NUMERICAL MODELING OF THE AVEIRO INLET DYNAMICS

Anabela Oliveira[1], André B. Fortunato[1] and João M. Dias[2]

The dynamics of the Aveiro lagoon is assessed through a combination of field data and numerical modeling. An unstructured grid hydrodynamic model is set-up for this system for the first time and its results compare well with data and with a well-established model. The model and the data are then used to analyze the propagation of the tide in the lagoon and the variability of tidal asymmetry in the upper and lower lagoon. The lagoon shifts from mild ebb-dominance at the inlet to strong flood-dominance in the upper lagoon. This variability may be responsible for the importing capacity suggested by the sediment particle model, estimated at 10% of the littoral drift. On the contrary, a preliminary application of the morphodynamics modeling system MORSYS2D suggests a net export capacity. These opposite results maybe due to the tidal excursion of sediments in the system, which is much larger than the scale of variability of the hydrodynamics.

INTRODUCTION

The Aveiro lagoon, a large and shallow system on the west coast of Portugal, is characterized by a complex geometry that includes large areas of intertidal flats and a web of narrow channels (Figure 1). The average depth of the lagoon is about 1 m, while the navigation channel can exceed 20 m deep. The total area varies between 63 and 88 km^2, depending on the tidal level.

This system is connected to the sea by a 350 m wide inlet, fixed by two jetties. Despite these maritime structures, important morphological changes have been occurring. Until recently, the Aveiro Harbor Administration has regularly dredged the sand that accumulates at the inlet due to the southward littoral drift. This activity has now ceased due to environmental regulations. Recent bathymetric surveys reveal erosion at the entrance channel close to the north jetty, and sand deposition close to the south jetty.

Because this system harbors an important port, the inlet has often been modified to provide adequate bathymetric configurations. However, the morphological behavior of the inlet is still not fully understood. The present paper constitutes a first step towards understanding and modeling the inlet morphodynamics, which will help analyzing solutions for the morphological problems occurring in the tidal inlet.

Flow and sediment fluxes in the system are mostly driven by tides and waves. River flows are negligible (except in the upper reaches of the lagoon), with average values of about 55 m^3/s (Dias and Lopes, 2006a), which leads to a freshwater input below 3% of the spring tidal prism. Tides are semi-diurnal, ranging from 0.6 m in neap tides to 3.2 m in spring tides (Dias and

---

[1] Estuaries and Coastal Zones Division, National Laboratory of Civil Engineering, Av. do Brasil, 101, 1700-066 Lisbon, Portugal

[2] CESAM, Physics Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

Lopes, 2006b). The adjacent coast is subject to a highly energetic wave climate, typical of the west coast of Portugal (Barata et al., 1996).

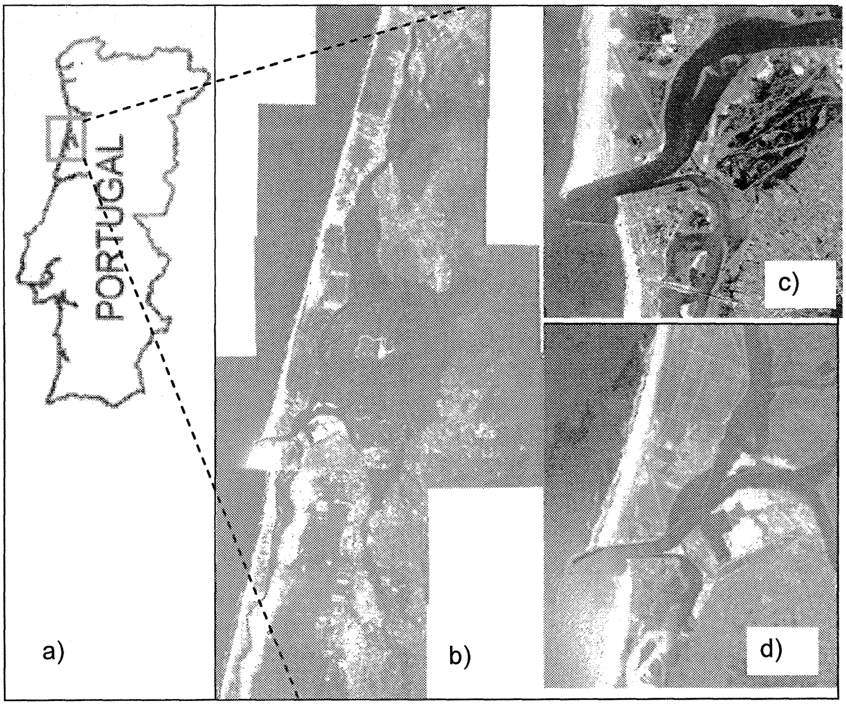

Figure 1. The Aveiro lagoon. a) Geographical location; b) 1995 aerial photo of the whole lagoon; c) Inlet in 1979 aerial photo; d) inlet in 1995 aerial photo.

