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Field Measurements of Longshore Sand Transport and Control Processes on a Steep Meso-Tidal Beach in Portugal

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ABSTRACT

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A field experiment was carried at Culatra Beach in Algarve (Southern Portugal) to determine longshore transport rates and sand mixing depth on a steep (slope 0.11) meso-tidal beach. The experiment was undertaken over one and a half tidal cycles using sand tracers in conjunction with wave and current monitoring. Variation of mean significant wave height during the experiment was limited (0.34–0.37 m) with mean zero-up crossing periods of 5.1–5.8 sec. Mean longshore current velocities in the breaker zone reached a peak in the second tide (0.28 m sec^{-1}), while they were one order of magnitude smaller during the first (0.02 m sec^{-1}) and third tide (0.04 m sec^{-1}). The increase in current speed was due to a moderate wind that was blowing along shore during the second tide. Average advection velocity of the tracer cloud and longshore currents showed a good correlation, leading to calculation of much larger transport rates for the second tide (1.38×10^{-2} m^3 sec^{-1}) than for the other two (0.23×10^{-2} m^3 sec^{-1}). Average depth of sand mixing of 10.6 cm in the beach face was 29% of breaking wave height and showed a marked uni-modal distribution, with maximum of 15 cm in the breaker zone. Previously published empirical formulae do not predict satisfactorily this behavior in depth of sand mixing that seems to be peculiar of steep beaches under plunging waves. Empirical formulae were used to compute theoretical longshore transport and compare it with field observations. They all underestimated measured transport rates of about one order of magnitude, thus confirming that the morphodynamics of steep beaches are characterized by relatively high sediment transport even in relatively low energy regimes.

ADDITIONAL INDEX WORDS: *Meso-tidal beach, plunging waves, fluorescent sand tracers, mixing depth, longshore transport, longshore wind, empirical models.*

INTRODUCTION

The prediction of littoral sand transport has important applications both in earth sciences and coastal oceanography and in the past 40 years efforts by oceanographers, sedimentologists and coastal engineers have greatly improved the understanding of the physical forces that control the process.

Net rates of longshore transport under carefully monitored physical conditions have been previously studied using large-scale sediment traps (DEAN *et al.*, 1982; KAMPHUIS *et al.*, 1986), portable sediment traps (KRAUS, 1987), dispersion of sand tracers (INGLE, 1966; KOMAR and INMAN, 1970; INMAN *et al.*, 1980; KRAUS *et al.*, 1982; TABORDA *et al.*, 1994) and beach profiles (BEREK and DEAN, 1982). Many of these beach experiments have led to the production of empirical formulae for predicting longshore sand transport mainly based on modifications of the original work of KOMAR and INMAN (1970). The main problem in using these empirical notations is that they contain an empirical coefficient which shows large variability due to environmental factors (KOMAR, 1988) that include beach characteristics such as grain size (DEAN *et al.*, 1982; KAMPHUIS *et al.*, 1986) and slope (KAMPHUIS *et al.*, 1986). Values of this empirical coefficient as proposed in the international literature varied by a factor of four since introduction (BODGE, 1989).

Recent reviews of field data on longshore sediment transport have concluded that there are large uncertainties regarding the distribution of sediment movement across the surf zone (BODGE, 1989), and the behavior of beaches for transport rates exceeding 0.2×10^6 m^3/year, significant wave height larger that 1.8 m, grain size coarser than 0.6 mm and beach slope steeper than 0.06 (SCHOONEES and THERON, 1993). The lack of information on steep beaches seems to be of particular importance, since their hydrodynamic behavior is radically different from that of low-gradient beaches

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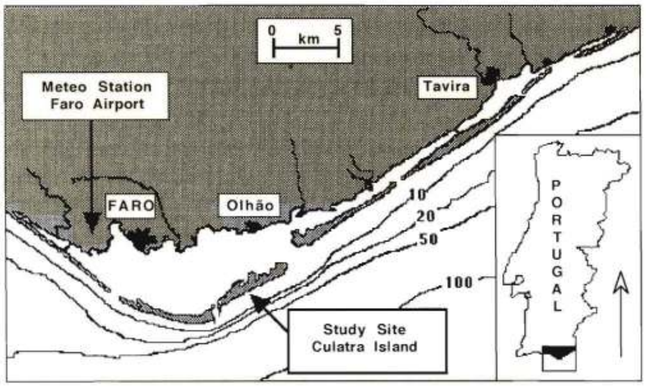

Figure 1. Index map of the Algarve barrier island system and continental shelf (depth contours are in meters below Mean Sea Level).

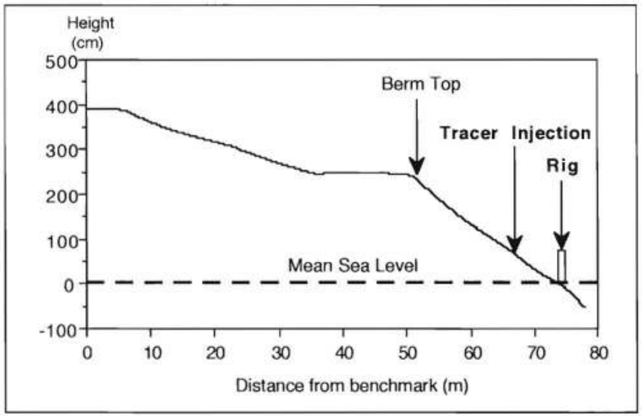

Figure 2. Beach profile at Culatra Beach at the beginning of the experiment and location of tracer injection and oceanographic rig.

(HUNTLEY and BOWEN, 1975). On steep beaches the surf zone tends to be narrow and swash processes and wave characteristics (e.g. plunging) become particularly important for sand remobilization (JACKSON and NORDSTROM, 1993).

The field experiment described in this paper took place over one and a half tidal cycles on 7 and 8 October 1993 on the beach of Culatra Island in Southern Portugal (Figure 1). The experiment was part of a field study (LUAR-Culatra '93) undertaken between 7 and 12 October 1992 by several Portuguese and European universities (Algarve, Lisbon, Southampton, East Anglia, Liverpool, Bordeaux) with the support of local and national authorities (Instituto Hidrográfico, Parque Natural da Ria Formosa, Capitania do Porto de Faro-Olhão).

