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Changing use and hydromorphological adjustment in a coastal lagoon–estuarine system, the Ria de Aveiro, Portugal

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Abstract Today the Ria de Aveiro of northern Portugal has a hydromorphological regime in which river influence is limited to periods of flood. For most of the annual cycle, tidal currents and wind waves are the major forcing agents in this complex coastal lagoon–estuarine system. The system has evolved over two centuries from one that was naturally fluvially dominant to one that is today tidally dominant. Human influence was a trigger for these changes, starting in 1808 when its natural evolution was halted by the construction of a new inlet/outlet channel through the mobile sand spit that isolates it from the Atlantic Ocean. In consequence, tidal ranges in the lagoon increased rapidly from ~0.1 m to >1 m and continued to increase, as a result of continued engineering works and dredging, today reaching ~3 m on spring tides. Hydromorphological adjustments that have taken place include the deepening of channels, an increase in the area of inter-tidal flats, regression of salt marsh, increased tidal propagation and increased saline intrusion. Loss of once abundant submerged aquatic vegetation (SAV), due to increased tidal flows, exacerbated by increased recreational activities, has been accompanied by a change from fine cohesive sediments to coarser, mobile sediments with reduced biological activity.

Key words human use; hydromorphological regime; Ria de Aveiro, Portugal; seagrasses; sediments

INTRODUCTION

The Atlantic coast of Portugal, to the south of the city of Porto, is wave-dominated and has evolved as sea levels have risen since the Last Glacial Maximum by the accumulation of sand deposits derived principally from the north (Dias *et al*., 2000). This has formed an essentially linear coast aligned at an angle of ~15º to the east of north; while the present sea level was reached *c*. 3500 years BP, the coast became linear more recently. Inland lies a coastal plain that was formerly the location of an embayment. Once isolated from the ocean, in the 16th century the resulting lagoon started to infill with river sediment. This process resulted in the formation of the Ria de Aveiro, today noted as the most remarkable geomorphological feature of the coast of northern Portugal (Fig. 1). This comprises a combined shallow coastal lagoon–estuarine system with a complex morphology and productive ecosystem (Rebelo, 1992). The physical system is today characterized by many branching channels that are connected to the ocean by a single tidal channel. It is relatively small; the area

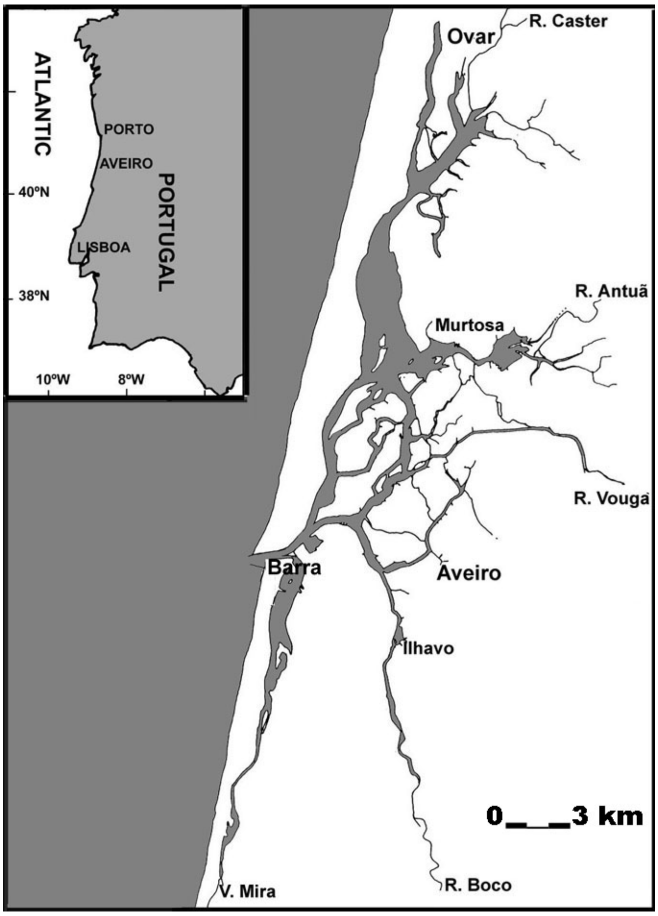

Fig. 1 The coastal lagoon–estuarine system of the Ria de Aveiro. Note the single inlet channel at Barra and the River Vouga. The grey areas are covered by water at mean sea level.

