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Methodology of data generation and calculation of erosion rates applied to littoral areas: Evolution of the Andalusian shoreline on exposed beaches during the 21st century (2001-2019)

Metodología de levantamiento de datos y cálculo de las tasas de erosión en el litoral: la evolución de la línea de costa andaluza en las playas expuestas para el s.XXI (2001-2019)

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Abstract

This paper describes the methodology used for the data collection and calculation of erosion rates and presents the recent results for the period 2001-2019 for all the beaches of the Andalusian shoreline. This period is divided into two subperiods (2001-2011 and 2001-2019) to detect possible trend changes during the study years. The proxy corresponding to the internal limit of the backshore has been used, which is very useful for medium to long-term coastal erosion rates. The results show the rates calculated for this proxy, which reveal a high presence of artificially stabilised sectors where the inward migration of the shoreline associated with it is hindered, together with an intensification of the retreat rates in natural sections. Similarly, there is a clear differentiation between a relatively dynamic Atlantic façade with a higher percentage of erosive sectors and a Mediterranean façade highly conditioned by anthropic presence, with a lower percentage but a higher intensity in their values.

Keywords: shoreline; exposed beaches; evolution; erosion rates; 21st century; Andalusia.

Resumen

El presente trabajo muestra la metodología seguida para el levantamiento de datos y el cálculo de tasas de erosión, así como el resultado de las mismas durante el período reciente de 2001-2019 para la totalidad de las playas del frente litoral de Andalucía. Dicho período es dividido, a su vez, en dos subperíodos (2001-2011 y 2001-2019), con el objetivo de detectar posibles cambios de tendencia durante los años de estudio. Se ha utilizado el indicador (proxy) correspondiente al límite interno de la playa seca (backshore), de gran utilidad para cálculos de tasas a medio-largo plazo. Los resultados recogen las tasas calculadas para este indicador, las cuales muestran una elevada presencia de sectores estabilizados artificialmente por la presencia de infraestructuras longitudinales que dificultan la migración hacia el interior de la línea de costa asociada al mismo, así como una intensificación del fenómeno erosivo en aquellos tramos libres de infraestructuras. De igual forma, se constata una clara diferenciación entre una fachada atlántica relativamente dinámica con mayor porcentaje tramos erosivos y una fachada

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mediterránea muy condicionada por su presión antrópica, que presenta un menor porcentaje, pero una mayor intensidad en los valores negativos de las tasas.

Palabras clave: línea de costa; playas expuestas; evolución; tasas de erosión; s.XXI; Andalucía.

1. Introduction

1.1. State of the question and objectives

The coastal area is considered as being one of the principal natural transition zones, due to its high ecological and social value that enables it to provide a large number of ecosystemic services, such as climate regulation, the preservation of natural ecosystems, leisure opportunities, etc. (Georgiou & Turner, 2008). All of these factors make the coastal strip a space that is highly sensitive to the pressures exercised on it by the increasing human presence in littoral areas. In this respect, coastal erosion is one of the principal processes that has been intensified by this pressure. According to Mentaschi et al. (2018), approximately 2.8 million hectares of coastline have been eroded over the past 30 years on a global scale, approximately twice the area gained by accumulative processes.

Andalusia, the area of study for this article, with more than 900 km of coastline, is one of the most highly demanded tourist destinations on a national and international level, which has led to an exponential increase in the anthropic pressure on the shoreline. The anthropic pressure exerted on extensive sectors of the Andalusian coast, with the Costa del Sol as a paradigm of the sun and beach tourism model and the resulting urbanisation of the area, has led to the mass occupation of land that is vitally important for the coastal systems. The definitive sealing of the areas close to the coast alters the necessary adjustments of the transversal beach profile, fostering the loss of vital sedimentological resources for the natural regeneration of the dune system and, therefore, of the beach over time.

On the other hand, coastal erosion is closely related to the concept of sedimentary balance, understood as the net volume of sediments transported in a specific area during a certain period of time and to the coastal dynamics that transport them, generating processes of erosion or accumulation (Komar, 2018). The movement of sedimentary material on the beaches is, therefore, a volumetric phenomenon, and its comprehensive study would require data sources that provide tri-dimensional data of the whole transversal profile of the beaches (digital terrain models, LiDAR data, etc.). Due to the difficulty involved in obtaining these data retrospectively in medium to long term studies, it is more common to use the changes in the shoreline to calculate different proxies in which their oscillations (advances or retreats) are quantified. There are many studies that use these proxies in the international scientific literature (Esteves et al., 2009; Moore et al., 2006), in a national scale (Di Paola et al., 2020; Pérez-Alberti et al., 2013) and for the coast of Andalusia (Gracia et al., 2005; Molina et al., 2019).

The overall objective of this study is to show the results of the evolution of the shoreline for all of the exposed beaches of the autonomous region of Andalusia, generically expressed as erosion/accumulation rates (in this case understood as rates of retreat / advance of the shoreline) through the proxy that we have considered to be most appropriate, taking as an overall time reference the period 2001-2019. In turn, the following specific objectives are also sought:

- To present the methodology used and the results obtained with the chosen proxy (internal limit of the backshore) to calculate the erosion/accumulation rates for all of the beaches of the exposed shoreline of Andalusia.
- To describe, quantify and compare the results obtained both on a statistical and spatial level in the two coastal façades of the Andalusian coastline (Atlantic and Mediterranean).
- To examine and quantify the possible trend changes of the different coastal sectors by dividing the overall period of study into two subperiods of a similar duration (2001-2011 and 2011-2019). The idea is to evaluate and quantify the state (erosive, accumulative or stable) of each sector in the initial period and to determine to which state it has evolved (to erosive, accumulative or stable states) in the final period.
- To present the results in an open access web client (geoviewer and dashboard) as the only way of spatially representing and interactively exploring the data generated on a detailed scale, given the extension of the area of study.

In order to fulfil these general and specific objectives, this study presents the results on a descriptive, statistical and spatial level for all of the exposed beaches of Andalusia through calculating rates. However, it only provides a brief interpretation of them in the cases that are most persistent over time (due to the extension of the area of study and the complexity of the erosive processes on a detailed scale), with the final objective of identifying the sectors that experience the most continuous movement of their shorelines (both retreats and advances) both on the Atlantic and Mediterranean façades due to their greater exposure to coastal erosion.

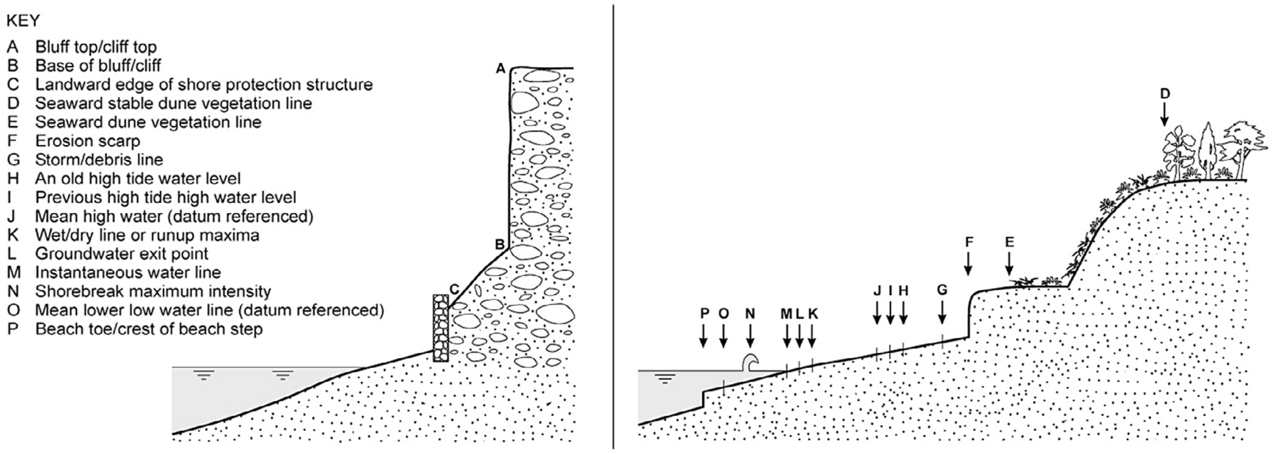
1.2. Theoretical framework of sources and shoreline proxies

As previously mentioned, coastal erosion is a volumetric phenomenon that needs tri-dimensional data sources for analysing the behaviour of the process as a whole, in the case of beaches for their entire active transversal profile, providing methodological solidity to the results of the studies obtained.

However, the range of available data sources that include the tri-dimensional variable is small and has only recently been incorporated into general public use (Ojeda-Zújar, 2000; Prieto-Campos, 2017). Sources that enable the generation of precise altimetric data are required for both the emerged and submerged part of the beaches. Given the extension of the area of study, these sources are scarce and very costly. The use of topographic profiles of the transversal beach profile (with total station or GPS) is a possible data source for small areas and, even so, it is difficult to reach the wave closure depth on the active transversal profile. The airborne LiDAR (*Light Detection and Ranging*) sensors meet these specifications as they obtain altimetric data with great precision for large areas of study through the combined use of topographic and bathymetric LiDAR (Sánchez-Carnero et al., 2014). Being an airborne device, it also offers the possibility of covering large areas of land in each flight, having been used for many short-term erosion studies (only for the emerged part of the beach) and for very disparate coastal environments (Obu et al., 2017; Pye & Blott, 2016; Terefenko et al., 2019). However, its high price and, particularly, its temporal limitation (generally not available for historical data) prevent its use in many medium and long-term coastal erosion studies such as this case (the LiDAR flights –only altimetric data for the emerged part of the beach– available for the area of study refer to two flight coverages in the periods 2014-2015 y 2020-2021 –PNOA Plan–). Currently, the incorporation of altimetric or photogrammetric sensors in drones, together with the use of oblique photogrammetry, have been included as new sources of information for detailed scales that also allow the volumetric measurement of the coastal erosion phenomenon (Casella et al, 2020; Guisado-Pintado & Jackson, 2020). However, obviously, they are not available retrospectively for medium and long-term studies. In the light of this problem, the ideal data sources, which enable their retrospective use in the medium to long-term, are photogrammetry flights, particularly the use of the orthophotos derived from them, given the geometric reliability of the final product and its availability from the second half of the twentieth century to the present day, although we lose the altimetry component. In this case, their nature only allows the data of changes of the shoreline to be obtained, enabling the calculation of unidimensional changes (distances in metres) and bidimensional changes (areas in m^2). In any event, these data do not directly quantify the erosion (volume eroded) but constitute a proxy (retreats and advances of the shoreline) that is closely related to it. Many types of these shoreline proxies have been used (Boak & Turner, 2005; Paris et al., 2013) and can be divided into two groups: the first, called "*feature-related proxies*", as their name indicates, are based on recognisable elements in the orthophotos (water, vegetation, etc.) or on field work to delimit the shoreline; the second type, called "*datum-related proxies*", are based on shorelines defined by altimetric thresholds (hydrographic datum, tidal levels, etc.) and are usually used when these high-precision altimetric data are available, normally drawn from LiDAR data (Aguilar et al., 2010). Therefore, the most used proxies to conduct these types of medium and long-term studies are *feature-related proxies* (Figure 1). These types of proxies are also those recently used in many global studies that use satellite images as an information source (Almonacid-Caballer et al., 2016; Espinosa-Montero & Rodríguez-Santalla, 2009; Luijendijk et al., 2018). The choice of the most suitable proxy of the many used of this type will depend, therefore, not only on the time frame of the study, but also on the characteristics of the shoreline where the beach is located (particularly in the case of micro or meso-tidal coasts) and on the elements that intervene in the coastal dynamics of the area of study (Paris et al., 2013).