Culatra Island is part of the 60 km long barrier island system of the Algarve, that exists under meso-tidal conditions (about 4 m maximum spring range), and moderate to high wave energy regime (PILKEY *et al.,* 1989). The studied beach had at the time of the experiment a reflective profile (Figure 2) with a steep foreshore (slope was 0.11), falling therefore within a category where published field studies are particularly scarce (SCHOONEES and THERON, 1993).

METHODOLOGY

A multi-instrument rig was deployed on the beach on 7 October 1993 at about 17 cm above local Mean Sea Level-MSL (Figure 2). The rig included a Sensym LX piezoresistive pressure transducer with onboard amplification and temperature compensation to record waves as in HARDISTY (1988). Currents were recorded by employing two discus type bi-axial electromagnetic Valeport 800 current meters mounted vertically in the structure at 17 cm (EMCM-1) and 45 cm (EMCM-2) above sea bed. Data from three successive high tides were logged on the morning of 7 October 1993 (05:20–08:23), hereafter indicated as 7/10am, evening of 7 October 1993 (17:40–21:28), hereafter 7/10pm, and morning of 8 October 1993 (07:09–09:03), hereafter 8/10am. Data logging was continuous during each tide using an IBM compatible desktop PC, running with an analog to digital converter card at a frequency of 5 Hz and segmentation of the information was in files corresponding to a duration of 10.24 minutes, thus giving 3072 data points for each time series.

The pressure transducer was calibrated in the laboratory to establish a linear relationship between pressure and water level and to determine the offset typical of the sensor as suggested by DAVIDSON (1992). A Fast Fourier Transformation was applied to each time series following the methods of EARLE and BISHOP (1984) before calculating significant wave height (H_s) and mean zero-up crossing period (T_z) with spectral methodologies using routines available in the popular MATLAB® environment (digital signal processing toolbox). Angles of wave approach at breaking point were calculated by refraction of deep water waves hindcasted for the time of the experiment using a wind stress model (PIRES and RODRIGUES, 1988) and validation by field observations. Times when the rig was inside the surf zone were also recorded in the field. Voltage readings of longshore and cross-shore currents collected in the field were converted into speed units (m sec^{-1}) using a laboratory calibration carried out at the University of Southampton following the methodology of GUZA *et al.* (1988).

Hourly average wind speed and direction for the time of the experiment was supplied by the weather station of the Instituto de Meteorologia located at the nearby Faro airport (15 km distant, see Figure 1), being collected by an anemometer located at 17 m above MSL.

A composite sediment sample of about 120 kg was collected at the field site on the lower foreshore and a sub-sample of 120 g was analyzed for particle size determination by dry sieving using a set of meshes ranging between 4 mm (−2 Phi) and 0.063 mm (4 Phi), following the methodology of INGRAM (1971). Mean grain size, sorting and skewness of the sand population was calculated using the FOLK's (1974) graphical parameters. After collection the composite sample was dried in the open air and tagged using an orange fluorescent paint, according to criteria outlined by previous investigators (INGLE, 1966; YASSO, 1966). The tagged sand was then dried again in the open air and sieved afterwards using a 2 mm (0 Phi) mesh to screen for aggregates. A sub-sample (120 g) of

Table 1. *Significant Wave Height (H_s) and Zero-up Crossing Period (T_z) measured during the experiment.*

Tide	Maximum H_s (m)	Mean H_s (m)	Minimum T_z (sec)	Maximum T_z (sec)	Mean T_z (sec)
7 October am	0.44	0.37	5	6.5	5.8
7 October pm	0.38	0.34	4.1	6.1	5.1
8 October am	0.41	0.37	4.6	5.5	5.1

the tracer sand was then analyzed for grain size determination to assess statistical similarity between the original sand population and the tagged one.

On 7 October 1993 the tracer sand was injected at low tide on the lower foreshore at an horizontal distance of 16 m from the berm top (Figure 2) immediately before starting to collect oceanographic data. The method of injection is comparable to that used by previous authors (King, 1951; Williams, 1971; Corbau *et al.,* 1994; Taborda *et al.,* 1994; Dolphin *et al.,* 1995) by digging a shallow trench with an area of 2 m² and average depth of 3 cm. In order to obtain an independent assessment of the thickness of the mixing sand layer (Komar and Inman, 1970; Kraus *et al.,* 1982; Kraus, 1985; Sunamura and Kraus, 1985; Jackson and Nordstrom, 1993) a control hole 30 cm deep was dug next to the injection trench and filled with tracer sand up to surface level (King, 1951; Komar and Inman, 1970; Williams, 1971; Taborda *et al.,* 1994). At each low tide four beach transects were studied for changes in beach profile using a standard theodolite, being located at 0, 20, 40 and 60 m eastwards of the injection site.

Following field observations of the gross direction of longshore drift, shallow cores (about 25 cm long) of the beach face were collected at low tide along a grid of sample stations eastwards of the injection site. No cores were collected where *in situ* inspection of the sand surface revealed that the site was not covered by water at high tide.

The cores were collected using 30 cm long PVC tubes that were split lengthwise. Each core provided vertical samples equivalent to 5 cm intervals. Samples were put into plastic bags and back in the laboratory oven dried at 40°C and carefully desaggregated using an Agate mortar before undertaking counting under an UV source. The total number of grains counted in each sample was normalized by the sample weight to obtain an absolute mass value (number of grains per unit weight of sediment). In order to assess tracer advection behavior a Lagrangian approach was adopted (Madsen, 1987), commonly known as the Spatial Integration Method (Komar and Inman, 1970; Inman *et al.,* 1980; Kraus *et al.,* 1982; Madsen, 1987; Taborda, 1993; Taborda *et al.,* 1994):

$$Y = \frac{\Sigma P_i d_i}{\Sigma P_i} \qquad (1)$$

where Y is the location of the mass center of the tracer cloud along the two-dimensional sampling grid, P_i is the mass of tracer recovered at each grid point and d_i is the distance of the grid point from the injection site. For each sampling exercise the position of the mass center was calculated independently for every depth interval within the cores (0–5, 5–10, 10–15 cm, etc.) and a weighted position of the total mass center was calculated according to the tracer concentration in each interval. The horizontal translation of the center of mass was referred to the injection point for the first tide, while the position measured at the previous low tide was used for the second and third counts (Kraus *et al.,* 1982).

