Origin and Evolution of Tagus Estuarine Beaches

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ABSTRACT


Estuaries are unique systems with an unquestionable economical, ecological and recreational value which has motivated a large amount of research work. Out of the research focus emerge the estuarine margins and more particularly the estuarine beaches, especially in what concerns their macro-scale evolution. This work aims to understand the origin and evolution of Tagus estuary beaches. To meet this objective, a detailed geomorphological characterization of peri-estuarine margins, complemented with geological and sedimentological data, was performed. This study was coupled with the analysis of meteorological and hydrodynamic processes that control the estuarine sedimentary dynamics; particular attention was given to local waves through the application of a wind-wave generated model calibrated with field data.

The origin of Tagus estuarine beaches is related with the Holocene transgression, which promoted the drowning of the present-day upper estuarine depression and generated a wide and shallow fetch-limited basin. From the transgressive maximum onwards the estuary initiated an infilling process dominated by fluvial fine-grained deposition within the estuarine basin, whereas sand input was retained in a bay-head delta. At the same time, fetch-limited waves promoted the erosion of estuarine margins, initiating beach development, related to the growth of sand spits anchored in Plio-Pleistocene reliefs. This process depended on wave energy and also on mean wave power direction, which controlled the spit growing pattern. At present, beach evolution reflects the disturbance of sediment budget due to the increase of human intervention in estuarine margins.

ADDITIONAL INDEX WORDS: wave generation, sediment transport, Holocene transgression.

INTRODUCTION

Estuaries are unique systems with an unquestionable economical, ecological and recreational value. This has motivated a huge amount of research work, though, as expected, this effort has been strongly biased towards the environments with either larger ecological relevance (mudflats and salt marshes) or greater economical importance (subtidal areas, mostly related with industrial and port activities). Out of the research focus emerge the estuarine margins and more particularly the estuarine beaches. This is mainly due to the fact that estuarine beaches generally have an unattractive appearance, the water quality is usually poorer than in ocean beaches, reducing their recreational value, and support less diversified and productive habitats, in comparison to other portions of the estuary. However, the dynamics and evolution of estuarine beaches are the basis of some estuarine management problems, for example, the loss of marsh areas by erosion or by sedimentary burial under transgressing bay barriers, the loss of buildings, roads, and upland habitat as a result of beach erosion (NORDSTROM, 1992). Moreover, estuarine beaches can also have large recreational and ecological value; for instance, in cases where water quality is suitable for bathing, estuarine beaches can be considered an alternative to ocean beaches, near urban areas. Furthermore, while beaches are generally regarded as “deserts” in what concerns life support, for ecologists they are key ecosystems (SCAPINI, 2003). Only recently these issues were properly recognized and, since the pioneer work of NORDSTROM (1992), the number of publications on estuarine beaches has increased exponentially. Research work on estuarine beaches has, generally, focused on short term dynamics (e.g. JACKSON et al. 2002; NORDSTROM et al., 2003), geomorphic-biotic interactions (JACKSON et al., 2005) and management problems (NORDSTROM, 1992; JACKSON, 1996). However, process-based studies dealing with larger timescales, that can give valuable insights on estuarine beach origin and evolution, are still relatively scarce.

Accordingly, the main objective of the present work is to contribute to understand the dynamics of beaches in the Tagus inner estuary, in what concerns their origin and long-term evolution, focusing on the forcing mechanisms and sediment budget. This analysis was supported by the study of sediment supply and key distribution processes, and linked with the Late Pleistocene and Holocene paleogeography of the lower estuary.

STUDY AREA

The Tagus estuary, located on the Portuguese western coast near Lisbon, is one of the largest estuaries in Europe covering an area of nearly 320 km², extending about 40 km from the estuary mouth up to Vila Franca de Xira (Figure 1), the upward limit of the saline intrusion in normal meteorological conditions. The Tagus estuary presents a peculiar morphology, with a large and shallow inner domain, maximum margin separation along the NNE-SSW direction of 15 km and a narrow fault-controlled deep inlet channel trending ENE-WSW. The estuary is a semi-diurnal
mesotidal system, with tidal amplitudes of 1.0 m (neap tide) to about 3.5 m (spring tide) at the mouth. The inner estuary is characterized by extensive mudflats and salt marshes nourished by fluvial input of fine sediments (Freire and Andrade, 1999); this is mainly related with the discharge of the Tagus river with a mean annual value of 300 m$^3$s$^{-1}$ (SNIRH, 2008), ranging between 100 and 2200 m$^3$s$^{-1}$ (Fernandes, 2005). Concerning tidal currents, the estuary shows an asymmetric behavior with floods typically longer than ebbs (Fortunato et al., 1999; Vieira and Bernardino, 2005; and propagation along several specific sites at the estuary (e.g. Sanches and Silva, 2009). Typical tidal current speed is about 1.0 ms$^{-1}$, with maximum values at the inlet of 2.5 ms$^{-1}$ (MARETEC, 2001).

