

# Development of a Morphodynamic Indicator for Sub-regional Integrated Coastal Area Management

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## ABSTRACT

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The rapid development of infrastructure to cope with the expansion of the tourist industry along the coasts of the Mediterranean Sea has introduced numerous instabilities on the natural environment that are reflected by a long history of coastal planning and management efforts. The development of indicators has been established as a powerful approximation to characterizing certain measures of coastal state. Using the power and relative accuracy that wave propagation models have proved on non quantitative applications, a method is used in this paper that incorporates high resolution bathymetries and synthetic wave fields to produce characteristic energy settings in the nearshore region. The directional component of the wave forces are analyzed and a "cell" system depicted following basic gradients that should drive wave induced currents (and associated sediment transport) from a high momentum transfer area to a low momentum transfer area, corresponding to potential erosion and deposition events. Following this simple conceptual model, residual cells can be drawn and thus a cartographic version of potential erosion-deposition sites developed. This analysis provides repeatable and measurable ranked geographic data yielding an indicator of great potential use for decision makers and agencies monitoring coastal evolution. The analysis is performed along the eastern portion of the Costa del Sol in Andalusia, southern Spain, which environment is dominated by narrow beaches and occasional river deltas that influence sediment input as well as wave refraction and nearshore processes. The final maps, with the residual cells marked indicating points of potential erosion and deposition, has been presented and utilized as an aid to improve integrated coastal management by the Andalusian regional government allowing inventory and characterization for future reference.

**ADDITIONAL INDEX WORDS:** *Costa del Sol, Spain, circulatory cells, Mediterranean Sea, management indicators.*

## INTRODUCTION

Over the past 50 years the Mediterranean littoral has undergone some of the fastest rates of urban development worldwide. Nowhere is this better illustrated than in the Costa del Sol on the southern coast of Spain (figure 1), where population has risen by over 10% per annum between 1950 and 2001, a figure that closely matches the growth of visitor traffic to Spain over the same period. Costa del Sol has become during the one of the best known coastal resorts in Europe and worldwide. The rapid development of its infrastructure to cope with the expansion of the tourist industry has introduced numerous instabilities on the natural environment that are reflected by a long history of coastal planning and management efforts. However, coastal protection works (most management efforts are, in fact shoreline protection measures) have not identified the underlining problem of sediment starvation and disruption of the dynamics of the coastal system.

The physical setting of the Costa del Sol responds to the recent adjustment of terrigenous sediments emplaced upon a steep shelf at the confluence of the Euroasiatic and African Plate (MALVAREZ *et al.*, 1998). Marine processes are dominated by a typically low energy setting and short crested, high frequency waves that perform work upon the nearshore bed (sands) very near the shoreline, which is mostly located on a very narrow band of about a few metres wide given that the amplitude of the tides is less than 50 cm on average (*i.e.* non to microtidal environment).

In recent years engineers, scientists and managers have learned from previous experiences in shoreline management, while legislators and planners have made concerted efforts to set out the basis for a more effective and comprehensive system of coastal management. However, although progress has undoubtedly been made in Spain, the identified need appears to be the development of effective methods to monitor and control

coastal evolution from a geomorphological stand point. This implies the analysis of current and potential evolution of the physical and biological environment on a applicable scale for management situations.

The development of indicators has been established as a powerful approximation to the characterization of certain measures of coastal state. In terms of sedimentary dynamics, wave-sediment interactions are amongst the best studied phenomena, both from a theoretical and empirical basis and although researchers are still far from a precise or predictable measure of nearshore dynamics, it can be considered that a method that enables a classification of beach states and its associated behavior can contribute to better characterize and monitor potential coastal evolution.

The scale for an optimal usage of indicators could be that utilized in physiographic studies, once a consensus has been achieved in relation to the indubitable control that physical parameters exert on coastal dynamics. Thus, coastal fluctuation need to be identified and studied in the light of potential and true evolution considering the interlinked effects of the natural and human induced evolution of the coastal segment. Another consideration that cannot be left aside when intending effective coastal evolution monitoring is the full integration of nearshore and emerged beach (SHORT, 1993). Nearshore morphodynamics are in fact the spatial objective that would determine the optimal working scale since coastal processes on emerged beaches respond to submerged controls. Although this is true for most known coastal settings, the idea needs to be emphasized in regions where non tidal settings coincide with a steep nearshore zone. Processes in these types of coasts are intense in comparison with the potential work that waves can bring about; in other words, an apparent low energy coast can be as dynamic as a high energy coast and thus sedimentary change can translate in overly erosional rates that are commonly understated when utilizing "standard" classification schemes or

