MAPPING COASTAL VULNERABILITY AGAINST EROSION ALONG THE ALICANTE COASTLINE, SPAIN

José I. Pagán, Pablo Ortiz, Isabel López

Abstract: The assessment of coastal vulnerability helps prioritize investments to increase coastal resilience. This work aims to map the vulnerability of a 12 km coastal stretch of the province of Alicante, Spain. It is an area where natural spaces with wetlands and important dune ridges alternate with highly urbanized spots. The method calculates a Coastal Vulnerability Index (CVI) through three main indicators: geomorphology (geology, coastal slope, erosion rate, beach width and dune width), hydrodynamics (significant wave height, mean tide range and flood level indicator) and vegetation variables (state of seagrass meadows, depth and width of these meadows and backshore area covered by vegetation). The coastal strip studied was divided into sections of 200 m, obtaining the CVI on each one. The vulnerability of each variable was evaluated from 1 (Very low) to 5 (Very high) and the overall CVI was obtained. The higher values of CVI were detected in the urbanized areas (41 % of the sections). Dune ridges serve as barriers to flooding and reduce erosion. A sufficient beach width and slope are crucial to preventing flooding during extreme weather events.

Keywords: CVI, coastal vulnerability index, coastal erosion, shoreline, coastal management

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Introduction

Coastal areas are currently facing increased vulnerability, exacerbated by coastal erosion - a natural phenomenon - which increases combined with the effects of climate change, extreme events and human activities [11]. This situation not only compromises the stability of coastlines, but also threatens the well-being of the communities that inhabit these regions. Furthermore, the potentially massive impact of climate change on coastal zones, which is globally recognized, should be contemplated [18]. The Mediterranean Sea region is considered one of the main hotspots, due to the agglomeration of residents, tourists, urban growth, infrastructure, and biodiversity in its coastal areas [8].

In addition, coastal erosion is one of the most important problems on a global scale, with about 70 % of the world's sandy beaches undergoing erosion [3]. However, it is not easy to recognize whether a coastal system is affected by erosion processes. It can be influenced by a variety of factors, each one with different underlying causes: natural factors like the morphology or the composition of the sediments, wave energy and littoral drift or anthropic actions such as ports or beach nourishments [2, 15, 19, 23].

Moreover, the disappearance of dune areas deserves special attention, as they constitute a natural reservoir of sand for beaches and are essential for the creation and stabilisation of wetlands and shorelines. In many places they have been destroyed for the construction of promenades and buildings [9]. These environments have specialised flora and fauna, providing unique ecological services such as flood control and storm protection [21]. Likewise, the presence or absence of marine phanerogams such as *Posidonia oceanica* can be of great relevance to the coastline. Several studies have demonstrated their influence on the nature and dynamics of coastal sediments, playing a crucial role in the physical equilibrium of a large part of the Mediterranean coasts, both by reducing incident wave energy and by protecting against coastal erosion [6, 7]. The three-dimensional structure of the rhizomes constitutes a certain reinforcement of the sandy sediment of the submerged beach which, together with the roots and leaves, slows down the sedimentary movements of the seabed, causing changes in the submerged beach profile to be considerably slower than they would be in the absence of the meadows [14].

Thus, the Spanish Mediterranean coastline is a region of special interest, since it has been subject to sociopolitical, economic and environmental changes at local, national and even international scales since the 1960s [22]. A significant modification of the morphology and, consequently, the coastal dynamics of the area have been detected [28]. To tackle this problem, a growing interest in understanding and including vulnerability studies in coastal zone management policies has arisen [1, 26, 29].

The Coastal Vulnerability Index (CVI) is a synthetic index to assess coastal vulnerability [10]. A series of variables are calculated to evaluate the relative vulnerability of different stretches of a coastal area. Regarding the application of the CVI in the Mediterranean area, a study was conducted to map the relative vulnerability of the western Peloponnese in Greece for a coastline length of about

50 km [5], while the Egyptian Mediterranean coast was also examined [13]. In Italy, it was applied on the Apulian coast [25] and in Spain across the 160 km coastline of the province of Barcelona [17].

