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Long-shore distribution of morphodynamic beach states along an apparently homogeneous coast in SW Spain

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Abstract. We present a morphodynamic study of an apparently homogeneous rectilinear coast in SW Spain. The study area covers 14 km of mesotidal sandy beaches, interrupted in some places by rocky-shore platforms. The method used consisted of a monthly monitoring of 12 beach profiles during two years. According to the results obtained from the study, which also include granulometric analyses and *in situ* determination of the beach disturbance depth, three main beach classes have been differentiated: low-reflective beaches, dissipative beaches and rocky-shore platform beaches. Their longitudinal distribution is not linked to their distance to the main source of sediments in the area (mouth of the river Guadalquivir). Instead, a very irregular long-shore variation of morphodynamic beach states appears. It is deduced that this long-shore variation is mainly linked to local contouring conditions (e.g. the presence of rocky shoals which affect wave-breaking processes), and not to the regional long-shore currents prevailing in the zone.

Keywords: Chipiona; Dissipative; Low-reflective; Rocky-shore platform; Rota; Surf scaling; Surf similarity.

Introduction

Human interest in coastal areas has been growing during the last decades and nowadays about two-thirds of the World population live within this narrow belt. In Spain the good weather conditions make the coastal environment very attractive for several months per year and beaches have become an important economic resource. As a result, the recreational use of beaches has substantially increased and many man-made structures have been built quite close to the shoreline and are now threatened by coastal retreat.

The study area is located in the Gulf of Cadiz (SW Spain) and consists of a linear coast formed by natural and urban beaches between Chipiona and Rota (Fig. 1). The natural beaches are well developed and occupy the central sector of the littoral. At present they are threatened by the construction of summerhouses and other man-made structures, which lead to a progressive environmental degradation (Muñoz & Gutiérrez 1999). The second ones prevail in the North (Regla beach, Chipiona) and in the South (La Costilla beach, Rota), being backed by promenades and apartment buildings. Traditional environmentally friendly activities as salt harvesting and fish farms are developed in salt marshes close to the river Guadalete (Fig. 1), while agriculture, farming and traditional fishing prevail in the coastal zone between Chipiona and Rota.

During the last decades, the whole littoral experienced retreat rates greater than 1 m/yr (Muñoz & Enríquez 1998). This retreat is counteracted in some places by protective plans, mainly consisting of beach nourishment, sometimes accompanied by the construction of small jetties. In general, the nourishment works have had limited durability due to different causes (Anfuso et al. 2001), mainly because the lack of information on the environmental dynamics.

Coastal environments and shoreline orientation are broadly constant along the studied zone, without any significant break or change in the general geomorphological characteristics of the beaches. However, this apparently homogeneous coast suffers very different rates of coastal retreat and beach changes along-shore, indicating the complexity of the coastal processes acting on the zone, and the existence of important non-evident factors controlling beach dynamics.

In order to prevent or solve erosive problems and better manage coastal resources, it is important to understand the littoral morphodynamic behaviour. The present paper represents a first step in this direction, through a beach monitoring program in order to evaluate the long-shore distribution of beach morphologies and estimate the associated littoral dynamics.

Field sites

The area between Chipiona and Rota (Fig. 1) includes 14 km of a southwest- facing coast, interrupted, in places, by intertidal rocky-shore platforms. The beaches are composed of quartz-rich medium to fine sands,

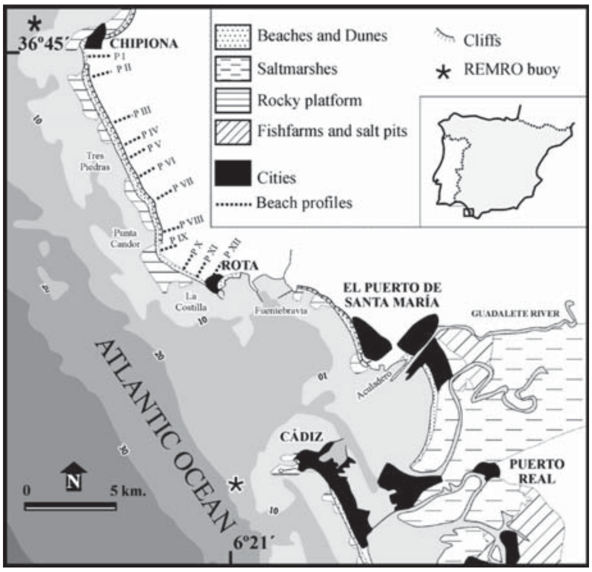

Fig. 1. Location map of the studied zone with the most important coastal environments. Modified from Anfuso et al. (2001).

