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CHARACTERISATION OF THE ALONGSHORE DYNAMICS OF AN ESTUARINE BEACH

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Key words: Estuarine beach, low energy beach, fetch-limited beach, low gradient terrace, wind regime, wind wave, longshore transport, SWAN model, LITPACK model.

ABSTRACT

The hydrodynamics and alongshore sediment dynamics were evaluated on a meso-tidal estuarine beach, submitted to wind and vessel waves generated in an area of restricted fetch, not affected by oceanic waves. The beach morphology is characterised by two main features, a steep upper beach followed, seaward, by a low gradient terrace, both engaged in the surf zone depending on the tidal level. Sedimentologic surveys revealed the presence of coarser sand grains at the steep upper beach, finer sand grains at the low gradient terrace and a large geometrical spreading at the base of the beach face. The characterisation, based on a six-year wind data series, of the average annual wave climate in front of the beach, indicates a low energy environment where the estimated longshore transport is $14.5x10^3$ $m^3.year^{-1}$, equally distributed in both directions. This study also concluded on the cross-shore distribution of the longshore sediment transport in the active part of the beach and on the contribution of each wind wave component to the longshore transport. Despite the important impact that the catamarans can have on cross-shore beach dynamics, their effect on the longshore transport is irrelevant.

INTRODUCTION

Unlike most of the beaches in Portugal that face either west or south into the Atlantic and are dissipative by nature as response to the well developed wave field of oceanic origin, Alfeite is an estuarine beach submitted to wave action generated in a fetch-limited estuary. The objective of the present study was to evaluate the average annual alongshore sediment transport of this estuarine sandy beach, subjected to wind and wake wave action and to the astronomical tide. The geomorphology of the estuary is such that, unlike for the beaches located in the estuary mouth, oceanic waves do not reach this internal beach. Alfeite beach fits into the classification of low energy beach, despite the great variety in the application of his term. It satisfies the

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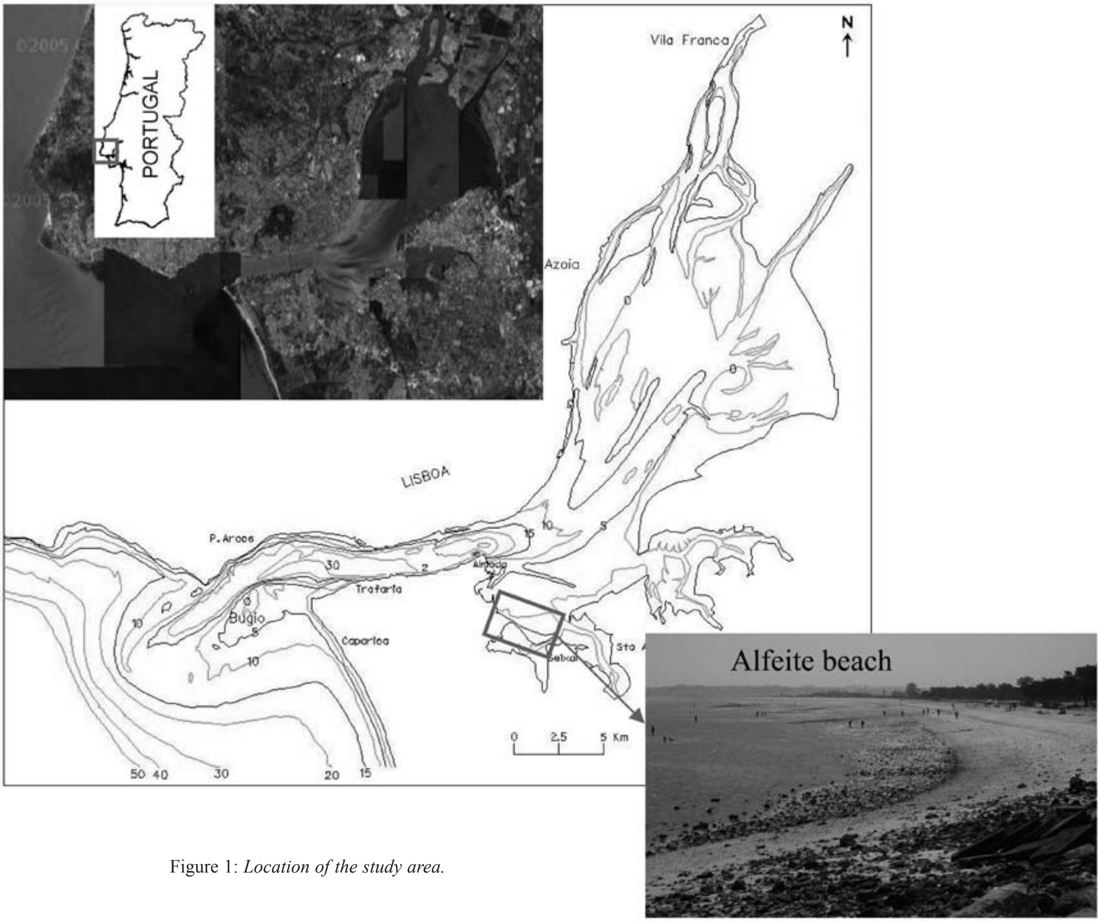

Figure 1: *Location of the study area.*

definition suggested by Jackson *et al*. (2002), based on the characteristics of the incident waves (height and period); but also a more vague definition as suggested by other authors (Ragan and Smosna, 1987; Barusseau *et al*., 1994), based on the geomorphology and site-specific sheltering conditions.

