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Multidecadal characterisation of shoreline changes as a response to coastal engineering actions. A case study in Almenara, Valencia (E Spain)

Carlos CABEZAS-RABADÁN [1,2], Josep E. PARDO-PASCUAL [1],
Jesús PALOMAR-VÁZQUEZ [1]

1. Grup de Cartografia GeoAmbiental i Teledetecció, Dept. d'Enginyeria Cartogràfica, Geodesia i Fotogramet., Universitat Politècnica de València, 46022, Valencia, Spain. *carcara4@upv.es, jepardo@cgf.upv.es, jaialca@upv.es, jpalomav@upv.es*
2. Univ. Bordeaux, CNRS, Bordeaux INP, EPOC, UMR 5805, 33600 Pessac, France.

Abstract:
The evolution of Almenara Beach (Gulf of Valencia, E Spain) constitutes a good example of the morphological alteration of beaches along a heavily artificially modified coast affected by a significant littoral drift. During the last decades, this beach (about 3 km long) has experienced important erosion problems in parallel with the implementation of numerous engineering actions. The shoreline evolution was characterised over the last four decades using 1120 images from the Landsat 5, 7, 8, 9 and Sentinel 2 satellites. The series of satellite-derived shorelines were automatically obtained using the extraction tool SHOREX. A spatial-temporal model of the beach width was created to characterise the changes compared with the situation in 1984. Results show how the whole area has been affected by an erosive process associated with the interruption of the longitudinal transport of sediments. The erosion was originally linked to the construction of the Port of Borriana 16 km northward, but the coastline retreats displaced southwards in parallel with the construction of breakwaters and groins. Compared to the situation in 1984, by 2018 about 50% of the coastline had retreated more than 45 m. After 2013, lower erosive rates were registered in the northern (and most affected) section as the construction of alongshore defences backing the beach impeded further landward retreat. In 2022, several groins were built and completely changed the shape of the northern part of the beach, leading to shoreline recovery in several sectors and erosion in others. Remote sense techniques allow a detailed characterisation of the coastline response to engineering actions, which seem to have transferred the erosive problem alongshore following the littoral drift.

Keywords:
Subpixel waterline definition, Coastal engineering, Beach monitoring, Beach nourishments, Coastal erosion, Remote sensing, SHOREX, Western Mediterranean.

1. Introduction

Over the Western Mediterranean, the human-induced alteration of the coastline significantly contributes to the occurrence of high erosive rates that jeopardise the beaches after the second half of the 20th century. On the coast of Valencia, this phenomenon is a problematic issue for the maintenance of beach functions. This is especially important considering that sun, sea and sand tourism significantly contributes to the gross domestic product of the region (RICO-AMOROS *et al.*, 2009).

In the face of erosion problems, coastal engineering actions in the form of groins, breakwaters and sand nourishments have the potential to modify the beach morphology. In an attempt to contribute to the physical maintenance of the beaches, these actions are the usual response both worldwide (HANSON *et al.*, 2002) and in the Valencian case (OBIOL-MENERO, 2003). The evaluation of these engineering actions is essential to ensure their real efficiency, as they can present undesired effects on the environment (SPEYBROECK *et al.*, 2006) and lead to a transfer of the erosion problem to other surrounding coastal segments. However, due to the high cost of acquiring beach morphological data, in many cases, the monitoring of the effects of the engineering actions is limited in time and space.

The recent free access to the optical satellite images of the Landsat and Sentinel-2 series has opened up a new scenario for the efficient characterisation of coastal morphology and its dynamism. Based on these satellite images which offer worldwide coverage and high revisit frequency it is possible to characterise shoreline changes efficiently over time and covering large coastal segments (see VOS *et al.*, 2023). For this same purpose, the tool SHOREX includes all the necessary steps for the automatic definition of the waterline position with high accuracy (CABEZAS-RABADÁN *et al.*, 2021; PALOMAR-VÁZQUEZ *et al.*, 2018).

Based on remote sensing, this paper presents the characterisation of the morphological changes associated with coastal engineering actions on Almenara Beach (E Spain) during the last four decades.

2. Study site

The coastal section analysed (about 3 km long) comprises the beach of the municipality of Almenara (northern part of the Gulf of Valencia, E Spain, Figure 1). Composed of mixed sand and gravel, this Mediterranean site presents NNE-SWW orientation, almost negligible astronomical tidal amplitude (<20 cm) and small waves (Hs = 0.7 m; Tp = 4.2 s). The largest waves come from the first quadrant, mainly ENE, and to a lesser extent, NE, leading to a significant southward longshore drift (PARDO-PASCUAL & SANJAUME, 2019). The segment is heavily urbanised in its northern part, while it remains free of buildings close to the shore in its southernmost part.