moderately well sorted. They are commonly backed by dune ridges and eroded cliffs cut into Plio-Quaternary clays, sandstones and conglomerates. The mean fluvial sources of sediment are the rivers Guadalquivir and Guadalete, located north and south of the studied zone, respectively. According to Muñoz & Enríquez (1998) the sedimentary supplies of these two rivers are not very important and the littoral acts as an independent sector in which sediments proceed from the submerged beach.

The coast is a semi-diurnal mesotidal environment with 3.2 m of mean spring and 1.1 m of mean neap tidal ranges. The area is affected by westerly winds associated with Atlantic fronts and by southeasterly winds coming through the Strait of Gibraltar. Incidental waves generally approach from the west with an average wave height of both sea and swell waves less than 1 m (Reyes et al. 1999). Dominant littoral drift is associated with Atlantic wave fronts and moves to the south. However, an opposite long-shore current is also detectable during brief but strong periods of southeasterly winds, especially in the southern sector of the area, due to its orientation (ESE-WNW; Fig. 2).

The studied littoral shows a great and apparently accidental long-shore variation in beach slope and width, not related to local contouring conditions or local sedimentary inputs.

Methods

A beach monitoring program was effected from 1996 to 1998. An electronic theodolite was used to survey beach profiles once a month at fixed points from the backshore to a closure depth equivalent to the mean spring tide low water level. The treatment of the topographic data led to the calculation of beach gradients and morphology, and the estimation of lost/gained volumes of sand. Samples of beach sediment were collected and analysed by dry sieving in the laboratory using a nest of sieves at 1.0 ϕ intervals, and granulometric parameters were calculated according to Folk & Ward (1957). Several field assessments were carried out to evaluate small topographic changes in the foreshore

Fig. 2. The SSW facing coast between Punta Candor (P. IX) and Rota (P. XII), see Fig. 1. The rocky-shore platform is quite extended in P. Candor (upper-left side in the picture), and a small groin limits south-eastward La Costilla beach (lower-central part in the picture). Obtained from Demarcación de Costa, Spanish Ministry of Environment.

and, at the same time, the disturbance depth. This is the thickness of the bottom layer affected by hydrodynamic processes during a tidal cycle (Williams 1971; Jackson & Nordstrom 1993; Anfuso et al. 2000).

Wave data were obtained from a near offshore buoy of the Spanish Sea Wave Recording Network (REMRO) and estimated in the surf zone during the field assessments with a metric pole. Breaking wave height (H_b) was obtained according to Komar & Gaughan (1972), by considering the mean wave height of the month prior to the beach profiling (Benavente et al. 2000).

A classification according to Masselink & Short (1993) was applied to classify the morphodynamic state of the studied beaches. For this purpose, the relative tidal range (Davis & Hayes 1984) was calculated. Other parameters widely used in coastal engineering and based on beach and grain size characteristics ($\tan\beta$ = beach slope, W_s = settling velocity of sediment) and wave data (H_b = breaking wave height, T = wave period) were also used. The Surf scaling parameter (Guza & Inman 1975), the Surf similarity parameter (Battjes 1974) and Dean's number (Dean 1973).

The Surf scaling parameter, is indicated as ε:

$$\varepsilon = (2\pi^2 H_b) / (gT^2 \tan^2\beta) \qquad (1)$$

Surf zone conditions may be differentiated into reflective ($\varepsilon < 2.5$), intermediate ($2.5 < \varepsilon < 20$) and dissipative ($\varepsilon > 20$) (Carter 1988).

The Surf similarity parameter, ξ, follows from:

$$\xi = \tan\beta / (H_b/L_0)^{0.5} \qquad (2)$$

It predicts the type of wave breaking. One usually differentiates between surging ($\xi > 2$), plunging ($0.4 < \xi < 2$) and spilling breakers ($\xi < 0.4$) (Fredsoe & Deigaard 1992).

