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The application of morphodynamic indices to exposed beaches of Cadiz Bay

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ABSTRACT

The aim of the present paper is to assess the validity of several energetic, morphological and morphodynamic indices, and their application to Vistahermosa and La Barrosa beaches (Cadiz Bay), as a preliminary attempt to establish the morphodynamic behaviour of these coastal zones. Earlier studies have used some of these indices, while others are completely new. All of them are involve the integration of field data, topographic restitution and granulometric analysis, as well as instrumental wave monitoring during a complete seasonal cycle. Although a good general behaviour of the indices can be concluded, the addition of high-energy data from storm events should be included in future studies.

Key words: Morphodynamics indices, exposed beaches, Cadiz Bay.

RESUMEN

Aplicación de índices morfodinámicos a playas expuestas de la bahía de Cádiz

En el presente trabajo se valora la adecuación de diversos índices energéticos, morfológicos y morfodinámicos a las playas de Vistahermosa y La Barrosa como paso previo al establecimiento del comportamiento morfodinámico de las mismas. Estudios anteriores han empleado algunos de esos índices, mientras otros son totalmente nuevos. Estos índices se construyen mediante la integración de datos de campo, restitución topográfica y análisis granulométrico, y con datos instrumentales de oleaje a lo largo de un ciclo estacional completo. Aunque la valoración general del funcionamiento de los índices aplicados es buena, se concluye la necesidad de incluir situaciones energéticas de temporal en análisis ulteriores.

Palabras clave: *Índices morfodinámicos, playas expuestas, bahía de Cádiz.*

INTRODUCTION

To fully understand beach behaviour and beach evolution it is necessary to relate the energetic conditions with the observed morphodynamic stages. Thus, the application of different indices related to coastal processes makes it possible to integrate a wide range of variables (e.g., energetic, textural, sedimentary, morphologic), simplifying this relationship and the comprehension of these processes. There are several examples of the use of indices for classifying processes and morphodynamic stages. One of these is Dean's parameter, W (1973). This index reflects the beach's tendency towards equilibrium-disequilibrium. Sunamura's parameter, k (1986), relates the cross-shore transport and the tendency towards bar formation. Masselink and Short (1993) proposed a morphodynamic classification for beach based on Dean's parameter and the relative tide range (RTR).

But the dominion for the application of these indices does not exactly match the general energetic conditions or even the tidal range found in the beaches of Cadiz Bay. Therefore, we have applied another series of parameters, of an energetic, morphologic and morphodynamic nature; some of them have been described previously, while others are completely new.

Study area

- Vistahermosa beach is an exposed, lineal beach with a general north-northwest/south-southeast orientation, located north of Cadiz Bay. It has a total length of about 1.5 km, and a mean dry beach width (above mean sea level) of 50 m, with an overall slope of 0.053, measured in the intertidal area. The backshore zone has experienced high anthropogenic impact, with only a residual dune ridge on its central part. A rocky platform constitutes the meridional limit. It shows seasonal behaviour, with alternative dissipative and reflective stages.
- Santa Catalina and La Puntilla beaches, both located south of Vistahermosa (figure 1), are pocket beaches. The first one has a total length of 250 m, with a dry beach width of 45 m and a higher slope (0.061) than in the previous case, and it is closed by a back cliff. The second one is located in a little bay made up with breakwaters and shows a length of 700 m, a dry beach width of over 100 m and a small intertidal slope (0.026). None of them presented seasonal behaviour during the survey period.
- La Barrosa beach is located south of Cadiz Bay (figure 1), with a general northwest/southeast orientation. It develops a downdrift off La Barrosa cliff, to the north. Its total length is 3 km, but with two different sectors: the northern sector, approximately 1 km, comprises a promenade with a high degree of urban development and a dry beach width of 40-50 m. This sector was nourished with an amount of 500 000 m^3 in late 1994. The southern sector shows a dune ridge with lower human occupation and a dry beach width of 10 m, or even less. The mean slope is intermediate (0.035), although higher in the promenade sector than in the dune ridge sector. From a morphodynamic point of view, and although La Barrosa shows seasonal behaviour with accreted profiles in summer and erosive profiles in winter, it has a noteworthy dissipative trend, often showing typical morphologies of intermediate stages in its intertidal zone.