The area is affected by an erosive process associated with the interruption of the longshore transport, as well as a reduction in sediment input to the littoral system. The major obstacle to transport in this coastal segment is the Port of Borriana (16 km to the north, i.e., updrift from the study site). Built in 1933, the port currently presents jetties of more than 300 m transverse to the coast and a depth of 7 m on the outside, causing almost complete retention of the downdrift transport (PARDO-PASCUAL, 1991).

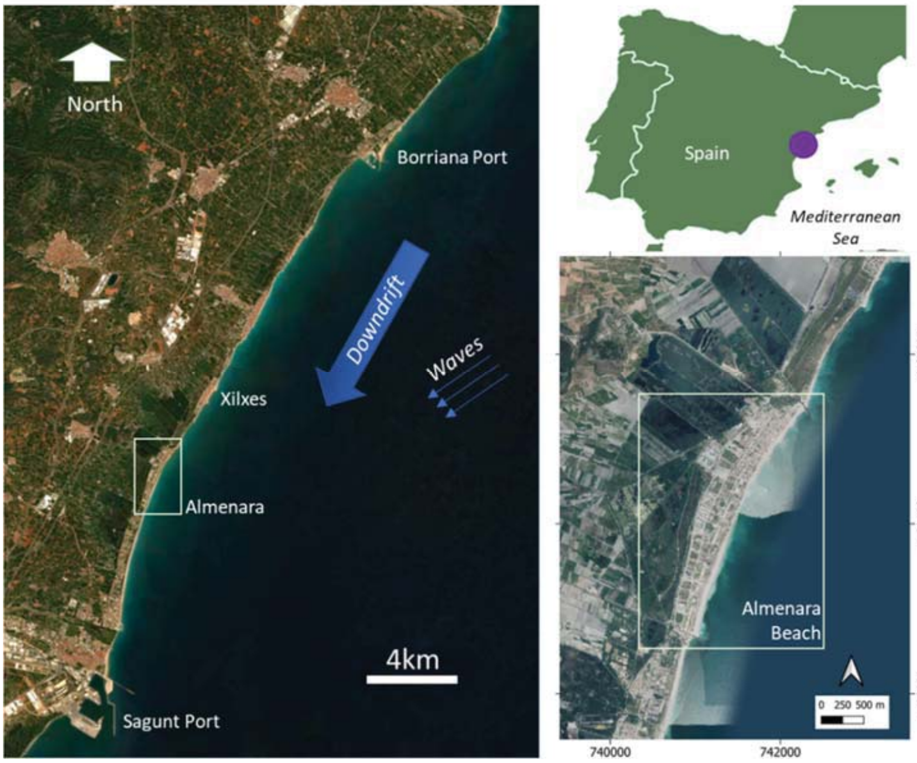

Figure 1. Location and aerial image of Almenara Beach. The main direction of the incident waves leading to the longshore drift is indicated.

Between this port and Almenara Beach, at least 31 sand nourishments were carried out between 1996 and 2010 involving more than 1,500,000 m^3 of sediment (Table 1; IHC, 2011). At the same time, more than 40 rigid structures such as breakwaters and groins were implemented. In response to the erosion process, these actions progressively expanded further south until they reached the Sagunt Port (south of Almenara Beach). Most of those defences and structures to accumulate and stabilise the sediment have been concentrated on the beaches of the municipalities of Xilxes and Almenara (see Figure 1) to maintain their physical integrity and guarantee the recreational function and the protection of assets in the coastal front. In the case of Almenara Beach, it was delimited by groins (Figure 2) aiming to stabilise the inlets both in the north (70 m length, built in the second half of the 1990s) and in the south (25 m, 1981-1989). Apart from those, four other groins were built in 2022 in the northern part of the beach. The southernmost of them exceeds the 150 m cross-shore.

