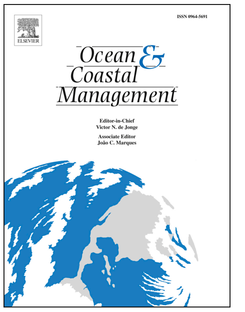
Journal Pre-proof



Developing a beach erosion sensitivity indicator using relational spatial databases and Analytic Hierarchy process

Pilar Díaz-Cuevas, Antonio Prieto-Campos, José Ojeda-Zújar

PII: S0964-5691(20)30056-9

DOI: https://doi.org/10.1016/j.ocecoaman.2020.105146

Reference: OCMA 105146

To appear in: *Ocean and Coastal Management*

Received Date: 24 July 2019

Revised Date: 7 February 2020

Accepted Date: 15 February 2020

Please cite this article as: Díaz-Cuevas P, Prieto-Campos A, Ojeda-Zújar J, Developing a beach erosion sensitivity indicator using relational spatial databases and Analytic Hierarchy process, *Ocean and Coastal Management*, https://doi.org/10.1016/j.ocecoaman.2020.105146.

DEVELOPING A BEACH EROSION SENSITIVITY INDICATOR USING RELATIONAL SPATIAL DATABASES AND ANALYTIC HIERARCHY PROCESS

Pilar Díaz-Cuevas[1]*, Antonio Prieto-Campos[2], José Ojeda-Zújar[3]

Department of Physical Geography and Regional Geographical Analysis

Doña María de Padilla s/n. University of Seville, 41004 Seville, Spain;

[1] pilard@us.es. ORCID: 0000-0003-0846-9930

[2] pcampos@us.es ORCID: 0000 -0001-6946-9622

[3] zujar@us.es ORCID: 0000-0002-4672-064X

** Corresponding author*

DEVELOPING A BEACH EROSION SENSITIVITY INDICATOR USING RELATIONAL SPATIAL DATABASES AND ANALYTIC HIERARCHY PROCESS

Highlights

- A simple beach erosion sensitive indicator is developed an applied in Cadiz (south of Spain).
- Mediterranean beaches are more likely to be erosion sensitive than Atlantic ones.
- Results are validated by comparing with regenerated beaches.
- The indicator points out zones where more detailed analysis is desirable optimising time and resources.
- The indicator can be applied to other regions and is useful for coastal planners.

Abstract

This paper presents a methodology that is based on the use of relational spatial databases and Analytic Hierarchy Process (AHP), to generate an indicator of sensitivity to erosive processes for dry beaches, which was then applied in the province of Cádiz (Southern Spain). The variables 'width of dry beach'; 'accommodation space – width and type of sedimentary substrate'; and 'mid-term erosion rate' (1977-2013) are calculated in detail (1:2500). Following this, the accommodation space variable is weighted according to its sedimentary substrate before calculating the sensitivity indicator by aggregating all variables. Results suggest that Mediterranean beaches are more likely to be erosion sensitive than Atlantic ones (69% against 62% respectively). Both groups share similar features: similar dry beach width, a tendency to erode, and the existence of little or no accommodation space.

Of those beaches in the extremely sensitive bracket, 29% are located in urban areas, especially common along the Mediterranean facade, where the presence of infrastructure (mainly retaining walls and seaside promenades) prevents both the increase of the beach's potential expansion areas and the oscillation of the shoreline.

The methodology developed can be applied to other regions and will be of interest for coastal planners and managers, whom can use this information to understand coastal erosion hazards and to readily identify areas that are less resilient to erosive phenomena and where more detailed analyses should be carried out.

Keywords: dry beach, coastal erosion, accommodation space, resilience, Cádiz

1. Introduction

Coastal areas provide key ecological services and are an important economic asset, and thus need to be adequately managed and protected. It is, therefore, essential to understand erosion hazards and to identify the potential impact of erosion and the areas which are especially prone to it.

Erosion is one of the main threats to coastlines worldwide, and the topic has received much attention in recent decades (Bird, 1985; Eurosion, 2004; Gracia et al., 2018; Luijendijk et al., 2018). According to Mentaschi et al. (2018), approximately 28,000 km^2 of coastline were eroded away between 1984 and 2015, about twice as much as was deposited by accumulation

processes. In Europe, 16% of the population (70 million) live in coastal areas, and about 20% (20,000 km) of this coastline is at risk of erosion (EEA, 2010).
As such, coastal erosion-related methodologies are as diverse as the characteristics of research programmes and their objects of study (erosion of beaches, cliffs, tidal marshes, etc.). Thus, coastal erosion is a common variable in studies related to shoreline changes (Mujabar and Chandrasekarn, 2013; Kabuth et al., 2014; Tamassoki et al 2014; Kankara et al., 2015; Prieto-Campos et al., 2018) and studies on the impact of erosion on coastal infrastructure and vice versa (Olympio et al., 2014; Chenthamil et al., 2016; Muthusankar et al., 2017; Rangel-Buitrago et al., 2018).

Along with other variables, erosion also features frequently in coastal vulnerability studies, the main focus of which is the rise of sea levels owing to climate change or extreme natural phenomena such as storms, tsunamis, etc.… (Kumar et al., 2015; López et al., 2016; Vousdouskas et al., 2016; Angelica et al., 2017; Priya et al., 2019, etc.). Studies on vulnerability to erosion are few and have adopted a variety of approaches (Zhu et al., 2019).

Coastal vulnerability indices can be assessed in a variety of ways (Balica et al. 2012). Some authors calculate physical and natural vulnerability (Bagdanavičiūtė, et al., 2015; Kumar et al. 2015; Pantusa et al., 2018; Priya et al., 2019), while others combine these with socioeconomic vulnerability variables (Ojeda et al., 2009; Murali et al., 2013; Zhu et al., 2019). Concerning physical-natural vulnerability, it is possible to distinguish between external and internal variables. Internal variables are concerned with the physical characteristics of coastlines-characteristics which are related to resilience and susceptibility-while the effects on the beach of marine forces are regarded as external variables (McLaughlin and Cooper, 2010; Zhu et al, 2019).

The number of variables used to classify beaches varies drastically from one index to another. Composite indices range from five variables (Priya et al., 2019) to complex analyses with both physical and socioeconomic variables (12) (Zhu et al., 2019). In most cases, all variables are deemed to contribute equally to beach erosion, but some recent studies have begun to weight variables. Identifying how and to what extent variables contribute to an index is not easy and requires the input of experts both in relation with the specific issue at hand and the broader area under study. Murali et al. (2013); Bagdanavičiūtė et al. (2015) and Zhu et al. (2019), used Saaty's Analytical Hierarchical Processes (AHP) (Saaty, 1989; 1990) to weight criteria. In this sense, whereas Bagdanavičiūtė, et al. (2015) took the presence of sand bars, followed by historical shoreline change rates, as the variables with the greatest weight, in the case of Murali et al. (2013), the experts assigned greater weight to slope and beach geomorphology.

The definition of beach limits is a complex matter that is still being debated; the dynamic nature of beaches, which are affected primarily by waves and tides and, to a lesser extent, by wind and other meteorological and anthropic phenomena, makes a stable definition of limits difficult. In this work we shall refer to dry beaches, defined as the area measured inland from the high water mark to the upper limit of storm wave effects (US Army Corps of Engineers, 2008).

Most coastal erosion studies focus on dry beaches and, to a lesser degree, on submerged beaches. Only with the generalisation of airborne Light Detection and Ranging systems (LiDAR) have morphodynamic studies that consider whole beaches begun to appear (Prieto, 2017). In addition, although 3D volumetric analysis is the most reliable method to calculate erosion (Ojeda, 2000), the lack of historical 3D data prevents a retrospective analysis (LiDAR data is available only for certain locations and for recent dates). Although 3D data based on aerial photographs and GPS are available, and studies monitoring 3D coastal morphological changes have been undertaken using these techniques (Ojeda et al., 2002; Pierre, 2006; Obanawa and Hayakawa, 2018, among others), this research has been mainly confined to small study areas and requires photogrammetric processing skills (Westoby et al., 2018).

Beaches which have the highest rates of erosion are generally deemed to be the most vulnerable. However, similar erosion rates may have very different effects according to various variables, such as the size of the beach, the presence of dunes and the morphology of the beach, etc. (Alexandrakis and Poulus, 2015). Generally, not all variables are available for all areas, and they are costly to obtain, especially for large areas.

Calculating the slope, profile and morphology of exposed and submerged beaches is costly and difficult, especially in large study areas for which no LiDAR information is available. With the development of geographic information technologies, this sort of information can be generate on a global scale. Especially of note is the recent work by Athanasiou et al. (2019), who published the first ever global database of nearshore coastline slopes, which could be enormously valuable for the calculation of future indices.

The aim of this work is to develop a methodology to calculate a 'beach sensitivity to erosion rates' indicator; a simple and reliable indicator that could be reproduced in other areas, allowing meaningful comparisons to be carried out. This indicator will constitute the first attempt to characterise beaches according to their capacity to withstand erosive phenomena (whatever their cause) on a the regional scale.

This indicator will allow coastal planners to gain a general understanding of the allocation of resources and of where to focus more detailed analyses, where other variables (beach slope, presence of underwater bars, height...), which are costly and difficult to obtain for large extensions, should be taken into account.

In this work, we note that the concept of beach sensitivity is closely linked to beach resilience, and this reflects how the physical features of beaches help them cope with erosive phenomena.

In essence, sensitivity will be measured using three variables, calculated on the basis of aerial orthophotographs, namely: width of the dry beach, mid-term erosion rates and availability of accommodation space, taking into account its width and typology. Accommodation space is the free space (i.e. free from buildings, rock cliffs and other non-decomposable material) which allows the beach to react naturally to possible erosive processes (Prieto et al., 2019; Jiménez et al., 2017).

The present paper contributes to the existing literature in five main ways:

1. The indicator is simple, since it is based on three variables that are easy to obtain from orthophotos, and this increases replicability and therefore comparability. The indicator points out zones where more detailed analysis is desirable, taking into account cost variables and optimising the use of time and resources.
2. Despite the presence of foredunes reducing the risk of erosion (Tomasicchio et al., 2011; D'Alessandro et al., 2012: 2016), this variable is rarely incorporated in coastal indices, and, when it is, it is only regarded as a nominal variable (presence/absence) - Murali et al. (2013); Zhu et al. (2018). This study not only takes into account the potential presence of dunes, but also incorporates other potential sedimentary sources (accommodation space).

The measurement of the width of the dune, is rarely taken into consideration for coastal indices, unless only a small area is being examined (Pantusa et al., 2018), in which case it is measured directly from orthophotos. In this study, the width of the accommodation space is measured from orthophotos (1D) for the whole area under study, which comprises 260 km of coastline. Together with these orthophotos, additional sources of information have been used (e.g. physiographic maps of the Andalusian coast).

3. The width of the accommodation space has been weighted according to type of sedimentary substrate. The weighing process was carried out by an expert panel according to AHP methodology (Saaty, 1989; 1990), which applies consistency ratios to ensure the consistency of judgments established by these experts.
4. Since the variables used to calculate the sensitivity indicator are based on proxies, additional thematic and geomorphological information has been incorporated in order to ensure the correct interpretation of the results.
5. The spatial study presented in this paper has been carried out with the aid of a relational spatial database, through the open-access spatial database management system PostgreSQLPostGIS and the construction of spatial Structured Query Language (SQL) sentences. It facilitates reproducibility, scalability and automatisation of the analysis to other areas.

2. Materials and Methods

2.1. Study area

The study focuses on exposed beaches in the province of Cádiz, the southernmost province in continental Spain (Figure 1). The coastline of Cádiz is 260 km long and is divided into different sectors: the 220 km-long straight Atlantic sector is broadly NW-SE oriented (170 km), and SW-NE oriented (50 km-long sector around the Strait of Gibraltar). The Mediterranean sector is NNE-SSW oriented (approximately 40 km long).

Of the total length, 65% (170 km) comprises beaches, divided into two facades separated by the Strait of Gibraltar (Punta de Tarifa). According to Del Río et al. (2013a), four types of exposed beaches have been identified: rectilinear, reef-supported, z-bays, and enclosed beaches. The features currently presented by beaches are the result of multiple factors (geomorphology, hydrodynamic conditions, wind regime, human presence). The Atlantic (133 km of beaches) and Mediterranean shores (37 km) have different morphologies, as a result of the impact of two main geographical features, the Baetic Range and the Tertiary Guadalquivir Basin.