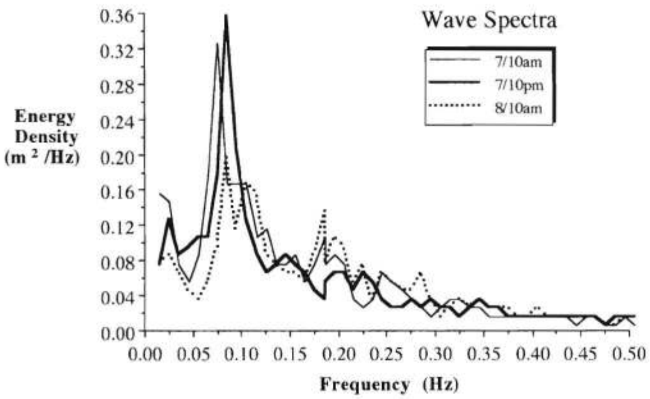

Figure 3. Wave energy spectra for the three tides measured at high water outside the breaker zone. The spectra are typical of a 10.24 min data run.

Average advection speed of the tracer was calculated by dividing the distance covered by the center of mass during half tidal period for the interval between two consecutive high tides (12 hours and 30 minutes). A line of cores was collected at 400 m from the injection point orthogonally from the berm to provide information on cross-shore changes in the thickness of the moving sand layer as previously done by Komar and Inman (1970). Total sand transport rate was then obtained by multiplying the tracer advection speed by the area of the moving sand layer (Komar and Inman, 1970).

RESULTS

Physical Processes

During the first semi-tidal cycle that was studied on 7 October (7/10am) wave motion was weak, with H_s ranging between 0.33–0.44 m and T_z between 5.0 and 6.5 sec (Table 1). Mean H_s and T_z measured in the breaker zone were respectively 0.37 m and 5.8 sec. Southwesterly waves were breaking at an estimated angle of 5° with the shoreline, plunging directly onto the beach face. The wave spectrum measured at high tide indicates the presence of long period waves ($T = 14$ sec) together with shorter period waves (Figure 3). Longshore currents were weak and predominantly eastwards, with EMCM-1 recording an average value 0.01 m sec^{-1} within the breaker zone (Figure 4a) and EMCM-2 recording 0.02 m sec^{-1} (Figure 4b). Maximum tidal elevation was 0.84 m above MSL and there was no significant wind (Figure 5).

Wave motion during the second half tidal cycle on 7 October (7/10pm) did not change significantly, with H_s ranging between 0.28–0.38 m and T_z of 4.1–6.1 sec, giving for the breaker zone values of mean H_s of 0.34 m and T_z of 5.1 sec (Table 1). Southwesterly waves approached the shoreline at

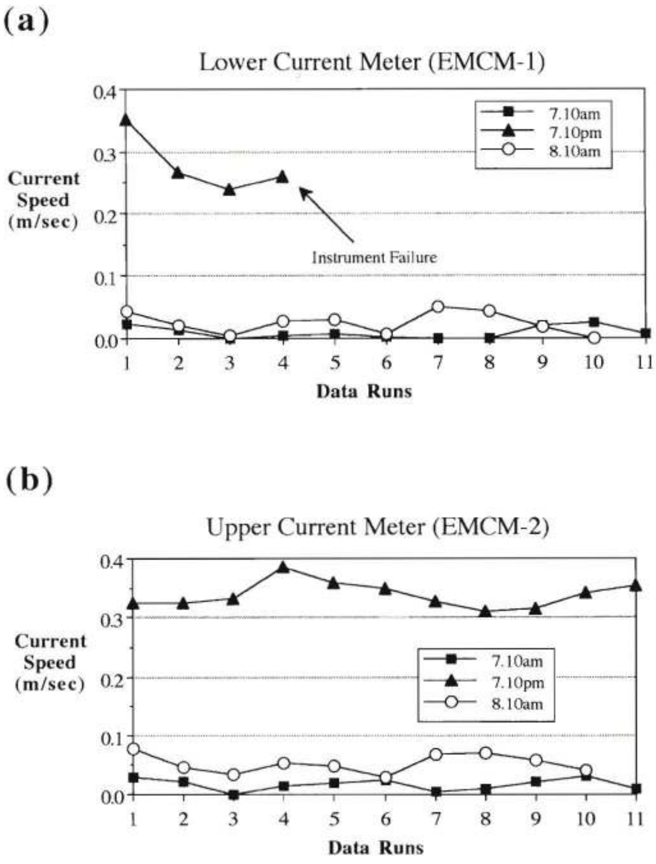

Figure 4. Longshore current speeds measured during the experiment by the lower (4a) and upper (4b) current meters. Notice that the lower current meter (EMCM-1) did not provide a continuous record during the second tide because it became buried under the sea bed. Longshore current readings are averaged over every 10.24 min data run.

an angle of about 5°, and similarly to the previous tide, plunging waves were breaking directly onto the foreshore. Examination of the wave spectrum at high tide (Figure 3) points out analogies with the previous dataset, particularly the existence of a swell with a period of about 13 sec. The lower current meter (EMCM-1) stopped working at 18:20, probably because it became buried under the sea bed. However, prior to failure, longshore current readings were in the order of 0.24–0.35 m $\sec^{-1}$ (Figure 4a). The upper current meter (EMCM-2) provided instead more reliable data until starting to come out of water at 20:25, giving average readings of an eastward longshore current of 0.28 m $\sec^{-1}$ (Figure 4b). A brisk longshore wind was blowing from a westerly direction (azimuth 260–300° N) with hourly average speeds of up to 28 km hr^{-1} (Figure 5). Maximum tidal elevation was 0.64 m above MSL.

The wave climate during the third half tidal cycle on 8 October (8/10am) was characterized by southwesterly waves with H_s ranging 0.34–0.41 m and T_z of 4.6–5.5 sec (Table 1). Plunging waves were breaking directly onto the beach face at an estimated angle of 5° with the shoreline and average wave conditions at breakers were H_s of 0.37 m and T_z of 5.1 sec. The wave spectrum shows that the swell was still present with a period of 13 sec but higher frequency waves had increased in energy (Figure 3). Longshore currents were eastwards with a magnitude comparable to the first tide since the average recorded by EMCM-1 within the surf zone was 0.03 m $\sec^{-1}$ (Figure 4a) and by EMCM-2 was 0.06 m $\sec^{-1}$ (Figure 4b). During the collection of oceanographic data a weak easterly wind (azimuth 80–110° N) was blowing with average hourly speed up to 9 km hr^{-1} (Figure 5). Maximum tidal elevation was 0.72 m above MSL.

