

Field Determination of Sediment Transport Patterns: a Case Study from Patos Beach (Northwest Spain)

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ABSTRACT

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Transport patterns at Patos Beach, in the Northwest of the Iberian Peninsula, were studied by performing different field experiments under various spatial and time scales. For the purpose of the present work, the central part of the beach was selected, where the highest morphodynamic changes occurred. Monthly monitoring consisting on beach profile surveys and sediment sampling were carried out from November 1999 to February 2001. Detailed fieldwork were conducted on 18-19 September 2000, during two tidal cycles, in order to acquire specific data from topography, fluorescent tracers and mixing depth experiments. Seasonal study shows a great variation, ranging from reflective to dissipative morphodynamical states, according with the prevailing wave climate. Temporal evolution of the beach morphology, volumetric and sedimentary variations presented no significant longshore changes, confirming cross-shore transport as the main pattern in the beach. The short-term study reinforces this assumption. Results obtained from the short term analysis (topographic evolution and tracer distribution) agree with the medium term trends approach and revealed the existence of weak transport rates towards onshore direction, under calm conditions, pointing out to a very gradual recovery of the beach.

ADDITIONAL INDEX WORDS: *Beach morphodynamics, fluorescent tracers, NW Spain.*

INTRODUCTION

Sediment transport patterns and the associated morphological change, are one of the major concerns in the study of sedimentary systems in the coastal environment, and can be examined at many spatial and temporal scales (LARSON and KRAUS, 1995; MORTON *et al.*, 1995; PEDREROS *et al.*, 1996; ALONSO *et al.*, 2000). Sediment transport behavior may show different trends depending on the temporal and spatial scales observed.

Different methodologies have been developed to measure coastal sediment transport in situ. Their application depends on the particular situation of the study to carry out, taking into account the temporal and spatial scales to analyze (WHITE, 1998). Transport rates can also be inferred from numerical models (KAMPHUIS *et al.*, 1986; VOULGARIS *et al.*, 1998; BALOUIN *et al.*, in press) developed from beach experiments data.

The purpose of this study is to describe the sediment transport directions in Patos Beach (Figure 1a). To achieve this objective, two different spatial and temporal scales were considered: seasonal and short-term studies. The former gives information about the annual transport patterns related to variations in wave climate. The short-term study provides detailed data on transport processes under specific conditions. Different methodologies were used to reach this aim.

STUDY AREA

The field site is located in the northwest coast of the Iberian Peninsula, in the Ría of Vigo, the southernmost part of the Galician Rías (Figure 1a). This stretch of coast is characterized by the presence of rocky headlands. Bays between headlands present accumulation of Quaternary unconsolidated sediments (VILAS *et al.*, 1995), forming partially sheltered beaches. Beaches are also protected from the most energetic Atlantic storms by Cíes Islands, located at the mouth of the Ría of Vigo.

Patos Beach is located in the southern outer zone of the Ría, partially protected from the winter energetic South-westerly waves by Monteferro Peninsula (Figure 1b), allowing a wide range of exposition to the incident waves along the beach. This 1500 m length beach is locally interrupted by Precambrian-Silurian schist outcrops, with an approximately North-South

orientation (VILAS *et al.*, 1995). These outcrops delimit different sectors in the beach with particular morphodynamic behaviours (REY, 2001; REY *et al.*, 2002).

Summer conditions are characterized by dominant northerly winds, but the rest of the year, specially at winter time, southerly winds are predominant. Prevailing waves are from the Southwest, which also the most energetic during winter. The semidiurnal tide is mesotidal, with a mean tidal range of 2.2 m. Following the classification suggested by HAYES (1979) this stretch of coast is mixed-energy.

Results reported in this paper were obtained from experiments carried out just in the central part of the beach (Profiles 2 to 8, Figure 1a). With rocky outcrops just at its lateral limits, this 600 m length sector is the most exposed to the incident waves, where the highest morphologic changes occurred (REY, 2001).

METHODS

Two temporal and spatial scales were considered and different methodologies were used to examine the sediment transport patterns.