This severe wave climate leads to an average southward annual littoral drift of about 1.5×10^6 m^3/year, with important seasonal variations (Vicente and Uva, 1989). In the maritime winter (November to April), the littoral drift is intermittently directed in both directions, with a net budget of about 0.75×10^6 m^3 northward, as a result of the wide range of wave directions (SW to NW). During the maritime summer, waves are smaller but have a predominant NW direction. As a result, there is a large southward sediment budget (about 2.25×10^6 m^3).

This paper describes the sediments dynamics through the application of several numerical models. Tidal propagation in the lagoon is presented first, based on the analysis of tidal data and on the application of an unstructured-grid hydrodynamic model, whose results are validated by comparison with both field data and the results of the well-established model of Dias and Lopes (2006b). Then, sediment dynamics are studied with a morphodynamic modeling system (Section 3) and a Lagrangian model (Section 4). The paper closes with a summary of the major conclusions.

TIDAL PROPAGATION IN THE RIA DE AVEIRO

Brief description and establishment of the hydrodynamic model ELCIRC

ELCIRC is a fully non-linear, three-dimensional, baroclinic shallow water model which is being developed as an open source community model at the Center of Coastal and Land-Margin Research of the Oregon Health Science University (Zhang *et al.* 2004). The equations are solved with a finite volume technique for volume conservation and a natural treatment of wetting and drying. The horizontal domain is discretized with a triangular mesh for flexibility, and z-coordinates are used in the vertical. A semi-implicit time-stepping algorithm and the Lagrangian treatment of the advective terms ensure stability at large time steps.

For the Aveiro lagoon model, a single vertical layer is used, so ELCIRC reverts to two dimensions. Due to the shallow depths and minor freshwater inputs, circulation can adequately be simulated with a depth-averaged model. The hydrodynamic model was forced by the eleven constituents taken from the regional model of Fortunato et al. (2002), without any river flow. Results were condensed through harmonic analysis for the same constituents.

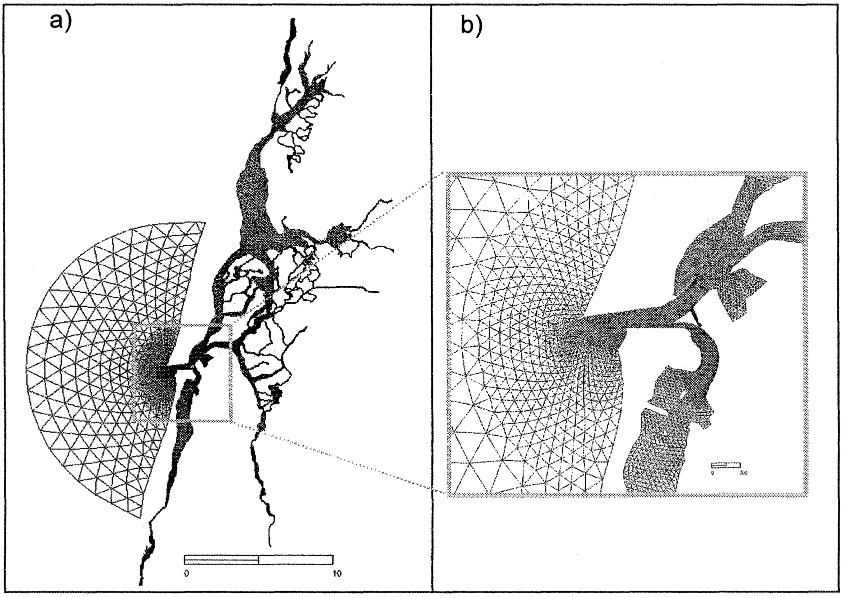

Figure 2. Horizontal grid, with 18851 nodes: a) full grid; b) detail of the grid near the inlet.

The computational domain, which extends from the upstream limits of the lagoon to the continental shelf, was discretized with an unstructured grid of 18851 nodes (Figure 2). Resolution varies from 0.5 km near the open boundary to 1 m in the narrow channels and at the inlet. The time step was set to 90 s.

Simulations were conducted for two distinct parametrizations of friction: a constant Manning coefficient, with values of 0.018, 0.023 and 0.030, and a depth-dependent Manning coefficient, following the relationship proposed by Dias and Lopes (2006b) for the Aveiro lagoon (Figure 3a). This screening analysis showed that the proposed friction relationship leads in general to better results in the Barra (inlet) station (Figure 3b). The remaining simulations were thus performed with this approach.