Beach Characteristics and Sand Transport

The beach foreshore maintained a steep profile with an average slope of 0.11 during the time of the experiment. Comparison between surveys carried out on 7 and 8 October 1993 showed weak accretion above MSL and erosion below MSL

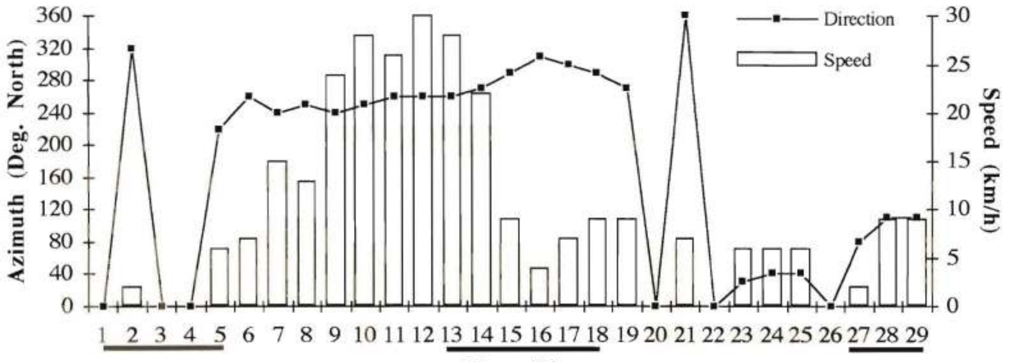

Figure 5. Wind data collected at the meteorological station of Faro Airport. Directions and speeds are hourly averages. Time is indicated in hours from the beginning of the beach experiment, monitored tides are indicated with underlined numbers. N.B. Intervals when there was no wind are indicated by a null value in the graph of wind direction.

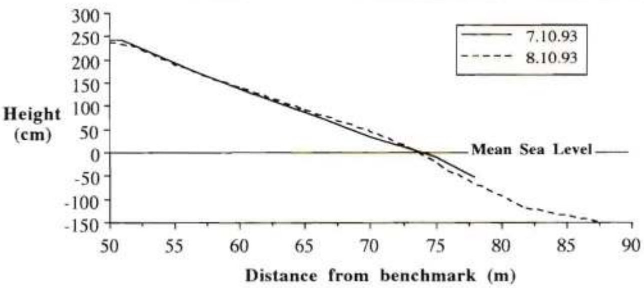

Figure 6. Beach profiles at the study site carried out on 7 and 8 October 1993.

of about 20 cm (Figure 6). During the second tide small beach cusps developed, with an average spacing of 20 m on the foreshore. In order to define the energy regime of the beach, typical during the experiment, the surf *scaling* parameter (ϵ) was calculated (GUZA and INMAN, 1975):

$$\epsilon = \frac{(a\omega^2)}{g \tan^2\beta} \quad (2)$$

where a is the wave amplitude (H/2), ω is the wave radian frequency ($2\pi/T$), g is the gravitational constant and β is the beach slope. Values of (ϵ) range from 1.78 for the first tide, 2.20 for the second and 2.31 the third one, describing the morphodynamic behavior of the beach as reflective (GUZA and INMAN, 1975). As recently MASSELINK and HEGGE (1995) pointed out, (ϵ) is interchangeable with the surf *similarity* parameter (ξ) of BATTJES (1974) considering that $\xi=(\pi/\epsilon)^{1/2}$. Values of (ξ) for the first (1.33), second (1.19) and third tide (1.17) predict breaking waves as plunging breakers, thus in agreement with field observations.

The beach consists of moderately sorted fine to medium sand (M_z=0.26 mm) with predominant quartz grains. Assessment of grain size distribution before and after coating with fluorescent paint did not show significant changes (Figure 7). Using the sediment fall velocity (w_s) together with the measured modal wave height at breakers (H_{bm}) and modal wave period (T_m), the dimensionless fall velocity ($\Omega=H_{bm}/w_sT_m$) describing the beach state during the experiment (WRIGHT and SHORT, 1984) is 1.59 for the first tide, 1.67 for the second and 1.81 for the third one, which together with the mean spring-tide range (about 3 m) classify the beach as *reflective with low tide terrace* (MASSELINK and SHORT, 1993; MASSELINK and HEGGE, 1995), a conceptual model that agrees well with the morphology of the profile surveyed on 8.10.1993 (Figure 6) despite that the latter did not extend far enough to include the terrace. Indeed yearly monitoring at a nearby site (Praia de Faro) shows that this is the most frequent beach state for the barrier-island beaches (TOMÉ MARTINS *et al.*, 1996).

On the first low tide in the evening of 7 October, 24 cores were collected every ten meters from the injection point in a longshore direction at distances between 0 and 20 m from the berm top. The last core was collected at a longshore distance of 100 m. On the low tide in the morning of 8 October, 14 cores were collected every 50 m along a line at 20 meters from the berm top, the last core being 700 m eastward of the injection site. On the low tide in the afternoon of 8 October 11 cores were collected every 100 m at a distance between 15 and 20 m from the berm top, with the last sample located at 1000 m from the injection point. The discrepancy between the number of cores recovered at different samplings is due to the fact that sites uncovered at high tide were not considered. The position of the high tide mark varied during the experiment due to changes in tidal excursion, beach cusp topography and wave and wind set-up. The longshore distance between sampling transects varied during the three tides (every 10 m for the first one, every 50 m for the second one and every 100 m for the third one) in order to obtain the best coverage of the area of tracer dispersion considering time constraints. Information on cross-shore variations of the depth of sand mixing were obtained studying in detail a line of cores located at 400 m from the injection point where five cores were collected at 0, 5, 10, 15 and 20 m from the berm top. The majority of tracer recovered in each core, calculated using a cut-off percentage of 80 % (KRAUS *et al.*, 1982), was on average distributed within the interval 0–15 cm in all three

