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SEDIMENTARY DYNAMICS OF THE MONDEGO ESTUARY

Abstract

The Mondego estuary is composed of two subsystems with contrasting sedimentary, hydrodynamic, physical and chemical characteristics. Is affected by a mesotidal, semi-diurnal, regime. The Mondego subsystem, currently including a navigation channel, is exclusively bounded by artificial banks. The Pranto subsystem is more shallow and less affected by anthropogenic interventions. The aims of this study are the recognition of freshwater/saltwater circulation and the analysis of surface sediments in order to propose a pattern of sediment circulation. Studies on grain-size, mineralogy and quartz-grains surface textures and roundness of surface sediment samples were conducted and a detailed grain-size map was obtained. Most of the data was acquired in 1994 to 1996, at low and high tide of neap and spring tides, including measurements in selected locations, at several depths, of conductivity, salinity, temperature, current velocity/direction, turbidity, concentration of silt/clay, pH and Eh. The Mondego subsystem is under significant tidal control, being well mixed with reduced fluvial flow and stratified during seasonal floods. The hydrodynamic pathways (tidal ***vs***. fluvial, this prevailing in the northern margin) causes clear contrast in sediment transport. The Pranto subsystem is mainly brackish, well mixed, with strong tidal hydrodynamic, physical and chemical fluctuations; fluvial floods rarely have high discharges. The well developed Gala flood tidal delta, and the extensive saltmarsh and intertidal mudflat, dissected by tidal creeks, are the main features of this subsystem. The Pranto subsystem is tidal dominated, while the Mondego subsystem is both tidal or fluvial dominated.

Introduction

The sedimentary dynamics is one of the main controls in an estuarine ecosystem, a complex transitional environment with a delicate balance. This work is focused on the sedimentology and hydrodynamics of the Mondego estuary and adjacent shore (Fig. 1). As discussed in this work, the Mondego estuary is composed of two subsystems — the Mondego and the Pranto — with contrasting sedimentary, hydrodynamic, physical and chemical characteristics.

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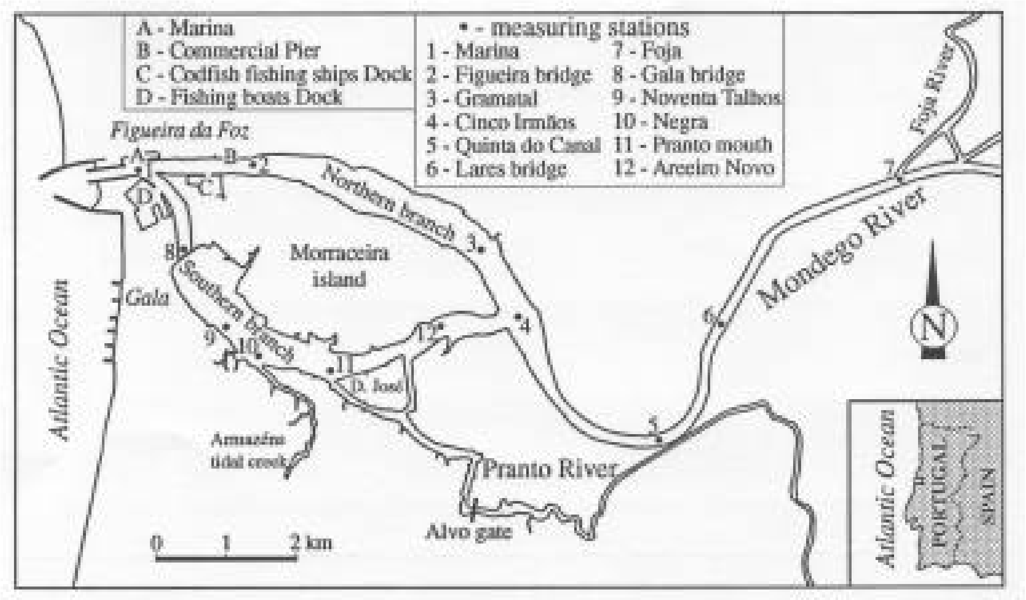


FIG. 1. Location and map of the Mondego estuary (except a small portion of the upstream sector), with the position of water properties measurements stations.

Estuarine deposits are controlled by periodic phenomena, at different time and space scales, as tides (Allen, 1993) and seasonal floods. In this study, the surface sediments after a 125-years return flood were characterised, allowing the estimation of water and sediment flow and provenance. The water mixing and circulation pattern was evaluated through the study of the hydrodynamic, physical and chemical parameters variation.

The role of natural or human processes is discussed, as well as the long-term and long-distance impacts of changes in the main controls of the sedimentary system dynamics. In particular, the morpho-sedimentary evolution can assess the impact of the extensive human modification and occupation, and contributes for the acquisition of fundamental elements in the decision-making, towards a sustainable and integrated management of natural resources in coastal zones.

Regional Setting

Geological and geographical setting

The Mondego River has a catchment basin of 6671 km^2, draining granitoids, metamorphic and sedimentary rocks. Downstream of Coimbra the river flows in a floodplain up to 4 km wide. The estuary location is fixed just south of an uplifted relief, the Serra da Boa Viagem. Despite the significant fluvial and tidal flows (specified bellow), the strong southwards longshore current built an important spit, such that the estuary can be morphologically classified, after Fairbridge (1980), as bar-built. About 6.5 km upstream of its mouth the river is divided in two branches (northern and southern), corresponding to the above mentioned subsystems, that converges again defining the Morraceira Island (Fig. 1). The sedimentary areas reaches 4.64 km^2 in the Mondego subsystem and 2.20 km^2 in the Pranto subsystem.

Fluvial regime

Before the construction of several dams during the decade of 1970, the fluvial regime was directly controlled by the seasonal precipitation in the catchment basin (Tab. 1), with a large bed-load inflow to the estuary and coastal areas. However, essentially with the construction of the Aguieira and Fronhas dams, the fluvial regime was smoothed, reducing slightly the water discharge, but most of bed-load remains trapped (compare Tabs. 1 and 2). Notice also that the average discharge for the days of each year with highest discharge was quite reduced. For instance, the 10 days with highest discharge of a wet year reached a mean of 825 m^3/s before the construction of several dams, and only 700 m^3/s after the construction.

TABLE 1. Water and solid discharges (m^3/s) of the Mondego measured in the Coimbra streamflow station, before the construction of several dams (DIRECÇÃO GERAL DE RECURSOS E APROVEITAMENTOS HÍDRICOS 1987).

Days/year (total 360)	Average year	Wet year	Dry year
10	490	825	245
50	175	325	75
100	85	210	40
200	20	25	5
Annual mean waterflow	84	155	37
Dominant waterflow	370	490	230
Solid flow	0.0075	-	-
Estimation for a 100-years return flood: peak flow of 3663 m^3/s			

TABLE 2. Estimated water and sediment discharges (m^3/s) of the Mondego measured in the Coimbra streamflow station, after dams construction, embankment and canalisation of the river (DIRECÇÃO GERAL DE RECURSOS E APROVEITAMENTOS HÍDRICOS 1987).

Days/year (total 360)	Average year	Wet year	Dry year
10	500	700	160
50	175	360	58
100	85	240	30
200	18	40	5
Annual mean waterflow	72	145	27
Dominant waterflow	340	440	150
Solid flow	0.0015	-	-
Peak flow (100-year return period) in Coimbra considered for the main river channel: 1200 m^3/s in Coimbra (corresponding to about 2955 m^3/s in the mouth)			

The total freshwater inflow of the tributaries downstream of Coimbra is very reduced (Tab. 3), including in the right margin the Ançã and Foja Rivers, and in the southern margin the Cernache, Ega, Arunca and Pranto Rivers. The freshwater in the Pranto subsystem is usually limited to the flow of the Pranto River and the Esteiro dos Armazéns.

The solid inflow to the estuary from the Mondego tributaries downstream of Coimbra is about 26.5 x 10^3 m^3/year (after Tab. 3 data).