The northern sector of the Atlantic facade, which is the westernmost sector of the study area, is characterised by an extensive and gently sloping continental platform, which is largely due to the influence of the Guadalquivir Basin. The presence of important sedimentary inputs (from the Guadalquivir and Guadalete rivers among others), along with a significant NW-SE coastal drift, has led to the formation of large dune cordons (barrier islands) enclosing wide bays, which in turn has led to the formation of extensive saltmarshes. All of this has contributed to the formation of large, flat and fine-sanded beaches with substantial dunes. As it approaches the Strait of Gibraltar (the southernmost reaches of the Baetic range), the coastline becomes progressively more abrupt. There, tectonic dynamics raised Palaeogene and Miocene sea levels (Martín-Algarra, 1987), leading to the formation of turbiditic outcrops (flysch, Campo de Gibraltar complex). This resulted in the alternation of enclosed beaches, z-bays, and littoral platform-supported beaches at which sediment is less readily available and which are characterised by coarser sands and fewer dune formations (Prieto, 2017), with the exception of a few river mouths (Barbate) and tombolos (Cabo de Trafalgar).

Tides become progressively less acute from NW to SE, especially from Cabo Trafalgar eastwards, going from 2.96 m in the westernmost sector of the study area (Cádiz) to 1.22 m in Punta de Tarifa (Del Río et al., 2019). Waves, that have a long fetch and are clearly dependent on the dominant south-westerly winds, have led to substantial NW-SE coastal drift, between 20,000 and 100,000 m^3 per year (MAPAMA, 2013), depending on morphologic conditions and the availability of sediment.

From the point of view of dynamics, storm events constitute the most important cause of coastal erosion, as no single sea level trend has been attested to dominate coastal dynamics in the area over the last 40 years (Rangel-Buitrago and Anfuso, 2011; Marcos and Tsimplis, 2008). However, recent decades have witnessed a clear process of coastal stabilisation. This process of stabilisation has intensified in recent years, mostly for two reasons: the aforementioned construction of infrastructure parallel to the coastline and the construction of reservoirs higher up the course of those rivers which contribute the most sediment. As a result, the quantity of sediment being deposited at the beaches has decreased (Prieto et al., 2018), which in some cases has called for artificial beach nourishment measures to be implemented.

The Mediterranean shore, located to the south-east of the study area, is subsumed in the Complex of Gibraltar formation, the geomorphological characteristics of which are similar to those in the southern sector of the Atlantic facade. Despite the fact that sediment is less readily available, with the absence of major inputs, there are important sandy formations (barrier islands and tombolos) have been formed in the Bay of Gibraltar and the mouth of the main rivers (Palmones, Guadiaro, etc.). However, it should be noted that these areas present a high degree of anthropisation (Del Río et al., 2019).

A micro-tidal (< 1 m) regime prevails between Punta de Tarifa and Punta Chullera (Del Río et al., 2019). Waves present little fetch and depend on north-westerly winds (Levante), which are especially strong around the Strait of Gibraltar, leading to a NE-SW coastal drift that is rarely above 20.000 m^3 per year (MAPAMA, 2013).

From the point of view of dynamics, the torrential nature of storm events constitutes the most important cause of beach erosion in the Mediterranean coastline (Molina et al., 2019). This sector is more heavily anthropised, and therefore very stable; this, alongside beach nourishment practices, may contribute to masking erosive processes (Del Río et al., 2019).

Approximately 35% of the coast of the province of Cádiz is situated in protected areas, 60% of which is comprised of beaches of great natural and ecological value. Acknowledgement of this value has contributed to limiting urban pressure, although beach tourism has increased in recent years: the number of overnight tourist stays during the summer months of 2019 was 314,315, about 40% more than in the summer of 2005 (INE, 2019).

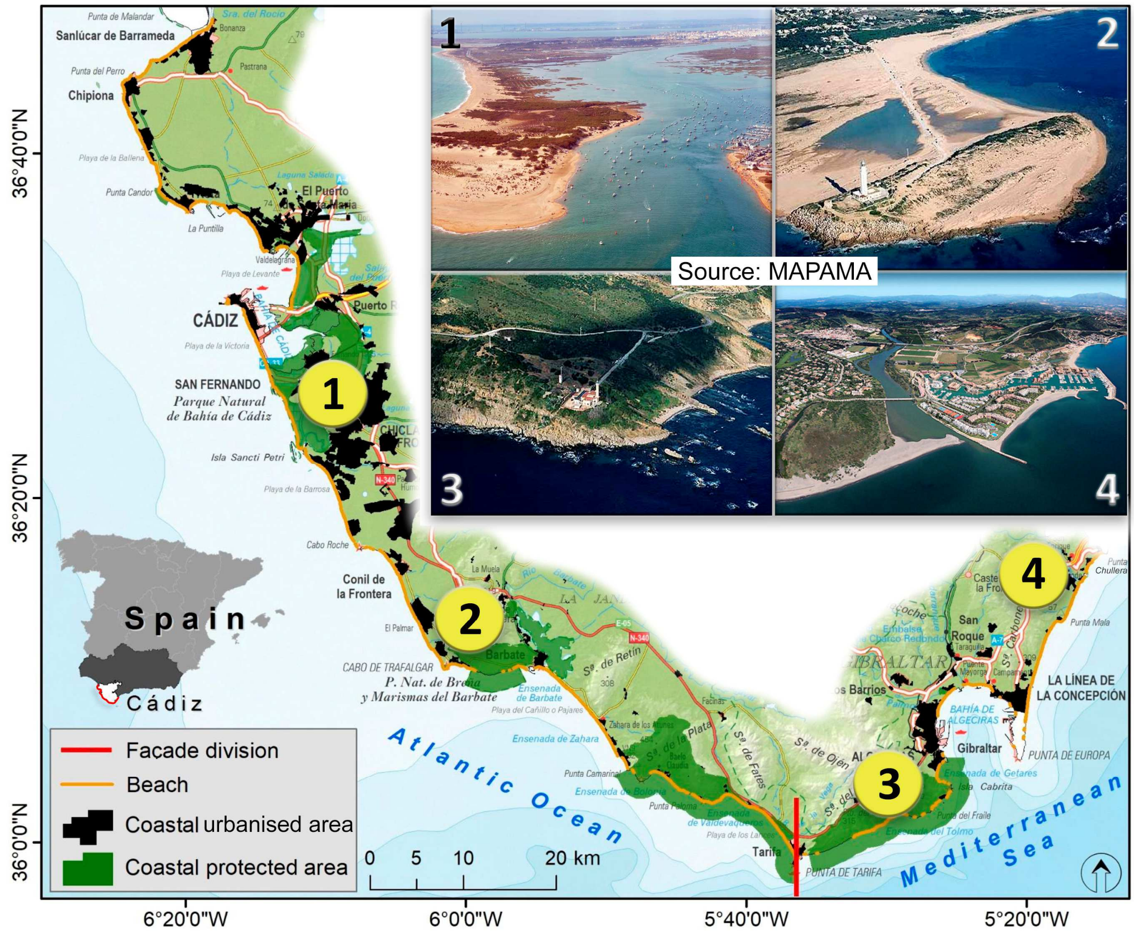


Figure 1. Study area

2.2. Methodology

The methodology devised to characterise dry beaches according to erosion sensitivity is based on data that has been integrated into a relational spatial database, and consists of five steps:

- Identification and calculation of the necessary data and variables,
- Design of the database's conceptual model.
- Implementation of the model in a spatial data-management system,
- Exploitation and analysis of the data the calculation of a sensitivity indicator,
- Spatial display of results.

The coordinate reference system used throughout the process – European Terrestrial Reference System 1989 (ETRS89), UTM zone 30 N – follows current regulations (Royal Decree 1071/2007).

Each of these steps is explained in detail in the following sections.

2.2.1. Identification and calculation of the necessary data and variables

The selection of suitable variables is an important step in the development of any index. Inevitably, the selection of variables is a subjective exercise. In this study, variables are chosen in order that the indicator would: provide a simple indicator that can be used in other areas, be capable of characterising beaches according to their ability to withstand erosive phenomena, and indicate areas where more detailed analysis may be required.

Accordingly, variables are chosen largely based on their contribution to the indicator and statistical independence, and on the availability of data.

The three variables selected are: erosion rates (expressed as rate of shoreline change), backshore width, and accommodation space (width and typology).

Regarding the contribution of variables to the sensitivity indicator, it can be argued that wider beaches that are subject to accumulation trends and possess a wider accommodation space are less sensitive to erosion, and thus are more resilient to this process. In contrast, narrower beaches that are subject to higher erosion rates and possessless accommodation space are regarded as more sensitive to erosion.

Concerning the availability of data, the 3D data necessary to carry out a full retrospective analysis to calculate erosion rates were lacking. Also, given the large area of study (260 km), the use of 3D data based on aerial photographs and GPS would be inappropriate. Table 1 presents the sources used for the characterisation of spatial data related to the selected variables and based on existing orthophotos.

Digitalisation was undertaken at a 1:2500 scale by a single interpreter, as a way of ensuring spatial and thematic consistency.

Table 1. Characteristics of orthophotos based on photogrammetric flights.

Flight name	**Date**	**Pan / Colour**	**Spatial resolution**
Interministerial flight (IRYDA)	1977	Panchromatic	0.5 m
Andalusian digital photogrammetric flight	2009	Colour	0.5 m
Andalusian digital photogrammetric flight	2011	Colour + NIR	0.5 m
Andalusian rigorous photogrammetric flight	2013	Colour + NIR	0.25 - 0.5 m

It is also important to note that the variables selected are statistically independent of one another: after selecting the , a linear regression analysis was carried out to establish this. Figure 2 expresses the statistical independence of variables, and thus their suitability for generating the sensitivity indicator.

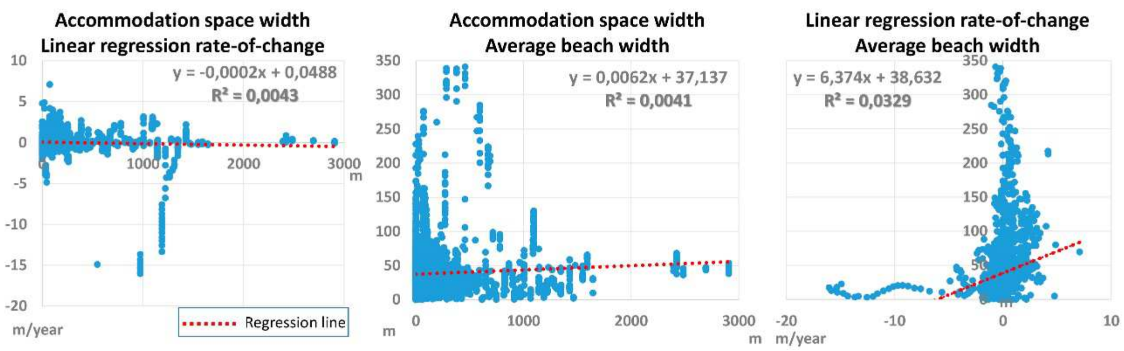


Figure 2. Statistical independence of the variables

- Erosion rates

The proxy selected to calculate erosion rates was the contact backshore/foredune, cliff foot or line of infrastructure (Figure 3); these are regarded in the specialised literature as the most stable variable in the mid-term in meso-tidal coastlines (Anfuso, 2001; Moore and Giggs, 2002; Del Río, 2007; Del Río et al., 2013a; Paris et al., 2013; Prieto, 2017; Prieto-Campos et al., 2018).

Since long-term coastal changes tend to homogenize in response to a gradual change in the coastline, widespread digitalisation has been carried out in order to avoid abrupt variations that could lead to erroneusinterpretations (Prieto-Campos et al., 2018).

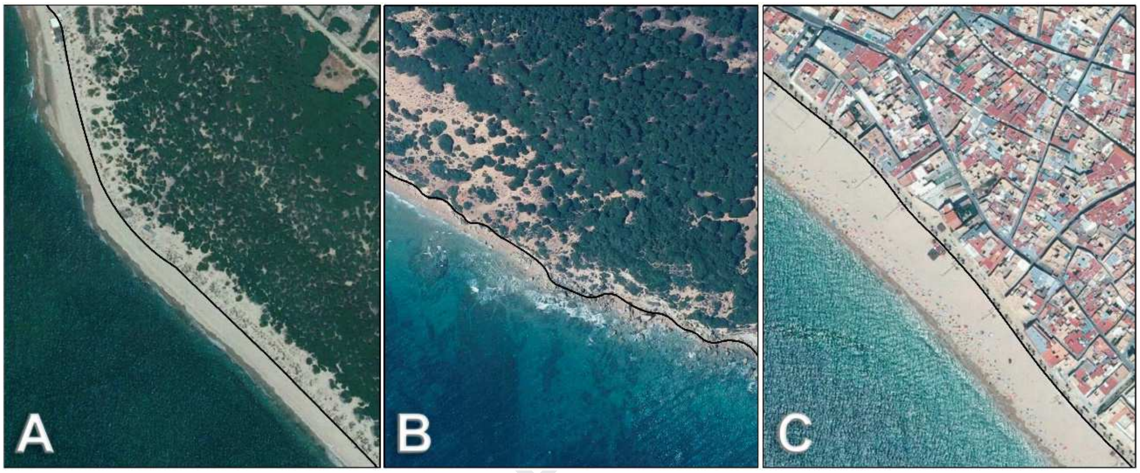


Figure 3. Digitalisation criteria based on different kind of contacts. A) Foredune; B) Cliff foot; C) Infrastructure.

