Available online at www.sciencedirect.com
SCIENCE DIRECT®
Coastal Engineering 52 (2005) 205–219
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

Temporal assessment of sediment transport from beach nourishments by using foraminifera as natural tracers

Javier Benavente*, Francisco-Javier Gracia, Giorgio Anfuso, Francisco Lopez-Aguayo

Dpto. Geología, Facultad de Ciencias del Mar y Ambientales, Universidad de Cadiz, 11510 Puerto Real, Spain

Received 26 November 2003; received in revised form 14 December 2004; accepted 24 December 2004

Abstract

This paper presents the application of a technique that can be easily applied in monitoring programs following beach fills, where sand is dredged from subtidal zones, seabed or bays, usually rich in foraminifera shells. Its utility lies in a simple and rapid estimation of the prevailing longshore transport paths and determination of the main eroding/accreting zones. A beach monitoring program was undertaken in a embayment on the South Atlantic Spanish coast, where several nourishments were carried out in order to recover an eroding beach. Once the nourishment was complete, a temporal analysis of foraminifera shell distribution was made in a nearby beach inside the embayment by monthly sediment sampling. Foraminifera shells were used as natural tracers for estimating sediment pathways. The results showed a complex pattern of sedimentary transport between both beaches, where wind action and reflected/diffracted waves interfered with the dominant longshore current, depending on the prevailing hydrodynamic regime. These results were later confirmed by a 3-year morphodynamic study. Although foraminifera dispersion only accounts for the behaviour of fine fractions, the monitoring of shell dispersion after dumping demonstrated to be a useful tool for studying the stability of nourished beaches. In the case of nourished beaches foraminifera shells could be considered as mixed tracers, with many advantages over both natural and artificial traditional tracers.

Keywords: Beach nourishment; Foraminifera; Tracers; Littoral currents

1. Introduction

A common problem in nourishment projects is the sand loss by transport to neighbouring beaches (Everts et al., 1974; Dean, 1988). In these cases, and especially when programming periodical nourishments, it would be very useful to know the paths and velocity of longshore sediment transport from the nourished beach to other beaches. Sediment transport rates can be estimated through several field techniques, although not all of them are very efficient when applied to nourished beaches. For example, longshore variations in grain size have been used as an indicator of longitudinal transport (Komar, 1998). However, in nourished beaches the lack of sediment compaction and the usually steep shoreface gradient resulting

* Corresponding author. Tel.: +34 956 01 64 47; fax: +34 956 01 67 97.
E-mail address: javier.benavente@uca.es (J. Benavente).

0378-3839/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.coastaleng.2004.12.002

from the works make them highly sensitive to erosion, especially of the medium and fine fractions. This is often prevented by dumping coarser sediments, whose transport is more limited and less representative than the original one.

Some techniques have been used for calculating with some accuracy the total (suspended and bed load) longshore sediment transport. The impoundment technique consists in the construction of specially designed temporal groins to intercept sediment transport (Bodge and Dean, 1987). The volume transport rate is obtained by quantifying the morphological changes at both sides of the groin. Sediment streamer traps have also been used for this purpose and are made of bags or series of bags that are mounted on racks, which are installed at different water depths (Kraus, 1987). Artificial sand tracers are helpful in the determination of "instantaneous" littoral transport rates, with the possibility of controlling the moment and location of sediment injection. However, mixing depth and center of mass, two important measurements required in this technique, are difficult to define and quantify (Wang et al., 1998; Benavente and Gracia, 2003). A variant of this method consists in using natural tracers, mainly represented by heavy minerals and biogenic debris. The former have been commonly used in provenance studies and also for estimating direction and relative intensity of longshore sediment transport at the long term (Eitner and Ragutzki, 1994; Del Río et al., 2001). However, the accurate recognition of heavy minerals is often difficult and the method cannot be used for the quantification of the present longshore transport rates.

Biogenic debris as tracers include a wide variety of forms and species, from coccolithophorids to diatoms (Murray et al., 1983), although foraminifera shells have been mostly used. Studies based on foraminifera distribution are numerous since the technique is simple and economical, and presents a broad range of applicability. They have been widely used as coastal palaeoenvironmental indicators and for establishing former sea levels (Alejo et al., 1999; Haslett et al., 2000). Foraminifera have also been employed as natural tracers for estimating sediment transport in continental shelves (Nigam, 1986), or in tidal inlets (Gao and Collins, 1995). However, the use of foraminifera in beaches has been limited to the reconstruction of littoral sediment provenance (Davaud and Septfontaine, 1995; Hippensteel and Martin, 1999; Haslett et al., 2000).

The present paper exposes an additional potential use of foraminifera shells as a tool for defining sediment transport paths and rates in nourished beaches. The appearance and later dispersion of foraminifera in the beach sediments after nourishment is a side effect that can be used for evaluating the prevailing longshore transport directions. The foraminifera existing in the dumped sediments are exotic natural elements that can be used as if they were artificial tracers. This study examines the efficiency of foraminifera as sediment transport tracers in a beach nourishment carried out in SW Spain. The replenishment system consisted of the dredging of sublittoral bottom sands and their placement on the dry beach (high shoreface and backshore). The obtained results indicate that this economical technique can be a very useful tool for engineering purposes and coastal research.

2. Study area

The study area (Fig. 1) includes Aculadero and La Puntilla beaches, located in the northern zone of the Cadiz Bay (southwestern Atlantic Spanish coast). Both beaches form a self-related system inside a bay defined by Sta. Catalina Point to the West and the Guadalete river mouth to the East. After the construction of the Guadalete river mouth jetties in the 1970s, and the Puerto Sherry marina in 1984, this bay became highly restricted and protected against westerly storms. The harbour and the river jetties were enlarged in the late 1980s, leading to the final configuration of the bay, where wave dynamics and currents are strongly controlled by the limiting structures.

Tides are semidiurnal, with an average range of about 2.2 m. Prevailing sea and swell waves approach from the NW quadrant. Winds blowing from E and SE (Gibraltar Strait) are strong and persistent but only produce low-energy waves due to the limited fetch. The most frequent and intensive storm wave fronts approach from WSW, a direction broadly normal to the shoreline. As a consequence, longshore currents are regionally not very important and are associated with local energetic events that