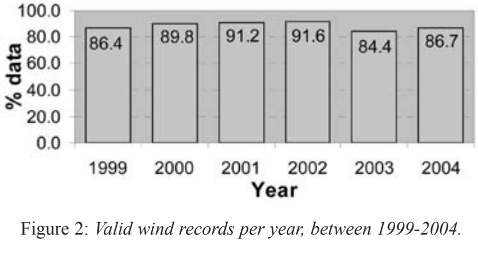

Figure 2: *Valid wind records per year, between 1999-2004.*

STUDY AREA

The Tagus estuary, of about 320 km^2, extends from the Tagus mouth until a location called Vila Franca de Xira, where the salinity is negligible (at normal hydrological conditions). The estuary has two main parts: the channel, deep and narrow, with main alignment ENE-WSW, and the internal estuary, shallow and large, with main alignment NNE-SSW (Figure 1). The sea water temperature varies along the year: 14-15º C in the first trimester; 16-17º C in the second and fourth trimester; and 18-19º C in the third trimester. The internal estuary has a maximum width of 15 km in the alignment of the predominant wind, favouring the establishment of a sandy beach,

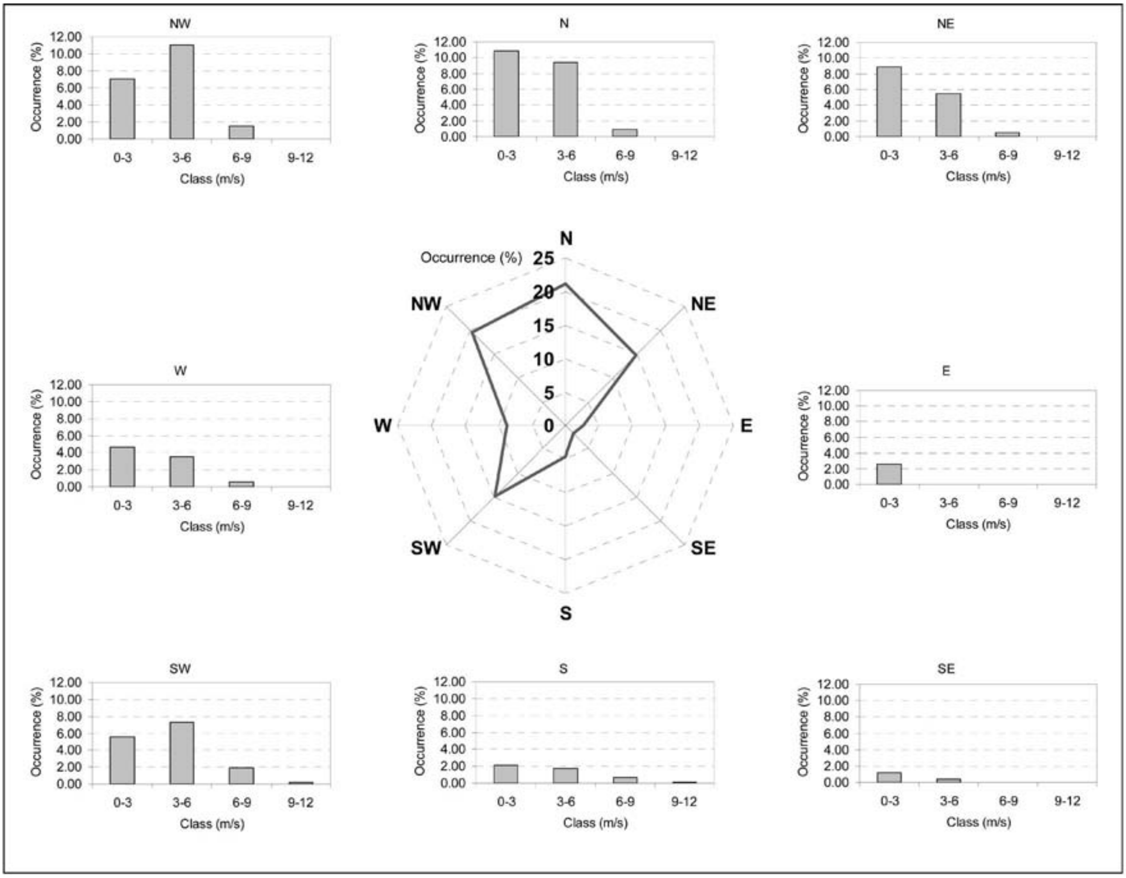

Figure 3:
Results of the wind statistical analysis: average annual occurrence per octant, and, for each octant, per class of intensity of velocity.

called Alfeite, in the south bank of the internal estuary. This beach, with main alignment WNW-ESE, is characterised by having a steep upper slope (average 0.15) until mean sea level (MSL), followed, seaward, by a low gradient terrace of approximately 800 m width, and a bimodal sediment distribution. The steep upper beach, with coarse sand grains (D_{50} = 1.26 mm, where D_{50} is the mean grain diameter), terminates in its base at a low gradient terrace, with finer grains (D_{50} = 0.33 mm). Both the steep upper beach and the low gradient terrace are engaged in the surf zone at different states of the tide, therefore, the beach responds as a reflective beach and as a dissipative beach. The Tagus estuary is submitted to a semi-diurnal astronomic tidal cycle and a meso-tidal regime, according to the classification established by Davies (1964). At Alfeite beach the average tidal range at spring tide is 3.2 m and at neap tide is 1.5 m. The alongshore extension of the beach is about 2.5 km.