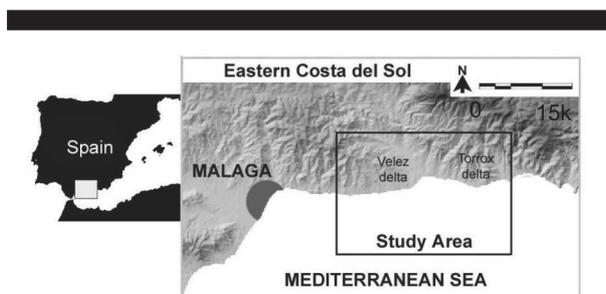


Figure 1. Location of sample area in Costa del Sol, Spain.

monitoring tools.

Among the usual monitoring, control measures and/or methods, there are those which synthesize complex information by analysing the resulting environment. Of this type, the most popular is the utilisation of remote sensing techniques (satellite or airborne) which allows rapid cartographic interpretation of coastline position and thus erosion or accretion rates (e.g. FEMA, 2000). Events are filtered through the evidence of coastal retreat or advance; little is known about how it happened.

At the other end of the spectrum are methods which resolve the morphosedimentary evolution of a coastal segment on a great temporal and spatial scale. This approach is typical of coastal protection projects and is not commonly viable for planning scales since the efforts, costs and complexity of the analyses is above the usual allowance of most policies and planning scales. Even on a sub regional scale (e.g. 10-to 100 km of coast) this approach could become only an utopia commonly using complex numerical models that incorporate high resolution bathymetries and wave and wind fields that yield results to quantify coastal sediment transport. A degree of potential monitoring validity can also be found although the heavily criticized long term modelling approach is now been a questioned technique, particularly when quantification on long term is attempted (MALVAREZ and COOPER, 2000). The demonstrated high nonlinearity of coastal processes in particular and coastal evolution in general is now prompting at accepting that the only thing predictable in coastal behaviour is its unpredictability.

A now traditional idea has been the segmentation of the coast into coastal cells (in terms of sedimentary circulation) depicting units for monitoring and control. The long-term development of morphodynamic processes can be portrayed by the effects of coastal cellular circulation. After waves are refracted in the nearshore, zones of concentration and divergence can be identified. Driven by topographic discontinuities and variations in wave crest dimensions, wave energy tends to concentrate or diverge around coastal features such as canyons or headlands. This dichotomy of concentration-divergence can be mapped along the coastline in the context of these cellular circulations.

Such "cells" represent the fundamental units of study for nearshore evolution (CARTER, 1988) and, within them, system inputs and outputs (i.e., erosion and deposition areas in the nearshore area) can be defined and monitored.

In this paper an analysis is performed along the eastern portion of the Costa del Sol (c. 60 kms. of mostly rectilinear, south exposed coast) which is dominated by narrow beaches and occasional river deltas that influence sediment input as well as wave refraction and nearshore processes. The final maps show residual cells indicating points of potential erosion and

deposition, shoreline maps zoning morphodynamic states, location of residual rip currents and main cell boundary structures. The method has been utilized as an aid to improve integrated coastal management by the Andalusian regional government since it allows some degree of predictability as interpreted from the knowledge of the potential behavior of these coastal segments.

## ENVIRONMENTAL SETTING

Costa del Sol's coastal environments are wave dominated and subjected generally to low energy (MALVAREZ, 1999). Tidal range is small (<50cm average astronomical tidal range). The mean significant wave height is 1 m. with a mean period of 5 seconds producing a coast dominated by high frequency waves. The average directional components of the dominant wind waves are East to West and West to East that generates intense surf zone longshore drift along the mostly south facing coast and active cross shore sediment transport in directly exposed areas. The effective fetch is limited to an average 500 km. and only rarely do swell waves filter from the Atlantic Ocean.