The main objective of this work is to map the coastal vulnerability of a 12 km stretch of the Costa Blanca, in the province of Alicante, Spain. It is an area where natural beaches, wetlands and important dune ridges alternate with highly urbanized spots, detecting relevant erosion of the beaches in some sections. A CVI adapted to the area will determine the vulnerability of coastal stretches based on existing data and a reliable approach, which is critical for developing appropriate coastal management strategies.

Materials and Methods

The area of study is located in the province of Alicante, southeast of Spain. Particularly, a stretch of 12 km from Cape Santa Pola to Alicante city was studied, encompassing the beaches of El Carabassí, Arenales del Sol, El Atlet, El Saladar - Urbanova and Agua Amarga. (Figure 1). This is mainly a sandy coast with a relevant dune ridge, interrupted by the urban developments of Arenales del Sol and Urbanova, which is also next to the salt marsh of Agua Amarga.

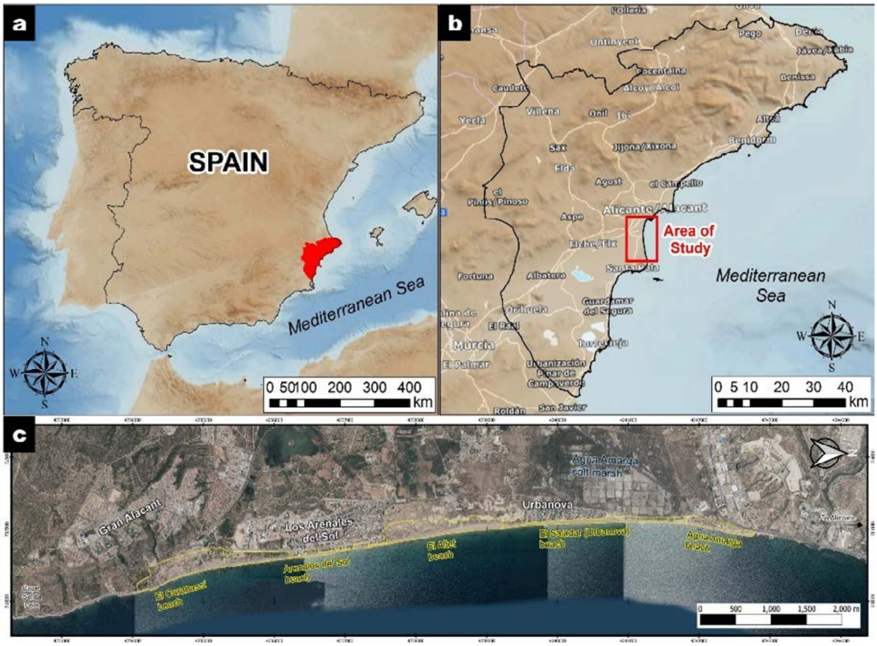

Figure 1 – a) Province of Alicante, Spain. b) Location of the area of study and c) detail of the coastal stretch studied with beaches (yellow) and urban developments (white).

Data used to assess coastal vulnerability were grouped into three main indicators: geomorphology (coastal slope, erosion rate, beach width and dune width), hydrodynamics (significant wave height, mean tide range and flood level indicator) and vegetation variables (presence of seagrass meadows, depth and width of these meadows and backshore area covered by vegetation). A total of 11 variables were considered.

All the required data were downloaded from open and official sources and stored within a geographic information system. For this research, data sources were the websites of the Valencian Spatial Data Infrastructure, IDEV (https://geocataleg.gva.es/#/?lang=spa), Ministerio para la Transición Ecológica y el Reto Demográfico (https://www.miteco.gob.es/es/costas/temas/proteccion-costa/ecocartografias/ecocartografia-alicante.html) and Puertos del Estado (https://www.puertos.es/en-us/oceanografia/Pages/portus.aspx). Thus, a geodatabase in GeoPackage format was created containing all the geospatial information collected in the ETRS89 / UTM zone 30N coordinate system.