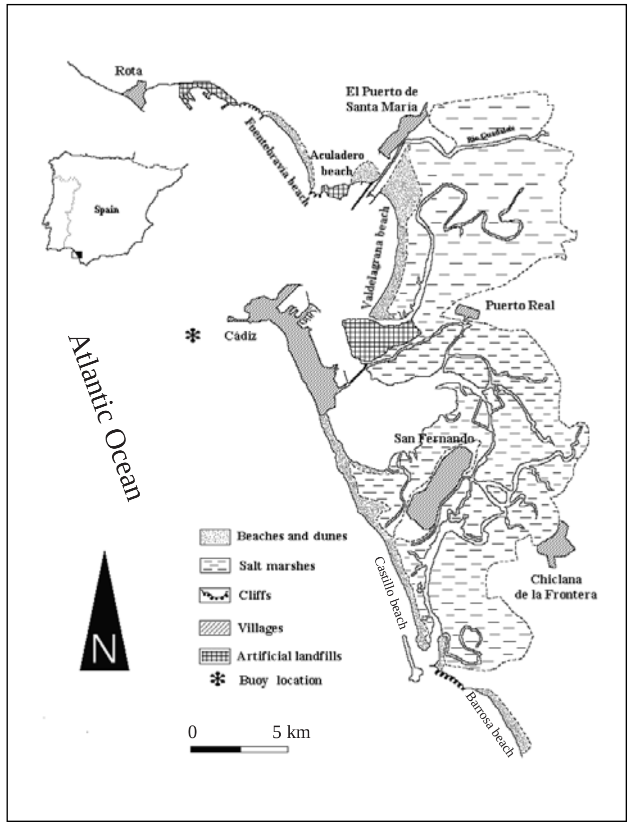

Figure 1. Location map

MATERIALS AND METHODS

Field data were obtained during monthly beach-monitoring campaigns by profiling surveys from winter 1995 to winter 1996. The number of profiles was of 15 for La Barrosa beach, 5 for Vistahermosa, 3 for Santa Catalina, and 7 for La Puntilla. During these campaigns, 3 sand samples were collected in the intertidal zone of each profile. The morphological and sedimentary variables have been used in previous survey studies of Cadiz Bay beaches by the authors (Benavente, 1997; Reyes, 1997).

In these studies, the beaches were monitored monthly for 13 months, with weekly monitoring during certain periods.

The wave variables were provided by State Ports of Spain (an agency of the Public Works Ministry), and other data were obtained from the offshore buoy *Cádiz*.

Description of indices

Each index is analysed below, divided into three groups: energetic indices, morphological indices and morphodynamic indices.

Energetic indices

- Wave range (WR): This parameter shows the erosional or depositional character of incident waves. Its expression is: WR = Hs/Tz, where Hs is the significant wave height and Tz is the zero crossing period. This expression was deduced from the dimensionless grain fall velocity parameter, suggested by Dean (1973). D_{50} was considered constant, because during the study period it showed slight variation range.
- Energetic density (E): This parameter has been widely used in coastal studies (Carr, Blackley and Ring, 1982; Oyegun, 1991) and enabled us to clearly characterise the wave's energetic evolution throughout the study period and in the study zone.
- Erosivity (FE): This index shows the erosive capacity of incident waves. This parameter results from multiplying the two preceding parameters (Benavente, 1997).

Morphological indices

- Intertidal slope (tan b): This is a direct index, widely used in beach studies (Orford, 1977; Hardisty, 1986).
- Accumulated volume (Q): It has been employed to calculate and compare, from mean profiles, the amount of sand per lineal meter of beach, only considered up to the mean sea level.
- IQ index: It considers, in addition to the accumulated volume of each profile (Q), the volume of an erosive profile, which is described by an exponential function with a slope in the origin of 0.12, and a concavity constant, K, of 0.0145, compared in each case with the volume of the profiles. Thus, when the index IQ is equal to 0, profile is erosive, and when it is equal to or greater than 1, the profile is accumulative.
- Erodibility (FR): This is the capability of a profile to be eroded or built up, as a function of its morphological and sedimentary characteristics (Benavente, 1977).

