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Coastal changes and anthropogenic structures: An analysis of the beaches of the Gulf of Roses (NW Mediterranean Sea, Spain)

Cambios costeros y estructuras antropogénicas: un análisis de las playas del Golfo de Roses (Mediterráneo NO, España)

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Abstract

The main goal of this work is to assess the mid-short term (2004 to 2020) spatial and temporal width variations and sedimentological behaviour of the northern beaches of the Gulf of Roses (NW Mediterranean, Spain). The study zone covers 10 km at the northern part of the gulf. Two GIS methodologies were employed to quantify coastal changes by transects and by areas. Sediment samples were collected from both the dry beach and swash areas for each transect. Profile-based analysis shows an average annual rate of -0.11 m•y^{-1} (ranging between 0.53 and -0.55 m•y^{-1}), while areal-based results indicate a total loss of -20810 m2 (-1300 m^{2}•y^{-1}). Sediment grain size decreases northward (from 745 to 264 µm in the swash zone). Changes in beach width and grain size illustrate the impact of anthropogenic structures on morphodynamic behavior. These structures preferentially deposit specific grain sizes and impede sediment transport, leading to increased beach width and sediment grain sizes upstream and a reverse process downstream, generating distinct morphodynamic behavior.

Keywords: *coastal evolution; beach width; grain-size trend; coastal anthropization; Gulf of Roses; NW Mediterranean*

Resumen

El principal objetivo de este trabajo es evaluar las variaciones espaciales y temporales de anchura y el comportamiento sedimentológico a medio-corto plazo (2004 a 2020) de las playas del norte del Golfo de Roses (NO Mediterráneo, España). La zona de estudio cubre 10 km en la parte norte del golfo. Se emplearon dos metodologías SIG para cuantificar los cambios costeros por transectos y por áreas. Se recolectaron muestras de sedimento tanto de la playa seca como de las áreas de lavado para cada transecto. El análisis basado en perfiles muestra una tasa anual promedio de -0,11 m•y-1 (que oscila entre 0,53 y -0,55 m•y-1), mientras que los resultados regionales indican una pérdida total de -20810 m2 (-1300 m2•año-1). El tamaño del grano de sedimento disminuye hacia el norte (de 745 a 264 µm en la zona de balanceo). Los cambios en el ancho de la playa y el tamaño del grano ilustran el impacto de las estructuras antropogénicas en el comportamiento morfodinámico. Estas estructuras depositan preferentemente tamaños de grano específicos e impiden el transporte de sedimentos, lo que lleva a un aumento del ancho de la playa y del tamaño de los granos de sedimento aguas arriba y un proceso inverso aguas abajo, generando un comportamiento morfodinámico distinto.

Palabras clave: *evolución costera; ancho de playa; tamaño de grano; antropización costera; Golfo de Rosas; Noroeste del Mediterráneo.*

1. Introduction

The central concept of coastal morphodynamics revolves around the interplay between morphology and sedimentology (Wright & Thom, 1977). This interaction involves both positive and negative feedback loops, ultimately striving for an equilibrium that is seldom attained, driving changes across diverse temporal and spatial scales. Despite their susceptibility to natural and anthropogenic influences, coastal environments possess significant resilience, owing in part to transitional areas like wetlands and dune systems. However, disturbances like storms or human activities related to climate change and coastal planning respectively, can lead to sediment loss and beach erosion. Given that 37% of the global population depends on coastal resources (UN, 2017), coastal erosion has emerged as a critical issue in territorial planning and monitoring becomes imperative, especially in urbanized coastlines with substantial tourist activity, Understanding, defining, and evaluating coastal processes are then essential to mitigate the adverse impacts of coastal anthropization.

This study focuses on describing morpho-sedimentological changes along the beaches of the northern sector of the Gulf of Roses, where anthropogenic interventions exhibit progressive intensification from south to north. To achieve this goal, a morphological analysis employing GIS tools was conducted to identify short to medium-term variations in the coast between 2004 and 2020. The year 2004 has been selected as the initial date of the analysis because the last analysis prepared by the LVCC (GC, 2010) was for the period 1997-2004. In addition, a sedimentological analysis was performed to discern trends in grain size distribution across the study area.