Aerial images from all available years were obtained: 1929, 1956, 2002, 2005, 2007, 2009, 2012, 2014, 2017, 2018, 2019, 2020, 2021, 2022 and 2023, for a total of 94 years of study. These images were downloaded in TIFF mosaics of panchromatic black and white colour (1929-1956), a mosaic of natural colour (RGB) for 2002 - 2014 and natural and false colour infrared (RGBI) orthophotographs for the period 2017 to 2023, with a spatial resolution of 25 cm. The use of RGBI images enabled the calculation of the Normalized Difference Vegetation Index (NDVI), an effective indicator for assessing the greenness, density and health of vegetation in each pixel of an image, as well as to map the vegetation cover of an area (Figure 2).

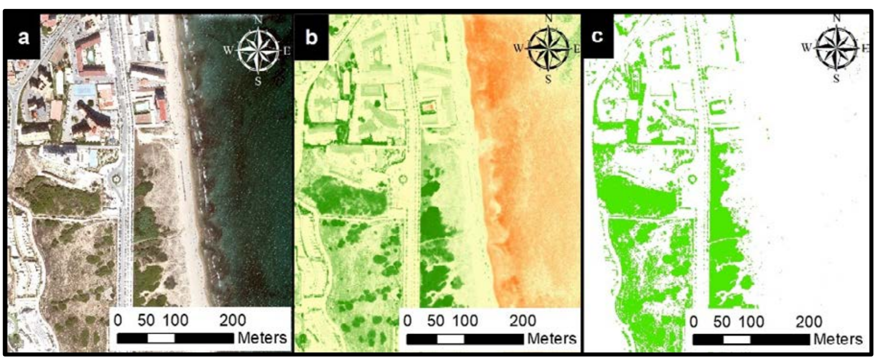

Figure 2 – a) RGB Orthoimage of 2023. b) NDVI for 2023 and c) Area covered by vegetation (green colour) extracted from orthoimage and NDVI.

A Digital Terrain Model (DTM) in raster format with 1 m of spatial resolution, derived from a LiDAR survey carried out in 2016, were used. Bathymetry obtained with a Multibeam sounder at a 1:1000 scale from 0 to – 40 m depth was also collected, as well as other cartography (geological maps, biological underwater species). The swell data were obtained from the SIMAR node 2078099. The SIMAR data is an hourly record of wave height, swell period, and direction from 1958 to the present.

The coastal strip studied was divided into sections spaced 200 m apart, obtaining the CVI on each one from representative transverse profiles created perpendicular to the shoreline, from the baseline to the bathymetric – 20 m. The vulnerability of each variable was evaluated from 1 (very low) to 5 (very high), according to the ranges of Table 1.

Table 1 – Vulnerability ranges for each variable.

Variable (Vulnerability)	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
a. Geology	High cliff (> 20 m)	Medium – cliff (20 –10 m)	Low cliff (5 – 10 m)	Gravel / pebbles beach	Sand beaches, marshland
b. Coastal slope (%)	> 12	12 - 8	8 - 4	4 - 2	< 2
c. Erosion rate (m/yr)	> +1.5	+1.5 –+0.5	+0.5 – -0.5	-0.5 – -1.5	< -1.5
d. Beach width (m)	> 100	100 – 60	60 – 30	30 - 15	< 15
e. Dune width (m)	> 100	100 – 75	75 – 50	50 - 25	< 25
f. Significant wave height (m)	< 1.0	1.0 – 2.0	2.0 – 3.5	3.5 – 5	> 5
g. Mean tide range (m)	< 0.2	0.2 – 0.4	0.4 – 0.6	0.6 – 0.8	> 0.8
h. Relative flood level (m)	< -1.5	-1.5 – -0.5	-0.5 – +0.5	+0.5 – +1.5	> +1.5
i. Presence of seagrass meadows	*P. oceanica* meadow	*P. oceanica* with other species	*P. oceanica* in regression	*P. oceanica* degraded	Absence of *P. oceanica*
j. Upper depth of these meadows (m)	< 4.0	4.0 – 6.0	6.0 – 9.0	9.0 – 12	> 12
k. Backshore area covered by vegetation (%)	> 80	80 — 60	60 — 40	40 — 20	< 20