Morphodynamic indices

- Morphodynamic situation (SM): This parameter shows the erosive or accumulative trend that the beach presents as a function of its own characteristics, as well as the characteristics of the incident waves. It is equal to the erodibility for a fixed moment multiplied by the wave erosivity for a fixed period of time (Benavente, 1997).
- Sunamura parameter or index: This has been used by some authors to show the erosive or aggradational trend of a profile (Sunamura, 1986) and to show bar formation (Muñoz-Pérez and Fages, 1993). This parameter relates bathymetric slope, medium grain size, wave height and wavelength.

RESULTS

Vistahermosa

To study the characteristics of the incident waves, the WR parameter was used for this zone, calculated from wave data for 1995. We can observe the results obtained for the evolution of the energetic density (figure 2, where only the value of Hs^2 is represented) and wave height, compared with the evolution of WR. It can be seen how the evolution of the latter is different from the other two.

During the study period, daily visual observations of the state of the sea were made, on a nearby beach running in the same direction. Figure 2 shows the main storm, calm and swell periods. It can be seen how the peaks of WR greater than 0.3 correspond to storm conditions, while the lowest values correspond to swell or calm conditions.

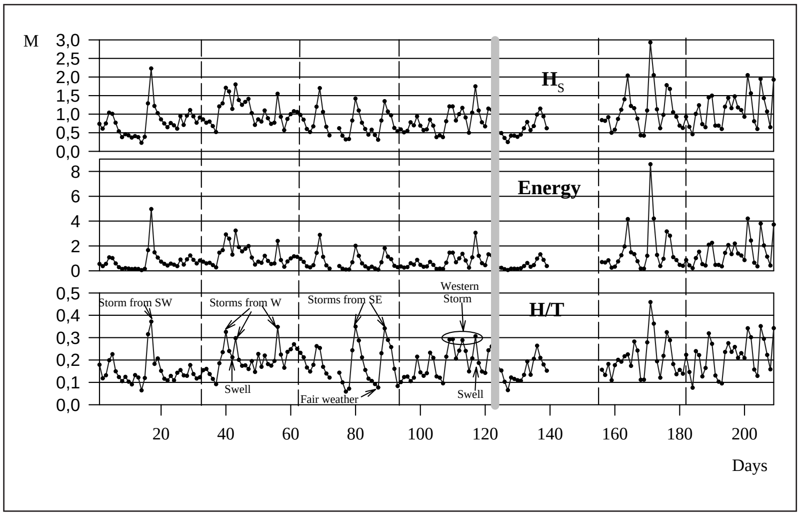

Figure 2. Evolution over time of energy (only Hs^2 is represented), zero crossing period and wave erosivity. The figure indicates high storm values, while calmness corresponds to low values

In spite of the good correspondence between WR and the storm periods, the problem of identifying the intensity of every storm emerges. It was decided to join the parameter WR, which identifies the erosive/aggradational character of the waves, with the energetic density parameter. The resulting parameter was named erosivity of the waves (FE).

To demonstrate its utility, it was represented versus the evolution of the mean volume of Vistahermosa beach (figure 3). A relatively good correlation can be seen, with a clear tendency towards loss of volume, while the value of erosivity increases. The correlation factor would increase if the contribution of the profiles influenced by the presence of shore platforms (profiles V4 and V5) were omitted.

If we observe FE behaviour versus slope (figure 3), the obtained correlation is better, with a clear decrease of the mean slope while increasing FE. On one hand, the slope is a good indicator of the aggradational/erosive state of the beach, as can be observed in figure 3. The relationship between slope and volume shows a good correlation (0.9). On the other hand, the behaviour of the sedimentary parameter D_{50} was also studied. If we represent its behaviour versus the volume and versus slope, a clear decrease trend of the grain size in aggradational conditions can be observed, behaviour already described by Guillén (1992) on other beaches. Such a parameter is better interrelated with volume (0.9) than with slope.

The behaviour of this factor in relation to FE showed a trend towards increasing grain size, while increasing the erosive conditions, where a correlation near 0.9 was obtained.