The Mondego discharge measured in Coimbra during the field work period shows that, despite the construction of the dam system upstream, the flow regime is irregular (Tab. 4) and quite seasonal.

TABLE 3. Water and sediment discharges (m^3/s) of the Mondego tributaries downstream of Coimbra, after dams construction, embankment and canalisation of the river (DIRECÇÃO GERAL DE RECURSOS E APROVEITAMENTOS HÍDRICOS 1987).

Tributary	Streamflow annual mean	Solid flow annual mean	Streamflow dominant mode	Flood flow (25 years return period)
Ançã	1.1	0.00016	2.8	325
Foja	1.3	0.00017	2.6	135
Cernache	0.5	0.00002	1.8	175
Ega	1.9	0.00004	7.1	70
Arunca	4.9	0.00018	15.9	895
Pranto	1.9	0.00027	5.1	315
Total	11.6	0.00084	35.3	1915

TABLE 4. Extreme Mondego streamflow daily mean discharge (m^3/s) measured in Coimbra, during the considered field work.

Year	Minimum	Maximum
1994	12.6 (April, 3)	694.5 (January, 7)
1995	8.6 (November 4)	1013.0 (December, 26)
1996	6.0 (November, 8)	1034.6 (January, 7)

Tidal regime

The tidal regime, coupled with the fluvial inflow, controls the estuary shape and sedimentary dynamic of the Mondego estuary. It is affected by a mesotidal regime (Hayes, 1975), with semi-diurnal tides and small diurnal inequality. In the predicted tidal levels for 1996, the most frequent range is 2.4 m, with a mean of 2.2 m, a minimum of 0.9 m and a maximum of 3.6 m.

During seasonal low fluvial flow and spring tides, measurable tidal range reaches 26 km upstream of the mouth (Montemor-o-Velho). For instance, in the summer of 1989 in the

Ereira bridge (18 km upstream), a range of 2 m was recorded in spring tide and 0.7 m in neap tide (Baptista 1990), with fluvial discharge of 8 to 24 m^3/s in Coimbra (Açude measuring station). According to Duarte and Reis (1994), during fluvial floods the tidal wave penetrates only 16 km, but these authors do not provide the correspondent fluvial discharge. The Pranto subsystem is nowadays limited upstream by the Alvo gate (Fig. 1), avoiding the propagation of the tidal wave.

Methods

The field work was performed between 1994 and 1996 (details in Cunha et al. 1997a). Measurements of conductivity, salinity, temperature, current velocity and direction, turbidity, concentration of silt/clay, pH and Eh were carried out in selected locations (Fig. 1). The field analysis of water properties were carried with fluvial discharges lower than the annual mean, at low and high tide of neap and spring tides, in order to recognise the freshwater and saltwater circulation pattern. Separate longitudinal profiles were recorded in each subsystem, in an upstream direction (Fig. 1). A total of 23 profiles were obtained: 12 in the Pranto subsystem and 11 in the Mondego subsystem, corresponding to 12 tidal cycles (2 in 1994, 6 in 1995 and 4 in 1996). The collected data of water properties is considered as representative of frequent situations of annual and inter-annual variability. All the stations were located in the thalweg, and the measurements were made at each meter of depth, from the surface to the bottom.

The field description of surface sediment samples, collected directly in the intertidal and supratidal areas and by dredging in the channels (164 of the Mondego subsystem and 63 of the Pranto subsystem), were used to elaborate a detailed grain-size map (Udden-Wentworth scale; see the Mondego Estuary grain-size map in appendix). A study on grain-size, mineralogy and quartz-grain roundness and surface textures was performed on selected samples — 114 of sand and 15 of mud.

Surface sediment was sampled just after the important fluvial winter flood of 1995-1996, with a maximal discharge of 1210 m^3/s in Coimbra corresponding in the estuary to an inflow near 3000 m^3/s (Tab. 2). This flood is estimated as having an 125-year return period, considered here as a situation of maximal fluvial control in the estuary.

Water properties

The obtained physical, chemical and hydrodynamic information, combined with previous data, allowed the characterisation of the estuarine freshwater and saltwater, and to recognise the way in which they interact in space and time during seasonal and tidal cycles. Furthermore, these informations are relevant contributions to understand the sedimentary dynamics. In fact (e.g. Perillo, 1995), the bed load deposition is strongly controlled by the velocity and pathway of tidal and fluvial currents, the suspended load deposition depends on the margins hypsometry and the maximum flocculation occurs in the zone of sharp salinity change (halocline).

Currently, the salinity increase induced in the Mondego subsystem by tidal propagation reaches the Foja station, 15 km upstream of the mouth (Fig. 1; salinity of 7 ‰ in the spring high tide of 96/07/02, with a discharge of 16.7 m^3/s in Coimbra; Cunha et al. 1997), but a salinity of 5 ‰ was already recorded near the Ereira bridge (18 km upstream) in September of 1989 (Baptista 1990), with a fluvial discharge of 8 m^3/s in Coimbra. According to Duarte and Reis (1994), the brackish water can penetrate only 8 km in the Mondego subsystem during fluvial floods, but these authors do not provide quantitative discharge data.

During the field work of March to July 1996 the discharge in Coimbra oscillated from 13 to 182 m^3/s, covering a wide range of water mixing and variation of physical and chemical parameters. The presented longitudinal profiles (Figs. 2 to 4) exemplifies the main interpretations.

The saltwater temperature is frequently different from the freshwater, specially during the hot and dry season (spring and summer). Eh and pH can be directly correlated with the salinity — saltwater average: pH=8,1 and Eh=65 mV; freshwater average: pH=7,4 and Eh=30 mV — and presence of contamination can be related with abnormally high values of those parameters (Fig. 2). The turbidity, in general lower then 10 MTU, has a complex distribution, attaining peaks in the narrow zones of sharp salinity change (halocline) or near the main bottom morphologies. The concentration of silt and clay was always lower than 0.1 g/l.

Mondego subsystem

With neap tides this subsystem presents a salt-wedge during low tide, changing to partially-mixed during high tide. Fig. 2 shows the salt-wedge and the upstream current, even with the upstream stations under a dominant fluvial influence; the pH, Eh and turbidity values indicates water contamination in the Quinta do Canal station.

Contrasting trends were recorded in spring tides: slightly partially-mixed in low and well-mixed in high tide. Fig. 3 is an example of a fully mixed situation, since there is no vertical differences on salinity. The Pritchard (1955, see also Dyer 1995) approach points to a stratified situation in the Mondego subsystem with high ratio between the fluvial flow (Tabs. 2 and 3) and the tidal volume (spring tides: 12.5×10^6 m^3, average tides: 11.5×10^6 m^3 and neap tides: 8.0×10^6 m^3; Consulmar 1973), frequent during the rain season.

A moderate increase of the fluvial discharge affects mainly the salt-wedge thickness, rather then its upstream extension. The 30 ‰ isohaline swings about 9 km in a spring tide cycle and near to 4 km in a neap tide cycle.

The flow velocity clearly decreases to the bottom. During flood, fluvial and tidal currents merges in the Cinco Irmãos area. Mainly in neap tides, the flood current frequently continues after the highest water stage, creating a salt-wedge. The maximum ebb velocity is attained in the mouth, where the flow of both subsystems converge. The bottom morphology and the water quality of the small tributaries can be better evaluated during low tide. Ebb velocity in neap tides decreases gradually downstream and, due to the fluvial current, the maximum velocity of flood current is located about half depth (Fig. 2).