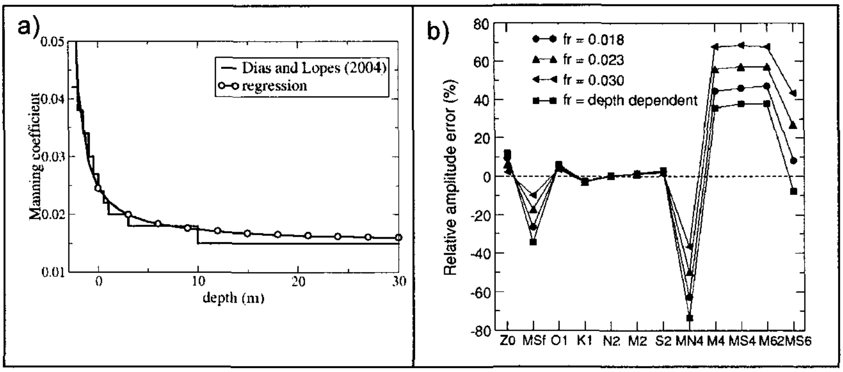

Figure 3. a) Friction parametrization; b) amplitude errors at the Barra station for several friction coefficients.

Comparative assessment of the simulated tidal elevations

ELCIRC results were compared with the amplitudes and phases obtained from the harmonic analysis of the elevation data measured in 1987/88 at 22 stations scattered throughout the lagoon (IH, 1991). They were also compared with results from the Aveiro hydrodynamic model developed previously by Dias and co-workers (Dias et al., 2000, Dias and Lopes, 2006a,b). The latter model has been extensively calibrated and validated, and has achieved a high level of accuracy in the representation of elevation and velocities throughout the lagoon.

The accuracy of ELCIRC is similar to the previous model (Figure 4), suggesting that limitations in the data, in particular in the bathymetry, may explain most of the errors. Errors increase towards the upper reaches of the lagoon, in particular in the northern channel, mostly due to insufficient channel resolution. Phase errors are also small (Table 1).