WIND REGIME

A series of four daily records (every 6 hours) of intensity and direction of the wind registered at the meteorological station Lisboa - Gago Coutinho of the Meteorological Institute, near the estuary, was statistically treated and analysed. The six-year series corresponds to the period 1999-2004. Only 10.8% of the total expected data was either missing or not valid.

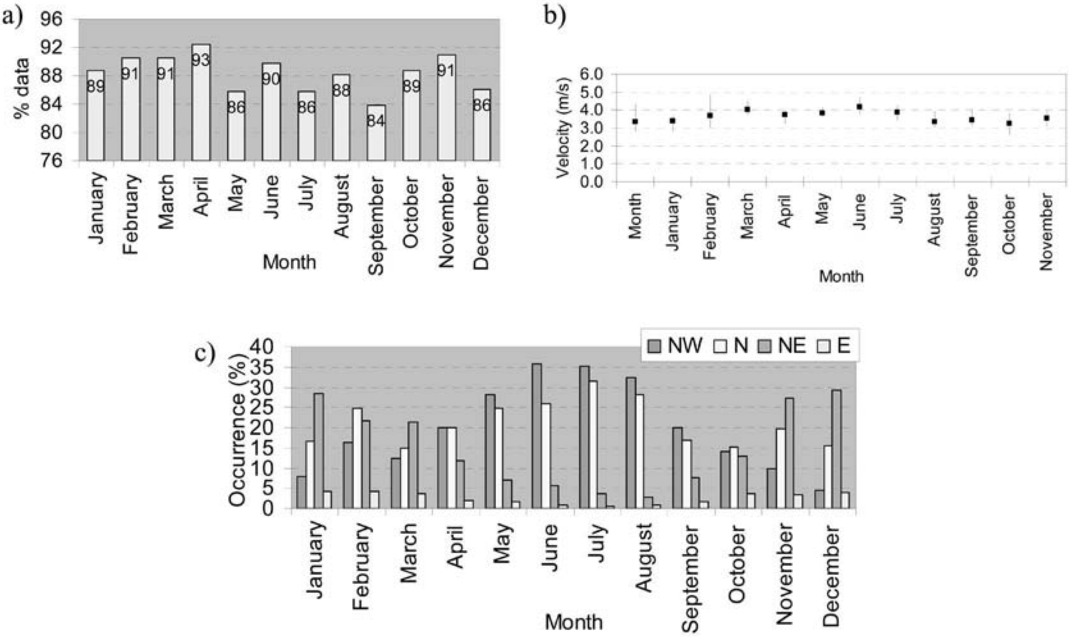

Figure 4:
Results of the wind statistical analysis:
a) Valid records per month; b) Average monthly velocity; c) Monthly occurrence per octant.

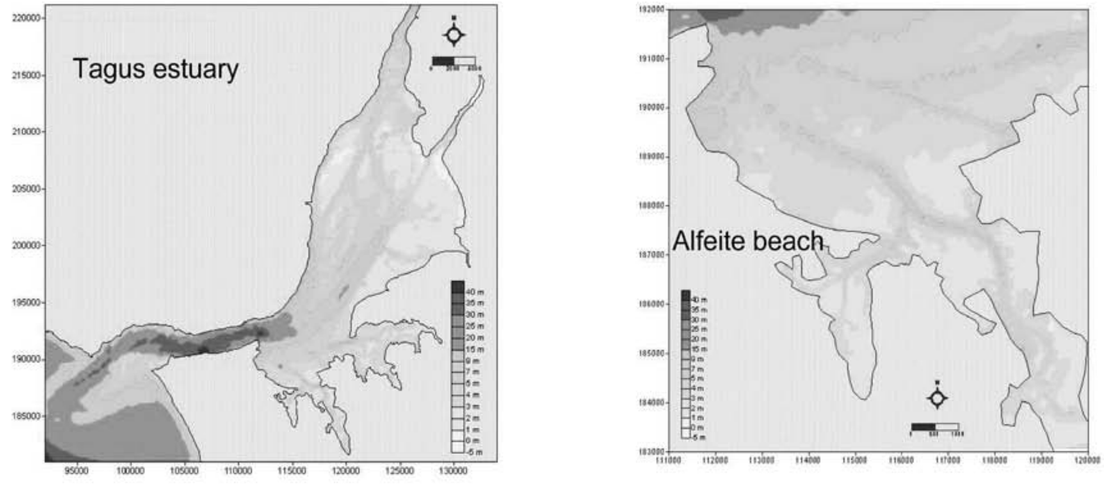

Figure 5:
Numerical domains for the application of SWAN model: bathymetry for sea level at +1.6 above MSL

Table 1:
Representative wind regime and calculated wave climate at point B.

