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Effect of the bathymetric changes on the hydrodynamic and residence time in Óbidos Lagoon (Portugal)

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ABSTRACT

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Óbidos Lagoon is a small coastal system connected to the sea through a shallow, narrow and mobile inlet. The lagoon is characterized by large accretion rates and cyclic water quality problems due to large water renewal time scales. Over the years the inlet position often drifted from north-south and south-north. As a consequence, every time the inlet position approaches to the north or south shoreline the associated erosion threatens local houses and some emergency interventions to protect the northern shoreline were needed in the past. In the 1990s Danish Hydraulic Institute (DHI) proposed some local solutions to improve the water fluxes between the lagoon and the ocean, and to create conditions to maintain the inlet in a central position. These interventions included the construction of a guiding wall to prevent the inlet migration to the north. However, in the last years an extreme migration of the inlet to south was observed, generating severe erosion problems and damage to the local houses.

This paper investigates the effect of artificial morphological changes (e.g., dredging works) on tidal propagation and residence time (RT) in Óbidos coastal lagoon. Hydrodynamic and RT simulations were performed for three bathymetric configurations of the lagoon, representing the reference or present situation and two dredging scenarios. The results confirmed that tidal propagation depends strongly on the bathymetric configuration. Dredging the channels and relocating the inlet may increase the tidal prism by about 20% to 35% in relation to the reference scenario. The major differences are observed in the lower lagoon with an improving in velocity fields in the north and south channels and the reposition of the inlet to the central position. The tidal prism increasing promotes higher water renewals in the lower lagoon and contributes to improve the water quality in this area. In the upper lagoon the effects of the dredging, it are less visible and relevant changes in the water RT (of the order of 3 weeks) were not observed. The most relevant changes can be observed after dredging the Barrosa branch, with an increasing in the RT on the order of 50% compared to reference situation

ADITIONAL INDEX WORDS: *MOHID, Bathymetric changes, Hydrodynamic, Residence time, Inlet, Óbidos Lagoon.*

INTRODUCTION

Óbidos Lagoon is a small and shallow, Portuguese coastal lagoon located between Nazaré-Peniche at west coast (39º24´N, 9º17'W, Figure 1). The lower lagoon, connected to the sea trough a shallow, narrow and mobile inlet (on the order of 100 m width), is characterized by narrow channels and large sand banks. The velocities in this region often exceed 1 ms^{-1} along the northern channel and of about 1.6 ms^{-1} in the inlet (MALHADAS, 2008). The upper lagoon is characterized by small velocities (less than 0.4 ms^{-1}, MALHADAS, 2008) and muddy bottom. A detailed description of the system is given in MALHADAS *et al.* (*in press*).

The bathymetry can vary significantly on monthly time scales. The morphological evolution is essentially driven by tidal currents and, in a smaller extent, by waves (FORTUNATO and OLIVEIRA, 2007a). For instance, the main channel can migrate very rapidly and, within a few months, a meander can form and disappear.

The lagoon problems are mostly related to its morphological evolution (FORTUNATO and OLIVEIRA, 2007b), differing substantially from the lower to the upper lagoon. In the lower lagoon the instability of the inlet constitute the major problem. In the upper lagoon-characterized by progressive accretion rates- the low water renewal rates are one of the major problems. This contributes to water quality deterioration in this lagoon area.

In the past, several strategies were implemented to minimize the problems referred to above. These strategies include several dredging works in the northern and southern channels as well as the inlet reposition in 1995, 1999, 2001 and 2003 (FORTUNATO and OLIVEIRA, 2007b). These dredging efforts were complemented by the construction of a guiding wall that was built near the northern shoreline (DHI, 1997). After this intervention, until the winter of 2008 the inlet remained close to the south margin suggesting that the structure solved one of the major concerns-the protection of the northern shoreline (FORTUNATO and OLIVEIRA,