In order to ensure the continuity of the digital shoreline, infrastructures, anthropic elements, tidal areas and rocky outcrops were also digitalised. Thematic information concerning the coastal typology (anthropic, beach, rocky, marshy) has been added to each independent coastal segment, as well as complementary information (official toponymy), to aid the interpretation and analysis of erosion rates (see Fernandez-Nunez et al., 2015; Prieto-Campos et al., 2018).

After digitalising lines for different dates, the Digital Shoreline Analysis System (DSAS) was used to calculate changes over time (Thieler et al., 2003; US Geological Survey, 2007; Thieler et al., 2009). In order to do this, an onshore baseline parallel to coast was digitalised, from which a series of transects orthogonal to shoreline were generated at 50 m intervals. Thus, 4,020 transects were thus created.

The method used to calculate the rates was simple linear regression, as according to the specialist literature this is the most reliable method for examining shoreline trends over mid-to-long-term periods based on several lines (Crowell et al, 1997; Douglas et al, 1998; Luijendijk et al., 2018). The availability of different orthophotos has made it possible to generate real absolute measurements (m) between the most current and the oldest line (Net Shoreline Movement –NSM-) as well as rates (m/yr) based on a linear regression (Linear Regression Rate-of-change –LRR-). A weighted analysis has been disregarded (Weighted Linear Regression –WLR-) since it has the same characteristics in terms of spatial resolution (Figure 4). The uncertainty range (±m/yr) has been calculated as the quadratic sum of the errors in the data sources divided by the total time period (Coyne et al., 1999; Del Río, 2007).

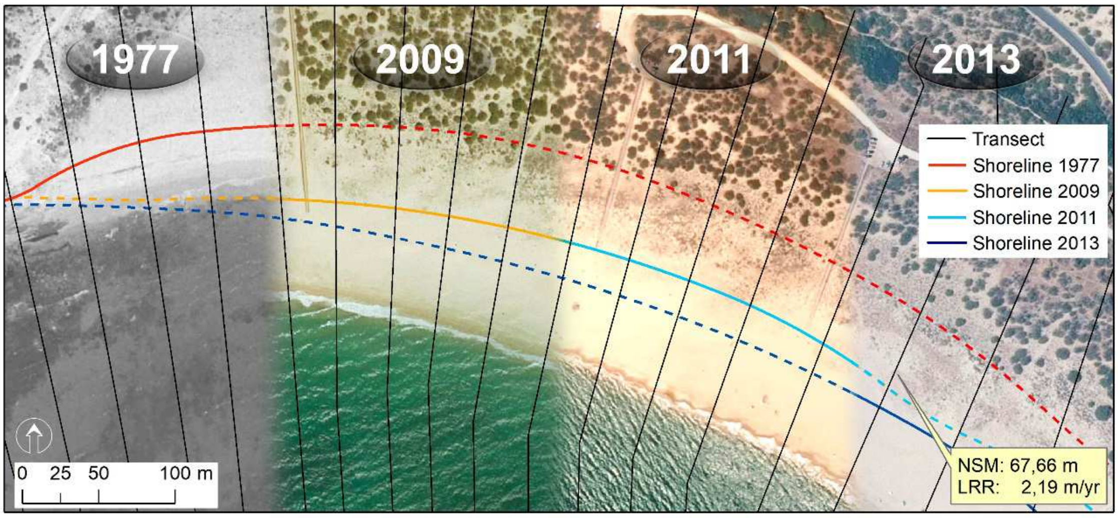


Figure 4. Rate-of-change by transects in the period 1977-2013.

- Average beach width

Beach width (backshore) is closely related to its physical tourism carrying capacity (Ojeda et al., 2013). This value has been calculated using two proxies: i) the lower limit, marked by the highest tidal water mark; and ii) the backshore described in the previous section. The difference between these two points was calculated with a DSAS tool in the polygons formed by the transects and the backshore and high water line limits.

Given the highly dynamic nature of beaches, the time interval between orthophotos and the high number of variables that may affect beach width at any given time, the values obtained at different dates were averaged. The data for 2009, 2011 and 2013 were considered most suitable, because they were not only the most recent but were also all taken during the summer, making their profiles more comparable (Figure 5).

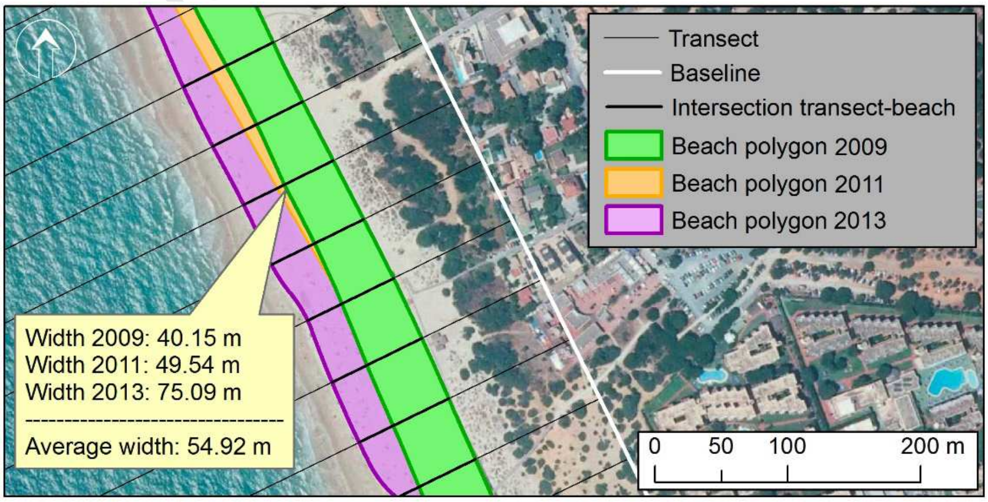


Figure 5. Digitalisation of inner (in this case, foredune) and outer (high water line) of coastlines and calculation of average width.

- Width and typology of accommodation space

The calculation of accommodation space width was based on the most recent orthophoto. Digitalisation was based on identifying its inland limit from the proxy backshore/foredune (Figure 6). Data concerning the type of substrate was added to polygon data. In order to calculate accommodation space width, the accommodation space polygon was adjusted to the transects.

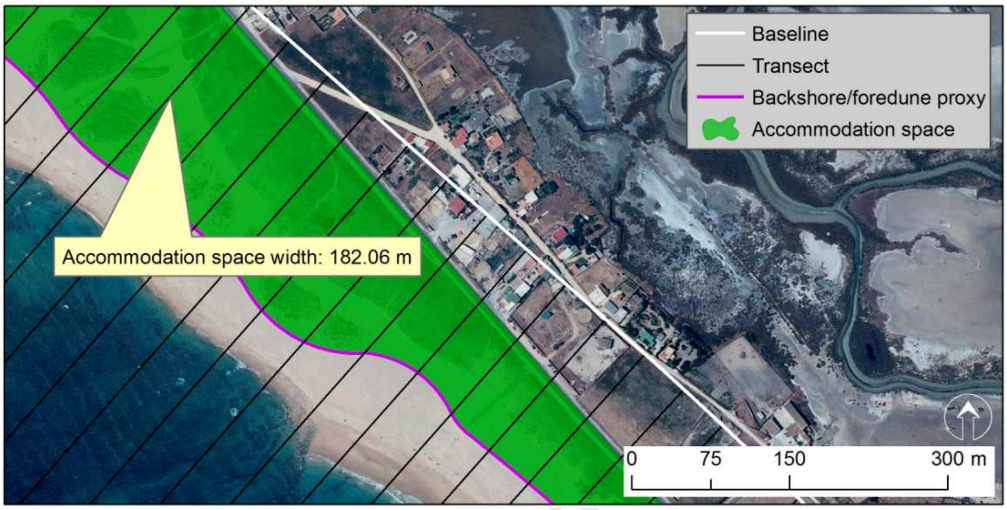


Figure 6. Calculation of accommodation space width.

Finally, it should be noted that the substrate of the accommodation space will also affect sensitivity. Foredunes and other sedimentary formations allow beaches to maintain their profile and quality, as well as allowing for a faster response than that afforded by more compact substrata, such as fractured cliffs or other rock sedimentary substrata. These, while allowing for the beach to retreat, lead to a decrease in quality from a touristic perspective, owing to changes in sand granulometry. The type of substrate used in the analysis was based on the *Mapa de Unidades Fisiográficas del Litoral de Andalucía* (Department of Agriculture, Livestock, Fisheries and Sustainable Development, 2007), which identifies four types of substrata (foredunes, aeolian dunes, detritic substrate associated to deltas, floodplains and coastal plains, fractured rock sediments and other rock sediments substrate).

2.2.2. Design of the database conceptual model

After the data and variable requirements were established, it was necessary to design the database conceptual model (Figure 7).

The data was modelled with an entity relationship diagram (ERD) which allows the relevant entities in an information system, as well as their relationships and properties, to be represented (Dhabe et al., 2010).

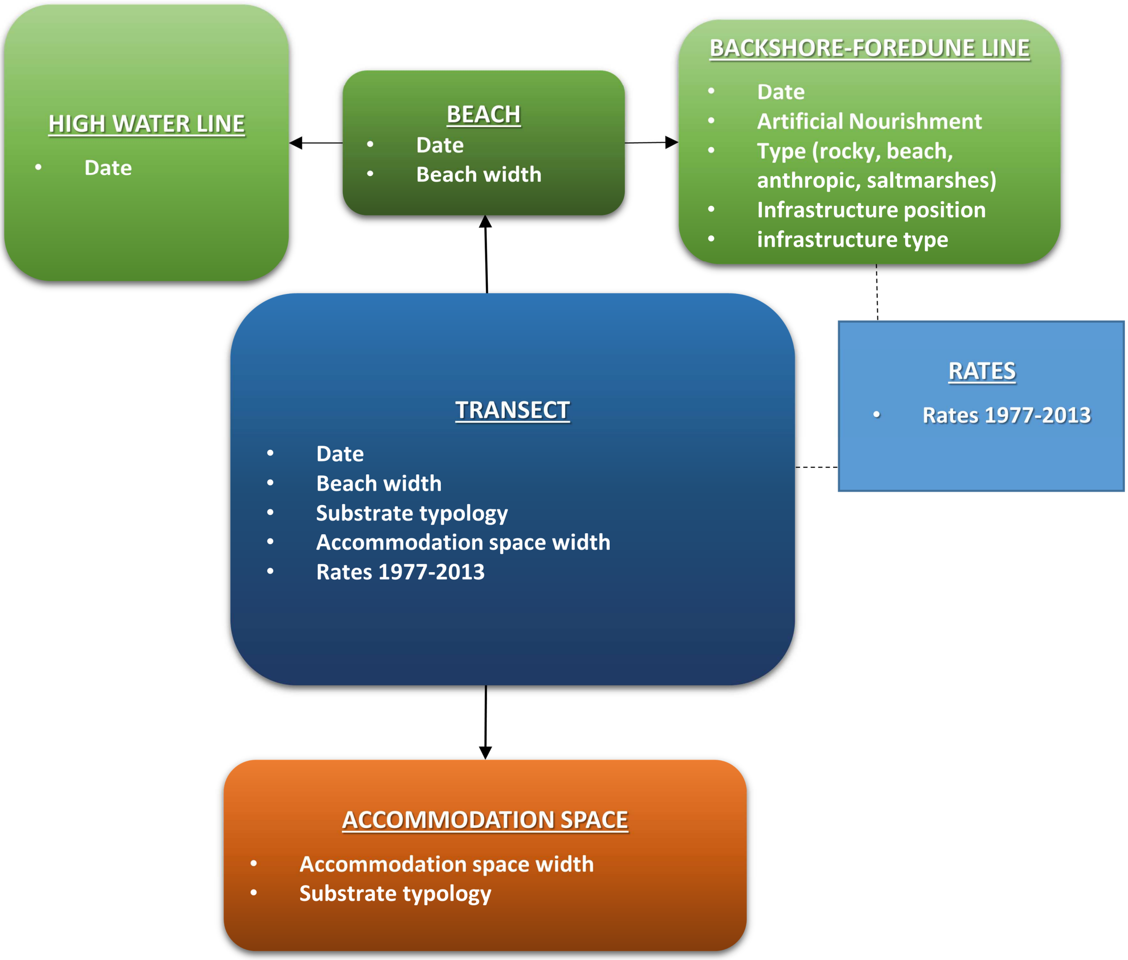


Figure 7. Data model

The ERD was comprised of a central geometric entity (*TRANSECT*), representative of the 50 m-interval transects (4,020 in total), and is related to a series of entities/tables that characterise these transects. The following points describe each table and their mutual relationships:

