bidireccional y/o transversal). Entre paréntesis se muestra el número de transeptos estudiados de cada tipo.

En la provincia de Almería (Fig. 1 y 3), la evolución erosiva de los deltas y el área oriental de la provincia está muy influenciada por la naturaleza torrencial de los ríos y otros arroyos, además de por la progresiva construcción de presas que reducen considerablemente los aportes sedimentarios al litoral (Viciana Martínez-Lage, 2007). Esta tendencia general se ha observado también en otros deltas en Andalucía como los de los ríos Vélez y Guadalfeo (Fig. 1, Prieto *et al.,* 2012), en los deltas del río Ebro en Cataluña (Jiménez y Sánchez- Arcilla, 1993), y del Arno en Italia (Pranzini, 2007).

En las playas en bolsillo (*pocket beaches*), se observa estabilidad y un comportamiento típico pivotante (Valdemoro y Jiménez, 2006), como por ejemplo en la playa de La Herradura, en la provincia de Granada (Fig. 1 y 3). Este comportamiento se debe a que las playas en bolsillo son sistemas sedimentarios restringidos que experimentan muy poca o ninguna conexión con otros sistemas debido a la presencia de promontorios rocosos que las limitan (Dehouck *et al.,* 2009).

4.1.2. Sectores influenciados por estructuras antrópicas (presas y estructuras de protección)

En sectores arenosos, la distribución espacial de áreas en acreción, erosión y estabilidad se encuentran esencialmente influenciadas por el emplazamiento de estructuras de protección costeras, puertos y promontorios naturales, y por la forma en la que estas estructuras interaccionan con el oleaje, tal y como se ha observado en otras áreas (Manno *et al.* 2016; Anfuso *et al.,* 2007; Bray *et al.,* 1995; Pranzini *et al.,* 2018).

Como se ha mencionado antes, los ríos han visto menguada su capacidad para aportar sedimento al litoral debido a las numerosas intervenciones que se han llevado a cabo en los últimos años. Como ejemplo, en el río Verde (provincia de Málaga, Fig. 1 y 3), se encuentra la presa de La Concepción, la obra de ingeniería fluvial más importante de la Costa del Sol: antes de la construcción de esta presa, el río Verde constituía la principal fuente de sedimento del área costera de Marbella (Del Río y Malvárez, 2016).

Respecto al efecto de las estructuras de protección costeras, éste varía dependiendo del tipo de estructura (Molina *et al.,* 2019a), como se observa en la Figura 4b. Los muros y revestimientos reflejan la energía del oleaje, restringiendo la migración natural del sedimento hacia tierra e induciendo a la erosión y a la pérdida de las playas que se encuentran frente a estas estructuras (Griggs, 2005; Dugan *et al.,* 2011). Específicamente, las áreas estudiadas que se localizaron frente a este tipo de estructuras, así como las que se encontraban aguas arriba y abajo de ellas, se caracterizaron por registrar valores de erosión altos (desde 0,13 a 0,35 m/año) (Figura 4b). En cuanto a los rompeolas, éstos producen tómbolos (Nordstrom, 2000; Miles *et al.,* 2001), muy frecuentes en la provincia de Málaga (p. ej., Málaga y Puerto Banús, Fig. 1). En las áreas caracterizadas por la presencia de rompeolas se registró acreción, especialmente donde estas estructuras eran muy numerosas. Este tipo de estructuras son mucho más efectivas reteniendo sedimentos respecto a los espigones y muestran valores medios de acreción de hasta 0,89 m/año, cercanos a los valores que se registran aguas arriba de puertos (Figura 4b y c). Las estructuras perpendiculares a la orilla (diques y espigones) y los puertos actúan como límites absolutos o permeables de celdas (Bray *et al.,* 1995) que afectan a la circulación de la zona de surf y, normalmente, producen acreción aguas arriba y erosión aguas abajo, tal como observado también por Rangel-Buitrago *et al.* (2012, 2018) a lo largo de la costa caribeña de Colombia o por Anfuso *et al.* (2013) en el sureste de Sicilia. En este trabajo, los valores medios registrados en las áreas aguas arriba y abajo de estas estructuras reflejan el efecto del trasporte longitudinal: valores medios de acreción aguas arriba de 0,16 m/año y de erosión aguas abajo de 0,13 m/año (Fig. 4 b). En cuanto a las áreas cercanas a puertos, éstas se dividen en dos grupos: áreas aguas arriba y abajo cuando los puertos se encuentran en sectores costeros *drift-aligned* (áreas costeras donde se observa una dirección clara de transporte longitudinal) y áreas este y oeste cuando los puertos se encuentran en sectores *swash-aligned* (áreas costeras donde la dirección de transporte es bidireccional y/o transversal).

Las áreas localizadas aguas arriba de los puertos registraron los valores más altos de acreción respecto a aquellas localizadas en correspondencia de todos los demás tipos de estructuras, y los valores de erosión se observaron en áreas aguas abajo (Figura 4c), una tendencia común a lo largo de costas arenosas (Dugan e*t al.,* 2011; Miles *et al.,* 2001). Los puertos situados en sectores *swash-aligned* muestran acreción a ambos lados (Fig. 4c). La forma y dimensiones de las playas recién formadas dependen de las características de las estructuras y del régimen de oleaje, tal y como han observado diferentes autores en diversas áreas (Manno *et al.,* 2016; Anfuso *et al.,* 2012; Bray *et al.,* 1995).

Cabe señalar que la evolución de la línea de costa no se ha producido siempre de manera uniforme, es decir, se ha registrado una inversión en la tendencia, normalmente de erosión a acreción, en muchos lugares puntuales en los que la tendencia erosiva se ha contrarrestado con la construcción de estructuras costeras y/o regeneraciones artificiales de playa.

4.2. Evolución de los sistemas dunares

En cuanto a los sistemas dunares, se han calculado y clasificado las superficies de las dunas y se ha analizado la variación de éstas para el periodo 1977-2016. Un total de 15 sistemas dunares desapareció durante el periodo estudiado, 7 de ellos localizados en la provincia de Málaga, otros 7 sistemas en la provincia de Almería y un sistema en la provincia de Cádiz. La comparación de la superficie total de dunas en erosión y en acreción muestra un claro balance negativo en 49 de los 53 sistemas y positivo para los 4 sistemas restantes (Fig. 5). Finalmente, para determinar con mayor detalle la influencia de la presión antrópica sobre la evolución de las dunas, se han calculado las superficies ocupadas por estructuras y/o intervenciones humanas dentro de cada sistema dunar y su continuidad lateral a partir de un índice de fragmentación del pie de duna (Molina *et al.,* 2020b).

La erosión o la completa desaparición de los sistemas dunares se pueden producir como consecuencia de actividades humanas o por procesos naturales (Hesp, 2002; Sanjaume Saumel y Gracia Prieto, 2011), siendo los impactos antrópicos los más evidentes en el área de estudio, especialmente en las costas de las provincias de Málaga y Almería (Viciana Martínez-Lage, 2007; Malvárez *et al.,* 2000; Sanjaume Saumel y Gracia Prieto, 2011; Prieto *et al.,* 2012; Gómez-Zotano, 2014; Del Río y Malvárez, 2016; Manno *et al.,* 2016; Castaño Camero *et al.,* 2017; Díez-Garretas *et al.,* 2019; Molina *et al.,* 2020b).

En el área de estudio se han encontrado muy pocos casos de sistemas dunares en áreas naturales que permanezcan sin alterar, bien por la ocupación de su superficie o por la presencia de estructuras de protección costeras y, en general, se encuentran en erosión.

Las condiciones para la formación y el desarrollo de las dunas han sido discutidas por un gran número de autores quienes concuerdan que los factores más importantes que controlan la relación del sistema playa-duna son la variación temporal de los aportes sedimentarios y los regímenes de viento (Hesp, 2002; Nordstrom, 2000; Martínez y Psuty, 2008). En este trabajo, los pocos casos de sistemas dunares en acreción se asocian a procesos naturales de sedimentación, o ligados a la presencia de estructuras antrópicas, registrados en las playas directamente ubicadas en frente de los sistemas o al suministro de sedimento de los ríos que desembocan en su correspondencia.

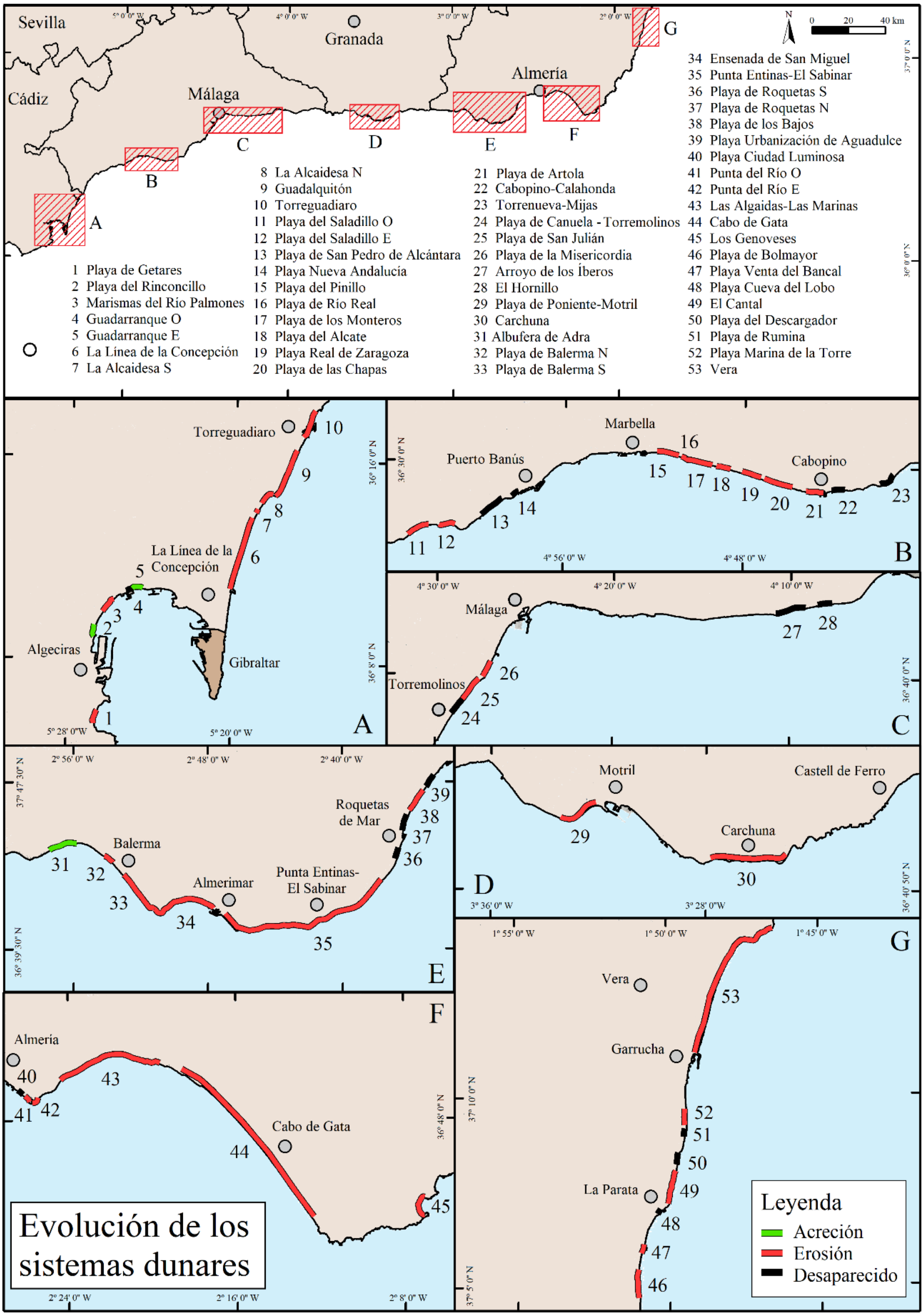

Figura 5. Resultados de la evolución de los sistemas dunares.