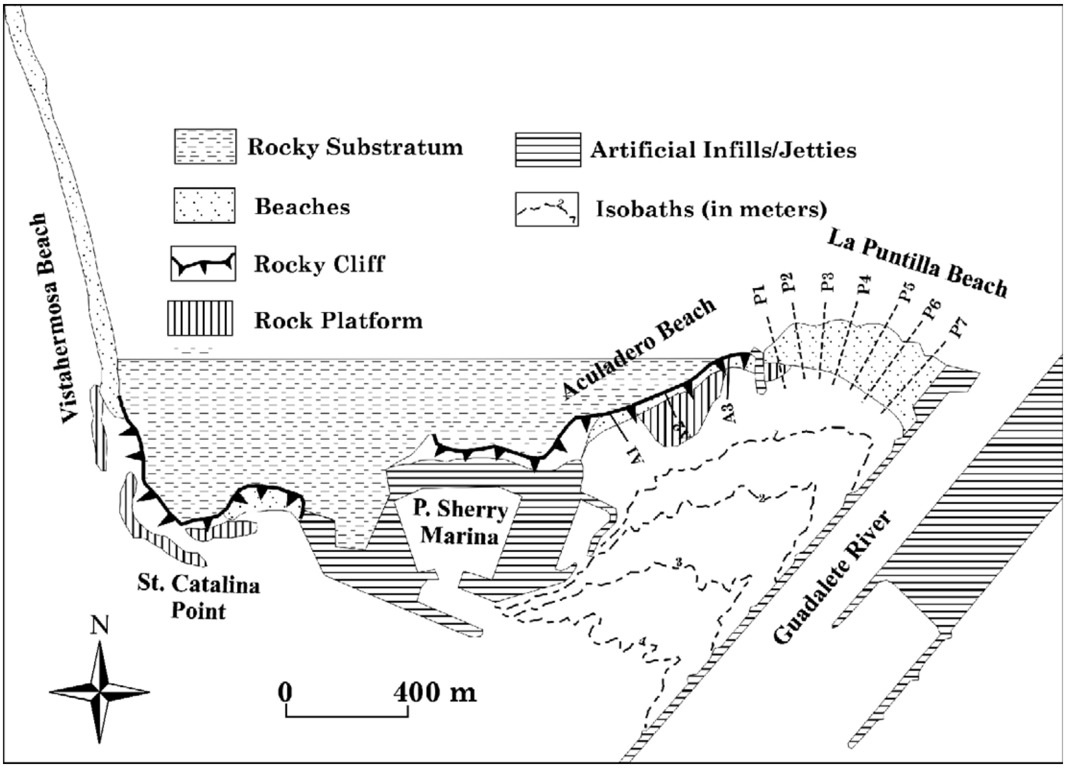


Fig. 1. Location map and main geomorphological features of the studied zone.

create a southward littoral drift of low intensity (Benavente et al., 2000). The zone is a low energy wave environment, where typical winter storm conditions are achieved when waves are higher than 1.5 m (ROM 0.3, 1991). Beach closure depth in exposed beaches of the zone is considered less than 6 m (Muñoz-Perez et al., 1999).

2.1. La Puntilla beach

This is an urban beach around 700 m long with a crescent plan-form and a WNW–ESE direction. The beach has a flat and wide supralittoral zone, greater than 100 m and increasing to the East (Fig. 2). The intertidal zone is narrow and steeper (about 2.25% of

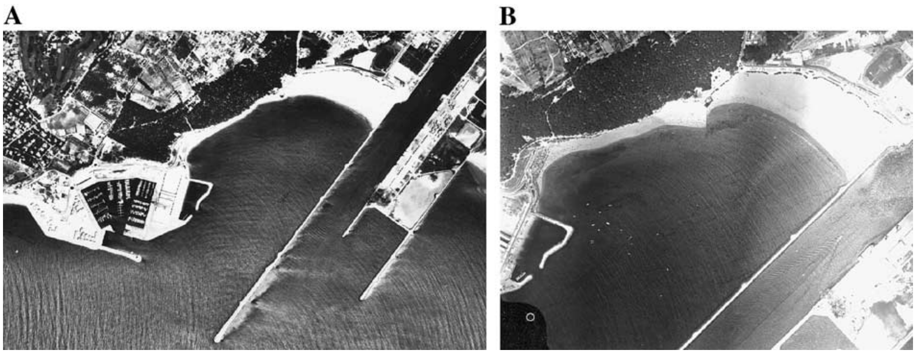


Fig. 2. Two examples of aerial photographs used for the estimation of wave shoaling processes in the studied zone. (A) 1991 flight, scale 1:40.000, Instituto Geográfico Nacional. (B) 1994 flight, scale 1:15.000, Junta de Andalucia.

mean gradient). With the exception of some incipient dunes in the back beach, there is a virtually absence of mesoforms. Human contribution to this morphological uniformity only takes place in summer, by raking. The beach finishes landward with a promenade that constitutes an obstacle to the aeolian transport, which tends to accumulate sand in the high backshore. This beach presents small morphological variations and weak volumetric changes. The average beach cross section shows a well developed berm and a low tide terrace, visually close to the reflective beach type described by Wright and Short (1984). A rocky substratum of Pliocene sandstones forms a discontinuous intertidal shore platform of up to 10 m wide.

2.2. Aculadero beach

Before any nourishment, Aculadero consisted of a small and narrow beach, WSW–ENE oriented and about 650 m long, accumulated at the toe of a 2–5 m high cliff (Figs. 1 and 2A). As in La Puntilla, the central low beach finishes on a wide intertidal rocky platform which extends almost horizontally at about 0.5 m above the mean low water level and ends in the seaward side with an abrupt escarpment of about half a metre. The construction of Puerto Sherry harbour triggered beach erosion until the beach disappeared in the late 1980s. In 1993 the Spanish Ministry of Environment decided to intervene by periodically nourishing the beach. These works considerably enlarged the dry beach width and protected the back cliff from wave action. The intervention was completed by the construction of a 117 m long low groin between the two beaches (Fig. 2B) and by installing sand fences in the eastern Aculadero backshore in order to create small artificial dunes. Significant erosion was recorded on the beach after the initial nourishment in 1993–1994, and hence successive nourishments were performed in the following years. The sand volume involved in these later nourishments was reduced as a consequence of a substantial decrease in the annual erosion rates (Muñoz-Perez et al., 2001). Table 1 shows the quantity of sediment used for the two major nourishment works and some textural characteristics. During recent years maintenance work was limited to seasonal sand by-passings within the beach, from the artificial small dunes to other retreating areas.

3. Methodology

Beach sediments in this region were studied previously by Mabesoone (1963) and Perez-Mateos et al. (1982), who described a complete absence of foraminifera shells in the beach sands. Recent systematic observations between the Guadalquivir river mouth and the Bay of Cádiz has confirmed that foraminifera shell is not a common component of the beach sediments in this part of the Iberian coast (Anfuso et al., 1999).

However, after replenishment works in Aculadero beach in October 1994, visual observations of Aculadero and La Puntilla beach sediments under a stereomicroscope revealed high concentrations of foraminifera shells. They included several benthonic species belonging to the Miliolidae suborder, usually associated with coarse sediments and shallow waters (González et al., 2001). In Cadiz Bay this suborder is typical of sublittoral environments, with a water depth of about 10 m (Villanueva, 1994), the depth at which sediment was dredged for the nourishment of Aculadero beach. Under fair weather conditions sediment deposited at this depth, below the closure depth value, cannot return to the beach. As a consequence, foraminifera could only reach the beach as a result of nourishment works and the shells were used as

Table 1
Major nourishment works carried out in Aculadero beach

Year	Volume (m^3)[a]	D_{50} (μm)	Shell fraction[b] (%)	Carbonate content (%)	Sediment loss (m^3/year)	Volume/beach length (m^3/m)[a]	Volume/dry surface (m^3/m^2)[a]
1993–1994	172,448	390	17	19.84	35,000	287	7.2
1995–1996	75,625	250	14	20.03	11,000	126	6.3

[a] Offical technical data obtained from Muñoz-Perez et al. (2001).
[b] Molluscs and equinoderms.

indicators of the presence of sand derived from the nourished sediment.