- Table *Beach*: polygonal geometric entity that is representative of the beach area polygon for each date. It is related by a 1:M cardinal intersection spatial relationship with table *TRANSECT*. Table *Beach* is calculated from 1:M cardinal intersection relationships with tables *High Water Line* (representative of proxy ”highest water mark” for each date), and *Backshore/foredune* (representative of proxy “Backshore/foredune *Line*”).
- Table *Backshore/foredune line*: it represents the “backshore/foredune” line for each date. Gemorphological (beach, estuary, marsh) and anthropic information (type and position of infrastructures) was collected for each independent coastal segment.
- Table *Rates*: Alphanumerical entity resulting from a M:M cardinal relationship between table *Backshore/Foredune* and table *Transect*. It represents erosion rates for each date.
- Table *Accommodation space*: polygonal geometric entity that is representative of the accommodation space polygon and the type of substrate for the most recent date (2013). It is related by a 1:M cardinal intersection relationship to table *Transect.*

2.2.3. Implementation of the model in a spatial data management system

The data model was implemented by means of a spatial data-management system (open access PostgreSQL) which, in combination with PostGIS, allows for the implementation of spatial functions. In this way, all data was entered (PostgreSQL 10.2/PostGIS 2.3) and prepared for analysis by the physical assignation of primary and foreign table keys, required in any methodology of relational spatial database. These keys uniquely identifies each record in the table and allow relationships between tables, as well as the integration and consistency of the database to be maintained (Dhabe et al., 2010; Díaz et al., 2018; Prieto-Campos et al., 2019). Finally, the construction of spatial and thematic indices has been carried out to speed up the process of analysis.

2.2.4. Exploitation and analysis of the data for the calculation of the indicator

After implementing the data management model, a series of spatial SQL sentences were designed in order to obtain the primary results. First, variables were standardised in a range between zero and one values with Malczewski's Eq. (A.1) (1999), where x equals the value of a variable in the original data set:

$$Xz = \frac{(\mathrm{x} - \min(\mathrm{x}))}{\max(x) - \min(x)} \quad \text{Eq. (A.1)}$$

Table 2 presents the statistical values of the quantitative variables used to standardise the variables.

Table 2. Standardised variable statistics

	Max(x)	Min(x)	Average (x)
Beach average width (m)	340.86	0.05	39.33
Accommodation space width (m)	2906.01	0	269.43
Erosion rates 1977-2013 (m/yr)	-0.11	-16.04	-0.83
Accretion rates 1977-2013 (m/yr)	7.09	0.11	0.75

Once criteria were standardised, experts were asked about the possibility of weighting these. As the experts were not able to make judgments on the importance of one variable with respect to another, we decided to maintain the same weight to all the variables. Nevertheless, the variable space of accommodation was weighted according to its type of substrate. Weights have been established using the Analytic Hierarchy Process (AHP), proposed by Saaty (1989; 1990). This method allows for the analysis, integration and weighting of qualitative variables, which are typically left out of the analysis owing to the complexity of their measurement.

The AHP method is based on the linguistic decision-maker's preferences, incorporated by a pairwise comparison process that compares the importance of each criterion using the values of the Saaty scale (Saaty 1989), see Table 3. Values 2, 4, 6 and 8 on the Saaty scale correspond to intermediate situations.

Table 3. Saaty scale

	1	3	5	7	9
Definition	Equal importance	Moderate importance	Strong importance	Very Strong importance	Extreme importance

According to the reciprocal judgments, this process generates an auxiliary matrix “X”, where if the relative importance of the criterion 1 over the criterion 2, C12, is judged to be 5 “strong importance” in Saaty scale (see Table 3), the relative importance of the criterion 2 with regard to the criterion 1, C21, has the reciprocal value, that is 1/5.

$$X = \begin{bmatrix} \mathbf{C11 = 1} & C12 = 5 & C13 = 3 \\ C21 = 1/5 & \mathbf{C22 = 1} & C23 = 2 \\ C31 = 1/3 & C32 = 1/2 & \mathbf{C33 = 1} \end{bmatrix} \quad \text{Eq. (A.2)}$$

When the pairwise comparisons were obtained, the matrix was normalised. This process involved dividing the elements of each column by the sum of the elements of the same column. Subsequently, a geometric average was applied to the responses and produced the final weightings. Finally, the weight vector is obtained using a linear algebraic operation, which is the principal eigenvector of the matrix (Zhu et al., 2019).

To verify the accuracy and consistency of the pairwise comparisons, the consistency ratio (C_r), is calculated using Eq. (A.3). The consistency ratio determines the internal coherence of the decision-maker’s judgments. This is calculated using the consistency index (C_i) Eq. (A.4) and the random index (R_i) by applying the following formula:

$$Cr = \frac{Ci}{Ri} \quad \text{Eq. (A.3)} \qquad Ci = \frac{(\lambda - n)}{(n-1)} \quad \text{Eq. (A.4)}$$

Where n is the number of variables in the comparison matrix, and λ is the value of the main eigenvector normalised “W” multiplied by the pair comparison matrix.

The random index (R_i) is the C_i of a randomly generated pairwise comparison matrix of order 1 to 10 (Saaty, 1989). Table 4 shows the value R_i sorted by the order of matrix.

If $C_r < 0.10$, the ratio indicates a reasonable level of consistency in the pairwise comparisons; if, however, $C_r > 0.10$, then the values of the ratio are indicative of inconsistent judgments and requires the weighting to be revised.

Table 4. Value of Random Index

Order matrix	1	2	3	4	5	6	7	8	9	10
Definition	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Concerning the weight of accommodation space width, in this work, two PhD holders (an expert in integrated marine and coastal management and a geographer, specialised in the study area and coastal geomorphology) were asked to obtain the pairwise comparisons. Results obtained for accommodation space revealed that foredunes, followed by aeolian dunes sediments, had the lowest sensitivity and highest resilience values (0.467 and 0.327 respectively), because these types of substrate not only guarantee the survival of the beach, but also the ready availability of a high-quality substrate (Table 5).

Table 5. Pairwise comparisons relating type of substrate of accommodation space

	V1	V2	V3	V4	V5	W
V1	**1**	**2**	**6**	**8**	**9**	**0.467**
V2	1/2	1	5	7	8	0.327
V3	1/6	1/5	1	5	6	0.127
V4	1/8	1/7	1/5	1	3	0.049
V5	1/9	1/8	1/6	1/3	1	0.029

V1= FOREDUNE; V2= AEOLIAN DUNES; V3= DETRITIC SUBSTRATE; V4= FRACTURED ROCK SEDIMENTS; V5= OTHER ROCK SEDIMENTS

W1= ORDER OF PRIORITY OF FACTORS; W= VALUE OF THE WEIGHTS, IN THIS CASE NORMALISED TO 1.

$\lambda = 5.440$; $C_r = 0.098$

Once weights have been assigned and their consistency has been estimated, the beach erosion sensitive indicator (SI) was calculated using the linear weighted sum. Due to the disparity in rate-of-change results, a data standardisation was undertaken separately (positive rates –accretion-, and negative rates –erosion-). For this reason, both trends were taken into account separately in the same equation, adding or subtracting according to their sign.

$$\text{Eq. (A.5).}\ SI = BW + (W1xAS) + A - E \qquad \text{Eq. (A.5)}$$

where, BW= beach average width; W1= weights obtained according to type of substrate of accommodation space; AS= accommodation space width; A= accretion; E= erosion.

2.2.5. Spatial presentation of results

The mapping and semiological representation of results was undertaken by means of open access GIS QGIS software. This software allows for the reliable and fast visualisation of data stored in PostgreSQL/PostGIS.

3. Results

3.1. Variables

3.1.1. Erosion rates

Figure 8 presents the erosion rates results for the period 1977-2013, by facades.

In general both facades show a stable trend. Nevertheless, the Atlantic coastline is more dynamic (33% accumulative sectors and 29% erosive sectors), than the Mediterranean. The proxy used means that this stability should not be mistaken in all cases for stable sedimentary behaviour. The presence of cliffs and artificial infrastructures (retaining walls, seaside promenades) "rigidise" the coastline used for the calculation of rates, preventing natural oscillation and, therefore, leading to 0 values. This perception of stability might mask severe erosive processes, hampering the identification of vulnerable beaches. In these circumstances, the thematic information included in the database is essential (section 2.2.2) and could ensure the correct interpretation of the results. Similarly, those low values within the uncertainty range of the data (±0.1 m/yr) have been taken into account within the same interval.

The thematic information has made it possible to differentiate between the different causes of stable values. The Atlantic facade shows a predominance of values by natural trend of the coast (17%). The forced stable sectors are mostly due to the presence of cliffs (13%), whereas infrastructures cause only 8%. For the Mediterranean facade, however, stable sectors caused by the presence of cliffs (28%) and infrastructures (15%) predominated. The stable sectors caused by natural factors account for only 9%

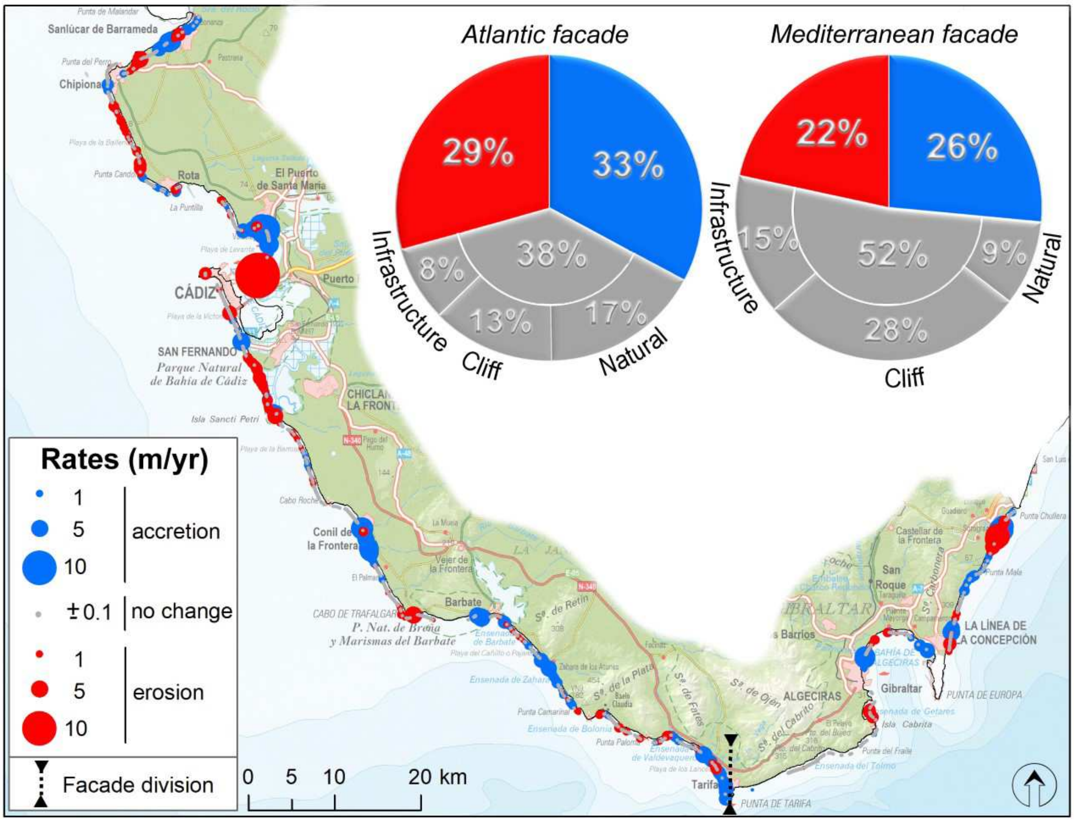


Figure 8. Percentage, distribution and rates by facade and period

3.1.2. Average beach width

Despite there being substantial differences in the average width of Atlantic and Mediterranean beaches, the proportion of beaches whose width is less than 25 m (Figure 9) clearly predominates, including 44% of Atlantic beaches (56 km) and 52% of Mediterranean ones (19 km).

Beaches between 25 and 50 m wide are primarily with urban beaches and embedded beaches which have not changed greatly. The percentage is very similar for both facades: ranging from 28% (36 km) on the Atlantic facade to 25% (10 km) on the Mediterranean.