Inner estuarine beaches (5 to 9, Figure 1) are subject to a low energy wave climate related to locally generated wind waves. Several studies have been performed regarding wave generation and propagation along several specific sites at the estuary (e.g. Freire and Andrade, 1999; Vieira and Bernardino, 2005; Santos et al., 2006; Fortes et al., 2007, Oliveira et al., 2008), however there are no analysis aiming the characterization of the wind wave climate along the estuarine margins.

Tagus estuarine margins are extensively artificialized (Table 1) as most of the waterfront is engineered by seawalls, dykes, breakwaters, jetties and various rock-armored structures, which were built for port and urban protection and to shelter farmland mostly developed in the upper estuary. “Natural” margin environments (salt marshes, beach and cliff) represent about one third of the estuarine perimeter; cliffs are dominant at the estuarine channel, whereas salt marshes are most frequent in the left embankment of the inner estuary.

Figure 1. Location of Tagus estuarine beaches (numbered beaches have a longshore extent greater than 700 m).

Table 1: Tagus estuarine margins.

<table>
<thead>
<tr>
<th>Margin type</th>
<th>Length (km)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beach</td>
<td>26</td>
<td>13%</td>
</tr>
<tr>
<td>Artificialized</td>
<td>136</td>
<td>66%</td>
</tr>
<tr>
<td>Salt Marsh</td>
<td>40</td>
<td>19%</td>
</tr>
<tr>
<td>Cliff</td>
<td>4</td>
<td>2%</td>
</tr>
<tr>
<td>Total</td>
<td>206</td>
<td>100%</td>
</tr>
</tbody>
</table>

**WAVE MODEL**

The assessment of sediment transport pattern induced by locally-generated waves was based on a semi-empirical wind wave generation model (SMB89- Hurdle and Stive 1989). This model relates the significant wave height and period to wind speed, fetch distance and water depth. The SMB model performance, was evaluated by comparing model estimates with field measurements at Alféite beach, along a wide range of wind conditions (intensity from 3.7 ms$^{-1}$ up to 46.3 ms$^{-1}$ and fetch from 6.5 km to 24.5 km, Table 2), in cases where wind conditions presented rotational behavior, and therefore, variable fetch, wave parameters were computed using average results. A quite reasonable fit between model predictions and field measurements was obtained (Figure 3), with a slight overestimation (≈ 20 % on average).

Table 2: Measured wind (fetch – F; speed - U) and wave characteristics (significant height – H$_{m0}$) at Alféite beach. The last column shows significant wave height as computed by the SMB model (H$_{b}$).

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Date</th>
<th>H$_{m0}$ (m)</th>
<th>Direction</th>
<th>F (min-max) (m)</th>
<th>U (m/s)</th>
<th>H$_{b}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berna III</td>
<td>07-11-2005</td>
<td>0.08</td>
<td>NNE</td>
<td>24500</td>
<td>7.4</td>
<td>0.09</td>
</tr>
<tr>
<td>Berna IV</td>
<td>17-11-2005</td>
<td>0.08</td>
<td>ESE</td>
<td>3000</td>
<td>3.7</td>
<td>0.02</td>
</tr>
<tr>
<td>Berna V</td>
<td>29-01-2006</td>
<td>0.84</td>
<td>N-NE</td>
<td>23700</td>
<td>38.9</td>
<td>0.88</td>
</tr>
<tr>
<td>Berna XIV</td>
<td>21-03-2007</td>
<td>0.35</td>
<td>NW</td>
<td>6500</td>
<td>46.3</td>
<td>0.54</td>
</tr>
<tr>
<td>Berna XV</td>
<td>29-03-2007</td>
<td>0.12</td>
<td>N</td>
<td>8000</td>
<td>31.5</td>
<td>0.33</td>
</tr>
<tr>
<td>Berna XVI</td>
<td>01-06-2007</td>
<td>0.13</td>
<td>NW</td>
<td>4500</td>
<td>22.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Berna XVII</td>
<td>09-07-2007</td>
<td>0.37</td>
<td>NW</td>
<td>6500</td>
<td>48.2</td>
<td>0.54</td>
</tr>
<tr>
<td>Berna XVIII</td>
<td>11-07-2007</td>
<td>0.14</td>
<td>NW</td>
<td>6500</td>
<td>31.5</td>
<td>0.31</td>
</tr>
</tbody>
</table>