Dean's number is a dimensionless parameter proposed by Gourlay (1968) and Dean (1973), that incorporates both wave and sediment characteristics:

$$\Omega = H_b / (W_s T) \qquad (3)$$

where W_s is the fall velocity of the sediment. It predicts the beach morphodynamic state, from reflective ($\Omega < 1$), intermediate ($1 < \Omega < 6$) to dissipative states ($\Omega > 6$) (Wright et al. 1985).

Results

Wave climate

Wave height and period obtained from the buoy presented an important seasonal variation. Higher waves were observed in November, December and January and secondly during spring, while lower values were common in February-March and in summer (Fig. 3 a).

Wave period (Fig. 3 b) presented higher values in winter, intermediate values in autumn and spring and lower values in summer. Moreover, wave period was not related to wave height, as Benavente et al. (2000) observed at a neighbouring coast, indicating that this is not a good tool to characterize wave types in this coastal

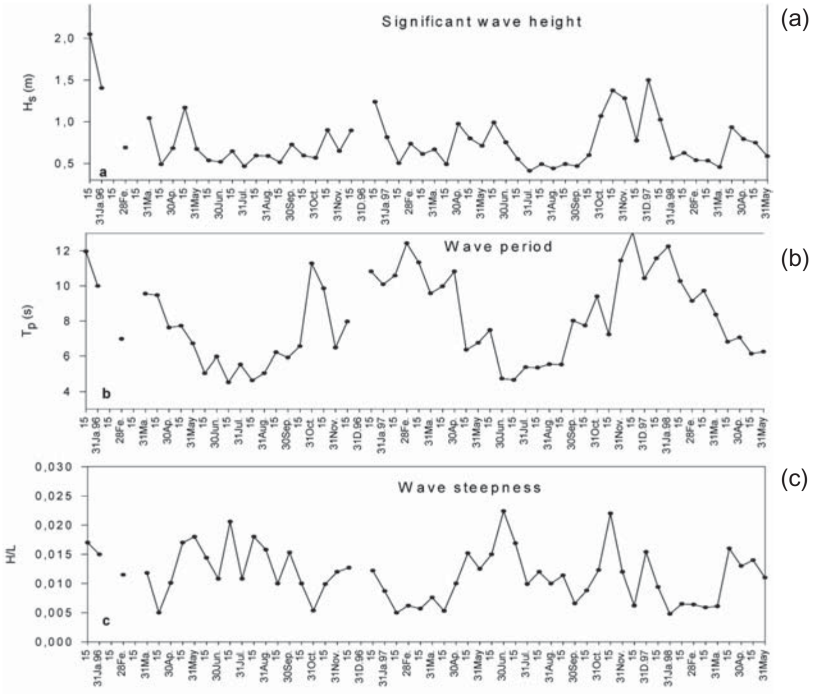

Fig. 3. Wave climate distribution during the studied period: **(a)** significant wave height; **(b)** peak wave period; **(c)** wave steepness (wave height/wave length).