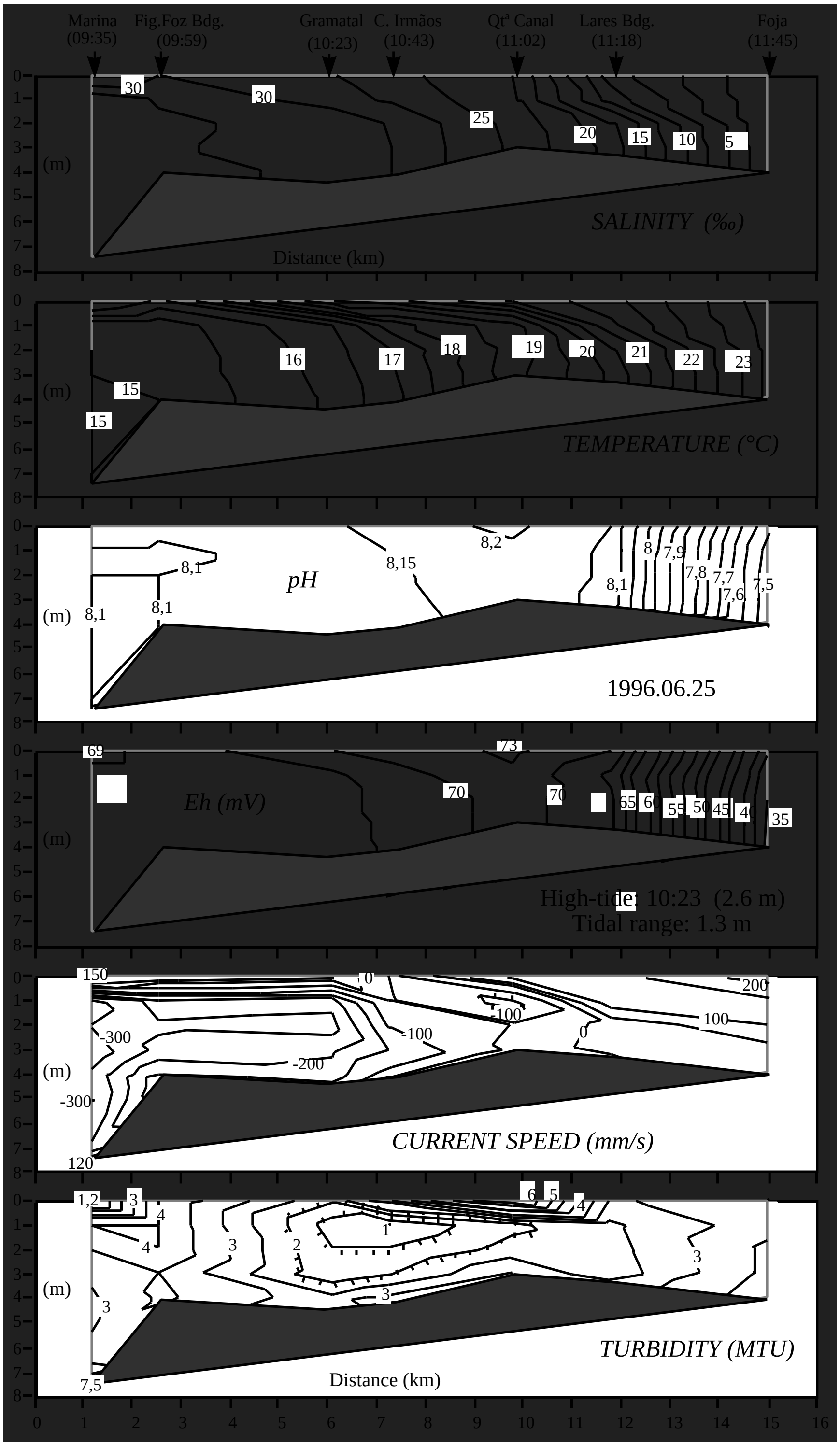


Fig. 2 - Physical and chemical parameters of the Mondego subsystem water in a high neap tide, with a fluvial inflow about 20 m^3/s (17.2 m^3/s measured in Coimbra and 1.6 m^3/s in the Ponte de Mocate-Arunca station). The high tide value is referred to the Portuguese Hydrographical Zero. Negative current values indicate upstream displacement and positive downstream.

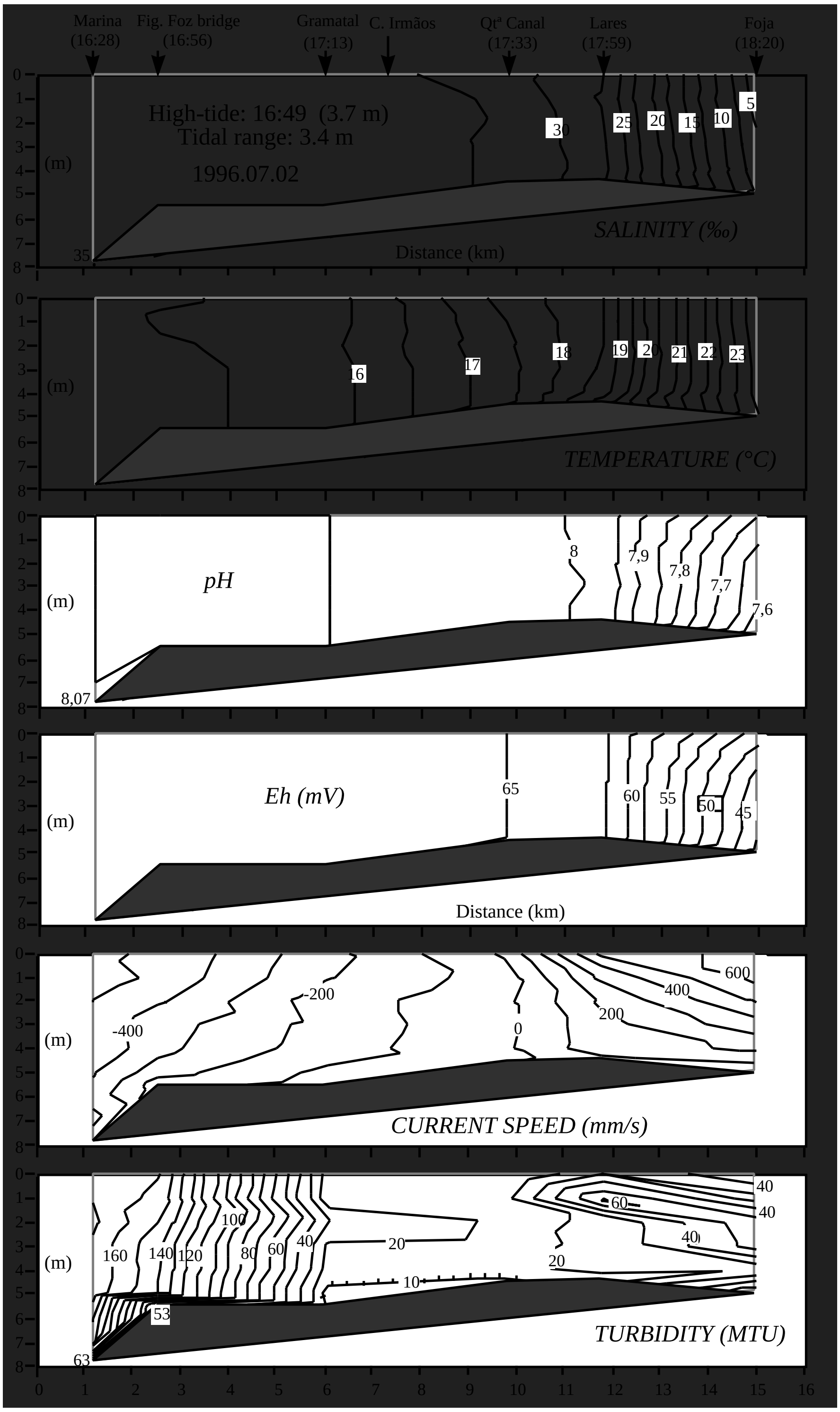


FIG. 3 - Physical and chemical parameters of the Mondego subsystem in high spring tide, with fluvial inflow about 20 m^3/s (16.7 m^3/s measured in Coimbra station).