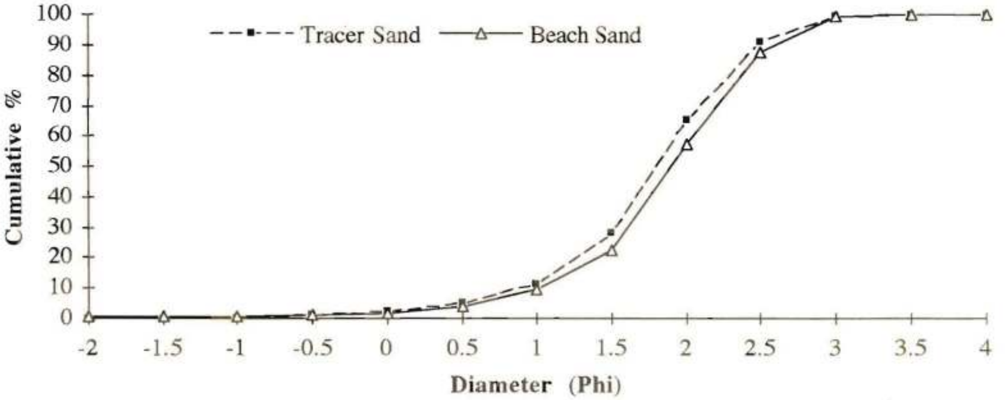

Figure 7. Cumulative distributions of grain size in the original and tagged beach samples.

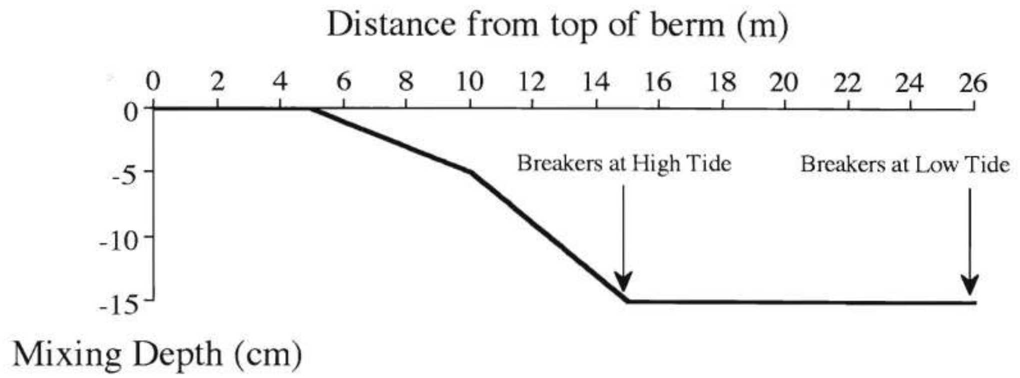

Figure 8. Changes in depth of activity along a shore-normal transect located at 400 m from the injection site. The represented pattern was constant throughout the experiment.

tides. Depth of sand mixing varied between 2.5 cm in the swash zone and 15 cm at the breaker line (Figure 8). The control hole dug near the injection site and filled up with tracer sand measured a depth of sand mixing during the first tide of 13.5 cm, showing therefore good agreement with the results obtained from the cores that were used for calculating the thickness of the sand layer in motion. From the graph in Figure 8, it can be seen that the average mixing depth (Z_m) in the five cores is 10.6 cm, while the maximum values are observed in the breaker zone (15 cm).

Observed average longshore velocity of tracers advection during the first tide was 0.96×10^{-3} m sec^{-1}, leading to a displacement of 43 m of the mass center of the tracer cloud. The second tide registered larger values, with an average advection speed of 5.69×10^{-3} m sec^{-1} and a mass center displacement of 256 m. Values for the third tide reversed to levels similar to the first tide, with an average advection speed of 0.94×10^{-3} m sec^{-1} and a displacement of 43 m. Calculated rates of total longshore transport obviously reflect the data presented above, with 0.23×10^{-2} m^3 sec^{-1} for the first tide, 1.38×10^{-2} m^3 sec^{-1} for the second tide and 0.23×10^{-2} m^3 sec^{-1} for the third one.

DISCUSSION

Sand Mixing Depth

The usage of sand tracers for empirical calculations of longshore sand transport is dependent upon a reliable assessment of the thickness of the moving sand layer (KRAUS, 1985; SUNAMURA and KRAUS, 1985). Previous authors have tried to take direct measurements in the field using plug holes filled up with tagged sand (KING, 1951; WILLIAMS, 1971; SONU, 1972; TABORDA *et al.*, 1994), distribution of tracer sand in beach cores (KOMAR and INMAN, 1970; GAUGHAN, 1978; KRAUS *et al.*, 1982; KRAUS, 1985; SUNAMURA and KRAUS, 1985; SHERMAN *et al.*, 1990; SHERMAN *et al.*, 1994; DOLPHIN *et al.*, 1995) and depth-of-disturbance rods (GREENWOOD and HALE, 1980; JACKSON and NORDSTROM, 1993; DOLPHIN *et al.*, 1995). An empirical method for the calculation of the average mixing-depth on a non-barred beach is that of KRAUS (1985):

$$Z_m = 0.027\ H_b \tag{3}$$

where Z_m is the average sand mixing depth and H_b is the significant wave height at breaking point. If the method is applied using the wave data from the LUAR-Culatra '93 experiment, predicted values of average mixing-depth are 1.0 cm for tide 7/10am, 0.92 cm for 7/10pm and 1.0 cm for 8/10am, thus significantly less than the average calculated using the values of Figure 8 (10.6 cm). Moreover, the distribution of depth of activation in the surf zone at Culatra is uni-modal (Figure 8) and not bi-modal as observed by previous studies on gentle beaches (INMAN *et al.*, 1980; KRAUS, 1985), which show maxima near the breaker line and the shoreline. According to JACKSON and NORDSTROM (1993), breakers plunging onto steep foreshores are converted directly into swash and cannot produce variations in activation landward of the breaker line.