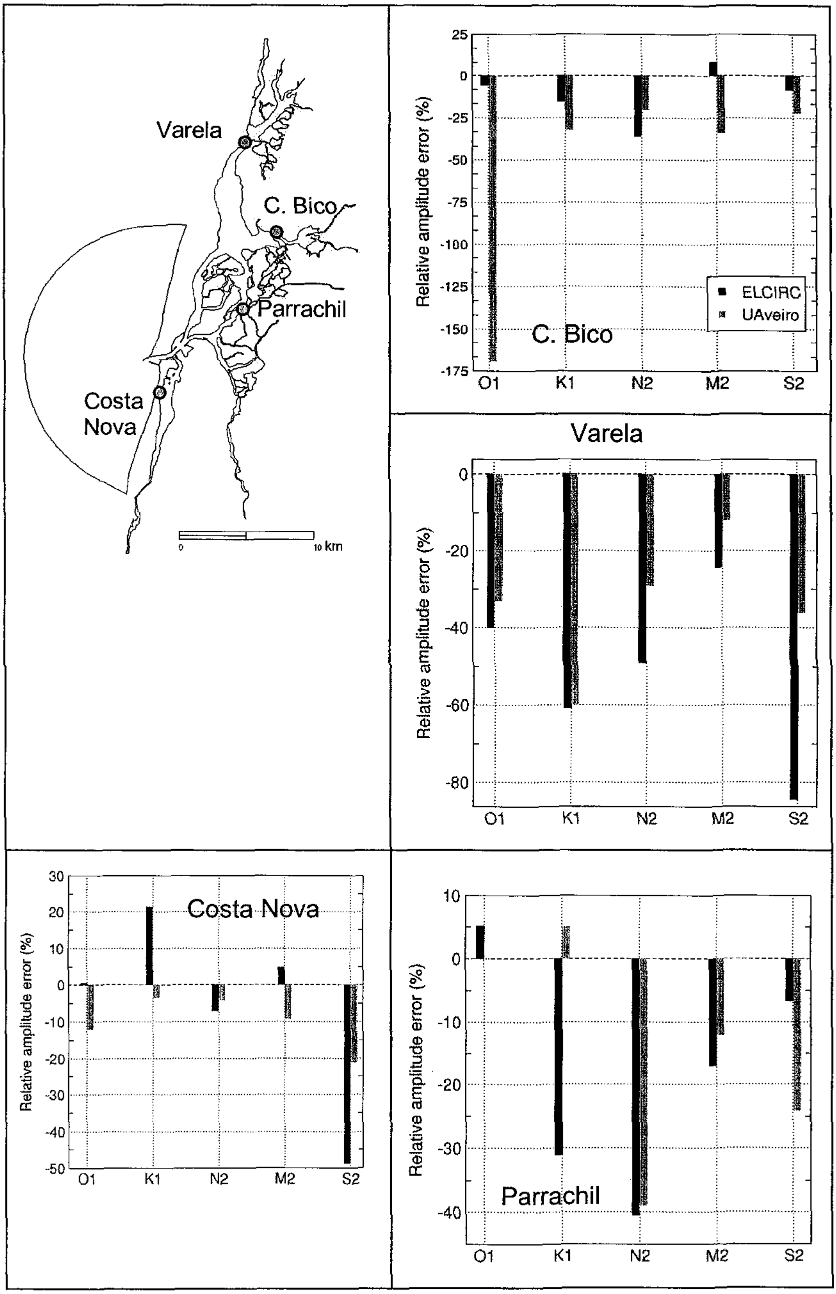

Figure 4. Comparison of amplitudes errors at 4 stations between ELCIRC and the results of the Aveiro university model (Dias and Lopes, 2006b).

Table 1. Phases at the Barra station (degrees)

Constituent	Data	Model
MSf	132.8	170.3
O1	319.5	321.2
K1	64.6	67.1
N2	61.9	62.7
M2	79.3	81.1
S2	105. 9	108.1
MN4	247.5	248.9
M4	265.5	267.5
MS4	310.1	299.7
M6	320. 7	326.6
2MS6	338.9	4.2

Tidal Propagation

Tidal propagation was analyzed along four major channels (Figure 5): N (S. Jacinto), NE (Espinheiro), SE (Ílhavo) and S (Mira) channels. The analysis was based on the amplitudes of the M2 and M4, as well as on the tidal asymmetry, measured by the differences between ebb and flood durations.

Figure 5. Channels and stations used for the tidal propagation analysis.

Both data and model results show that the amplitudes of the astronomic tidal constituents decrease steadily along the channels (Figure 6). The major reduction occurs for the S channel. In contrast, fourth-diurnal constituents are fairly constant along the channels (Figure 6). As a result, the ratio between the amplitudes of the M4 and the M2, regarded as a measure of tidal asymmetry, increases along the channels. Differences between ebb and flood durations show that the system shifts from mildly ebb dominant at the mouth to strongly flood dominance in the upper reaches of the lagoon (Figure 7).

This tidal asymmetry suggests that the upper lagoon, in particular the N and S channels, acts as a sediment trap. Hence, this area should be prone to accretion.

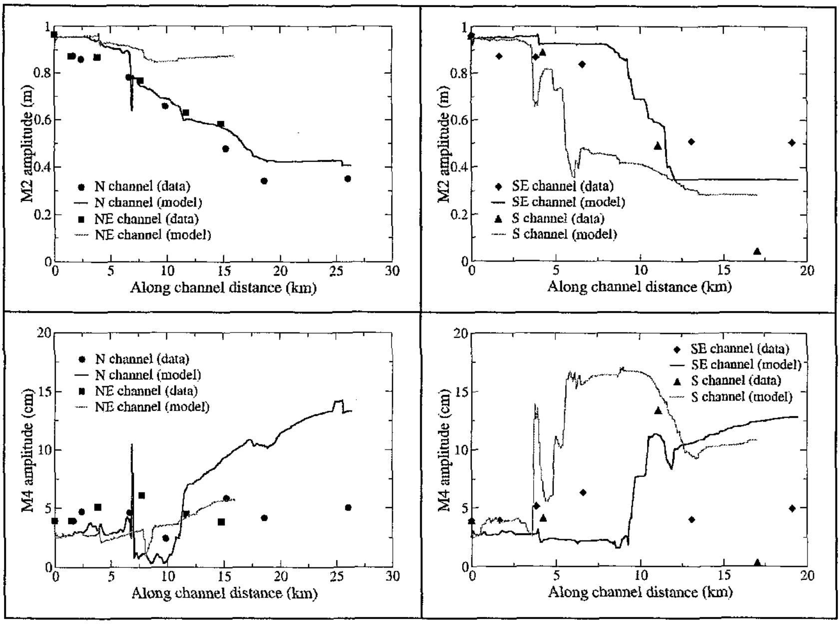

Figure 6. Tidal amplitudes along the channels.

