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# ASSESSMENT OF MORPHOLOGICAL CHANGE IN ESTUARINE SYSTEMS – A TOOL TO EVALUATE RESPONSES TO FUTURE SEA LEVEL RISE. THE CASE OF THE SADO ESTUARY (PORTUGAL)

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## RESUMO

Neste trabalho são apresentados os resultados preliminares da evolução morfológica a mesoescala no Estuário do Sado, baseados na comparação de cartas topo-hidrográficas. Esta comparação serviu para determinar e representar tendências evolutivas passadas, com o objectivo de modelar respostas do estuário a cenários futuros de subida do nível do mar. Quatro mapas hidrográficos, com informação diacrónica recolhida entre 1930 e 2002, foram processados, utilizando o SIG ArcView, para produzir MDT (modelos digitais de terreno), posteriormente subtraídos para obtenção de superfícies representativas de alterações volumétricas. A integração, no espaço e no tempo, de variações de profundidade, originou taxas médias de sedimentação para as principais unidades morfosedimentares do estuário. Os resultados sugerem alguma consistência nas tendências dominantes das alterações volumétricas dentro das unidades maiores; o valor total para toda a área de estudo indica o sistema como um forte, embora não uniforme, poço sedimentar. As tendências de variação e as quantidades relativas de alteração dentro dos domínios estuarinos parecem aceitáveis como primeira estimativa da resposta do sistema a agentes forçadores recentes. Estes resultados estabelecem uma base a partir da qual modelos hidrodinâmicos poderão ser corridos, incorporando diferentes cenários de elevação do nível médio do mar, para inferir plausíveis previsões de expansão/retracção de zonas húmidas, alterações na salinidade, dispersão de matéria suspensa/dissolvida e tempos de imersão/submersão.

## ABSTRACT

This work presents first results of mesoscale morphological evolution of the Sado Estuary, based upon topo-hydrographic chart comparisons. This comparison has been carried out to measure and map past evolutionary trends, in order to model distinct responses of the estuary to future sea level rise scenarios. Four hydrographical maps, containing diachronic data, surveyed between 1930 and 2002, were processed using the ArcView GIS to produce DTMs that were further subtracted to obtain three surfaces representing volumetric change. Space and time integration of measured depth variation resulted in average sedimentation rates of the main morpho-sedimentary estuarine units. The results suggest that there is some consistency in the dominant trends of volumetric change within major units; the grand total for the whole study area indicates the system as a strong, yet non-uniform sediment sink. The variation trends and the relative amounts of change within estuarine domains seem acceptable as first estimates of the system's response to recent forcing. These results set a foundation upon which numerical models of estuarine hydrodynamics may be run, incorporating different scenarios of mean sea level elevation, to infer plausible forecasts of wetlands' expansion/retraction, changes in salinity, dispersion of suspended/dissolved matter, and times of emersion/submersion.

Keywords: estuarine evolution, coastal zones, gis.

## 1. INTRODUCTION

The global warming of the Earth's climate system may increase the global sea level rise rate in the next 100 years (IPCC, 2001) and the available scenarios suggest an average elevation within the range 0,09 to 0,88 meters. This may have important impacts in coastal zones, which have a high socio-economic value.

A first integrated assessment of climate change impacts and adaptation measures in mainland Portugal has been conducted by a multidisciplinary research team under the auspices of SIAM Project; this assessment relied upon climate scenarios produced by General Circulation Models and Regional Climate Models and focused on a core-set of socio-economic and biophysical impacts, affecting vital sectors of the economy, including the coastal zone (cf. Santos et al., 2002).

The results of SIAM indicated the Sado Estuary as a particularly susceptible tidal wetland to future climate change and selected this area as a case study to evaluate the potential impacts of sea level rise in coastal zones. In fact, the Sado River catchment's area may experience, by 2100, a reduction in runoff in the order of 60% (Santos et al., 2002), which will probably translate in a changing sediment supply. The decrease in freshwater flow may induce important changes in the estuarine physical structure and functioning, which will certainly affect the entire ecosystem. In addition, the expected elevation in sea level will probably translate into changing tidal behavior within the estuary, with effects in the time and space distribution of salinity, immersion times of intertidal areas, currents and ebb/flow asymmetry.

A comprehensive study of this area is presently in progress, aiming to improve the understanding of the interactions between the Sado Estuary, the ocean, shelf and the terrestrial margin. One important aspect of this study is the evaluation of time/space variability in morphology, in order to produce a conceptual functioning model of use to predict future responses of the estuary to distinct sea level rise scenarios. The first step of this study consists in the comparison of available topo-hydrographic charts to measure and map the estuary's morphological evolution trends. These data will be used to feed numerical hydrodynamic models of tide propagation in different climatic and morphologic scenarios. This paper presents the first results of our study on the morphological changes in the Sado Estuary from 1930 onwards.