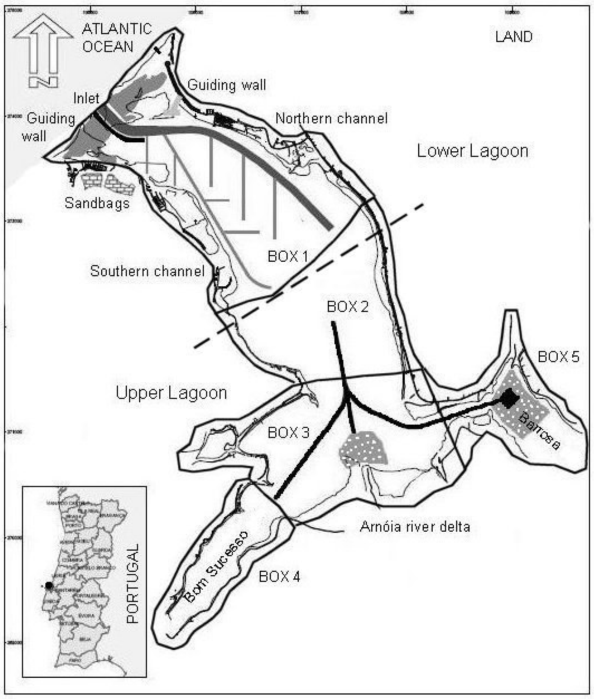

Figure 1. Geographical location and place names of the Óbidos Lagoon. The lagoon is divided into 5 boxes for the residence time analysis. Bathymetric configurations proposed within the lagoon are also marked (solution 1- guideline wall, main channels, 7 transverse channels and a main channel in the central body with connection to Bom Sucesso and Barrosa branch, solution 2- the same strategy referred previously plus dredging the Barrosa branch and Arnóia river delta).

2004). However, the southward migration of the inlet to started top pose new security problems in the south shoreline, and, to prevent the excessive erosion in this area, a temporary solution based on the disposal of sandbags in the beginning of the winter, was adopted in recent years (Figure 1, location of the sandbags). This, was however a remediation solution requiring sometimes recharging during the winter period because the sandbags are often removed by waves and current actions, and falls into the channel.

In order to achieve more effective and permanent solutions different studies were conducted by Laboratório Nacional de Engenharia Civil-LNEC (LNEC, 2002). As a result of these studies, were proposed two type of interventions (Figure 1): the construction of a new guideline wall to keep the inlet in a central position and the execution of a number of dredging operations in the northern and southern channels (solution 1) to increase the tidal prism and to achieve better self maintenance conditions. The second intervention (solution 2) proposed as a part of this project, include the same interventions for the solution 1 plus dredging Barrosa branch and Arnóia river delta.

The study described herein aims to evaluate the effect of the bathymetric changes on the hydrodynamic and RT in Óbidos Lagoon, in face of the proposed dredging works. This evaluation was based in the execution of numerical simulations using MOHID modelling system. A total of three scenarios including the reference situation and two project solutions were evaluated. For all of these scenarios tidal propagation and current fields were analysed with the support of the hydromorphological model. The wave-current interaction was computed coupling STWAVE (Steady-State Spectral Wave-STWAVE) model to MOHID. The RT was evaluated using a lagrangian transport approach, coupled with the circulation model.

The paper structure is as follows: Section 2 describes the model physics and configuration for the Óbidos Lagoon; and in the following sections the results and conclusions are presented.

METHODS

Morphodynamic modeling system (MOHID)

The MOHID modeling system is a fully non-linear, three-dimensional, baroclinic water model developed in the Technical University of Lisbon (IST). MOHID is under continuous development; the home page can be found at http://www.mohid.com. Some of the key features of the model are highlighted below and a complete description of the model can be found in MARTINS *et. al* (2001).

The implemented modeling system (Figure 2) is able to simulate the non-cohesive sediment-dynamics in lagoon driven by tide, waves and rivers flows. It integrates MOHID hydrodynamic (AIRES *et al.*, 2005; NEVES *et al.*, 2000), sand transport modules (SILVA *et al.*, 2004) and STWAVE model (SMITH *et al.*, 2001).