2. Area of study

The Gulf of Roses is the largest and most extensive bay in the northeast of the Iberian Peninsula (Fig. 1). This gulf has a total coastline length of 25 km and is bounded by two rocky promontories, Cap de Creus to the north and the Montgrí massif to the south. The gulf is part of the Empordà basin located at the North Catalan Margin, an environment with a preferential deposition of alluvial materials from the main rivers: the Fluvià and the Muga rivers.

The study area focuses on the northern sector of the Gulf of Roses (Figure 1), covering a length of 10 km, bounded to the south by the mouth of the Fluvià River and to the north by the breakwater of the Port of Roses. They comprise natural beaches in the south and urban beaches in the north. The beaches are listed in Table 1 following their spatial order, from south to north: (1) Can Comes, (2) Empuriabrava, (3) La Rovina, (4) Santa Margarida, (5) El Salatar, (6) El Rastrell, (7) La Nova, and (8) La Punta. Table 1 outlines the main morphological characteristics of the different beaches studied.

The study area's location and the presence of Cap de Creus and Montgrí Massif promontories (Figure 1) mean that the ENE-SSE component (70º-160º) significantly impacts the coastal drift of the examined beaches. Statistical analysis of wave conditions in the region reveals that significant wave height (Hs) is below 1 m 76% of the time, with a peak period (Tp) ranging between 5 and 6 seconds. The highest recorded Hs was 7.0 meters in January 2020 during the Gloria storm. Longitudinal sediment transport, especially from waves originating in the second quadrant, mobilizes sediments from south to north along the coastline. According to the LVCC (GC, 2010), the net rates of longitudinal transport estimated using the CERC model for the Gulf of Roses exhibit rates from 81,900 $m^3 \bullet y^{-1}$ in the central area to 64,200 $m^3 \bullet y^{-1}$ in the southern zone and, only 3,700 $m^3 \bullet y^{-1}$ in the northern zone.

3. Materials and methods

The quantitative analysis of the variations of the coastline has been carried out using a Geographic Information System (GIS). The analysis has been made by two methodologies: (1) the calculation by transects of the rates of variation of the width of the beaches based on the DSAS 4.0 extension (Digital Shoreline Analysis System) developed by the USGS (Thieler et al. 2009) within ArcGis ® software; and (2) the calculation by areas, forward and backward with the free software QGIS.

Fig. 1. Location of the study area. Beaches studied and sampling stations (red dots) used for the sedimentological analysis.

Table 1. Length, direction, and width of the differentiated beaches in the study area, see figure 1 for their location. The number of transects studied and the sediment sampling stations on the beaches studied are also indicated.

Beach	Length (km)	Direction (º to N)	Width (m)	Number of DSAS transects	Sediment Sampling Stations
Can Comes	3.94	18	87.05	38	25-36
Empuriabrava	1.30	35	95.74	13	21-24
La Rovina	1.79	44	73.21	18	15-20
Sta. Margarida	0.61	58	42.16	6	12-14
El Salatar	0.46	68	29.04	4	10-11
El Rastrell	0.46	94	36.54	5	7-9
La Nova	0.80	143	26.30	8	4-6
La Punta	0.50	134	56.59	8	1-3
TOTAL	**9,86**			**110**	

The DSAS allows to calculate the rates of variation and distances between different shorelines from transects. Statistically, there are mainly three parameters that measure the evolution of the coastline: the NSM (Net Shoreline Movement in m); the EPR (End Point Rate in $m \cdot y^{-1}$), and the LRR (Linear Regression Rate in $m \cdot y^{-1}$). The digitization of the coastlineusing QGIS makes it possible to know what the rates of advance or retreats are based on the calculation of areas. From the data on the accretion and erosion surfaces, two parameters like those obtained in the analysis by transects have been calculated: (1) the Areal End Point Rate (EPRa) as the relationship between the total balance and the number of years between the dates considered in $m^2 \cdot y^{-1}$, and (2) the Normalized Areal End Point Rate (EPRna) that consists of the EPRa normalized concerning the length of the considered beach in $m^2 \cdot y^{-1} \cdot m^{-1}$. Orthophotos from the "Cartographic and Geological Institute of Catalonia-ICGC" (years 2004, 2008, 2012, 2016 and 2020), with a resolution of 0.25 $m \cdot pixel^{-1}$, have been used for the digitization of the coastline.