Wind parameters Direction*	Velocity [m.s^{-1}]	Occurrence [%]	Wave climate at point B Hrms [m]	Tm [s]	Direction** [°]
N	2.17	10.83	0.05	0.7	6.3
N	4.60	9.44	0.16	1.3	9.2
N	7.17	0.90	0.28	1.7	9.1
N	10.42	0.02	0.43	2.1	6.6
NE	2.04	8.85	0.05	0.7	38.9
NE	4.57	5.52	0.17	1.3	30.4
NE	7.27	0.55	0.28	1.6	30.2
NW	2.27	7.09	0.05	0.7	321.1
NW	4.75	11.09	0.13	1.1	324.0
NW	7.26	1.51	0.21	1.4	326.8
NW	10.42	0.02	0.32	1.7	329.4
E	2.14	2.57	0.04	0.6	79.4
E	5.00	0.02	0.14	1.1	66.0

* bisecting line of the octant
** relative to geographical North

The distribution of the valid data per year is according to Figure 2. The amount of missing data varies between 8.4 and 15.6%, being 2003 the worst year.

The distribution of the records per octant of incident direction (wind rose in the centre of Figure 3) shows that there are four predominant directions of incidence: octants NW and N, with about 20% each; and octants NE and SW, with about 15% each. The distribution of the intensity of the wind velocity (in m.s^{-1}), per octant (shown in eight graphs around the wind rose), shows that the largest occurrence is observed in classes [0-3] and [3-6], being the first one predominant in all the octants except SW and NW. The results of the statistical analysis also show that it is for the octants S and SW, which do not generate waves with impact on Alfeite beach, that the highest class of velocity intensity, [9-12], has the highest occurrence, even though it is low, 0.1 and 0.2%, respectively.

In order to evaluate the seasonality of the wind regime, the statistical monthly distribution of the parameters intensity and direction was analysed. The distribution of the valid data per month is plotted in Figure 4-a. The amount of missing data varies between 7 and 16%, being September the worst month. The results revealed an inter-annual variation of the average monthly velocity; however, it is noticeable that from February to July the average velocity is slightly higher than during the rest of the year (Figure 4-b). In what concerns direction, the monthly distribution of the frequency of occurrence of the octants that can generate waves with impact on the beach (Figure 4-c) reveals that the NW and N octants occur predominantly from April to September (during Spring and Summer) and the other two octants, particularly NE, have the opposite distribution of occurrence, meaning, clearly a higher occurrence from November to March (mostly during Autumn and Winter).

WIND WAVES

The numerical model SAWN (vastly divulged and applied, therefore here dismissed description) was applied to simulate the processes of wave generation and propagation in the internal estuary, an area of restricted fetch. The numerical domain was discretised through two rectangular grids: one enclosing the

Table 2:
Distance from the sailing line to the waterline at different sea levels.

Profile	Distance from the waterline to the sailing line [m]		
	LSL	MSL	HSL
A	910	1300	1325
B	1030	1360	1375
C	1240	1460	1470

whole estuary and part of the coastal area; and the other (that fits into the first) enclosing the area of interest (Figure 5). The application of the model was performed in two phases: in the first, the still MSL was submitted to a uniform wind field all over the domain; in the second, the boundary conditions were forced with the results obtained from the first phase.

Based on the results of the wind statistical analysis, it was established the representative average annual wind regime, i.e., a set of pairs of velocity parameters, [intensity; direction], considered to generate the average annual wind wave climate in the internal estuary (Table 1), where offshore ocean waves have no impact, as shown by Oliveira (2000). The velocity intensity of each pair was derived as being the average of all the values of each of the classes [0-3], [3 6], [6-9] and [9-12], for each octant that generates waves with impact on the beach.

The numerical model was applied for the thirteen cases above, at MSL (Figure 6). The simulations allowed to obtain the wave climate in front of the beach, at three positions, A, B (in Table 1 and Figure 7, where Hrms is the root-mean-square wave height) and C. The analysis of these results showed

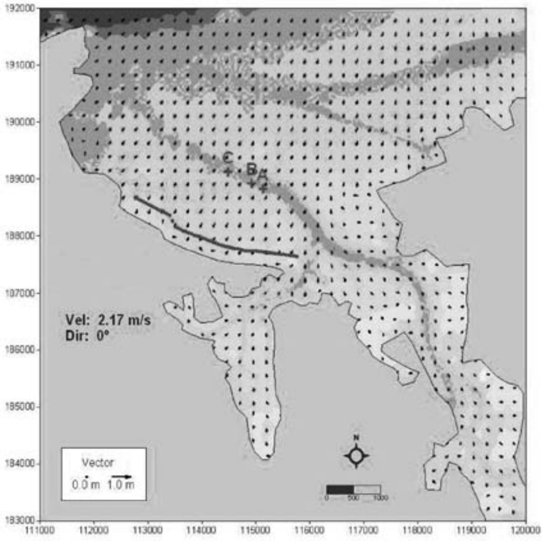

Figure 6:
Numerical results of wave propagation (for 1st case in Table 1)