The MOHID hydrodynamic model solves the equations of motion with a finite volume technique for volume conservation. Wave radiation stresses were computed with STWAVE model based upon the linear wave theory for shallow water-waves (Smith *et al.*, 2001). The sediment fluxes due to waves and currents were computed with the Van Rijin (1989) formula. Bottom is updated with a predictor corrector in time using a mobile bed approach.

MOHID lagrangian transport module (BRAUNSCHWEIG *et. al*, 2003; SARAIVA *et al.*, 2007) was coupled to circulation model and used to evaluate RT in different areas of the lagoon, assuming the residence time as the time required to water or tracers leave the lagoon. For calculus, lagoon was divided into five boxes (Figure 1), filled with lagrangian tracers having the volume, spatial coordinates, and the number of the box, where they were released as associated properties. Boxes were divided based on previous knowledge of physical and biologic characteristics of the lagoon. Box 1 represents all inlet part until the central body, box 2 represents the central body, and box 3 represents the delta of Arnóia river. The branches are covered by box 4 (Bom Sucesso) and box 5 (Barrosa).

Model configuration for the Óbidos Lagoon

The configuration applied in the Óbidos coastal lagoon included two levels of nested models with one-way coupling (Figure 3).

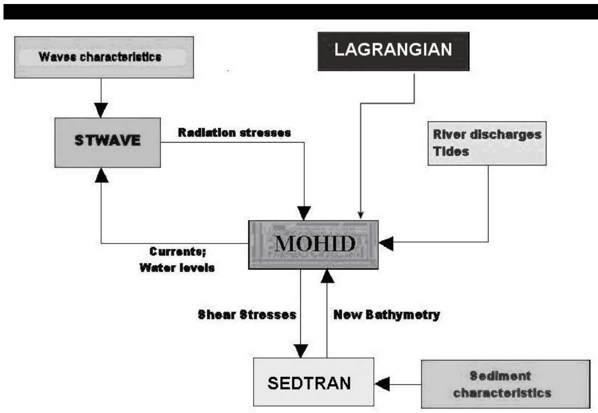

Figure 2. MOHID morphodynamic modeling system.

This nesting methodology is described in detail in Leitão *et al*., (2005).

The first level covers the Nazaré-Peniche coast (between 39.1ºN and 39.8ºN) with a grid spacing less than 100 m nearshore and about 200 m offshore. The model is forced through prescribed surface elevations from FES95.2 global tidal solution (Le Provost *et al*., 1998) at the open boundaries (see Fig. 3a). The model is 2D and is initialized with null-free surface gradients and zero velocities in all grid points. This level was used only to prescribe the open sea boundary conditions for the second level. For that reason a 2D model was implemented.

The second level includes the Óbidos Lagoon and the transition zone between coastal waters with a constant grid spacing of about 25 m. The solution of tide in level one was downscaled to this level. The open boundary was also forced with the coastal waves. Boundary wave conditions used Hs, Tp and average direction derived from typical values measured at west Portuguese coast (MALHADAS *et al*., *in press*). The theoretical JONWASP spectrum was applied at the model boundary.

Freshwater fluxes from river runoff were specified at three locations at the Óbidos Lagoon model (Figure 3b) for each of the three small rivers: Arnóia (3 m^3s^{-1}), Cal (0.14 m^3s^{-1}), and Vala do Ameal (0.08 m^3s^{-1}) (VÃO, 1991). A 2D depth integrated model was used because it was assumed that study area presents a homogeneous water column due to shallowness depths and minor freshwater inputs. A more detailed description and model validation of the 2D Óbidos Lagoon model can be found in MALHADAS *et al.* (*in press*).

The hydrodynamic and residence time simulations covered a period of 1 month. For sediment fluxes long periods were required and for that reason simulations have been performed for 5 years.