Beaches between 50 and 100 m wide are characterised by the presence of transverse infrastructures, which alter the longitudinal dynamics, generating accumulation zones and thereby increasing the average width of certain sectors. The percentage is still very similar for the Atlantic and Mediterranean facades, ranging from 21% (27 km) to 22% (8 km), respectively.

The width of beaches greater than 100 m was determined, firstly, by the presence of major transverse infrastructures (ports, dikes...) and, secondly, by the presence of a gently sloping continental platform. This geomorphology, which has been mentioned above and which is present in most of the Atlantic shore, permits the development of wide beaches. Such beaches make up 6% of the total (9 km) as opposed to 1% (0.15 km) of the Mediterranean facade, where the absence of beaches greater than 200 m stands out.

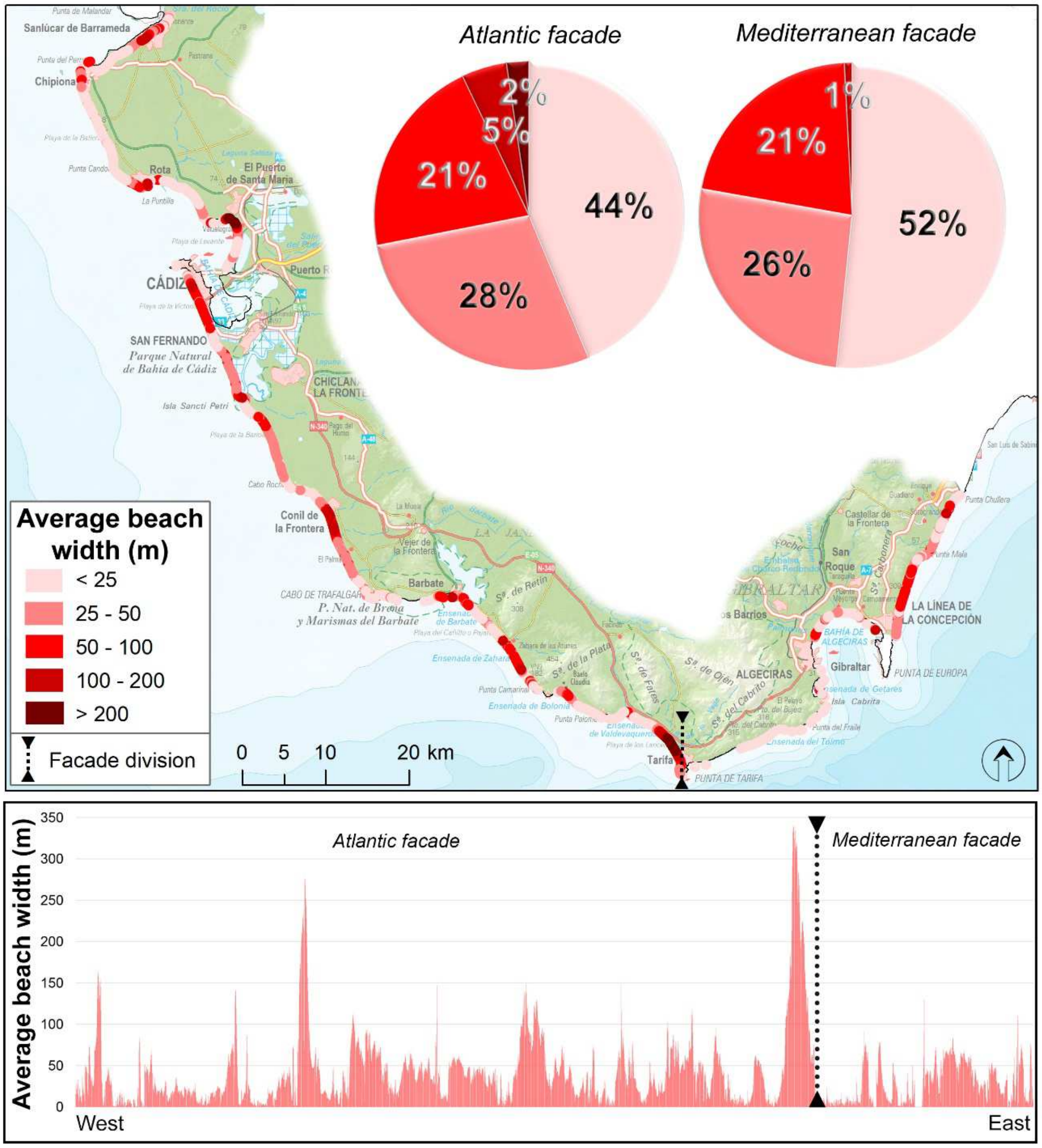


Figure 9. Percentage and spatial distribution by facade.

3.1.3. Accommodation space typology and width

Concerning the width and type of accommodation space (Figure 10), the results indicate that a large proportion of Atlantic beaches (82%) have accommodation space (104 km). The Mediterranean facade, which is more abrupt, has a lower percentage of beaches with accommodation space (52%; 19 km).

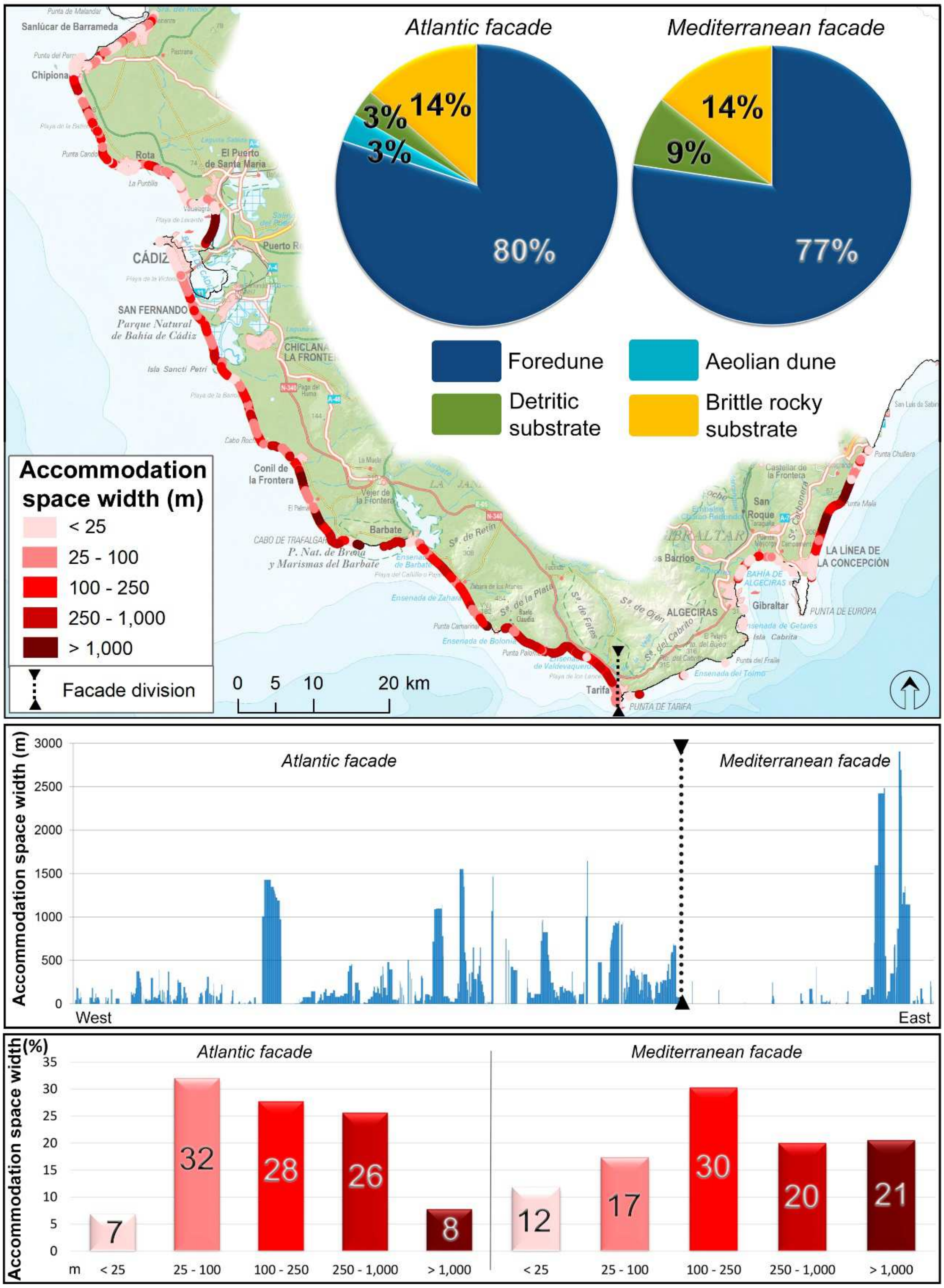


Figure 10. Width, spatial distribution and typology of accommodation space substrate* by facade

*The typology called "brittle rocky substrate" incorporates fractured rock sediments and other rock sediments substrate.

The less extensive accommodation spaces (less than 25 m) correspond to areas which have an anthropic presence closer to the coast, and to abrupt areas with little margin for foredune development; these areas account for 7% of Atlantic beaches and nearly double that (12%) for Mediterranean beaches.

The ranges 25-100 m and 100-250 m correspond to areas where the urban presence respects the beachfront and where the accretion of sediments (due to the presence or not of transversal infrastructures) has allowed an important foredune development. Both ranges are predominant on both facades (60% of Atlantic beaches and 47% of Mediterranean ones).

The widest ranges of accommodation space (250-1,000 and more than 1,000 m) are associated with non-anthropised areas. On the Atlantic facade, the natural character of many of these areas is due to the presence of protected beaches (natural parks Bahía de Cádiz, La Breña and Marismas de Barbate, El Estrecho...), which constitude34% of the beaches, where they can reach 1,500 m width. On the Mediterranean facade, the greatest widths of accommodation spaces are concentrated on both sides of Punta Mala (41%), where the accommodation space is not limited and reaches almost 3,000 m. Limitations to space mainly consists of cliffs made of brittle rocky material.

Concerning the type of substrate of the accommodation spaces, both facades are dominated by foredunes (80 y 77%, respectively), regardless of the accommodation space width. This is the best possible substrate in terms of beach quality. In a substantial number of beaches in both facades the predominant substrate constitutes eroded rock material (14%), especially in cliff-encircled coves in the vicinity of the Strait of Gibraltar. The detritic substrate is mainly observed on the Mediterranean facade (9%), where fluvial deposition platforms (deltas) predominate more than on the Atlantic facade. Conversely, the aeolian dune substrate, elevated from the current sea level, exists only in the Atlantic area (3%); its gently-sloping relief is interrupted only by the vicinity of the Strait of Gibraltar.

3.2. Sensitivity indicator

Figure 11 and Table 6 present the sensitivity indicator results. Each value corresponds to intervals of 50-m distance.

Table 6. Sensitivity indicator values, percentage and beach length by facade

		Extremely sensitive *-0.68-0.10*	**Highly sensitive** *0.10-0.26*	**Moderately sensitive** *0.26-0.49*	**Slightly sensitive** *0.49-0.83*	**Very slightly sensitive** *0.83-1.24*	**Total**
Atl. Facade	Percentage (%)	36	37	16	7	4	**100**
	Length (km)	46.5	47.4	20.4	8.3	4.9	**127.5**
Med. Facade	Percentage (%)	53	26	11	5	5	**100**
	Length (km)	19.3	9.4	4	2	2	**36.7**

The indicator values range between -0.68 and 1.24, categorised by natural breaks (jenks). Of the beaches under consideration, 75% (123 km) are regarded as highly or extremely sensitive to erosive processes. These beaches share similar features: reduced dry beach width, exposure to high erosion rates, and little to no accommodation space. Although the Atlantic facade presents a lower percentage of beaches in the high or extreme sensitivity bracket (73%; 94 km), it also presents the lowest individual value (-0.68): this is at the distal end of Playa de Levante (Puerto de Santa María), which is affected by the dynamic of the mouth of the San Pedro River. The Mediterranean facade, on the other hand, has a higher percentage of beaches in the high or extreme sensitivity bracket (79%). Its lowest value (-0.21) is scored near to Punta Chullera.

Of those beaches in the extremely sensitive bracked, 29% are located in urban areas, where the presence of infrastructures (mainly retaining walls and seaside promenades) restricts the formation of accommodation spaces and the oscillation of the shoreline. The Mediterranean facade presents a slightly higher percentage of urban beaches than the Atlantic facade (31% and 29% respectively).