The overall CVI was obtained as the square root of the product of the value of vulnerability for each variable divided by the number of variables (Equation 1)

$$\mathrm{CVI} = \sqrt{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f \cdot g \cdot h \cdot i \cdot j \cdot k}{11}} \qquad (1)$$

Results

A total of 60 transects were obtained along the 12 km of the coast studied. The overall CVI shows that 23 % of them have “Very High" vulnerability, 18 % “High”, 23 % “Moderate”, 16.4 % “Low” and 19.7 % “Very Low". The higher values of CVI were obtained on the urbanized areas of the beaches of Arenales del Sol and El Saladar (Urbanova), whereas the lower ones were obtained in the El Carabassí beach (Figure 3).

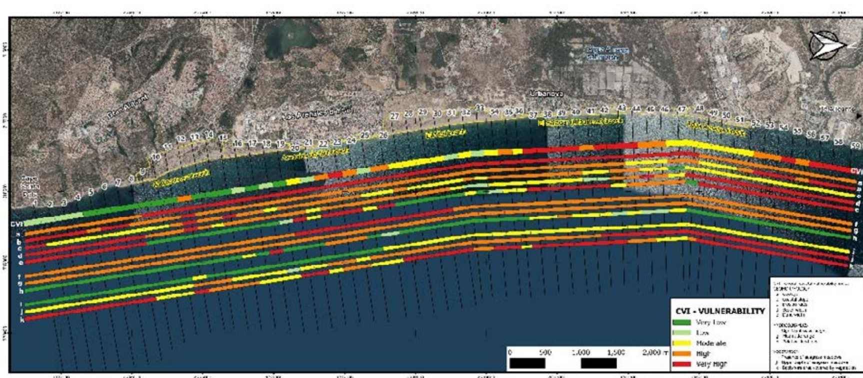

Figure 3 – Overall CVI obtained and vulnerability for each variable.

Analysing the vulnerability by variables, the majority of the sections correspond to sandy beaches or marshlands, which is the most vulnerable category. Coastal slope is typically between 2 and 4 %, which means a High vulnerability. Regarding the erosion rate obtained, 59 % of sections have an average erosion rate near 0 m/year, so although it means a stable situation, have a Moderate vulnerability. However, in 39 % of transects erosion rates of 1 m/year have been identified, which represents a High vulnerability.

Lower values of vulnerability were observed in transects with dunes and more than 35 m of beach width (Figure 4). There are two main stretches without dunes, coinciding with the urban developments of Arenales del Sol (sections from 20 to 26, which represent a length of 1200 m) and Urbanova (37 – 42, 1000 m).

Regarding hydrodynamics variables, significant wave height and mean tide range is almost the same for all transects, 4.71 m and 0.69 m, respectively. This means a High vulnerability. Only in front of Arenales del Sol beach, the wave height reaches more than 5 m, coinciding with one of the most exposed areas (Figure 3) with the lowest beach width (Figure 4).

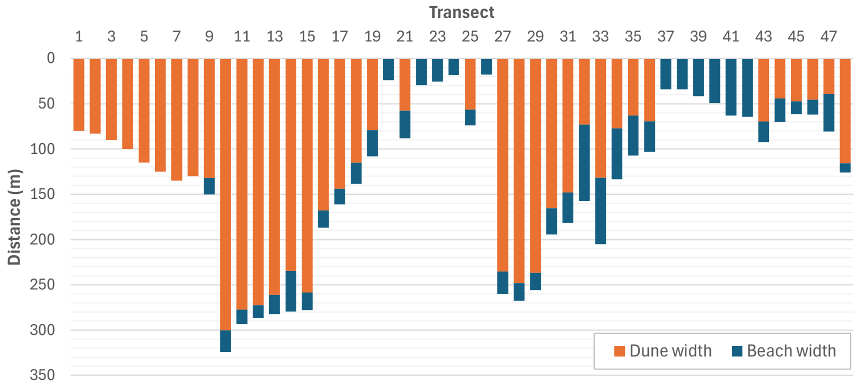

Figure 4 – Average beach and dune width for each transect during the last 3 years.