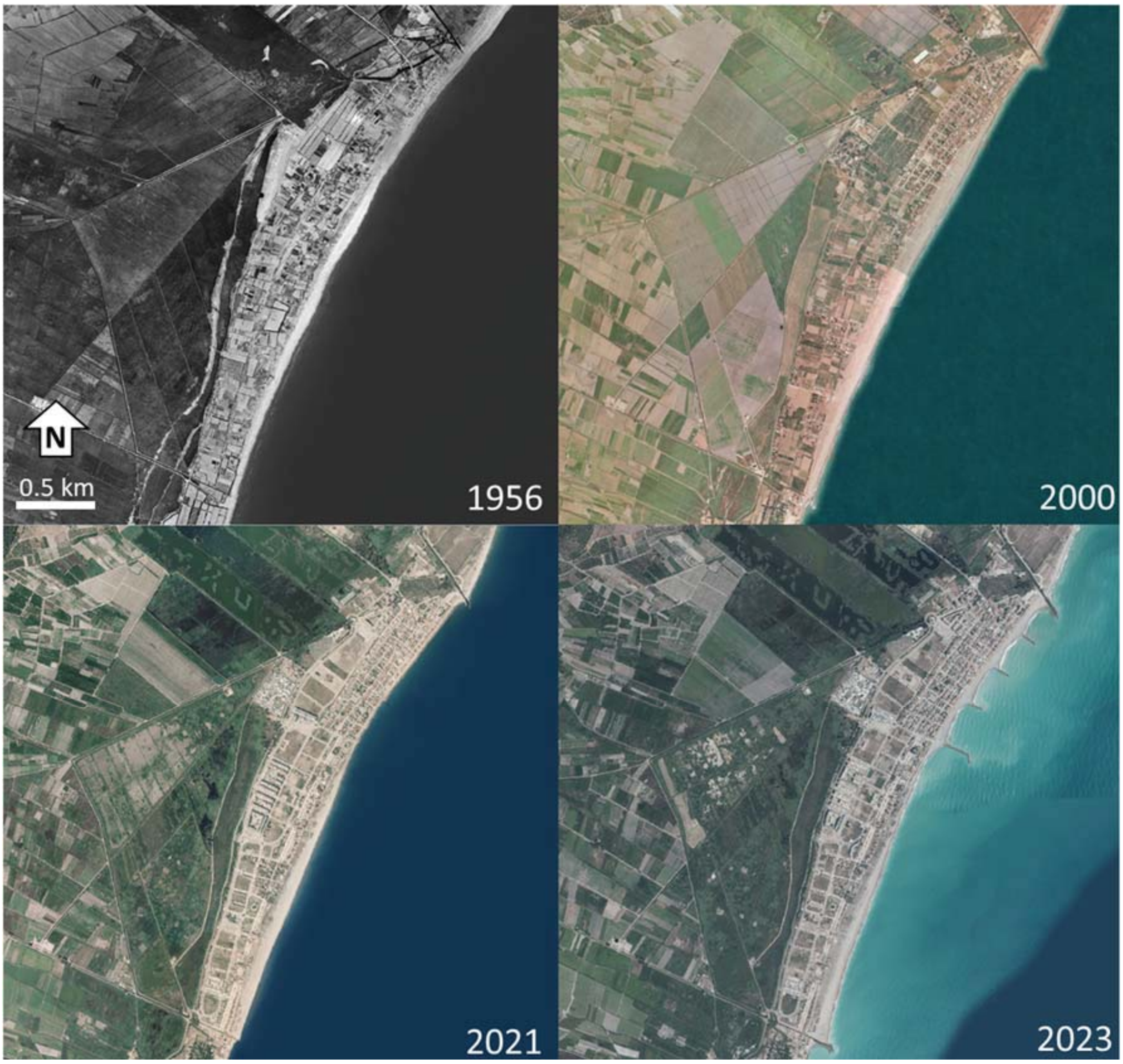

Figure 2. Evolution of Almenara Beach. Source: Institut Cartogràfic Valencià (ICV).

Table 1. Nourishments (1986-2009) in the municipalities of Xilxes and Almenara. Data compiled by the Environmental Hydraulics Institute of Cantabria (IHC). Note that nourishments are alternatively quantified by their volume (m^3) or their weight (tones).