In this sense, the afore-mentioned proxies are concentrated in the visible area of the information source, that is, the areas of the beach that are highest and emerged most of the time (depending on the tidal state at the time when the photo or satellite image is captured). These areas correspond, first, to the *backshore*, defined as the higher part of the beach exposed to the waves and unaffected by the normal wave run-up except during extreme weather events (Bird, 2011). In this part of the beach, the proxy that uses the "internal limit of the backshore" is used, principally marked by a change in the granulometry of the sediment and the possible presence of vegetation or other formations and morphologies (dunes or cliffs) or anthropic elements, with the wind processes in the area being more active than on the rest of the beach. The proxies associated with this internal limit are more isolated from the frequent wave and tide variations as they are located in the upper limit of the transversal beach profile, if the photos are taken on dates when calm profiles are predominant, and are less vulnerable to seasonal changes. Therefore they are ideal for medium and long-term studies.

Figure 1. Principal *feature-related proxies* used



Source: Boak & Turner, 2005. Own elaboration

The second area of the beach where proxies can be located is the *foreshore*, which is defined as the intertidal zone of the profile. This area is dominated by hydrodynamic processes (Komar & Holman, 1986), principally the wave conditions, whether seasonal or occasional under the effects of an extreme weather event. In this case, the proxies taken in this coastal strip usually correspond to the different "wave run-up marks on the foreshore", being highly prone to frequent daily changes in the waves and the tide as it is clearly located in the active beach profile. Therefore, they are problematic on meso or macro-tidal coasts due to the major impact of the tidal variation on them (Anfuso et al., 2007; Del Río et al., 2013; Díaz-Cuevas, 2020). However, it is the proxy most used for micro-tidal coasts (Guisado-Pintado & Malvárez, 2015; Rodríguez-Santalla et al., 2021) and/or when satellite images are used, given the current facilities for the almost automatic photointerpretation or the classification of the water line on the exposed beach (Alicandro et al., 2019; Pardo-Pascual et al., 2018; Viaña-Borja & Ortega-Sánchez, 2019).

Therefore, due to its greater suitability for the medium-term analyses of this study, which includes a mesotidal Atlantic façade and a microtidal Mediterranean façade, it has been considered that the most appropriate proxy to use is the one corresponding to the internal limit of the *backshore*, adapting to the possible elements that come into contact with it. In this way, in coastal sections where the beach connects with sandy formations, the limit will be marked by the foot of the dune (whether stable with vegetation or embryonic); in coastal cliffs with exposed beaches associated, the limit is marked by the contact between the base of the cliff and the interior limit of the transversal beach profile; and in areas altered by anthropic activity the limit is marked with the longitudinal infrastructures or other types of constructions located on the beach.

2. Methodology

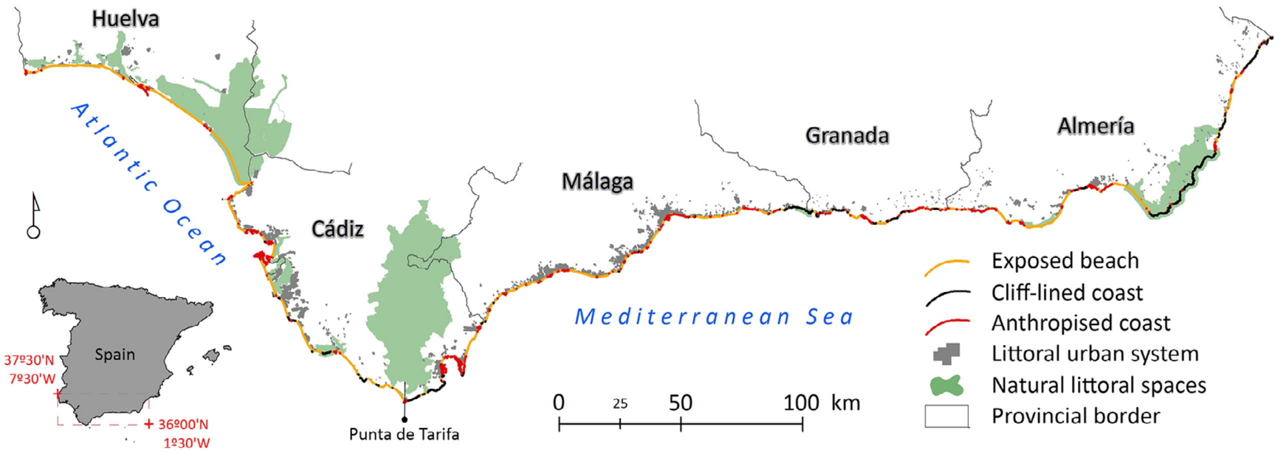
2.1. Area of study

The study exclusively focuses on all of the beaches on the Andalusian coast, composed of more than 900 km of shoreline exposed to waves (hereafter, ES), of which, almost 70% (630 km) correspond to exposed beaches. Given its location in the extreme south of the Iberian Peninsula, the Andalusian shoreline is divided into two clearly differentiated façades, bathed by two seas with different characteristics, which, together with the geomorphological characteristics of each of them, should be taken into account independently in the analysis of the results (Figure 2). This extensive area of study is, undoubtedly, one of the unique elements of this article, as it includes all of the exposed beaches in Andalusia, both on the Atlantic and Mediterranean coasts.

The Atlantic façade (317 km) runs from the border with Portugal and the mouth of the River Guadiana (Ayamonte, Huelva) to the Punta de Tarifa (Cádiz). It is a low coast, mostly sedimentary, where the beaches are long and wide with golden and fine sand. They represent 80% (250 km) of the shoreline of this façade.

The intense quaternary and historical sedimentary deposits of the large rivers of this coast (Guadiana, Guadalquivir, Guadalete, etc.) are currently limited to mainly the contributions of the Guadiana. However, the high availability of sandy sediments, together with the direction of the dominant waves and the orientation of the coast generates a dominant longshore drift from east to west throughout the whole sector, whose average fluctuates between 45,000 and 60,000 m^3/year, with zonal peaks of up to 100,000 m^3/year (Ministerio de Agricultura, Alimentación y Medio Ambiente [MAGRAMA], 2013). This has led to the development of many barrier islands and littoral sandy spits, which have isolated large sectors of former estuaries and bays from the waves, generating very large interior tidal marshes (including the vast Guadalquivir marshes that have mostly evolved into fluvial-pluvial marshes). The waves that affect the beaches on this coast have a moderate energy, with a significant average wave height (hereafter, Hs) that fluctuates between 1 and 1.5 m (Ministerio de Transportes y Movilidad Sostenible [MTMS], 2023), but with a large fetch and a tide range typical of a mesotidal coast (around 3-2 m on average), decreasing from west to east as it nears the Strait of Gibraltar where it is around 1 m. The greater presence of the Baetic foothills close to the Strait is evident in the geomorphology, where the low reliefs progressively give way to the occasional presence of cliff sectors and pocket beaches associated with flysch outcrops. The human presence on the Atlantic coast, despite being concentrated around the large coastal historical urban centres (Huelva or Cádiz), has grown exponentially throughout the twentieth and twenty-first century. Together with the expansion of the urban centres and peripheries, another part of urban growth corresponds to newly built residential areas, either as an extension of pre-existing urban centres or as isolated urban developments. The presence of many protected natural spaces in the area (around 30% of the Atlantic Andalusian beaches), of different types (National Parks, Natural Parks, etc.), has played a fundamental role in the natural preservation of the shoreline.

Figure 2. Area of study



Own elaboration

The Mediterranean coastline, runs from the Punta de Tarifa (Cádiz) to the Playa de los Cocedores (Pulpí, Almería), marking the border with the neighbouring region of Murcia. The presence of large mountainous relief (Baetic System) a few kilometres from the coast has generated a more diverse shoreline, broken by capes and the development of coastal plains at the bottom of the mountainous foothills with which the different coastal features are associated. On this coast, the hydrographic network has a considerable average slope, which, together with the torrential nature of its flows, gives the rivers a large sediment input capacity in is final section, historically generating the formation of deltas at its mouth, which are distributed along the coastline. The beaches in this case are shorter and narrower and are composed of sediments of a large granular size than the Atlantic beaches, representing 63% (370 km) of the ES of the coastline (590 km). There is a greater presence of cliff sections (almost 25% of the total façade), which has generated the presence of small bays and pocket beaches. The waves affecting the Andalusian Mediterranean coast have a lower average energy, with an average Hs of 0.5 m (MTMS, 2023). There is also a lower fetch and the tidal range corresponding to a microtidal coast (less than 1 m) along the whole of its length. The directions of the dominant waves and the orientation of the coast generate less intense coastal longshore drifts than on the Atlantic coast. In general, from Estepona to Gibraltar the direction of the dominant longshore drift is east to west, from Estepona to Cabo de Gata west to east and north to south in the eastern sector of Almería. Together with the current lower availability of sediments, the average intensity fluctuates between 35,000 and 40,000 m^3/year, with zonal peaks of up to 75,000 m^3/year (Ministerio de Medio Ambiente y Medio Rural y Marino [MARM], 2009). The urban growth on the Mediterranean shoreline has been much greater than that on the Atlantic coast, particularly from the 1960s. The early development of the tourism activity, in many cases before the enactment and existence of laws to protect natural areas, has generated an urban continuum in large areas of many sections, clearly visible in the sector of the Costa del Sol in Málaga.