4.2.1. Sistemas en erosión

Respecto a los 53 sistemas dunares estudiados, todos menos 4 registraron una reducción de su superficie, o incluso su desaparición (Fig. 5), especialmente en los lugares donde los sistemas se han visto afectados por intensas intervenciones humanas (Gómez-Zotano, 2014; Díez-Garretas *et al.,* 2019; Castaño Camero *et al.,* 2017; Viciana Martínez-Lage, 2007; Sanjaume Saumel y Gracia Prieto, 2011) y, secundariamente, por la pérdida de superficie producida por la erosión de la línea de costa (Viciana Martínez-Lage, 2007; Fernández-Salas *et al.,* 2009; Malvárez *et al.,* 2019).

La mayor pérdida de superficie de dunas se produjo en el periodo 1977-2001 debido a la ocupación urbana masiva de las áreas costeras, no obstante, en el periodo 2001-2016 se ha observado una disminución de la superficie de las dunas debido a que las principales causas de su destrucción registradas en el periodo anterior cesaron parcialmente. Aún se siguen observando casos de desaparición por ocupación urbana, especialmente en la provincia de Málaga (Gómez-Zotano, 2014; Molina *et al.,* 2020b), sin embargo, la presión antrópica derivada del uso turístico de las playas y la disminución de las contribuciones de los ríos no fueron tan evidentes en el periodo 1977-2001 (Malvárez *et al.,* 2000; Castaño Camero *et al.,* 2017; Viciana Martínez-Lage, 2007; Sanjaume Saumel y Gracia Prieto, 2011).

La pérdida de superficie de dunas ha estado relacionada con la fragmentación del pie de duna (es decir, el incremento de la discontinuidad del cordón dunar), la cual es un factor a considerar para la estimación de la vulnerabilidad costera y la sensibilidad de las dunas (Gracia Prieto *et al.,* 2009; García-Mora *et al.,* 2001; Rangel-Buitrago y Anfuso, 2015; Rizzo *et al.,* 2018) ya que un sistema dunar fragmentado es más sensible a la inundación temporal que se da durante las tormentas (Gracia Prieto *et al.,* 2009; Rangel-Buitrago y Anfuso, 2015; Rizzo *et al.*, 2018). En este estudio, los sectores más fragmentados (y por tanto más susceptibles) se han observado en un área natural en el lado oeste del delta del río Andarax en la provincia de Almería (se trata del sistema más fragmentado, Fig. 1 y 5), y el sistema dunar de la playa de Las Chapas en la provincia de Málaga, situado en un área urbana fuertemente desarrollada (Fig. 1 y 5). En la mayoría de los sectores la fragmentación de las dunas se debe principalmente a la apertura de caminos y a su progresiva expansión debido a procesos de erosión marinos y eólicos, también observados en otras áreas por Gracia Prieto *et al.* (2009), Pintó *et al.* (2014), Rangel-Buitrago y Anfuso (2015) y Rizzo *et al.* (2018). Debido al detalle de las ortofotografías utilizadas en este estudio, las discontinuidades causadas por procesos de *overwash* se han podido detectar en muy pocos lugares.

En resumen, la mayoría de los sistemas dunares que han mostrado una disminución en su superficie han sido afectados por factores antrópicos, subrayando la importancia de las ocupaciones urbanas y agrícolas que han sido muy relevantes en las provincias de Málaga y Almería.

4.2.2. Sistemas en acreción

En cuanto a los 4 sistemas dunares que han registrado acreción, el incremento de los sistemas situados en la Bahía de Algeciras (Fig. 1 y 5) está asociado a los procesos de sedimentación registrados en sus respectivas playas (Molina *et al.,* 2019a; REDIAM, 2016) que reciben un suministro de sedimento de los ríos Palmones y Guadarranque (Sanjaume Saumel y Gracia Prieto, 2011). Además, estas playas se localizan cerca de dos grandes estructuras de protección costeras que promueven los procesos de sedimentación (Fig. 5 y 6). Sin embargo, los sistemas en Guadalquitón y Albufera de Adra (Fig. 1 y 5) se encuentran en áreas que han registrado una erosión importante (Molina *et al.,* 2019a; REDIAM, 2016) y una ocupación antrópica significativa. El sistema dunar de Guadalquitón registró su mayor incremento durante el periodo 1977-2001, y fue debido a la degradación de la vegetación que facilitó la migración hacia tierra de las dunas (Molina *et al.,* 2020b). La formación de grandes dunas móviles en esta área se debe también a los fuertes vientos del este (Fig. 1 y 2), en especial en playas orientadas a esa dirección. En el caso del sistema dunar de la Albufera de Adra, se produjo una importante pérdida de superficie de dunas en el periodo 1977-2001 debido a la erosión de la línea de costa y a la importante presión antrópica (intensas actividades agrícolas) (Molina *et al.,* 2019a; Prieto *et al.,* 2012; REDIAM, 2016); sin embargo, la sedimentación que se produjo en el extremo norte del sistema (Molina *et al.,* 2019a; REDIAM, 2016) apoyó el desarrollo de dunas móviles (Molina *et al.,* 2020b).

Figura 6. Playa del Rinconcillo (de Molina et al., 2020b). En esta playa se registró un aumento de la superficie del sistema dunar de 732,26 m^2 en el periodo 2001-2006. (A) 1977, (B) 2001 y (C) 2016.

4.2.3. Evolución de los tipos de dunas

Muchos de los sistemas dunares estudiados en este trabajo han sido descritos por diferentes autores (Gómez-Zotano, 2014; Díez-Garretas *et al.,* 2019; Viciana Martínez-Lage, 2007; Sanjaume Saumel y Gracia Prieto, 2011; Fernández-Salas *et al.,* 2009; Malvárez *et al.,* 2019), pero ninguno de ellos ha proporcionado una descripción de todo su conjunto a lo largo de la costa mediterránea de Andalucía.

A la hora de analizar la evolución de cada uno de los tipos de dunas, cabe destacar que cada tipología representa un claro estado de evolución, desde las dunas embrionarias y móviles (Tipo I) hasta las dunas estabilizadas (Tipo III) (Hesp, 2002). El incremento durante el periodo 1977-2016 de las dunas estabilizadas (Tipo III) se debió a la progresiva evolución de las dunas fijadas por céspedes (Tipo II) (Molina *et al.,* 2020b), un proceso natural descrito por Hesp (2002).

Las variaciones de superficie de los diferentes tipos de sistemas dunares fueron relativamente homogéneas. A excepción de la provincia de Cádiz, el resto de provincias mostraron una disminución de los tres tipos de dunas en el primer periodo y, en el segundo periodo, una disminución de los tipos I y III junto al incremento de las dunas de tipo II en todas las provincias excepto Almería. La disminución general registrada en el periodo 1977-2001 se debió principalmente a la ocupación urbana, la explotación agrícola intensiva y la extracción de arenas – actividades que no fueron reguladas hasta la aprobación de la Ley de Costas en 1988 (Gómez-Zotano, 2014; Malvárez *et al.,* 2000; Díez-Garretas *et al.,* 2019; Castaño Camero *et al.,* 2017; Viciana Martínez-Lage; 2007; Sanjaume Saumel y Gracia Prieto, 2011). La destrucción de las dunas se evidencia especialmente en las provincias de Málaga y Almería, donde han desaparecido sistemas de dunas completos: en la provincia de Málaga se perdió una superficie total de 1.766.711 m^2, de la que cerca de 1 x 106 m^2 correspondían a dunas de tipo II y cerca de 600.000 m^2 fueron dunas de tipo III y, en la provincia de Almería, se perdió una superficie de unos 56.300.000 m^2, de la cual unos 4.360.000 m^2 correspondieron a dunas de tipo II. Algunos ejemplos de trabajos que han cuantificado la pérdida de superficie de dunas en áreas específicas son el de Viciana Martínez-Lage (2007) que cuantificó una pérdida de 262 ha de dunas en el Paraje Natural de Punta Entinas – El Sabinar, en la provincia de Almería, debido a las extracciones de arenas, o el trabajo de Gómez Zotano (2014) que cuantificó una reducción del 44,5% de la superficie de dunas durante el periodo 1956-2007 en el área de El Saladillo, en la provincia de Málaga.

El incremento, en el periodo 2001-2016, de la superficie de las dunas de tipo II en la provincia de Málaga estuvo ligado a la degradación de las dunas de tipo III, evidenciado especialmente en el área oeste de la ciudad de Marbella que fue fuertemente afectada por el desarrollo urbano, una tendencia muy común en la provincia de Málaga (Gómez-Zotano, 2014; Malvárez *et al.,* 2000; 2003; Molina *et al.,* 2020b). El incremento de las dunas de tipo III en la provincia de Almería se debió a la estabilización de las dunas de tipo II, en especial en un área cuya línea de costa es estable. En general, en la provincia de Cádiz, se observó un pequeño incremento de dunas de tipo III, y el resto de tipos registraron pequeñas variaciones. Este comportamiento se debió a una presión antrópica baja, las condiciones estables e incluso en acreción del área (Molina *et al.,* 2019a; REDIAM, 2016) y a la acción de los fuertes vientos del este que favorecen el crecimiento y la movilidad de las dunas (Sanjaume Saumel y Gracia Prieto, 2011).

5. Conclusiones

En cuanto a la evolución de la línea de costa, el área de estudio se dividió en 47 unidades; 9 unidades registraron prevalencia de clases de acreción, 19 registraron prevalencia de estabilidad y otras tantas prevalencias de procesos erosivos. Un balance positivo se observó en 17 unidades mientras que 28 presentaron un balance negativo.

Respecto a la influencia de las estructuras costeras, se ha observado acreción en áreas esencialmente localizadas aguas arriba de puertos y espigones y en correspondencia de rompeolas. Las áreas costeras frente a muros y revestimientos han mostrado siempre erosión, la cual fue también relevante aguas abajo de puertos y espigones, así como en las desembocaduras de grandes ríos y deltas (p. ej., los deltas de los ríos Vélez y Adra en las provincias de Málaga y Almería, y el río Verde en Málaga). Estabilidad se observó en muchas playas en bolsillo y en áreas estabilizadas por estructuras de protección costeras.

En relación a la evolución de los sistemas dunares, de los 53 sistemas estudiados, todos menos 4 registraron una reducción de su superficie, o incluso desaparecieron, especialmente durante el periodo 1977-2001 cuando fueron afectados por severas intervenciones humanas, como el emplazamiento de edificios y construcciones turísticas, en especial en la provincia de Málaga y la expansión agraria en la provincia de Almería y, secundariamente por procesos de erosión costera. La pérdida de los sistemas dunares se asoció a la fragmentación del pie de duna, principalmente como consecuencia de la apertura de caminos y su progresiva expansión debida a procesos erosivos eólicos y/o marinos. Un incremento de la superficie de las dunas se observó tanto en áreas naturales como antrópicas en las provincias de Cádiz y Almería, en playas en acreción y/o estables, normalmente en áreas aguas arriba de puertos, o debido a la acción de fuertes vientos del este en playas orientadas hacia esa dirección.