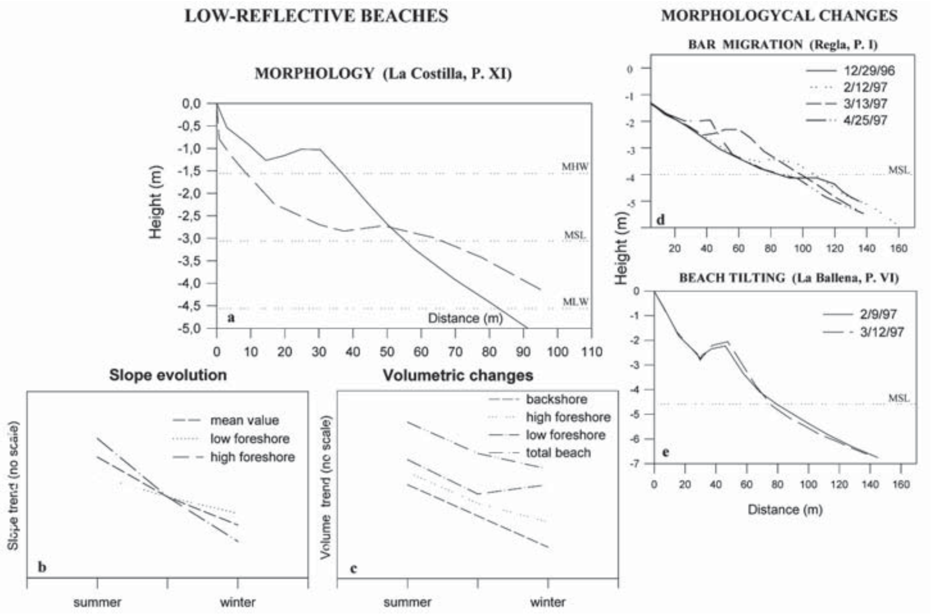

Fig. 4. Low-reflective beaches: **(a)** morphological behaviour; **(b)** seasonal slope changes; **(c)** volumetric evolution; **(d)** morphological changes through bar migration; **(e)** beach tilting. MHW = Mean high water level; MSL = Mean sea level; MLW = mean low water level.

region. Indeed, wave steepness showed an irregular behaviour (Fig. 3 c). No trend was observable in 1996 and a small trend was visible in 1997 and 1998: low values, associated to swell waves, usually characterized February-March and the summer period, while higher values, associated to sea waves, prevailed in autumn and spring.

Beach morphology and sediment

Beach morphology and sand volumetric changes reflected a great seasonal variation according to wave climate distribution. More erosive beach states were observed in November-December and more constructive states in September-October and in February-March, due to fair weather conditions. In general, erosion affected at the same time all the beaches, with a sediment shift from the backshore and the foreshore to the low foreshore

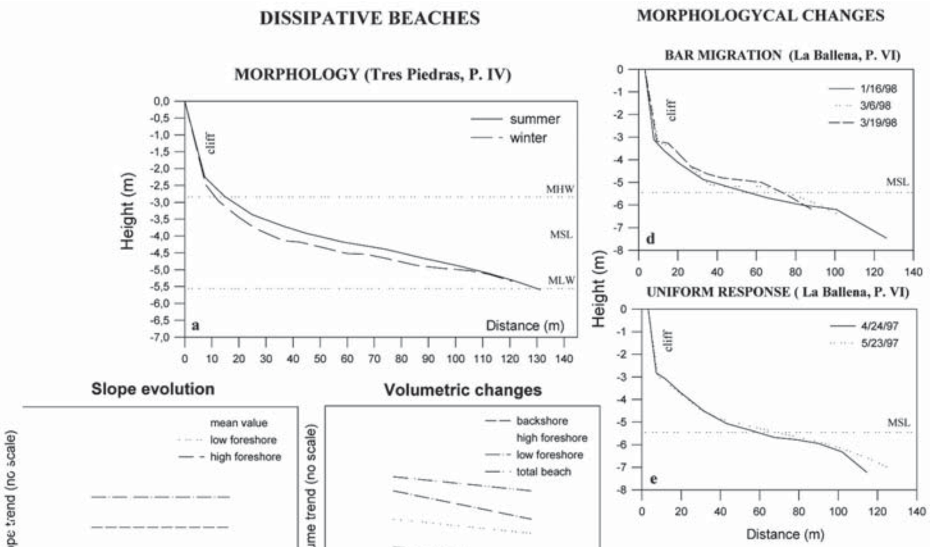

Fig. 5. Dissipative beaches: (**a**) morphological behaviour; **(b)** seasonal slope change; **(c)** volumetric evolution; **(d)** morphological changes through bar migration; **(e)** uniform response.