For grain size analysis, 36 sampling stations were established, distributed along the 10 km of the study area. Sampling planning and station location were carried out with the help of GIS tools. The stations were located about 200 meters apart. For each station, 2 samples were taken; one in the area closest to the berm, classified as a dry area; and another closer to the coast, classified as a wetland. The grain size was analysed using Coulter LS 230 particle analyser and mechanical sieving for samples with grain size greater than 2 mm. The statistical treatment and the different granulometric parameters have been obtained by the moment's method from the program Gradistat v9.1 (Blott, S.J. & Pye, K., 2001).

***Table 2**. Summary of Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR), Surfaces of accretion and erosion, the Areal End Point Rate (EPRa) and the Normalized Areal End Point Rate (EPRna) of the studied beaches*

Beach	**NSM (m)**	**EPR** ($m \cdot y^{-1}$)	**LRR** ($m \cdot y^{-1}$)	**Accretion Surface (m^2)**	**Erosion Surface (m^2)**	**Total Balance (m^2)**	**EPRa ($m^2 \cdot y^{-1}$)**	**EPRna ($m \cdot y^{-1}$)**
Can Comes	2.94	0.18	0.40	22,821	-23,242	-421	-26.31	-0.006
Empuriabrava	7.61	0.48	0.53	10,099	-3,951	6,148	384.25	0.30
La Rovina	-4.73	-0.30	-0.35	431	-12.400	-11.969	-746.19	-0.42
Sta. Margarida	-2.06	-0,13	-0.15	225	-3.338	-3.113	-194.56	-0.32
El Salatar	-1.58	-0.10	-0.06	0	-1.095	-1.095	-68.44	-0.15
El Rastrell	-5.04	-0.32	-0.21	0	-2.376	-2.376	-171.00	-0.37
La Nova	-3.04	-0.19	-0.13	49	-3.610	-3.560	-222.50	-0.28
La Punta	-9.21	-0.58	-0.43	203	-4.627	-4.424	-276.50	-0.55
				33,828	**54,638**	**-20,810**		

4. Results

The results of the different morphological analysis carried out by trancsects NSM, EPR and LRR, using ArcGIS-DSAS, and by Surfaces of Accretion and Erosion, the Areal End Point Rate (EPRa) and the Normalized Areal End Point Rate (EPRna), using QGis, are presented in Table 2.

The sediments of the dry beach broadly exhibit higher mean and standard deviation (SD) values compared to those of the wet beach (Table 3). Conversely, La Punta beach exhibits the lowest mean and SD values for both dry and wet locations. When examining the spatial evolution of the samples analyzed for each beach at the two sampling stations (wet beach and dry beach), a general decrease in grain size due to sediment transport toward the north is noted. However, the beaches of Empuriabrava and La Rovina, situated in the central zone between kilometers 4 and 7, exhibit different behaviors.

5. Discussion

For the transects study, EPR (End Point Rate) and LRR (Linear Regression Rate) parameters exhibited very similar values, this suggest that these two parameters indicates that they both reflect the same processes influencing the evolution of the coastline. Empuriabrava Beach exhibited the highest values for EPR and LRR, measuring 0.48 and 0.53 $m \cdot y^{-1}$, respectively. These maximum values can be attributed to the presence of the jetties of the marina habours, which serve as boundaries for the beach. Conversely, the lowest values for EPR and LRR coincide in the northern portion of the study area, specifically at La Punta Beach, with measurements of -0.58 and -0.43 $m \cdot y^{-1}$, respectively.

