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

JOSEP E. PARDO-PASCUAL [iD], **JESÚS M. PALOMAR-VÁZQUEZ** [iD], **CARLOS CABEZAS-RABADÁN*** [iD]

Geo-Environmental Cartography and Remote Sensing Group, Department of Cartographic Engineering, Geodesy and Photogrammetry, Universitat Politècnica de València, Camí de Vera s/n, 46022 Valencia, Spain.

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

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

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

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

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

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

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

*****Corresponding author:** Carlos Cabezas-Rabadán, Geo-Environmental Cartography and Remote Sensing Group, Department of Cartographic Engineering, Geodesy and Photogrammetry, Universitat Politècnica de València, Camí de Vera s/n, 46022 Valencia, Spain. E-mail address: carcara4@upv.es

1. Introduction

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

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

In the last few years, it has been possible to use the successive multispectral images acquired from artificial satellites as a source of environmental information. Among them, two series of satellite images stand out: Landsat images acquired by NASA and managed by the United States Geological Survey, and Sentinel 2 images acquired and managed by the European Space Agency. Their main advantages are the high frequency of acquiring images (every 2 to 5 days when combining images from different satellites) of the whole planet since the mid-eighties of the last century, and the fact that since 2008 they are available free of charge. These images present a great opportunity to deduce indicators capable of characterizing the morphology of the beach. Among them, the position of the shoreline (Satellite-Derived Shoreline, SDS) stands out as an intuitive and clear descriptor of the physical dimensions of the subaerial beach. The essential limitation in defining the shoreline with sufficient precision for coastal monitoring purposes comes from the spatial resolution of the satellite images. Thus,

while Landsat offers 30 m of pixel size, Sentinel 2 offers 10 m and 20 m. This limitation has been overcome by different algorithmic solutions (e.g. Pardo-Pascual *et al.,* 2012, 2018; Vos *et al.,* 2019; Bishop-Taylor *et al.,* 2019, Sánchez-García *et al.,* 2019) that extract the position of the shoreline with sub-pixel accuracy. Thus, the integration of the extraction algorithm originally proposed by Pardo-Pascual *et al.* (2012) and Almonacid-Caballer (2014) with other necessary tools for the download and pre-processing of the images has led to the creation of SHOREX (Sánchez-García *et al.,* 2020; Cabezas-Rabadán *et al.,* 2021). This extraction system follows an efficient workflow to obtain the SDSs from the image servers. In turn, the extracted SDSs constitute the input data for the creation of Spatial-Temporal Models (STMs) that characterize the morphological changes at different temporal and spatial scales (Cabezas-Rabadán *et al.,* 2019a).

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

2. Study area

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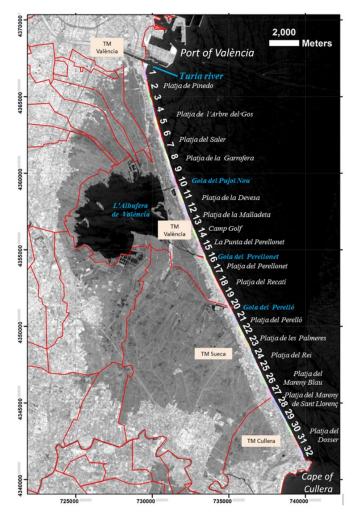

Figure 1. Study area divided into 32 sections of 900 m to facilitate subsequent analyses. It comprises beaches of the coastal front of the municipalities of València, Sueca, and Cullera.

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

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

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

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

intact until the 1960s, the urbanization process seriously altered its ecosystems (Sanjaume and Pardo-Pascual, 2011a).