2.2. Data sources

The data selected for the study are made up of the orthophotos generated from the photogrammetric flights of 2001-2003 (panchromatic), 2010-2011 (colour) and 2019 (colour) corresponding to the PNOA Plan. Those that are downloadable in digital files have been used, as those accessed as an interoperable WMS (*Web Map Service*) from the Spatial Data Infrastructure of Andalusia website (IDEAndalucía) can lose visual quality when sent to de web client in formats with destructive compression (.jpg) and their use can be problematic from a geometric perspective if the web client that uses the WMS service transforms the coordinate reference system prior to their application in the visualisation and digitalisation processes (Figure 3).

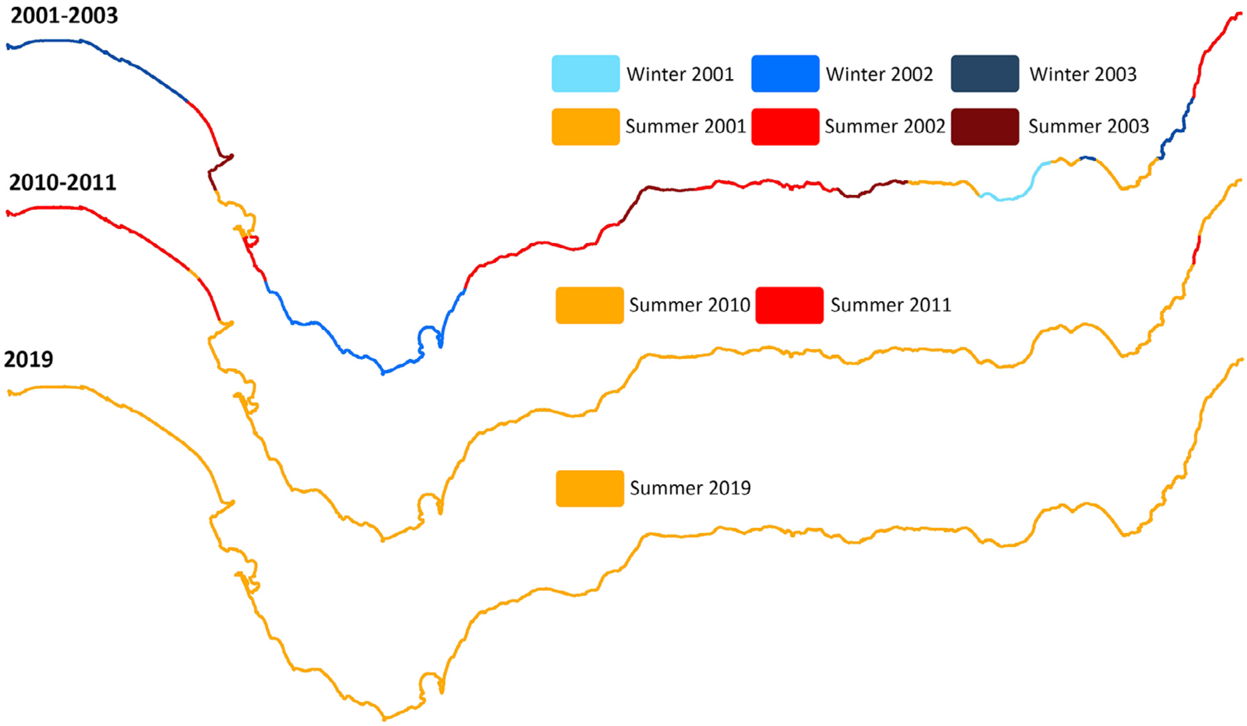
Figure 3. Orthophotos used for the photointerpretation process

Source: the Spatial Data Infrastructure of Andalusia (www.ideandalucia.es)

For the cliff areas, the Ortoimagen Quickbird-Ikonos of 2005 was used (provided by the Cartographic and Statistical Institute of Andalusia –IECA–), with a spatial resolution of 0.7 m. The height of the spatial platform from which the image was taken eliminates possible errors in the photointerpretation caused by the apparent displacement of objects with a certain height, such as cliffs. However, given its very occasional use for higher cliffs, it has not been taken into account when calculating digitalisation errors and does not participate in the calculations of the retreating or advancing rates of the shoreline.

As previously mentioned, the date when the orthophotos were taken is vitally important for choosing the proxy to use and for the subsequent interpretation of the rates. In order to obtain it, a review of the dates when the photographs were taken has been made, using the information of the centroids of the photos of the photogrammetric flights (available as metadata in the IECA). In this way, the date of each photo was obtained and was subsequently integrated into the orthophotos used as a source of information. As a result, it may be observed that, while the flights of 2010-2011 and 2019 corresponded to dates generally associated with a calm or summer period, those of 2001-2003 was made up of different flights at very different times of year, with sectors of the provinces of Huelva, Cádiz and Almería covered in the winter, so care should be taken when considering the calculations in which the shorelines of this date are included (Figure 4).

Figure 4. Dates of data sources



Source: Prieto-Campos (2017). Own elaboration

2.3. Data model

A peculiar feature of this study is the fact that each digitalised shoreline is incorporated into a spatial database (PostgreSQL/PostGis) which is associated with both the geometry and a data model composed of thematic alphanumeric information. It provides full descriptive information about each digitalised section of coastline from a physiographic point of view (hierarchical coastal type, presence and characteristics of infrastructures, cliffs, dunes, beaches, type of substrate and accommodation space –Prieto-Campos et al., 2019–), toponymic information (toponymic sub-model) and the key aspects of the digitalisation, which are interesting for the subsequent calculation of the retreat/advance rates (criterion and digitalisation errors, presence of coastal infrastructures, proximity to urban land, etc.).

Subsequently, a new set of tables was added to this data model with the calculations of the rates, through the spatial intersection of the shoreline with the transects that contain all the information about their calculation for the different periods. This data model has been presented in different articles (Fernandez-Nunez et al., 2015; Prieto-Campos et al., 2018a) and national and international congresses (Prieto-Campos et al., 2018b). In this article, the incorporation into the transects of the types of longitudinal coastal infrastructures and the built areas on the shoreline in a detailed working scale, has been essential for interpreting and classifying the results.

2.4. Data gathering and collection

The photointerpretation and digitalisation process of the shoreline with the chosen proxy have been conducted on a 1:2,500 scale for the whole area of study using the proprietary software ArcGis 10. The coordinate reference system used in the whole process, in accordance with the current legislation (RD 1071/2007), is the *European Terrestrial Reference System 1989* (ETRS89), using the UTM projection zone 30, coinciding with that of the original orthophotos used.

As already mentioned in the section on the theoretical framework the proxy chosen, corresponding to the internal limit of the *backshore*, marks the contact between the beach and the first dune ridge, either stable (with vegetation) or embryonic. In the case where there are cliffs with associated beaches, the contact between the beach and the base of the cliffs is taken into account. For the cases in which the limit coincides with a coastal anthropic infrastructure (breakwater, maritime promenade, buildings, etc.), its contact with the transversal beach profile is used (see section 3.1).

Another unique aspect of the process of shoreline digitalisation is that, although the large scale enables a detailed and in-depth digitalisation to be made, given the medium-term nature of the study, a detailed and more smoothed digitalisation of the shoreline has been performed of certain sections, mainly those with small but abrupt interruptions of the shoreline (for vehicle access, small river mouths, etc.) that alter the continuity of the shoreline (Figure 5). This strategy is more suitable for the nature of the erosive processes, which in the medium to long-term, tend to generate a homogeneous retreat of the shoreline. On the other hand, it is very useful for calculating (to eliminate *outliers*) *setback retreat* (Goble & MacKay, 2013; Ramsay et al., 2012) in future scenarios, for which there are tools in the software (ArcGis 10) used in this study, in this case, the *Digital Shoreline Analysis System* –hereafter, DSAS– (Himmelstoss et al., 2021).

2.5. Error assessment

Digitalisation errors are inherent in the data collection process and should be taken into account when exploiting and interpreting the results. The errors made directly affect the reliability of the results obtained and depend both on the characteristics of the data sources used (von Meyer et al., 1999) and the physical and morphodynamic characteristics of the coast in relation with the chosen proxy and, finally, on the digitalisation process of the operator. This aspect is extensively debated in the international scientific literature (Apostolopoulos & Nikolakopoulos, 2020; Genz et al., 2007; Moore, 2000) and different estimations has been proposed in the literature published on certain sectors of the area of study (Aguilar et al., 2018; Del Río & Gracia, 2013, Molina et al., 2019). However, in these latter cases, they have been used in studies mostly using different "water mark" proxies both on the Mediterranean coast due to its microtidal nature (Viciana, 2001) and on the Atlantic mesotidal coast for which its application is more problematic. In the cases that refer more to the use of photogrammetric flights, the errors associated with the source used are incorporated (scanning error, co-registration errors of the different photos/images, orthorectification and pixel size errors), together with errors related to the morphodinamic characteristics of the coastal section (wave run-up, tidal range, transverse profile slope, etc.), essential when the water marks proxies are used and, finally, those related to the digitalisation process caused by the human error of the operator (precision of the operator in accordance with the scale of the study and the photo interpretation of the criterion used –shoreline proxy–).

In the case of this study, three types of errors have been taken into account. The first is related to the source of information. As the orthophotos were taken within the national plan (PNOA) and due to the recent and mostly digital nature of the flights (twenty-first century), the error associated with scanning and co-registration between dates has been ruled out, as using the same support points for the triangulation and orthorectification, the quality of the adjustment is excellent (see Figures 2 and 5). Furthermore, the calculations of the rates will be carried out with relative values (distance between the lines of the proxy on different dates), not with absolute positional error. Given the data sources used, the error related to the pixel size (spatial resolution) is included in this group, which fluctuates between 0.25 for the most recent date (2019) and 0.5 m for the other two dates.