A total of 17 km (13 of Atlantic and 4 of Mediterranean beaches) are slightly or very slightly e sensitive: about 10% of the total percentage per facade. Most of these beaches share the same features: a wide dry beach, the presence of a wide accommodation space dominated by dune formations, and an accumulative dynamic. The Atlantic facade presents the highest values (1.24) around the mouth of the Guadalete River, the effect of which is supported by dykes in both margins. The highest value on the Mediterranean facade (1.15) corresponds to Playa de La Hacienda (in the North of the municipality of La Línea de la Concepción). The low sensitivity values in this sector are mainly due to the existence of wide accommodation spaces. However, these mostly correspond to cliffs made of brittle rocky material, and the availability of sediments would not be immediate (as would be the case with other substrates with low compaction).

The study area has a total of 49 km of protected natural areas. Almost 36% of the least sensitive beaches are located in protected natural areas, all of which are situated in the Atlantic facade, adding up to a total of 2.5 km length. Conversely, 34% of the most sensitive beaches (22 km) are in these areas, which represent 28.5% of the Atlantic seaboard (13 km) and 46% of the Mediterranean seaboard (9 km). These mainly correspond to small beaches associated with protected natural spaces characterised by cliffs without accommodation space.

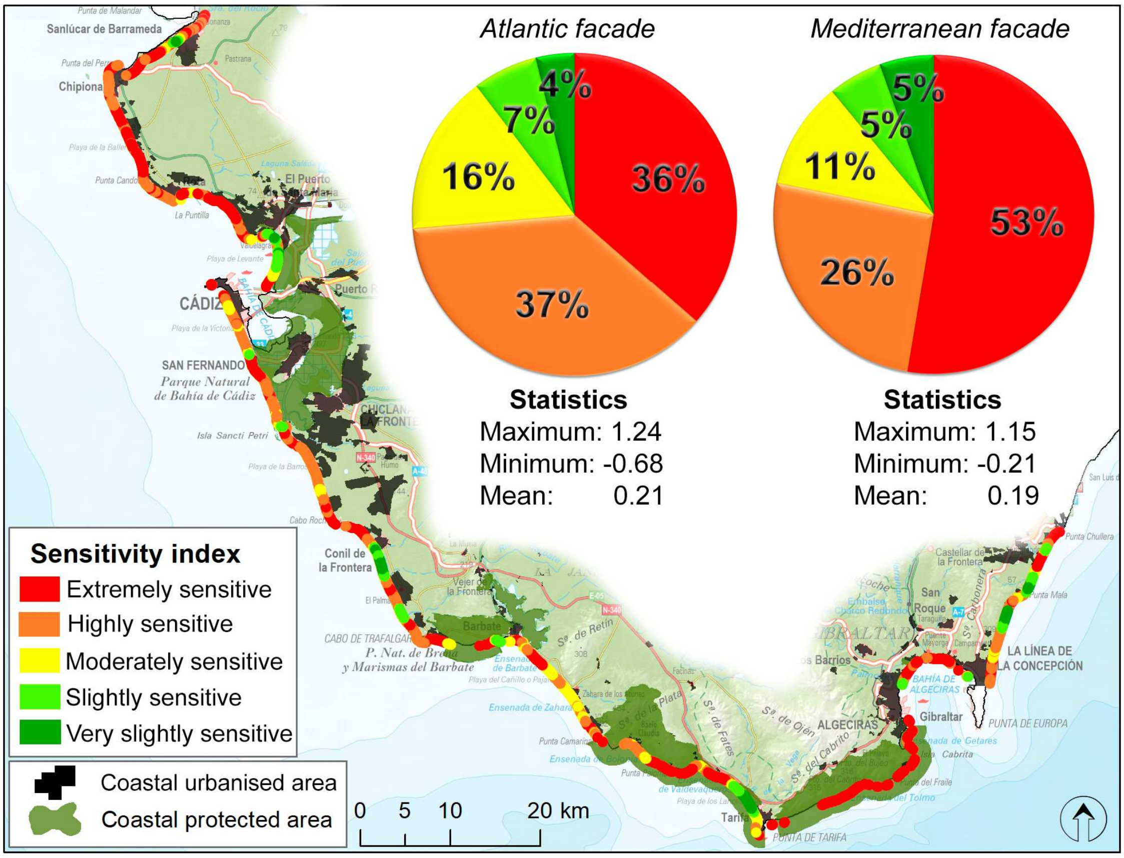


Figure 11. Sensitivity indicator and percentage per facade

4. Discussion

Decision-making processes involving coastal regions must be based on precise data (Rumson et al., 2017), and access to information plays a crucial role (Mokrech et al., 2011; Nicholls et al., 2015). Although this necessity is recognised in many planning documents, it is frequently and inexplicably not accompanied by any detailed information about the coastal and marine environment in question. This is most likely because collecting such detailed information can be costly both in terms of time and money (Ojeda et al., 2013).

The present work aims to design an indicator which would represent the sensitivity of beaches to erosive processes in the province of Cádiz, based on three variables – beach width, accommodation space (width and typology), and erosion rates.

Variables were selected based on a number of criteria: relative weight, statistical independence (in order to avoid over-dimensionality), and availability of data (as the purpose is to make the methodology suitable for other scenarios).
Although it should be note that the number of variables used to develop other coastal indices is not fixed and is usually higher than that used here, these indices include physical vulnerability, internal and external variables (McLaughlin and Cooper, 2010; Zhu et al., 2019), and socioeconomic vulnerability. In this work only internal variables, which aim to measure the beach's resilience to erosive phenomena, were taken into account. In line with this, although the use of fewer variables could make an indicator less reliable, this can also translate into

greater replicability and reduced data redundancy (Del Río and Gracia, 2009). Indeed, ensuring that variables are statistically independent is essential in the creation of composite indices; this has been lacking in some previous studies, even though potentially interdependent variables (coastal geomorphology/coastal geology and breaking wave height/ wave energy, among others) have been used in these studies.

Following McLaughlin and Cooper, ‘at each scale of management there are different considerations and different types of data. There is no “one size fits all” index of coastal vulnerability that can be applied at all scales’ (McLaughlin and Cooper, 2010: 234). The developed indicator is the first attempt to characterise beaches on a regional scale according to their ability to withstand erosive phenomena. Several issues concerning the variables, the methodology and the results are worth discussing further.

Concerning measurement of the variables, the lack of 3D data, together with the need to use easily obtainable variables to make the indicator more replicable, meant that we decided on a 1D analysis. We are aware of the possible limitations of using 1D information, and thus we have been especially careful with identifying and measuring the accommodation space and with interpretating erosion rates.

In the methodology developed, variables used to calculate the indicator are based on proxies, and thus additional thematic and geomorphological information has been incorporated in order to ensure correct interpretation of the results. The incorporation of thematic data related to the presence of coastal infrastructure (transversal and longitudinal) allows for certain trends in sedimentary dynamics to be attested. This is especially significant for stable sections where the presence of infrastructure can ‘rigidise’ the proxy used to calculate erosion rates, correspondingly preventing the natural oscillation of the coastline and potentially masking serious erosive processes (Prieto et al, 2017). Similarly, it is possible to identify sections which present accumulative or erosive tendencies whose origin lies in the presence of transversal infrastructure that, by interrupting the flow of sediments along the beach, seriously alters its longitudinal dynamics.

In contrast with most previous calculations of coastal sensitivity indices, which are based on proprietary-GIS, the present work develops a methodology based on relational spatial databases. For this purpose, it was necessary to design a conceptual data model that demonstrates the relationships between all the entities. Also, the data model had to be capable of meeting the proposed objectives. This data model is dynamic, enabling new data and erosion rate calculations to be entered, making it a tool that can be adjusted to different data needs. Subsequently, the model was implemented in a conceptual database management system, in this case Postgre SQL/PostGIS. This allowed for an analysis to be undertaken through the creation of SQL codes. Once the codes have been created, the methodology can easily be reproduced and applied to other settings and can also be used to recalculate the sensitivity indicators automatically whenever changes in the original data occur (erosion rate, beach width, etc.). The code does not need updating—only the input tables in the database manager need to be changed—turning the model into a very valuable tool for planners and managers (Díaz et al., 2018). It thus facilitates reproducibility, scalability and automating of the analysis in other areas.

Regarding the use of AHP, this technique is widely used in decision-making, planning, and resource allocation in general, as well as for the development of coastal vulnerability indices in particular (Murali et al., 2013; Bagdanavičiūtė et al., 2015; Lin and Pussella, 2017; Zhu et al., 2019). As such, although the weighting process brings in subjectivity, this method underpins consistency of the judgments made by the experts.

Concerning the results, historical changes in the coastline are often a central variable in the calculation of coastal indices (Kumar et al., 2015). With regard to beaches, despite the importance of beach width in dissipating wave energy, the absence of 3D data makes the inclusion of this variable in coastal indices less frequent. Usually, when this variable is incorporated into vulnerability analyses, especially analyses of large areas, 1D data is used (Pantusa et al., 2018). This work uses 1D beach measurements that are based on the digitalisation of high water mark and backshore/foredune proxies for the full 260 km of coastline under study. As we are aware of the variability of beaches, data from different dates were collected (2009, 2011 and 2013) and averaged, making sure that the data was comparable (all photos were taken during the summer).

Regarding the dunes, these are mostly only noted as presence/absence (Murali et al., 2013; Zhu et al., 2018). The width of dunes rarely features in coastal indices, except for certain small areas, in which case it is measured directly from orthophotos -1D- (Pantusa et al., 2018). This study takes into account not only the potential presence of dunes, but also their accommodation space. Also, the width of the accommodation space is measured from orthophotos (1D) for a 260 km-long study area. Together with the orthophotos, additional sources of information for the interpretation have been used (e.g. physiographic maps of the Andalusian coast). It is worth noting that elevation data and other variables are lacking, and thus, for instance, the health of dune formations, which could lead to some inconsistencies.

Although on a regional scale the indicator presents a simple picture of sensitivity to erosion, it is more complex than a picture painted by studying erosion rates alone or by noting the presence/absence of dunes. Figure 12 illustrates sensitivity measured according to erosion rates and the sensitivity indicator according to erosion rates, width and type of accommodation space by quintiles. Several points are worth stressing. Some beaches, despite being exposed to a low erosion rate, present decreasing values over time, owing to their having little or no accommodation space (for instance the eastern sector of Tarifa, Chipiona and Rota-El Puerto de Santa María). In contrast, other beaches which are exposed to high erosion rates but are endowed with a wide accommodation space present increasing values over time (for instance Bolonia – Tarifa – and Camposoto –San Fernando).

Indicators are generally verified by comparison with other studies in the area. However, although works exist in relation to erosion rates (Prieto-Campos et al., 2018; Del Río et al., 2019), the vulnerability of the Andalusian coast to sea level rise (Ojeda et al., 2009; López et al., 2016), and on sensitivity to tourism (Díaz et al., 2014), none research has been found which measures physical factors and beach resilience to erosive processes. Domínguez et al. (2008) carried out an analysis of vulnerability to erosion for the north-west sector, but this only applies to the stretch of coastline between Sanlúcar de Barrameda and Rota (23 km). Their calculations are based on the semi-quantitative combination of erosion rates and beach use.

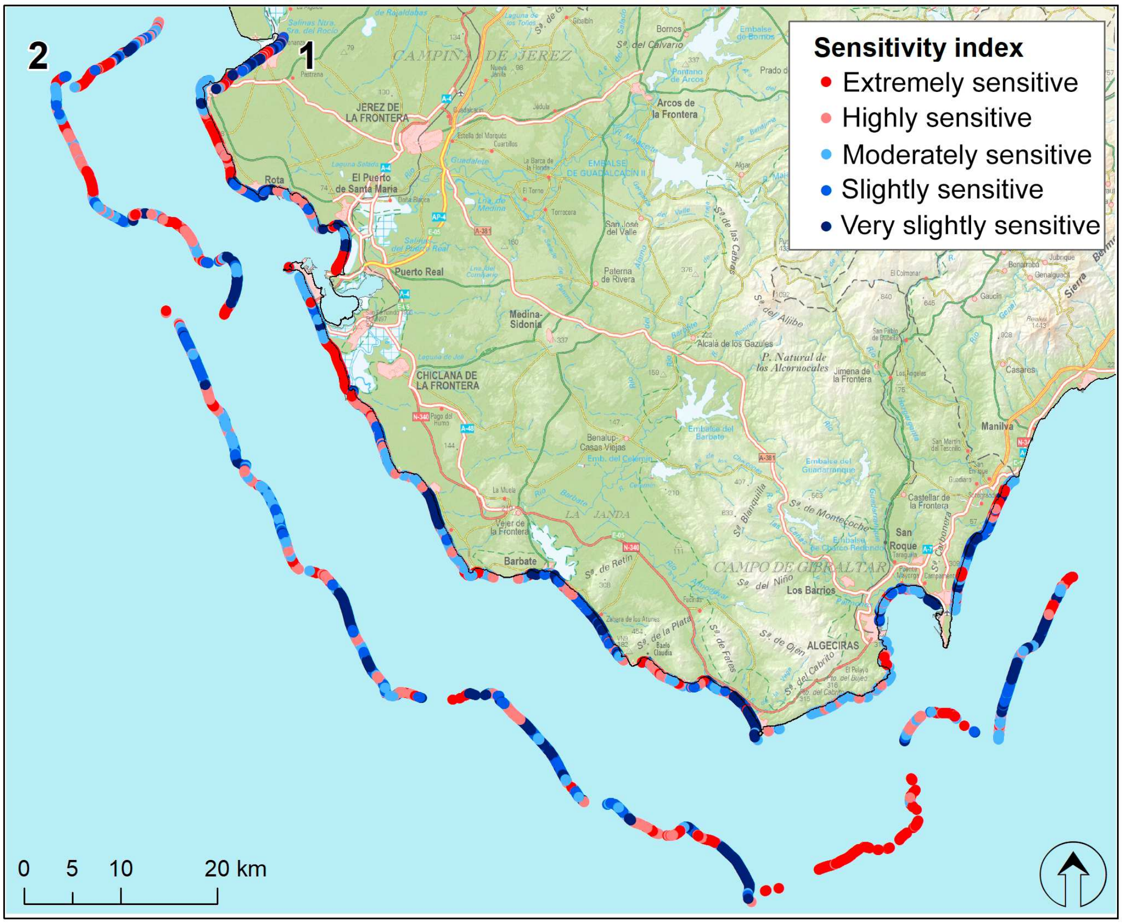


Figure 12. Comparison by quintiles between: 1) Sensitivity measured by erosion rate; 2) Sensitivity measured by sensitivity indicator (erosion rates, average beach width and width and type of accommodation space).