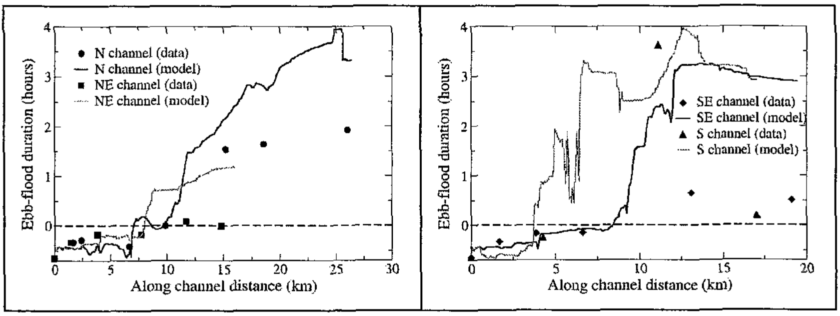

Figure 7. Differences between ebb and flood durations along the channels.

TIDALLY-DRIVEN MORPHODYNAMICS

Brief description and establishment of the modeling system MORSYS2D

The morphodynamics modeling system MORSYS2D (Fortunato and Oliveira, 2004, 2007, Oliveira et al., 2005) simulates the non-cohesive sediment dynamics driven by tides, wind, river flows and waves (Figure 8). ELCIRC is used here as the hydrodynamic engine, although other options are available. Waves are omitted, as well as riverflow. Sediment fluxes are computed with the van Rijn (1984) formula. Bottom is updated by solving the Exner equation, using a node-centered finite volume discretization in space (Fortunato and Oliveira, 2004) and a combination of a Runge-Kutta method with a predictor corrector in time (Fortunato and Oliveira, 2007).

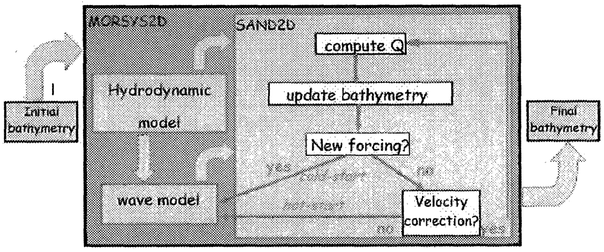

Figure 8. MORSYS2D solution procedure.

In this preliminary simulation, the mean sediment diameter is held constant at 400 μm, because available information is too scarce to specify a more correct spatial variability (Figure 9). A M2 tide with an amplitude 10% above the average tide is used as the representative tide, following Grunnet et al. (2004). The morphological time step is set to 1 tidal cycle, and the morphological factor is set to 0.5 to reduce the Courant number and stabilize the model. Finally, a dimensionless diffusion coefficient of 4 is specified, based on experience from other systems. Simulations are performed for a 6 month period.

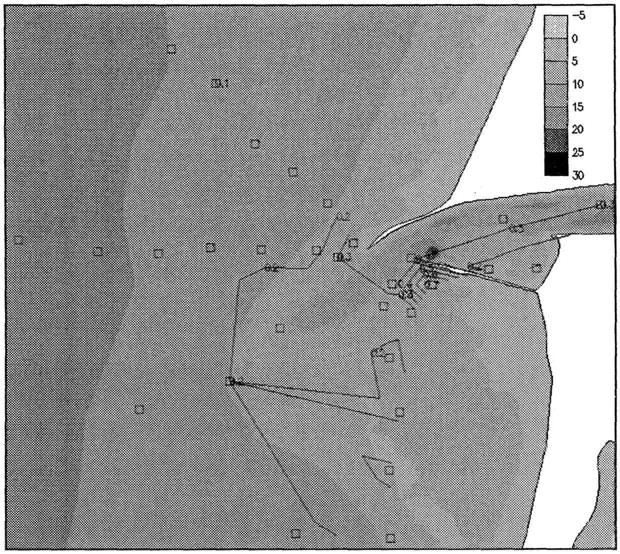

Figure 9. D50 distribution (in mm) and sampling points (squares).

Preliminary results

A preliminary application of MORSYS2D to the Aveiro inlet revealed a strong seaward sediment flux (Figure 10). This flux is consistent with the ebb-dominance at the inlet, and leads to a seaward migration of the bed forms (Figure 11). Some shallow areas near the margins are the exceptions, exhibiting small landward sediment fluxes.

A very rough estimate indicates that tides have the ability to flush out about $0.7\text{x}10^6$ m^3/year.