The morphology of the inner shelf is steep and narrow. Oceanic depths are reached within two kilometres from the coast in some sections. This results in a concentration of wave action on a narrow fringe of steep coastal shelf, with predominantly intermediate to reflective beaches. Sediment supply is mainly reworked fluvial sands and supply is episodic and concentrated in time around seasonal heavy rainfall in September and February-March (SENCIALES and MALVAREZ, 2003). Another source of local sediment is that from littoral drift from neighbouring areas, which boundaries is highly dynamic due to the bidirectional nature of prevailing winds.

## METHOD

Wave modeling was conducted to reproduce nearshore wave conditions given the initial deep water wave parameters stated in table 1. The objective was to generate high resolution wave parameters in the nearshore for further interpretation. After simulation of wave propagation from the deep water boundary, co-ordinates of the points where wave energy dissipation occurs were used to isolate wave/sediment interaction zones (then nearshore circulations can be calculated including sediment transport, surf scaling parameter, etc). The geographical extent and the morphology of the surf zone have, in fact, been used as an indicator of nearshore and beach state and type in earlier research itself (MALVAREZ and COOPER, 2000).

Once the geographical extent of the surf zone has been identified, the appropriate phenomena should be considered to investigate the magnitude and nature of wave generated processes. It is significant to focus in the directional components that drive littoral drift, because of the sensitivity of these to be over or underestimated in oversimplified modeling approaches. In the surf zone the reduction in water depth and the number of waves present induces an excess flow of momentum (KOMAR, 1976) or radiation stress. It drives the changes in mean water level (wave set-up) at the shoreline and is directly caused by the presence of waves (LONGUET-HIGGINS and STEWART, 1964a).

The application of the concept of radiation stress has also helped in the development of theories of nearshore current generation (KOMAR, 1975). With shoaling waves and no

Table 1. Wave conditions considered for wave propagation simulation. Data from REMRO wave gauge ([www.puertoes.es](http://www.puertoes.es))

	Deepwater significant wave height (Hs m)	Mean zero crossing period (Tz secs)	Mean wave direction (Deg)
Modal East	1.0	5.0	80
Storm East	2.5	7.0	80
Modal West	1.0	4.5	255
Storm West	2.5	7.0	255

externally driven current, circulations are generated in the surf zone due to a decrease in radiation stresses (LONGUET-HIGGINS, 1970; DEIGAARD *et al.*, 1986). The gradients of the radiation stresses are also present outside the breaking region and are induced by shoaling and refractive processes (LONGUET-HIGGINS and STEWART, 1964b).

The directional component of the radiation stress is taken in this method as the driving force generating circulatory cells across the surf zone.

In the original concept of littoral cells (e.g. MAY, 1974; STAPOR and MAY, 1983; STONE *et al.*, 1992) a quantitative interpretation is made from the available wave power at the breaker point. Cells vary in response to changing wave conditions and results were particularly susceptible to small variations in deep water wave approach. Based on the interpretation of the directional component of the wave power boundaries were established including free and fixed boundary types. The main modification introduced for the interpretation of circulatory cells in this study are: firstly, the entire surf zone is observed from gridded model results of wave propagation. This enables a characterisation of wave induced stress across the breaker but also in all other areas where wave energy dissipation occurs, thus improving (overestimating) the active area in the nearshore. This interpretation includes a longshore cross-shore approach. Secondly, instead of taking wave power as the main driving force, gradients in radiation stress are analysed delineating circulations that can be potentially derived from both longshore and cross-shore fluxes across the surf zone.

Points or areas along the coast where force fluxes converge can be labelled fixed boundary 'a'/a'. The location of maximum intensity in the gradient would be the 'c' point and the end of the cell, understood as the end of potential transport given by a zero crossing point in the flux is the 'e' point. Fixed points delimit cells which diverge in intensity and direction. These environments tend towards reflective modes. Areas of convergence are mainly tending to dissipative morphodynamic environments.

For the construction of the indicator the following steps are taken:

- Construction of high resolution spatial and temporal database for the coastal segment.
- Development of sub datum digital terrain model and integration with subaerial data set (geometric correction of datum needs to be considered).
- Acquisition and statistical analyses of deep water wave field.
- Acquisition and statistical analyses of nearshore wind regimes (for direction in sea wave dominated environments plus wind effects on generation and propagation)
- Execute wind wave generation and propagation model. In our study we used HISWA (HOLTHUIJSEN *et al.*, 1989; BOOIJ *et al.*, 1993, 1995) considering all statistically significant wave approaches.
- After isolation of the surf zone (on wave energy dissipation criteria) interpret radiation stress outputs.
- Mapping of output as residual circulatory cells on base map of the coast highlighting cell points, boundaries and direction.