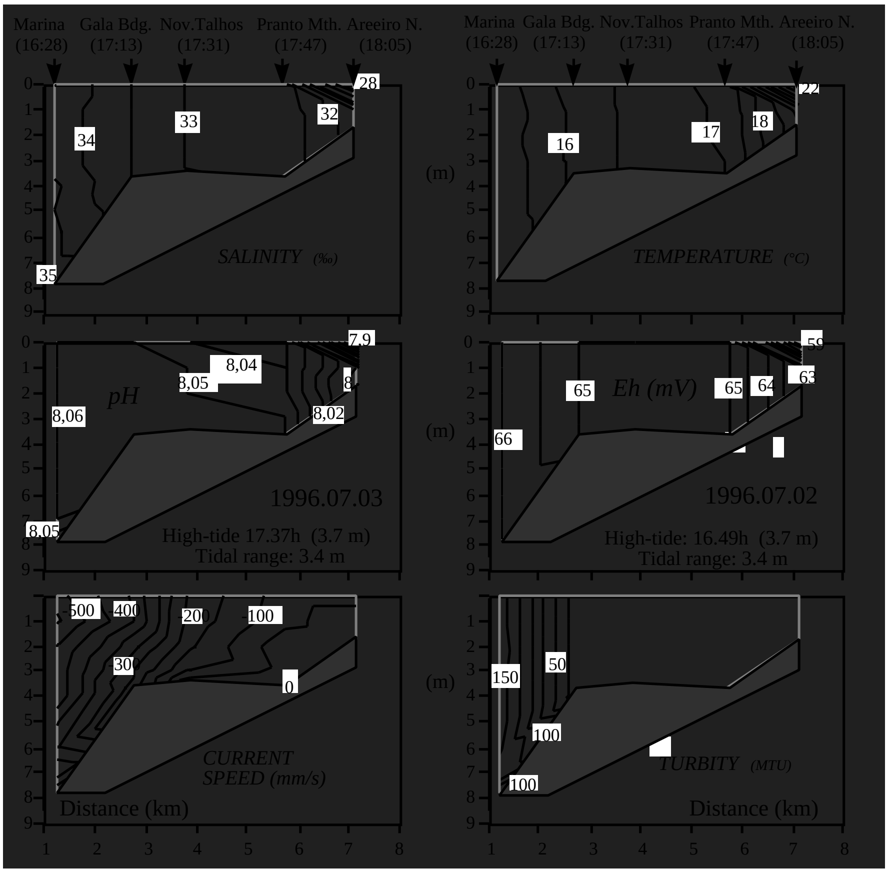


FIG. 4 - Physical and chemical parameters of the Pranto subsystem in a high spring tide.

The ebb velocity in the northern estuarine branch during a 100-year return period fluvial flood (1200 m^3/s in Coimbra) is estimated in 2.7 m/s, decreasing to about 1.6 m/s with a 1000 m^3/s discharge in Coimbra (Consulmar et al. 1991). With a low river discharge (13.6 m^3/s in Coimbra), the maximum ebb velocity recorded reached 0.86 m/s in the Marina station.

Under weak fluvial discharge, the spring tide flood can have a significant control even in the upper estuary. Field experiments of 95/04/12 and 96/07/02 had a low fluvial flow and, therefore, considered as representative of such conditions. In 95/04/12, under a 14.1 m^3/s Mondego discharge measured in Coimbra, upstream velocities of -0.36 m/s in the Foja station and -0.60 m/s in the Ponte de Lares station were recorded. In the same conditions, the maximum flood velocity was measured in the Marina station at the surface (-0.70 m/s). Near the bottom, upstream velocities of -0.25 m/s were recorded in Ponte de Lares (spring tide flood of 95/04/12) and -0.3 m/s in the Marina, about 20 minutes before the high spring tide of 96/07/02.

The high and homogeneous turbidity of the seawater inflow shows a clear upstream dilution. The over-flowing fresh water turbidity has its maximum at the surface with a gentle decrease to the bottom (Figs. 2 and 3). The ebb flow friction over the bottom increases the turbidity (Kappenberg et al. 1995).

Pranto subsystem

During low tide this subsystem is almost completely exposed, with small fluctuations of several parameters probably due to local damming of brackish water by the large sandy-muddy bars between Ponte da Gala and the mouth of the Pranto River. Usually fully mixed, it can be partially mixed during the rare fluvial floods, as also suggested by the ratio (after Pritchard 1955) between the fluvial flow (Tabs. 2 and 3) and the tidal volume.

The subsystem attains high salinity in each tidal cycle - even during a spring low tide, values of 23-25 ‰ were recorded at the bottom near the Pranto mouth. During high tide all the area is filled with salt water (33 ‰ in spring and 25 ‰ in neap tides at the Areeiro Novo station).

The temperature can show significant fluctuations, specially with spring tides. For instance in the Noventa Talhos station variations of 8 °C were recorded during a tidal cycle (16-24 °C).

The upstream decrease of turbidity reflects the mixing of salt water, typically with high values, but during neap tides the variation of this parameter is more irregular, with high values related to the friction of fast current in channels over the sandy-muddy bottom (Kappenberg et al. 1995). The maximal speed of spring tide flood is attained in the downstream zone, at the surface, but throughout neap tides it was recorded in the narrow channel at Ponte da Gala station.

In high spring tides, the upstream brackish water inflow from the Mondego River is expressed by several parameters recorded in the Areeiro Novo station. On Fig. 4 we can see that salinity, turbidity, pH and Eh documents brackish water inflow from the Mondego River and negligible fresh water inflow from the Pranto, in a typical fully mixed situation.

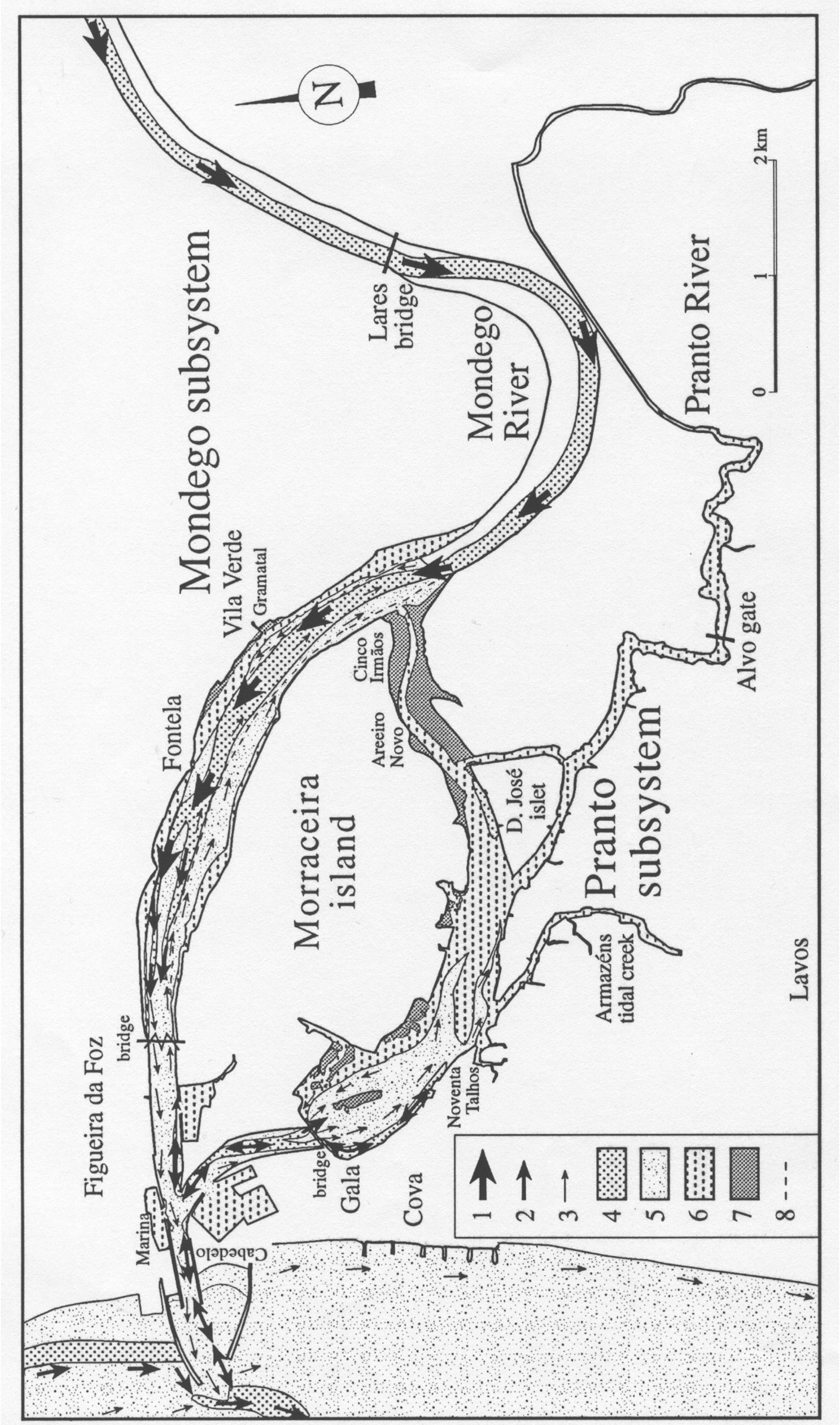
Surface sediments description

Mondego subsystem grain-size distribution

Sector I (Montemor-o-Velho to the Lares bridge)