Disparity between the predictions of KRAUS (1985) and field observations on steep beaches had been noted in previous studies (JACKSON and NORDSTROM, 1993; SHERMAN *et al.*, 1994; TABORDA *et al.*, 1994). There is indeed some debate in the literature on the predominant factors controlling the depth of sand activation at a given site. Although it is recognized that there is a direct relationship of some kind with breaker height (KING, 1951; WILLIAMS, 1971; KRAUS, 1985), it is also evident that there is a great variability when data from different sites are compared (JACKSON and NORDSTROM, 1993). The field database of KRAUS *et al.* (1982) and KRAUS (1985) contained only one beach (Hirono) with characteristics comparable to Culatra. Results from steep beaches in low-wave energy environments have proved that mean depths of activation tend to be greater than in gentle beaches (JACKSON and NORDSTROM, 1993; SHERMAN *et al.*, 1994) and of the order of 22% of the breaker height according to SHERMAN *et al.* (1994). The average value measured at Culatra (10.6 cm) provides a relationship with the wave height at breakers (assuming a value of 0.36 m as an average for all three tides) of 29%, thus showing close agreement with SHERMAN *et al.* (1994). In a similar way, the maximum value observed (15 cm) provides a ratio with the breaking wave height

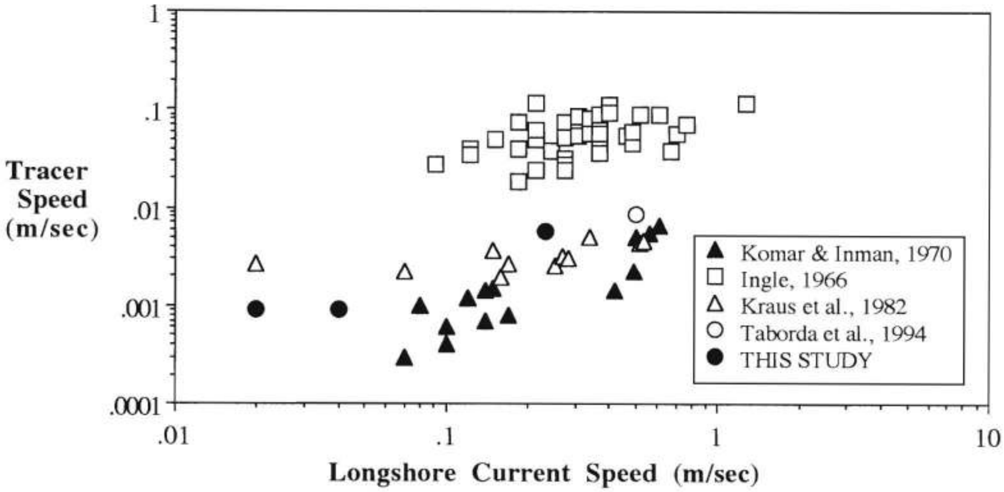

Figure 9. Plot of tracer advection speed versus average longshore current speed measured during the experiment and by previous authors.

of 41%, very similar to the 40% obtained by WILLIAMS (1971) on Honk Kong beaches.

Longshore Sand Transport

The obtained field measurements of sediment transport offer an opportunity to test empirical formulae for the prediction of longshore drift although the single point measurements of flow oscillations are spatially limited. However, since the foreshore at Culatra had a constant slope and no bar was present, mean flows across the nearshore should not show the large spatial variations observed on barred beaches.

Although criticisms have been made of tracer methodology due to its sensitivity to variations in the transporting system and inability to reach equilibrium conditions (SCHOONEES and THERON, 1993), the technique is nevertheless simple to use for estimating total longshore drift within an entire semi-tidal cycle. In the Culatra experiment the advection speed of the tracer cloud correlated with the acceleration in longshore current speed that was measured during the second tide. The results are consistent with those obtained by other authors using comparable methodologies (Figure 9), with the exception of the data of INGLE (1966), where advection speeds are greater. However, careful re-interpretation of that data set may prove fruitful as the transport rate was computed using only surface dispersion of the tracer.

For computations of theoretical transport rates it is useful to express rates of littoral drift as immersed transport rates (I_l) as given in INMAN and BAGNOLD (1963):

$$I_l = (\rho_s - \rho)(1 - p)Q \qquad (4)$$

where ρ_s is the sand density, ρ is the sea water density, p is the sand porosity (0.4) and Q is the volume of sand transport. If one uses S.I. units for the densities [kg m^{-1}] and for the volumes [m^3], (I_l) will be expressed as [Newton sec^{-1}], which have a physical meaning and can be related to the forces driving the sediment alongshore (BAGNOLD, 1963; INMAN and BAGNOLD, 1963):

$$I_l = K'(ECn)_b \cos \alpha_b \frac{\bar{v}_l}{u_m} \qquad (5)$$

where $(ECn)_b$ is the wave energy flux within the breaker zone, α_b is the breaker angle, v_l is the longshore current in the surf zone (here taken as an average), u_m is the maximum wave orbital velocity at breakers computed using linear wave theory and K′ is an empirical dimensionless coefficient that KOMAR and INMAN (1970) calculated as 0.28 and KRAUS *et al.* (1982) as 0.21. Since for small α_b the term ($\cos \alpha_b$) can be considered equal to one, uncertainties in the determination of the breaker angle have limited effects on the determination of I_l (KOMAR, 1988).

Although Equation 5 is often presented in the form directly related to the longshore component of wave power at breakers (KOMAR and INMAN, 1970), whenever external factors such as tides, cell circulation or local winds are present, such a formula cannot be applied (KOMAR, 1976; ALLEN, 1985; KOMAR, 1988). The difference in magnitude of longshore current that was observed in the breaker zone on 7/10pm (average speed of 0.28 m sec^{-1}) can only be explained by the effect of the local longshore wind blowing at the time of the measurements in the same direction as the current, since no appreciable change in wave characteristics was observed, thus justifying the application of Equation 5. HUBERTZ (1986) had indeed noticed at the CERC's Field Research Facility (Duck, Carolina, USA) that longshore wind can increase the longshore current up to a factor of three.