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

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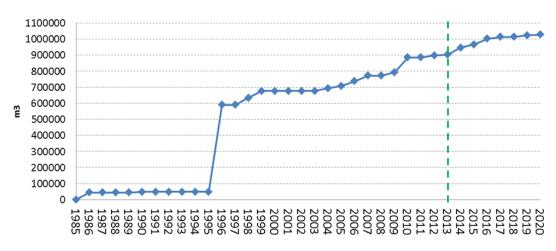

Figure 2. Volume of sand nourishments accumulated along the period 1985-2020 carried out in the study area. Data provided by the Coastal Demarcation of the General Directorate for Sustainability of the Coast and the Sea (DGSCM). The vertical line highlights the start of the study period.

3. Methods

3.1. Shoreline extraction

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

The images were downloaded and pre-processed using the system SHOREX (Cabezas-Rabadán *et al*., 2021). A manual cloud-checking was carried out, and the resulting images were georeferenced using orthorectified aerial photography. From the resulting images, SDSs were automatically defined as the water/land intersection at the acquisition time applying the sub-pixel algorithm proposed by Pardo-Pascual *et al.* (2012) operating over the Short-Wave Infrared bands (SWIR1) using a third-degree polynomial, and 3x3 analysis kernel. As a result, 236 SDS were obtained, and they are expected to offer an accuracy of 3-4 m RMSE according to previous assessments at micro-tidal beaches (Sánchez-García *et al*., 2020).
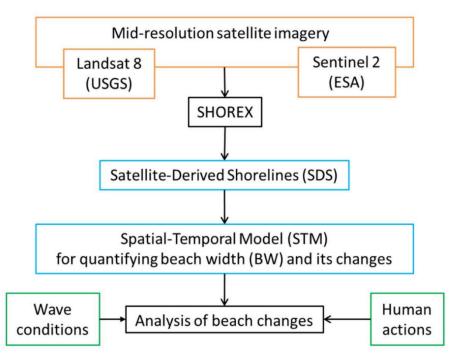
Figure 3. Diagram with the methodology followed in this work. The satellite imagery (orange) constitutes the input data. They are used by the SHOREX system for extracting the satellite-derived shorelines (SDS) and the spatial-temporal model (STM) of beach width (BW) as products for characterizing the beach morphology (light blue). These products, together with the external information (green) regarding the wave conditions (wave height and peak) and human actions (nourishments, dredgings, and coastal constructions) will make it possible for the analysis of beach changes.

3.2. Spatial-temporal models of the beach width

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

3.3. Identifying problematic beach sections

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

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

4. Results

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

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

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

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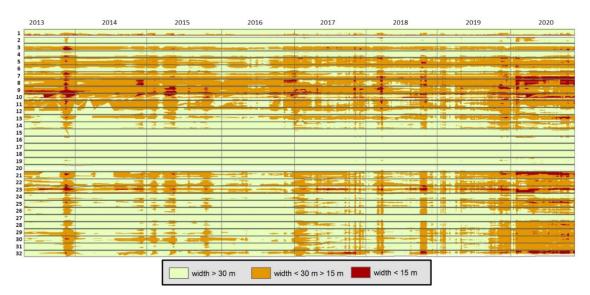

Figure 4. For the period 2013- 2020, characterization of the beach width of the 32 sections into which the study area is divided. Sections with problematic widths (below 30 m, in orange color) and critical widths (below 15 m, red), and those with no problems (green) have been identified.

Problematic widths affect each sector very differently. Figure 5 shows the percentage of time a section shows widths below 30 m, that is experiencing a problematic width. These results allow recognizing more clearly how the northern zone (sector A) has a clear dominance of problematic conditions. This is especially noticeable in sections 5 and 7 to 11, where more than half of the time the width is below 30 m. Moreover, as evidenced by the very low standard deviation values, this is a sector without large variations in width over the study period, so that this problematic situation has remained constant. The intermediate sections (sector B) delimits the area with wider beaches in which a