A systematic sampling, identification and counting of foraminifera shells present in La Puntilla beach sediments was carried out. Four sediment sampling surveys were carried out during and after nourishment works (12/7/1994, 1/14/95, 2/16/95 and 3/16/95). Three intertidal surficial sand samples were taken monthly along seven beach profiles (Fig. 1), resulting in more than 80 sediment samples. Calcimetric and textural analysis were made and sediment statistical parameters were calculated according to the graphic method of Folk and Ward (1957). Shell counting was performed in 100 g fractions taken from the finest grain size class (smaller than 0.25 mm), where foraminifera shells concentrated. In order to find any possible relationship between shell distribution and sediment type, a multivariant correlation analysis was applied to the results, by comparing shell content and textural parameters of each sample using the statistical software BMDP®.

Monthly topographic profiling surveys (by using an optical theodolite) were also performed on the two beaches with the objective of analysing the evolution of the nourishment finished in October 1994. The topographic study began in November 1994 and was interrupted in the beginning of 1995 at Aculadero due to the construction of a promenade on the cliff top. After the second important replenishment (end of 1995), a monitoring program was carried out and extended during 3 years, from January 1996 to January 1999, when Aculadero beach completely disappeared.

Since foraminifera shells were mainly transported by wave action, wave parameters were also taken into account in order to know possible changes in longshore current direction and/or intensity. Wave climate was determined from the significant wave height (H_s) and the zero-crossing period (T_z), obtained from an offshore wave-rider scalar buoy. In the studied zone complex wave shoaling processes introduce important wave height modifications and disable the application of traditional wave-propagation programs. To solve this point, a 2.5 m graduated stake was installed upon the end of the jetty between both beaches, in order to visually estimate shallow water wave height, period and length during spring high tides. These data, together with observations of wave front patterns obtained from aerial photographs and periodical visual observations, helped in deducing the specific wave shoaling processes in the bay where the two beaches are placed.

Physical and topographic data were used for the morphodynamic characterization of La Puntilla beach, by applying classical parameters used in coastal engineering like the "Dean Number" (Dean, 1973) or the Surf Scaling Parameter (Guza and Inman, 1975). The Dean Number, Ω, relates wave characteristics (height, period) and sediment grain size (represented by the dimensionless grain fall velocity). The second parameter, ε, also takes into account the average beach gradient. These parameters have been mostly used for the morphodynamic classification of beaches: they present high values in dissipative beaches and low values in reflective ones. Beach plan evolution was estimated by using aerial photographs taken before and after nourishment. Finally, a comparison was made between number of foraminifera shells and water depth, in order no know any possible zone of prevalent shell accumulation.

4. Results and analyses

4.1. Wave climate and shoaling processes

Visual observations indicated that waves approached mainly from the West. They had deep-water heights ranging between 0.3 and 2.5 m, and zero-crossing periods between 2.5 and 9 s. Fig. 3 shows a typical winter deep-water wave record for this zone, in which several storm episodes can be recognized.

Relationships between deep-water and visually estimated surf conditions are shown in Fig. 4. Waves experienced an average height reduction of up to 82% due to shoaling processes, resulting in breaking wave heights always lower than 0.4 m, while surf wave periods varied within a broadly similar range as the zero-crossing periods. Regarding wave periods, extreme values (very small and very long periods) were shortened, while intermediate values (4–6 s) remained more or less unchanged.

Waves approaching from WSW did not affect the centre of La Puntilla beach. Instead, diffraction of waves when reaching the northern Guadalete jetty

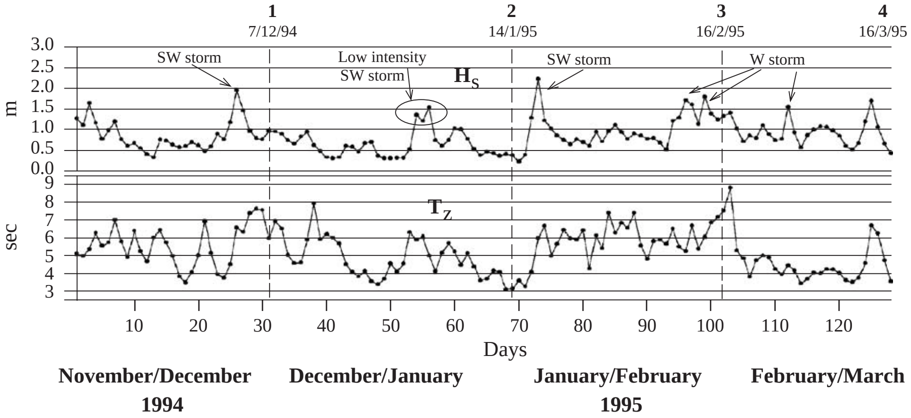


Fig. 3. Deep-water wave characteristics recorded in the offshore buoy from December/1995 to March/1996. H_s: significant wave height, T_z: zero-crossing period. Vertical dashed lines indicate monitoring campaigns.

produced two wave groups: a first one of reflected waves directed to the centre of Aculadero beach (Fig. 2A), and a second one of refracted waves that followed the jetty rim with little dissipation (less than 70% of height reduction), until finally reaching the eastern end of La Puntilla beach (profiles P6 and P7 in Figs. 1 and 2B).

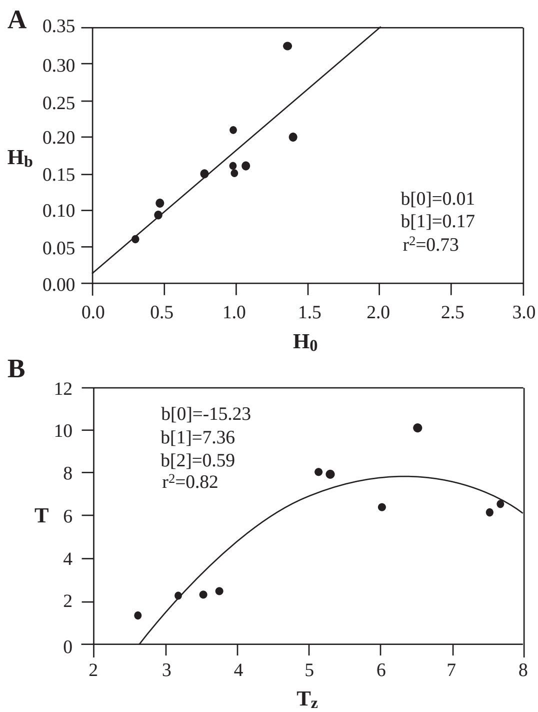


Fig. 4. Relationships between visual estimations of wave variables between breaking and deep-water conditions: (A) wave height; (B) wave period.

4.2. Beach morphodynamic behaviour and medium term tendencies

4.2.1. Aculadero beach

Between 1994 and 1999 the beach recorded continuous erosion. In December 1994, a high erosion scarp was observed on the beach and the central and western parts had virtually disappeared. During the following fair weather periods, the intertidal shore platform and especially the seaward escarpment, acted as an obstacle to the arrival of sand from the nearshore zone and inhibited natural recovery, a common process in the beaches limited by rock platforms along this region (Muñoz-Perez et al., 1999). Moreover, Puerto Sherry harbour blocked sedimentary contributions from updrift. Only a small amount of sand was preserved in the beach by seasonal replenishments. In this sense, the morphological behaviour of Aculadero beach was completely distorted by artificial interventions. As a consequence, it was not possible to make a morphodynamic classification of Aculadero beach because most part of the beach disappeared about 3 months after nourishment.