Table 3. *Values of the grain size parameters of studied beaches. N= number of sampled profiles; Mean (µm); SD: Standard Deviation; CV: Coefficient of Variation.*

		WET BEACH			DRY BEACH		
Beach	**N**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Can Comes	12	421,25	155,27	0,37	505,50	235,75	0,47
Empuriabrava	4	745,25	473,75	0,64	985,50	768,00	0,78
La Rovina	6	497,17	322,33	0,65	1171,50	1027,67	0,88
Sta. Margarida	3	446,00	233,67	0,52	519,00	321,67	0,62
El Salatar	1	476,00	260,00	0,55	479,00	425,00	0,89
El Rastrell	2	338,00	125,50	0,37	441,00	279,00	0,63
La Nova	5	307,60	111,04	0,36	358,20	221,60	0,62
La Punta	3	264,00	106,83	0,40	237,00	110,50	0,47

The areal study experienced an overall net loss of -20,810 m^2, with a gain of 33,828 m^2 in surface area and a loss of 54,638 m^2. Only Empuriabrava Beach showed a net gain in surface area of 6,148 m^2 and a EPRa of 0.30 $m^2 \cdot y^{-1}$. Can Comes each had a net balance closest to 0, with a net loss of -421 m^2 that results in a EPRan of -0.006 $m \cdot y^{-1}$. The remaining beaches exhibited a negative net area balance. La Rovina Beach suffered the most significant surface area loss of approximately 12,000 m^2 (EPRan of -0.42 $m \cdot y^{-1}$) between 2004-20 (Table 2).

The grain size distribution, shows a decrease in grain size as distance increases from the Fluvià river mouth, mainly in samples obtained from the wet zone. The relationship between the standard deviation (SD) and the mean of the samples from the wet zone, the lower means are associated with lower standar deviation values, which suggests that sediments that have undergone extensive transportation are more well-sorted and classified. This transport occurs through different accretion bulges or sediment waves, that are observable in the beaches of Can Comes and Empuriabrava. Similar processes have been described in natural areas such as the Ebro River Delta (Guillén & Jiménez, 1995) or in areas affected by artificial nourishment projects (Guillén & Hoekstra, 1997; Huisman et al., 2016).

The Empuriabrava Beach has the highest accretion rates and the largest grain sizes in the study area. This can be attributed to a combination of factors, including its proximity to sediment contributions from the Muga River, the northern direction of sediment drift, and the presence of a jetty located at its northern boundary, which acts as the first barrier in the study area, initiating the fragmentation of the coastal drift. It is responsible for the accumulation of coarse sediments and the subsequent increase in accretion on the Empuriabrava Beach. The Rovina Beach, has experienced the highest rates of erosion. The presence of two jetties enclosing the beach may worsen the retreat of the coastline. There is a reduction in grain size between Empuriabrava and La Rovina. This decrease is attributed to the location of the jetties, which encourage the deposition of coarser material and disrupt the coastal drift. As an example of the impact of anthropogenic structures on grain size evolution, the grain size between the south side and the north side of the structures shows an increase (gap) in grain size reduction. The beaches near the urban area of Roses are all receding, with La Punta, La Nova, and Rastrell being the most severely impacted by coastal erosion. These beaches have fine grain sizes due to their distance from the primary sediment entry points in the region and the presence of breakwaters that impede the transportation of coarser material. They are the beaches in the study area with the finest and most well-classified sediment. In La Punta Beach, anthropization and fine grain size can exacerbate its vulnerability to erosion.

6. Conclusions

Changes in beach width and granulometric properties reflect the impact of various man-made structures on the morphodynamic behaviour of each beach segment. The jetties at the entrance to the Marina of Empuriabrava, between the beaches of Empuriabrava and La Rovina, is the starting point for the interruption of the littoral drift and sediment transport restriction. This results in the accumulation and preferential deposition of coarse-grained sediments on the Empuriabrava Beach, while erosion and a decrease in grain size occur on the La Rovina Beach to the north of the breakwater. This process of increasing grain size is also observed along the Rovina Beach. Changes in grain size towards the north can have implications for overall beach stability.

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