## 2. SETTINGS

The Sado Estuary, located on the west coast of Portugal, 40 Km to the South of Lisbon, (Fig. 1), has a flooded surface of 150 km$^2$ (Quevauviller, 1985) and a drainage basin of 7600 km$^2$ (Peneda et al., 1982).

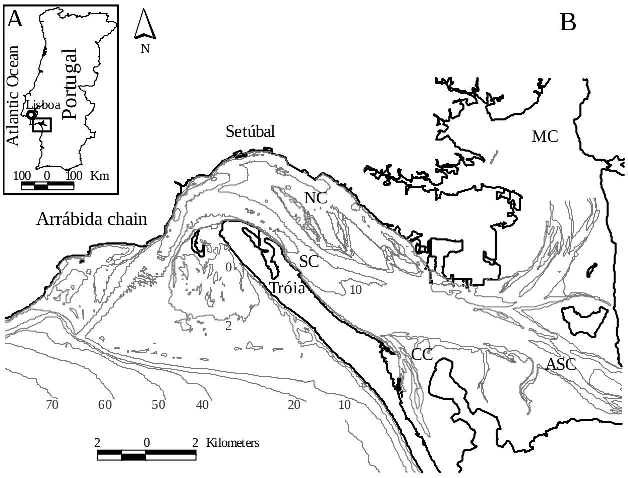


Fig. 1 – Location (A) and bathymetry (B) of the Sado estuary (contours in meters below HZ).

The Sado River is the most important source of fresh water to the estuary, with a Summer runoff of 0.7 m$^3$/s, which increases to 60 m$^3$/s in Winter (Vale & Sundby, 1982). Two subsidiary channels, the Marateca Channel (MC), and the Comporta Channel (CC), also drain directly to the estuary, but their contribution in fresh water is small in comparison with the main channel.

The estuarine inlet, with maximum depth of 40 m and 1,5 Km width (Vale & Sundby, 1982), is constrained between the north tip of the Tróia Peninsula and the Arrábida chain (Fig. 1). The inlet channel bifurcates upstream in the North Channel (NC), which provides access to the Setúbal harbor, and the South Channel (SC), witch extends across the estuarine basin until it meets the Alcácer do Sal Channel (ASC) - the Sado's outlet. The estuary is mesotidal, the amplitude ranging between 3,5 m (spring) and 1,5 m (neap). There is strong asymmetry between the tidal regimes in both main channels (Ambar et al., 1982). The spring tidal prism reaches 400x10$^6$ m$^3$ and the dynamic tide extends up to 65 Km upstream.

This estuary shows diverse land uses and the population density is highly variable along the estuarine margin. The harbor of Setúbal, one of the most important Portuguese ports and cities, is located on the North bank of the estuary and this encourages periodical dredging of navigation channels.

The northern estuarine shoreline bears the highest population density, associated with intense urban (e.g. Setúbal) and industrial development (e.g. shipyards, thermal power plant, paper-mill); in consequence, it has been extensively intervened and artificialized. Beyond the influence of Setúbal urban and industrial perimeter, the Sado Estuary area includes 23160 ha of a natural park. Within this park, traditional activities of fishing and agriculture are maintained, besides a growing tourist demand, which involved and transformed the northern third of the Tróia Peninsula since the 1970's.

Under the geomorphologic point of view this estuary is a bar built estuary (Pritchard, 1960; Fairbridge, 1980 in Perillo, 1995), separated from the ocean by the Tróia barrier, a large sand spit with extensive dune fields and beaches, nourished by net littoral drift directed northward. The estuarine coast also contains other relevant features, such as cliffs, tidal flats and salt marshes. The Arrábida chain and headland shelter the estuary from the prevailing swell that approaches mainly from NW. Wave refraction along the estuarine (submarine) outer delta, which extends for more than 5 km offshore, also contributes to this sheltering effect.

## 3. METHODS

A total of only four topo-hydrographical maps containing reliable data and encompassing the whole study area are available; they were surveyed in different dates and are presented in different scales: 1930 (1:150000); 1968 (1:25000); 1979 (1:25000) and 1995/2002 (1:15000). Moreover, the hydrographical information in each map results from the compilation of diachronic surveys (Fig. 2 represents polygonal areas with synoptic data), further complicating the comparison between different documents. The ArcView GIS has been used to georeference maps and to digitize both the bathymetric information and the reference polygons.