Seasonal or medium-term scale study, consisted on monthly monitoring along six beach profiles (Profiles 2 to 8, Figure 1a), carried out from November 1999 to February 2001. Surveys were made with a theodolite during low tides. To define the

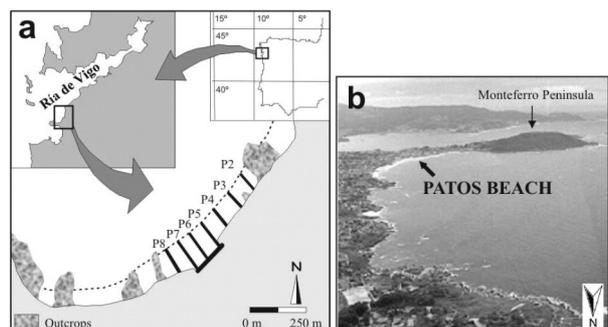


Figure 1. Study area: (a) location of Patos Beach and situation of monitored profiles; (b) aerial view of Patos Beach.

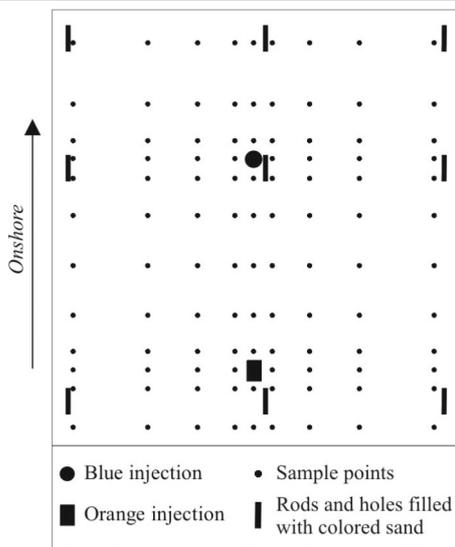


Figure 2. Location of tracer injection points, core sampling grid and position of rods and holes filled with colored sand.

morphodynamical states of the beach were used the classifications proposed by WRIGHT and SHORT (1984) and MASSELINK and SHORT (1993). Beach volume variations were computed from monitored profiles. Sediment samples were also gathered along the profiles to attend temporal and spatial variations in sediment characteristics. Sand samples were dry sieved using $\frac{1}{2}$ phi (Φ) intervals. Grain size parameters were calculated following the graphic method proposed by FOLK and WARD (1957).

Tidal or short-term scale study was developed along two tidal cycles on 18-19 September 2000. This experiment was carried out in the central part of the beach, between profiles 5 and 7 (Figure 1a). Different methodologies were involved in this experiment:

- 3-D topographies were surveyed at low tides using an electronic total station to estimate morphologic changes and volumetric variations.
- Sediment characterization was made from sand samples collected along cross-shore beach profiles.
- Fluorescent tracer experiments were used to quantify tidally averaged sediment transport patterns at specific sites (KING, 1951; SHERMAN *et al.*, 1990; CIAVOLA *et al.*, 1997). Natural sand from the upper and lower part of the foreshore was manually dyed with blue and orange fluorescent paint, respectively. The tracer sand was injected at the same part of the beach as it was collected (18/09/2000 at 3:00 p.m. local time). The dispersion was monitored during the subsequent two low tides (19/09/200 at 3:30 a.m. and 3:50 p.m.). Samples were gathered using 5 cm height cores, following a particular grid (Figure 2). Counting was performed under an UV source. Total number of grains was normalized by the sample weight. Tracer advection behavior was calculated with the Spatial Integration Method (KOMAR and INMAN, 1970; MADSEN, 1987; CIAVOLA *et al.*, 1997):

$$Y = \frac{\sum P_i d_i}{\sum P_i} \quad (1)$$

where Y is the location of the center of mass, or centroid, of the tracer cloud, P_i is the mass of the recovered tracer at each grid point and d_i is the distance of the grid point from the injection site. The horizontal translation of the center of mass was referred to the injection point.

Average advection speed (V_y) of the tracer was calculated using:

$$V_y = \frac{Y}{t} \quad (2)$$

where t is 12h30m, which is the interval between two consecutive tides.

Total sand transport rate (Q) was obtained by multiplying the tracer advection speed by the area of the moving sand layer:

$$Q = V_y A \quad (3)$$

- Mixing depth measurements (KING, 1951; GREENWOOD and HALE, 1980) were determined by rods and holes filled with colored sand as reference level (Figure 2), in order to calculate the volume of transported sand.