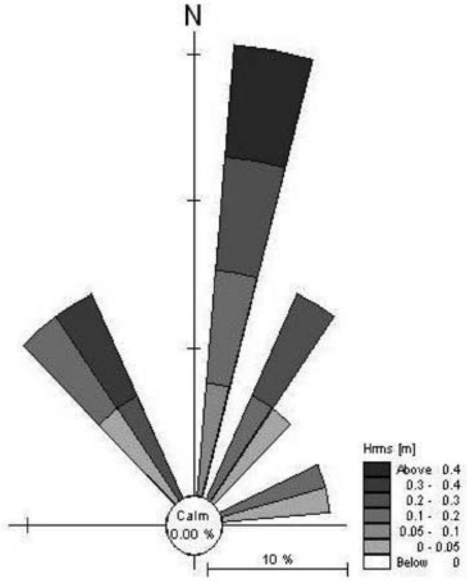

Figure 7:
Wave climate at point B: Hrms per directional sectors of 10º

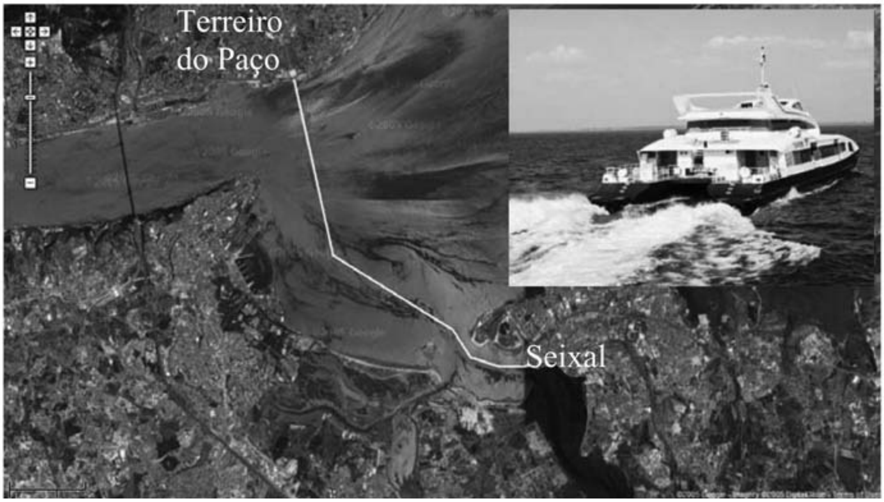

Figure 8:
Oblique photograph of catamaran (property of Transtejo) in its route Terreiro do Paço – Seixal (aerial photograph).

a great similarity of the wave climate in the three points, indicating uniformity of the wind wave action alongshore for this particular beach. Despite the majority of the energy that reaches the beach at this depth, 7.2 m bellow MSL, having normal incidence to the shore (with main alignment about N97º), there is still a significant amount of energy that reaches the beach obliquely at this depth, because the incident waves are short (maximum and minimum wave length of about 6.9 and 0.6 m). It is therefore expected that the wave action upon the beach is capable of mobilizing and transporting sediments.

Figure 9:
Passage of catamarans in front of the beach.

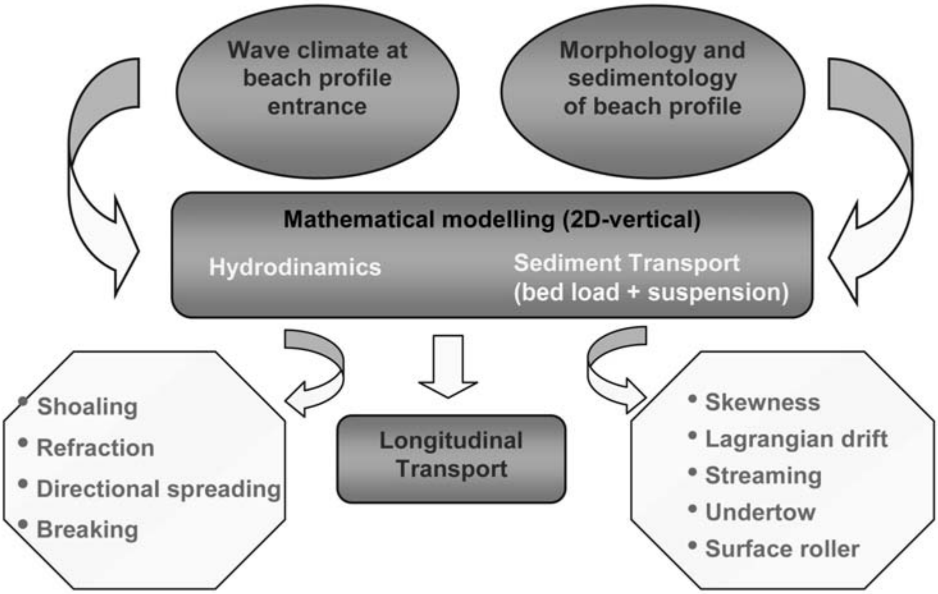

Figure 10: *Schematic description of the sediment transport model.*

WAKE WAVES

In the present study, the wake waves that reach the beach are generated by twin hulls, or catamarans, of approximately 45 m length (Figure 8), which travel approximately along the route, or sailing line, marked in Figure 8. In front of the beach the catamarans travel over a depth that varies between 7 and 12 m at MSL. The approximated distances from the waterline, at mean low sea level (MLL), MSL and mean high sea level (MHL), to the sailing line (along the directions of profiles A, B and C, located in the east, central and west parts of the beach, as referred in the next section) are presented in Table 2.