Input data, mainly bathymetric and deep water wave data are the most significant sets needed for the construction of the morphodynamic indicators. Bathymetric charts need to be digitized from high resolution records to enable reasonable output resolution. In this study data sets from the hydrographic office (Instituto Hidrografico de la Marina) were digitized, georeferenced and interpolated for gridding input to the wave modeling package. The initial high resolution of the soundings in the charts (the data was the sounding logs from the survey on 1:25000) enabled an "interpolated" resolution of 10 m<sup>2</sup> without too much generation of spurious artificial data.

Wave records were taken from the oceanographic stations deployed all around the coastlines of Spain by the port

authorities (Puertos del Estado) of the Ministerio de Fomento. The records extended back to 1985 and a total of 10 years were analysed to establish significant wave height, zero crossing period and mean wave direction

## RESULTS

Multiple wave conditions were simulated in this study (table 1) However, the results introduced for the construction of the indicators are those related with morphodynamic factors. Results of some residuals of eastern and western wave simulations are commented here.

Incoming modal waves from the East produce energetic flows towards the West upon the steep surf zones given the near 45 degree angle of approach to the shoreline.

The simplified flow diagrams (figure 2A) illustrate that the Torrox (submerged) delta behaves as a free boundary only when wave energy is modal and is not capable of producing significant wave induced stress in the reverse direction when storm waves approach. This translates in the positive bypassing of the cell, which justifies the intense refraction around the delta producing a transfer of local beach sediment (natural and lately renourished). This results combined with the traditional shoreline retreat analysis provides a complete definition of the potential coastal behavior at this location (figure 2B). Beach fill projects have found difficult to stop the eroding beach from depleting (at location 'c' opposite to the Torrox delta under storm eastern waves) while a very dissipative profile is emerging at this location (as illustrated in figure 2A by the location of a cell boundary under all wave conditions).

Another type of interpretation enabled by the method, is the localization of potential morphodynamic boundaries which allow a better understanding of potential beach behavior. Around the prominent delta of the Velez river the diminishing river yield (due mainly to intensive damming upstream) and the new morphosedimentary inputs brought about by neighboring beach fill project caused intense fluctuation of the delta feature. Using shoreline comparison methods only a region of dynamic coastlines appear to the west of the delta. However, a clear free boundary 'a'/e' was located when examining nearshore flows. There a realisation of the flows are matched by occasional deposition (particularly evident after storm wave simulations from the East, figure 2A) and thus it appears that the instability of the nearshore processes identified there are directly responsible for the variations measured on the subaerial beach. Simulations from the west suggest that the free boundary disappears and then the apex of the delta can be established as

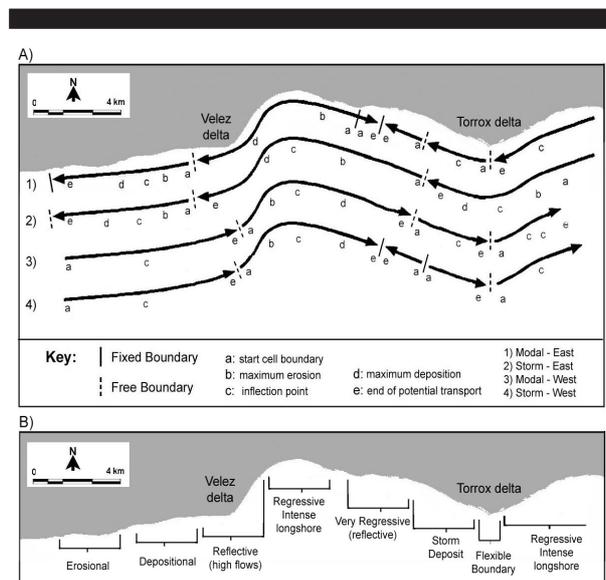


Figure 2. A) Synthetic representation of residual littoral cells. B) Schematic morphodynamic map.

the flexible flow limit for both, modal and storm waves.