However, we tried to test the indicator by analysing the percentage of regenerated/artificial beaches with the aid of Web Mapping Services (WMS) provided by the regional environmental bodies (Plan Hidrológico 2009-2015) responsible for the Guadalete and Barbate river basins,[1] as well as for the Mediterranean basins[2]. Along with this, we also took into consideration regeneration work undertaken in the Bay of Cádiz between 1989 and 1999 (Muñoz et al., 2000).

The question remains whether those beaches that yield a higher sensitivity index are in fact the most sensitive and in most acute need of regeneration. The results, as shown in Figure 13, indicate that 83% of regenerated beaches are in the 'extremely sensitive' and 'highly sensitive' brackets.

[1] http://www.juntadeandalucia.es/medioambiente/mapwms/REDIAM_regulac_flujo_GB_2009_2015?
[2] http://www.juntadeandalucia.es/medioambiente/mapwms/REDIAM_regulacion_flujo_MED_2009_2015?

Figure 13. Percentage of regenerated beaches according to the sensitivity indices yielded by the study.

5. Conclusions

Any study concerned with coastal areas, regardless of its aim, must make use of a large amount of detailed information and then include representative indicators of the environmental conditions prevailing in these areas. However, the data available for different coastal sectors varies greatly.

This article aimed to present a simple and reliable indicator of sensitivity of dry beaches to erosion, and discuss its implementation in the province of Cádiz. The indicator is based on three variables (width of the dry beach, mid-term erosion rate, and availability of accommodation space), which are easily obtainable from other sources.

The methodology used, which is based on spatial databases, involves the design of a data model and its implementation by a spatial data-management system (in this case PostgreSQL). The exploitation and analysis of the data were undertaken by means of a SQL code, which makes the methodology easily scalable and replicable in other settings simply by changing the input data. This model is therefore very useful for coastal managers as it allows results to be continuously updated.

Results show that 75% of the beaches in the province are in the high or extremely high sensitivity bracket; along the Mediterranean facade, the percentage is 79%. Of those beaches in the extremely sensitive bracked, 29% are located in urban areas, where the presence of infrastructure (mostly retaining walls and seaside promenades) limits the development of accommodation spaces and hinders oscillation of the shoreline. These beaches should become a management priority, and more detailed analysis should be carried out.

The indicator is simple and easy to reproduce. It helps planners to allocate resources and determine where to focus further analysis where other variables (beach slope, presence of underwater bars, height, etc.) that are costly and difficult to obtain for large areas should be investigated. The indicator and the associated methodology provide first-hand information to other researchers and policymakers, enabling them to mitigate the sensitivity of beaches to erosive events. The indicator can also be used by non-experts, as a first step towards more comprehensive assessments. It also allows for comparability and a direct and clear identification of the most sensitive areas although mitigation measures should be based on more detailed analysis using a finer scale and additional variables.

Acknowledgments

This research was supported by Ministry de Economy and Competitiveness (Grant No. CSO2014-51994-P) and (Grant No. PGC2018-095992-B-I00) financed by the Ministry of Science, Innovation and Universities of Spain`s Government.

The authors would like to thank the editor and reviewers for their comments which have undoubtedly improved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Alexandrakis, G., Poulos, S.E., 2015. A *holistic approach to beach erosion vulnerability assessment.* Sci. Rep. 4, 6078. https://doi.org/10.1038/srep06078
2. Angélica, K., de Souza, P., Silva-Casarín, R., Vasconcelos, A., 2017. The Influence of Climate Change on Coastal Erosion Vulnerability in Northeast Brazil. Coast. Eng. 59. https://doi.org/10.1142/S0578563417400071
3. Athanasiou, P., van Dongeren A., Giardino, A., Vousdoukas, M., Gaytan-Aguilar, S., Ranasinghe, S., 2019. Global distribution of nearshore slopes with implications for coastal retreat. Earth Syst. Sci. Data. 11, 1515–1529 https://doi.org/10.5194/essd-11-1515-2019
4. Anfuso, G., 2001. Morfología y dinámica sedimentaria del litoral gaditano entre Chipiona y Rota. Cádiz.
5. Balica, S.F., Wright, N.G., van der Meulen, F., 2012. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Nat. Hazards 64 (1), 73–105. https://doi.org/10.1007/s11069-012-0234-1
6. Bird, E.C.F. 1985. Coastline changes: A Global Review, New York, New York: John Wiley & Sons, 219p.
7. Bagdanavičiūtė, I., Kelpšaitė, L., Soomere, T., 2015. Multi-criteria evaluation approach to coastal vulnerability index development in micro-tidal low-lying areas. Ocean Coast. Manag. 104, 124–25.https://doi.org/10.1016/j.ocecoaman.2014.12.011
8. Coyne, M.A., Fletcher, C.H and Richmond, B., 1999. Mapping coastal erosion hazard areas in Hawaii: observations and errors. J. Coast. Res. SI 28, 171-184.
9. Chenthamil, S., Kankara, R.S., Markose, V.J., Rajan, B., Prabhu, K., 2016. Shoreline change and impacts of coastal protection structures on Puducherry, SE coast of India. Nat. Hazards 83, 293–308. https://doi.org/10.1007/s11069-016-2332-y
10. Crowell, M., Douglas, B.C., and Leatherman, S.P., 1997. On Forecasting Future US Shoreline Positions : A Test of Algorithms. J. Coast. Res., 13(4), 1245–1255.
11. D'Alessandro, F., Tomasicchio, A., 2016. Wave–dune interaction and beach resilience in large-scale physical model tests. Coast Eng. 116, 15-25. https://doi.org/10.1016/j.coastaleng.2016.06.002

12. D'Alessandro, F., Tomasicchio, G.R., Musci, F., Ricca, A., 2012. Dune erosion physical, analytical and numericalmodelling. Proceedings 33th International Conference on Coastal Engineering, Santander.
13. Del Río, L., 2007. Riesgos de Erosión Costera en el Litoral Atlántico Gaditano. Ph.D. Thesis, University of Cádiz, Spain.
14. Del Río, L., Gracia, J., 2009. Erosion risk assessment of active coastal cliffs in temperate environments. Geomorphology, 112, 82-95. https://doi.org/10.1016/j.geomorph.2009.05.009
15. Del Río, L., Gracia, F.J., Benavente, J., 2013a. Shoreline change patterns in sandy coasts. A case study in SW Spain. Geomorphology 196, 252–266. https://doi.org/10.1016/j.geomorph.2012.07.027
16. Del Río, L., Benavente, J., Gracia F.J., Anfuso, G., Aranda, M., Montes, J.B., Puig, M., Talavera, L., Plomaritis, T.A., 2019. "The Spanish Coastal Systems: dynamic processes, sediments and management". In: Morales J.A. (Ed.): The Spanish Coastal Systems: Dynamic Processes, Sediments and Management, Springer, 311-335.
17. Department of Agriculture, Livestock, Fisheries and Sustainable Development, 2007. Map of physiographic units of the Andalusian coast. Junta de Andalucía.
18. Dhabe, P.S., Patwardhan, M.S., Deshpande, A.A., Dhore, M.L., Barbadekar, B.V., Abhyankar, H.K., 2010. Articulated Entity Relationship (AER) diagram for complete automation of relational database normalization. Int. J. Database Manag. Syst. 2, 84–100. https://doi.org/10.5121/ijdms.2010.2206
19. Díaz, M.P., Ojeda, J., Álvarez, J.A. y Prieto, A. 2014. Sensibilidad de las playas en función de la accesibilidad de los potenciales usuarios turísticos (plazas regladas) en la costa andaluza y los procesos de erosión. In: Zaragozí, A., Morte, R. (Ed.), Tecnologías de la información para nuevas formas de ver el territorio: XVI Congreso Nacional de Tecnologías de la Información Geográfica (pp. 954-966). Universidad de Alicante.
20. Díaz-Cuevas, M.P., Camarillo-Naranjo, J.M., Pérez-Alcántara, J.P., 2018. Relational spatial database and multi-criteria decision methods for selecting optimum locations for photovoltaic power plants in the province of Seville (southern Spain). Clean Tech Environ Policy. 20, 8, 1889-1902. https://doi.org/10.1007/s10098-018-1587-2
21. Domínguez, L., Gracia, F.J. y Anfuso, G. 2008. Evaluación de la vulnerabilidad del litoral Noroeste de la provincia de Cádiz frente a la erosión. Territoris, 7, 99-113.
22. Douglas, B.C., Crowell, M., and Leatherman, S.P. 1998. Considerations for Shoreline Position Prediction. J. Coast. Res., 14(3), 1025–1033.
23. European Environment Agency (EEA), 2011. Annual report 2010 and Environmental statement 2011. Publications Office of the European Union, Luxembourg. https://doi.org/10.2800/72655
24. EUROSION. Living with coastal erosion in Europe: Sediment and Space for Sustainability. PART I - Major findings and Policy Recommendations of the EUROSION project. 57 (Directorate General Environment, European Commission, 2004).
25. Fernandez-Nunez, M., Díaz, P., Ojeda, J., Prieto, A., Sánchez, N., 2015. Multipurpose line for mapping coastal information using a data model: The Andalusian coast (Spain). J. Coastal Conserv, 19, 461–474. https://doi.org/10.3390/geosciences8090335
26. Institute National of Statistics (INE), 2019. Encuesta de Ocupación Hotelera [WWW Document]. URL https://www.ine.es/jaxiT3/Tabla.htm?t=2074 (accessed 6.1.19).