Thus, it can be observed how the beach, under certain energetic conditions, presents some of its own characteristics that make it be more or less susceptible to erosion. These intrinsic characteristics would be what other authors have defined as erodibility of the natural system (Selby, 1982). The erosion rate would thus be a function of the erodibility (facility to be eroded) that an area presents, and of the erosivity (erosive capacity) of the natural agents acting upon it. Medina, Losada and Dalrymple (1990) had previously pointed out the greater erodibility of reflective profiles, compared with dissipative ones. Thus, as proper factors of the beach we will have one that is morphological (slope) and another that is sedimentological (D_{50}). The resulting parameter would be the erodibility of the beach, and could be expressed by:

$$FR = b \times D_{50} \quad [1]$$

By comparing this parameter with the accumulated volume, we see (figure 4) how both parameters are directly proportional, with a high correlation; we can consider this factor as representative of the aggradational state of the beach.

If we now relate this parameter to the erosivity of the waves (figure 4), we see a strong inverse relationship, with a high correlation. This would indicate how the beach is acquiring dissipative characteristics, while increasing the energetic conditions of the incident waves.

Finally, after proving the parameter FR to be a good indicator of the beach's morphodynamic state, we can analyse the relationship between this parameter and the erosivity of the incident waves,

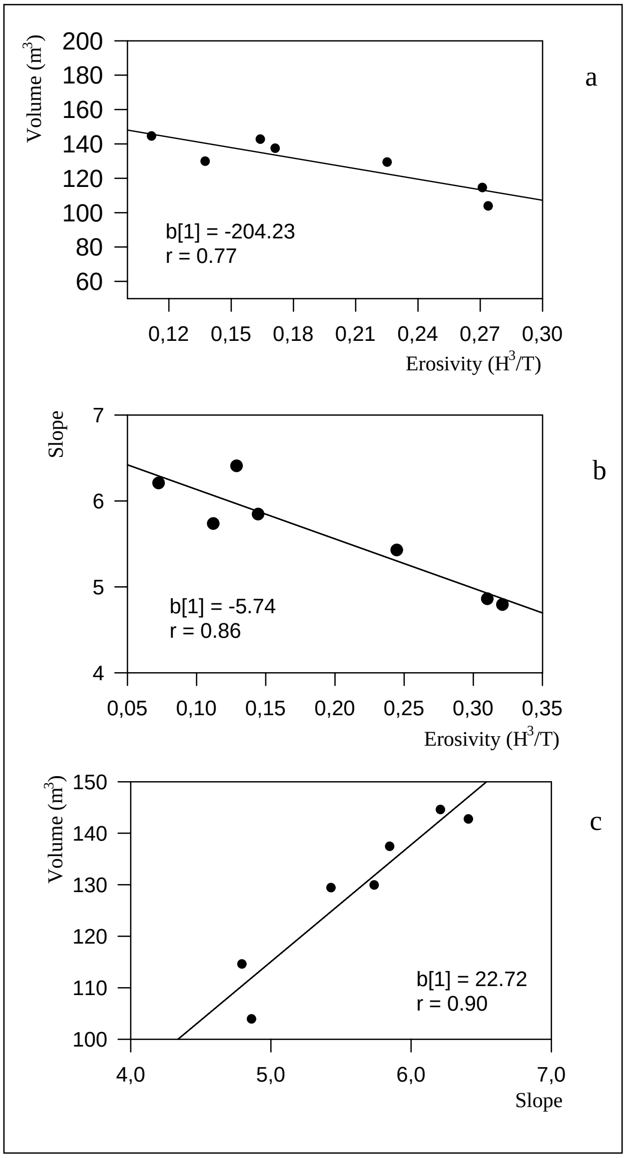

Figure 3. (a): Volume evolution of Vistahermosa beach, vs wave erosivity. (b): Intertidal slope of Vistahermosa beach vs wave erosivity. (c): Volume evolution vs intertidal slope evolution of Vistahermosa beach. b[1] represents the regression slope, while r^2 is the regression coefficient