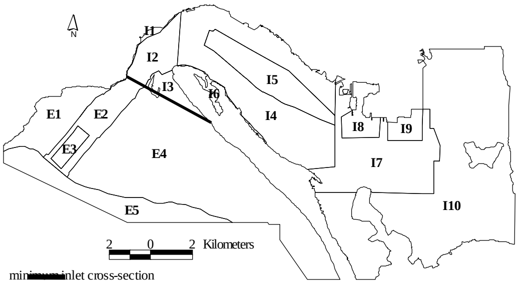


Fig. 2 –Reference polygons (E – external; I – internal).

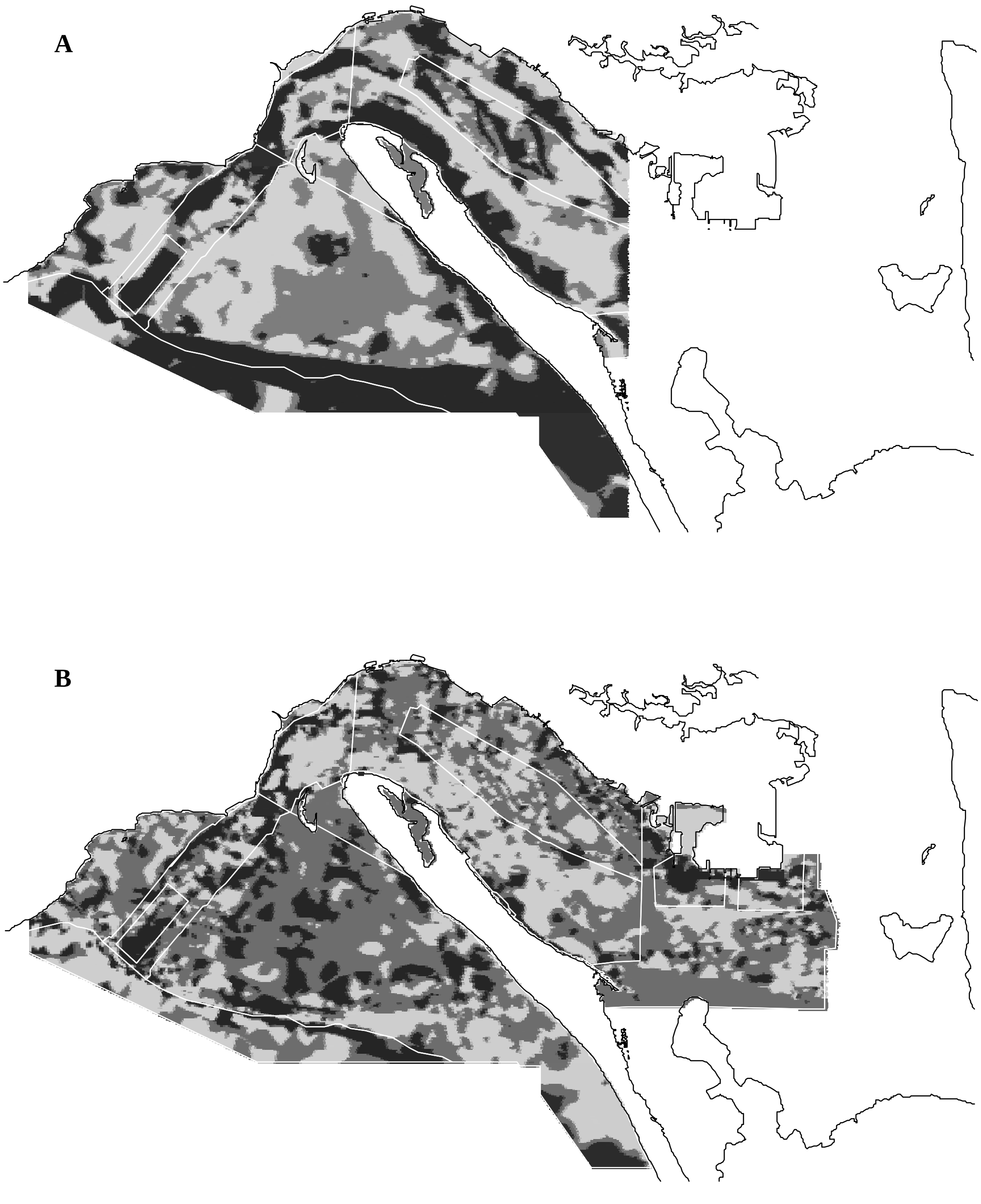
The coastlines obtained from the digitizing of the four surveys show significant differences and, to simplify further procedures, the line enclosing the minimum wet area has been selected as representative of the coast.