Relative flood level refers to the highest water level (the sum of the combined action of the astronomical tide, meteorological tide and run-up) reached during a coastal flood event, compared to the maximum height of the beach profile. 72 % of transects have a value higher than -1.5, with an average value of – 5.0 m. These sections match the ones with dunes. However, in 13 sections the flood level is higher than the maximum height of the profile, so achieve High or Very High vulnerability according to the ranges of Table 1.

Vegetation variables are also relevant. Near the coastline of the study area, *Posidonia oceanica* meadows were detected in different conditions. In 60% of the sections *P. oceanica* in regression were observed, whereas in the remaining 40% *P. oceanica* meadows were observed in a good state. However, it is also relevant to note the depth at which these meadows appear. In 18 sections, the upper depth is higher than 12 m, so it means a Very high vulnerability. In 22 sections is on average 10.6 m (High vulnerability) and in the 20 sections remaining is 7.7 m (Moderate vulnerability).

Finally, the backshore area covered by vegetation was studied. The presence of vegetation on the dunes is useful for reducing erosion and dissipating wave energy in case of extreme events. In our case, only 12 sections have between 40 - 60 % of the backshore area covered by vegetation, with 11 sections ranging between 20 - 40 % and 9 sections with lower than 20 % of its surface covered.

Discussion

Mapping coastal vulnerability using an index such as CVI enables coastal managers to have a clear idea not only of the most vulnerable locations in a coastal stretch but also of the variables that affect more. The results of our study are totally in line with other studies carried out on the Mediterranean coast [13, 17, 25]. Moreover, the assessment of coastal vulnerability helps prioritize investments to increase coastal resilience [5]. The method followed in this research has studied 11 variables obtained using geographic information systems (GIS) and can be easily applied in other areas with available data. Having reliable, open access sources with a sufficient period of collecting data is key to performing accurate analysis [27], but certainly is not a common situation in many countries, relaying expensive data acquisition such as high-resolution aerial images or LiDAR DTMs in governmental initiatives, which are scarce [20].

The analysis of the different variables used to calculate the CVI enables us to highlight those on which it is possible to act anthropically to reduce vulnerability in that section. There are variables such as geology, coastal slope, tidal range or presence and depth of marine phanerogams on which it is almost impossible to interfere. However, there are others such as beach and dune width, flood level, backshore vegetated surface or even incident waves on which it has been developed techniques that can be used to reduce their impact on the coast.

Relative flood level indicates the importance of dunes and coastal slope to prevent flooding during extreme events, being the most vulnerable transects the ones without dunes ridges due to urbanization developments (Figure 3 and Figure 4). The inclusion of vegetation variables, particularly those related to the marine phanerogams like *Posidonia oceanica*, as well as dune vegetation coverage, are crucial as an indicator of its capability to dissipate wave energy, fix sediments and reduce beach erosion. Beach nourishment projects should consider this, not only focusing on gaining beach width but also restoring or creating dunes ridges fixed using indigenous species that facilitate sustainable management and reduce the need for costly interventions [12, 24].

The impact of urbanization and tourism on the coastal environment, especially in these vulnerable areas, should be also considered [4]. Managing erosion-induced problems in urbanised areas is as important as maintaining natural environments safe from new developments [16]. In our study area, the destruction of the dune ridge by these urban developments, together with the beach erosion and the extreme maritime events causes these stretches to be the most vulnerable ones, while the natural ones, with the dunes protected and the beach not invaded by houses or promenades, have the lowest vulnerability.

Conclusion

Mapping coastal vulnerability using a CVI helps prioritize investments and actions to increase coastal resilience. A sufficient beach width and slope are key elements to prevent flooding during extreme weather events. Dune ridges serve as barriers to flooding and reduce erosion. The most vulnerable transects coincide with urbanised zones that destroyed dune ridges.

The methodology developed in this work has made it possible to identify the most vulnerable stretches, making it easier for coastal managers to prioritise investments for the adequate maintenance and protection of the coast which, due to climate change, will be increasingly necessary.

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