The other two types are related to the precision of the operator in the digitalisation process. One of them refers to the precision of the operator in relation to the scale of the digitalisation (Vila & Varga, 2008), in this case 1:2500. In order to obtain a quantifiable error of this kind, a recognisable point element on the same orthophoto has been digitalised by a single photo interpreter ten times and on the same sized screen, obtaining an average distance between them of 1.5 m. The third error used is related to the precision of the photo interpreter in the digitalisation of the criterion (shoreline proxy) used. To do this, three pilot zones were chosen in the area of study, one for each coastal type with which the proxy is associated (dunes, cliffs with associated beaches and beaches in contact with infrastructures or anthropogenic elements) and the lines of contact of the upper limit of the transversal beach profile for each type were digitalised ten times by the same photo interpreter and the different tests were quantified. In this way, an average error of 1.25 m was obtained throughout the lines digitalised. Finally, the errors related to the physical and morphodynamic characteristics of the coastal section were ruled out by the type of proxy chosen because, as this proxy is located in the internal limit of the backshore, it is on the upper limit of the transversal beach profile and, therefore, would not be affected by the changes in waves or tide in the cases where the date of the orthophoto is in the summer (calm profile). This occurs in all of the cases in this study except for certain sections of shoreline in 2001 (see section 2.2), the results for which should be taken with more caution.

The calculated error, therefore, is the root of the quadratic sum of the previously described errors (*Root Mean Square*, hereafter, RMS). This error expresses the average value of the distance between the estimated location of an object and the real location (Morton et al., 2004), determined by the following formula:

$$\mathrm{RMS} = \sqrt{Error^2_{resolution} + Error^2_{scale} + Error^2_{criterion}}$$

The result, expressed in metres, shows the total mean square (Table 1).

Table 1. RMS through data sources

Orthophotography	Resolution error (m)	Scale error (m)	Criterion error (m)	RMS (m)
2001-2003	0.5	1.5	1.25	2
2010-2011	0.5	1.5	1.25	2
2019	0.25	1.5	1.25	1.9

Own elaboration

However, the RMS has also been calculated for each period of study, expressed in m/year.

$$\mathrm{RMS_{period}} = \frac{\sqrt{RMS^2_{date\,1} + RMS^2_{date\,2}}}{Time}$$

In this way, they can be applied to the rates as they are expressed in the same unit. The RMS by period is shown in Table 2.

Table 2. RMS by period

Period	Time per period (years)	RMS by period (m)	RMS by period (m/years)
2001-2019	18	2.7	0.2
2001-2011	8.58	2.8	0.3
2011-2019	8.5	2.7	0.3

Own elaboration

2.6. Calculation of erosion rates

After digitalising the shorelines, the erosion rates of the beaches were calculated, both for the entire period and for the two subperiods using the previously mentioned DSAS tool. This tool has been extensively used in many studies on coastal morphological evolution for both coastal areas protected from the waves (Bera & Maiti, 2019; Thinh & Hens, 2017) and exposed areas (Fernandez-Nunez et al., 2015; Prieto-Campos et al., 2018a; Kabuth et al., 2014; Quang et al., 2021).

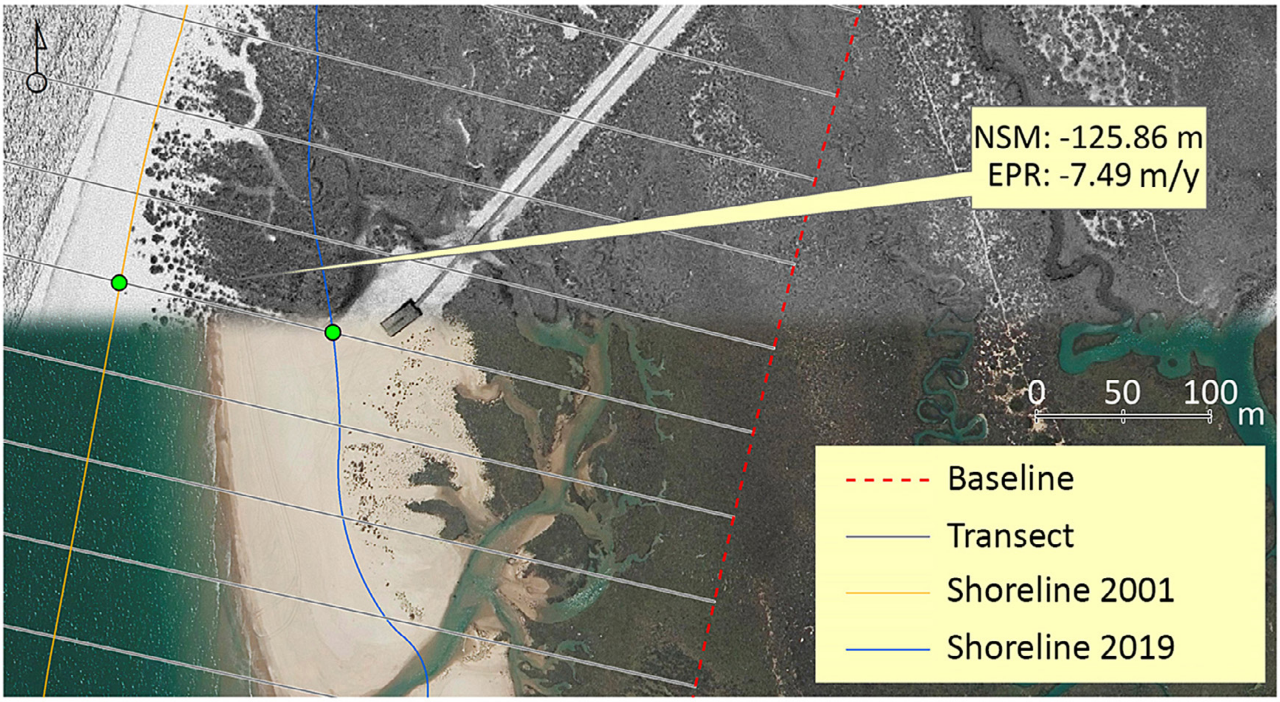
The rates have been calculated using a baseline, parallel to the shoreline, along which 50 m equidistant transects have been generated that perpendicularly cut the shoreline of the proxy (Figure 5). A total of 15069 transects have been generated, of which almost 80% (11835 transects) correspond to exposed beaches, amounting to a total of 250 km of beaches on the Atlantic coast and 370 km on the Mediterranean coast.

The periods contemplated for calculating the erosion rates correspond to the overall period (2001-2019) and have been complemented with the rates calculated for two subperiods (2001-2011 and 2011-2019), to capture changes in trend of the different coastal sectors throughout the entire period of the study.

Of the wide range of statistics resulting from the process of calculating the rates using the afore-mentioned tools, and due to the number of orthophotos used, only two statistics have been used: the *Net Shoreline Movement* (hereafter, NSM) expressed in metres, which shows the net distance between the oldest and newest shoreline; and the *End Point Rate* (hereafter, EPR) or annual rate of change, expressed in m/year, which is the result of dividing the distance calculated in the NSM between the time elapsing between the two data sources (Figure 5).

The results obtained from the former (EPR) are those mainly used in this study. To do this, those sectors with an uncertainty range equal to or lower than the highest value estimated by the RMS of the periods previously calculated, have been considered as "stable". To do this, the threshold of ±0.3 m/year has been established. In this way, the sectors where there is a predominance of negative (retreat) and positive (advance) rates are more solidly identified on a regional level.

Figure 5. Calculation of erosion rates through transects



Own elaboration

3. Results

First, and as explained in the methodology, the results of this study are embodied in the creation of a spatial database (PostgreSQL/PostGis) for all of the exposed beaches, where for each transect all the statistics are calculated for the rates (NSM and EPR), together with all of the information generated in the shoreline photo interpretation and digitalisation process (geomorphological types, dates of the centroids of the orthophotos, toponomy, the presence and type of anthropic infrastructures, the proximity to the built-up space, etc.), which is highly interesting for future studies and facilitates a detailed interpretation. From this, the calculations of the rates have been extracted (EPR and NMS), together with the thematic information on longitudinal coastal infrastructures or other types of anthropic construction for their classification and interpretation, the results of which on an overall time scale, by period and by façade are presented on a regional scale. As a transversal and complementary result to those offered in this article, a free access web client has been elaborated (geoviewer and widgets) for geovisualization, consulting and filtering (by façade, province, type of behaviour and trends, etc.) all of the data obtained at a maximum level of detail. To do this, the *Builder* tool of the *cloud* platform of the company CARTO[1] has been used, which connects to the data stored in the spatial database (PostgreSQL/PostGis) generated for this article. The link to access the web client is https://universidad-sevilla.carto.com/u/univ-sevilla-admin/builder/8f7ec7b6-70df-4378-8eec-ce9f561f6672/embed

3.1. For all the beaches of Andalusia

The overall results are shown in detail in the afore-mentioned web client link and summarised in Figure 6. Given the semiological problems that are derived from the scale of the figure, two sectors at a detailed level (1 and 2) have been incorporated in the figure to assess its original spatial expression. Both the map and the graph of the Figure 6 reveal the predominance of sectors with a negative evolution in the rates (retreats) in relation to those that show a positive evolution (advances) and the much more dynamic behaviour on the Atlantic coast than the Mediterranean coast (variability of the intensity of the values of the rates).