The sector from Montemor-o-Velho (26 km upstream of the estuary mouth) to the Lares bridge is dominated by the fresh water flow, but records also the variation of water stage over a tidal cycle. It consists of a channel with hard bank protection (Fig. 5) with a very coarse sand and gravel bed, frequently organised in isolated longitudinal and point bars.

FIG. 5. Schematic summary of the sediment circulation pattern of the Mondego estuary and adjacent beaches - maximal transport capability of traction currents (1 - up to granules, 2 - up to very coarse sands, 3 - up to medium sands); bottom sediments mean grain-size (4 - granules to coarse sand, 5 - medium to fine sand); tidal mudflats and muddy bottoms (6); saltmarshes (7); navigation channel boundary.


N
Mondego subsystem
Lares bridge
Mondego River
Pranto River
0
1
2 km
Vila Verde
Gramatal
Fontela
Cinco Irmãos
Areeiro Novo
Alvo gate
Morraceira island
D. José islet
Pranto subsystem
Armazéns tidal creek
Lavos
Figueira da Foz
bridge
Noventa Talhos
Gala bridge
Cova
Marina
Cabedelo
1
2
3
4
5
6
7
8

Sector II (Lares bridge to Cinco Irmãos)

Includes part of the sector channelised with a bank protection wall finished in 1984, increasing the agricultural use of the muddy floodplain. The thalweg has granules and is bordered by very coarse to medium sand (Fig. 5), but some marginal locations are covered with fine sand to mud.

Sector III (Cinco Irmãos to the Figueira da Foz bridge)

In this section, dredged and totally bounded by hard bank protection after 1995, the water is usually brackish, except during fluvial floods. The morphology and dynamics are slightly dominated by fluvial processes. The channel bottom has granules to medium sand and, in some marginal areas with reduced hydrodynamics, fine sand to sandy mud (Fig. 5). The longitudinal belt of coarse bottom sediments bifurcates downstream in response to the interconnection of tidal and fluvial dynamics. Intertidal margins consist in medium sand (near the channel), grading laterally to sandy mud. Large sectors were filled with dredged material in 1995-1996, later mixed with overbank flow sediments. Small areas of saltmarshes occur in the right margin, upstream of Fontela, representing what is left of very extensive marshes now largely reclaimed.

Sector IV (Figueira da Foz bridge to the branches confluence)

Salt water and tidal dynamics predominate in this section. A straight channel with rockwalls and dredge filled margins was finished in 1984, were the Commercial Pier, the Bacalhoeiros (codfish fishing ships) Dock and the Marina are located.

The thalweg follows closely the southern margin and is covered with coarse sand, grading laterally to medium sand (Fig. 5). Near the margins there are small areas of fine sand to sandy mud sedimentation, namely at the commercial pier. Settling out of black organic mud is the only sediment accumulation in the Bacalhoeiros dock and in the Marina

Sector V (branches confluence to the seaward end of external jetties)

Corresponds to the estuary mouth and the associated estuarine beach/uncovered aeolian dune complex, and is the only sector of the estuary influenced by wave dynamics. A belt of coarse and very coarse sands reflects the sediment transport during tidal floods along the southern external jetty, following along the margin of the Cabedelo beach and the southern margin of the navigational channel. The channel axis is covered mainly with medium sand, but a medial ribbon with fine sand probably reflects the different pathways of salt water flood and freshwater flow during high fluvial discharge. The Cabedelo beach, between the internal and the external southern jetties (Fig. 5), is composed of micaceous fine sand and feeds the adjacent aeolian dune field.

Pranto subsystem grain-size distribution

Sector I (branches bifurcation to the D. José islet)

The area from the Cinco Irmãos station to the small channel east of the D. José islet is mainly composed of saltmarsh and intertidal mudflats, dissected by narrow, meandering, muddy tidal creeks (Fig. 5). It must be stressed that, even during the seasonal floods, the Mondego supplies no bedload sediments to this subsystem.

Sector II (D. José islet to the Noventa Talhos station)

Intertidal mudflats and sinuous creeks cover most of this sector, associated to minor amounts of fine to very fine sand downstream of the Pranto mouth (Fig. 5). The main tidal channel, near the southern margin, is covered with medium to coarse sand, remains of recent times when this subsystem had a significant upstream connection with the Mondego River. The Pranto River feeds exclusively suspended material (silt and clay).

Sector III (Noventa Talhos station to the Gala bridge)

The margin of the Morraceira Island is composed of saltmarshes and intertidal mudflats, dissected by meandering tidal creeks, among which many connected with fish farms and salt-pans. The sudden widening upstream of the Gala bridge created a flood tidal delta — composed chiefly by coarse to medium sands — with a major south-western ebb channel covered with bioclast rich medium sand. Fine sand covers the shallower north-east ebb channel.

Sector IV (Gala bridge to the branches confluence)

The downstream sector of the Southern branch, already fully limited by rockwalls by 1934, is dominated by medium sand, but the thalweg, close to the right margin nearby the confluence, is covered with coarse sand (Fig. 5). Downstream of the Fishing-boats Dock entrance, a zone of fine sand to sandy mud deposition occurs, and upstream of the entrance a medium sand intertidal bar is formed. Black organic mud accumulates in the Fishing-boats Dock.

Grain-size of the beaches adjacent to the Mondego mouth

The influence of wave dynamics inside the estuary is reduced. However, it is the main control on beaches and on estuary mouth grain-size, morphology and evolution (Carvalho and Barceló 1966, Almeida and Santos 1991, Santos et al. 1991, Cunha and Dinis 1998). In the beach north of the jetties, nourished by the southward prevailing longshore current, the intertidal sector has essentially coarse sand, grading offshore to medium sand and to micaceous fine sand. The narrow beach south of the river mouth (Fig. 5) is mainly constituted by medium sand and nourished by the longshore current and the local erosion of the aeolian dune field.

Composition of the coarse fraction (0.5-1 mm) of estuarine sands

Colourless quartz grains have marine and fluvial provenance. Upstream of the branch bifurcation (Cinco Irmõs) the proportion of colourless quartz, feldspars and milky quartz are high, but just downstream, in the northern branch, the percentage of quartz diminishes due to high proportion of micas and estuarine bioclasts. The colourless quartz content increases again from the Fontela to the mouth, but downstream of the Figueira bridge it occurs mainly near the southern margin by the mixing with the marine provenance, also rich in bioclasts. The highest contents of quartz are coincident with the energy axes, as also happens in the southern branch with an upstream dissipating axis.

Feldspars grains are concentrated along the northern margin of the northern branch (Mondego subsystem), reflecting the fluvial input in this concave sector. In the Pranto subsystem, feldspars found at some places (trapped within depressions of the main channel) are considered as remains of a formerly wider upstream connection with the Mondego River.

High amounts of bioclasts (mainly of calcium carbonate) occur bellow the tidal level in the beach, as well as concentrations of estuarine molluscs shells, namely in the southern branch upstream of the Gala bridge.