En cuanto a los tipos de dunas estudiados, esto es, dunas embrionarias y móviles (Tipo I), fijadas por céspedes (Tipo II) y estabilizadas (Tipo III), durante el periodo 1977- 2001 se registró, en la mayoría de las provincias, una disminución de la superficie de los tres tipos de dunas. En el periodo 2001-2016, en todas las provincias excepto Almería, se registró una disminución de las dunas de tipo I y III y un aumento de las de tipo II. Este incremento de dunas de tipo II estuvo vinculado a la degradación de las dunas de tipo III en áreas muy antropizadas. En Almería se produjo un incremento de dunas de tipo III, en el periodo 2001-2016, en áreas estables y en acreción.

En definitiva, la costa mediterránea de Andalucía muestra una tendencia general erosiva en cuanto a la evolución de la línea de costa y de los sistemas dunares, siendo la ocupación y presión antrópica factores fundamentales a tener en cuenta en su evolución. Dichos factores, junto con la implementación de estructuras de protección costera, han aumentado considerablemente en las últimas décadas la sensibilidad del litoral frente a la erosión.

Los resultados obtenidos en este trabajo sobre la evolución de la línea de costa y los sistemas dunares pueden utilizarse para mejorar las bases de datos sobre las características de la costa mediterránea andaluza, sobretodo de las dunas, cuyo estudio se ha enfocado en pasado a nivel local sin tener una visión global. Finalmente, los datos obtenidos abren una puerta a la utilización de soluciones para la protección del litoral basadas en la mejora de los ecosistemas costeros que complementen o sustituyan al tradicional enfoque basado en la construcción de obras de defensa rígidas.

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EVOLUTION OF THE BEACH-DUNE SYSTEMS IN THE BALEARIC ISLANDS FROM THEIR GEOMORPHOLOGICAL MANAGEMENT (2000-2021)

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ABSTRACT. In order to restore, maintain and protect the beach-dune systems of the Balearic Islands different management techniques have been applied. They have been based on the artificial emulation of natural processes to favour the recovery of the system, on the installation of elements that prevent the frequenting and on trampling of the dune systems. Some techniques are positive while others have aggravated erosive processes due to a lack of geomorphological criteria. This work analyses good and bad practices on beach-dune systems of the Balearic Islands between 2000-2021.

Evolución de los sistemas playa-duna en las Islas Baleares a partir de su gestión geomorfológica (2000-2021)

RESUMEN. Para restaurar, mantener y proteger los sistemas playa-duna de las Islas Baleares se han aplicado diferentes técnicas de gestión. Se han basado en la emulación artificial de procesos naturales para favorecer la recuperación del sistema y en la instalación de elementos que impidan la frecuentación y el pisoteo de los sistemas dunares. Algunas técnicas son positivas mientras que otras han agravado los procesos erosivos por falta de criterios geomorfológicos. Este trabajo analiza las buenas y malas prácticas en los sistemas playa-duna de las Islas Baleares entre 2000-2021.

Key words: Balearic Islands, beach-dune systems, erosion, restoration, management, recovery.

Palabras clave: Islas Baleares, sistemas playa-duna, erosión, restauración, gestión, recuperación.

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1. Introduction

Coastal dunes represent fragile and dynamic morphological systems fundamental in the balance of the sandy coastline, providing protection functions against erosion. However, these morphologies are located in fragile environments threatened by natural and human factors, with degradation processes that involve the loss of their geo-environmental values and the goods and services they represent.

In recent years there has been awareness of the constant deterioration of natural ecosystems, among which the coastal systems stand out. The stability and balance of dune morphologies are determined by different factors, such as the supply of sand, sedimentary transport rate (Delgado-Fernández, 2011), waves and wind forces (Walker *et al*., 2006), the long-term condition of the beach (Davidson-Arnott *et al*., 2005), the occurrence and magnitude of storms, and vegetation (Miot da Silva *et al*., 2008). The anthropic impact on these morphologies has been widely studied and described, pointing out the causes of their degradation to massive tourist development, construction of promenades, high anthropic pressure, installation of services and the incorrect planning and management that they generate impacts on the system (Carter, 1988; Nordstrom, 2008; Gómez-Piña *et al*., 2002).

To reduce these processes, focused on the loss of beaches, morphologies and vegetation, mitigation strategies have historically been applied through the management and/or defence of the coast, which have conditioned its evolution over the last decades (Lithgow *et al*., 2013). According to Roig-Munar (2011), interventionist actions are determined by the genetic conditions of each space, highlighting:

1. *Hard actions*: structures to resist wave energy, such as breakwaters, in order to retain sediment and prevent coastal erosion.
2. *Soft actions*: they are based on “respect” for the environment, such as artificial beach regeneration (Charlier and Meyer, 1989). These methods generate erosive impacts in the loan sedimentary areas, either submerged or emerged ones (Schooler *et al*., 2019), and imbalances in the area of action (Rodríguez-Perea *et al*., 2000).
3. *Sustainable actions*: they are based on emulating the natural processes with the aim of restoring the dynamic balance between the emerged beach and the dune sector. They need spaces that allow the development of dune morphologies and plant colonization (Roig-Munar *et al*., 2005).

Restoration takes place through the emulation of natural processes that affect the functionality and resistance of the ecosystem (Lithgow *et al*., 2013). According to Psuty and Silveira (2013) the objective is to restore the characteristics in the natural context, being the most suitable to preserve and recover the beach-dune system, since their stability determines the balance of the system as a whole (Roig-Munar *et al*., 2018). Although lately, greater dynamism has been advocated to improve diversity through dune mobility (Arens *et al*., 2013; Delgado-Fernandez *et al*., 2019; Castelle *et al*., 2019).

The structure of the beach-dune systems of the Balearic Islands ranges from the submerged to the emerged area (Figure 1), and can be described based on five sectors described by Servera (1997), Rodríguez-Perea *et al*. (2000), Balaguer and Roig-Munar (2016) and Roig-Munar *et al*. (2018).

Submerged beach is where the *Posidonia oceanica* meadows develop (offshore, 1) and where a redistribution and sediment transport to the emerged beach takes place (nearshore, 2). In the case of the Balearic Islands, the origin of the sediment is a conditioning factor, with a sediment production from biological origin greater than 80%, associated with the *Posidonia oceanica* meadows (Rodríguez-Perea *et al*., 2000; Gómez-Pujol *et al*., 2013).

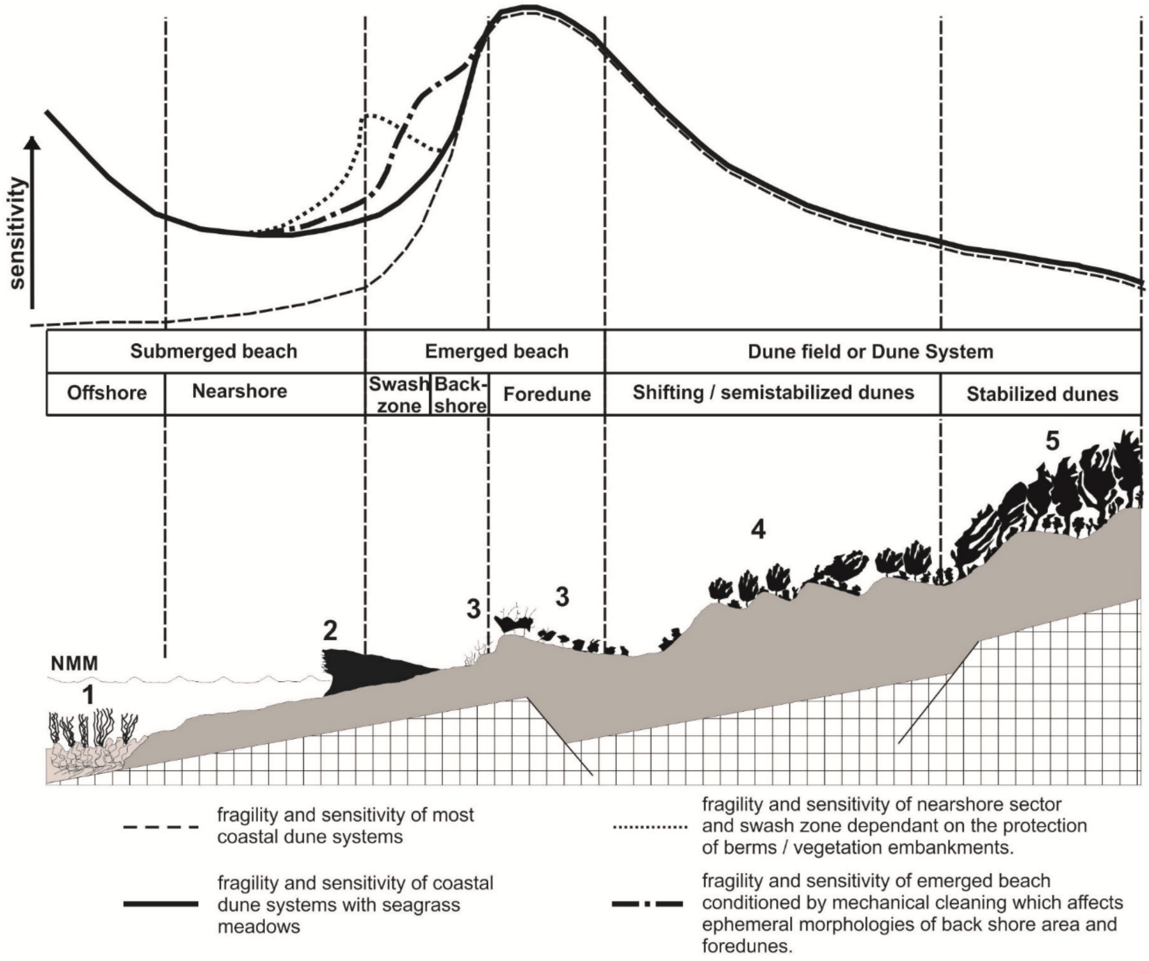

Figure 1. Beach-dune sectors and their different degrees of geo-environmental sensitivity. Source: Roig-Munar et al. *(2018).*

Backshore is the area that shows the sedimentary balance between the submerged and the emerged area. (Woodroffe, 2002). Most of the remains of *Posidonia oceanica* meadows accumulate in the swash zone). Most of the management and maintenance actions are carried out in this area to ensure a good state of the beach.

Foredunes (3 in fig. 1) are characterized by wind processes, only affected by marine processes during episodes of great storms. The first ephemeral morphologies develop with pioneer vegetation. Any alteration of its vegetation can cause rapid destabilization and erosion, giving rise to lobes of deflation (Hesp, 2002; Bouma *et al*., 2013). Foredunes ensures the balance of the beach against strong storms allowing the natural recovery of the beach (Martín-Prieto *et al*., 2009). They also make less strong the force of the wind and marine spray, allowing the development of tree vegetation.

Dune systems are built by a mobile and semi-stabilized area (4 in fig. 1) followed by a stabilized dune area (5 in fig. 1). Behind the foredunes are the mobile dunes fixed towards the interior by the vegetation, configuring the area of semi-stabilized dunes. The extension of this area is usually conditioned to the state of conservation/degradation of the foredune (Hesp, 1988). Edaphic soil increases inland, where the wind deflation processes are lower, and the morphologies are estabilized by shrub and forest vegetation. There is little contribution of sand, and this only takes place during episodes of strong winds, according to the environmental state of the foredune (Lynch *et al*., 2010). Often the vegetation of these areas is shaped by human action for agricultural purposes (Mayol, 2006; Roig-Munar *et al*., 2009).