As an illustration of simplified output maps of beach states, figure 2B shows a basic morphodynamic classification of the area. The variation is limited in this environment but the dynamic mapping identifies areas ranging from reflective to semi dissipative according to the potential behavior of the Beaches under modeled wave conditions. In the figure, areas where simulation and cell analyses showed intense longshore flows combined with a regressive trend (from shoreline comparison) are labeled reflective or regressive. Some sections are marked by recurrent cell boundary locations and thus need to be identified as the limit of a circulatory pattern where deposition (on the beach or nearshore area) is potentially dominant.

## DISCUSSIONS

A methodological approach that combine the principles of dynamic and physiographic analysis of the cellular type that can cope with the appropriate working scale for monitoring management measures (which we have considered to be sub regional) can help improving existing trends of indicator development and implementation. The combination of methods that commonly measure the resulting action of coastal evolution (e.g. FEMA, 2000 methodology) with the dynamic approach introduced in this article is intended to use all the advances made in coastal classification (from complex to simplistic ones; e.g. WRIGHT and SHORT, 1983; CARTER, 1988, KOMAR, 1996) and bridge some of the gaps existing between pure scientific interest and the need for easy to use and easy to understand and repeat tools for coastal monitoring.

Results of simulated wave propagation over complex bathymetries need emphasizing the role of interpretation of results in depicting characteristic energy settings on the nearshore region. For instance the directional component of the wave forces are analyzed producing a "cell" system interpreted following basic gradients that should drive wave induced currents (and associated sediment transport) from a high momentum area to a low momentum area, corresponding to erosion and deposition events.

In the context of coastal classification numerous methods have been developed to perform basic and complex characterizations. However, classifications are frequently based on either single point measurements along coastal segments considered homogeneous and/or mean wave-sediment conditions that render the indices and classifications static and thus far removed from the very dynamic nature of the changing nearshore environments. A method to characterize "dynamically" can and must be useful because once scientists, engineers, planners and users identify nearshore and subaerial domains on a useful scale (i.e. sub-regional) as one on the beach a better approximation can be undertaken at understanding (if not predicting) beach behavior.

It is important to highlight that there are obvious limitations when conceiving a "working method" that is intended for use of public administrations on multiple scenarios. Among the most important is that data sets need to be manageable, in the sense that ideal data sets can not be achieved when large segments of coasts are to be monitored or classified. Although following this pattern oversimplified methods arise, one should determine what sort of data is available and/or measurable for the management project prior to establishing utopian methodologies that end up in academic exercises that do not enable better management of coastlines. In relation with this, the method presented in this paper, although a little complex in its design allow the use of common data sets and also introduces the possibility of calculation of wave parameters with a variety of modeling tools that are nowadays easy to access by most coastal authorities.

In terms of academic discussion, it should be noted that a series of advancements are introduced in the proposition of a "new" cellular approach. Mainly, the view is that a single point representation of a surf zone, where all the transfer of wave energy and momentum that is effective for nearshore evolution

is to be allocated at the wave breaker is not taken on board. A whole surf zone approach is only possible because the numerical modeling tool utilized provides output on grids and thus information is available on the entire simulation field. Another important addition to the traditional cell concept is the utilization of the force as magnitude and direction generating nearshore currents rather than wave power. Finally a very detailed description of the Cartesian relationship of nearshore radiation stress directions and shoreline exposure aims at correcting the differential treatment of longshore and cross shore circulations. This proves quite important when attempting to draw simplistic cellular structure since diagrams showing the directional component of the force are relative to the grid axis (of the computational grid) and do not recognize the "true" shoreline. Hence a subroutine needed to address this problem by calculating the relative position of each surf zone point in relation with the shoreline intersection of the Cartesian axis. In this way a plus or minus sign for the force is exactly a left or right direction as relative to the shoreline.

The resulting maps, produced after interpretation and georeferencing of cells, can be presented in a variety of scales and resolutions following the most appropriate level determined by the end user. This implies that if a 1:2000 scale is needed for management situations, cells can be investigated at this level too, although generic morphosedimentary units will remain consistent with the sub regional scale.

## CONCLUSIONS

In this article some basic concepts are introduced that present a methodology developed with the view to characterize the nearshore environments of a highly developed coast in the Mediterranean coast of Costa del Sol in Spain.

The main points developed are:

- An introduction of the complex example that Costa del Sol presents as a highly developed fragile coastal environment.
- A quick review of the methods traditionally utilised to characterise coastal evolution on three different temporal and spatial scales.
- A method based on the traditional approach of coastal cell descriptions and mapping, is introduced with a variety of modifications that simplifies its usage in order to establish a repeatable mechanism for the development of a morphodynamic indicator.
- Brief results are described in the light of the main points highlighted in the presentation of the methodology and
- A simplified discussion presents a series considerations on the ideas behind the method, avenues for future research and reflections on the potential applicability of the method in other regions.