While erosion occurred in the western and central zones, the eastern area experienced accretion, fed from the rest of the beach. This trend had consequences on the grain size evolution (Fig. 5): the western zone experienced a coarsening trend while grain size in the eastern one progressively decreased. The central part showed an initial finning trend and a later stabilization after spring 1996, when this zone decreased to a small sand accumulation at the toe of the cliff.

During replenishment works, some sand was taken from this eastern area and redistributed along the western eroded zones. Accumulation in profile A3 is indicative of a prevailing sedimentary transport from Aculadero to La Puntilla (i.e. eastward), interrupted by the groin separating the two beaches. This structure produced a typical upstream triangle-shaped deposition (class 3 of the classification of groin effects proposed by Sukhodolov et al., 2002), as can be seen in Fig. 2B.

4.2.2. La Puntilla beach

In the months following the nourishment works the general grain size distribution in La Puntilla beach showed a decrease in size toward the central zone (profile P5). The western half (profiles P1 to P4 in Fig. 1) was characterised by greater slopes and coarser grain sizes than the eastern one (Fig. 6). At the same time volumetric changes exhibited clear longitudinal variations that made it easily divisible into two sectors (Fig. 7). The western sector showed a clear accretional tendency, with a maximum at P4. After a limited decrease at P5, a definite erosional trend was recorded in the eastern zone, near the Guadalete river jetty. The associated morphological changes resulted in a counter-clockwise rotation of the beach plan form.

In the following years (1996–1999), the decreasing grain size to the East was also recorded and is reflected in Fig. 8A (the Dean Number varies inversely with grain size). During that time the beach showed an increasing eastward intertidal slope, P4 having the steepest profile (in Fig. 8B slope variations are represented by the Surf Scaling Parameter). From a morphodynamic point of view, the western sector can be classified as intermediate (following Wright et al., 1985), close to the reflective limit (Fig. 8A and B). The eastern sector includes profiles P5 to P7, with P5

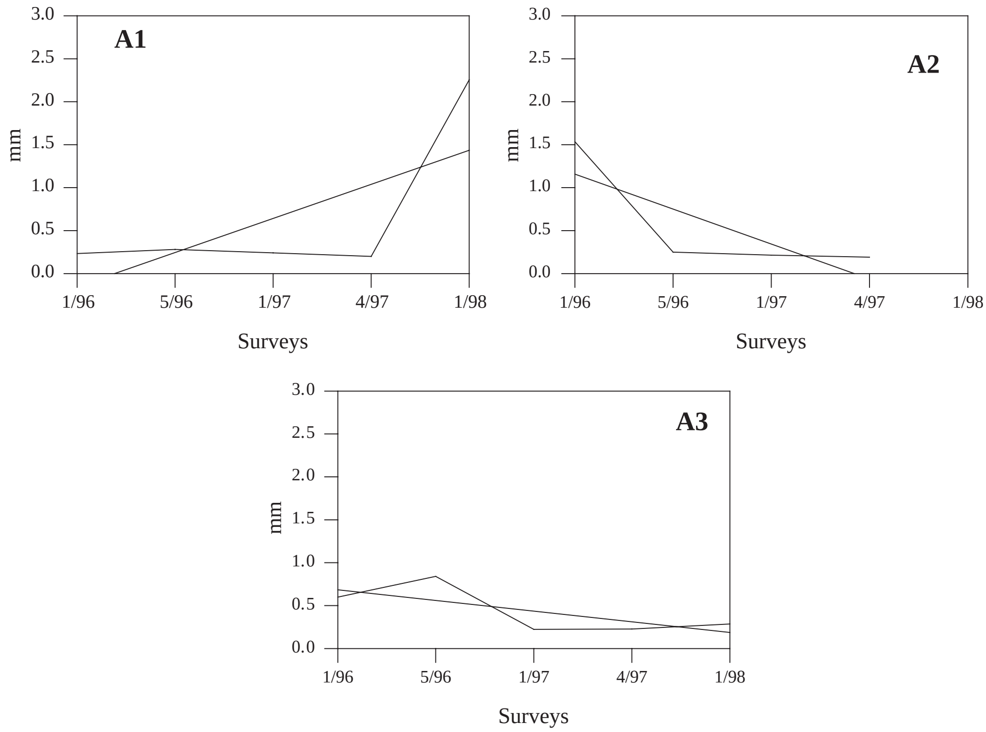


Fig. 5. Evolution of sediment grain size (D_{50}) in Aculadero beach along several surveys made between 1996 and 1998. Profile location in Fig. 1.

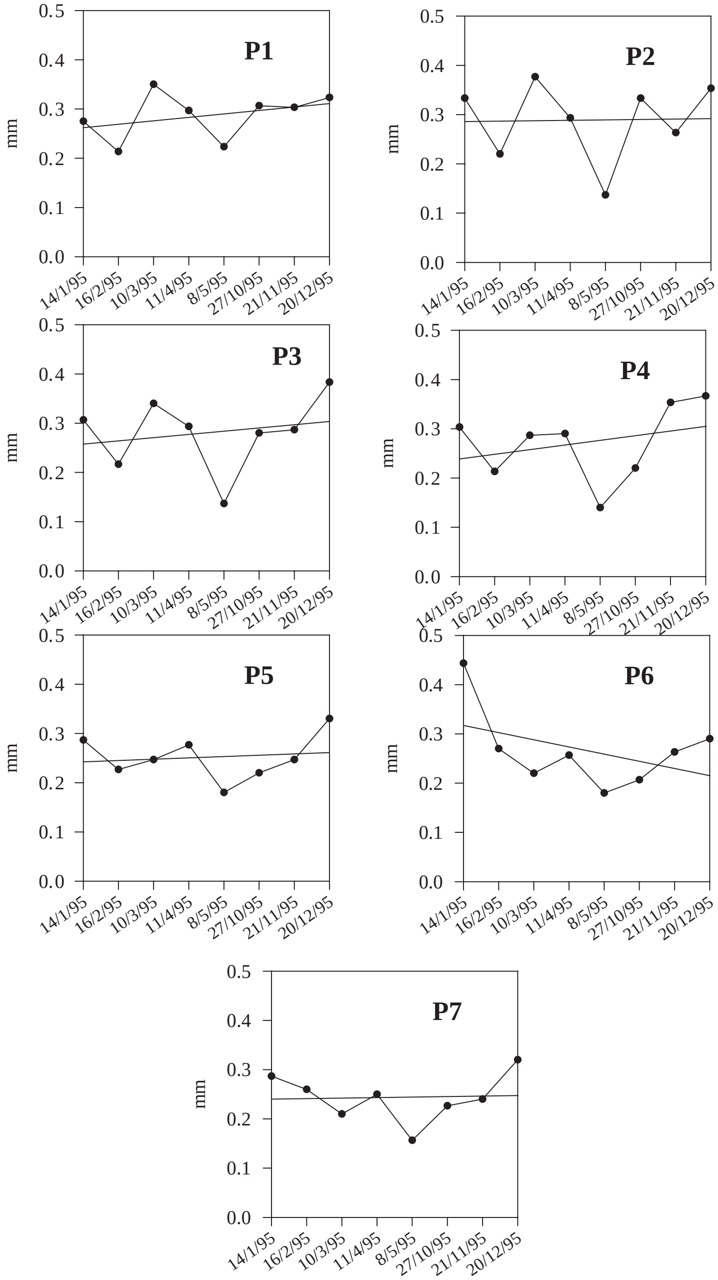


Fig. 6. Average grain size evolution in La Puntilla beach profiles during 1995. Profile location in Fig. 1.

representing a transitional zone. P6 and P7 showed an intermediate morphodynamic character, near to the dissipative limit of Wright et al. (1985). The volumetric evolution between 1996 and 1999 (Fig. 8C) confirmed the trends observed during 1995.