problematic width situation is not reached. This is the segment that extends between La Punta beach and Gola del Perelló. However, south of El Perelló Port begins a stretch of about 2.6 km in length (Les Palmeres beach) in which at least 50% of the time the beach is narrower than 30 m. This happens mostly after storm episodes but becomes constant since mid-2019. To the south (sector C) we find El Rei beach where there are very strong variations in the width of the beach, which often leads to a problematic situation. Section 27 (corresponding to Mareny Blau beach) is maintained with sufficient width practically throughout the entire period studied. However, further south the problematic width conditions -even critical- are repeated on multiple occasions, especially from autumn 2019 when it can be considered constant. The critical condition (width less than 15 m) is practically limited to El Dosser beach (sections 31 and 32) during 2020.
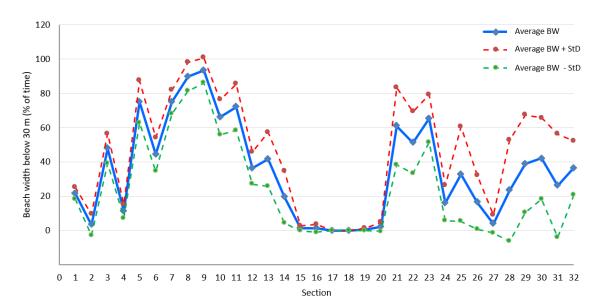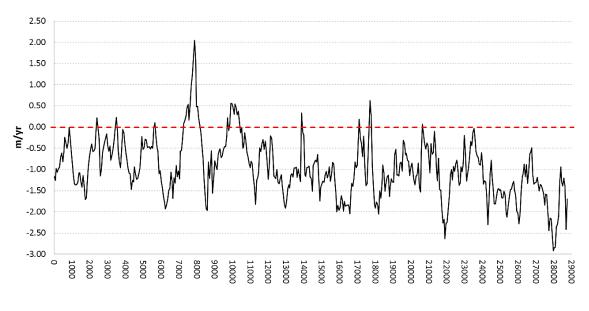

Figure 5. For each of the sections composing the study area, the amount of time (%) for which the beach width is below the 30 m threshold, considering the average beach width (blue color) and adding/substracting the associated standard deviation along the year (red and green respectively).

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

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

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

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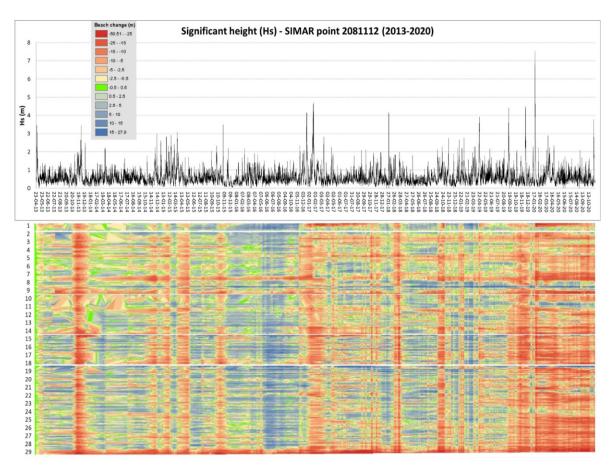

Figure 7. The upper part of the figure shows the significant wave height (Y-axis, in m) obtained from the SIMAR point 2081112 for the period 2013-2020 (X-axis). The lower part shows the associated spatial-temporal model of width changes, taking as reference the first recorded date (23/04/2013), along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

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

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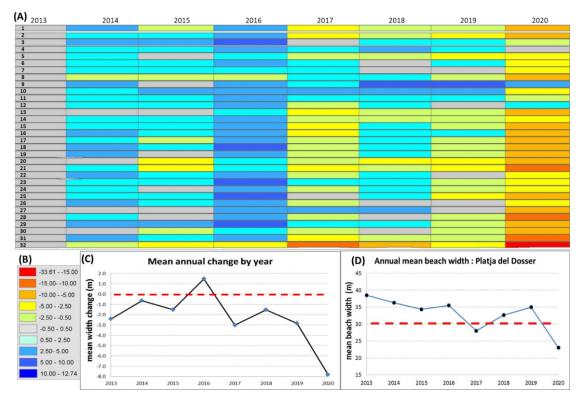