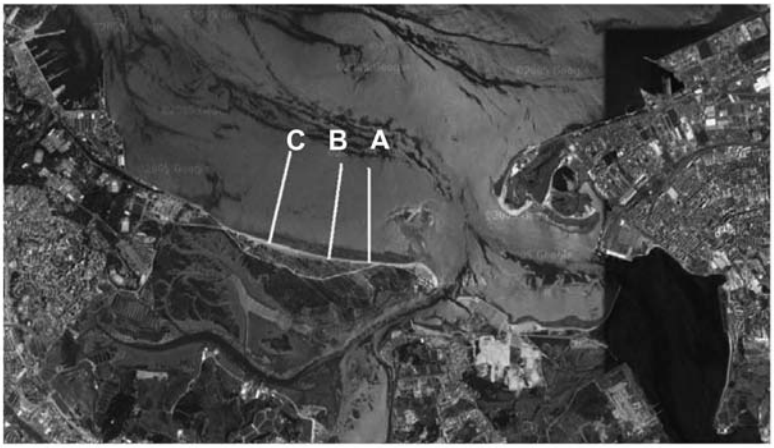

Figure 11: *Location of the three profiles A, B and C.*

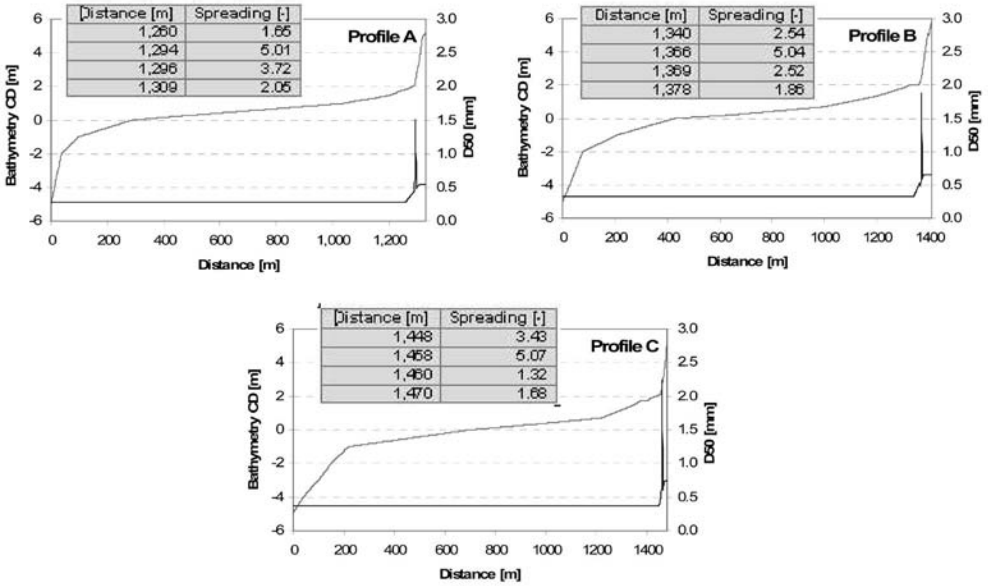

Figure 12: *Profiles geometry and grain size distribution (D_{50} and geometrical spreading).*

The passage of the catamarans in front of the beach has no impact on the overall longshore sediment transport because the catamarans transit is performed in both directions, as can be seen in Figure 9 (photograph taken from the beach), the same number of times.

Despite the irrelevance of the impact of the passage of the catamarans in the longshore sediment dynamics, the effect on the transversal dynamics can be more important than the wind effect, depending on the catamaran' speed. This subject is further described in Vargas (2006) and Oliveira (2006).

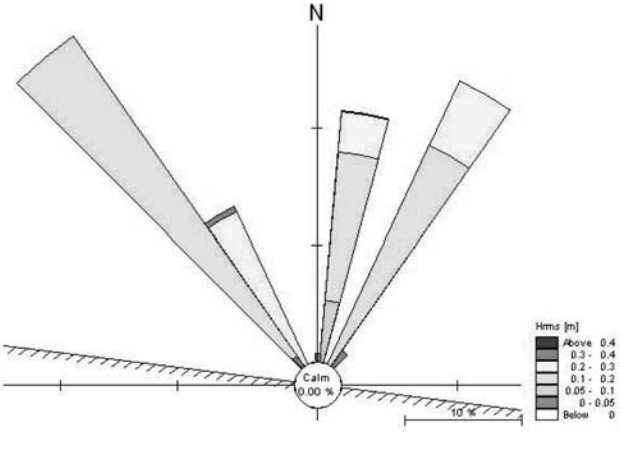

Figure 13: *Discretisation of the longshore sediment budget at profile B.*

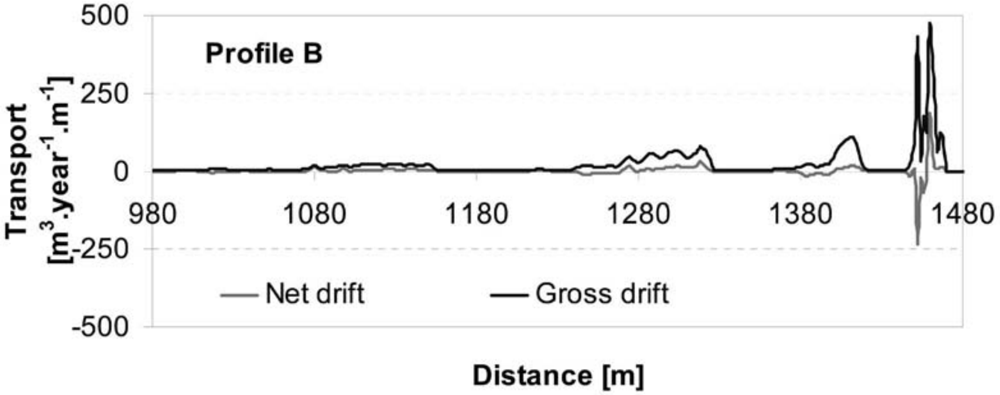

Figure 14: *Longshore transport along the active part of profile B.*

LONGSHORE SEDIMENT DYNAMICS

The longshore sediment transport was estimated through the application of a process based numerical model, a profile type model, LITDRIFT (Figure 10) of the LITPACK package (vastly divulged and applied, therefore here dismissed description).