27. Jiménez, J.A., Valdemoro, H.I., Bosom, E., Sánchez-Arcilla, A., Nicholls, R.J., 2017. Impacts of sea-level rise-induced erosion on the Catalan coast. Reg. Environ. Chang. 17, 593–603. https://doi.org/10.1007/s10113-016-1052-x
28. Kabuth, A.K., Kroon, J., Pedersen, J.B.T., 2014. Multidecadal Shoreline Changes in Denmark. J. Coast. Res. 30, 714. https://doi.org/10.2112/JCOASTRES-D-13-00139.1
29. Kankara, R.S., Selvan, S.C., Markose, V.J., Rajan, B., Arockiaraj, S., 2015. Estimation of Long and Short Term Shoreline Changes Along Andhra Pradesh Coast Using Remote Sensing and GIS Techniques. Procedia Eng. 116, 855–862. https://doi.org/10.1016/j.proeng.2015.08.374
30. Kumar, M., Sarathi, S., Mondal, B, Pal, R., 2015. Coastal vulnerability assessment of the predicted sea level rise in the coastal zone of Krishna–Godavari delta region, Andhra Pradesh, east coast of India. Environ Dev Sustain, 18(6), 1635-1655. https://doi.org/10.1007/s10668-015-9708-0.
31. Lin, L., Pussella, P., 2017. Assessment of vulnerability for coastal erosion with GIS and AHP techniques case study: Southern coastline of Sri Lanka. Nat. Resour. Model. 30, e12146. https://doi.org/10.1111/nrm.12146
López, R.M., Ranasinghe, R., Jiménez, J.A. 2016. A rapid, low-cost approach to coastal vulnerability assessment at a national level. J. Coast. Res., 32 (4), 932-945. https://doi.org/10.2112/JCOASTRES-D-14-00217.1
32. Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S. 2018. The State of the World's Beaches. Nature. Sci Rep. 8, 6641. https://doi.org/10.1038/s41598-018-24630
33. Malczewski, J., 1999. GIS and multicriteria decision analysis. John Wiley & Sons, Ltd, New York, NY.
34. McLaughlin, S., Cooper, A. 2010. A multi-scale coastal vulnerability index – a tool for coastal managers?. Environ Hazards 9, 233-248. https://doi.org/10.3763/ehaz.2010.0052
35. Martín-Algarra, A. 1987. Evolución geológica alpina del contacto entre las zonas internas y las zonas externas de la Cordillera Bética (sector central y occidental). PhD Thesis, University of Granada, Spain.
36. Marcos, M., Tsimplis, M., 2008. Coastal sea level trends in Southern Europe. Geophys. J. Int. 175, 70–82. https://doi.org/10.1111/j.1365-246X.2008.03892.x
37. Mentaschi, L., Vousdoukas, M.I., Pekel, J.F., Voukouvalas, E., Feyen, L., 2018. Global long-term observations of coastal erosion and accretion. Sci. Rep. 8, 12876. https://doi.org/10.1038/s41598-018-30904-w
38. Ministerio de Agricultura, Pesca y Medioambiente (MAPAMA), 2013. Estudio ecocartográfico del litoral de la provincia de Cádiz. 85 pp.
39. Mokrech, M., Hanson, S., Nicholls, R.J., Wolf, J., Walkden, M., Fontaine, C.M., Nicholson, S., Jude, S.R., Leake, J., Stansby, P., Watkinson, A.R., Rounsevell, M.D.A., Lowe, J.A., Hall, J.W., 2011. The Tyndall coastal simulator. J. Coast. Conserv. 15, 325–335. https://doi.org/10.1007/s11852-009-0083-6
40. Molina, R., Manno, G., Lo Re, C., Anfuso, G., Ciraolo, G., 2019. Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia (Spain). Water, 11(3), 509. https://doi.org/10.3390/w11030509

41. Moore, L.J., Griggs, G.B., 2002. Long-term cliff retreat and erosion hotspots along the central shores of the Monterey Bay National Marine Sanctuary. Mar. Geol. 181, 265–283. https://doi.org/10.1016/S0025-3227(01)00271-7
42. Mujabar, P.S., Chandrasekar, N., 2013. Shoreline change analysis along the coast between Kanyakumari and Tuticorin of India using remote sensing and GIS. Arab. J. Geosci. 6, 647–664. https://doi.org/10.1007/s12517-011-0394-4
43. Muñoz, J.J., López, B., Gutiérrez, J.M., Cuenca, G., 2000. La regeneración de playas en el Golfo de Cádiz. Un coste asumible y sostenible. Revista de Obras Públicas, 33399, 23-28.
44. Murali, M.R., Ankita, M., Amrita, S., Vethamony, P., 2013. Coastal vulnerability assessment of Puducherry coast, India, using the analytical hierarchical process. Nat. Hazards Earth Syst. Sci., 13, 3291–3311. https://doi.org/10.5194/nhess-13-3291-2013
45. Muthusankar, G., Jonathan, M.P., Lakshumanan, C., Roy, P.D., Srinivasa-Raju, K., 2017. Coastal erosion vs man-made protective structures: evaluating a two-decade history from southeastern India. Nat. Hazards 85, 637–647. https://doi.org/10.1007/s11069-016-2583-7
46. Nicholls, R.J., Whitehead, P., Wolf, J., Rahman, M., Salehin, M., 2015. The Ganges–Brahmaputra–Meghna delta system: biophysical models to support analysis of ecosystem services and poverty alleviation. Environ. Sci. Process. Impacts 17, 1016–1017. https://doi.org/10.1039/C5EM90022K
47. Obanawa, H., Hayakawa, Y.S., 2018. Variations in volumetric erosion rates of bedrock cliffs on a small inaccessible coastal island determined using measurements by an unmanned aerial vehicle with structure-from-motion and terrestrial laser scanning. Prog. Earth Planet. Sci. 5, 33. https://doi.org/10.1186/s40645-018-0191-8
48. Ojeda, J., 2000. Métodos para el cálculo de la erosión costera. Revisión, tendencias y propuesta. Boletín la Asoc. Geógrafos Españoles. 30, 103–118.
49. Ojeda, J., Borgniet, L., Pérez, A.M., Loder, J.F., 2002. Monitoring morphological changes along the coast of Huelva (SW Spain) using soft-copy photogrammetry and GIS. J. Coast. Conserv. 8, 69. https://doi.org/10.1652/1400-0350(2002)008[0069:MMCATC]2.0.CO;2
50. Ojeda, J., Álvarez, J. I., Martín, D., Fraile, P., 2009. El uso de las TIG para el cálculo del índice de vulnerabilidad costera (CVI) ante una potencial subida del nivel del mar en la costa andaluza (España)", GeoFocus, 9, 83-100.
51. Ojeda, J., Díaz, P., Prieto, A., Álvarez, J.I., 2013. Línea de costa y sistemas de información geográfica: modelo de datos para la caracterización y cálculo de indicadores en la costa andaluza. Investig. Geográficas. https://doi.org/10.14198/INGEO2013.60.02
52. Olympio, G.F.A., Amos-Abanyie, S., 2014. Effects of shoreline erosion on infrastructure development along the coastal belt of Ghana: Case of Nkontompo community. J. Sci. Technol. 33, 39. https://doi.org/10.4314/just.v33i3.5
53. Pantusa, D., D'Alessandro, F., Riefolo, L., Principato, F., Tomasicchio, G., 2018. Application of a Coastal Vulnerability Index. A Case Study along the Apulian Coastline, Italy. Water 10, 1218. https://doi.org/10.3390/w10091218
54. Paris, P., Starek, M.J., Hardin, E., Kurum, O., Overton, M., Mitasova, H., 2013. Lines in the sand: Geomorphic and Geospatial characterization and interpretation of sandy shorelines and beaches. Geography Compass 7, 5, 315-343. https://doi.org/10.1111/gec3.12041

55. Pierre, G., 2006. Processes and rate of retreat of the clay and sandstone sea cliffs of the northern Boulonnais (France). Geomorphology 73, 64–77. https://doi.org/10.1016/j.geomorph.2005.07.002
56. Prieto, A., 2017. Metodología para el cálculo, explotación y difusión de líneas de costa y tasas de erosión a medio-largo plazo (1956–2011) en Andalucía. Ph.D. Thesis. University of Seville, Spain.
57. Prieto, A., Díaz, P., Ojeda, J., Álvarez, J.I., 2017. Tasas de erosión en las playas de Andalucía: el efecto de infraestructuras costeras longitudinales y urbanización, Geotemas 17, 243-246.
58. Prieto-Campos, A., Díaz-Cuevas, P., Fernandez-Núñez, M., Ojeda-Zújar, J., 2018. Methodology for improving the analysis, interpretation, and geo-visualisation of Erosion Rates in coastal beaches—Andalusia, Southern Spain. Geosciences 8, 335. https://doi.org/10.3390/geosciences8090335
59. Prieto, A., Díaz, P., Ojeda, J. 2019. 'Accommodation space' at beaches in Andalusia: calculations derived from the 2013 shoreline data model and the use of spatial databases. Geofocus 23, 97-117. http://dx.doi.org/10.21138/GF.628
60. Priya, S.M., Nellayaputhenpeedika, M., Prakash, S., Vengadasalam, R. 2019. Mapping and analysis of the physical vulnerability of coastal Tamil Nadu, Hum, Eco Risk Asses. https://doi.org/10.1080/10807039.2019.1602752
61. Rangel-Buitrago, N., Anfuso, G., 2011. Coastal storm characterization and morphologicalimpacts on sandy coast. Earth Surf. Process. Landforms. 36, 1197-2010. https://doi.org/10.1002/esp.222
62. Rangel-Buitrago, N., Williams, A.T., Anfuso, G., 2018. Hard protection structures as a principal coastal erosion management strategy along the Caribbean coast of Colombia. A chronicle of pitfalls. Ocean Coast. Manag. 156, 58–75. https://doi.org/10.1016/j.ocecoaman.2017.04.006
63. Royal Decree 1071/2007, of 27 July, regulating the official geodetic reference system in Spain. Madrid (Spain). Official State Bulletin (BOE), 207, pp. 35986-35989.
64. Rumson, A.G., Hallett, S.H., Brewer, T.R., 2017. Coastal risk adaptation: the potential role of accessible geospatial Big Data. Mar. Policy 83, 100–110. https://doi.org/10.1016/j.marpol.2017.05.032
65. Saaty, T.L., 1989. Group Decision Making and the AHP, in: The Analytic Hierarchy Process. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 59–67. https://doi.org/10.1007/978-3-642-50244-6_4
66. Saaty, T.L., 1990. The Analytic Hierarchy Process: planning, priority setting, resource allocation. McGraw Hill, New York, NY.
67. Tamassoki, E., Amiri, H., Soleymani, Z., 2014. Monitoring of shoreline changes using remote sensing (case study: coastal city of Bandar Abbas). IOP Conf. Ser. Earth Environ. Sci. 20, 012023. https://doi.org/10.1088/1755-1315/20/1/012023
68. Tomasicchio, G.R., D'Alessandro, F., Barbaro, G., 2011. Composite modelling for largescale experiments on wave–dune interactions. J. Hydraul. Res. 49 (S1), 15–19. https://doi.org/10.1080/00221686.2011.604576
69. Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Ergun, A., 2009. Digital Shoreline Analysis System (DSAS) version 4.0— An ArcGIS extension for calculating shoreline change.
70. Thieler, E.R., Martin, D., Ergun, A., 2003. Digital Shoreline Analysis System (DSAS) version 2.0: An ArcView extension for calculating shoreline change. Reston, VA. https://doi.org/10.3133/ofr0376

71. US Army Corps of Engineers. 2008. Coastal Engineering Manual, Part IV, EM 1110-2-1100.
72. US Geological Survey. 2007. National Assessment of Shoreline Change Project. *National Assessment of Shoreline Change Project.*
73. Vousdoukas, M.I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., Feyen, L. 2016. Developments in large-scale coastal flood hazard mapping. Nat. Hazards and Earth Sys. 16, 1841-1853 https://doi.org/10.5194/nhess-16-1841-2016
74. Westoby, M.J., Lim, M., Hogg, M., Pound, M.J., Dunlop, L., Woodward, J., 2018. Cost-effective erosion monitoring of coastal cliffs. Coast. Eng. 138, 152–164. https://doi.org/10.1016/j.coastaleng.2018.04.008
75. Zhu, Z.T., Cai, F., Chen, S.L., Gu, D.Q., Feng, A.P., Cao, C., Qi, H.-S., Lei, G., 2019. Coastal Vulnerability to Erosion Using a Multi-Criteria Index: A Case Study of the Xiamen Coast. Sustainability 11, 93. https://doi.org/10.3390/su11010093

DEVELOPING A BEACH EROSION SENSITIVITY INDICATOR USING RELATIONAL SPATIAL DATABASES AND ANALYTIC HIERARCHY PROCESS

Highlights

- A simple beach erosion sensitive indicator is developed an applied in Cadiz (south of Spain).
- Mediterranean beaches are more likely to be erosion sensitive than Atlantic ones.
- Results are validated by comparing with regenerated beaches.
- The indicator points out zones where more detailed analysis is desirable optimising time and resources.
- The indicator can be applied to other regions and is useful for coastal planners.

DEVELOPING A BEACH EROSION SENSITIVITY INDICATOR USING RELATIONAL SPATIAL DATABASES AND ANALYTIC HIERARCHY PROCESS

Pilar Díaz-Cuevas[1]*, Antonio Prieto-Campos[2], José Ojeda-Zújar[3]

Department of Physical Geography and Regional Geographical Analysis

Doña María de Padilla s/n. University of Seville, 41004 Seville, Spain;

[1] pilard@us.es. ORCID: 0000-0003-0846-9930

[2] pcampos@us.es ORCID: 0000 -0001-6946-9622

[3] zujar@us.es ORCID: 0000-0002-4672-064X

** Corresponding author*

DECLARATION:

- Authors have no conflict of interest to declare.
- All Authors have seen and approved the manuscript being submitted. We warrant that the article is the Authors' original work.
- We warrant that the article has not received prior publication and is not under consideration for publication elsewhere.
- This research has not been submitted for publication nor has it been published in whole or in part elsewhere.
- Authors listed on the title page have contributed significantly to the work, have read the manuscript, attest to the validity and legitimacy of the data and its interpretation, and agree to its submission to Ocean and Costal Management.

Yours faithfully
Dra. Pilar Díaz Cuevas (Corresponding author)