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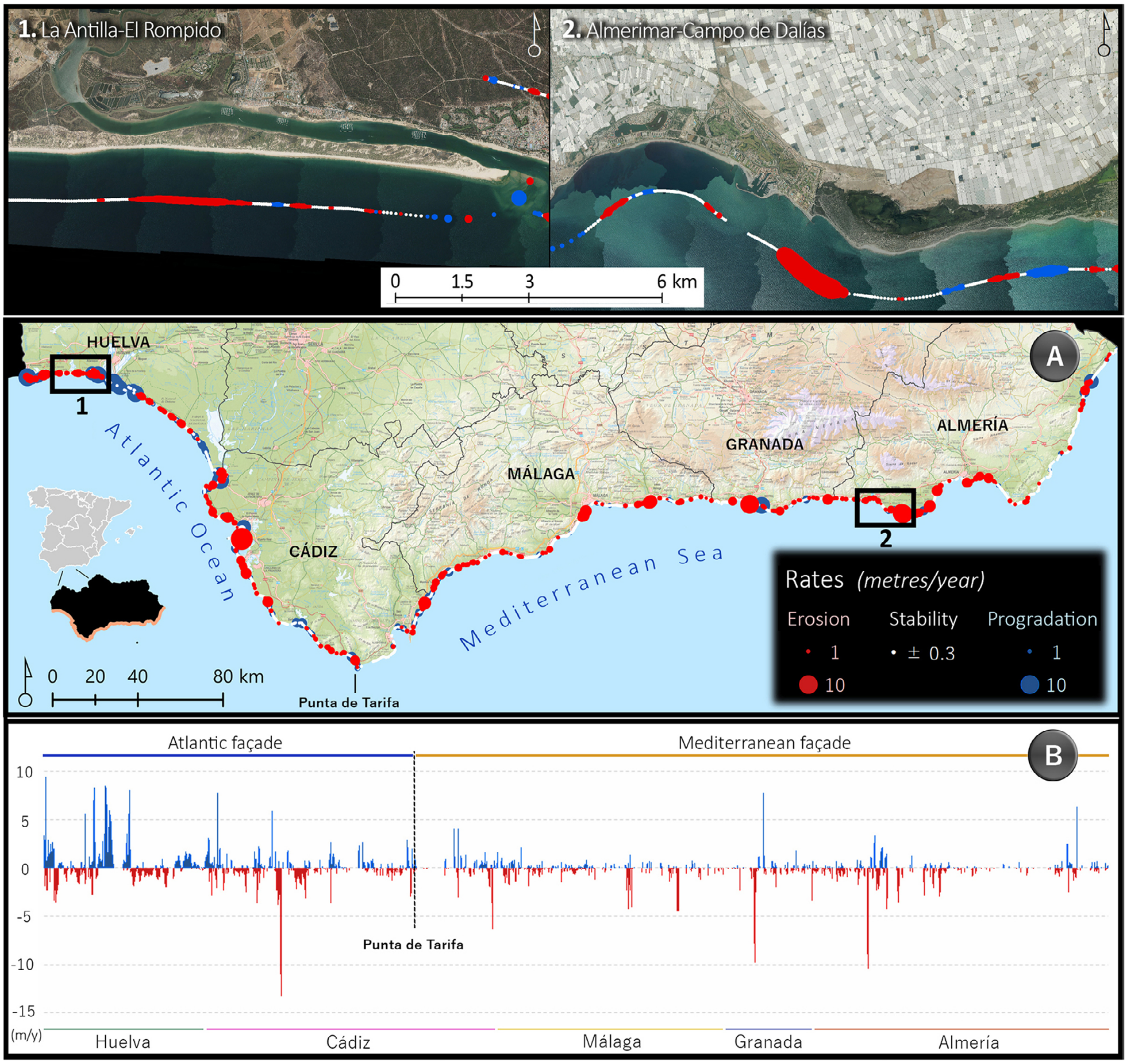
[1] To optimise its use and possibilities, consult the following link: https://carto.com/help/tutorials/using-builder/#widgets

Figure 6. Map (A) and graph (B) showing the spatial distribution of the erosion rates (EPR) for the global period 2001-2019

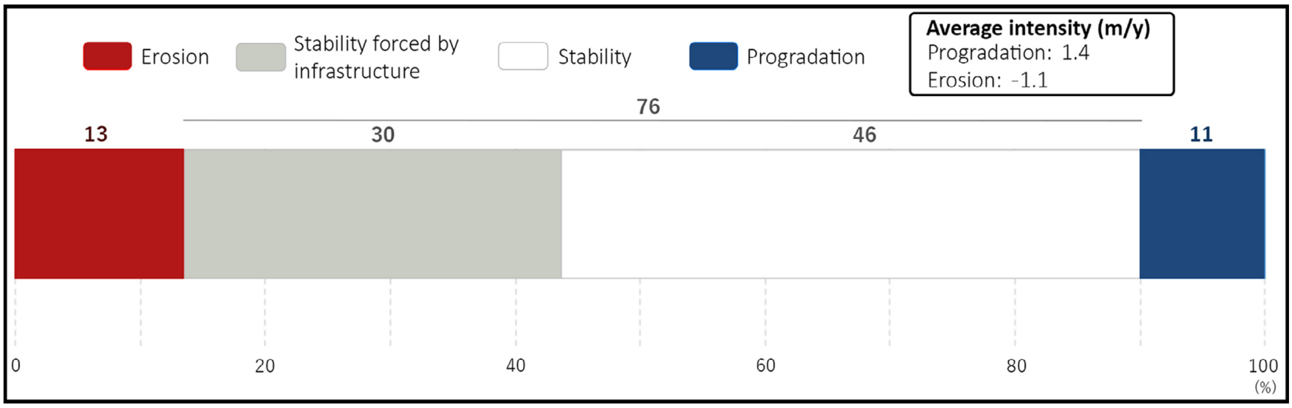


Own elaboration

Figure 7 has also been elaborated for the overall period, summarising the percentages of each of the sectors with a different behaviour or trend on a regional scale (with the use of the chosen proxy). Particularly noteworthy is the spatial predominance (number of transects) of the stable sectors (understood as those that have rates contemplated within the square mean error adopted as a level of uncertainty –±0,3 m/year–), which are associated with 76% of the beaches, although this behaviour usually responds, in almost half of the cases (30%) to anthropic causes (stability forced by infrastructure) related to the “rigidisation” of the shoreline through longitudinal infrastructures (retaining walls, maritime promenades, etc.) or other anthropic elements. As these longitudinal infrastructures prevent the free fluctuation of the shoreline, the sectors with a presence of these infrastructures appear to be stable when applying the internal limit of the backshore as proxy and the level of uncertainty adopted. However, the presence of these defence structures would, on the whole, indicate a regressive behaviour that justifies the protection measures.

On the other hand, it may be observed that the sectors with negative rates (retreat) and positive rates (advance) represent 13% and 11% of the total of the beaches analysed, respectively. The erosive sectors (retreat) are predominant along the length (number of transects) but the values of the rates within them have a lower average intensity (-1.1 m/year) than the prograding sectors (1.4 m/year). This paradox (spatial extension/intensity) resides, on the one hand, in the nature of the coastal features of which both sectors are composed and, on the other hand, in the techniques that measure the retreat/advance with the shoreline proxy used. Being a unidimensional measurement technique (distance of fluctuation between shorelines), the height of the sectors involved is not taken into account, which is a critical factor for the correct volumetric interpretation of the erosive processes. In this way, the rates of the regressive sectors mostly affect beaches associated with different sized cliffs or micro cliffs associated with dunes, the height of which generates a deceleration of the shoreline retreat, although they mobilize and contribute a larger volume of sediments to the coastal system that the sectors with the same rate but a lower height in coastal features. The rates of the prograding sectors, on the other hand, have higher shoreline advance values, as they are usually associated with low height sedimentary features (whose advance needs to move a lower volume of sediments), such as the prograding sectors of the deltas or prograding beaches with incipient dunes.

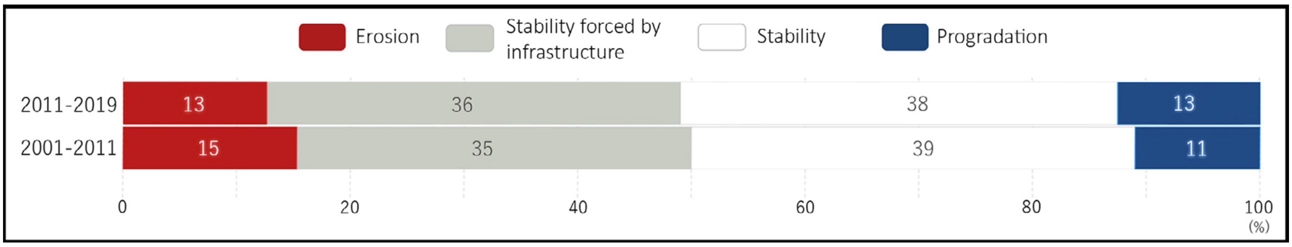
Figure 7. Percentage of trends for the overall period



Own elaboration

Figure 8 shows the overall behaviour by subperiod, reflecting a slight increase in the percentage of the sectors with prograding rates in the final period increasing from 11% to 13%. Another phenomenon observed is the slight reduction in the clearly regressive sectors, which have decreased by 2% with respect to the previous period (from 15% to 13%). However, half of this reduction (1%), rather than a change in trend, corresponds to sections that shift to a stability forced by the presence of infrastructures designed to combat the retreat of the shoreline during the preceding subperiod. The percentage of these sections has risen from 35% to 36%.

Figure 8. Overall trends by subperiod of the study



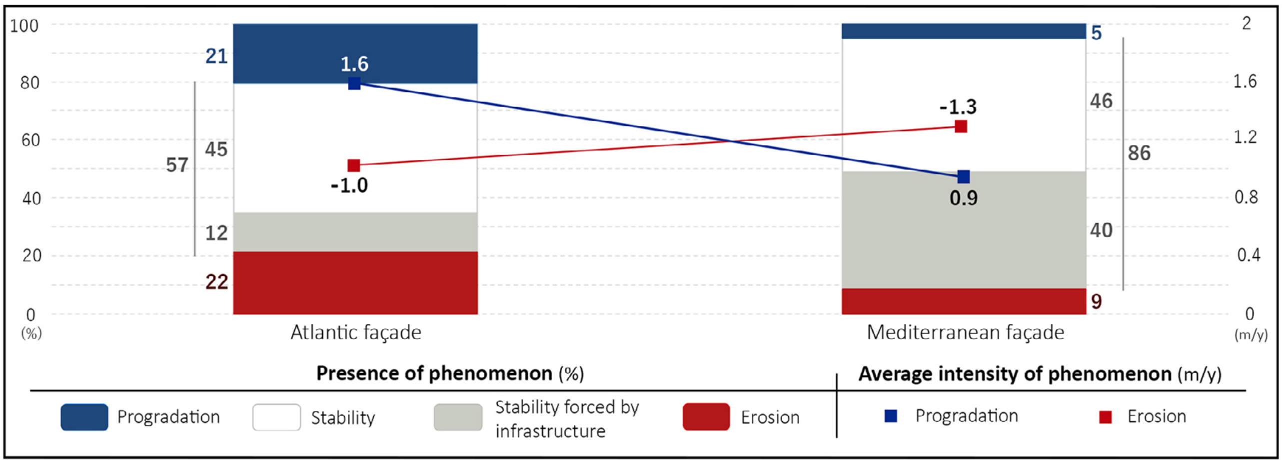
Own elaboration

3.2. By façade (Atlantic and Mediterranean)

The analysis by façade (Atlantic and Mediterranean) for the overall period shows substantial differences (Figure 9).