enclosed by the maximum high water line is ~120 km^2, yet its ecosystem provides all of the 17 categories considered by Costanza *et al.* (1997) in the assessment of world ecosystem services and functions. However, human use of this ecosystem has had a profound impact on the natural evolution of the Ria de Aveiro; the hydromorphological adjustment accompanying the change in its use forms the subject of this paper.

METHODOLOGY: CHARACTERIZATION OF RECENT CHANGES IN THE RIA DE AVEIRO

Morphological change in the Ria de Aveiro has been documented by using old maps and more recently by airborne photography of inter-tidal areas. The change in tidal prism volume was estimated by simple cubature methods, applied to old tide elevation and area data. The recent tidal volume was also measured based on Acoustic Doppler Current Profiler (ADCP) measurements in the inlet channel.

Since most of the activities in the Ria de Aveiro require the use of boats, the recent changes in use of the lagoon may be characterized by the changes in the numbers and types used. An analysis was thus undertaken on the basis of the numbers of the various types of vessels in operation with a navigation licence through time. The boats registered in the Capitania do Porto de Aveiro are classified into recreational boats (registration plate AV) and professional boats which are sub-divided into:

- auxiliary boats (registration plate AL), used for collecting seaweed and marsh plants (for agriculture) and to be used in salt production and transport;
- boats with the registration plate L, used for professional fishing.

Characterization of surface sediment was carried out on samples hand collected from the uppermost 3 cm of the bed at 10 points located in the major inter-tidal areas. All sampling locations were determined with Magellan® Promark X-CM GPS (accuracy of ~10 m). The sampling programme extended from September 2002 until December 2004 and included nine campaigns (September 2002, October 2002, February 2003, June 2003, September 2003, January 2004, May 2004, September 2004 and December 2004) that spanned the variation of natural hydrological conditions. Samples were analysed to determine grain-size distributions (Beckman Coulter Laser Granulometer LS230), organic matter content (determined by combustion for 1 hour at 550ºC), and Fe and Ca content (determined by acid digestion and Atomic Absorption Spectrometry).

EVOLUTION OF THE RIA DE AVEIRO

From an analysis of maps dating back to the 13th century AD some authors (Dias *et al.*, 2000; Rocha e Cunha, 1930) have suggested that the present Aveiro lagoon developed from a gulf ~70 km in length and 20 km wide at the mouth of the River Vouga, separated from the Atlantic Ocean only in the north by an incipient sand spit. By the end of the 16th century this spit had accreted rapidly southwards almost completely enclosing the lagoon behind it to the east (Fig. 2). This enclosure greatly reduced the prosperity of the port of Aveiro by impeding navigational access to the ocean, as measured by a fall in the urban population (Dias *et al*., 2000). The ria system was naturally fluvially dominant, the water level in the lagoon being controlled mainly by river flow. The winter level, during floods, was up to 2 m higher than the summer level superimposed upon which, as recorded in 1802, were small tidal variations of between 0.07 and 0.13 m over most of the lagoon (Carvalho, 1947). Wave-dominated conditions prevailed along the open ocean coast of the spit. Lagoons formed by spit enclosure along such wave-dominated coasts tend to have simple topography inherited from the bevelled shore face surface (Oertel *et al*., 1992). Had the spit enclosing the Aveiro lagoon been permitted to continue to evolve naturally, much of the lagoon would have become ever more choked (cf. Kefevre, 1994) with sediment derived from the Vouga and other influent rivers, and increasing areas of the floor would have become exposed between high water and mean sea level. Marsh colonization would have occurred and its progressively less navigable channel connection with the Atlantic Ocean would have migrated southwards as spit accretion progressed in that direction. During the 17th century the connection with the Atlantic Ocean was intermittent.