RESULTS

Seasonal Study

Surveyed profiles from monthly monitoring show a great beach shape variation, ranging from reflective to dissipative morphodynamical states (REY, 2001). As an example, profile 6 is represented in Figure 5.

During summer conditions Patos Beach develops a wide berm and a moderate beach face slope ($\tan \beta = 0.05-0.07$). Swash bars are present in the foreshore during fair weather conditions characterizing the morphodynamic state of the beach as *barred*. These morphologies are more pronounced in the central part of the study area, as the distance increases from the lateral rocky boundaries (REY *et al.*, 2002). Further these evidences, no significant longitudinal morphodynamic variations are observed.

Winter conditions lead to the erosion of the beach resulting from the higher hydrodynamism. *Barred dissipative profiles* are developed ($\tan \beta = 0.04$) and a non-barred dissipative state is reached during very high-energy events ($\tan \beta = 0.03$).

Volume variations computed from beach profiles show a great resemblance between contiguous profiles. High seasonal variations are observed. Sediment is gradually accumulated under summer conditions, until total beach recovery is reached, and quickly eroded when wave energy increases during storm events.

Sediment characteristics present a clear spatial and temporal behavior. Since no longshore significant variations were observed during the study period, cross-shore mean grain size parameters show an offshore increase of sediment size (from 2.21Φ to 1.86Φ), as well as a decrease in sorting (from 0.37Φ to 0.84Φ) and more negative skewness (from 0.01 to -0.34). This pattern is always observed even from calm to storm conditions.

Short-term Study

Whilst the seasonal study relates data obtained under a wide range of hydrodynamic conditions, this specific experiment was carried out under calm conditions, while the beach was in an accretion process. However, some differences in wave height were noticed by visual observations. A slight increase in wave height had occurred from the low tide when the first dispersion of tracers was monitored to the next one.

Topography and Sediments

The topographical study reveals the existence of a swash bar system (Figure 3), composed by two intertidal bars migrating

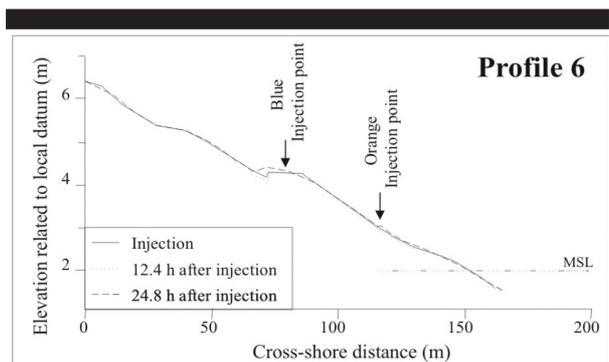


Figure 3. Cross-shore profiles at Patos Beach during the short-term study.

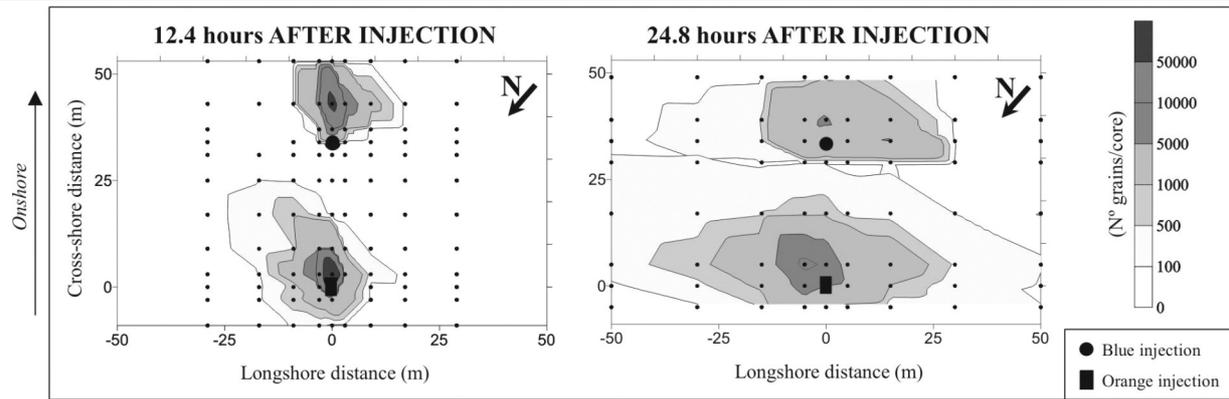


Figure 4. Maps of tracer dispersion for each tide surveyed, expressed as number of grains per volume of the sampling cores (220 cm^3). The reference point is the orange injection at the seaward slope of the bar.

onshore. A well developed swash bar and a bar and rip morphology around low tide level. This morphodynamical situation corresponds to a *low tide bar/rip* state. Beach face gradient ($\tan \beta = 0.04$) also classify the beach as intermediate.