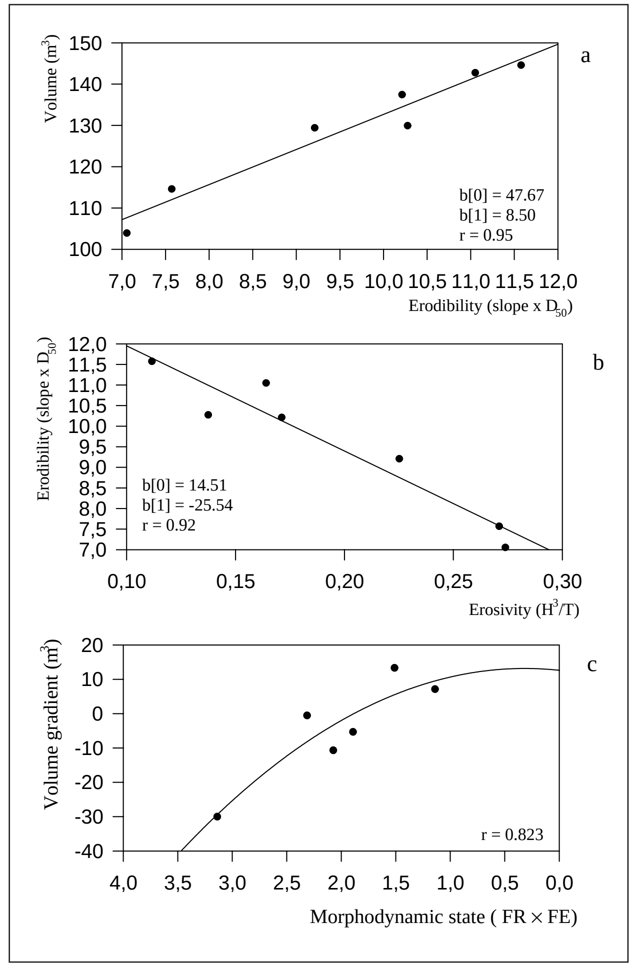

Figure 4. (a): Mean volume evolution vs erodibility evolution of Vistahermosa beach. (b): Erodibility evolution of Vistahermosa beach vs wave erosivity. (c): Volume gradient between surveys vs the evolution of Morphodynamic Situation. b[1] represents the regression slope and, while r^2 is the regression coefficient

and the rates of accretion/erosion produced between campaigns. In order to do this, we used the morphodynamic situation parameter:

$$SM = FR \times FE = D_{50} \times b \times Hs^2 \times Hs/T \qquad [2]$$

In this expression, the erodibility value corresponds to the one that the beach presents during a given campaign, while the erosivity factor corresponds to the one that the prevailing waves present between that campaign and the next. Figure 4 shows how the evolution acquires a clear asymptotic trend, indicating that, for a monthly period, the beach would have a maximum profit limit of volume, even under good prevailing conditions.

Santa Catalina

The behaviour of this beach's parameters, described above, was not the same as that of Vistahermosa. The FR index could not be constructed: this parameter presents a practically null correlation with the accretion/increase in volume.

In the case of the FE factor, it shows an inverse correlation (figure 5). This would indicate an indirect influence of the waves on the beach, while the relationship between erosivity and accumulated volume is direct, and would indicate that the beach operates as a sedimentary trap, so that it would increase its volume when other nearby beaches were eroded (primarily Vistahermosa).

La Puntilla

In the case of La Puntilla, a similar behaviour was observed, with an indirect influence of the waves. Nevertheless, the beach can be divided into two zones. The first one, zone A, which includes profiles P1 to P4, presents a behaviour quite similar that of Santa Catalina: increase in accumulated volume while increasing the erosivity (figure 5). The second zone, B, includes profiles P5 to P7, presents a different behaviour, reducing the accumulated volume while increasing the energetic conditions (figure 5). This behaviour was corroborated by field observations, which showed how waves coming from the northwest (typical of the most severe storms) affected the central zone of the beach directly, whereas their influence on the western zone was quite smaller.