Figure 8. (A) Spatial-temporal model of beach changes for the 32 sections that compose the study area taking 2013 as reference the initial date of the series of records (April 23, 2013). (B) color legend representing the magnitude of the change, (C) graph of the mean annual change by year, and (D) annual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

5. Discussion

The results presented show that the coastal segment has mostly suffered a strongly recessive trend during the period 2013-2020. Among the results obtained in this work, this is probably the most remarkable, as it breaks with the historical behavior of this coast. The whole sector is deeply affected by the complete interruption of the longitudinal sediment transport caused by the dykes of the port of València for decades. The old coastal sedimentary cell is fragmented and, therefore, the sediment no longer arrives from the north. In addition to this phenomenon, the Túria River is artificialized and with

different dams along its course, meaning that it also does not constitute a sedimentary input. All this translates into an erosive trend that for years has been taking place causing a progressive emptying of the submarine profile and a retreat of the shoreline position. These retreats are the most obvious signs of the erosive scenario, and they have been expanding southward over the years. In the 1930s and 1940s, the effects were obvious, especially on Pinedo beach (Vilar, 1934; Yordi, 1943). At the end of the 1980s and based on a systematic analysis of successive series of aerial photographs Pardo-Pascual (1991) detected the end of the effect caused by the port of València on El Saler beach, about 4 km north of Gola del Pujol Nou. Some decades later, in a study based on the analysis of successive images captured from Landsat 5 and 8 between 1984 and 2014 (Pardo-Pascual *et al.,* 2015), the effect had reached La Malladeta beach (1.5 km south of Pujol Nou). Now, after the strong storms of 2017 and 2020, it can be seen how the most accelerated erosive processes cover practically the entire study area.

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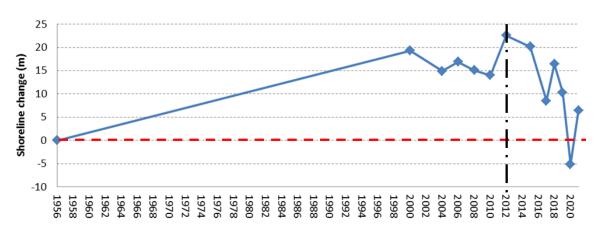

Figure 9. Shoreline change in El Dosser beach for the period 1956-2020. The registers appear as blue points, being the position of 1956 considered as reference. The year 2012 constitutes a turning point in the evolution of the shoreline position. The shoreline position was manually defined using historical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

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

The comparison of the wave conditions and the evolution of the beach width shows how the shoreline systematically retreats linked to storm events. As a clear example of this, after the first available SDS (20/04/13) a storm with Hs of 3.46 m causes a retreat from which the beach widths do not recover. In fact, in late autumn 2013, several weeks with energetic waves (Hs of 3.46 m in December 2013) cause a critical situation with widths below 15 m (on days with significant energetic swell). After that storm, there is a recovery, showing widths about 40 m compared to the 30 m previously observed. When waves reach again Hs of 3 m, critical widths of 15 m appear, from which they tend to recover