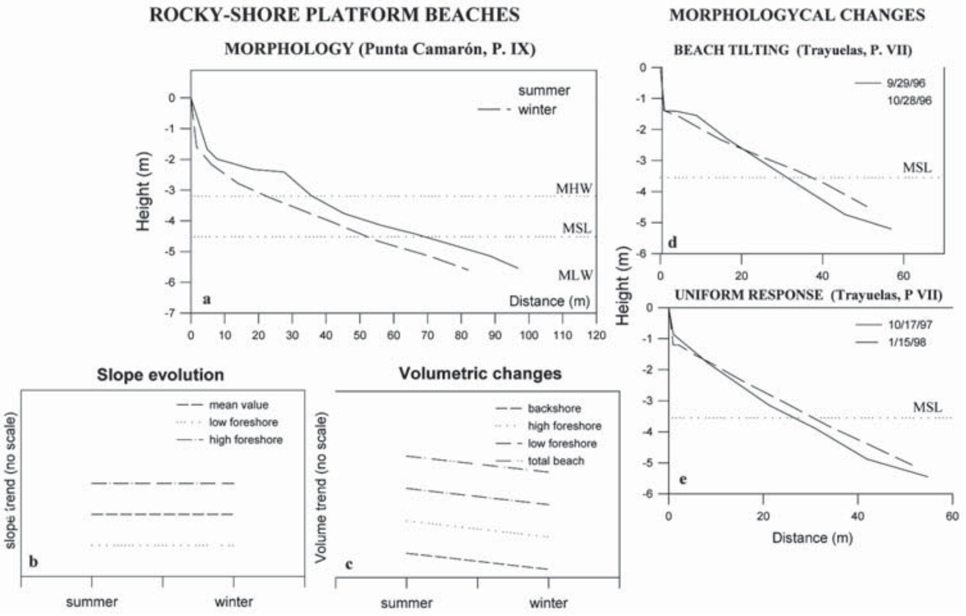

Fig. 6. Rocky-shore platform beaches: morphological behaviour **(a)**, seasonal slope change **(b)**, volumetric evolution **(c)**, morphological changes through beach tilting **(d)** and uniform response **(e)**.

and/or the near-shore. Only in few cases a soft long-shore transport was evident.

Beach sediment was composed of medium to fine sand, with coarser sediments prevailing during winter and finer sediments in summer, with average seasonal differences of 0.5 phi. A very small long-shore variation in grain size was observed.

Morphological groups

The studied beaches have been grouped in three classes, taking into account beach morphology, slope and seasonal beach states: low-reflective, dissipative and rocky-shore platform beaches.

Low-reflective beaches (PI, PVI, PVIII and PXI) presented important seasonal changes according to Shepard (1950), Bascom (1951) and Nordstrom & Jackson (1992). In summer they showed a steep slope, especially in the upper foreshore, with a well developed berm. In winter a smooth profile prevailed, with a greater slope at the low foreshore (Fig. 4 a, b). When these beaches presented a homogeneous slope waves affected the whole foreshore. Volumetric changes took place with a tilting point around the mean sea level: sand moved from the backshore and high foreshore to the low foreshore (Fig. 4 c). Bars were quite common and constituted the most important way of beach restoration, although a pivoting process was observed in some cases (Fig. 4 d, e).

The disturbance depth, evaluated through several field assessments, was relatively high (15% H_b) and related to plunging breakers.

Dissipative beaches (P IV and P V) experienced smaller topographic seasonal changes (Fig. 5 a). The upper foreshore presented a greater slope, related to the confining role of the cliff and the prevalence of aeolian sand transport. Beach slope was homogeneous along the foreshore (Fig. 5 b). Bars were recorded in the middle and low foreshore, giving rise to important volumetric changes (Fig. 5 c) but never forming a berm. Morphological changes took place through bar migration or homogenously along the foreshore (Fig. 5 d, e).

Disturbance depth was quite small (4% H_b) and uniform, always associated to spilling breakers.

Rocky-shore platform beaches (P II, P III, P VII, P IX, P X and P XII) recorded small topographic and morphologic seasonal variations (Fig. 6 a). Beach slope and erosion/accretion processes took place homogenously along the beach profile (Fig. 6 b, c). Erosive processes affected the whole beach giving rise (Fig. 6 e) to a parallel retreat (Nordstrom & Jackson 1992). However, when a berm was present (always of small dimensions), a tilting in the mean high water level took place (Fig. 6 d). Few bars were observed.

No field assessments were carried out to quantify disturbance depth, although high values are expected to occur on these beaches, due to the important foreshore slope.