Xilxes		***Almenara***	
Year	***Nourishment***	***Year***	***Nourishment***
1986	*175695 m3*	*1998*	*37392 m3*
1987	*38274 m3*	*2001/02*	*89219 m3*
1987	*246991 m3*	*2002*	*824 m3*
1989	*27854 m3*	*2006*	*53823 m3*
1996	*100069 tm*	*2007/09*	*49499 tm*
1996	*53568 m3*	*2022*	*50000 m3*
1998	*29389 tm*		
2010	*6000 m3*		

3. Methods

3.1 Shoreline definition

The characterisation of the coastline evolution was carried out using 1120 images from Landsat 5, 7, 8, 9 and Sentinel 2 satellites over the period 1984-2023 (Figure 3). The series of satellite-derived waterlines (SDWLs) were automatically obtained using the extraction tool SHOREX (CABEZAS-RABADÁN *et al.*, 2021; PALOMAR-VÁZQUEZ *et al.*, 2018), which includes all the necessary steps from image download to the final definition of the waterline. It follows the phases of (a) image downloading, (b) selection of cloud-free images, (c) sub-pixel georeferencing, (d) approximate waterline definition at pixel level by applying the Automated Water Extraction Index (AWEI) by FEYISA *et al.*, (2014) in its no shadow version (AWEInsh) with a threshold = 0, and (e) definition at sub-pixel level by points (vertices) obtained every 5 m and 7.5 m (S2 and Landsat imagery respectively) describing the instantaneous position of the water/land interface. No tidal or other elevation corrections were applied as the study site is located on a microtidal and low energetic coast with no availability of reliable slope data to address such corrections. Taking this into account, the satellite-derived waterlines have been assimilated as satellite-derived shorelines.

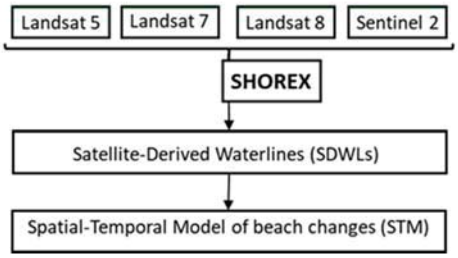

Figure 3. Methodological workflow for defining SDWLs and beach width changes.

3.2 Characterization of beach width changes

Following the methodology described by CABEZAS-RABADÁN *et al.*, (2019a) a spatial-temporal model characterising the beach width changes was created. Thus, (i) the inner limit of the beach was defined by a line subsequently segmented every 50 m; (ii) the distance between each segment and SDWL was measured constituting the beach width at each date; (iii) the change of width was calculated with respect to the average width during the first of the years with SDWL records (1984); and (iv) all those measurements were organised over space and time to subsequently generate a spatial-temporal continuum of values on which to perform analyses and measurements.

4. Results

Shoreline position and beach width changes show the morphological alteration associated with coastal engineering interventions (Figure 4). The shoreline presented stability until the early 90s, even lightly increasing the beach width until 1993. Nevertheless, from the mid-90s the shoreline retreat started in the northern part of the site, and it was exacerbated during the following years affecting a larger portion of the beach.