Digital terrain models (DTM) have been built for each map, by triangulation of the digitized bathymetric data, subsequently transformed in a 5x5 m cell-grid. Subtraction of DTM pairs resulted in cartographic representation of depth variations integrated in space for different time intervals: 1930-1968, 1968-1979 and 1979-1995/2002 (Fig. 3).

The minimum cross-section area at the inlet gorge, which separates the internal and external domains of the estuary, was calculated using the 2002 DTM (Fig. 2).

## 4. RESULTS

Maps in Figure 3 depict a summary image of the spatial variation of erosion/accretion trends within the study area; stability corresponds with an interval of [-0.5, +0.5] m depth variation during each of the considered periods.



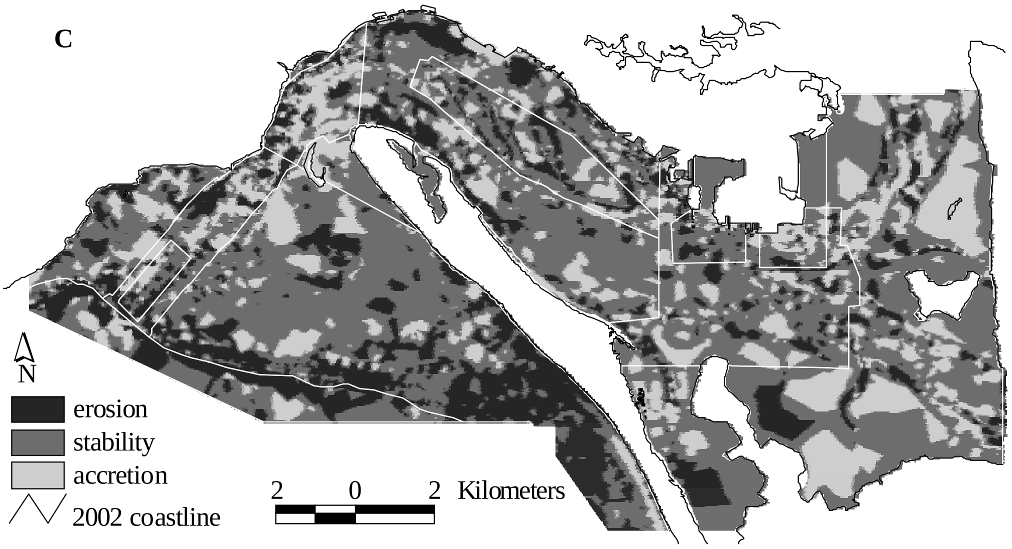


Fig. 3 - Erosion/accretion trends between: A) 1930 and 1968; B) 1968 and 1979; C) 1979 and 2002.

At first sight the spatial distribution of depth variation is not easy to interpret, given the scattering of small elements of the grid with contrasting trends. However, a closer inspection suggests that there is some consistency in the dominant trends of volumetric change of major morpho-sedimentary units, such as the ebb delta's boundary slope and surface, the access channel, both main tidal channels of the inner estuary, which straddle sandy shoals, and the intertidal flats extending further upstream. These units may show different intensities or even reverse signal of volumetric change between successive comparisons but, in any case, they are more coherent internally than when compared with contiguous polygons.

The limiting slope of the outer delta systematically shows dramatic variation in intensity and signal of change, regardless the comparison period. In contrast, the delta surface shows moderate changes and it may have experienced progressively increasing sediment loss with time. The main channel, as well as limited sections of the northern margin, strongly reflect the effects of dredging or landfill. In general, the inner estuary channels, shoals and flats, show accretional resultant, although the intensity and distribution of the components are variable in time and space.

Based upon the previous analyses, average sedimentation rates have been computed for a number of polygonal domains with morpho-sedimentary expression, integrating the spatial extent of each polygon. The results yield a first quantitative assessment of morpho-dynamic change. Figure 4 illustrates these results for the period 1979-2002.

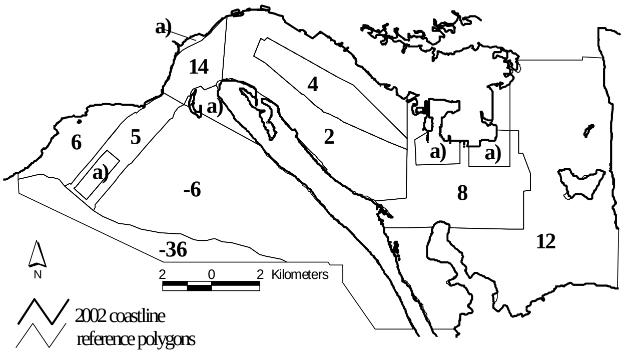


Fig. 4 - Average sedimentation rates, in mm/year, for polygonal domains, 1979-2002; a) problematic areas due to proximity to the margins or high dredging/landfill.