The three points A, B and C, where the wave climate was previously obtained, correspond to the entrance (offshore position) of three profiles, also named A, B and C in agreement with their entrance point, normal to the waterline at MSL, distributed along the beach (Figure 11). Topo-hydrographic and sedimentologic (grain size) surveys were performed along these three profiles (Figure 12).

The application of the model, considering the sea surface described by the wave theory of Doering and Bowen (1995) and the sea level variations correspondent to a semi-diurnal tidal cycle of average tidal range 2.4 m, results in the average annual longshore transport in Alfeite beach of 14.5×10^3 $m^3.year^{-1}$. This volume of sediment is divided equally in both longshore directions, i.e., the net transport is null.

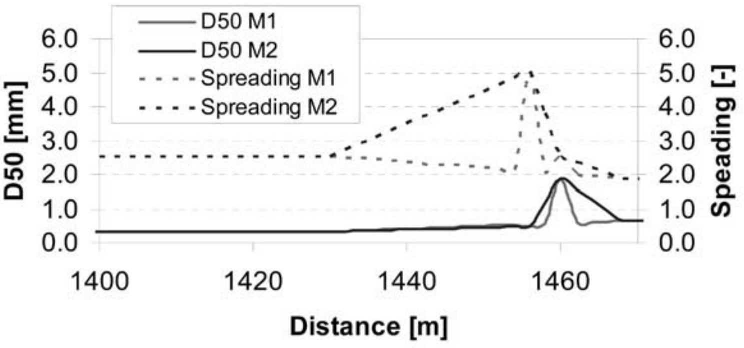

Figure 15: *Parameters D_{50} and σ for methodologies M1 and M2 along profile B (detail).*

The discretisation of the longshore sediment budget, as function of directional sectors and classes of Hrms (Figure 13), shows, when comparing with the wave climate (Figure 7), that the most frequent incident sector, which also contains the highest waves, is not the one with the largest contribution to the transport due to its location (nearly normal) relativity to the shoreline. In opposition, the most western sector of incidence contributes largely to the transport directed to east because, despite it does not contain the highest waves, its direction relatively to the shoreline normal is about 45º (the most effective direction in generating longshore transport).

The distribution of the net and the total transport along profile B (Figure 14) reveals that the longshore transport component that is directed eastward (positive values) is predominant at deeper waters whereas the western component prevails closer to the waterline. This can be explained because the highest waves, the ones that break at higher depths, with capacity of generating longshore transport due to its obliquity have incidence from western sectors, as can be confirmed through the discretisation of the sediment budget (Figure 13), whereas the highest waves with incidence from the eastern sectors and obliquity to induce longshore transport have smaller amplitudes and therefore break closer to the waterline.

As described by Freire (1999), the beach profile is only modified when rare storms occur. No inter-annual or seasonal morphological changes have been observed in the last decade, i.e., the beach presents a medium-term permanent profile. This fact validates qualitatively the numerical results obtained, i.e., that the integrated net transport along the beach profile is null.

Since Alfeite is a low energy beach, field measuring of the sediment transport was likely to be a difficult task. Therefore, testing sedimentologic parameters and evaluating the amount of uncertainty that they bring to the calculations was considered to be a suitable option to verify the results obtained. Thus, the transversal distribution of the beach grain size was tested.

The sedimentologic survey consisted in the collection of four surface sediment samples (one from the low gradient terrace; one from the base of the steep upper beach; and two from the steep upper beach, one from the lower part above the base and the other from the upper part) from each of the beach profiles. This information was used to describe the grain size distribution, or more exactly, the mean grain diameter, D_{50}, and the geometrical deviation or spreading, $\sigma = (D_{84}/D_{16})^{½}$ (D_{84} and D_{16} being the sizes for which 84% and 16% by weight of the material is finer), in all the grid nodes of the profile (every 2 metres). A particular problem when modelling numerically the beach morphodymanics concerns the implications of interpolating and extrapolating the grain size distribution for all the calculation points required. In the application of the model, the theoretical distribution of the grain size was based on the following methodology, M1: (i) at the low gradient terrace - sediment graded according to the parameters D_{50} and σ of the sample collected from the terrace; (ii) at the steep upper beach – sediment graded based on a linear interpolation of the parameters D_{50} and σ between the sample at the low gradient terrace and the sample at the upper part of the steep upper beach, except for the locations (in between) of the two other samples, where their own parameters prevailed. In order to test the results obtained to the variability of the grain size distribution, another theoretical distribution was experimented. It was based on the following methodology, M2: (i) at the low gradient terrace – the same as M1; (ii) at the steep upper beach – sediment graded based on a linear interpolation of the parameters D_{50} and σ between each pair of consecutive samples. The result of this application is an average annual longshore transport of 16.1×10^3 $m^3.year^{-1}$, which corresponds to an increase of approximately 11%. To interpret and explain the impact of the theoretical grain size distribution on the longshore transport, the parameters D_{50}, σ and total longshore transport have to be analysed together.