RESULTS AND DISCUSSION

Sea level and tidal prism

Figure 4 compares sea level model predictions in the reference situation and dredging scenarios for spring tide (Figure 4a) and for neap tide (Figure 4b) conditions, at a station measurement in the middle of the northern channel.

In general it can be concluded that substantial differences will be observed after dredging operations (dashed and light gray curve) in terms of amplitude and duration of the tide compared with the reference situation (black curve). Similar results were obtained for solution 1 and 2 because the dredging operations proposed for the upper lagoon are the same in both project solutions.

As we can see from the results, the reference scenario reveal a flood dominated lagoon-stronger currents during the flood phase with the duration of the ebb phase (~7h) longer than that of the flood phase (~5h). After dredging operations lagoon tidal asymmetry will be significantly reduced; the ebb phase lasts similar than the flood phase (~6h). In terms of the tide amplitude the differences it are more visible for spring tide and ebb conditions.

The feasibility of maximizing ebb dominance is achieved through transverse channels (optimal depth and orientantion-45º between main and secondary channels); they are the relevant part of the overall solution. This indicates that transverse channels improve the ability of the velocity flow during the ebb.

Tidal prism results are shown in Fig. 5 during a spring-neap tide for reference scenario and project solutions. Model predictions suggest an increasing in tidal prism by about 20% to 35% (depending on the tide) after dredging. This is evident from the fact that tidal amplitude will be increasing as referred to above.

Currents

Comparison between currents in the reference scenario (black arrows) and artificial changes (grey arrows) for flood and ebb times is depicted in Figure 6. The timing chosen to analyze the currents patterns reflects the case of the instant that corresponds to maximum current. Here, only the results of one solution in the lower lagoon are presented, because the artificial changes proposed, are the same in both solutions. The upper lagoon is not represented because there are no significant differences between phases (ebb and flood) and scenarios.

Results reveal that one of the major differences observed in the circulation patterns is at the lagoon entrance, due to the reposition of the inlet to the central position. Other differences are introduced

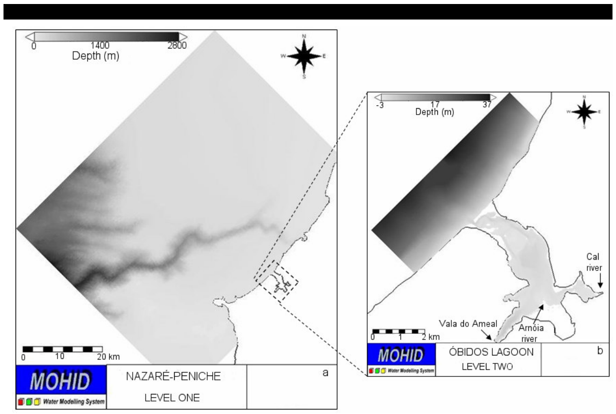

Figure 3. Domain bathymetry for the two implemented nested models: (a) Nazaré-Peniche coast and (b) Óbidos Lagoon. The freshwater fluxes are marked in the Óbidos Lagoon domain.

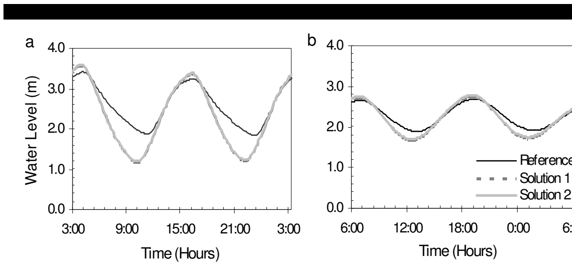

Figure 4. Lagoon sea level predicted by the model for the reference scenario (black curve), solution 1 (dashed gray curve) and solution 2 (light gray curve).Spring tide (a) and neap tide (b).