A clear predominance of the stable sectors (86%) can be observed on the Mediterranean façade, of which 40% correspond to sectors of stability forced by the presence of large anthropised sectors (mainly the Costa del Sol). The Atlantic façade, on the other hand, exhibits a reduction of these sectors, representing 57%, of which only 12% correspond to forced stability sectors. This fact indicates, most of all, the greater anthropic pressure on the Mediterranean coast, whose growing urbanisation has taken up a large part of the shoreline with large built-up spaces that are in direct contact with the transversal beach profile and, in other parts, have required the construction of longitudinal coastal infrastructures for their defence (walls, breakwaters, maritime promenades, etc.).

Figure 9. Percentage and intensity of the rates for the period 2001-2019 according to the coast



Own elaboration

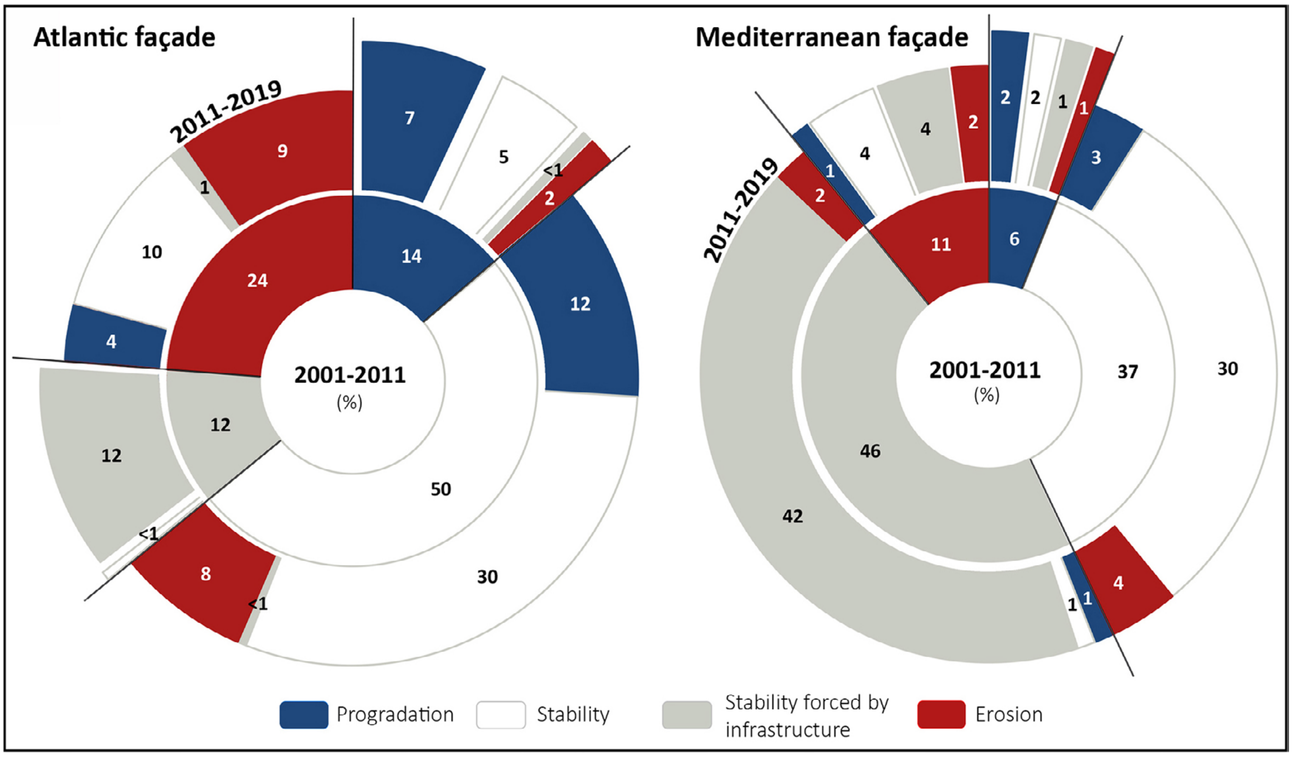
Meanwhile, there are more regressive sectors on both façades than prograding sectors, representing 22% on the Atlantic façade and 9% on the Mediterranean one. However, the intensity of the regressive sectors is lower than that of the prograding sectors on the Atlantic coast (-1 m/year as opposed to -1.3 m/year), corroborating the previously described paradox due to the presence of cliffs on soft rocks and microcliffs on dunes, whose height slows down the retreat. On the Mediterranean façade, this phenomenon changes completely. Here, the retreat rates (erosion) are higher in intensity (-1.3 m/year) to the prograding rates (0.9 m/year). On the Andalusian Atlantic coast, the regressive sections are, mostly, related to the effects of the sedimentary deficit caused by the presence of large coastal infrastructures, in this case transversal (dikes, breakwaters, ports, etc.), which intersect the longshore drift, which is very strong on the Huelva coast, generating a sedimentary deficit in the adjacent sections. Therefore, the effects of the dikes and jetties constructed for the channelling of the Guadiana may be observed in certain sectors of the beaches of Isla Canela (with regressive rates that are sometimes over -4 m/year). Similarly, the effect of the dikes and jetties of the Ría Carreras (Isla Cristina) are also clearly manifested in the adjacent beaches of Redondela, Islantilla and La Antilla, beyond the shadow effect cast by the infrastructures. On the other hand, the enormous Tinto-Odiel dike generates erosive effects towards the east on all of the beaches connected to the impressive Asperillo cliff. In Cádiz, the effect of the channelling of the Guadalete is manifested at the distal end of the beaches associated with the barrier islands of Los Toruños (Playa de Valdelagrana) and, occasionally, the effects of the dikes of the river Barbate and its port are manifested to a lesser extent (less coastal drift) on the beaches located south of them. On the Mediterranean coast, the most significant regressive sectors are related to the erosion of the deltas of the rivers that drain onto this coast, the majority with a sedimentary deficit due to the regulation of the basins. The most evident cases are those associated with the rivers Guadiaro, Guadalfeo, Guadalhorce, Vélez or Andarax. They are also connected to the effects of coastal transversal infrastructures. An extreme case is that of the Almerimar Port with rates of up to -10 m/year. Finally, the high dynamism of the exposed shoreline of Campo de Dalías also has regressive sections, but in this case with a greater temporary mobility due to the natural dynamics of this sector.

In the case of the prograding sectors (accumulation), the changes of the shoreline of the chosen proxy also enables sectors with an undeniably positive balance to be identified (advances). On the Huelva coast they are logically located in the prograding sections associated with the barrier effect exercised by the aforementioned large transversal infrastructures to the longitudinal sedimentary drift and the resulting sediment retention. Prograding sectors may be observed in occasional sections of the beaches of Isla Canela or Isla Cristina, derived from the combined barrier effect of the Guadiana and Careras dikes or, on the Punta Umbría beach, due to the effect of the breakwater channelling the outflow of the Tinto-Odiel estuary at the far end of the beach. Special cases, unrelated to the barrier effect of the infrastructures include the case of the distal end of the littoral spit of El Romido where sediments continue to be deposited originating from the regressive sections of the beaches to the west or the advances of the shoreline on the littoral spit of Punta del Malandar, which receives all the sediments eroded from the El Asperillo cliff. This is added to the effect of the orientation of the beaches of this littoral spit with respect to the dominant wave which, as it turns south, reduces the coastal longshore drift processes significantly. The prograding sectors identified on the beaches of Cadiz are also clear but more intermittent. This is due to the barrier effect of the port breakwaters such as the one in Chipiona or in the Hierbabuena beach due to the retention of sediments by the Barbate port. On the Mediterranean coast, the prograding sectors are also associated with the barrier effect to the longitudinal sedimentary transit of the dikes in ports such as Sotogrande and Cabo Pino and the western sector of La Azucena beach (Motril port) with retreats of -4 m/year or the Puerto del Rey (Vera) with -2.2 m/year. The rest of the prograding beaches are scarce on the Mediterranean coast due to the chronic sedimentary deficit arising from the reduction in fluvial inputs as a result of the regulation of the drainage basins and/or the anthropisation of the coast. Only in the case of the beaches of the exposed shoreline of Campo de Dalias can we find prograding sectors that are unrelated to the barrier effect of the many transversal infrastructures located on the Mediterranean façade due to their high level of dynamism.

3.3. Percentages and trend changes by subperiod and façade

Figure 10 shows the changes in trend generated in each coastal section characterised by a type of behaviour and trend (erosion, accumulation, stability forced by infrastructures and stable) in the initial period (2001-2011) and their evolution towards other types of trend in the final period (2011-2019), for each façade (Atlantic and Mediterranean)[2].

Figure 10. changes in trend by subperiod and coast



Own elaboration

Analysing the trends of the rates during the first subperiod (2001-2011), a clear majority of stabilised sectors can be observed (stable and forced stability) with a different spatial expression depending on the façade. On the Atlantic façade, 62% of the sectors display a stable behaviour, of which only 12% are due to sections with longitudinal infrastructures on the seafront. On the Mediterranean façade, the stable sections account for 83% of the total, and more than half of these (46%) correspond to sections with stability forced by infrastructure.