The degree of sensitivity of the beach-dune systems has been established for those areas where planning and management take place through the sensitivity curve. The first sensitivity curve is located on the *Posidonia oceanica* meadows as a sediment-producing habitat, stabilizer of the submerged beach and dissipator of wave energy (Rodríguez-Perea *et al*., 2000). The second sensitivity curve is located on *Posidonia oceanica* remains deposited on the swash. It works as a buffer against the force of wave storms. The mechanical removal of these vegetal berms gives rise to the continuous erosion of the backshore (Roig-Munar and Martín-Prieto, 2005; Roig-Munar *et al*., 2019). The third sensitivity curve is on the emerged beach, where the mechanical cleaning actions affect the ephemeral morphologies and the destabilization of dune slopes (Roig-Munar, 2004). The fourth one is located on the foredune, which defines their weakening, erosion and/or disappearance of the beach-dune system (Brown and McLachan, 1990; Rodríguez-Perea *et al.*, 2000; Hesp, 2002; Martín-Prieto *et al*., 2009). It is affected by the urbanization, frequentation of users, presence of services and by the degradation of the dune vegetation.

In this way, we can differentiate four critical points in the degree of sensitivity of the beach-dune profile being the front dune sector which gives the stability of the system (Hesp, 2002; Martín-Prieto *et al*., 2007). Not taking these points into account has led to the loss of areas and volumes of the beach-dune, and even their disappearance. Reversing these trends through efforts based on the application of geomorphological criteria has allowed the recovery of several systems in the Balearic Islands (Roig-Munar *et al*., 2017). Working without criteria has aggravated erosive processes, either due to errors in management, monitoring or maintenance.

The goal of this work is to analyse the management carried out over the last two decades (2000-2021) on the front dune sector in 10 dune systems of the Balearic Islands (Table 1, Figure 2). Its geomorphological and its spatio-temporal evolution has been based on the morpho-ecological classification of Hesp (2002). These work analyses the different restoration techniques considered sustainable on the foredune sensitivity curve. Six beach-dune systems have been analysed in Menorca: La Vall, Es Bot, Tirant Son Saura N and Es Grau in the northern coast and Son Bou in the southern coast. Three beach-dune system was analysed in Mallorca: Cala Mesquida at the northeast and Es Trenc-Sa Rapita and Es Carbó in the south. And finally, one system, Es Cavallet, in south Ibiza.

Table 1. Relationship of values for each variable.

Variable	1	2	3	4	5
Beach state	Erosion		Sedim.		Equilibrium
Foredune (Hesp, 2002)	1	2	3	4	5
Neo-morphologies in the foredune	Yes		Medium		No
Inner deflation channels	Yes		Medium		No
Beach	C		B		A
Revegetation	Yes				No
Cordoning	Yes				No
Walkways	Yes				No
Wind fences	Yes		Some		No
***Posidonia oceanica* removal**	Yes	No			
Mechanical cleaning	Yes	No			
Natural area (ANEI)	Yes	No			
Natural park	Yes	No			
Management measures	Yes	No			
Degree of frequentation	Low		Medium		High

Figure 2. Location of the analyzed beach-dune systems.

2. Study area/regional setting

The main source of income for the Balearic Islands comes from tourist activity. Concentrated on its sandy coastline, beaches, "calas" (little pocket beaches) and beach-dune systems, representing an important economic resource (Roig-Munar *et al*., 2015). The lack of knowledge of its natural dynamics by managers has led to aggressive actions causing its alteration (Alonso *et al*., 2002). Since the approval in 2002 of the European Recommendation on the Integrated Management of Coastal Zones (2002/413/CE), both the national administration, as well as the regional administrations with powers on the coast, have developed convergences to consolidate and apply an integrated coastal management (Balaguer, 2012). Over the past decades, different approaches have been applied to the Spanish coastline in order to restore beach-dune systems (Gómez *et al*., 2002; Ley, 2012; Roig-Munar *et al*., 2019). Dune restoration must consider the spatial and temporal scale of their evolution, their different morphologies, structures and functions (Boak and Turner 2005; Martín-Prieto *et al*., 2010). Restoration plans (Gallego-Fernández *et al*., 2011) must be adapted to the geomorphological and topographic characteristics of each action (Roig-Munar *et al*., 2009, 2017). The correction of the erosive processes is recent, on in many occasions the efforts give positive results until re-naturalization, but in other cases the measures are deficient (Martín-Prieto *et al*., 2007; Roig-Munar *et al*., 2018).

The most widely methods used for restoration are wind interference traps, elevated walkways and perimeter cords of dune fronts. The elimination of recreational use on dunes and/or their revegetation have giving satisfactory results in recent decades (Gómez-Piña *et al*., 2002; Lithgow *et al*., 2013; Roig-Munar *et al*., 2015, 2018). Dune restoration techniques must be carried out after analysing the spatio-temporal evolution of the system, identifying the impacts and their causes and effects, as well as the natural and/or anthropic elements that favour their erosion (Hesp and Walker, 2012; Cabrera - Vega *et al*., 2013). Protective measures require monitoring and maintenance.

Based on experiences of sustainable management carried out at the state level, the Ministry of Agriculture, Food and Environment (MAGRAMA) prepared the Manual for sustainable restoration of the beach-dune systems (Ley *et al*., 2007). Nevertheless, the Manual does not consider the need to limit, regulate the criteria that affect the upper beach and the swash zone (Figure 1), such as removals of *Posidonia oceanica* remains and / or mechanical cleaning throughout the beach extension. These two tasks affect the sedimentary balance between beach and dunes (Roig-Munar *et al*., 2019).

3. Materials and methods

Beach-dune interaction models can be evaluable tools for managers to apply management and restoration strategies (Figure 1). Short and Hesp (1982) studied the beach-dune interaction with emphasis on morpho-dynamics and its response to wind and wave energy. Psuty (1990) models provided a starting point to identify the most important variables, such as the supply of sediment between beach-dunes to predict the behaviour of the foredunes. Hesp (2002) carried out a morpho-ecological classification of foredunes based on different conservation stages, where stage 1 represents maximum stability and naturalness while stage 5 represents erosion with a tendency to disappear of the front dune system.

However, this knowledge is far from being used in coastal planning and management, since managers focus on socioeconomic aspects (Ariza *et al*., 2010). Not taking these considerations into account can lead to poor management, where erosion problems continuously worsen over time (Rodríguez-Perea *et al*., 2000; Roig-Munar, 2011; Roig-Munar *et al*., 2018).

Since 2000, restoration actions have been carried out in different beach-dune systems of the Balearic Islands which work with the environmental sensitivity curve (Figure 1) of the dune system. In order to evaluate those actions, we take as a starting point the studies carried out in the Balearic Islands by Roig-Munar *et al* (2012), who established a classification analysis of beach-dune systems through the use of variables and established a temporal evolution model (1956-2004). This methodology should be a management tool for future actions.

For this study, in order to establish an evolutionary trend from 2000 to 2021, fifteen variables (Table 1, 2) have been identified using physical, geo-environmental parameters, (García *et al*., 2001; McLaughlin *et al*., 2002; Hesp, 1998 and 2002), and parameters of status, use and management (Williams and Davies, 1997; Williams and Morgan, 1995; Leatherman, 1997; Laranjerira *et al*., 1999; Roig-Munar *et al*., 2018), following the criteria established by Laranjeira *et al*. (1999) and Roig-Munar *et al*. (2006, 2012). The variables are classified from 1 to 5, with 1 being a very positive indicator and 5 very negative within each parameter, in order to perform a statistical analysis (Table 1):

Table 2. Hesp (2002) values by dune system and year analyzed.

Beach-dune name		***2000***	***2006***	***2012***	***2017***	***2019***	***2021***
Es Grau	GR	4	2	1	1	1	1
Son Saura N	SS	5	4	3	2	2	1
Tirant	TR	5	4	3	5	5	5
Son Bou	SB	5	3	2	2	3	3
Cala Mesquida	CM	5	3	2	2	2	2
Rápita-Trenc	RT	5	4	4	5	5	5
Es Cavallet	CV	5	4	4	4	4	4
Es Carbó	CB	1	2	2	2	2	3
La Vall	LV	3	3	4	3	3	4
Es Bot	EB	2	2	2	3	2	2
Average value		*4,2*	*3,2*	*2,8*	*2,9*	*3,0*	*3,1*

Geomorphological variables (4): beach state, foredunes state (Hesp, 2002), neo-morphologies in the foredune and internal deflation channels in the dune system.

Variables of use and management (11); degree of beach frequentation, removal of *Posidonia oceanica* accumulations, mechanical cleaning, Natural Area of Special Interest (ANEI), Natural Park, and measures of management, protection and recovery (wind fences, cordoning, revegetation and/or walkways).

4. Geomorphological management background

Different management techniques have been applied in several dune systems of the Balearic Islands (Figures 3 and 4). The main ones are described below.

Figure 3. Dune systems of A.- es Trenc, Mallorca, and B.- Es Cavallet, Ibiza. Both systems located in natural parks.

Figure 4. Dune system of A.- Tirant, Menorca, and B.- Son Bou Menorca. Both systems are located in natural areas of special interest.

4.1. Wind interference barriers

The recovery and stabilization of dunes using artificial barriers is a well-known technique (Lithgow *et al*., 2013; Grafals-Soto and Nordstrom, 2009). It is the most used in most of the systems studied. The lack of geomorphological criteria, wind characterization and monitoring and maintenance can compromise their good morphological results.

4.2. Revegetation

Nowadays, this practice extends to many dune systems (Ley *et al*., 2007). It may imply some fixation of the system, a decrease in biodiversity and even the reintroduction of non-native species, favouring and excessive stability of the systems.

4.3. Enclosures

The placement of perimeter cords to avoid the passage of users to the systems allows a slow but progressive recovery of the dune morphologies and their associated vegetation (Acosta *et al*., 2011). On occasions, when the recovery of the dune front takes place, the enclosure has been moved towards the beach to recover its original space (Martín-Prieto *et al*., 2007).

4.4. Walkways

The purpose of this technique is to concentrate the flow of users over dune morphologies. These walkways are installed in the dune system if there are no other alternatives to access the beaches, but always with elevation and orientation criteria.

4.5. Maintenance and monitoring

In dune restoration works, the results are not immediate, but it takes time for the techniques to work. Then, it is necessary to carry out follow-ups from the beginning of the action with seasonal or annual continuity. This monitoring allows an objective and critical view of objectives and results, as well as the response of the dune systems. For monitoring, it is necessary to develop a specific vulnerability index (Williams *et al*., 2001).

4.6. Passive management

In some dune systems, the procedures have been based exclusively on the control of the beach user and the limitation or elimination of mechanized actions on the dune fronts and beach.

5. Results

Results are based on a principal component analysis (PCA) of a matrix defined by the 15 variables and the 10 beach-dune systems evaluated in the years 2000, 2006, 2012, 2017, 2019 and 2021 (900 values). Each variable can be considered as a different dimension, and PCA reduces the dimensionality of a multivariate data to two. The resulting figure shows graphically (Figure 5) with minimal loss of information, which variables are the main components of the statistical analysis, and according to the distribution of the individuals in the graph, clusters can be established to group and describe the phenomena evaluated.