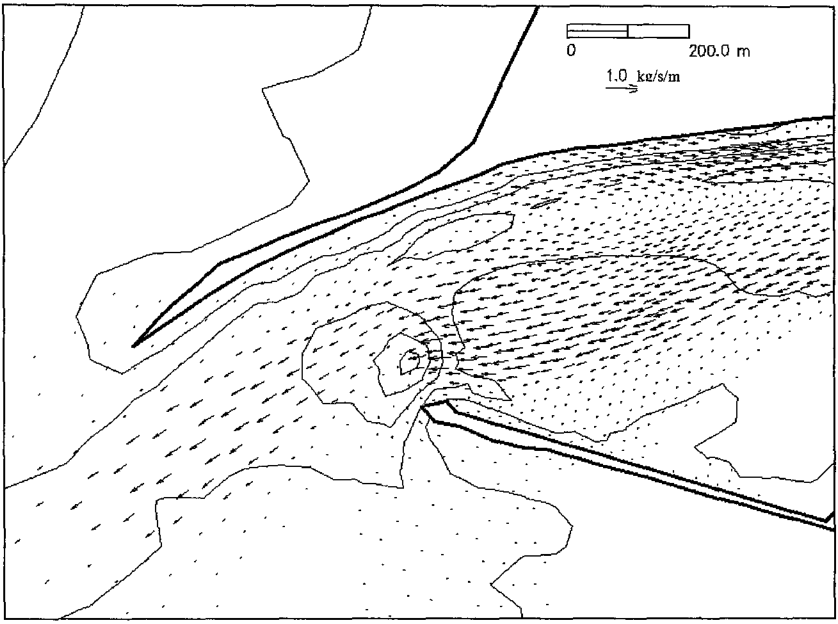

Figure 10. Initial tidally-averaged sediment fluxes.

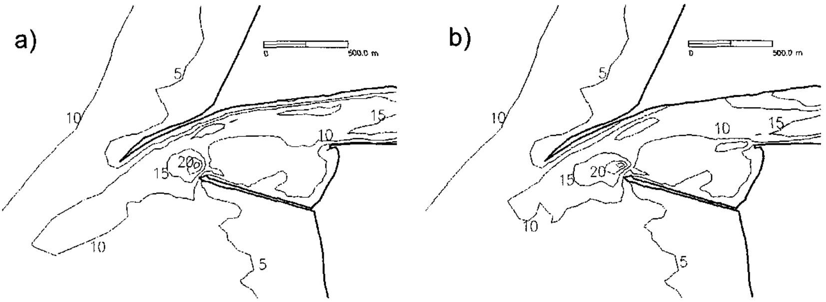

Figure 11. Bathymetry in meters, relative to MSL: a) Initial; b) after 6 months.

SEDIMENT PATHWAYS

Brief description and establishment of the sediment particle model VELApart

VELApart (Oliveira and Fortunato, 2002) is a quasi-three-dimensional model to simulate particle pathways in surface waters, including sediment particles. Sediment particles are subject to a settling velocity defined according to the type of sediments under study and using the expression proposed by van Rijn (1984). They are forced by horizontal velocities, read in the frequency domain, while a logarithmic profile is assumed for the velocities vertical distribution. Ressuspension effects due to turbulent diffusion are also included. The model uses an adaptive, embedded fourth-order Runge-Kutta method for advection and a random walk method for both horizontal and vertical diffusion. Simulations were conducted with a horizontal diffusion coefficient of 0.01 m^2/s and a closing error of 10^{-3} m.

Analysis of export/import capabilities of the various channels

Sediment exchange at the 4 channels defined in the previous section was examined in a set of 15 day simulations conducted for the 6000 sediment patches defined in Figure 12, initially distributed at 5 levels in the water column. A range of sediment diameters representative of the classes observed in the samples collected in 1994 (Figure 9) was used (0.2, 0.4 and 0.9 mm), for particles released on ebb and flood of a spring and a neap tides. Results show that the simulated sediment diameters present a similar behavior: while flood releases lead to sediments being trapped in the upper lagoon, ebb releases lead to an almost complete export of sediments (Figure 13).

A more detailed analysis of the mouth patch, which included 8 release times in spring and neap tides, showed that the inlet captures about 10% of the total littoral drift. These results are not consistent with the morphodynamic analysis, which showed a net exporting capacity of the inlet. They may however be explained by the tidal excursion of sediments released on spring tides (Figure 13d) which includes ebb-dominated regions (near the mouth) and flood-dominated areas (upper lagoon). In a single half tidal cycle, sediments released at the mouth can be transported to the upper reaches of the lagoon. Hence, although the lagoon mouth is ebb-dominated, a particle released may end up in a flood-dominated area and become trapped.

CONCLUDING REMARKS

Hydrodynamic, morphodynamic and sediment particle models were applied to the Aveiro lagoon to examine several aspects of its dynamics. The hydrodynamic application allowed for a very detailed representation of the elevation and velocities at the narrow channels, through a very fine unstructured grid. These results compared well with data and a well-established model of the lagoon, but they can be improved by further refinement in the upper channels and the consideration of the very high tidal flats that contribute, occasionally but significantly, to the lagoon's tidal prism. A detailed analysis of tidal asymmetry, based on data and model results, showed that the lagoon shifts from mild ebb-dominance close to the mouth to strong flood-dominance in the upper lagoon. This variability may be responsible for the importing capacity suggested by the sediment particle model, estimated at 10% of the littoral drift.