Micas are concentrated in several zones with reduced hydrodynamic, as in the convex sector of the northern branch, along the right margin of the southern branch (just upstream of the Gala bridge) and in the internal beach of Cabedelo.

Quartz-grains roundness and surface textures

The roundness and surface textures of quartz-grains were studied through binocular microscope examination of the coarse fraction of sands (0.5-1 mm).

Sands with fluvial provenance are predominantly angular and very angular, shiny, but minor amounts of any other arrange of roundness and shininess can occur. Considering all the estuary, the roundness decreases upstream, as well as, less clearly, the shininess increases.

All across the northern branch, upstream of Fontela, the dominant population has characteristics that clearly points to a fluvial provenance, except in the southern margin upstream to Gramatal, where two modes of roundness correspond to the mixing of fluvial and marine sand. These were carried by tidal floods over an intertidal margin (formerly used as dredge disposal area). The roundness and shininess distribution shows a dominance of the marine provenance over the fluvial sub-population between the Marina and the Figueira da Foz bridge, in particular near the southern margin. A minor population of angular and frosted grains found upstream of Gramatal, quite rare between Fontela and Gramatal, is interpreted as redeposited from Cretaceous and/or Tertiary deposits. The mixed population of the mouth sector, up to the Marina, has a major component of fluvial (angular) sands, but the high proportion of more rounded sand in the Cabedelo beach reveals the dominant transport of marine sands by tidal floods and the protection effect of the internal jetty in relation to the fluvial transport.

In the Pranto subsystem, the sector between the branches confluence and the Gala bridge has sands with a bimodal roundness distribution, more obvious in the talwegue where rounded and sub-rounded grains are the more frequent types. In the same sector, the bar linked to the western margin is mainly composed by rounded sands coupled with a minor mode of sands with fluvial provenance. Around the flood delta, the marginal ebb channels between Gala and Noventa Talhos, and in particular the main one (southwest), are covered essentially by angular and shiny grains, but including sands with marine provenance. Most of those sands with fluvial characteristics were probably injected is this subsystem before the enormous reduction of the upstream connection with the Mondego River.

The flood tidal delta located upstream of Gala bridge is composed of sands with a high mean roundness and reduced shininess (trend more pronounced within the well rounded class) allowing its attribution to a marine provenance. The delta is created by the loss of competence when the tidal flood reaches the sudden widening of the channel. Also a significant aeolian provenance can be inferred by the high content of frosted grains, quite probable considering the short distance to the uncovered aeolian dune field (Fig. 5) and the dominant winds with an eastward component.

On the beaches adjacent to the estuary, despite the wide range of roundness, the sub-rounded class is the dominant mode and well rounded grains are rare. Shiny grains are dominant, but the classes of better roundness include high contents of frosted grains, probably reflecting the fact that the intense beach erosion has already reached the aeolian foredune (Cunha et al. 1997b).

Sediment circulation pattern

The integration of hydrodynamic data (contrasting salinity mixing types and flows) and the analysis of surface sediments (grain size, composition and quartz-grains surface texture) supports the proposed pattern of sedimentation on both estuarine subsystems (Fig. 5). In detail, the figured situation corresponds to a boundary situation, after a major fluvial flood and with a reduced sediment supply. The map of provenance and transport potential synthesises a qualitative model of the sedimentary dynamic and its controls. These data, linked with the morpho-sedimentary units distribution, clearly emphasises the differences between the two estuarine subsystems.

In a long-term scale (years to decades), the bottom morphology and the sediments of the Mondego subsystem are dominated by fluvial processes related to floods (Cunha et al. 1997b), as expected in a laterally restricted estuary fed by a large river (Cooper 1993). The studied situation shows that the fluvial flow was able to transport granules as far as Fontela, nearby the right margin in this sector, coarse to very coarse sands untill the Figueira da Foz bridge, and medium sands down to the mouth. The tidal flood flows, essentially, along the southern margin of the mouth channel, transporting coarse to very coarse sands up to the commercial pier and carrying medium sands up to the Cinco Irmãos station, mixing gradually with fluvial sands. In the area between the northern internal and external jetties, the hydrodynamic protection from the prevailing waves (WNW) and from fluvial flow favours deposition.

In the Pranto subsystem the flood tidal delta of Gala is similar to those created by a narrow inlet (Dalrymple et al. 1992). Flood follows mainly the south-western marginal channel and the delta ramp, whereas the ebb sedimentary transport is essentially along both marginal channels. In the small scale sandy bay located south-east of the Gala bridge, the sand grain-size and the total sand content shows a clear increase towards west, probably as a result of the Coriolis effect (e. g. Van den Berg et al. 1996). This subsystem shows a clear trend to an almost complete infilling, mainly by fine-grained sedimentation in marshes and mudflats, accelerated, as expected (Patchineelam 1999), by the artificial constraining of the Mondego branch connections (Cunha et al. 1997b, Cunha 1998, Dinis and Cunha 1998). In fact, most of the mechanisms operating in this subsystem corresponds to a saltmarsh estuary, characterised by tidal regime dominance and little or no fluvial input (Frey and Howard 1986). The location of the limit between saltmarshes and mudflats reflects the average wind waves above the erosion threshold (Pethick 1996). The dominance of north and north-western winds (Arroteia 1985), coupled with the flow hydrodynamic asymmetry, explains the larger area occupied by saltmarshes in the Morraceira Island margin of this subsystem (Fig. 5).

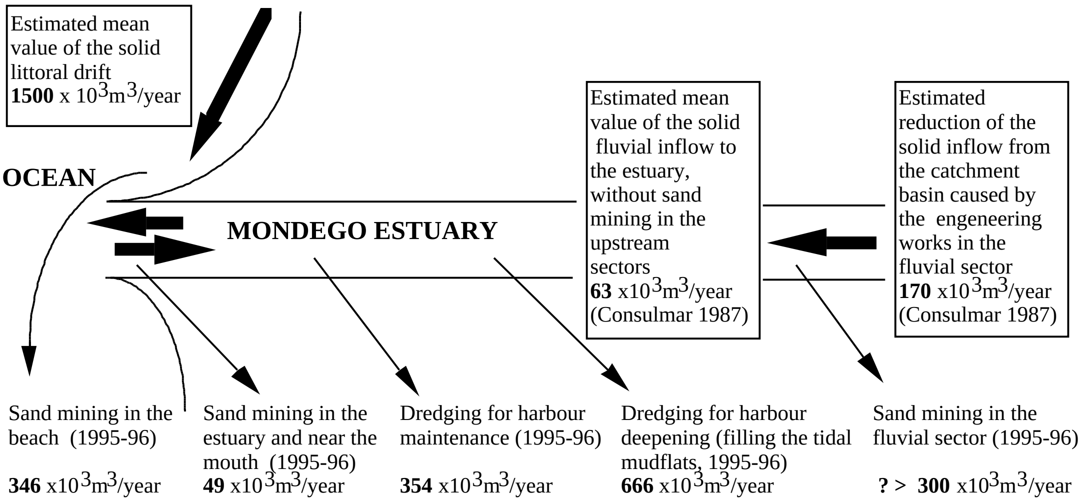


FIG. 6. Estimated volumes of inflow, solid littoral drift and artificially removed sediments in the Mondego estuary, during 1995-96 (adapted from Cunha et al. 1998).

The most intense anthropogenic impact on the sedimentary processes of the Mondego estuary results, probably, from dredging and sand mining. For purposes of harbour maintenance and enlargement, large volumes are removed from the sedimentary system (see data from the Port Authority of Figueira da Foz and environmental agencies in Cunha et al.

1995, 1998; Fig. 6), reaching values higher than the sum of fluvial and littoral sediment inputs. Even if the direct quantification of the marine sediments entrance is not available, it can be considered as similar to the total of sand mining at the mouth and in the adjacent beach (around 400 x 10^3 m^3/year during 1995 and 1996). The evaluation of the solid longshore drift is still under discussion (see Cunha and Dinis 1998), but the value of 1 500 x 10^3 m^3/year seems a reasonable estimate.