There is however the problematic issue of what value of K′ should be used, since there are environmental controls (e.g. grain diameter, settling velocity, beach slope, wave steepness) that should be accounted for (KOMAR, 1988). Previous papers (ALLEN, 1985; ALLEN, 1988) have discussed the variability of the empirical coefficients in the two equations of KOMAR & INMAN (1970) despite attempts of researchers to relate them to mean sand diameter (DEAN *et al.*, 1982), beach slope, significant breaker height and breaker index (KAM-

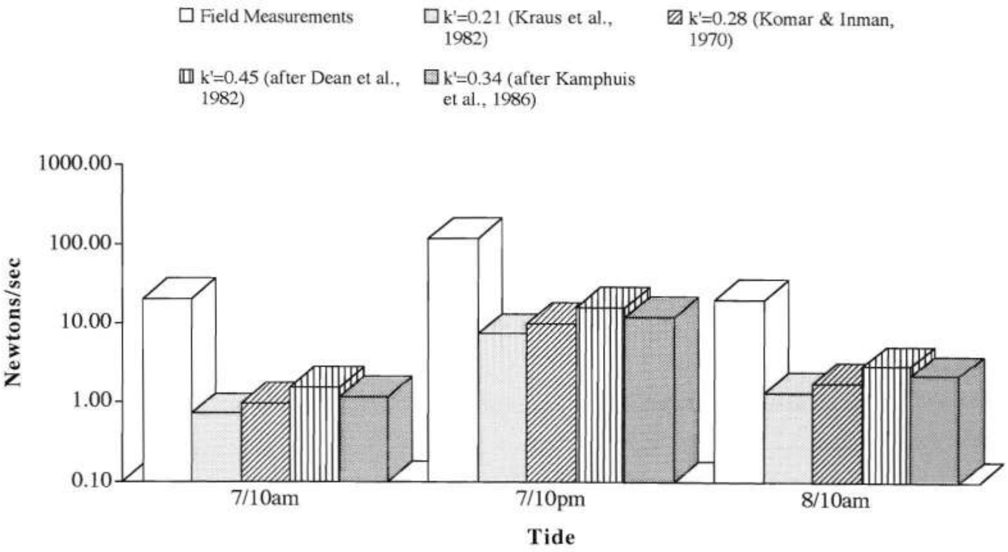

Figure 10. Comparison between observed and predicted values of Immersed Weight Sand Transport Rate (I_l). The predictions are computed using different K′ coefficients in Equation 5.

Kamphuis *et al.*, 1986). Values of field observations of I_l calculated using Equation 4 are compared in Figure 10 with theoretical predictions using in Equation 5 the K′ constants of 0.28 (Komar and Inman, 1970) and 0.21 (Kraus *et al.*, 1982), or K′ values of 0.45 calculated using the methodologies of Dean *et al.*, (1982) and 0.34 of Kamphuis *et al.*(1986). All solutions predict a transport rate an order of magnitude less than that observed, thus within the accuracy of prediction that Allen (1988) believes to be typical of the methodology. In a field study comparable to Culatra Island, Allen (1985) concluded that the energy flux approach offers better accuracy of prediction than the energetics model, since the orbital wave velocity in Equation 5 is difficult to measure. However, since in the Culatra study large non-wave driven currents were present during the second tide, for uniformity of data comparison the energetic approach is preferred.

The difference between field observations at Culatra Island and theoretical predictions of longshore transport may be due to limited field information in the literature on steep beaches (Schoonees and Theron, 1993). As it can be seen in Figure 11, there is some scatter if all data on reflective foreshores (slope larger than 0.05) are plotted together, which becomes

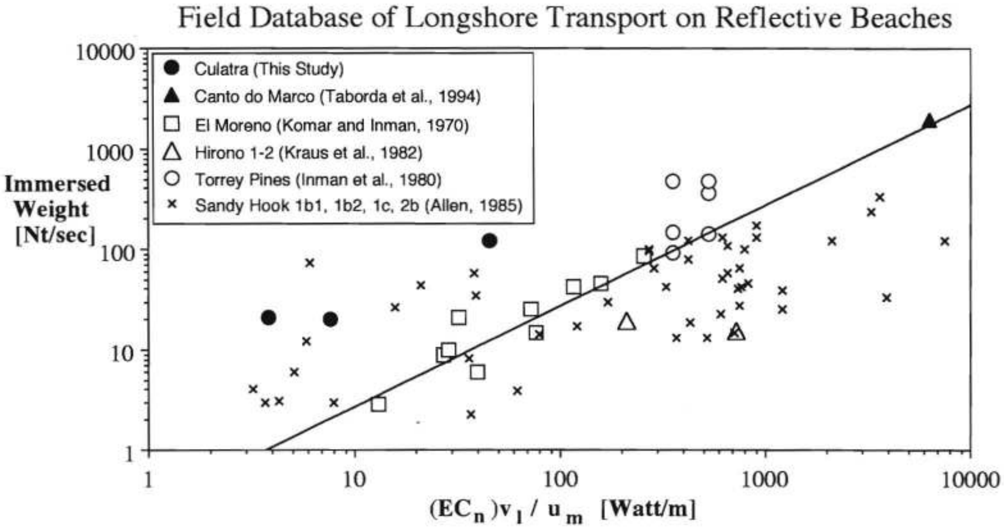

Figure 11. Measured Immersed Weight Sand Transport Rates (I_l) obtained during field studies of reflective beaches (slope larger than 0.05). Notice the restricted information available at the lower and upper ends of the scale. The line represents Equation 5 fitted with a K′ coefficient of 0.28.

more evident if the theoretical line of Equation 5 is plotted with a K′ of 0.28 (KOMAR and INMAN, 1970). The data from El Moreno Beach (KOMAR and INMAN, 1970) show a more linear trend than the rather large database of ALLEN (1985) which comes from several locations along the ocean side of Sandy Hook (NJ, USA). INMAN *et al.* (1980) even admit large uncertainty in their data, publishing not single values of transport but ranges for each experiment.

The available field database becomes even more restricted when only beaches with slope larger than 0.08 are considered. Published studies that are directly comparable to Culatra Beach are only El Moreno Beach in California (KOMAR and INMAN, 1970) and Hirono Beach in Japan (KRAUS *et al.* 1982), where however average (D_{50}) grain size was coarser (about 0.60 mm). Results of a study carried out in Portugal by TABORDA *et al.* (1994) at Canto do Marco Beach (slope=0.08 and D_{50}=0.60 mm) in high wave energy conditions are also presented in Figure 11 and seem to agree remarkably well with the theoretical prediction.

CONCLUSIONS

The field study carried out at Culatra Island confirmed a good correlation between speed of advection of tracer sands and longshore currents. Despite an almost constant wave regime throughout the experiment (H_s=0.28–0.44, α=5°) there was a change of one order of magnitude in longshore current and transport during the second tide (7/10pm). This is explained as due to a change in the azimuth and speed of local wind, that was blowing longshore with an average speed of 28 km hr^{-1} during that part of the experiment. Such a phenomenon has confirmed that is preferable to use the energetic model (BAGNOLD, 1963; INMAN and BAGNOLD, 1963), rather than the wave power approach (KOMAR and INMAN, 1970), for the prediction of longshore sand transport if field measurements of longshore current are available.