4.3. Foraminifera distribution in La Puntilla beach after nourishment

It is important to point out that, before the first nourishment, sediments from both beaches did not

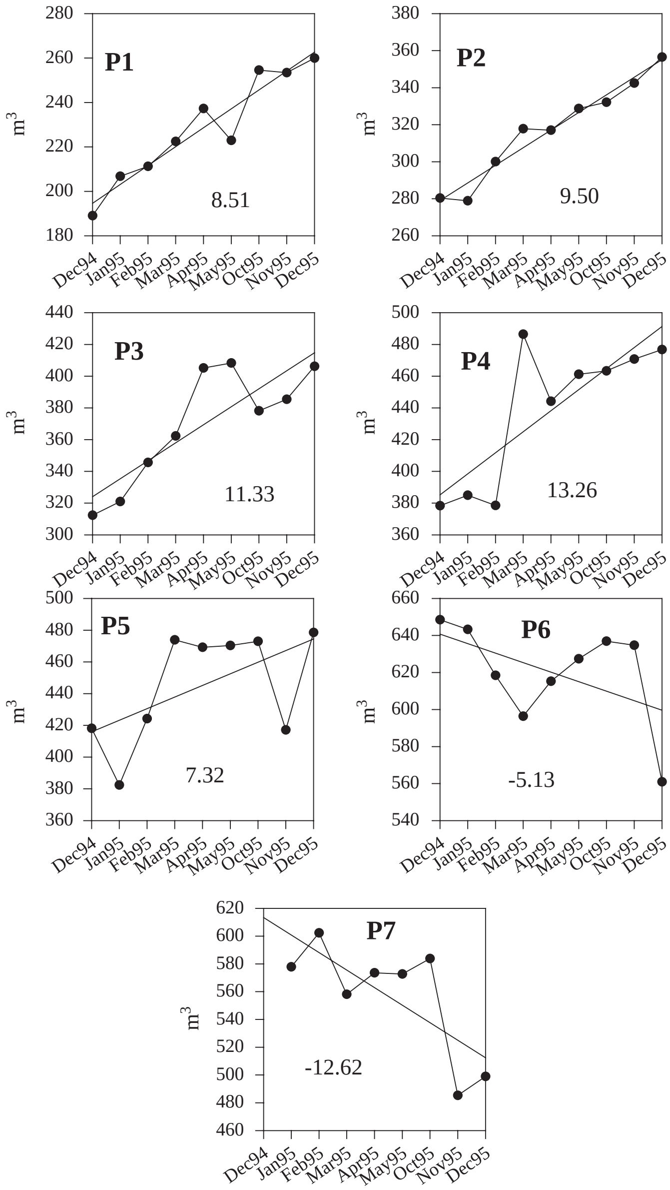


Fig. 7. Volumetric evolution of La Puntilla beach profiles during 1995. Volumes were calculated above medium sea level.

contain any benthic foraminifera shell. After the works, textural data from both beaches showed finer and better sorted sands in La Puntilla than in Aculadero (Table 1), with a greater concentration of foraminifera shells. These variables were compared through a correlation analysis. Fair positive relationships were obtained when number of foraminifera shells was compared with water depth and carbonate percentage (r^2=0.7). A negative relationship was obtained between foraminifera shells abundance and medium grain size (r^2=−0.6). These results indicate a clear association between foraminifera shells and the easiest transportable sand fractions, represented by the smaller grain sizes (0.125–0.25 mm) and by low-density, very porous, bioclastic fragments. The greater size of bioclasts made the correlation between foraminifera shells and grain size slightly worse than expected.

In a broad sense, low energy conditions prevailed after the Aculadero artificial fill of October 1994. At the beginning of December, a 1-day westerly storm (Fig. 3) was responsible for the initial sand transport towards La Puntilla beach. After that, sediments at La Puntilla showed an increase in foraminifera shells with even higher concentrations than in Aculadero, indicating a prevalent movement of the easiest transportable fractions. Resulting foraminifera distribution can be observed in Fig. 9a: high concentrations appeared in the profiles nearest to Aculadero beach (P1 and P2), especially around the mean sea level.

The following weeks were characterized by the prevalence of SW approaching waves, linked to a low intensity storm that reached the coast 12 days before the second sampling (Fig. 3). Volumetric changes showed a general accretion on the intertidal area, especially at the western profiles. Data from this second survey indicated two prevailing areas of shell accumulation (Fig. 9b). The first was located around the mean sea level between P1 and P3 and at slightly higher positions on profile P4. The second area appeared around the mean sea level on profiles P6 and P7. The zone around profile P5 exhibited low foraminifera concentrations, probably due to a smaller sedimentation rate. In general, the centroid of the fraction of the bed material that contained foraminifera moved about 80 m to the SE.

In the third survey foraminifera distribution appeared to be broadly similar to the previous one (Fig. 9c), although with a slight increase in the high beach and a more homogeneous distribution, especially on the western profiles (P1 to P4). This was due to the action of easterly winds that transported sediment from the eastern sector to the upper dry beach of the western sector. Therefore, low foraminifera concentrations were recorded in the eastern area, where aeolian deflation zones were formed. In relation to the previous one, the new centroid obtained appeared very close to the former, some 30 m to the SW.