The trend exclusively of the stable sectors remained unchanged on the whole during the last subperiod (2011-2019), with slight differences depending on the façade. On the Atlantic façade, there is a predominance of sectors with changes towards a positive trend (12%, equivalent to 27 km of coastline), in the river mouths of the Atlantic coast, in areas affected by large transversal infrastructures (beaches of Isla Canela, Punta Umbría or

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[2] To complement this figure (and for locating the place names included in the text) and as a way of exploring the results in more detail, the use of the web client developed is recommended. The rates calculated for each of the transects analysed may be accessed and the changes in trend from a particular trend type to any other possible trend in any of the period used may be explored and quantified.

Cañillos) and long beaches exposed to a significant coastal longshore drift (beaches of Castilla). The sections with changes towards a negative trend represent 8% (equivalent to 18 km), concentrated in the central sectors of the large littoral spits of this façade (Nueva Umbría or Camposoto beaches), in specific sections of the river mouths and in zones close to erosive sectors in the first subperiod (beaches of Mazagón or Punta Candor).

On the Mediterranean façade, on the other hand, there is a predominance of sectors with changes in trend towards erosion in the last subperiod (4%, equivalent to approximately 15 km), concentrated almost exclusively at the principal deltas (Guadalhorce and Andarax) and the Campo de Dalías, which has complex dynamics. The stable sectors that change to prograding trends account for just 3% (equivalent to 10 km) and are found intermittently along the whole of the coast in areas under the effects of the sedimentary retention caused by new transversal infrastructures (breakwaters), at some river mouths (Almanzora) and, again, on the exposed shoreline of the Campo de Dalías, where there is an alternation of progressive and regressive sectors.

The forced stable sections in the first subperiod with a change of trend in the second only occur on the Mediterranean coast, where 2% of sections with changes to retreat rates can be observed, which indicates the elimination of infrastructures in erosive areas and 1% of sections towards advance rates due to the emergence of dunes as a result of sedimentary accumulation in areas with longitudinal coastal infrastructures (Playa de Carchuna) or due to the extension of these infrastructures (Playa de la Butibamba).

In the first subperiod, a lower percentage of prograding sections than regressive sections can be observed on both façades, although there are also slight differences (see Figure 10). The Atlantic façade has a higher percentage of progressive sections (almost triple) than the Mediterranean coast. Half of these sections display the same trend throughout the second subperiod, located in historically accumulative sectors, such as the areas neighbouring the large river mouths (Guadiana and Guadalquivir), distal sections of the sandy littoral spits (El Rompido) and areas under the effects of the sedimentary retention of large transversal infrastructures such as dikes and ports (playas del Espigón and Hierbabuena beaches). A third of the accumulative sections (5%, equivalent to 12 km of beaches) shifted to a stable trend in the last subperiod, due to a reduction in the sedimentary input.

The Mediterranean coast also maintained its prograding trend in the majority of the accumulative sections in the first period, although with a lower percentage (less than one third). These sectors correspond to sedimentary retention areas due to large port infrastructures, such as the El Rinconcillo, Las Azucenas or Las Marinas beaches. There is a very similar percentage of sections with a change towards a stable trend, due to the construction of new longitudinal infrastructures on the seafront, such as the La Galera beach. Changes towards a regressive trend can be observed in specific sections of the shorelines of the deltas (Guadalhorce, Vélez, Andarax, Almanzora) and in areas of the exposed shoreline of Campo de Dalías, whose dynamics, as previously mentioned, are characterised by the alternation of accumulative and erosive sectors, although as a whole they do not account for more than 1% the Mediterranean coast (equivalent to 5 km).

Finally, the sections that were regressive during the first period also underwent changes in trend similar to their accumulative counterparts. On the Atlantic façade, 9% of the sections maintained their regressive trends (a total of almost 21 km of coastline), visible in specific sections of the Acantilado del Asperillo and sections of Punta Montijo, Punta Candor, Playa de Levante or Camposoto. Regressive sections may be observed with changes in trend towards stability in intermediate sectors of long beaches, due to a reduction in the inputs from the coastal longshore drift, as they are located close to erosive areas of the initial period and often adjacent to them.

On the Mediterranean coast, an overall change in trend may be observed in the regressive sections of the first period towards stabilisation (more than two thirds of the erosive sectors in the first period), half of them related to a stability forced y anthropic infrastructures. These sections correspond to urban expansions, such as the southern sectors of the San Andrés or Los Cerrillos beaches and the implementation of retention walls in clearly regressive areas (Playa de Torre del Mar).

4. Discussion

The volumetric nature of coastal erosion requires tridimensional information sources for its comprehensive quantification and the correct interpretation of the results. The lack of retrospective altimetric information sources for the whole period analysed, in this case, has led to the use of proxies based on shorelines ("*feature related proxies*") that only allow the unidimensional (m/year) or bidimensional (m^2/year) quantification of their fluctuations in order to assess the behaviour of the erosive processes during the overall period used (2001-

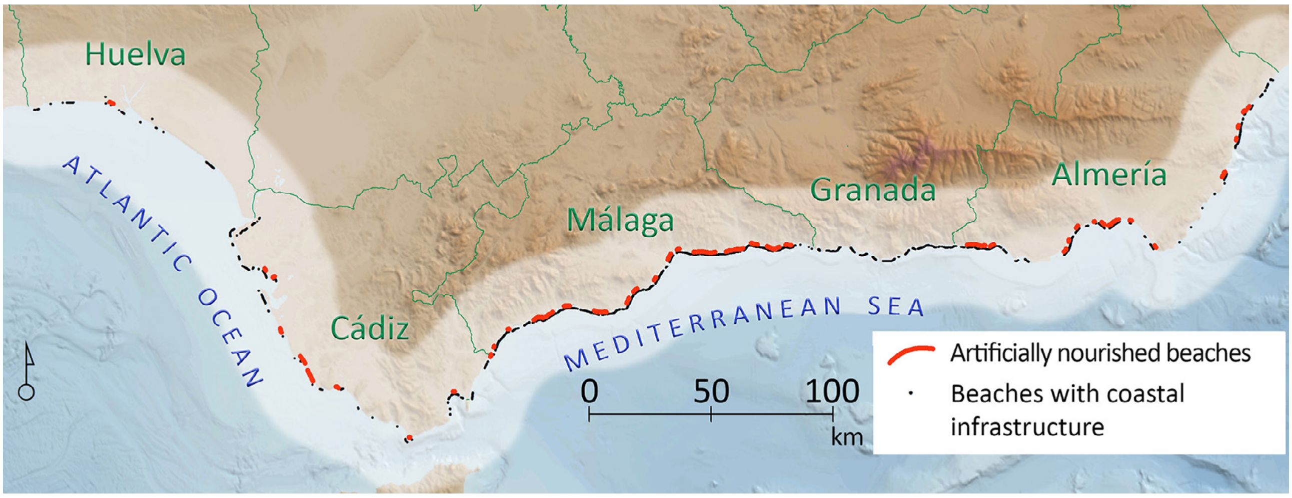
2019). To do this, recent photogrammetric flights have been used, from which orthophotos have been derived with a suitable spatial resolution (0.5 and 0.25 m) and high individual and comparative geometric fidelity as they are generated with shared support points for the orthorectification process for all of the flights within the PNOA Plan. This means that the uncertainty and error calculations related to the information source are simplified with respect to other previous studies, even in parts of the area of study (Molina et al., 2019), as certain components usually used in their calculation related to the source (scanning, co-registration, etc.) can be eliminated. On the other hand, the chosen proxy (internal limit of the backshore) is considered the most appropriate to use for the area of study for both mesotidal coasts (Atlantic façade) and microtidal coasts (Mediterranean façade). As it is located in the upper part of the transversal beach profile, this proxy combined with the flight dates (almost all associated with calm profiles –summer–) means that other components used to calculate the error when "water marks" proxies are used (always located within the active beach transverse profile) can also be eliminated (slope, characteristics related to the waves run-up, tidal range, etc.). However, two components related to the potential error in the digitalisation process made by the photo interpreter have been proposed, namely, the combination of the scale used (1:2500) and the size of the screen and the potential error in the digitalisation and interpretation of the chosen proxy. Therefore, it is considered that the error calculation used is solidly justified in the text and the uncertainty threshold finally chosen (±0.3 m/year), which is the higher of those calculated for all of the dates and periods, is also consistent with the objective of obtaining comparable rates for the Atlantic and Mediterranean beaches. On the other hand, it is logical that the results obtained differ partly with the errors and rates calculated by other researchers in partial sectors of the area of study (mostly using water marks indicators, flights with different dates, several photo interpreters, other error calculations, etc.), but they are consistent with the methodology used and the objectives of this article: to calculate comparable rates for all of the exposed andalusian beaches, using the proxy that is best suited to the two façades (Atlantic and Mediterranean) of the area of study.

The results obtained for the overall time period for all of the exposed Andalusian beaches and the use of two internal time subperiods to evaluate the changes in trend are, therefore, clearly novel elements, as no data have been found in the scientific literature referring to all of the andalusian beaches (Atlantic and Mediterranean) for the overall time period analysed and with the chosen proxy. This proxy and the uncertainty threshold chosen, clearly and undeniably identify the sectors with regressive and prograding trends on the two façades. However, despite being the ideal indicator for evaluating behaviour in the medium and long term, there are limitations when analysing coastal sectors as the internal limits defined by the proxy are occupied by longitudinal infrastructures or constructions that prevent the retreat of the shoreline associated with them. This "rigidisation" of the shoreline, on the other hand, clearly masks erosive processes in these sectors due to the chosen proxy, which is why they have been classified as having a "stability forced by infrastructure". The detailed identification of these sectors constitutes one of the principal results of the article. They are distributed along the whole coast, but mostly concentrated on the Mediterranean façade, for where previous studies have been published that relate the coastal erosion with the presence of infrastructures (Manno et al., 2016; Molina et al., 2019). The areas of study of these publications are found exclusively on this façade, where mostly the effects of the transversal infrastructures and their effect on the longitudinal sediment drift are analysed (breakwaters, dikes, etc.) based on rates calculated with a different proxy (water mark). Obviously, this is a different approach to the one used in this article, whose analysis is focused on the effects of longitudinal infrastructures and buildings (breakwaters, seafront promenades, buildings, etc.), which prevent the retreating processes and, therefore, the inward mobility of the proxy used in this article.