within a period of about three months. However, when more energetic storms occur in which the Hs exceeds 4 m as in January 2017 and especially in January 2020 (Storm Gloria), the retreat is more aggressive. It results in beach widths of only 5 m, followed by a very slow recovery. In the case of the Storm Gloria, the complete recovery does not occur, leaving a residual beach width (less than 10 m). A similar pattern of retreatment during the largest storm events and the subsequent lack of complete recovery was identified on beaches with similar characteristics at the southern part of the Gulf of València by Cabezas-Rabadán *et al.* (2019d). On the contrary, this behavior does not seem to take place associated with the storm in January 2017. This could be due to the sand nourishments carried out: 2065 m^3 and 5000 m^3 of sand were nourished in February and November 2017 respectively (marked with a blue arrow in Fig. 10). Although of small magnitude, these artificial inputs, seem to have an immediate effect on widening the beach. However, even though the wave conditions are quite calm, the effect is not sustained over time.
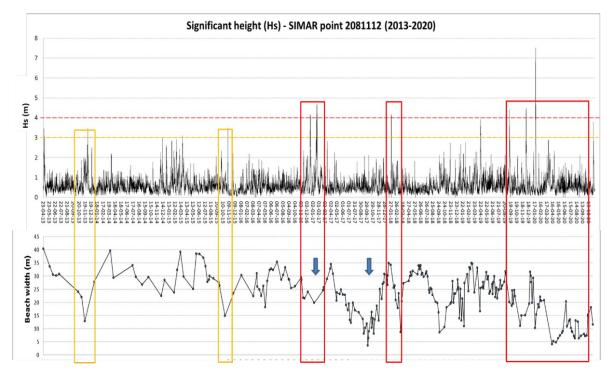

Figure 10. Shoreline changes in El Dosser beach (North of Cullera, section 32), together with wave data (SIMAR point 2081112) highlighting the storm episodes with Hs over 3 m (yellow) and 4 m (red). Blue arrows allow identifying sand nourishments

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

Until a decade ago, the erosive problem affected practically only the northern part of the Albufera barrier beach. However, it now includes places far away from the harbor dikes. This substantial change in the evolutionary dynamics of El Dosser beach is an example of this. All this raises the need to open the potential range of causes that would explain this erosive behavior, beyond the interruption of the southward drift of sands caused by the dykes of the port of València. Undoubtedly, the decrease in sedimentary inputs from the fluvial systems must also be taken into consideration. Throughout the 20th century, Valencian rivers experienced great anthropic alterations that have been associated with a significant hydro-sedimentary deficit (Segura-Beltrán and Sanchis-Ibor 2013; Sanchis-Ibor *et al.,* 2017). One of the most important impacts has been sediment retention in the reservoirs. It has been estimated that in the Benagéber reservoir alone in its first 37 years of operation 6.66 Hm³ of sediments were retained (Cobo, 2008). This effect is not only confined to the Túria basin but practically 75% of the area that drains to the Valencian coasts is controlled by the reservoirs (Pardo-Pascual and Sanjaume, 2019) so it is evident that the whole coastal system receives less sediment than it had historically received.

A third key factor, in addition to the effect of the port of València and the decrease in fluvial sediment inputs, is the fact that the magnitude of the storms seems to be increasing. Thus, both wave height and storm intensity expressed as a product of wave height and storm duration (Sénéchal *et al.,* 2015), are increasing in recent decades (Fig. 11). Prior to 2017 only one storm showed intensity values over 250 m²h, but since then six storms have been recorded. Likewise, prior to 2000 no storm had shown Hs of 4 m. In 2001, one case was recorded, but since 2009 there have been 10. This increase in situations of higher energy is associated with the wash of the beach and the sediment loss (especially of that of smaller caliber) towards deeper waters that cannot always be returned to the coast during calmer wave conditions.
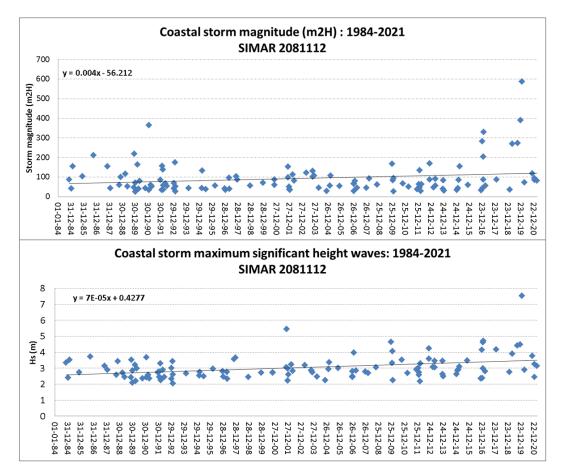

Figure 11. Changes in the magnitude of coastal storms according to two representative parameters: the maximum significant wave height and the intensity (in m2h). The latter one is the result of multiplying the maximum significant height squared by the duration of the storm.