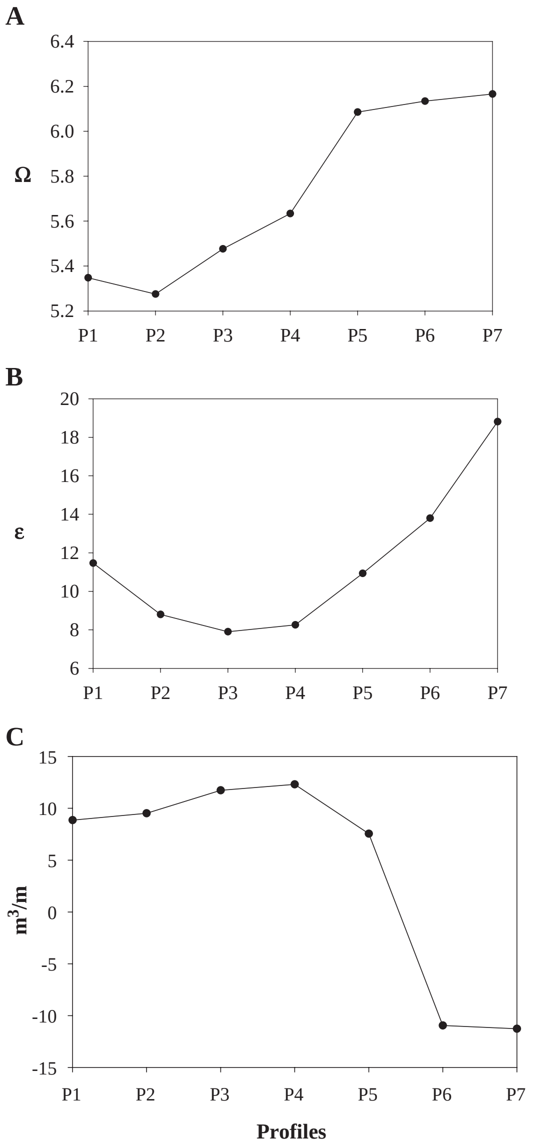
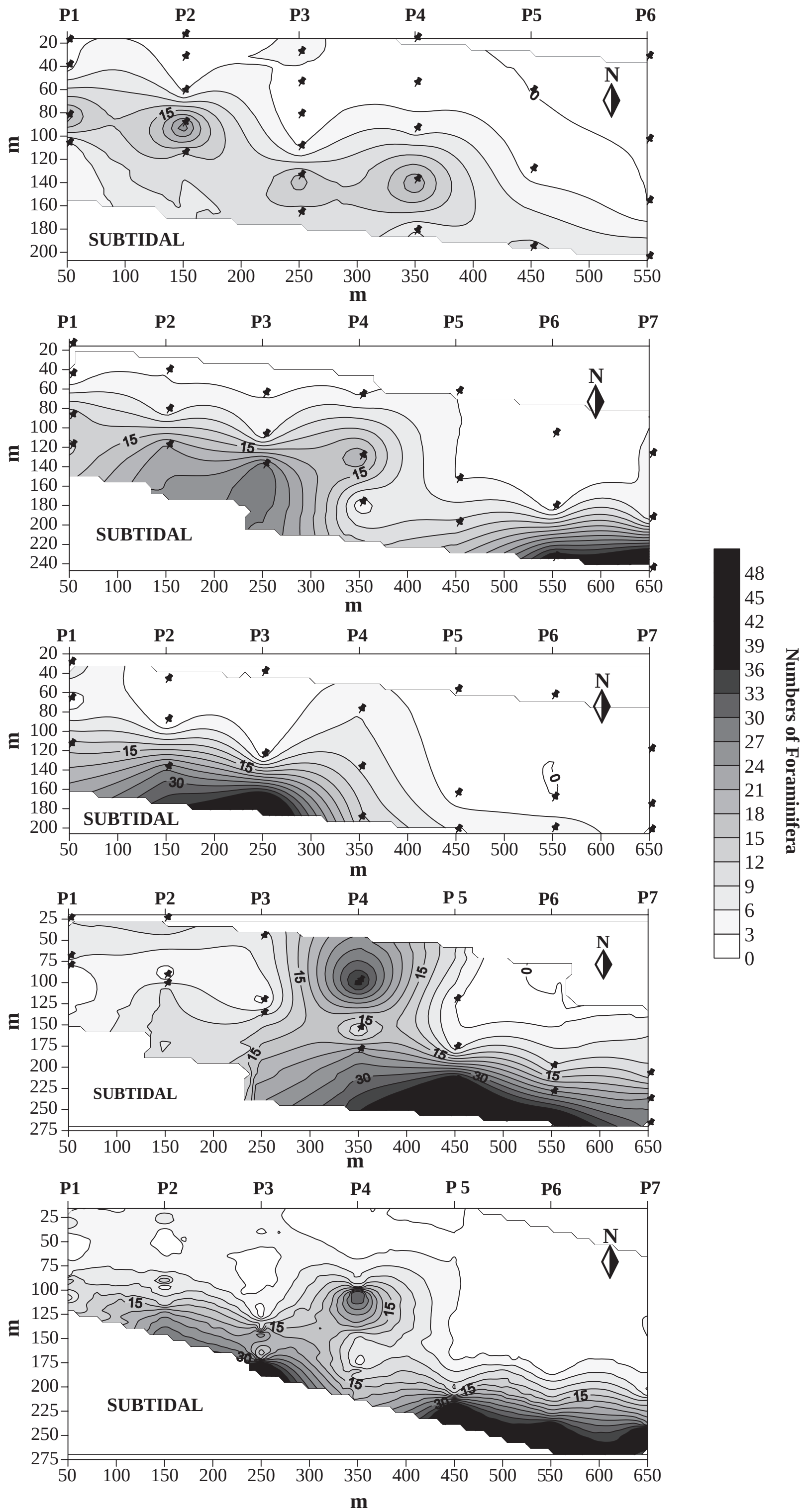


Fig. 8. Average values of (A) Dean's Number, (B) Surf Scaling Parameter, and (C) volumetric changes recorded in La Puntilla beach profiles between 1996 and 1999. See Fig. 1 for profile location.

Finally, in the fourth campaign (Fig. 9d) maximum concentrations were detected between P4 and P7, although this last one experienced erosion on the beach face. Easterly winds again transported foramin-

Fig. 9. Foraminifera distribution (number of shells per 100 g sample) in La Puntilla beach. *X* and *Y* indicate distances (in m). (a) First sampling campaign, Dec/7th/1994; (b) second sampling campaign, Jan/14th/1995; (c) third sampling campaign, Feb/16th/1995; (d) fourth sampling campaign, Mar/16th/1995; (e) average foraminifera distribution after considering data from the four surveys.


P1
P2
P3
P4
P5
P6
P7
N
SUBTIDAL
m
15
30
0
Numbers of Foraminifera
48
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3
0

ifera shells from the eastern dry beach (P6 and P7) to the central and western sectors, especially to P4. In the intertidal zone an homogeneous distribution was obtained for the whole beach, due to the constructive action of swell waves associated with low energy storms (Fig. 3). To the East (profiles P6 and P7), maximum concentrations were attained around the subtidal zone. The redistribution of sediment made the centroid to appear displaced about 200 m to the East from its former position.

Fig. 9e represents the average distribution of foraminifera shells after summing up the four surveys. According to the increasing concentration of natural tracers, deposition on La Puntilla took place in two prevailing zones: the western (profiles P1 to P4) and the eastern (P6 and P7) areas. The first one was characterized by a homogeneous shell distribution around the intertidal and supratidal zones, although this concentration increased around the central part of the beach (P4). In the eastern area only a slight accumulation of fine sands occurred on the intertidal and subtidal zones, induced by the blocking action of the Guadalete river jetty.

5. Discussion and conclusions

Sediments eroded from Aculadero beach are transported by littoral drift and deposited along La Puntilla beach, especially in the eastern sector, against the northern Guadalete river jetty. However, by taking into account the data obtained from the field surveys and foraminifera dispersion, important specifics can be pointed out for the transport paths inside the bay.

Average foraminifera distribution (Fig. 9e) indicates transport from lateral areas towards the central zone (P4). According to Komar (1977, 1978, 1998), coastal drift can produce a differential transport of the finest and lowest density sediments. In this sense, textural characteristics of La Puntilla beach confirms the results obtained from the foraminifera dispersion. Indeed, beach volumetric evolution of the beach (Fig. 6c) also showed this behaviour, P3 and P4 recording the greatest accretion.

Despite the general transport trend from Aculadero to La Puntilla, the net sediment budget for La Puntilla after 1 year of monthly monitoring was only about +4 m^3/m. This indicates that most of the sediment was transported to the nearshore zone. It also reveals the existence of a complex circulation pattern between the beaches. The small bay in which they are included can be considered as a very restricted system, with little supplies and losses, where sediments are continuously reworked depending on the prevailing hydrodynamic conditions.

All the data given above, especially those concerning the changing foraminifera distribution through time, were combined to estimate the main transport paths as a function of the two most common hydrodynamic conditions prevailing in the zone.