To compute wave forcing along the estuarine margins, the calibrated wave generation model was forced using a six-year time series (1999-2004) with a 6 hours resolution of wind direction and intensity recorded at the Gago Coutinho meteorological station (Lisbon) of the Meteorological Institute (see Oliveira et al., 2008, for details on wind climate). The estuarine margin was then segmented in 1 km long cells, where nearshore wave climate was estimated. The computation involved the determination of the fetch distance for every time step according to the wind direction and the use of the SMB formulation to compute wave height and period. Average annual parameters (mean wave height, period, power and direction) were then computed for each cell.
ESTUARINE SEDIMENTARY DYNAMICS

Sediment Sources
The lower Tagus valley intersects the Cenozoic sedimentary basin with a general NE-SW direction and is choked with alluvial sediment. The river valley shows a clear morphologic dissymmetry between margins mainly related to the geologic settings, and the alluvial plain exhibits a greater development in the southern margin.

The potential of the northern margin outcrops as sediment source for estuarine beaches is in general low, due to its geologic characteristics and due to human intervention (occupation/urbanization of land and estuarine margins). This NNE-SSW structurally-controlled margin, is defined essentially in silts, clays, limestones, marls and to a less extent sandstones, dated from Mesozoic to Mio-Pliocene, added by weathered Neo- cretaceous basalts and pyroclasts from the Lisbon Volcanic Complex.

The Tagus southern margin presents in general lower relief (up to 60 m) and shows an irregular, crenulated shape due to incision of several small scale tributaries. Its potential as sediment source is high, regarding the degree of erodibility and textural compatibility with estuarine beach sediments. In fact, it develops in extensive outcrops of sand, gravel, sandstones, conglomerates, silt and clay that constitute Pleistocene fluvial terraces and Miocene and Pliocene formations. Active cliffs between Almada and Trafaria are cut in Miocene formations (sand, silt, clay and limestone) while between Alcochete and Almada low cliffed margins are defined in detritical Plio-Pleistocene (sandstones, sand, gravel and clay) (Figure 3). Textural and compositional analysis of these sediments enabled Freire et al. (2007) to recognize them as the main source of estuarine beaches.

Distribution processes
The sediment distribution within the estuary is mainly related to the action of tidal currents, fluvial discharge and wind induced waves. Previous works concerned with long term sedimentation (e.g. Vis et al., 2008) considered currents, either related with tide or river discharge, as the dominant sediment transport process in the estuary. However, in what concerns the specific case of estuarine beaches, numerical model results and in situ measurements show that near the inner estuarine beaches those currents are generally of relatively low intensity. For that reason, in this work, waves were assumed to be the dominant controlling process in non-cohesive sediment redistribution and beach planform morphology.

The annual average wave parameters obtained with the model (Figure 4) show that estuarine margins are mostly affected by small waves, the higher-energy conditions (significant wave height, $H_s > 0.10$ m) restricted to the left margin, in coincidence with the occurrence of sandy beaches (see Figure 1).

The relationship between directions of the yearly average wave power and shoreline, enables the determination of the predominant longshore sand transport direction in each coastal cell (Figure 4). Two main longshore transport cells are present, one directed southwest to south in the sector between Alcochete and Base Aérea, and other directed eastward in the Alfeite-Seixal sector.

The comparison of this transport pathways with the existing
morphological features (e.g. growth of sand spits) confirm the model results for most part of the coast represented in figure 4. These results also prove that waves are the main forcing mechanism of estuarine beach development.

Figure 4. Average wave height and direction along Tagus estuarine margins. Black arrows represent the longshore sand transport deduced by the model and confirmed by morphological indicators; grey arrows indicate longshore sand transport deduced only by morphologic indicators. Digital elevation data from JPL (2008).