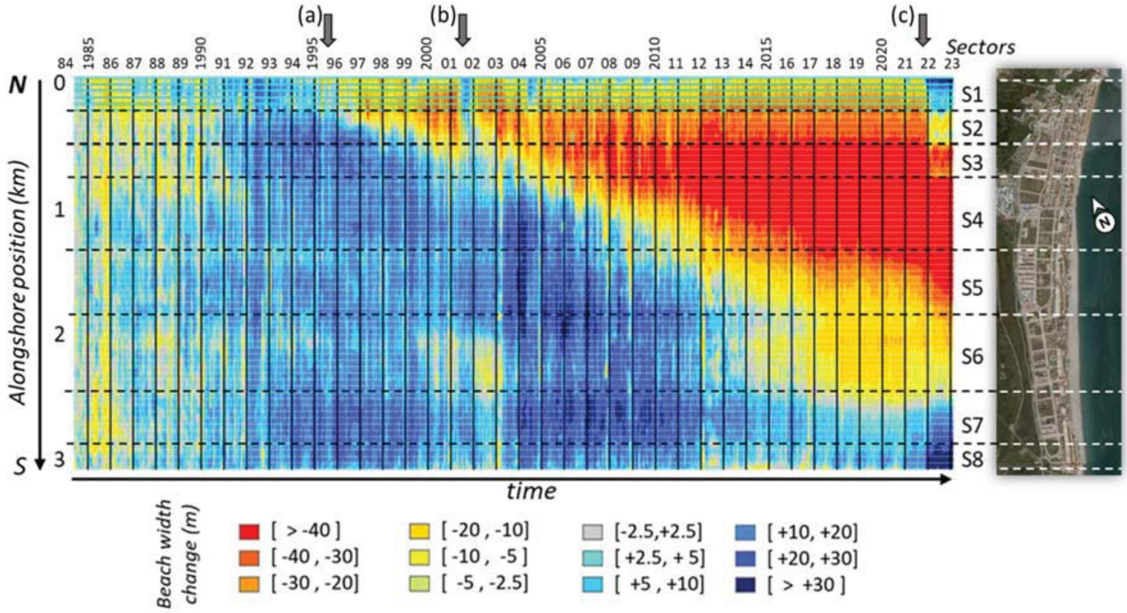

Figure 4. Spatial-temporal model of beach width changes (taking as reference the average width in 1984). The erosion and recovery are represented in different colours ranging from red to blue. The three most important engineering actions are highlighted by black arrows: (a) the implementation of the groin in the northern inlet, (b) the 2001-2002 nourishment, and (c) the ensemble of actions in 2022. To provide a more detailed analysis the site appears divided into eight sectors (S1-S8) according to its dynamism.

The erosive trend was uneven along the site, being the northern sectors affected earlier and to a greater extent (Figure 5). An erosive trend appeared after 1995 over the northernmost sector 1, and it was exacerbated during the following years coinciding with the implementation of the groin aiming to stabilise the northern inlet (Fig. 4a). Following certain temporary offsets, the erosion affected the adjacent sectors towards the south (2-4). This occurred despite occasional recovery processes associated with nourishment actions (Fig. 4b). After 2013, sectors 1 to 3 showed stability, although the beach width had already been reduced by several tens of meters compared to its initial situation in 1984 (about 20 m, 30 m and 70 m in Sectors 1, 2 and 3 respectively). The stabilisation coincides with the construction of seawalls in the inner limit of the beach (upper shoreface) in the northern part of Almenara when it had already eroded and completely disappeared. This action impeded further landward retreat of the shoreline. In parallel with this stabilisation, the southern sectors (4-7) continued to experience erosion. Thus, by 2018 about 50% of the coastal segment had experienced over 40 m of shoreline retreat, with the most affected sectors (3 and 4) experiencing more than 60 m retreat.

In 2022 four new groins were built in Almenara Beach (Fig. 4c). The existing ones located both at the northern and southern ends of the beach were enlarged, and beach nourishments were carried out. The implementation of these engineering actions coincided with a significant change in the shape of the beach. Shoreline recovery occurred in the northernmost sectors (1-3), as well as in those closer to the southern groin (S8). On the contrary, a light recovery was registered in the intermediate sectors 4 and 6, while the erosion increased in sector 5.