5.1. Westerly winds and waves

Under these conditions, important wave energy dissipation takes place into the bay, linked to diffraction and reflection processes imposed by the northern Guadalete river jetty (Fig. 10A). Diffraction makes the waves follow the jetty rim (Fig. 2B) and impinge on the sheltered area of La Puntilla beach (P6 and P7). This process causes an increased wave set-up in the eastern area, generating a longshore current toward the western sector of the beach and probably a structurally controlled rip current. These processes would be responsible for the erosion recorded in the eastern area and for the accretion produced on the rest of the beach.

At the same time, wave reflection takes place near the jetty end, with reflected waves directly reaching the central part of Aculadero beach (Figs. 2A and 10A). In situ observations showed that wave reflection is very effective due to the verticality of the outer jetty surface and is especially important during storm events. The process promotes important erosion in this area (profiles A1 and A2, Figs. 1 and 5), by the generation of two divergent longshore currents towards the extremes of the beach and probably a central rip current. The longshore currents accumulate sediment at both ends of the beach, while the latter would produce an offshore sedimentary transport beyond the rock platform during high tides. However, the analysis of aerial photographs, beach volumetric evolution and foraminifera dispersion revealed a greater efficiency of the eastward component, which affected most part of Aculadero beach. During westerly storms some significant erosion was recorded in the western beach end, probably associated with an insufficient sediment supply and with secondary wave diffraction processes imposed by a small auxiliary jetty of the Puerto Sherry marina (Fig. 2A), visually observed during the surveys. At a long term, all these processes caused accretion in the eastern area of Aculadero beach, close to the groin separating the two beaches.

5.2. Easterly winds

Winds blowing from E and SE have great intensity, but do not produce energetic waves due to the short fetch. Nevertheless, they generate a littoral current starting around the centre of La Puntilla beach and flowing towards Aculadero (Fig. 10B). The current induces accretion on the western end of La Puntilla beach and some erosion in the central part of Aculadero beach due to the direct approach of wind-generated waves to this zone. The high foraminifera concentration recorded in the western dry beach indicate that these strong winds promote a significant sand loss by deflation on the eastern area. This process was visually observed during an easterly storm event, after which sand accumulation in the upper beach had considerably increased.

The two hydrodynamic situations explained above are the most common in the zone and usually alternate through the year, although westerlies are more frequent. As a consequence, the central parts of Aculadero beach suffer erosion and the removed sand is mostly deposited against the groin and partially transported to La Puntilla beach. Downdrift from this structure, the sand deposition in the lee of the groin is explained by the counter-drift action of currents generated by wave set-up in the eastern end of La Puntilla, and also by aeolian transport during easterly windy storms. The further, 3 year monitoring program at La Puntilla beach, consisting of monthly topographic profiling and sediment sampling, confirmed this general behaviour. Over the medium-to-long term, La Puntilla beach experienced accretion on its western half and erosion on the eastern limit (Fig. 8C). Nevertheless, estimated erosion/accumulation rates in this beach are very low and indicate a slight sedimentary growth at the expense of Aculadero.

It is apparent that sediment transport paths in this structurally controlled small bay are complex, where wind action and reflected/diffracted waves interfere with the dominant longshore current, depending on the prevailing hydrodynamic regime. Nearshore circulation patterns are difficult to determine, especially on Aculadero beach, owing to the complex bottom topography imposed by the shore platform.

The use of foraminifera shells in the Aculadero–La Puntilla study case has demonstrated to be a very useful technique that supplied significant information about the most important transport paths between the beaches and about sedimentary transport agents (e.g., wind, longshore currents).

The use of foraminifera shells as tracers is somewhat related to the Eulerian sediment tracer technique,

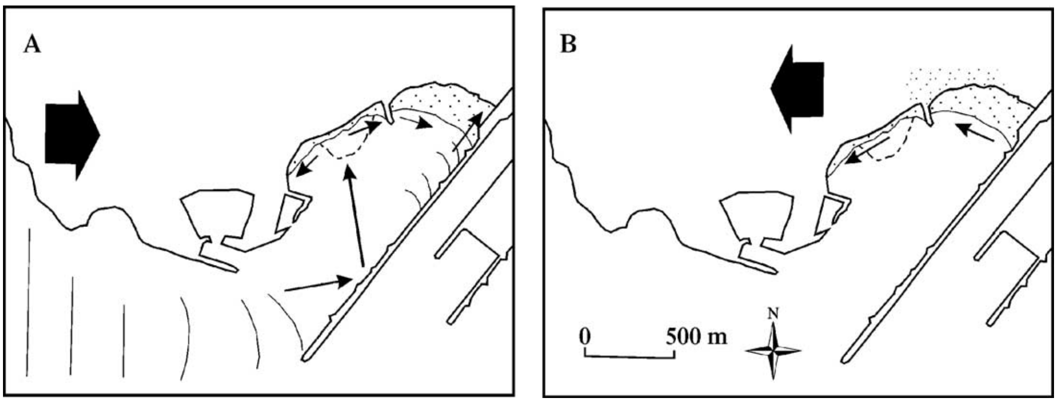


Fig. 10. Patterns of prevailing sedimentary transport paths at Aculadero–La Puntilla Bay associated to different wind and wave conditions: (A) Westerlies, (B) Easterlies; small points represent aeolian sedimentation.

by which concentration of tracer is measured at a fixed point as the tracer cloud passes through, integrating this over time (Duane and James, 1980). Important differences (and disadvantages) arise since no control is exerted on the amount, rate and grain size of the sand released, and thus no transport rate can be actually measured. However, its utility lies on the simple and rapid estimation of the prevailing longshore transport paths and determination of the main eroding/accreting zones. When nourished beaches are limited by terminal groins, sediment pathways around these structures are often difficult to estimate (Sherman et al., 1990) and hence foraminifera distribution analysis can help in drawing a schematic idea of the prevailing transport pattern. Moreover, many artificial sand tracers introduce some problems when applied to long periods of time (weeks to months) because fluorescent dyes commonly have a short life of not more than a few days. This difficulty can be substantially avoided by using these natural tracers, which can remain on the beach for several months.

The difference between the use of artificial and natural tracers lies in the possibility of defining net transport pathways (centroid movement) in the former case, which is impossible to define in the latter since the mere presence of the tracer is not indicative of a net transport direction (Gao and Collins, 1995). However, as it has been shown in the present work, beach nourishments constitute an exception to this rule. Foraminifera present many advantages of both natural tracers (no need to prepare and inject the material; the tracers form part of the beach sediment) and artificial tracers (exact knowledge of the site and moment from which the sediment begins to be transported). Foraminifera could be hence considered as a “mixed” (natural+artificial) tracer.

It is important to keep in mind that the study of foraminifera dispersion only accounts for the behaviour of fine fractions and no extrapolation can be made for the whole transport system. Nevertheless, Dette (1977) showed that losses from beach nourishment fills occur mainly in the finest grain-size fractions, and thus the monitoring of temporal variations on the foraminifera concentration immediately after the dumping can be also used as an indicator of stability of the beach.

Acknowledgements

The authors would like to thank the useful comments made by Prof. Simon K. Haslett (Bath Spa University College). The authors are grateful to Prof. K.F. Nordstrom for the detailed revision and constructive criticism of the article. We also acknowledge the helpful suggestions and comments made by Dr. D.J. Sherman and another anonymous revisor. The authors are very grateful to Prof. J.J. Muñoz-Perez and the Coastal Demarcation Service of the Atlantic Andalusia (Spanish Ministry of Environment), for the installation of the stake for visually measuring wave heights. Thanks to Ana Nistal and the Wave Climate Service of the Spanish General Direction of Ports for the wave data. This work was funded by the Spanish Ministry of Science and Technology and by European F.E.D.E.R. funds (Project BTE2003-05706), and is a contribution to Andalusia P.A.I. Research Group RNM-328.