In this respect, in an attempt to focus on the idea that the presence of these longitudinal infrastructures and buildings on the shoreline mask the presence of erosive processes, the article analyses whether there is a relationship between the artificial nourishment occurring on the beaches on the Andalusian coast (generally associated with regressive sectors) and the location of these sectors that have "stability forced by longitudinal infrastructures". To do this, the inventory of pressures on the different hydrographic basins has been used (rivers Tinto, Odiel and Piedras; Guadalete-Barbate; and Andalusian Mediterranean Basins), corresponding to the Hydrological Plan 2009-2015 (Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible, 2015, 2017, 2021), available on the Andalusian Environmental Information Network (REDIAM) (Figure 11).

The findings show highly disparate results depending on the coast. On the Atlantic façade, an occasional yet clear relationship may be observed between the presence of these longitudinal infrastructures and the regeneration of beaches located mainly in the province of Cádiz. On the other hand, the relationship between the two variables is much greater on the Mediterranean façade, particularly the Costa del Sol of Málaga, where 65% of the regenerated Mediterranean beaches are concentrated and 54% of the regional total, according to the source used. In all of these cases, it can be observed how the stabilisation of the shoreline with the construction of longitudinal infrastructures can mask serious erosive processes and, in the worst of cases, lead to a total loss of the beach as a natural and tourist resource, with the resulting damage to infrastructures, services and homes in the area.

Figure 11. Relationship between beaches with coastal infrastructures and artificially nourished beaches



Own elaboration

Undoubtedly, the results presented in this article add considerable value and differ from other more local or subregional studies (Del Río et al., 2013; Gong et al., 2012; Malvárez et al., 2019; Molina et al., 2019; Moore & Griggs, 2002; Stephenson et al., 2019), as they refer to the calculation of the rates for all of the exposed Andalusian beaches (620 km) with the proxy that is considered to best adapt to calculating the rates for mesotidal and microtidal sections of coast (the internal limit of the backshore). On the other hand, as it only uses one photo interpreter for the photointerpretation processes and the digitalisation rigorously uses a scale of 1:2500, the consistency of the comparisons between periods and façades is higher and the results significantly contribute to the knowledge of the erosive processes on Andalusian beaches.

5. Conclusions

From a methodological point of view, the proxy used has been found to be appropriate for medium and long-term studies as it lies outside the active profile of the beach and is slightly less affected by the changes of the foreshore due to the constant changes in the waves, tides or seasonal changes in the transverse profile, provided that the dates of the orthophotos are during calm periods (summer), as is the case of this study.

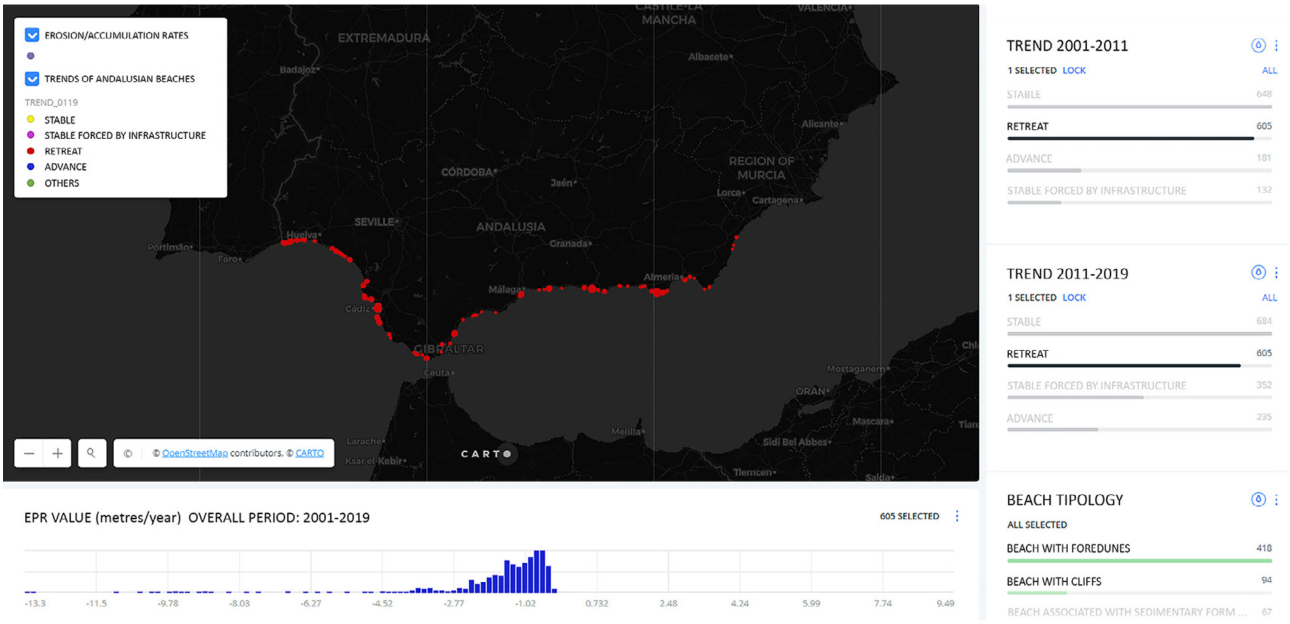
Similarly, the methodology proposed for the data generation, incorporating not only the geometry of the proxy (the shoreline) into a spatial database (PosgreSQL/PostGis), but also a whole set of thematic complementary variables (presence and type of infrastructures, geomorphological typology, presence of dunes, proximity of urbanisation, etc.) and subsequently, the data of the rates calculated (EPR, NSM, errors), constitutes the principal result of this study. In this respect, the complementary thematic variables of the data model have been critical in the classification processes of the different sectors and the interpretation of the results. Therefore, all of the results presented in this article are derived from this spatial database, which, in turn, provides the web client with its data (geovisor and widgets), developed in the CARTO platform, enabling the interactive exploration of the results on a detailed scale and the open access to their geovisualisation by any scientist. The facility to filter the data according to the user's wishes, the versatility for exploring them on different scales, the calculation in real time of the average rates on a regional level, by façade, by province, by municipality or any level of visualisation is another novel aspect and a methodological contribution that is interesting for the processes of interpreting the rates and dissemination on a detailed scale of the results.

The results obtained, on the other hand, are highly sensitive to the proxy and the threshold of the level of uncertainty used after analysing the potential errors (±0.3 m/year). This threshold is similar or slightly higher than that calculated in other publications for the area of study, but it is a high threshold and consistent with the objective sought to detect the sectors that are clearly regressive or progressive for all of the beaches of Andalusia and to facilitate a solid comparison of their rates by using the same proxy. The rates calculated for the overall period show that the percentages for the clearly regressive (retreating) beaches is 13% with an average intensity values of -1.1 m/year and affecting 96 km of the ES, while those that have positive values (advances) account for 11%, with average intensity values of 1.4 m/year and affecting 72 km. The analysis by subperiod indicates small differences, with an increase of 2% of the prograding sectors and a reduction of the regressive sectors of around the same size (2%) in the most recent period, although half of them have increased the forced stable sectors due to the presence of infrastructures, revealing their regressive nature in the previous period.

The analysis by façade has revealed processes that were masked in the global data. First, there are more regressive sectors than accumulative sectors on both façades and in both cases (regressive and prograding) there is a greater percentage on the Atlantic beaches than the Mediterranean ones. The average intensity of the regressive rates, however, is higher on the Mediterranean coast (-1.3 m/year) than the Atlantic coast (-1.1 m/year). This situation is inverted in the accumulative processes in which the average values of the advance rates on the Atlantic (1.6 m/year) are much higher than those of the Mediterranean (0.9 m/year). The paradox that explains these differences (length/intensity) is another conclusion of the study. This paradox shows a clear weakness of the chosen proxy (and of all those that use fluctuations of the shoreline) as it does not incorporate the altimetric variable. Therefore, the intensity of the erosive processes on the Atlantic façade, although lower than that of the Mediterranean, mask the volume of sediments really eroded, as they are associated with dune systems and cliffs on soft materials, sometimes with a great height (the El Asperillo cliff, for example). Although they slow down the retreating processes of the coast and have low values of intensity, in reality they indicate high volumes of eroded sediments that are incorporated into the coastal system that are higher than other regressive sectors of the Mediterranean coast affected by sedimentary formations with a lower height.

Another conclusion derived from the results is the large area of stable sectors, which, for the overall period, account for 76 % of the beaches, although, due to the chosen proxy, a significant number of them (30%) belong to the so-called sectors with "stability forced by longitudinal infrastructures or buildings" that prevent the shoreline from migrating inland. The vast majority are on the Mediterranean façade where the stable sectors account for 86% and, within these, the stable sectors forced by infrastructure represent almost 46%. This reveals, on the one hand, the strong anthropisation of the Mediterranean coast and, on the other hand, a masking of the dominant erosive processes in these areas, which, due to the presence of anthropic constructions, would be the most vulnerable areas where protection measures have been previously required (walls, breakwaters, etc.).

Figure 12. Transects of Andalusian beaches that display a regressive behaviour in the two subperiods (2001-2011 and 2011-2019)



Fuente: https://universidad-sevilla.carto.com/u/univ-sevilla-admin/builder/8f7ec7b6-70df-4378-8eec-ce9f561f6672/embed

Finally, the analysis conducted on the change in trends between the two subperiods and façades constitutes another novel result of this article, revealing the high spatial dynamism of the erosion processes on the

Andalusian coast. The web client developed constitutes a magnificent complement to the graphic results presented in this article as it enables the data to be filtered and the number of transects and average intensity of the rates of the filtered sectors to be calculated in real time. By way of example, if the data of the first period are filtered and only the regressive sectors are selected in the widget (Figure 12), we can observe towards which type of behaviour they have evolved in the second period. If, in addition to this filter, another is applied within widget of the second period, and the sectors with a regressive (retreating) trend are marked, those sectors subjected to a greater exposition of persistent erosion over time may be identified, as they have maintained the same trend in the two periods. The result obtained (Figure 12) is that these sectors account for 30 km of the beaches on the Andalusian shoreline (with an average intensity of -1.79 m/year), of which 20 km are located on the Atlantic coast (with an average intensity of -1.5 m/year) and 10 km on the Mediterranean coast, whose average intensity in regressive rates is double (-2.44 m/year).

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