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## LITERATURE CITED

- BOOIJ, N.; HOLTHUIJSEN, L.H. and SCHOONBEEK, R., 1993. Standard tests for the shallow water wave model HISWA, version 100.21, Delft University of Technology. Dept. of Hydraulic and Geotechnical Engineering.
- CARTER, R.W.G., 1988: Coastal Environments, Cambridge, Harcourt Brace Jovanovich
- DEIGAARD, R.; FREDSOI, J. and HEDEGAARD, I.B. 1986: Mathematical model for littoral drift. *Journal of waterway, Port, coastal and Ocean Engineering*, 112, pp. 351-369.
- FEMA, Federal Emergency Management Agency, 2000:

- Evaluation of erosion hazards. Report by the John Heinz III Centre for Sciences, Economics and the Environment.
- HOLTHUIJSEN, L.H.; BOOIJ, N., and HERBERS, T.H.C., 1989: A prediction model for stationary, short-crested waves in shallow water with ambient currents. *Coastal Engineering*, 13, 23-54.
- KOMAR, P. D., 1976: Short course Coastal Geology. XXV International Conference on Coastal Engineering". Orlando, Florida, USA.
- KOMAR, P. D., 1998: *Beach processes and sedimentation*. 2nd. edition. New Jersey. Prentice-Hall. 544 pp.
- LONGUET-HIGGINS, M.S., and STEWART, R. W., 1964: Radiation stresses in water waves: a physical discussion with application. *Deep Sea Res.*, vol.12, pp.529-562,
- LONGUET-HIGGINS, M.S., 1970: Longshore currents generated by obliquely incident sea waves. *J. Geophys. Res.* vol. 75, pp.6778-6801.
- MALVAREZ, G.C.; LARIO, J.; ZAZO, C.; GOY, J. L.; LUQUE, L., 1998: Evolución de la Costa de Málaga durante el Pleistoceno Superior y Holoceno y Morfodinámica Actual de los Sistemas Litorales. In: Itinerarios Geomorfológicos por Andalucía Oriental. Gomez, Franch, Schulte and G-Navarro Eds. Universitat de Barcelona Pub. 98 pp. (ISBN: 84-475-2037-4)
- MALVAREZ, G.C., 1999: Procesos morfodinámicos litorales en la Costa del Sol. In: Elementos de los Paisajes de la Provincia de Malaga. J.M. Senciales and E. Ferre, Eds. *Universidad de Malaga Publisher* (ISBN: 84-7496-732-5) pp 171-230.
- MALVAREZ, G. C. and COOPER, J.A.G., 2000: A whole surf zone numerical modelling approach to the characterisation of nearshore environments and beaches. *Journal of Coastal Research*. Vol 16 (3) pp 808-823.
- MAY, J. P., 1974: A computer program to determine the distribution of energy dissipation in shoaling water waves with examples from coastal Florida.
- SENCIALES, J. M., and MALVAREZ, G. C., 2003: La desembocadura del Rio Velez (Provincia de Malaga, España). Evolución reciente de un delta de comportamiento Mediterraneo. *Revista Cuaternario y Geomorfología*, 17 (1-2), pp 47-61.
- SHORT, A.D., 1993: Beach and Surf Zone Morphodynamics, Special Issue 15, *Journal of Coastal Research, Coastal and Educational Research Foundation*, Florida, 231 pp.
- STAPOR, F.W. and MAY, J.P., 1983: The cellular nature of littoral drift along the northeast Florida coast. *Marine Geology*, 51, 217-237.
- STONE, G. W.; STAPOR, F. W.; MAY, J. P. and MORGAN, J. P., 1992: Multiple Sediment Sources and a Cellular, Non-Integrated, Longshore Drift System: Northwest Florida and Southeast Alabama coast, U.S.A. *Marine Geology*, 105:141-154.
- WRIGHT, L.D. and SHORT, A.D., 1983: Morphodynamics of beaches and surfzones in Australia. I: P.D.Komar (ed) *CRC Handbook of Coastal Processes and Erosion*, CRC Press, 35-63.