These beaches are quite close to the ones described by Nordstrom & Jackson (1992) in Raritan and Delaware bays (New Jersey, USA) and their morphology could be linked to a prevalence of long-shore over crosshore transport. Muñoz & Enríquez (1998) stated that their low change rates are related to the presence of a rocky platform that acts as a breakwater dissipating wave energy far from the beach. In this case only the strongest storms heavily affect the coast and sand is shifted offshore over the platform.

Pictures of the three studied beach types are presented in Fig. 7. A berm characterizes the low-reflective beach (a), a smooth intertidal slope the dissipative one (b) and a wide rocky shore platform and a small foreshore, the rocky platform beach (c).

Fig. 7. Photographs of **(a)** a low reflective beach, Aguadulce – P. VI; **(b)** a dissipative beach, Tres Piedras – P. IV; **(c)** a rocky-shore beach, Peginas – P. VII.

Morphodynamic characteristics

Tidal range along the studied littoral does not change significantly, and most of the surveyed profiles belong to the 'dissipative with bar' and 'intermediate with bar' states of the Masselink & Short (1993) classification.

Mean values of Dean's number, Surf similarity and Surf scaling for the different beach classes are presented in Table 1 and Surf similarity development in Fig. 8.

Morphodynamic parameters reflect quite well the visually observed morphologies and breaking wave types as well as their seasonal variations. However, the observed limits do not coincide exactly with the limits proposed by others (Wright et al. 1985; Carter 1988).

Dean's Number classifies all the dissipative and low-reflective beaches of the zone as 'intermediate' during summer or fair weather conditions, and as 'intermediate-dissipative' during winter.

The Surf Similarity parameter presents low values close to the limit between plunging and spilling breakers. In general, spilling breakers characterize all the studied beaches during most part of the year and plunging prevails during fair weather conditions (Figs. 3 and 8).

Dissipative beaches (P IV and P V, Fig. 8 b), do not present seasonal changes in breaking wave type, while low-reflective beaches show strong seasonal variations due to foreshore slope evolution (P XI, Fig. 8 d). Finally, the steeper rocky-shore platform beaches usually present a prevalence of plunging breakers (P XII, Fig. 8 d).

The Surf scaling parameter, strictly derived from the former one, characterizes most beaches as 'intermediate' and presents important seasonal variations: more dissipative values are obtained in November-December and in April-May.

Table 1. Morphodynamic parameters applied to the obtained beach classes.

Beach class	Slope (tan β)	Foreshore width (m)	Grain size (mm)	Ω^1 Summer/winter	ξ^2 Summer/winter	ε^3 summer/winter
Dissipative	0.03	120	0.25	4.37/5.6	0.22/0.21	26.7/21.3
Low-reflective	0.046^4	80	0.28	3.56/4.63	0.40/0.27	10.0/16.7
Rocky-shore platform	0.054	50-70	0.26^5	4.28/4.7	0.46/0.36	11.5/17.1

[1] Dean's number; [2] Surf similarity; [3] Surf scaling; [4] Shows great seasonal oscillation, from 0.037 to 0.056; [5] Ranging from 0.20 to 0.33.