**BEACH EVOLUTION MODEL**

The integration of the results obtained in the scope of this work with multi-secular paleogeographical reconstructions of the estuarine space, enabled the development of a simple model for the origin and evolution of Tagus estuarine beaches

The origin of estuarine beaches is related to the early Holocene post-glacial sea level rise, which promoted by 7000 cal BP (Vis et al., 2008) the inundation of the lower Tagus basin, generating a large and relatively shallow (< 50 m) fetch limited surface (Figure 5). This basin covered an area of nearly 1300 km² (more than four times the actual area) and extended for more than 100 km, almost until the latitude of Torres Novas. From the transgressive maximum onwards, the estuary initiated an infilling process dominated by fluvial fine-grained deposition within the estuarine basin (representing, at present, about 0.6 x10⁶ m³/year according to PORTELA, 2004), while sand input (estimated in 0.3x10⁶ m³/year according to the same author) was preferably retained in a prograding bay-head delta. This prograding Tagus bay-head delta pushed the tidal environments southward, at a long term average rate of about 10 m/year. At the same time, the wind blowing over the large tidal basin promoted the generation of fetch-limited waves that began to rework the estuarine margins. Therefore, at the locations where the geomorphological and geological settings were favorable (i.e. small protruding capes shaped in soft detrital formations with high sand and gravel content of which the Pliocene outcrops on the left margin between Almada and Alcochete are examples), marginal erosion enabled the formation of sand spits. The long term sea level stability that prevailed after 7000 cal BP (Vis et al., 2008), favored the development of these spits, and this should have been an uninterrupted process persistent until present, although probably with variable rates, depending on local morphology and wave conditions (energy and direction). In the more recent past, human intervention started to play a major role in these processes. Since early civilization times deforestation and agriculture activities increased sediment supply to the estuary, leading to noticeable faster aggradation of natural levees and flood basins (Vis et al., 2008), though the impact on beach development should have been negligible, as it has no influence on beach sediment budget. More recently, however, the artificialization of estuarine margins and the development of harbor activities had a huge influence on beach stability, promoting changes in the natural patterns of development. As estuarine beaches are low energy environments, with small transport rates, any external perturbation of the system, either by reducing sand sources (e.g. building of coastal defenses, dredging), or by increasing the sand supply to the beach (e.g. sand disposal) can have dramatic consequences on the sedimentary budget. Examples of these are recorded at the Alféite sand spit, where erosion of the updrift spit attachment resulted from cut off of sand supply in consequence of the construction of a navy facility; at the opposite end, significant progradation has been observed in relation with disposal of sand dredged from the Seixal channel.

Figure 5. Paleogeography of Lower Tagus Valley around 7000 cal BP. Digital elevation data from JPL (2008).

**CONCLUSIONS**

The margins of the Tagus estuary, one of the largest estuaries in Europe, extend for about 200 km, and despite being extensively artificialized (around 2/3), still contain several fairly preserved beaches. Sand beaches of the Tagus inner estuarine are restricted to its southeast margin, and correspond to wide features that frequently exceed 2 km in length.

In this work, the origin and evolution of those estuarine beaches is discussed based on an integrated analysis of sediment sources
and distribution processes. Particular attention was given to wind wave processes, with the successful calibration of a semi-empirical wave generation model (SMB). Wave climate computed along the estuarine margins, is of low energy, with larger wave activity on the left margin (annual significant wave height between around 0.1 m). Sediment transport patterns deduced from nearshore wave climate is in agreement with the morphology and development of sand spit and beaches in the southeast margin and demonstrates the key role of locally generated wind waves in governing the dynamics of estuarine beaches.

These results support a conceptual model for the origin and development of Tagus estuarine beaches presented below:

1. A wide and shallow fetch-limited basin was formed in the lower Tagus valley related with the Holocene transgression; the area of this tidal environment reached maximum extend at about 7000 cal BP, when sea level rise decelerated;
2. From this stage onwards the estuary initiated an infilling process; fine sediment promoted the depth reduction of the estuarine basin, sand input was preferably retained in a prograding bay-head delta, and both contributed to shrink the estuarine domain. This wide basin favored the generation of fetch-limited waves that started to rework estuarine margins and initiated beach development at the southeastern margin, where most favorable geological/geomorphological (source) and wave (energy) conditions were present.
3. Human intervention disturbed the natural dynamics of the estuarine beach system. The most noticeable effects of this intervention was the reduction of sediment supply due to waterfront occupation and engineering, which has led to beach starvation and, consequently, marginal retreat. More recently, the deposition of dredged materials at the vicinity of some beaches has also lead to localized growth. As a result, the evolution trends of these features are, at present, mainly related to human activity.

**LITERATURE CITED**


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