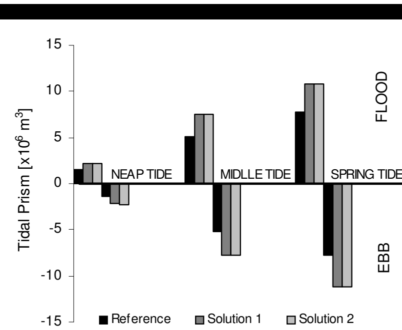

Figure 5. Tidal prism model predictions during a spring-neap tide cycle for the reference scenario (black bar), solution 1 (grey bar) and solution 2 (light grey bar).

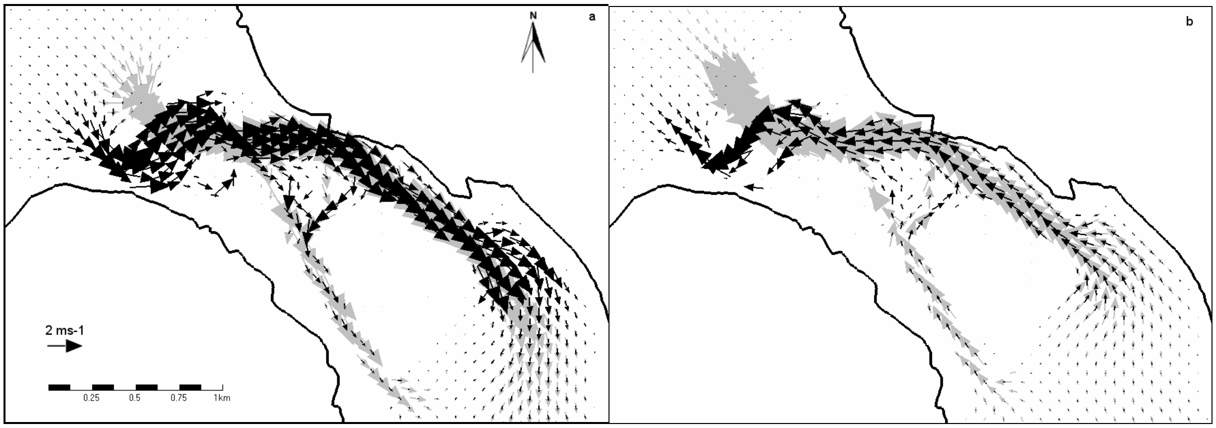

Figure 6. Spatial pattern of currents in the lower lagoon for flood (a) and ebb (b) times. Comparison between reference scenario (black arrows) and artificial changes (grey arrows).

by the dredging operations and are most significantly visible for ebb times. After dredging the channels it appears a circulation along the south channel for ebb and flood, whereas in the reference scenario only occurs for flood. This result is explained due to the effect of the transverse channels, which improves the tidal propagation in the entire lagoon. For that reason, after dredging, the water flows easily. The effect of the transverse channels will be more visible on maximum sea level, which is in the end of the ebb and in the beginning of the flood. In terms of magnitude it will be observed strongest currents for ebb and flood, diminishing the flood dominance, as required.

Deposition zones

Accretion zones predicted by the model for the reference scenario are presented in Figure 7a and for the project solutions in Figure 7b. Results presented here are evaluated only qualitatively because sand model was not validated since we don't have available data. In the first case (reference) accretion occurs mainly in northern channel and at the end of it. This result is a consequence from residual circulation which induces a residual transport within lagoon. After dredgings the accreation along the main channel, will be reduced in line with the reduction of the flood currents. According to the models predictions these interventions contribute to minimize the problems of the sand accreation although they do not represent a definitive solution. Predictions suggest that accretion is not stopped and it still occurs in the lagoon.

Residence time

RT results for reference scenario, solution 1 and solution 2 are presented in Table 1. The residence time was calculated for the areas presented in Figure 1. In the reference scenario, residence time varies between values less than 2 days close to the inlet and about 24 days in the Bom Sucesso branch.