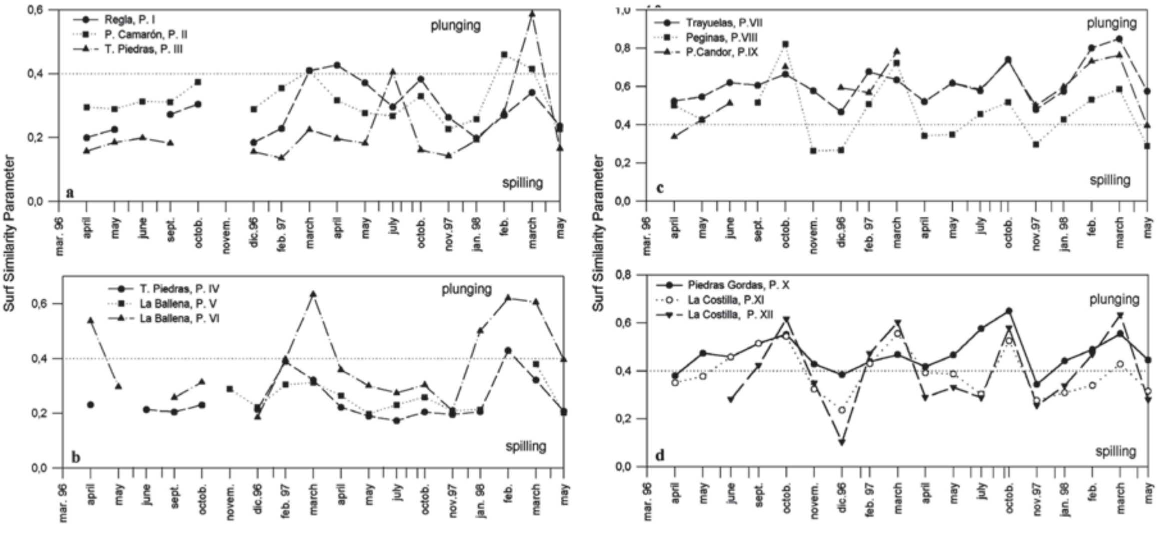

Fig. 8. Surf Similarity parameter evolution of the beach profiles during the studied period.

Discussion and Conclusions

The beach monitoring program has permitted an approach to the morphological behaviour, volumetric changes and long-shore distribution of the studied beaches (Fig. 9). A great long-shore variability in beach class is detectable. It is neither related to long-shore variations in sediment grain size, nor linked to local sedimentary inputs. So, beach class location could be related to the wave energy distribution along the coastline. This factor is directly linked to bathymetric characteristics that control wave propagation, as well as to other local bathymetric contouring conditions that act as submerged limits, dividing the coast into littoral cells in the sense of Carter (1988). According to Anfuso (2002), more detailed studies are required in order to reconstruct littoral cells distribution, their relationships with bathymetric morphologies and their spatial and temporal variations. Moreover, first results in this way explain in part the observed beach classes' long-shore distribution. Low-reflective beaches present a wide spreading along the littoral, and prevails updrift of natural or artificial structures, dissipative beaches occupy the central part of the littoral, probably more exposed to wave fronts, and rocky-shore platform beaches appear where the rocky substratum outcrops, in zones located between adjacent cells.

This study has also permitted to individualize the temporal trends of the coast: low-reflective beaches experienced accretion; rocky-shore platform beaches generally recorded small erosion and dissipative beaches did not show a definite tendency. This trend was linked to the dominance of SE winds and waves that generated a northwestward drift. Volumes involved in the littoral dynamics were evaluated and spatial and temporal distribution of bars was also obtained.

All the information collected in the present study is very useful for a better knowledge and management of coastal erosion/accretion processes and also for littoral planning. Data on beach morphodynamic behaviour and long-shore transport can be used to opportunely design a nourishment project, i.e. to decide the best artificial beach profile class and the best season to intervene in each case.

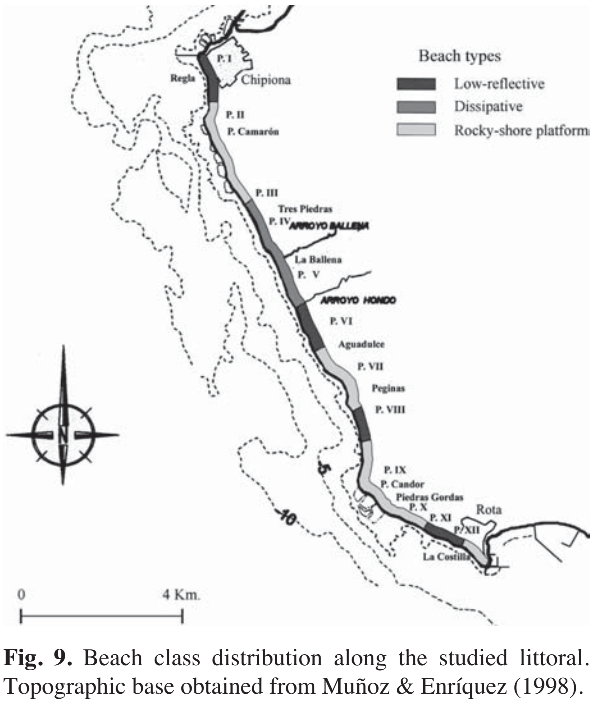

Fig. 9. Beach class distribution along the studied littoral. Topographic base obtained from Muñoz & Enríquez (1998).

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