The previous natural situation was characterised by an intense deposition of fluvial bed-load (Loureiro 1882, Oliveira 1967, Cunha et al. 1997b) and this estuary could be classified as river dominated (***sensu*** Cooper, 1993). Currently, the fluvial sediment inflow to the estuary is probably less than predicted by Consulmar (1987) for the situation after fluvial damming (63 x 10^3 m^3/year), due to the huge volumes removed by sand mining in the fluvial sector between the downstream dam and the estuary (at least 300 x 10^3 m^3/year). Dredging and sand mining are particularly intense in the Mondego subsystem, leading to its deepening. The tidal hydrodynamics play a major role in the natural trend to re-establish the equilibrium depth (Simmons and Herrman 1972), in particular in a situation where the mouth sand bar, coupled with the narrow navigation channel, constitutes an hydraulic constrain acting like an inlet. This effect creates a depositional trend similar to the occurring in a flood-tidal delta (Dalrymple et al. 1992, Perillo 1995). As a consequence, and as expected (Dyer 1973), this subsystem presents an upstream displacement of the sedimentary domains. In fact, the sampled surface sediments reflect a significant upstream penetration of marine sands along the Mondego subsystem, the huge decrease of fluvial bedload and the reduced transport capability of fluvial floods.

In the sector between the Figueira da Foz bridge and Cinco Irmãos the disposal of dredged spoils was made mostly in intertidal areas (Fig. 5). This led to reduction in the tidal prism, and, hence, a general decrease of the discharge and velocities of tidal currents (O'Brien and Dean 1972).

Synthesis and conclusions

The Mondego Estuary comprises two subsystems, with different hydrodynamics, morphologies and sedimentary characteristics, which have limited connections in space and time. In the hydrodynamics of the Mondego subsystem the river inflow is more important than the tidal control. The Pranto subsystem is clearly dominated by the tidal dynamic.

In the Mondego subsystem partially stratified to fully mixed situations were recorded with low fluvial inflow, and it can most probably be stratified with intermediate to high fluvial discharge. The deepening by dredging and the change to an artificial channel improved the upstream penetration of saline water and marine sands. In the channel the fluvial sediment transport is expressed by a grain-size decrease towards the mouth (gravel to fine sand), but an inverse variation results from the tidal flood currents. Fine sediments, like mud and muddy very fine sand, accumulated on areas of reduced hydrodynamics of the channel margins and in the tidal flats.

The Pranto subsystem is typically fully mixed, but during high fluvial discharges, rare nowadays, it probably grades to stratified. In a tidal cycle the salinity variation is high, mainly in the central sector (a small scale sandy bay), and an important local retention of waters was documented, caused by the muddy sand bars morphologies. The seaward area of marine influence is dominated by sand with some shell gravel, whereas the upstream area is mainly muddy. The Mondego River inflow of low salinity waters and sediments in this subsystem only occurs during seasonal floods.

Successive anthropogenic interventions led to an important artificialisation of the landscape. In particular, embankment and reclamation greatly reduced the natural areas, and changes on the hydrodynamics were also promoted by landfills of intertidal flats and dredging. Synthesising the last decades evolution of this estuarine system, several capital consequences must be stressed. A severe reduction of sediments in the estuary results from the upstream capture by dams and removal by sand mining and dredging. On the other hand, the dynamic of the system was reduced after stabilisation of the fluvial discharge, and tidal prism decrease due to successive landfills of intertidal flats. The fluvial and coastal heavy engineering works had major environmental impacts, namely the drastic reduction of the sedimentary inflow from the Mondego River to the littoral. This inverted the coastal progradation caused by man-driven increase of river sediment discharge during the last centuries (Ludwig and Probst 1998) and recorded in many estuaries of similar context in Iberia (e.g. Morales 1997, Dabrio et al. 2000). The intense harbour dredging induced the rapid trap of sandy sediments with marine and fluvial provenance. The interventions in the Pranto subsystem accelerated the silting, but in the Mondego subsystem the infilling trend resulting from energy decrease is not able to balance the fluvial sediment starvation and the removal of sediments.

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References

Allen, J.R.L. 1993. An introduction to estuarine lithosomes and their controls. ***Sedimentology review***, 1: 123-139.

Almeida, J.L. and Santos, F. Seabra 1991. Aplicação de modelos numéricos ao estudo da onda de “mareta” no Porto da Figueira da Foz. ***Estudos de Engenharia Civil***, Coimbra, vol. 3, nº 1/2: 99-111.

Arroteia, J.C. 1985. ***Figueira da Foz: a cidade e o mar***. ***Edited by*** Comissão de Coordenação da Região Centro, Coimbra, 115 p.

Baptista, A.M. 1990. ***Mondego Estuary: analysis of data on tides, salinities and temperatures (June 1989 - December 1989)***. Annex I of the "Estudo das marés e circulação hidrodinâmica". Progress Report "Lançamento de bases para o estudo integrado do estuário do Mondego". Fac. Ciências e Tecnol. Univ. Coimbra, 7 p.

Carvalho, J.R. and Barceló, J. 1966. Agitação marítima na costa Oeste de Portugal Metropolitano - Contribuição para o seu estudo. ***Lab. Nac. Eng. Civil.***, ***Mem***. nº 290, Lisboa, 34 p.

Consulmar 1973. ***Porto da Figueira da Foz. Plano geral das obras interiores do porto da Figueira da Foz e de valorização do estuário do Mondego. Esquema geral do Plano e plano parcial das obras da 1ª fase***. (Junho 1973), Tech. Report, 105 p.

Consulmar 1987. ***Estudo da viabilidade económica da exploração do Porto da Figueira da Foz***. (Maio 1987), Tech. Report, 68 p.

Consulmar, Hidroprojecto and HidroQuatro 1991. ***Regularização da zona estuarina de transição entre o porto da Figueira da Foz e o troço terminal de regularização do baixo Mondego. Estudo de impacte ambiental***. Direcção Geral de Portos. Tech. Report, 145 p.

Cunha, P. Proença 1998. A evolução actual do litoral de Portugal Central — o exemplo do Estuário do Mondego e litoral adjacente na análise das transformações globais e do desenvolvimento sustentável das zonas costeiras. ***III Jornadas de Outono da Geografia Física - "Gestão e conservação do litoral" (Communications)***, Univ. Porto, 13 p.

Cunha, P. Proença and Dinis, J. 1998. A erosão nas praias do Cabo Mondego à Figueira da Foz (Portugal centro-oeste), de 1995 a 1998. ***Territorium***, Revista de Geografia Física aplicada no ordenamento do território e gestão de riscos naturais, Coimbra, 5: 31-50.

Cunha, P. Proença, Dinis, J.L. and André, J.N. 1998. Interacção entre as operações de dragagem no Porto da Figueira da Foz e a dinâmica sedimentar no Estuário do Mondego e costa adjacente (Portugal central). ***In*** Proceedings of the ***Seminário sobre Dragagens, dragados e ambientes costeiros***. ***Edited by*** Associação Eurocoast-Portugal, Lisboa, pp. 27-45.

Cunha, P. Proença, Dinis, J. L. and Reis, R. Pena dos 1997a. ***Relatório Final do projecto de investigação PEAM/C/GEN/247/93 (Prog. Esp. Ambiente - JNICT/DGA): "Avaliação das modificações antrópicas actuais nos sub-ambientes sedimentares do estuário do Mondego"***. Faculdade de Ciências e Tecnologia da Univ. de Coimbra, (Final Report), 152 p., 8 anexes.

Cunha, P. Proença, Dinis, J.L., Silva, A.F. and André, J.N. 1995. Evolução estuarina condicionada por intervenções portuárias: modificações recentes no sector intermédio e distal do Estuário do Mondego. ***Memórias e Notícias***, Publ. Mus. Lab. Min. Geol. Univ. Coimbra, 120: 95-117.