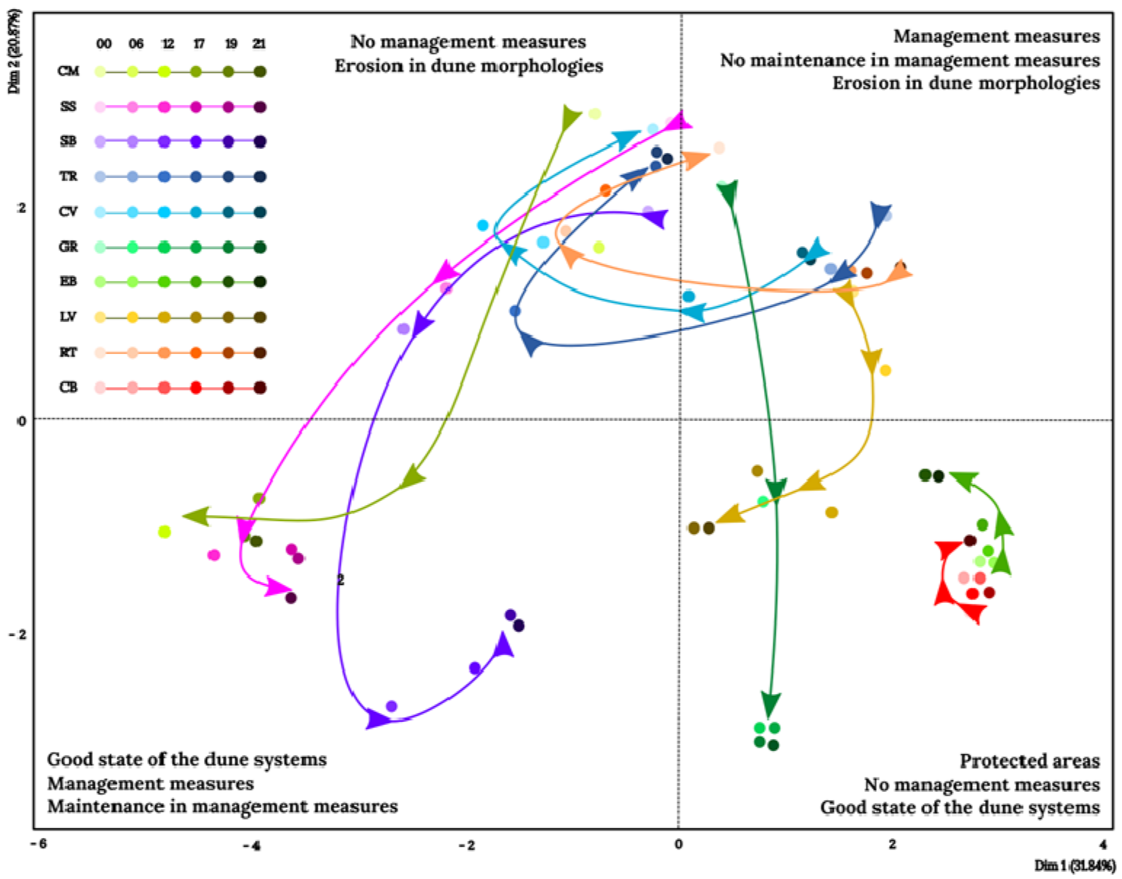

Figure 5. Distribution of dune systems in the factorial space defined for the period 2000-2021.

Components F1 and F2 define a factorial space divided into four quadrants according to the configuration of the values expressed by the set of variables (Figure 5). From the PCA the first two factors explain 52,71% of the variance. The first dimension (31,84% of the variance) is highly positively correlated with protected areas, good status of the foredune according to Hesp (2002) classification and lack of maintenance of management; and negatively correlated with management and maintenance of management.

The second dimension (20,87% of the variance) shows a high positive correlation with the lack of neo-morphologies and bad status of Hesp (2002) classification and presence of some measures (pathways, cordoned areas, mechanical cleaning, sand traps…), whereas the correlation is negative with management and good status of foredune and maintenance of management.

There are four spaces defined by F1 and F2. These quadrants respond to different states of conservation, use and management through their spatio-temporal evolution in the period analysed between 2000-2021:

1. Upper left quadrant: unmanaged beach-dune systems whose dune morphologies show widespread erosion.
2. Upper right quadrant: beach-dune systems where management is applied, but which are not maintained over time and whose morphologies show generalized erosion.
3. Lower right quadrant: these are protected natural areas where a good state of conservation of the dune systems is achieved with few management measures.
4. Lower left quadrant: beach-dune systems with long-term management and maintenance measures that allow optimal geomorphological states of the dune formations.

Throughout the period studied, the beach-dune systems have been analysed through the factorial plane showing a change, both in the management applied, and in their erosive state, always associated with their maintenance. The trend followed by the 10 beach-dune systems are: maintenance of the good state of conservation (CB-Es Carbó and EB-Es Bot), specific changes in the management without improvements in the erosive state of the system and a return to erosive processes (RT-Rapita-Trenc, TI-Tirant and CV-Es Cavallet), and improvement in the erosive state of the dune system linked to comprehensive management actions (CM-Cala Mesquida, SS-Son Saura, SB-Son Bou, GR-Es Grau and LV-La Vall).

The overall trend has been towards the renaturation. Starting from an average value of 4.2 in 2000 the average recovers to 2.9 in 2017 (Table 2). However, some lack of monitoring of measures and their maintenance, in subsequent years, shift the trend towards erosion, with values of 3.1 in 2021. If this management would have been adequate, the recovery trend would have tended towards a value closer to 1 in 2021 in all the analysed dune systems, but the results show us the opposite, a stagnation with a regressive trend. In some cases, like, erosive processes extend towards the interior of the system. Techniques have not been applied adequately in the beach-dune system or not have been adapted for each system.

6. Discussion

The F1 and F2 factors and the distribution of the 10 cases in the factorial space defined for the period 2000-2021, show the importance of the sensitivity curve of the dune system and the Hesp (2002) foredune stages. (2002). The principal component analysis has been able to define beach-dune evolution based on the correct or incorrect procedures carried out and their maintenance. The factorial quadrants express the lack or presence of management and its consequences. Therefore, the resulting evolutionary model allows to establish a predictive model, associated with the response to the management and planning of the system, mainly to different factors that work on the dune front.

Despite this, the procedures have only been applied in the foredunes, and the lack of maintenance or continuity has generated internal erosive processes of the dune system. Appealing to its evolutionary significance, it is observed that the starting point would be that of a hypothetical state of Hesp (2002) on which action is taken with sustainable techniques to re-establish the balance of the system.

Based on the premise of Hesp (2002), it is unlikely that a stage 5 can migrate to a stage 1 under natural conditions. However, it is reasonable to expect that a stage 5 can return to 4 if the geo-environmental conditions are adequate, with a possible advance towards stage 3. In stages 1, 2 and 3, foredunes continue to develop slowly while stage 5 is highly erosive with a tendency to disappear.

The results obtained for each area, determine that the evolution and trend are associated with management measures, with a rapid recovery with non-interventionist measures. The evolution of the different dune systems (Figure 5), shows three groups of behaviours associated with the management carried out on the front dune system. Group 1 (CM, SS, SB, GR LV): those systems start from a situation of degradation of the front dune and have moved from a morphological stage of 5 to 2. They show specific states of erosion due to poor management or lack of maintenance, as in the case of Cala Mesquida or son Saura N. The case of Cala Mesquida shows a stage of equilibrium that can be questioned since there have been processes of fixing morphologies through revegetation, the system is losing its dynamic function, which affects its biodiversity.

Group 2 (RT, TI, CV): these are systems that initiate with the most erosive stage (stage 5) and that despite the management measures have not been balanced or recovered, reaching an average value of 4 in 2017. Their evolution has been similar to the renaturation processes described by Hesp (2002), therefore, the measures have not favoured their recovery and maintenance. Tirant dune system stands out, which with the use of different management techniques (enclosure and barriers firstly), moved towards recovery, reached stage 3. However, in 2017 Tirant returns to a stage 5, that continues until 2021, due to an abandonment in management. The dune system of sa Rapita-Trenc and es Cavallet, despite the economic efforts in the installation of sand traps and enclosures, they have not recovered the continuity of their dune front. Probably a high frequentation of tourists will move these systems into stages 4 and 5.

Group 3 (GR, LV, EB): These systems have moved through erosive processes from an initial stage to stages 1 and 2in Es Grau and Es Bot and the reversion to 4 in the case of La Vall. The most notable of both is that only passive intervention techniques were used. Only user control measures through enclosures and limitation of mechanized actions were implemented. The absence of barrier installations has facilitated the naturalness of the system. Nevertheless, in La Vall extreme storm events affected the stabilization of the front and reactivation of blowouts.

7. Conclusions

The main conclusion of this work is that the use of principal component analysis (PCA) with a matrix, defined with 15 variables, over 10 beach-dunes systems and along a wide period of time, up to 21 years from 2000 to 2021, is a powerful tool to analyse their evolution and the utility of management actions applied on them.

The recovery trend of the front dune system shows a positive evolution until 2017. Nevertheless, all of them show points of reactivation or weakening, associated with the management carried out. From 2017, there is a return to regressive stages.

Dune restoration requires a significant effort, as well as the combination and integration of different environmental criteria. In this way, the benefits and services they provide are maximized. Dune restoration attempts have been partially done in the beach-dune systems described in this work. The geomorphological criteria must be taken into account. The main reasons for this poor implementation can be summarized in the following points:

1. Lack of knowledge of wind dynamics has generated erosive processes associated with the techniques applied, such as accesses or interference traps inside erosive morphologies.
2. Installation of wind interference barriers without considering the sectors of each beach, interferences that they may cause, revegetation and/or walkways with the existing morphologies.
3. Wrong location of dissuasive cords, without following the natural line of the front dune morphology and consolidating erosive processes that favour, in the short term, greater beach areas to the detriment of the dune system.
4. Inadequate installation of walkways, which in some cases lead to the fragmentation of the dune front and increase erosive processes and in others to the burial of the infrastructure itself.
5. The lack of monitoring and maintenance, which offers a bad image to users, generates wind distortion and erosive processes.

The beach management techniques used in the Balearic Islands are widely applied and successful if they are based on geomorphological criteria and geo-environmental analysis for each dune system. Its cost is low, easy to apply and reusable in many cases. They use nature for their purpose and even in the case of mistakes, these can be reversible. It is important to bear in mind that, due to the dynamic nature of these systems, the dune morphological restoration on the coast and its associated vegetation may take time to recover in periods of time that can reach and even exceed 10 years. In general, dune restoration based on sustainable criteria is usually a recurring action over time (Hesp and Hilton, 2011), hence the importance of its monitoring and maintenance.

The observation of long periods of time has not been considered in the restoration of the dune systems of the Balearic Islands. It is necessary in order to make a reliable diagnosis of the evolutionary behaviour of the coastline and its relationship with the front dune systems (Boak and Turner, 2005; Martín-Prieto *et al*., 2008).

Finally, measures that have been carried out in recent years have a markedly aesthetic character. As example, the installation and correction of wind interference barriers, not installed or installed just before the tourist season without previous studies of suitability or follow-up. Moreover, they are normally neglected in winter periods. It also has been found that the actions carried out in recent years –where some beach-dune systems show a regressive trend- have been minimal on the geo-environmental sensitivity curves of the system, some justified by the economic crisis (Roig-Munar *et al*., 2017).