This natural evolution was, however, halted abruptly in 1808 by the construction of a new inlet/outlet channel (Fig. 1) through the sand spit with a width of ~350 m and

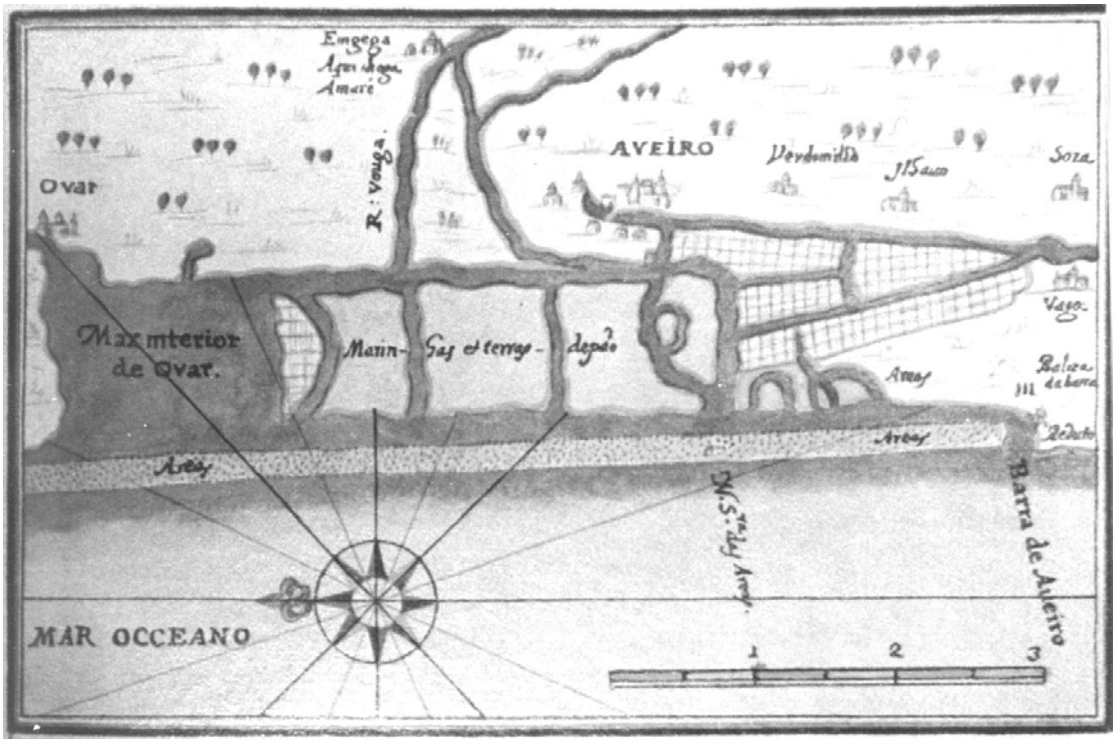

Fig. 2 Map dated 1648 AD showing the morphology of the Ria de Aveiro by the time the tidal penetration started to diminish at the end of the 16th century. The area shown in Fig. 3 is marked as saltpans. The scale divisions correspond to an old unit equivalent to 3 nautical miles (~5.6 km).

cross sectional area of ~1000 m^2. This was located closer to the lagoon, 18 km north of the natural channel outlet and was accompanied by the diversion of the River Vouga into an engineered channel that connected more directly to the outlet. As a direct consequence, the tidal range within the lagoon increased to >1 m, which initiated the re-establishment of navigable port facilities in Aveiro and an economic regeneration of the town (Silva & Duck, 2001). The area of the lagoon then permanently covered by water varied from 60 to 80 km^2 (Loureiro, 1904). This included ~270 saltpans, built over inter-tidal flats, which were enclosed by mud dykes, and covered an area of ~17 km^2 around the town of Aveiro. This area was also covered by water, but isolated from tidal oscillation.