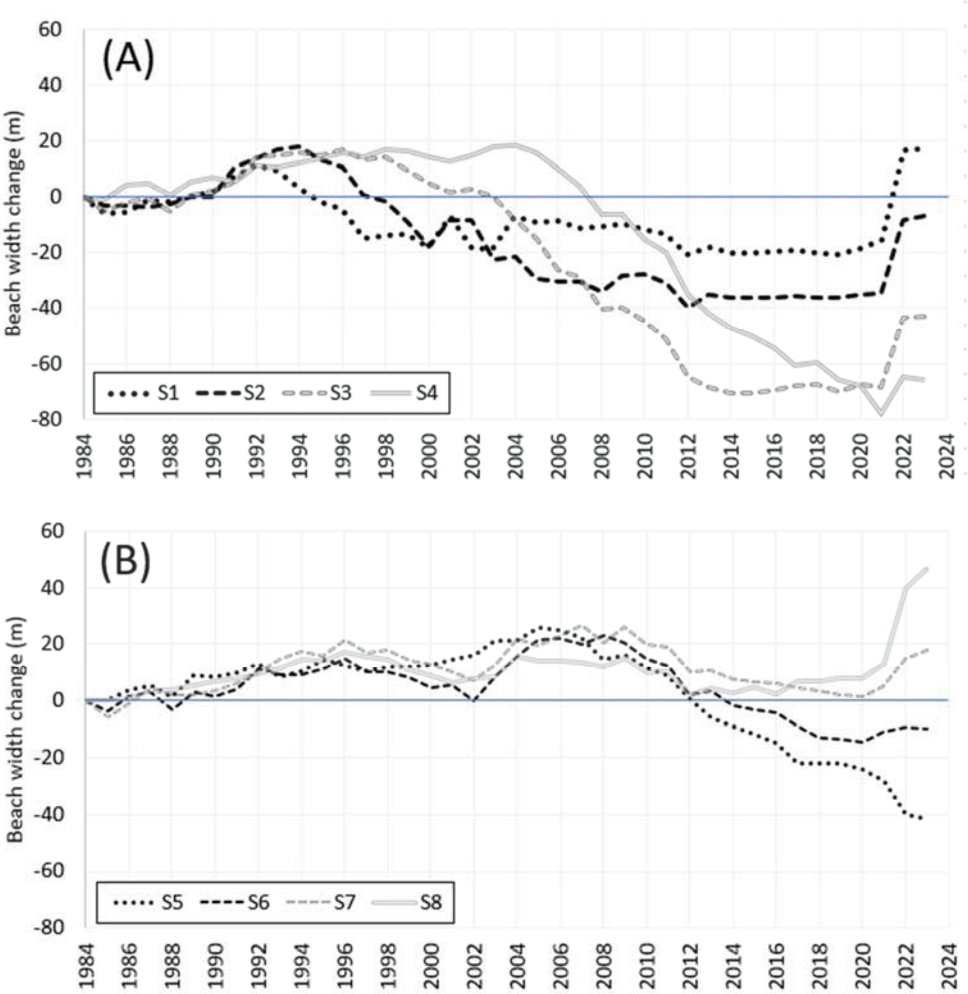

Figure 5. Average beach width evolution of sectors 1 to 4 (A) and 5 to 8 (B).

5. Discussion and conclusions

The evolution of Almenara Beach is a good example of the morphological alteration of a coastal segment due to direct human intervention. The definition of large SDWL datasets using the SHOREX tool from all Landsat and Sentinel 2 images acquired at a high revisit frequency enables the continuous monitoring of beach width changes as a response to coastal engineering projects.

Rigid engineering actions have been carried out to ensure the physical maintenance of the beaches, slowing down erosion. This ensures that the beaches continue to fulfil their function of protecting the assets built on the coastal front, as well as offering residents and visitors access to the resources of sun, sea and sand. However, these actions (especially the rigid ones) have a high economic cost and significant environmental impact (SPEYBROECK *et al*., 2006), so it is essential to evaluate their usefulness from a broad perspective.

The evolution of this coastal segment has been conditioned by the significant downdrift transport and the combination of diverse engineering actions (see Figures 4 and 5). In Almenara Beach, the sedimentary dynamism has been greatly altered by the various rigid coastal engineering works altering the alongshore distribution of the sediment. Originally, this was mainly caused by the Port of Borriana (PARDO-PASCUAL, 1991). However, the successive construction of breakwaters and groins displaced the erosive processes southwards. Almenara Beach experienced relative stability between 1984 (the start of the shoreline dataset) and the mid-90s, probably partly sustained by the sand nourishments carried out both in that same beach and others located updrift (see Tab. 1). Since the mid-90s and coinciding with the implementation of the northern groin the beach was affected by an important erosive process with an uneven effect on its different sectors. The subsequent rigid actions seem to have played a key role in modifying the shape of the beach, but mainly shifting the erosive trend southwards. Thus, groins and breakwaters have slowed down the erosion in certain beach segments such as those immediately north of the new groins (i.e., updrift). Nevertheless, these actions have not solved the erosive problem of the whole coastal sector. As a result of these actions, a highly anthropized beach can be observed (Figure 2), with the associated negative impact on the landscape and beach attractiveness (RODELLA & CORBAU, 2020). At the same time, the alongshore stiffening of the coast to protect inland assets leaves the beach with a greatly reduced capacity to adapt to future sedimentary and hydrodynamic scenarios, entirely conditioning its maintenance to continuous (and expensive) human interventions (COOPER, 2022).

Width recovery took place after nourishment actions on Almenara Beach, but also when the nourishments were carried out in other beaches updrift. This shows the positive role of new sediment inputs in mitigating the decline of sediment availability in the coastal system. The general lack of sediment in this sedimentary cell together with massive sediment traps has been pointed out as the main possible cause of the erosive trends observed at several points along the Gulf of Valencia (e.g., PARDO-PASCUAL *et al*., 2022), being especially striking in traditionally cumulative sectors located at the end of the sedimentary cell (CABEZAS-RABADÁN *et al*., 2019b). The reduction in fluvial sediment discharges appears as a major issue affecting coastal erosion (WILLIS & GRIGGS, 2003), especially considering the extremely reduced inputs in the Western Mediterranean (SANJAUME & PARDO-PASCUAL, 2005).

The combination of the large shoreline dataset and methods to organise and analyse this information offers a novel approach for monitoring coastal engineering interventions at different spatial and temporal scales. This may allow coastal managers to evaluate the real effectiveness of the interventions (for example in the surveillance programs within the environmental impact assessment framework) and ultimately support future decision-making.

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