Restoration works would have been more effective with the realization of spatio-temporal studies of each beach-dune system. Also, they need to apply geomorphological criteria on the front dune system and a plan for monitoring, maintenance and evolutionary analysis of each restoration.

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MANAGEMENT OF COASTAL DUNES ON THE CATALAN AND ON THE VALENCIAN COMMUNITY SHORELINES (SPAIN)

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ABSTRACT. Coastal areas constitute one of the most difficult domains to manage, due to the several human activities and natural processes concentrated in it. The case of the coastal dunes is special, since they are so fragile and any intervention on them can cause alterations in the landforms and dynamics. This work assesses the level and role of management and the morphological status of coastal dunes on the Catalan and Valencian shorelines. To that end, ten beach-dune systems from Catalan and Valencian shorelines have been studied to guess how management actions determine the morphological status of them. A set of variables, comprising management actions and morphological status, have been selected and analyzed through a Hierarchical Clustering on Principal Components (HCPC). Results show that the beach-dune systems can be gathered in 2 main groups: those where sustainable management measures were not applied and present an advanced erosive state, and the ones where sustainable management measures were applied and present a good state of conservation. The good state of conservation is related to restoring dunes applying nature-based solutions, whereas degraded morphologies appear when artificial management actions have been carried out.

Gestión de dunas costeras en las comunidades autónomas de Cataluña y Valencia (España)

RESUMEN. Las zonas costeras constituyen uno de los dominios más difíciles de gestionar debido a las numerosas actividades humanas y procesos naturales que pueden concentrarse en ellas. El caso de las dunas litorales es de especial interés dada su fragilidad y el hecho de que cualquier intervención en las mismas puede provocar alteraciones en sus geoformas y su dinámica. Este trabajo evalúa el nivel y papel de la gestión y el estado morfológico de las dunas litorales en las comunidades autónomas de Cataluña y Valencia (España). Para ello, se estudiaron diez sistemas de playa-duna para determinar en qué medida las actuaciones de gestión afectan a su estado morfológico. Se seleccionó un conjunto de variables, que comprendía acciones de manejo y estado morfológico, y se sometió a un agrupamiento jerárquico con análisis de componentes principales. Los resultados muestran que los sistemas playa-duna se pueden dividir en dos grandes grupos: uno en el que no se han aplicado medidas de gestión sostenible y se encuentran en un estado erosivo avanzado, y otro en el que sí se aplicaron medidas de gestión sostenible con un buen estado de conservación. El buen estado de conservación está relacionado con la restauración de dunas a partir de soluciones basadas en la naturaleza, mientras que las morfologías degradadas aparecen cuando se han llevado a cabo actuaciones de gestión artificial.

Key words: Beach-dune systems, coastal dunes management, dune restoration, Catalonia, Valencia.

Palabras clave: Sistemas de playa-dunas, Gestión de dunas costeras, Restauración de dunas, Cataluña, Valencia.

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1. Introduction

The coastal zone constitutes one of the most complex areas in terms of dynamics and management at a global level due to, mainly, its morpho-ecological complexity and fragility, as well as the great amount of population who lives in them (Martínez *et al.*, 2007). In terms of the Global Change, it receives major pressure in sandy coasts, where its intensive use causes serious geo-environmental problems (Defeo *et al.*, 2009).

In our case, the impact of tourism as a mass activity, implemented in Spain in the 1960s and 1970s (Yepes, 2002), has a dominant role in the environmental status of the coasts (Gómez-Pina *et al.*, 2002). Since then, coastal dunes have required an intense management activity that reconciles the land uses and the natural dynamics. The approval of the Coastal Act, in 1988, supposed the beginnings of the pretended regulation and protection of the littoral. Even so, these areas support different human and natural processes, which are objects of multiple interests that sometimes come into conflict. That is why these zones are complex and difficult to handle and this situation strongly requires the adoption of integrated coastal zone management as an indispensable resource for their management.

Attending the coastal dunes of Catalonia and Valencian Community, traditionally, and especially from the XIX century, dune management has been related to pine plantations in order to paralyze the sand to avoid burying the surrounding crops (de Ferrer, 1895). The implications of this affected the whole ecology of the system, and over its sedimentary dynamics (Frigola i Vidal, 1999). Nevertheless, the dune systems of the Costa Brava, until a decade ago, were considered simple resources associated with the tourist industry when actually they constitute very fragile natural systems with multiple values.

In this line, some decades ago, human activities related to tourism, such as urbanization, gardening and trampling, led dunes to a degraded state of conservation of coastal dunes (Brown y McLachlan, 2002; Nordstrom, 2000; Nordstrom *et al.*, 2011). Thus, during the 1990s, checklist methods for analyzing the dune systems came into wide use (Bodéré *et al.,* 1991; Davies *et al.,* 1995; García-Mora *et al.,* 2001; Laranjeira *et al.,* 1999). Recently this method was used again by other authors in arid and Mediterranean areas to assess both vulnerability and resilience of beach-dune systems (Peña-Alonso *et al.,* 2017; 2018; Ciccarelli *et al.,* 2017). Following the same methodology based on checklists, other authors have analyzed the management actions of the beach-dune environments and the degradation of dunes to relate human pressure to the status of dunes conservation (Roig-Munar *et al.,* 2006; Pintó *et al.,* 2014a; Garcia-Lozano *et al.,* 2020; Roig-Munar *et al.,* 2020).

Consequently, the foredune degradation has led to boost dune restoration projects along these sedimentary coasts. In the case of the Costa Brava, Roig-Munar *et al.* (2020) pointed out the relation between the current state of dunes and the management measures in the bays of Costa Brava. Management measures were related to good conserved and/or recovered dunes, and vice versa. An illustrative case is that of La Pletera, a system that was the object of a frustrated attempt of urbanization in the period 1956-1981. However, during the last decade management measures have been carried out to renaturalize the system and balance it. The management of this system has allowed it to recover its dynamics and naturalness (Roig-Munar *et al.*, 2017a).

Dune systems on the Valencian shoreline present a representative and pioneer case of management, the Devesa beach, in the Albufera (lagoon) of Valencian Community. The construction of a promenade, tracks, parkings, dwellings and infrastructures destroyed its ecosystems and natural equilibrium. As a response, from 1982 several projects of dune restoration have been carried out. The measures used were the gathering of species of interests, for their cultivation and replantation, and the removing of foreign species; elimination of the promenade, tracks, parkings and all type of infrastructures, or reduction of its width; reconstruction of dune morphology through the mechanical accumulation of sand and their fixation due to the construction of palisades; and the plantation of proper species of each environment involved. In some cases, the temporary closure through sticks and ropes in the zone in the recovery process has been performed (Quintana Trenor *et al.*, 2016).

Currently, a clear trend to sustainability has been detected, since part of these systems have been the object of sustainable planning and management through soft management measures.

The objective of this work is to assess the different management strategies of dune restoration carried out across the Catalan and the Valencian shorelines and determine how this human action affects the morphological status of dunes. For this purpose, ten beaches, five from Catalonia and five from Valencian Community, have been studied in detail.

2. Study area

The beaches of Catalonia and Valencian Community are made up of a large sedimentary cell, nowadays fragmented by different artificial sediment traps (Pardo-Pascual and Sanjaume, 2019). This area has a strong coastal drift that causes transport and contributes to the distribution of sediment on the coast from the N to the S. It is a sedimentary coast composed mainly of medium and fine sandy beaches, all of which also include some stretches of gravel. Catalan and Valencian Community shorelines comprise beaches that are in town centers surrounded by a high density of buildings; others are found in residential states with a low-density built-up environment; and, to a much lesser extent, others are located beside woodland or cropland with no adjacent developed land.

In Catalonia Garcia-Lozano and Pintó (2018) counted more than 800, of which 110 host some type of dune morphologies. A regression of dune morphologies derived from the lack of criteria in their use and management is denoted, which has affected their conservation (Garcia-Lozano *et al.,* 2020). In Valencian Community there are 328 beaches (Generalitat Valenciana, 2017).

In general terms, the dune systems of Catalonia and Valencian Community assume morphological, erosive and irreversible states, according to the classification of Hesp (2002), due to the effects of natural processes such as sedimentary disruption in river basins, coastal drift and lack of management for restoration purposes (Pintó *et al.*, 2014a, 2019). Additionally, a large part of the beaches is equipped for leisure (Obiol-Menero, 2003) as Valencian and Catalan beaches constitute the basic resource of the tourism industry. Most dunes are foredunes and embryodunes in Valencian Community (Garcia-Lozano *et al*., 2018; Pintó *et al.*, 2016; Sanjaume *et al.*, 2011). This high anthropogenic pressure has also degraded the coastline and contributed to a significant coastal regression (Obiol-Menero and Pitarch-Garrido, 2011; Yepes and Medina, 2005), causing numerous artificial actions to maintain the size of the beach.

In Spain, dune systems have been part of the public domain since the adoption of the 1988 Coastal Act, which was amended in 2013. This Act protects coastal dunes and puts responsibility for its management in the hands of local and regional administrations under the supervision of the state (BOE, 2013). Ownership of the terrestrial maritime public domain therefore continues to be centralized at the state level or at the regional administration level, through territorial planning departments. In this sense, municipalities play an important role in managing beaches, being it their responsibility to manage the seasonal facilities and keep beaches clean and free from waste, as well as making plans for their use before the start of the summer season. In spite of the above, dune systems are subjected to trampling, to their use as areas for sunbathing, to the erosive effects of civil engineering works, and to other disturbances deriving from the lack of management and planning (Gómez-Pina *et al.*, 2002). In addition, the introduction of invasive alien species (Panareda and Pintó, 2015; Pino *et al.*, 2006) threatens the conservation of dune morphologies and species and their more sensitive communities, as well as the stability of these dynamic systems.

The following ten beaches have been chosen to assess them from the point of view of level and role of management and dune conservation status.

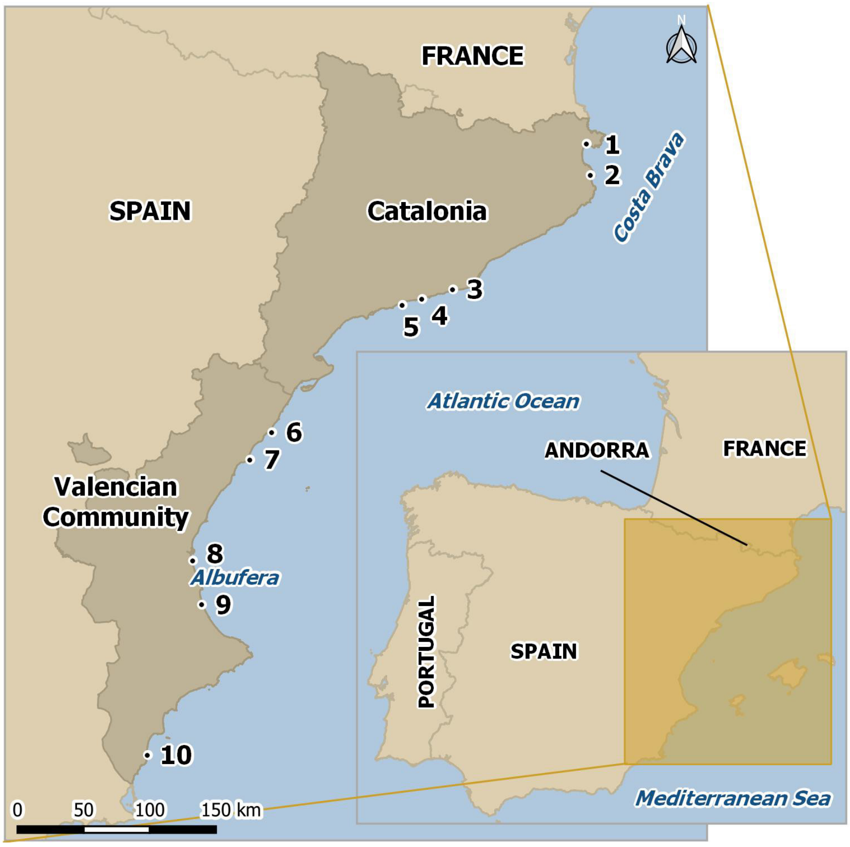

Figure 1. Beach-dune systems studied from the Catalan and the Valencian shoreline: 1. La Rovina, 2. La Pletera, 3. Castelldefels, 4. Els Muntanyans, 5. Platja Llarga, 6. Cabanes, 7. El Pinar, 8. El Saler, 9. Tavernes, 10. Guardamar.