Works to maintain the channel network wide and deep enough for navigation, including the building of breakwaters and training walls together with extensive dredging, began in 1936 and continue to this day (for details see Silva & Duck, 2001). Since the pre-1936 inlet/outlet channel was shallow, tidal flows involved a large loss of energy and the bed stresses caused the tides in the lagoon to have the characteristics of a progressive wave, propagating at different speeds at high and low tide. Deepening of channels by continual dredging and ongoing canalization has lessened the effect of energy loss, thereby causing a progressive increase in tidal ranges, which today are >3 m on spring tides. ADCP measurements in the inlet channel have shown that, for a spring tide (23 February 2004), the cross-sectional area at the inlet was up to 5000 m^2, the maximum tidal flow up to 7400 m^3 s^{-1} and the tidal prism volume up to 106 × 10^6 m^3. Thus, tidal currents, together with wind-generated waves, are today the major forcing

Fig. 3 Oblique aerial photograph (2005) of the area of old saltpans to the southwest of Aveiro. Those remaining unchanged are marked by a dotted line and a solid line marks those converted to fish farming. Note the erosion of sediment and also, in some areas, the growth of inter-tidal vegetation. Horizontal field of view = ~2.5 km; vertical field of view: ~3.6 km.

agents in the Ria de Aveiro. Most of the old saltpans are today open to tidal oscillation and mud dykes that had not been reinforced have now been partially destroyed due to the increasing stresses imposed by the larger tidal ranges (Fig. 3). Channels in the lagoon are widening and increasing in depth, leading to regression of salt marshes (Silva & Duck, 2001; Silva *et al*., 2004). The resulting changes in bathymetry have increased the "channelization" effect of the tidal flow in the lagoon and its bottom topography is not of the simple form that would have been characteristic of such systems had it been allowed to evolve naturally (Oertel *et al*., 1992). As conditions inside the lagoon are now tide dominated, it should revert to an open water body (Oertel *et al*., 1992). However, reinforcing the dykes protecting some intertidal areas is preventing this trend.

As a result of the progressive increase in the tidal prism that has taken place since 1808 (Silva & Duck, 2001), there has been a corresponding change in the spatial distribution of salinity. In 1910 waters with salinities >30 psu intruded inland for no more than 4 km (Nobre *et al*., 1915), but by 2000 fully marine waters were recorded penetrating the major channels over 15 km inland from the Atlantic Ocean (Silva *et al*., 2004).

Other important forcing factors were the collection of aquatic plants, the excavation of canals for boating and the drainage of the inner areas of the lagoon.

These traditional activities were regulated by the state and, until the 1960s, contributed to sustain a diverse and productive ecosystem. Until that time the collection of seagrasses and algae for use in agriculture was of great economic importance in the Ria de Aveiro (Santos & Duarte, 1991). This practice served to prevent the rapid accumulation of sediment on the extensive inter-tidal flats. After the 1960s, such traditional activities declined, due to socio-economic factors and not to a decline in the abundance of seagrasses or algae (Silva *et al*., 2004), but new pressures emerged due to harbour development and the rapid growth of leisure activities in the ria.

Since the 1960s, the steady increase in tidal action, triggered by the actions described above, has led to a major ecosystem change within the Ria de Aveiro, resulting today in a large reduction of SAV populations (including *Zostera noltii*, *Ruppia cirrhosa*, *Potamogeton pectinatus*) which formerly covered large inter-tidal flat areas (for full details, see Silva *et al*., 2004), leaving unstable sediment that is easily mobilized by the stronger tidal currents and is now colonized by macroalgae species only (*Enteromorpha* sp., *Ulva* sp. and *Gracilaria verrucosa*). Today the fully marine *Zostera noltii* is the only species of seagrass found in the lagoon, growing only in the inter-tidal zone. This positive feedback mechanism between submerged plant loss and sediment mobilization has been exacerbated by activities related to the recreational use of the lagoon, in particular increased motor boating and collection of invertebrates from the tidal flats.