Morphologic variations during the two day experiment are just remarkable in terms of onshore migration of the swash bar crest. No significant vertical changes were observed in the landward slope of the bar (Figure 3).

Sediment characterization of the area where the experiment was carried out presents no significant spatial variations. Sediments consist on medium sand (from 2.00Φ to 1.156Φ), moderately sorted (from 0.95Φ to 0.69Φ) and very negatively skewed (from -0.36 to -0.56).

Fluorescent Tracer and Mixing Depth Experiments

The two tracer colors were released in different sites of the beach. The blue one in the upper foreshore, in the crest of the swash bar, and the orange tracer in the lower foreshore, in the middle of the seaward slope of the swash bar (Figure 3).

Results obtained from the tracer experiment are presented in Table 1. However the displacement of the moving layer and the volume of sand transport were not great, it was observed some particular trends during this experiment.

Tracer dispersion detected (Figure 4) during the first low tide reveals a net movement of sand onshore. Sediment mixing depth was about 0.5 cm and volume of sand transport, considering the prevailing 100 m width intertidal area, was of $55.18 \cdot 10^{-6} \text{ m}^3/\text{s}$ ($2.48 \text{ m}^3/\text{tide}$) at the bar crest and minor at the lower foreshore ($24.22 \cdot 10^{-6} \text{ m}^3/\text{s}$ or $1.09 \text{ m}^3/\text{tide}$).

Direction of transport remained the same during the second tide but net displacement of the moving sand layer diminished. A higher sediment mixing depth was measured during this second dispersion monitored (4.5 cm), which induced a greater volume of transported sediment. Tracer advection onshore gives a residual sediment transport rate of $194.26 \cdot 10^{-6} \text{ m}^3/\text{s}$ ($8.74 \text{ m}^3/\text{tide}$) at the crest of the swash bar and $131.04 \cdot 10^{-6} \text{ m}^3/\text{s}$ ($5.90 \text{ m}^3/\text{tide}$) at the seaward slope of the bar.

DISCUSSION

Transport Patterns Evidences from Seasonal Study

Seasonal evolution of the beach morphology, with a large range of morphodynamic states, and volumetric and sedimentary variations reflect a great cross-shore sediment exchange, representing the main pattern of sediment transport in Patos Beach. No significant longitudinal variations of these parameters support this assumption.

Erosive trends during winter and accretion during summer conditions, as well as greater grain sizes following storm occurrences, denote the strong seasonal behavior of the beach,

related to the wave climate.

Seasonal variations of sediment volume, with erosion in winter and accretion during summer, point out to an equilibrium state of Patos Beach, showing a balance in the sediment budget at an interannual time scale. There are no significant sedimentary inputs from rivers or outcrops erosion, as well as there are no sediment losses from beach mining or any other natural or human impact.

Transport Patterns Evidences from Short-term Study

The existence of a well developed swash bar system with two intertidal bars is representative of the cumulative morphodynamical state of the beach at the time of this study. The tracer experiment demonstrates this fact. During the short-term study sediments were moved onshore at both sites analyzed.

Slight differences were found in terms of volume of sand transported during the two tidal cycles considered. This situation is related to the differences in the mixing depth, which is considered equivalent to the thickness of the moving sand layer. The greater mixing depth observed during the second tide induced a higher transport rate. This fact is likely related to the increasing in wave height, since it is the main variable controlling the depth of sand activation (KING, 1951).

Attending to the net transport rate, displacement at the swash bar crest was greater than at the seaward slope. This result was validated by the morphological evolution of the profiles.