3. Methodology

3.1. Data collecting and description of the variables

The methodology used is an adaptation of the procedure previously applied to assess the vulnerability of dune systems (Bodéré *et al.,* 1991; Davies *et al.,* 1995; García-Mora *et al.,* 2001; Laranjeira *et al.,* 1999). All these works are based on developing indices using checklist procedures, and most of the variables that feature in this analysis have been used previously in the cited studies. We identified and defined 18 variables related to the geomorphological status of dunes and human pressure activities on the beach-dune system. Following the criteria established by Bodéré *et al.* (1991), Davies *et al.* (1995), García-Mora *et al.* (2021) and Laranjeira *et al.* (1999) the variables were classified from 0 to 4, with 0 being a very negative indicator and 4 a very positive one within each parameter.

An analysis of redundancy of the 18 initial variables was carried out by means of a matrix of correlations in order to select a submatrix with nonredundant variables. From this, a matrix defined by 10 non-redundant variables (Table 1) were identified.

Table 1. Details of the 10 variables used for the management actions analysis of the studied systems.

Variables	**0**	**1**	**2**	**3**	**4**
1.Sand traps	Inefficient or absent		Stable		Efficient/ unnecessary
2. Revegetation	Inadequate or absent				Adequate or unnecessary
3. Managed paths	Not regulated	In access	On land	Suspended	Lateral
4. Dune area with restricted access	<25%	>25%	>50%	>75%	100%
5. Mechanical stockpiled sand for artificial dune build-up	Massive		Partially		Absent
6. Type of beach	Urban		Semi Urban		Natural
7. Mechanical cleaning/levelling	Causing dune scarp	Daily	Weekly	Occasionally	Absent
8. Distance from park cars to the beach	0 m	100 m	250 m	500 m	1000 m
9. Area of facilities near the foredune	>10%	<10%	>5%	<5%	0%
10. Status of foredune according to Hesp (2002) classification	Stage 5	Stage 4	Stage 3	Stage 2	Stage 1

The variables 1 to 9 correspond to human pressure and decision making and comprise a synthesis of the most important management measures carried out in the beaches studied from the 90's onward. On the contrary, variable 10 has to do with the morphological status of dunes and was obtained through the field work analysis of each of the 10 beaches during summers of 2020 and 2021. Hence, variable 10 has been considered a consequence of the variables 1 to 9 that correspond to a synthesis of the temporary evolution over decades.

Variables 1 to 9 are parameters related to the management and conservation actions, as well as the implementation of services and equipment in the beach-dune system. Specifically, we evaluated the following soft management measures: sand traps (1), revegetation (2), managed paths (3) or roped off areas (4). Some other actions have been used to measure the anthropic pressure received in the system as mechanical stockpiled sand for artificial dune build-up (5), mechanical cleaning (7), distance from park cars to the beach (8) or the temporary and permanent facilities on the foredune (9). Note that permanent facilities are those located on the foredune during all year long such as showers, whereas temporary facilities are those located during summer season such as beach bars. Finally, the type of the beach (6) has been taken into consideration for the analysis as a potential pressure to the system.

Variable 10 is the current status of the foredune according to Hesp (2002) classification. Geomorphological and ecological characteristics are the main indicators of the state of conservation and development of dunes (Hesp, 1988, 2002). That is the reason why we choose to assess the status of the foredune according to Hesp's classification in order to describe the general status of dunes conservation (Table 2). The five phases of dune degradation described by Hesp (2002) range from State 1 (the most developed natural state of the dune system comprised of a continuous, vegetation-covered foredune with seaward incipient morphologies) to State 5 (the most degraded status of the dune morphologies where small isolated hummocks are evidence of the existence of a former dune ridge currently present only discontinuously along the system). Degradation statuses 2-4 indicate the progressive advance of the erosion processes and the decrease in the vegetation cover of the dune morphologies. In our analysis, these phases have been converted into a 0-4 scale. Hesp (2002) determined that to reverse dune system degradation certain management measures, such as revegetation and the stabilization of the beach-dune system, must be implemented.

The matrix resulting from this classification has been evaluated under the following statistical analysis.

3.2. Statistical analysis

The results of this matrix defined by the 10 non-redundant variables and 10 beach-dune systems (which means 100 cases) have been assessed by means of a Hierarchical Clustering on Principal Components (HCPC) using the *FactoMineR* package from R software. The principal component analysis (PCA) summarizes the information in a chart containing individuals (beaches) and variables. Each variable could be considered as a different dimension, but PCA reduces the dimensionality of a multivariate data to two or three principal components, and performs a cluster analysis of the results obtained from the PCA. After reducing the dimension of the data into few continuous variables containing the most important information in the data, a cluster analysis on the PCA results was performed. Hierarchical clustering is performed using the Ward's criterion on the selected principal components, which is used in hierarchical clustering because it is based on the multidimensional variance like principal component analysis.

The resulting figure shows graphically, with minimal loss of information, which variables are the principal components in a statistical analysis. According to the distribution of individuals on the chart, clusters can be established to group and describe the phenomena assessed.

4. Results

Results reveal a set of values for Catalonia and Valencian Community that define the 10 variables chosen in five beaches of each study area. In the case of Catalonia, beaches of la Pletera and els Muntanyans have the highest values, while Castelldefels and Platja Llarga have the lowest ones. That means that the first two show positive indicators both of the management measures carried out in the system and of the conservation of dune morphologies. On the contrary, the last two systems show negative indicators of management actions and conservation of dune morphologies. In the case of the Valencian Community, the highest values are in Guardamar, while the lowest ones are represented in el Pinar and el Saler. The systems that present medium values of the ten variables analyzed are la Rovina and Platja Llarga beaches, located in Catalonia, and the Cabanes and Tavernes beaches, located in the Valencian Community.

Table 2. Values of the 10 variables studied for the Catalan and the Valencian beaches.

Study area	Beach	1	2	3	4	5	6	7	8	9	10
Catalonia	La Pletera	4	4	4	4	2	4	4	4	4	3
	La Rovina	0	4	1	4	4	4	0	0	2	1
	Castelldefels	0	0	2	2	0	0	0	0	0	2
	Els Muntanyans	4	4	3	4	4	4	3	4	4	3
	Platja Llarga	0	0	0	0	4	2	0	2	0	0
Valencian Community	Cabanes	0	0	0	2	3	2	0	0	4	1
	El Pinar	0	0	1	1	0	0	0	1	1	1
	El Saler	0	0	1	3	0	0	0	1	1	1
	Tavernes	0	0	0	4	4	2	3	4	4	3
	Guardamar	4	4	2	4	3	2	2	3	4	4

The components F1 and F2 define a factorial space divided into four quadrants according to the configuration of the values expressed by the set of variables. From the HCPC the first two factors explain 77,43% of the variance. F1 is highly positively correlated with soft management measures (sand traps, revegetation and roped off areas), the lack of anthropic pressure (type of beach, mechanical cleaning, distance from park cars to the beach and the temporary and permanent facilities on the foredune) and the good status of the foredune according to Hesp (2002) classification. The factor F2 shows a high positive correlation with mechanical stockpiled sand for artificial dune build-up and to a much lesser extent with managed paths.

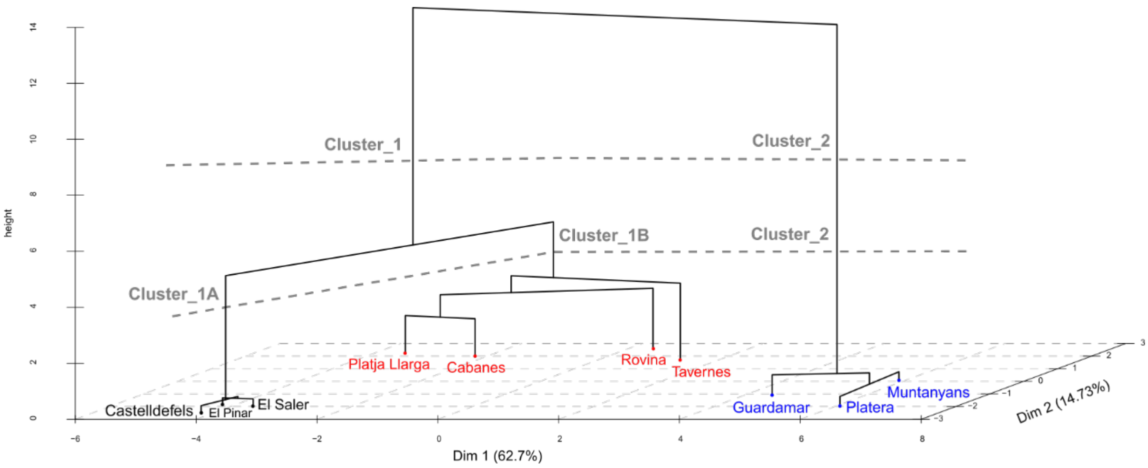

Figure 2. Dimensions and clusters resulting from the HCPC analysis.

The HCPC analysis clearly shows two beach groups: those where sustainable management measures were not applied and that present an advanced erosive state (cluster 1); and the ones where sustainable management measures were applied and that present a good state of conservation (cluster 2). Within the group of degraded systems (cluster 1), two types of beach-dune systems have been defined: those where dune construction has been carried out by mechanical stockpiled sand (cluster 1A) and those without artificial sand humps (cluster 1B).

5. Discussion

Most beaches are included in cluster 1 (7 out of 10) which means that they present degraded dunes and lack sustainable management measures. Pintó *et al.* (2014a) assessed the status of northern Catalan dunes and found highly degraded morphologies by human impacts (such as built environment, car parking and car tracks, beach raking, erosion pathways, dune breaches, invasive species and fixed dunes). Besides, Garcia-Lozano *et al.* (2020) studied 50 beach-dune systems along the Catalan coastline using management measures and the erosive state of foredunes and pointed out that most dunes were degraded and poorly (or not) managed, whereas a few ones presented a good state of conservation. The results of this research reveal that dune management on the eastern coast of the Iberian peninsula is directed to tourism demand of leisures on the upper beach and, consequently, dunes are managed accordingly.

5.1. Types of beach-dune systems

Cluster 1 makes up this group of beaches poorly managed and highly degraded. Sustainable measures of dune management are not applied here and, clearly, two types of management *status* can be distinguished: degraded dunes without management measures, and artificial dunes.

5.1.1. Artificial dunes

Cluster 1a is made up of three beaches (Castelldefels, el Pinar and el Saler illustrated in Fig. 3) where dunes were mechanically reconstructed after disappearing by stockpiled sand (Garcia-Lozano *et al.*, 2018). As an illustrative example, the case of Castelldefels beach (Fig. 3C), located in the Llobregat delta, has been chosen to develop the historical evolution of dune management of Cluster 1a.