References

Alejo, I., Austin, W.E.N., Francés, G., Vilas, F., 1999. Preliminary investigations of the recent foraminifera of Baiona Bay, N.W. Spain. J. Coast. Res. 15 (2), 413–427.

Anfuso, G., Achab, M., Cultrone, G., López-Aguayo, F., 1999. Utility of heavy minerals distribution and granulometric analyses in the study of coastal dynamics. Application to the littoral between Sanlúcar de Barrameda and Rota (Cadiz, southwest Iberian Peninsula). Bol. Inst. Esp. Oceanogr. 15 (1–4), 243–250.

Benavente, J., Gracia, F.J., 2003. Modelización del transporte sedimentario longitudinal en playas de poca energía. Playa de Vistahermosa (Bahía de Cádiz). Geogaceta 33, 7–10.

Benavente, J., Gracia, F.J., López-Aguayo, F., 2000. Empirical model of morphodynamic beachface behaviour for low-energy mesotidal environments. Mar. Geol. 167, 375–390.

Bodge, K.R., Dean, R.G., 1987. Short-term impoundment of longshore transport. Proceedings of Coastal Sediments’87, ASCE, New York. , pp. 468–483.

Davaud, E., Septfontaine, M., 1995. Postmortem onshore transportation of epiphytic foraminifera—recent example from the Tunisian coastline. J. Sediment. Res., Sect. A Sediment. Pet. Proc. 65 (1), 136–142.

Dean, R.D., 1973. Heuristic models of sand transport in the surf zone. Proc. Engineering Dynamics in the Surf Zone, Sydney, pp. 208–214.

Dean, R.G., 1988. Managing sand and preserving shorelines. Oceanus 31, 49–55.

Del Río, L., Gracia, F.J., Barbero, L., 2001. Uso de los minerales pesados como trazadores de la dinámica de playas arenosas: la

playa de Catania (Sicilia, Italia). Cuatern. Geomorfol. 15 (1–2), 75–86.
Dette, H.H., 1977. Effectiveness of beach deposit nourishment. Coastal Sediments'77. ASCE, 211–227.
Duane, D.B., James, W.R., 1980. Littoral transport in the surf zone elucidated by an Eulerian sediment tracer experiment. J. Sediment. Petrol. 50 (3), 929–942.
Eitner, V., Ragutzki, G., 1994. Effects of artificial beach nourishment on nearshore sediment distribution (Island of Norderney, southern North Sea). J. Coast. Res. 10 (3), 637–650.
Everts, C., Dewalls, A.E., Czeriak, M.T., 1974. Behavior of beach fill at Atlantic City, NJ. Proc. 14th Coastal Eng. Conf., ASCE, pp. 1370–1388.
Folk, R.L., Ward, W.C., 1957. Brazos River Bar. A study in the significance of grain size parameters. J. Sediment. Petrol. 27, 3–26.
Gao, S., Collins, M., 1995. Net sand transport direction in a tidal inlet, using foraminiferal tests as natural tracers. Estuar. Coast. Shelf Sci. 40, 681–697.
González, M.L., Ruiz, F., Tosquella, J., Baceta, J.I., Pendon, J.G., Abad, M., Hernandez, F.J., Somoza, L., Diaz-del-Rio, V., 2001. Foraminíferos bentónicos actuales de la plataforma continental del norte del Golfo de Cádiz. Geogaceta 29, 61–64 (Madrid).
Guza, R.T., Inman, D.L., 1975. Edge waves and beach cusps. J. Geophys. Res. 80 (21), 2997–3012.
Haslett, S.K., Bryant, E.A., Curr, R.H.F., 2000. Tracing beach sand provenance and transport using foraminifera: preliminary examples from northwest Europe and southeast Australia. In: Foster, I. (Ed.), Tracers in Geomorphology. Wiley, Chichester, pp. 437–452.
Hippensteel, S.P., Martin, R.E.F., 1999. Foraminifera as an indicator of overwash deposits, Barrier Island sediment supply and Barrier Island evolution: Folly Island, South Carolina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 149, 115–125.
Komar, P.D., 1977. Selective longshore transport rates of different grain-size fraction within a beach. J. Sediment. Petrol. 47, 1444–1453.
Komar, P.D., 1978. Relative quantities of suspension versus bedload transport on beaches. J. Sediment. Petrol. 48, 921–932.
Komar, P.D., 1998. Beach processes and sedimentation. Prentice-Hall, New Jersey.
Kraus, N.C., 1987. Application of portable traps for obtaining point measurement of sediment transport rates in the surf zone. J. Coast. Res. 2 (2), 139–152.
Mabesoone, J.M., 1963. Coastal sediments and coastal development near Cádiz (Spain). Geol. Mijnb. 42, 29–43.
Muñoz Perez, J.J., Tejedor, L., Medina, R., 1999. Equilibrium beach profile model for reef-protected beaches. J. Coast. Res. 15 (4), 950–957.
Muñoz-Perez, J.J., Lopez, B., Gutierrez-Mas, J.M., Moreno, L., Cuena, G.J., 2001. Cost of beach maintenance in the Gulf of Cadiz (SW Spain). Coast. Eng. 42, 143–153.
Murray, J.W., Weston, J.F., Sturrock, S., 1983. Sedimentary indicators of water movement in the western approaches to the English Channel. Cont. Shelf Res. 4 (1), 339–352.
Nigam, R., 1986. Foraminiferal assemblages and their use as indicators of sediment movement: a study in the shelf region of Navapur, India. Cont. Shelf Res. 5, 421–430.
Perez-Mateos, J., Pinilla, A., Alcala-del-Olmo, L., Aleixandre, T., 1982. Mineralogía de los arenales costeros españoles. Tramo Málaga–Ayamonte. Bol. Geol. Min. 93 (1), 1–18 (Madrid).
ROM 0.3, 1991. Clima marítimo en el litoral español. Dirección General de Puertos. Ministerio de Obras Públicas, Madrid.
Sherman, D.J., Bauer, B.O., Nordstrom, K.F., Allen, J.R., 1990. A tracer study of sediment transport in the vicinity of a groin. New York, USA. J. Coast. Res. 6 (2), 427–438.
Sukhodolov, A., Uijttewaal, W.S.J., Engelhardt, C., 2002. On the correspondence between morphological and hydrodynamical patterns of groyne fields. Earth Surf. Processes Landf. 27, 289–305.
Villanueva, P., 1994. Implicaciones Oceanográficas de los foraminíferos bentónicos recientes en la Bahía de Cádiz. PhD thesis, University of Cadiz, Puerto Real, Spain.
Wang, P., Kraus, N.C., Davis Jr., R.A., 1998. Total Longshore Sediment Transport rate in the surf zone: field measurements and empirical predictions. J. Coast. Res. 14 (1), 269–282.
Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118.
Wright, L.D., Short, A.D., Green, M.O., 1985. Short term changes in the morphodynamic states of beaches and surf zones: an empirical predictive model. Mar. Geol. 62, 339–364.