Beach Sediment Transport Patterns

GREENWOOD *et al.* (2003) describe the onshore migration of intertidal bars during successive tidal cycles. These authors identified a zone of accretion, i.e. the bar crest, that displaces progressively landward across the seaward slope of the bar complemented with a zone of erosion in the seaward slope. In Patos Beach this zone of erosion is not observed. Tracer analysis

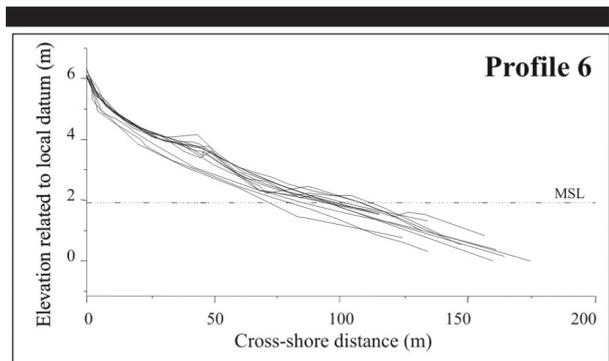


Figure 5. Representative beach profile evolution based on monthly beach profile data.

Table 1. Tracer experiment results.

Tracer experiment	Tracer location at bar	Centroid movement (m)		Distance (m)	Depth of disturbance (m)	Centroid velocity (V) (m/s * 10 ⁻⁶)			Transport rate (Q) (m ³ /s*10 ⁻⁶)		
		X	Y			V _x	V _y	V	Q _x	Q _y	Q
First Tide 19/09/00 (3:30 a.m.)	Crest	0.35	7.94	7.95	0.005	7.82	178.07	178.24	2.35	53.42	55.18
	Seaward slope	-0.50	3.45	3.49		-11.29	77.42	78.23	-3.39	23.22	24.22
Second Tide 19/09/00 (3:50 p.m.)	Crest	2.65	1.63	3.11	0.045	29.66	18.23	34.81	80.08	49.21	194.26
	Seaward slope	-0.51	2.03	2.10		-5.75	22.77	23.48	-15.51	61.48	131.04

also explains this situation. Displacement of the moving layer and sediment transport rates were greater at the crest of the swash bar. At the seaward slope of the bar the net transport was minor and also the topographic oscillations.

The short-term study reveals that the transport of sediments at Patos Beach, under calm conditions, is very weak. Transport rates over a few tidal cycles are no much significant. So the beach seems to need a longer time to recover from erosion processes.

CONCLUSIONS

The aim of this work was to investigate the sediment transport patterns on Patos Beach, an embayed beach located in the NW of the Iberian Peninsula. This study confirms a good correlation between direction of sediment transport inferred from medium term and short-term monitoring. The main pattern of sediment transport in the beach is in the cross-shore direction.

The seasonal study shows a great beach shape variation according to the hydrodynamic conditions prevailing. Sediment quickly eroded during storm events is gradually accumulated during calm conditions, until the total recovery of the beach is reached. This situation clearly evidence that Patos Beach is in morphodynamic equilibrium, adapting its profile to the new energetic conditions. The short-term study proves that the accretion process is very gradual. Transport rates over a few tidal cycles are very weak under summer conditions.

Results obtained from Patos Beach confirm that beach monitoring under medium term scale can be used as a tool for the prediction of sediment transport patterns. More specific spatial and temporal experiments, as tracer analysis, can be used to quantify and fully describe transport rates.