The coastal dunes of the Llobregat delta presented sand erosion, instability of the coast of Viladecans and the N of Gavà, sedimentation in the S Gavà and Castelldefels, the construction of Port Ginesta (1985), vulnerability, loss of surface of dune landforms, high frequentation, soil contamination and proliferation of invasive vegetation (Masip *et al.,* 2009). From the 90s onward, cords of sand were artificially piled up, simulating dunes that were later revegetated (Fig. 4). Later, under the Dunas Híbridas project (2014 to 2017 according to Palacios, 2017), new dunes were mechanically performed again and reprofiled some others. Afterwards, *Ammophila arenari*a was used to revegetate dune systems by fences, while invasive vegetation was removed. It is worth highlighting that many individuals of *Ammophila arenaria* from the Dunas Híbridas project died because of the lack of sand movement on the dune ridges. The artificial sand mounds present a granulometric stratigraphy with different grain sizes throughout the vertical segment. However, the dunes of aeolian origin present an ordered stratigraphic segment, with the coarsest and most compacted grains in the lower part and the finer and looser sand in the upper part. This natural arrangement favors the movement of sand grains located in the upper part of the dunes when soft winds blow. The lack of wind dynamics in artificial dunes favors compaction that, over time, ends up being a sandy plot rather than a dynamic dune area.

Figure 3. El Saler beach (A) in summer 2021, el Pinar beach in winter 2019 (B) and Castelldefels beach (C) in spring of 2019.

Castelldefels beach illustrates this phenomenon well, as dune morphologies are compacted and aeolian dynamics scarcely affect the foredunes (Fig. 3). The high frequentation of people and the usual mechanical cleaning of the dry beach avoid developing embryodunes in the upper beach (Fig. 4: right). From a biogeographic point of view, the revegetation was questioned by Panareda and Pintó (2015) and Pintó *et al.* (2014b) that carried out an exhaustive study of the vegetal species of the delta and perceive unsatisfactory results in relation to the vegetation and dune morphology. They describe the dune restoration practice of the 90s as a beach sand garden recreation, where aesthetic and recreational criteria prevail over the natural or ecological function of the dune landscape. The dune morphologies that are recovered are integrated into the promenades with gardening criteria rather than considering dunes as natural habitats.

Figure 4. Evolution of Castelldefels beach from 2008 (left) to 2018 (right). In 2008 cords of sand were artificially piled up. In 2018 artificial dune ridges were fully covered by dune vegetation.

5.1.2. Degraded dunes without management measures

Cluster 1b groups four beaches (Platja Llarga -Fig. 5-, la Rovina, Tavernes and Cabanes). These beaches are featured by the lack of sustainable management focused on the maintenance and recovery of the dune system. The access to the beaches is abundant, both spontaneous and managed. Mechanical cleaning scarps regularly the foredune and difficult the growth of incipient dunes in the upper beach. These pathways are zones vulnerable to erosion, which generates regression of the dune system when storms are of great magnitude. For instance, the Glòria storm caused a large sediment intrusion to reach the interior of the system via its blowouts that are used as unmanaged accesses (Pintó *et al.* 2020).

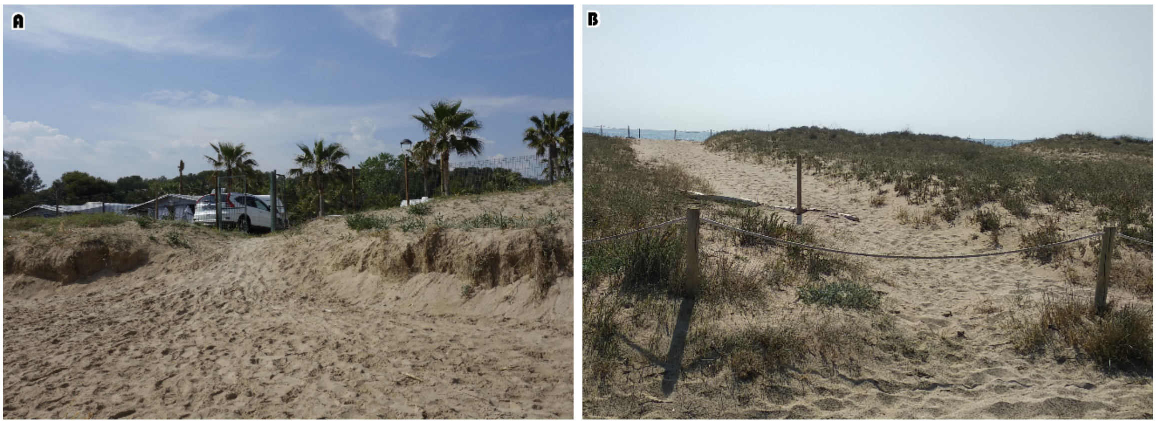

Figure 5. Pathways in Platja Llarga beach in spring 2019 (A) and la Rovina beach in spring 2021 (B). Often, campsites or parkings create unmanaged pathways that erode the foredune; whereas many times roped off dunes are not enough to avoid trampling.

5.1.3. Well-conserved dunes with sustainable management measures

Cluster 2 includes beaches well conserved from a morphological point of view where sustainable management measures were implemented (la Pletera, els Muntanyans and Guardamar) (Roig-Munar *et al.,* 2017). As la Pletera beach-dune system (Fig. 6) has been restored using soft management actions such as sand fences, managed paths, eradication of alien species, revegetation of foredune, and roped off dunes (Roig-Munar *et al.* 2020). Additionally, the deconstruction of the urban area adjacent to the dunes favored the restoration of salt marshes and the recovery of the whole coastal zone. The system evolved toward an erosive state due to the affluence of tourists. The degradation of the foredune morphologies accelerated in a regressive trend until the 2000s, due to the nonapplication of management measures for its recovery. Some sectors of the dune system disappeared and others were composed by isolated incipient dune. In the period 2009–2016 (Fig. 6), the system was subjected to sustainable management measures that allowed slow recovery of the dune system as a whole, migrating toward a state of naturalness. From 2011 onward, the first sustainable management actions were initiated through the use of sand retention fences, revegetation, managed paths, as well as the regulation of facilities on the foredune. During this period, a project of deconstruction of the abandoned area was carried out with the aim of recovering the coastal lagoons and salt marshes.

Figure 6. La Pletera beach in 2002 and in 2016.

In 2016, the system showed that it was in a balanced stage of renaturalization. The extinct line of dune morphologies in relation to the backshore was in the recovery phase; and the roped off areas were moved seaward to increase the width of the dunes. In 2019 the system presented a greater recovery of beach elevation in relation to 2010 and 2016 (Roig-Munar *et al.*, 2019), with a power of 1,63 m, with a volume of 97,185 m^3 in an analyzed area of 62,819 m^2. Therefore, this volumetric recovery reflects the clear trend towards renaturation of the emerged system.

Another interesting case to focus on is that of the Guardamar dunes (Fig. 7) in the province of Alicante (Valencian Community). Guardamar dunes have experienced the invasion of invasive alien species in the dune ridges and in the semi-fixed dunes as well as the destruction of the fixed dunes for the construction of parking areas and the degradation of dune ridges due to the transit of people and vehicles. To deal with it, actions have been taken towards the recovery of this area: the establishment of elevated gangway over the dunes for the people circulation; relocation of parking areas; restriction of access to the sensible zones, limiting the circulation of people and vehicles; restoration of the relief of the dune ridge through the placement of sand collectors across the dunes; elimination of foreign (not tree) species which have invaded the dunes, replacing them by proper species of these ecosystems; repopulation of the dune ridges with proper species and the protection of the recovered sectors; and making citizens aware of the enormous environmental value of dune ecosystems (Ministerio para la transición ecológica y el reto demográfico, 2021).

Figure 7. Guardamar beach in summer 2021

5.2. Limitations against other works

In former studies a spatio-temporal relationship between the variables were obtained, however in our case, we did not dispose of concrete data to analyze the temporal evolution for each studied variable (Roig-Munar *et al.,* 2020). Roig-Munar *et al.* (2020) studied several variables of a beach in different years, what allowed to relate the applied measures in each moment with the degradation/conservation degree of the dunes. Other studies considered the temporal evolution of the coast line, the intensity of storms or the increase in urbanization (Bodéré *et al.,* 1991; Davies *et al.,* 1995; García-Mora *et al.,* 2001; Laranjeira *et al.,* 1999), what also allows to do spatio-temporal study and comparisons with the beach-dune systems status in each moment.

Nevertheless, the present study relates the dominant management measures in each beach from the 1990s with the current geomorphological status, what can be considered a less-detailed study than others (Roig-Munar *et al.,* 2020) and it is rather an approach than a deep spatio-temporal analysis, such as those performed in other parts of the coasts, such as Catalan, Spanish or Italian coasts (Ciccarelli *et al.,* 2017; Pintó *et al.,* 2014; Garcia-Lozano *et al.,* 2020; Roig-Munar *et al.,* 2006; Peña-Alonso *et al.,* 2017; 2018). In fact, management actions carried out in a specific moment (sand stacking or massive revegetation) and their effects along the time have also been studied. Also, it has been considered if other management measures have been implemented sustained over time as for example mechanical cleaning, sand traps, roped off dunes, managed paths or the installation of services in the foredune.

Therefore, the method presented here has some limitations given that the measures considered in the studies above were not known in the 10 beaches examined, as well as the dune status for a concrete year were unknown as well. That is the reason why the present study is an approach, rather than a deep-study, based on the available data.

6. Conclusions

The checklist presented here allowed us to evaluate management techniques on dune areas of the eastern Iberian Peninsula developed coasts. The methodology is easily applicable in dunes with different morphological stages and different management and planning measures applied. Results show that the beach-dune systems can be gathered in 2 main groups: those where sustainable management measures were not applied and present an advanced erosive state (cluster 1), and the ones where sustainable management measures were applied and present a good state of conservation (cluster 2). Cluster 1 was subdivided into 2 subgroups: those beaches with artificial dunes, and those with degraded dunes without management measures. Hence, we found three types of beach-dune systems in the Catalan and the Valencian coastlines: artificial dunes, degraded dunes without management measures and well-developed dunes with sustainable management measures.

In the case of well-developed dunes with sustainable management measures, although the dune system can come from regressive stages before the applied procedures, it is shown that soft actions of an integral character allow the renaturalization of the whole complex, with natural colonization and dynamic processes that give again natural character to the system. In the cases of partial interventions throughout the system (such as degraded dunes without management measures), or interventions that favor fragmentation, their recovery is slower and subject to continuous actions. In the case of the morphologies created by means of stockpiles (artificial dunes group), these initially start from erosive stages or lack of dunes, where spaces without morphologies can be created and can be a good measure for the recovery of extinct dunes or creation of new ones, although their naturalness it is debatable and even its functionality as dynamic morphology and resilient to extraordinary storms events.

To sum up, dunes can be managed according to different objectives, the most important one has to do with the morphological criteria, which will allow for natural evolution, allowing an inherent resistance of the system as the changes associated with erosion, sedimentation or storms. This approach is more coherent with restoration if the objective is to renaturalize the dunes and make them a protection barrier for goods and services located in the shoreline. It is convenient to reach this objective through each beach adapted measures, rather than transformation practices using the artificial creation of dune surfaces.

Acknowledgments

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