Cunha, P. Proença, Pinto, J. and Dinis, J.L. 1997b. Evolução da fisiografia e ocupação antrópica na área estuarina do Rio Mondego e região envolvente (Portugal centro-oeste), desde 1947. ***Territorium***, Revista de Geografia Física aplicada no ordenamento do território e gestão de riscos naturais, Coimbra, 4: 99-124.

Cooper, J.A.G. 1993. Sedimentation in a river dominated estuary. ***Sedimentology***, 40: 979-1017.

Direcção Geral de Recursos e Aproveitamentos Hídricos 1987. ***Aproveitamento hidráulico do Vale do Mondego***. Tech. Report, Lisboa.

Dabrio, C.J., Zazo, C., Goy, J.L., Sierro, F.J., Borja, F., Lario, J.G. and Flores, J.A. 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, Southern Spain). ***Mar. Geol.*** 162: 381-404.

Dinis, J.L. and Cunha, P. Proença 1998. Impactes antrópicos no sistema sedimentar do Estuário do Mondego. ***Sociedade e Território***, Porto, 27: 47-59.

Duarte, D.N. and Pena dos Reis, R. 1994. Impact on sedimentary dynamic of the Mondego Estuary regularization works on the North Channel. ***ECSA24 Symposium northern and southern estuaries and coastal areas (Abstracts)***, Aveiro, 5-8 September, p. 73.

Dyer, K.R. 1973. ***Estuaries: a physical introduction***. Wiley, New York, 140 p.

Dyer, K.R. 1995. Sediment transport processes in estuaries. ***In*** Geomorphology and sedimentology of estuaries. ***Edited by*** G.M.E. Perillo, ***Developments in Sedimentology***, **53**. Elsevier, Amsterdam, pp. 423-449.

Fairbridge, R.W. 1980. The estuary: its definition and geodynamic cycles. ***In*** Chemistry and Biogeochemistry of Estuaries. ***Edited by*** E. Olausson and I. Cato. Wiley, New York, pp. 1-35.

Frey, R.W. and Howard, J.D. 1986. Mesotidal estuarine sequences: a perspective from Georgia Bight. ***Journal Sediment. Petrol.*** 56: 911-924.

Hayes, M.O. 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. ***Edited by*** L.E. Cronin, ***Estuarine Research***, Vol. II, Academic Press, New York, pp. 3-22.

Kappenberg, J., Schymura, G. and Fanger, H.-U. 1995. Sediment dynamics and estuarine circulation in the turbidity maximum of the Elbe River. ***Neth. J. Aquat. Ecol.*** 3-4: 229-237.

Loureiro, A.F. 1882. ***Memória sobre o porto e a barra da Figueira e as obras para o seu melhoramento***. Imprensa Nacional, Lisboa, 107 p.

Ludwig, W. and Probst, J.-L. 1998. River discharge to the oceans: present-day controls and global budgets. ***Am.. J. Sci.*** 298: 265-295.

Morales, J.A. 1997. Evolution and facies architecture of the mesotidal Guadiana River delta (S.W. Spain-Portugal). ***Mar. Geol.*** 138: 127-148.

O'Brien, M.P. and Dean, R.G. 1972. Hydraulical and sedimentary stability of tidal inlets. ***13th Coastal Engeneering Conference***, ASCE, New York, pp. 761-780.

Oliveira, F.M. de 1967. ***O porto da Figueira da Foz***. ***Edited by*** Biblioteca Municipal da Figueira da Foz, 29 p.

Patchineelam, S.M., Kjerfve, B. and Gardner, L.R. 1999. A preliminary sediment budget for the Winyah Bay estuary, South Carolina, USA. ***Mar. Geol.*** 162: 133-144.

Perillo, G.M.E. 1995. ***Geomorphology and sedimentology of estuaries***. ***Developments in Sedimentology***, **53**. Elsevier, Amsterdam, 471 p.

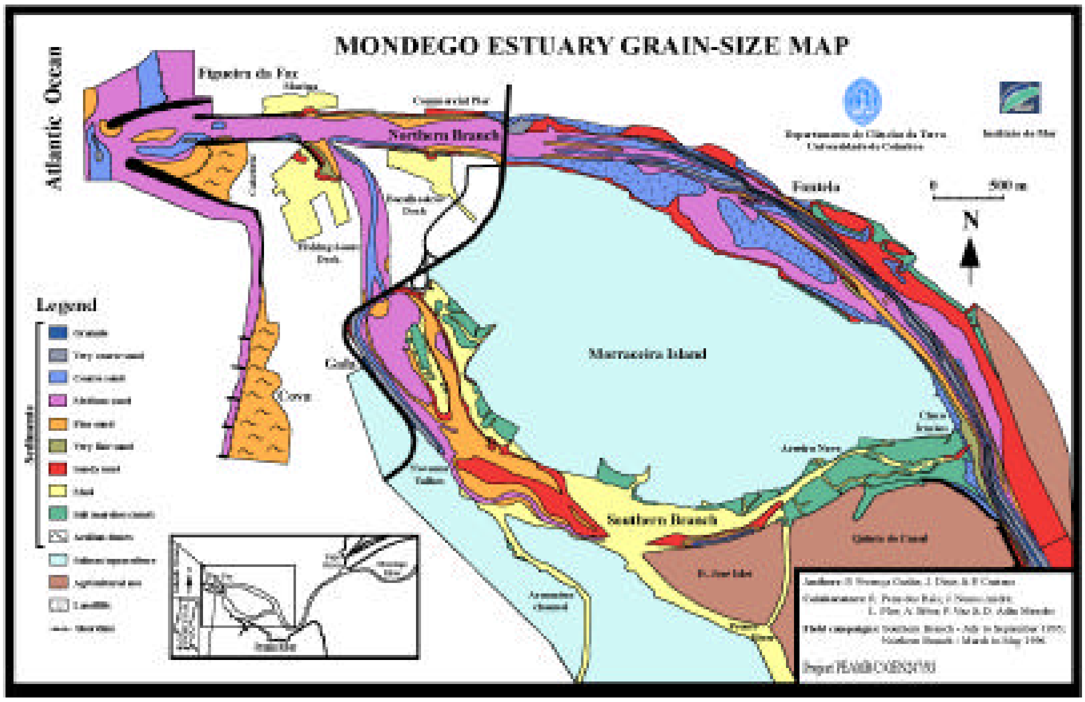
Pethick, J.S. 1996. The geomorphology of mudflats. ***In*** Estuarine shores. Evolution environments and human alterations. ***Edited by*** K.F. Nordstrom and C.T. Roman. Wiley, Chichester, pp. 157-184.

Pritchard, D.W. 1955. Estuarine circulation patterns. ***Am. Assoc. Civil Engeneers Proc***., 81, Separate 717, pp. 1-11.

Santos, F. Seabra, Almeida, J. and Carmo, J. Antunes do 1991. ***Estudo da agitação marítima***. 153 p. ***In*** Relatório final do projecto de investigação "Lançamento de bases para o estudo integrado do estuário do Mondego". Fac. de Ciências e Tecnologia da Univ. de Coimbra, Tech. Report.

Simmons, H.B. and Herrmann, F.A., Jr. 1972. Effects of man-made works on the hydraulic, salynity and shoaling regimens of estuaries. ***Mem. Geol. Soc. America***, 133: 555-570.

Van den Berg, J.H., Jeuken, C.J.L. and Van der Spek, A.J.F. 1996. Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary. ***In*** Estuarine shores. Evolution environments and human alterations. ***Edited by*** K.F. Nordstrom and C.T. Roman. Wiley, Chichester, pp. 157-184.


MONDEGO ESTUARY GRAIN-SIZE MAP
Atlantic Ocean
Figueira da Foz
Marina
Commercial Pier
Northern Branch
Fontela
0
500 m
N
Murraceira Island
Southern Branch
Gala
Cova
Quinta do Canal
Legend
Granule
Very coarse sand
Coarse sand
Medium sand
Fine sand
Very fine sand
Sandy mud
Mud
Sediments
Landfills