In contrast, preliminary morphodynamic simulations indicate that the inlet has a net exporting capacity. This apparent inconsistency can be explained by the tidally-averaged approach followed by MORSYS2D, common to other morphodynamic models. Indeed, Lagrangian quantities cannot, in general, be computed from an Eulerian perspective (Cheng and Casulli, 1982). In the Aveiro lagoon, the tidal excursion of sediments is much larger than the scale of variability of the hydrodynamics: sediment particles move from an ebb-dominated environment (mouth) to a flood-dominated region (upper lagoon) in half a tidal cycle. Hence, the tidally-averaged sediment fluxes computed by the morphodynamic model, which are Eulerian residuals, cannot represent the actual Lagrangian residual fluxes.

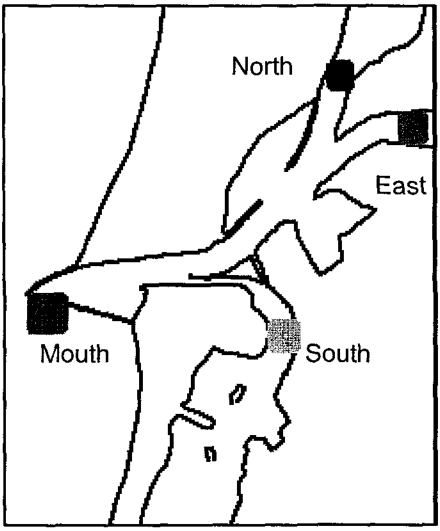

Figure 12. Location of the initial position of the sediment particles' patches.

ACKNOWLEDGMENTS

This research was partially funded by the *Fundação para a Ciência e a Tecnologia*, *Programa Operacional "Ciência, Tecnologia, Inovação"* and FEDER, project "EMERA: Estudo da Embocadura da ria de Aveiro", and LNEC's projects "Tidal inlet morphodynamics" and "Hydrodynamics and scalar transport in estuaries and lagoons". The authors are indebted to Prof. A.M. Baptista for the model ELCIRC and the software XMVIS.