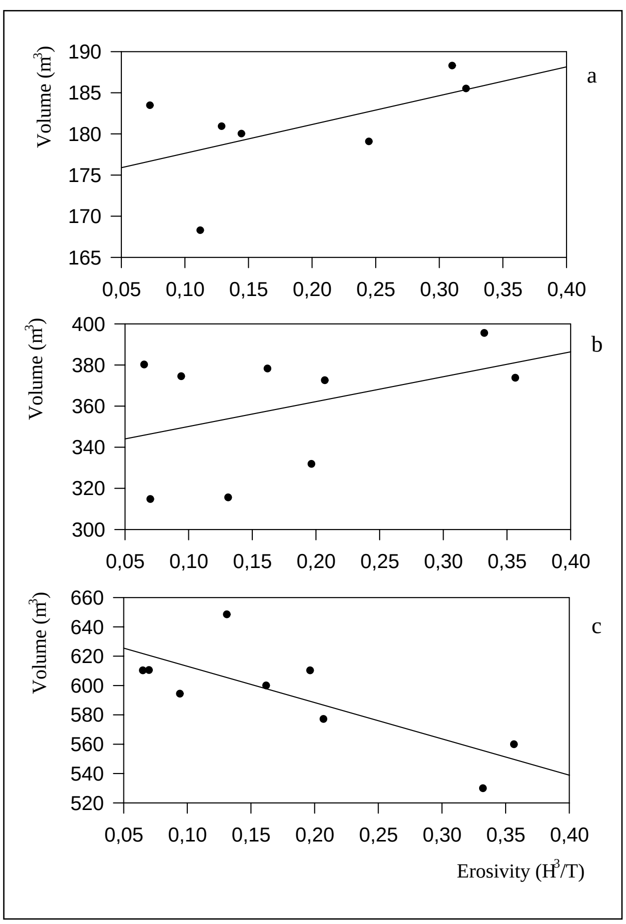

Figure 5. (a): Mean volume evolution of Santa Catalina beach versus wave erosivity. (b): Mean volume evolution of zone A of La Puntilla beach versus wave erosivity. (c): Mean volume evolution of zone B of La Puntilla versus wave erosivity

La Barrosa

In general, analysis of the indices shows how, for the case of the La Barrosa beach, there is a better correlation between the temporal evolution of the energetic density index and the Sunamura index with respect to the morphological index. Figure 6 shows how the Sunamura index adequately synthesises, in a simpler manner, the evolution of energetic density. The index takes higher values in moments when the energetic conditions of the waves are greater and lower values in periods with less energetic waves or calm sea.

On one hand, there are many low-energy situations with constructive waves, characterised by low K index values, high IQ index values, and the highest intertidal slope values. On the other hand,

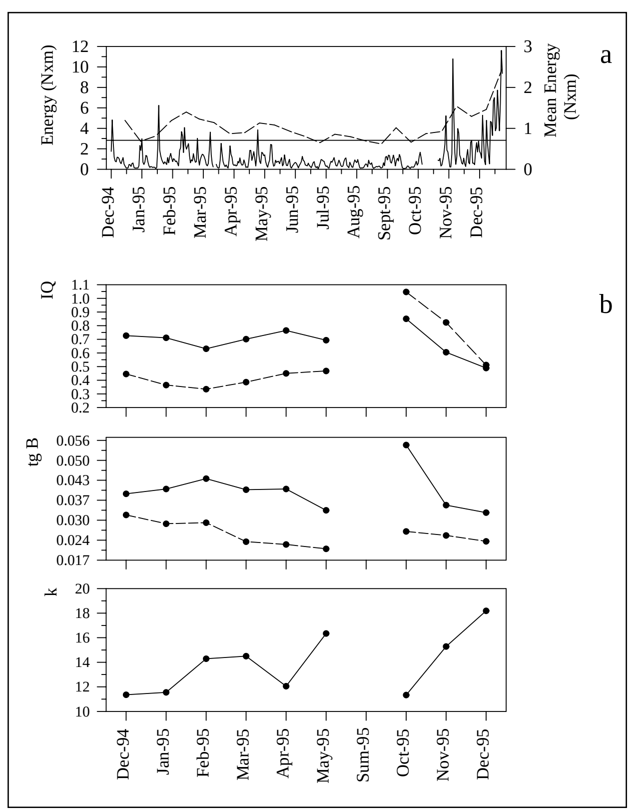

Figure 6. (a): Wave energy and mean monthly energy evolution during the study period. (b): Evolution of IQ index, intertidal slope (per cent) and K index of La Barrosa beach's evolution

there are high-energy situations with destructive waves and maximum K index values (about 20 in the month of December of 1995) versus a smaller quantity of sand, low IQ index values and a marked decrease of the slope.