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

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

6. Conclusions

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

Acknowledgments

References

Albarracín, S., Alcántara-Carrió, J., Barranco, A., Sánchez García, M.J., Fontán Bouzas, Á., Rey Salgado, J., 2013. Seismic evidence for the preservation of several stacked Pleistocene coastal barrier/lagoon systems on the Gulf of Valencia continental shelf (western Mediterranean). *Geo-Marine Letters* 33 (2-3), 217-223. https://doi.org/10.1007/s00367-012-0315-x

Alcántara-Carrió, J., Albarracín, S., Montes, I.M., Flor Blanco, G., Fontán Bouzas, A., Rey Salgado, J., 2013. An indurated Pleistocene coastal barrier on the inner shelf of the Gulf of Valencia (western Mediterranean): Evidence for a prolonged relative sea-level stillstand. *Geo-Marine Letters* 33 (2-3), 209-216. https://doi.org/10.1007/s00367-012-0316-9

Alemany, J., 1984. *Estat d'utilització de les platges del litoral català.* Departament de Política Territorial i Obres Públiques. Generalitat de Catalunya, Barcelona.

Almonacid-Caballer, J. 2014. *Obtención de líneas de costa con precisión sub-píxel a partir de imágenes Landsat TM, ETM y OLI.* [Tesis doctoral]. Universitat Politècnica de València, Valencia, 351 pag. https://doi.org/10.4995/Thesis/10251/48462

Benavent, J.M., Collado, F., Martí, R.M., Quintana, A., Sánchez, A., Vizcaíno, A., 2004. *La restauración de las dunas litorales de la Devesa de l'Albufera de Valencia*. Ajuntament de ValènciaValencia, 65 pag.

Bishop-Taylor, R., Sagar, S., Lymburner, L., Alam, I., Sixsmith, J., 2019. Sub-pixel waterline extraction: Characterising accuracy and sensitivity to indices and spectra. *Remote Sensing* 11 (24), 1-23. https://doi.org/10.3390/rs11242984

Cabezas-Rabadán, C., Pardo-Pascual, J.E., Palomar-Vázquez, J., Fernández-Sarría, A., 2019a. Characterizing beach changes using high-frequency Sentinel-2 derived shorelines on the Valencian coast (Spanish Mediterranean). *Science of the Total Environment* 691, 216-231. https://doi.org/10.1016/j.scitotenv.2019.07.084

Cabezas-Rabadán, C., Pardo-Pascual, J.E., Almonacid-Caballer, J., Rodilla, M., 2019b. Detecting problematic beach widths for the recreational function along the Gulf of Valencia (Spain) from Landsat 8 subpixel shorelines. *Applied Geography* 110, 102047. https://doi.org/10.1016/j.apgeog.2019.102047

Cabezas-Rabadán, C., Rodilla, M., Pardo-Pascual, J., Herrera-Racionero, P., 2019c. Assessing users' expectations and perceptions on different beach types and the need for diverse management frameworks along the Western Mediterranean. *Land Use Policy* 81, 219-231. https://doi.org/10.1016/j.landusepol.2018.10.027

Cabezas-Rabadán, C., Pardo-Pascual, J. E., Almonacid-Caballer, A., Palomar-Vázquez, J., Fernández-Sarría, A., 2019d. Monitorizando la respuesta de playas mediterráneas a temporales y actuaciones antrópicas mediante imágenes Landsat. *Geofocus: Revista Internacional de Ciencia y Tecnología de la Información Geográfica* 23, 119-139.