A disparity has been identified between field measurements of sand transport and predictions using empirical formulae (KOMAR and INMAN, 1970; DEAN *et al.*, 1982; KRAUS *et al.*, 1982; KAMPHUIS, *et al.*, 1985), proving that the accuracy of the methodology is not better than one order of magnitude (ALLEN, 1988). This could be due to several factors, such as scarcity of similar data in the literature and errors in measuring the effective sand transport rate. Field observations of the depth of activity due to wave action have confirmed the limitation of empirical formulations (KRAUS *et al.*, 1982; KRAUS, 1985) when applied to steep beaches under plunging wave conditions, as this had been noted by JACKSON and NORDSTROM (1993) and SHERMAN *et al.* (1994).

The present study does not introduce new empirical notations to replace those in the literature, since it is only based on one particular beach within quite a restricted wave energy spectrum and experience has shown the risks of generalization. The main conclusion is that it is necessary to improve the understanding of the sedimentary behavior of steep reflective beaches, where, because of the short surf zone, wave energy dissipation takes place over small distances, leading to relatively high alongshore sediment transport rates. If this concept is accepted, discrepancies between mean annual transport rates estimated using sediment budget analysis from wave models and field observations might be much larger than the one order of magnitude measured in this study or pointed out in previous reviews. The universal applicability of coefficients determined by other authors should not be assumed, because of the empirical nature of such parameters. Each beach type is believed to behave in an almost unique way regarding longshore sand transport and steep reflective beaches are certainly the least understood.

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☐ RIASSUNTO ☐

E' stato svolto un esperimento di campagna sulla spiaggia di Culatra (Portogallo meridionale), per determinare il tasso di trasporto di sabbie lungocosta e la profonditá di rimaneggiamento del sedimento di fondo su una spiaggia mesotidale (marea semidiurna) con elevata pendenza ($\tan\beta = 0{,}11$). L'esperimento é stato effettuato durante un ciclo e mezzo di marea utilizzando delle sabbie marcate come traccianti assieme a misure del moto ondoso e correntometriche. La variazione dell'altezza significativa media delle onde durante l'esperimento é stata limitata (0,34–0,37 m), mentre il periodo medio di zero-up crossing é stato nell'ordine di 5,1–5,8 sec. La velocitá media delle correnti lungocosta ha raggiunto un picco massimo durante la seconda marea (0,28 m sec^{-1}) per la presenza di un vento moderato che soffiava lungocosta, mentre durante la prima (0,02 m sec^{-1}) e la terza marea (0,04 m sec^{-1}) i valori di corrente sono stati nettamente inferiori. La velocitá media di trasporto della sabbia tracciante é risultata fortemente correlata con quella delle correnti lungocosta con una velocitá di trasporto molto maggiore per la seconda marea ($1{,}38\times10^{-3}$ m^3 sec^{-1}) che per le altre due ($0{,}23\times10^{-3}$ m^3 sec^{-1}). La profonditá di rimaneggiamento del sedimento di fondo nella porzione intertidale della spiaggia si é mantenuta costantemente su un valore medio di 10,6 cm durante tutto l'esperimento. Essa é risultata circa 29% dell'altezza d'onda nel punto di frangenza con una distribuzione unimodale e con punte massime di 15 cm nella zona dei frangenti. Le formulazioni empiriche pubblicate da precedenti autori non riproducono in maniera soddisfacente tale comportamento della profonditá di rimaneggiamento su spiagge a pendenza elevata sotto l'influenza di frangenti di tipo plunging. E' stato inoltre calcolato il tasso teorico di trasporto lungocosta e comparato con i dati di campagna. Tutti i calcoli teorici sottoestimano le osservazioni reali di circa un ordine di grandezza. Lo studio mette in evidenza come le spiagge a pendenza elevata presentino un tasso di trasporto alto anche in condizioni energetiche relativamente basse.

☐ RESUMO ☐

Realizou-se em 7 e 8 de Outubro de 1993 uma experiência de campo, na Ilha da Culatra (Algarve), tendo como objectivo a determinação de taxas pontuais de transporte longilitoral e de valores de profundidade de remobilização da areia numa praia mesotidal com forte pendor ($\tan\beta = 0.11$). A experiência decorreu durante um ciclo e meio de maré, tendo sido utilizada a metodologia de areias marcadas por fluorescência em simultâneo com a aquisição de dados de ondas e correntes. As médias das alturas significativas e as médias dos períodos obtidos durante a experiência tiveram variação reduzida, de 0.34 m a 0.37 m e de 5.1 sec a 5.8 sec respectivamente. A velocidade média das correntes longilitorais na zona de rebentação atingiu um pico na segunda maré (0.28 m sec^{-1}), enquanto que na primeira (0.02 m sec^{-1}) e na terceira marés (0.04 m sec^{-1}) as velocidades obtidas foram uma ordem de magnitude inferiores. O aumento da velocidade da corrente deveu-se à existência de vento moderado no sentido da corrente, durante a segunda maré. As velocidades médias obtidas para o transporte do traçador mostram uma relação directa com a velocidade da corrente, permitindo o cálculo de uma taxa de transporte sedimentar muito superior para a primeira maré (1.38×10^{-2} m^3 sec^{-1}) do que para as outras duas marés (0.23×10^{-2} m^3 sec^{-1}). A profundidade de remobilização da areia na face da praia foi relativamente constante ao longo da experiência, com um valor médio de 10.6 cm (29% da altura significativa na rebentação) e um máximo de 15 cm, na zona de rebentação. Várias fórmulas empíricas frequentemente utilizadas não reproduzem satisfatoriamente os elevados valores obtidos no campo para a profundidade de remobilização, facto que parece ser característico de praias com declive acentuado e com ondas na rebentação do tipo “plunging”. Foram ainda testadas as fórmulas empíricas mais frequentemente utilizadas para o cálculo do transporte longilitoral, tendo-se comparado os seus resultados com as observações de campo. Todas as fórmulas utilizadas subestimaram a taxa de transporte em diferenças de valores próximos de uma ordem de grandeza, confirmando que a morfodinâmica de praias com declive acentuado é caracterizada pelo elevado transporte sedimentar, mesmo que em regime de baixa energia.