A striking relationship was found between the morphological changes recorded in the profiles and the IQ index. Figure 7 shows the evolution recorded on some of the survey lines during a seasonal cycle (winter-summer-winter). In general, the IQ index reflects this behaviour properly. Thus, the October profile, corresponding to a summer profile not yet affected by storms, shows the maximum value of the index, if compared with the December profiles of 1994 and 1995, which are highly erosive (profile P-5 is located in the promenade sector, and shows a different behaviour due to the artificial nourishment carried out in December 1994). The behaviour noted by these profiles is, as a rule, homogeneous along the entire beach. This enables us to conclude that the promenade sector suffered a net loss of sand during the first year after the regeneration, while the profiles located in the dunes sector lost a smaller quantity of sand, reaching similar levels (P-9), and even slightly higher (P-12), than the volumes recorded during the preceding winter.

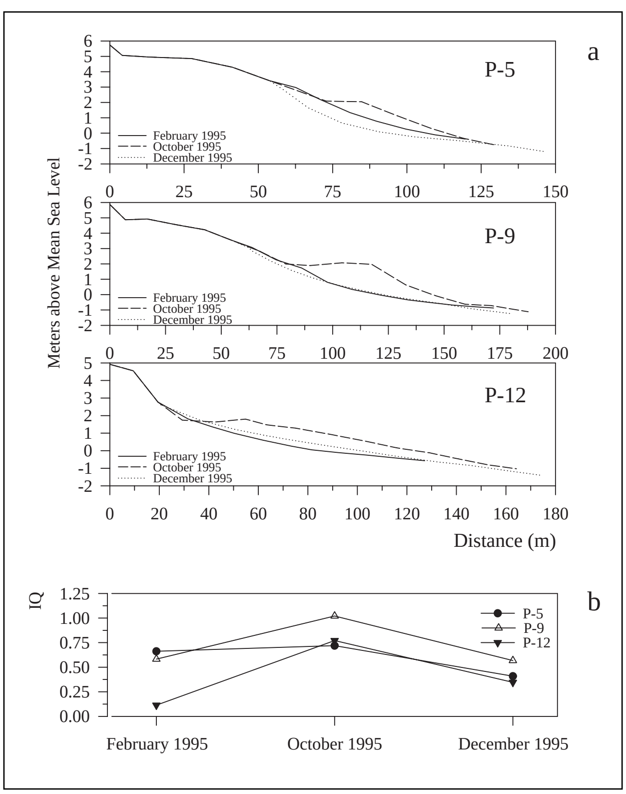

Figure 7. (a): Profile evolution for La Barrosa beach. (b): Evolution of the IQ index for La Barrosa beach; only maximum and minimum values have been represented

DISCUSSION

In the case of Vistahermosa beach, the applied indices have shown good behaviour, especially those for FE, FR and SM. However, the low energetic conditions recorded during the year 1995, covering a narrow energetic range of application, should be noted. The extension of this parameter to unexposed coasts, e.g. pocket beaches such as Santa Catalina or La Puntilla, showed slight incident energy and the indirect relationship between the characteristics of the waves and the changes produced on the beaches, due to their strong contouring conditions.

In the case of La Barrosa beach, the indices used operate well as a rule, although, as indicated above, the energetic conditions of the period studied provided few storm situations. Therefore, the exposed spectrum -in which the K index, the IQ volumetric index and the intertidal slope were related for mid-low energetic conditions- needs to be compared with higher energetic situations. Sunamura and Takeda (1989) report K-index values of 50 for near-breaking conditions, whereas the values recorded during the study period for La Barrosa beach do not surpass the value of 20 for deep-water conditions.

In conclusion, we should stress that all of these indices need to be validated by applying them to other beaches of the bay.

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