The grand total for the whole of the study area, and considering all comparisons, averages +9 mm/year, indicating the system as a strong sediment sink; this result contains a contribution of +20 mm/year of the inner estuary and –2 mm/year of the outer estuary; it should be noted that this total outcomes from the average of extremely contrasting partial results: -22 mm/year (1930-1968), +47 mm/year (1968-1979) and +0.1 mm/year (1979-2002).

The outer delta appears to have been shrinking through lowering of the swash surface and slope retreat, particularly in the SW area, while the inner channels and flats display a trend towards shallowing, which apparently increases upstream. The inner shoal and the westward section of the inner estuary have been infilling essentially with sand, part of which may have been sourced from the outer delta and conveyed through the south channel. In contrast, the innermost section of the estuary and intertidal flats appear to have accreted with cohesive sediment delivered from the watershed.

## 5. DISCUSSION AND CONCLUSIONS

The reliability of results obtained for depth variation partly depends on the documents' accuracy in representing the morphology; apparent translation of features due to inexactness (inherent to original maps) and resulting from the digitizing procedures, may result in spurious volumetric change, steeper slopes being the most susceptible. To assess the extent of this problem, the amount of change found through map comparison ($v_1$) has been checked against the equivalent figure ($v_2$) computed after lateral shifting of selected polygons up to 10 m, parallel to the maximum slope direction (Table 1).

Table 1 – Assessment of error affecting volumetric results

| Polygon studied | Dates | $(v_1-v_2)/v_1$ (%) |
|---|---|---|
| I5, sand shoals | 1979-2002 | 23 |
| I5, sand shoals | 1968-79 | 3 |
| E5, ebb delta slope | 1979-2002 | 32 |
| E5, ebb delta slope | 1968-79 | 53 |
| E5, ebb delta slope | 1930-68 | 11 |

Differences summarized in Table 1 are overestimated, and yet bias introduced by cartographic errors seems to be in general small, not exceeding 30%.

In the best judgement of the authors, the 1930 survey may have introduced significant distortion in the earlier comparison, especially in the marginal areas and steep slope elements, due to the small scale of this map. In general, accuracy improves in time, but two major drawbacks could not be overcome: the scarcity of data points in intertidal/supratidal areas and missing bathymetric contours in the older maps, the latter particularly affecting volumes limited by steeper slopes.

Estuarine systems are usually efficient sediment sinks and our results are in general agreement with this statement, regardless the time and space variation in sedimentation patterns in both inner and outer domains (Fig. 4). In the 1930-1968 comparison the strong accretion areas are associated to the northern margin and are mostly related to landfills. The pattern of change exhibited by the outer delta may reflect interaction with the adjacent coastal system and with the inner estuarine basin. It is unclear, at this stage, if the sediment loss of the outer delta reflects adjustment of its equilibrium volume to a changing tidal prism (as suggested by decreasing accommodation space upstream) or temporary borrow of sand to the Tróia sand spit.

The general accretion experienced in the inner estuary is in agreement with sea level rise, but exceeds the average rate in elevation of the base level since the 19th century (1-2 mm/year) by 2 to 6 times. Curiously, this has not been accompanied by extensive expansion of saltmarshes, most of the intertidal domain corresponding with tidal flats, which, according to our results, show large space variability in sedimentation rates. Psuty & Moreira (2000) used $^{14}C$ dating of short cores to assess accretion rates in fringing high marsh of the estuary between 1979 and 1990 and report figures of 2 mm/year; this may reflect different methodologies and, essentially, higher sedimentation rates in tidal flats and shallow subtidal shoals. The patterns of sediment movement between the outer delta and the inner channels remain to be confirmed by fieldwork and the rate of sedimentation derived from map comparison will be matched against $^{210}Pb$ data; further work on geomorphological and sedimentological mapping is required to validate and fine tune the results from map comparison. Regardless the significance of the absolute values found for volumetric change in different domains of the Sado Estuary, the authors are confident that both the variation trends and the relative amounts of change of different domains are acceptable as first estimates of the estuarine response to recent forcing. These data may be of use to construct a dynamic morphological basis, over which hydrodinamical models, incorporating different future scenarios of mean sea level, can be run; these are expected to yield possible scenarios of impacts within the estuary and upon its margins in terms of expansion/retraction of wetlands, changes in salinity, dispersion of suspended/dissolved matter, and times of emersion/submersion.

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