CHANGING USE AND HYDROMORPHOLOGICAL ADJUSTMENT

The Ria de Aveiro has always been of major importance to the regional economy (Santos & Duarte, 1991). The region was served by a large number of small quays used for transportation of goods such as aquatic vegetation, fisheries products, sea salt, wood and agricultural products. Seaweed collection and saltpan construction had a direct impact on the sedimentary balance of the lagoon. However, in spite of the large number of small boats used, their impact on the ecosystem was minimal, as they traditionally had a small draft and were sail- or oar-propelled. After the 1960s, the traditional activities declined while commercial navigation and recreation increased dramatically.

The data presented in Table 1 show the changes in the number of small boats in use in the Ria de Aveiro since 1985 according to category of use. The marked and progressive decline in the numbers of boats being registered for traditional activities

Table 1 New boats registered for use in the Ria de Aveiro in five years intervals and the total number of boats with a licence in 2004 (after Silva & Catarino, 2004).

Years	Plate AL Seagrass	Plate AL Agriculture	Plate L Fishing	Plate AV Recreation
1985–1989	131	116	~900 (total)	1180
1990–1994	64	46		1674
1995–1999	17	12		1675
2000–2004	10	3		>1800
Total	238	134	~600	>5000

such as seagrass harvesting (Plate AL) and the one third reduction in professional fishing boats (Plate L) since 1985 has been accompanied by an expansion in the numbers of recreational boats (Plate AV). The new boats coming into use in the ria, which increased in numbers by over 300 per year in the period 1985–2004 (Table 1), are generally equipped with outboard engines and have a high potential for disturbing the sediment of the shallow inter-tidal flats, particularly the areas covered with seagrasses. The widespread collection of bait for recreational fishing, by digging in the inter-tidal areas, also disturbs the sediment.

The results of the sediment analyses suggest that the presence of *Zostera noltii* is related to the distribution of appropriate sediment types. Sediment samples collected from inter-tidal areas covered by *Zostera noltii* and from areas with only macroalgae reveal significant differences ($P < 0.01$) in grain-size distribution and organic content. The presence of *Zostera noltii* clearly favours the retention of fine sediment particles and organic matter. The median grain size (± 1 standard deviation) of the sediment in the seagrass areas is 95 ± 65 μm ($n = 75$), the silt and clay fractions contributing ~43% of the mass. However, this cohesive sediment becomes depleted in fine particles after loosing the coverage of the seagrasses, giving rise to a mobile sediment characterized by dunes in which only macroalgae grow. In this type of sediment fine sand predominates, the median grain size is 239 ± 110 μm ($n = 52$) and the finer fractions contribute only ~13% of the mass. The reduction in organic matter, associated with the reduction in fine particles, corresponds to a decrease in the mean organic content from 8 ± 2% to 3 ± 2%. The fine particles lost are enriched in Fe, as coatings, while in the coarser fraction shell fragments are present causing enrichment in Ca. The mean Fe content decreases by 50% while the mean Ca content increases by 150%, comparing sediment from *Zostera noltii* beds to sediment from areas colonized by macroalgae only.

CONCLUSIONS

The over-arching and most profound hydromorphological adjustment triggered by human intervention in the Ria de Aveiro has been a change from a fluvially dominant to a tidally dominant system. The opening of the new channel two centuries ago, in 1808, was the catalyst to a chain reaction of changes that has seen the system evolve to its present-day state. The change in human use of this ecosystem, especially over the last four decades, has been from a situation in which the inhabitants of the area depended on the resources obtained from it, but in so doing preserved its biological productivity, to one in which the use is now mainly recreational but with a potentially significant environmental impact. The change occurring in the sediments of the extensive inter-tidal flat areas, from finer cohesive sediment supporting a very intense biological and chemical activity to coarser mobile sediment with a reduced biological activity, corresponds to a reduction in importance of the benthic compartment of the lagoon ecosystem. Since this compartment has an important role in filtering the pollutants reaching the lagoon, it is anticipated that the ecosystem will become more susceptible to the impacts of pollutant loads, potentially further reducing its biological productivity.

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