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LITERATURE CITED

- ALONSO, I.; VILAS, F. and ALCANTARA-CARRIÓ, J., 2000. Importancia de la escala temporal en estudios de dinámica litoral. In: DE ANDRÉS, J.R. and GRACIA, F.J. (eds.), *Geomorfología Litoral, Procesos Activos*. Cádiz, Spain: Instituto Tecnológico Geominero de España: pp. 31-43.
- BALOUIN, Y.; HOWA, H. and PEDREROS, R., in press. Longshore sediment movements from tracers and models. *Journal of Coastal Research*.
- CIAVOLA, P.; TABORDA, R.; FERREIRA, Ó. and ALVEIRINHO DIAS, J., 1997. Field measurements of longshore sand transport and control processes on a steep meso-tidal beach in Portugal. *Journal of Coastal Research*, 13(4), 1119-1129.
- FOLK, R.L. and WARD, W.C., 1957. Brazos river bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27(1), 3-26.
- GREENWOOD, B. and HALE, P.B., 1980. Depth of activity, sediment flux, and morphological change in a barred nearshore environment. In: MCCANN, S.B. (ed.), *The coastline of Canada*. Nova Scotia, Canada: Geological Survey of Canada, Paper 80-10, pp 89-109.
- GREENWOOD, B.; AAGAARD, T. and NIELSEN, T., 2003. Tidally modulated sand bed oscillations. In: SÁNCHEZ-ARCILLA, A. and BATEMAN, A. (eds.), *Proceedings of the 3rd IAHR Symposium on River, Coastal and Estuarine Morphodynamics*. Barcelona, Spain: IAHR, pp. 387-397.
- HAYES, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. In: LEATHERMAN, S.P. (ed.), *Barrier Islands*. New York: Academic Press, pp. 1-27.
- KAMPHUIS, J.W.; DAVIES, M.H.; NAIRN, R.B. and SAYAO, O.J., 1986. *Calculation of littoral sand transport rate*. *Coastal Engineering*, 10, 1-21.
- KING, C.A.M., 1951. Depth of disturbance of sand on sea beaches by waves. *Journal of Sedimentary Petrology*, 21, 131-140.
- KOMAR, P.D. and INMAN, D.L., 1970. Longshore sand transport on beaches. *Journal of Geophysical Research*, 75, 5514-5527.
- LARSON, M. and KRAUS, N.C., 1995. Prediction of cross-shore sediment transport at different spatial and temporal scales. *Marine Geology*, 126, 111-127.
- MADSEN, O. S., 1987. Use of tracers in sediment transport studies. *Proceedings of Coastal Sediments'87* (New Orleans, Louisiana, U.S.A., ASCE), pp. 424-435.
- MASSELINK, G. and SHORT, A.D., 1993. The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. *Journal of Coastal Research*, 9(3), 785-800.
- MORTON, R.A.; GIBEAUT, J.C. and PAINE, J.G., 1995. Meso-scale transfer of sand during and after storms: implications for prediction of shoreline movement. *Marine Geology*, 126, 161-179.
- PEDREROS, R.; HOWA, H. L. and MICHEL, D., 1996. Application of grain size trend analysis for the determination of sediment transport pathways in intertidal areas. *Marine Geology*, 135, 35-49.
- REY, S., 2001. *Caracterización morfoodinámica y sedimentaria de la playa de Patos (Ría de Vigo, NO de España)*. University of Vigo, Master's thesis, 105p.
- REY, S.; ALEJO, I.; ALCANTARA-CARRIÓ, J. and VILAS, F., 2002. Influence of boundary conditions on beach morphodynamics and sedimentology of Patos beach (Ría de Vigo, NW of Spain). In: VELOSO-GOMES, F.; TAVEIRA-PINTO, F. and DAS NEVES, L. (eds.), *Proceedings of Littoral 2002, 6th International Symposium of the European Coastal Zone Association for Science and Technology*. Porto, Portugal: EUROCOAST, pp. 277-280.
- SHERMAN, D.J.; BAUER, B.O.; NORDSTROM, K.F. and ALLEN, J.R., 1990. A tracer study of sediment transport in the vicinity of a groin: New York. U.S.A. *Journal of Coastal Research*, 6(2), 427-438.
- VILAS, F.; NOMBELA, M.A.; GARCIA-GIL, E.; GARCIA-GIL, S.; ALEJO, I.; RUBIO, B. and PAZOS, Ó., 1995. *Cartografía de sedimentos submarinos de la Ría de Vigo*. Vigo, Pontevedra: Xunta de Galicia, Consellería de Pesca, Marisqueo e Acuicultura, 40p.
- VOULGARIS, G.; SIMMONDS, D.; MICHEL, A.; HOWA, H.; COLLINS, M.B. and HUNTLEY, D.A., 1998. Measuring and modelling sediment transport on a macrotidal ridge and runnel beach: an intercomparison. *Journal of Coastal Research*, 14(1), 315-330.
- WHITE, T.E., 1998. Status of measurement techniques for coastal sediment transport. *Coastal Engineering*, 35, 17-45.
- WRIGHT, L.D. and SHORT, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology*, 56, 93-118.