Cabezas-Rabadán, C., Pardo-Pascual, J.E., Palomar-Vázquez, J., 2021. Characterizing the Relationship between the Sediment Grain Size and the Shoreline Variability Defined from Sentinel-2 Derived Shorelines. *Remote Sensing* 13 (14), 2829. https://doi.org/10.3390/rs13142829

Cobo, R., 2008. Los sedimentos de los embalses españoles. *Ingeniería del agua* 15 (4), 231-241.

European Comission, 2009. *The Economics of Climate Change Adaptation in EU Coastal Areas. Country overview and assessment.* Policy Research Corporation, Spain. Belgium, Brussels, 15 pag.

Lozoya, J.P., Sardá, R., Jiménez, J.A., 2011. A methodological framework for multihazard risk assessment in beaches. *Environmental Science & Policy* 14 (6), 685-696. https://doi.org/10.1016/j.envsci.2011.05.002

MITECO, 2018. *Proyecto Extracción de arena en aguas profundas de Valencia para alimentación de playas (Valencia).* DGSCM, 203 pag. Available at: https://www.miteco.gob.es/es/costas/participacion-publica/parte1_tcm30-498101.pdf

Pardo-Pascual, J.E., 1991. *La erosión antrópica en el litoral valenciano*. Generalitat Valenciana. Conselleria d'Obres Públiques, Urbanisme i Transports, 240 pag.

Pardo-Pascual, J.E., Almonacid-Caballer, J., Ruiz, L.A., Palomar-Vázquez, J., 2012. Automatic extraction of shorelines from Landsat TM and ETM+ multi-temporal images with subpixel precision. *Remote Sensing of Environment.* 123, 1-11. https://doi.org/10.1016/j.rse.2012.02.024

Pardo-Pascual, J., Sánchez-García, E., Almonacid-Caballer, J., Palomar-Vázquez, J., Priego de los Santos, E., Fernández-Sarría, A., Balaguer-Beser, Á., 2018. Assessing the Accuracy of Automatically Extracted Shorelines on Microtidal Beaches from Landsat 7, Landsat 8 and Sentinel-2 Imagery. *Remote Sensing* 10, 326. https://doi.org/10.3390/rs10020326

Pardo-Pascual, J.E., Sanjaume, E., 2019. Beaches in Valencian Coast. In: J. Morales (Eds), *The Spanish Coastal Systems.* Springer, Cham. https://doi.org/10.1007/978-3-319-93169-2_10

Prodger, S., Russell, P., Davidson, M., Miles, J., Scott, T., 2016. Understanding and predicting the temporal variability of sediment grain size characteristics on high-energy beaches. *Marine Geology* 376, 109-117. https://doi.org/10.1016/j.margeo.2016.04.003

Rey, J., Diaz del Rio, V., 1983. Aspectos geológicos sobre la estructura poco profunda de la plataforma del Levante Español. In: J. Castellví (Ed). *Estudio oceanográfico de la plataforma continental*, Cádiz, pp. 53-74.

Rosselló, V.M., 1979. Una duna fósil Pleistocena en la restinga de la Albufera de Valencia. *Cuadernos de Geografía* 25, 111-126.

Rosselló, V.M., 1995. *L'Albufera de València.* Publicacions de l'Abadia de Montserrat, Barcelona, 192 pag.

Sánchez-García, E., Balaguer-Beser, A., Almonacid-Caballer, J., Pardo-Pascual, J.E., 2019. A new adaptive image interpolation method to define the shoreline at sub-pixel level. *Remote Sensing* 11 (16), 1880. https://doi.org/10.3390/rs11161880

Sánchez-García, E., Palomar-Vázquez, J., Pardo-Pascual, J., Almonacid-Caballer, J., Cabezas-Rabadán, C., Gómez-Pujol, L., 2020. An efficient protocol for accurate and massive shoreline definition from mid-resolution satellite imagery. *Coastal Engineering* 160, 103732. https://doi.org/10.1016/j.coastaleng.2020.103732

Sanchis, C., 1998. *De la gola a les goles: canvi ambiental secular a l'Albufera de València*. Fundació Bancaixa, Valencia, 142 pag.