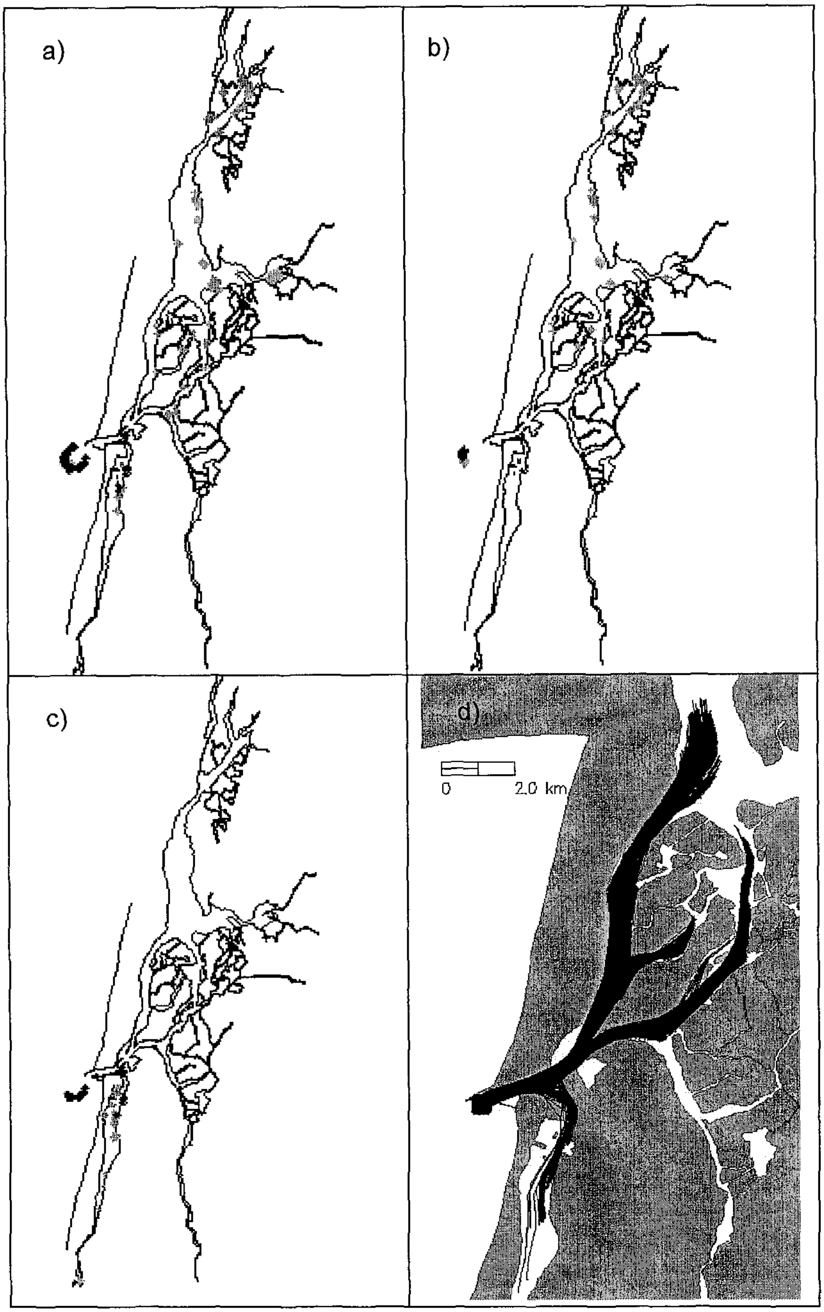

Figure 13. 15 day particle simulations (flood in black, ebb in gray) a) Mouth; b) North channel; c) South channel; d) Spring tide flood tidal excursions.

REFERENCES

Barata, A.M.G.O., M.J.B.S. Teles, and J.A.R. Vieira. 1996. Selecção de ondas representativa da agitação marítima para efeito da avaliação do transporte litoral na costa de Aveiro, *Recursos Hídricos*, 17/1, 43-74.

Cheng, R.T. and V. Casulli. 1982. On Lagrangian residual currents with applications in South San Francisco Bay, California, *Water Resources Research*, 18/6: 1652-1662.

Dias, J.M. and J.F. Lopes. 2006a. Calibration and validation of hydrodynamic, salt and heat transport models for Ria de Aveiro lagoon (Portugal), *Journal of Coastal Research*, 1680-1684, SI39, in press.

Dias, J.M., and J.F. Lopes. 2006b. Implementation and assessment of hydrodynamic, salt and heat transport models: the case of Ria de Aveiro Lagoon. *Environmental Modeling and Software*, 21, 1-15.

Dias, J.M., J.L. Lopes, and I. Dekeyser. 2000. Tidal propagation in Ria de Aveiro Lagoon, Portugal, *Phys. Chem. Earth*, 25/4, 369-374.

Fortunato, A.B., L. Pinto, A. Oliveira, and J.S. Ferreira, 2002. Tidally-generated shelf waves off the western Iberian coast. *Continental Shelf Research*, 22/14, 1935-1950.

Fortunato, A.B., A. Oliveira. 2004. A modeling system for long-term morphodynamics, *Journal of Hydraulic Research*, 42/4: 426-434.

Fortunato, A.B., A. Oliveira. 2007. Improving the stability of a morphodynamic modeling system, *J. of Coast. Res.*, SI50, submitted.

Grunnet, N.M., D.-J.R. Walstra, and B.G. Ruessink. 2004. Process-based modeling of a shoreface nourishment, *Coast. Engineering.*, 51: 581-607.

IH, 1991. *Recolha e processamento de dados de marés, correntes, temperaturas e salinidades na Ria de Aveiro.* Rep. FT.MC. 5/87, Lisbon.

Oliveira, A., A.B. Fortunato. 2002. *VELApart User's Manual: a Quasi-3D Particle Tracking Model for Shallow Water Simulations.* Rep. 82/02–NET, LNEC.

Oliveira, A., A.B. Fortunato, and F.E.P Sancho. 2005. Morphodynamic modeling of the Óbidos lagoon, *Proc. 29th International Conference on Coastal Engineering* (ASCE), vol.3, 2506-2518.

Oliveira, A., A.B. Fortunato, and J. Rego. 2006. Effect of Morphological changes on the hydrodynamics and flushing properties of the Óbidos Lagoon, *Continental Shelf Research*, 26/8, 917-942.

Zhang, Y., A.M. Baptista, E.P. Myers. 2004. A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: I. Formulation and skill assessment, *Continental Shelf Research*, 24/18, 2187-2214.

Van Rijn, L.C. 1984. Sediment transport – part 1: bed load transport. *Journal of Hydraulic Engineering*, 110/10, 1431-1456.

Vicente and Uva, 1989. *Porto de Aveiro. Obras exteriores. Estudo em modelo reduzido. Caracterização do regime fisiográfico.* Rep. 205/89-NET, Lisbon, in portuguese.