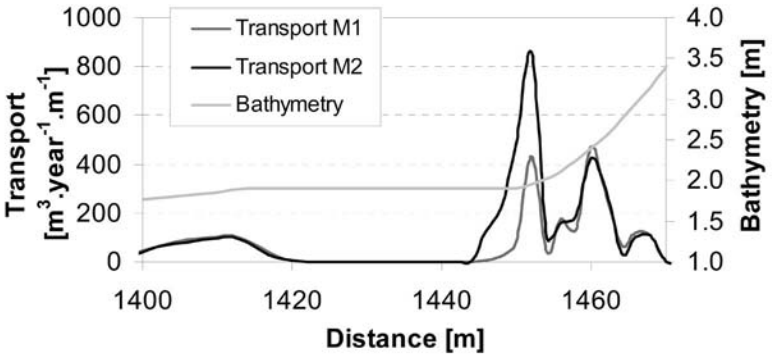

Figure 16: *Longshore transport for methodologies M1 and M2 along profile B (detail)*

This analysis shows that the methodology M1, which results in lower transport, generates a narrower extension of the profile with higher D_{50} (Figure 15). The samples with higher D_{50} are associated to the highest values of spreading and for this reason the methodology M2 generates a wider zone with higher spreading (Figure 15). When comparing the variation of the total longshore transport along profile B for both methodologies (Figure 16) it is observed that the higher transport obtained with M2 occurs in the area at the base of the steep upper beach, where, despite the D_{50} being higher, the effect of having a higher geometrical spreading and consequently also finer grains, prevails.

CONCLUSIONS

The alongshore dynamics of a low energy estuarine beach was analysed based on mathematical modelling. The beach is submitted to wind waves, generated in an area of restricted fetch, wake waves generated by catamarans that pass nearly parallel to the shoreline and a semi-diurnal meso-tidal regime. The analysis of the recent (last decade) evolution of the beach reveals an almost permanent morphology. The beach is characterised by having a steep upper slope until mean sea level, followed, seaward, by a low gradient terrace and a bimodal sediment distribution. The methodology of analysis integrates: field data (wind, topo-hydrographic and sedimentologic); results of process based numerical modelling (wave generation and transformation in an area of restricted fetch, nearshore wave induced currents and longshore sediment transport); and coastal dynamics parameters (such as the shoreline) extracted from aerial photographs. The methodology applied allowed to conclude: on the characterisation of the wave climate in three distinct positions in front of the beach and that the wave action is uniform alongshore; on the magnitude of the average annual longshore sediment budget, 14.5×10^3 $m^3.year^{-1}$; on the spatial distribution of the longshore sediment transport in the active part of the beach; on the contribution of each wind wave component to the longshore transport; and on the irrelevant impact of the wake waves in the alongshore transport at Alfeite beach. The effect of the uncertainty of the methodology applied to simulate numerically the transversal distribution of the beach grain size can increase the longshore transport 11%.

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REFERENCES

Davies, J. L. (1964). A morphogenic approach to world shorelines, Zeitschrift für Geomorphology, 8, Mortensen Sonderheft, pp. 127-142.

Doering, J. C., Bowen, A. J. (1995). Parametrization of orbital velocity asymmetries of shoaling and breaking waves using bispectral analysis. Coastal Engineering, Vol. 26, pp. 15 33.

Freire, P.M.S. (1999). Morphological and sedimentary evolution of estuarine banks (Tagus estuary, Portugal). PhD dissertation submitted in Faculdade de Ciências da Universidade de Lisboa, Lisboa, Portugal, pp. 320 (in Portuguese).

Jackson, N.L., Nordstrom, K.F., Eliot, I., Masselink, G. (2002). Low energy sandy beaches in marine and estuarine environments: a review. Geomorphology, 48, pp. 147-162.

Barusseau, J.P., Radulescu, M., Descamps, C., Akouango, E., Gerbe, A. (1994). Morphosedimentary multiyear changes on a barred coast (Gulf of Lions, Mediterranean Sea, France). Marine Geology, 122, pp. 47-62.

Oliveira, F.S.B.F. (2000). Numerical simulation of wave propagation in the entrance of the Tagus estuary, Spaulding *et al* [Eds], Estuarine and Coastal Modeling VI, ASCE, pp. 510-525.

Oliveira, F.S.B.F., Vargas, I.C., Coli, A.B. (2006). Evaluating the geomorphologic stability of an estuarine sandy beach. International Symposium on Integrated Coastal Zone Management (submitted).

Ragan, J., Smosna, R. (1987). Sedimentary characteristics of low-energy carbonate beaches, Florida Keys. Journal of Coastal Research, 3, pp. 15-28.

Vargas, I.C., Oliveira, F.S.B.F., Coli, A.B., Carvalho, F. (2006). Study of the morphodynamics of a low energy beach: numerical analysis. Recursos Hídricos (submitted, in Portuguese).

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