Sanchis-Ibor, C., Segura-Beltran, F., Almonacid-Caballer, J., 2017. Channel forms recovery in an ephemeral river after gravel mining (Palancia River, Eastern Spain). *Catena* 158, 357-370. https://doi.org/10.1016/j.catena.2017.07.012

Sanjaume, E.S., 1985. *Las costas valencianas: sedimentología y morfología*. Sección de Geografía. Universidad de Valencia, Valencia, 505 pag.

Sanjaume, E., Carmona, P., 1995. L'Albufera de Valencia: rasgos geomorfológicos y evolución cuaternaria. In: *El Cuaternario del País Valenciano*. Universitat de Valencia, València, pp. 155-162.

Sanjaume, E., Pardo-Pascual, J.E., 2005. Erosion by human impact on the Valencian coastline (E of Spain). *Journal of Coastal Research* 49, 76-82. http://www.jstor.org/stable/25737408

Sanjaume, E., Pardo-Pascual, J.E., 2011a. Degradación de sistemas dunares. In: *Las dunas en España*. Sociedad Española de Geomorfología, pp. 609-639.

Sanjaume, E., Pardo-Pascual, J. E., 2011b. Las dunas de la Devesa del Saler. In: *Las dunas en España*. Sociedad Española de Geomorfología, pp. 263-283.

Sanjaume, E., Pardo-Pascual, J. E., 2019. Littoral Dunes on Valencia Coast. In: J. Morales (Ed). *The Spanish Coastal Systems*. Springer, Cham, pp. 631-659. https://doi.org/10.1007/978-3-319-93169-2_27

Sanjaume, E., Pardo-Pascual, J.E., Segura-Beltran, F., 2019. Mediterranean Coastal Lagoons. In: J. Morales (Ed). *The Spanish Coastal Systems*. Springer, Cham, pp. 237-267. https://doi.org/10.1007/978-3-319-93169-2_11

Segura-Beltrán, F., Sanchis-Ibor, C., 2013. Assessment of channel changes in a Mediterranean ephemeral stream since the early twentieth century. The Rambla de Cervera, eastern Spain. *Geomorphology* 201, 199-214. https://doi.org/10.1016/j.geomorph.2013.06.021

Sénéchal, N., Coco, G., Castelle, B., Marieu, V., 2015. Storm impact on the seasonal shoreline dynamics of a meso- to macrotidal open sandy beach (Biscarrosse, France). *Geomorphology* 228, 448-461. https://doi.org/10.1016/j.geomorph.2014.09.025

Sutherland, J., Gouldby, B., 2003. Vulnerability of coastal defences to climate change. In: *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering*. Thomas Telford, pp. 137-145. https://doi.org/10.1680/wama.156.2.137.38008

Valdemoro, H. I., Jiménez, J. A., 2006. The influence of shoreline dynamics on the use and exploitation of Mediterranean tourist beaches. *Coastal Management* 34(4), 405-423. https://doi.org/10.1080/08920750600860324.

Vilar, J., 1934. *Proyecto de defensa de la playa desde la desembocadura del río Turia al Perellonet*. Unpublished document, Archive of Port of Valencia.

Vos, K., Splinter, K. D., Harley, M. D., Simmons, J. A., Turner, I. L., 2019. CoastSat: A Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available satellite imagery. *Environmental Modelling and Software* 122, 104528. https://doi.org/10.1016/j.envsoft.2019.104528

Yepes, V., 2002. Ordenación y gestión del territorio turístico. Las playas. In: D. V. Blanquer Criado (Ed). *Ordenación y gestión del territorio turístico*. Tirant lo Blanch, Valencia, pp. 549-579.

Yordi, L., 1943. *Proyecto de defensa de la costa sur*. Informe mecanografiado. Unpublished document, Archive of Port of Valencia.