A quick renewal occurs in the lower lagoon, because velocities are strong (~ 2 ms^{-1}); particles are "flushed out" in every tidal cycle. The upper lagoon is characterized by larger RT, because velocities are weaker-less than 0.4 ms^{-1}. As a consequence water remains several days over this region.

For project solution 1, a reduction by about 50% in RT will be expected in Box 1 and Box 2 when compared with reference scenario. This occurs due to tidal prism increasing. In the lower lagoon, modest reductions could be expected, with a broad interval between 8% (Box 4) and ~30% (Box 3).

In the project solution 2 larger differences will be expected in Box 5 relative to the reference scenario and solution 1. In this case model predictions suggest an increasing in residence time by about ~40% for Box 5 (Barrosa branch). This kind of response is due to the fact that the export of the water through the channel or

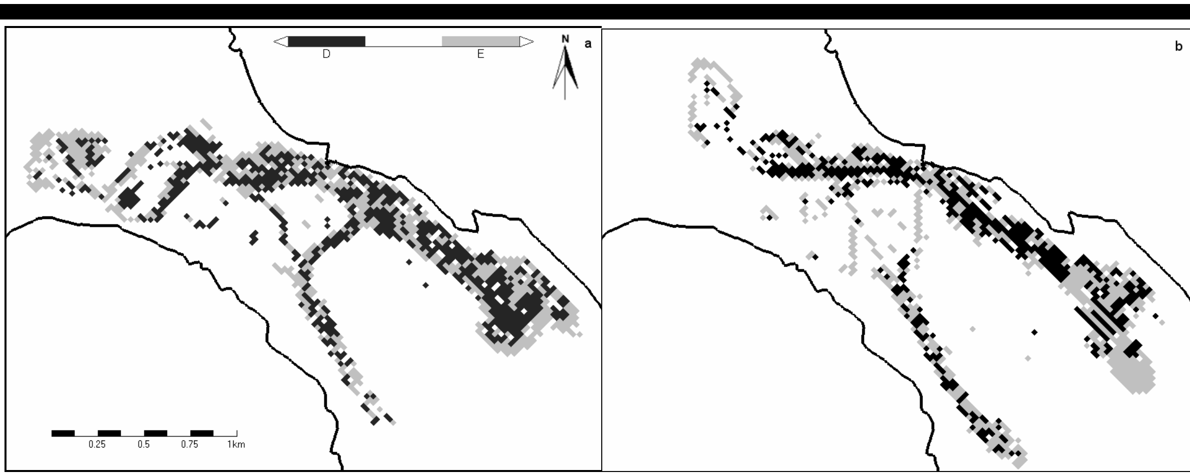

Figure 7. Accretion zones predicted by the model in the lower lagoon for the reference scenario (a) and artificial changes (b). The grey color meant accretion.

Table 1: Residence time (in days) for all scenarios (reference, solution 1 and solution 2).

BOX	Reference	Solution 1	Solution 2
Box 1	2	1	1
Box 2	4	2	4
Box 3	6	4	4
Box 4	24	22	22
Box 5	5	5	8

lagoon branch depends on the relation between capacity of the cross-sectional channel area and the volume of the bay created after dredging. This could be an unfavorable result because Barrosa branch is the most sensible area of the lagoon, since it was exposed throughout the decades, to principle sewage discharge of the Caldas da Rainha urban area. Hence, the area presents peculiar conditions, with high nutrients concentration in reduced forms (ammonia and phosphate) and predominance of macroalgae, *Ulva sp.* (Santos *et al.*, 2006).

CONCLUSIONS

Strategies to avoid the lagoon´s accrettion and to prevent the safety of local houses at the lagoon margins were presented and compared providing MOHID model predicitons. Two project solutions were evaluated: Solution 1 includes a guideline wall to limit the inlet migration, dredging of the main channels and 7 transverse channels in the lower lagoon, and a main channel in the central body with connection to Bom Sucesso and Barrosa branches; Solution 2 adds to the solution 1 the dredging of the Barrosa branch and Arnóia river delta. Numerical model results for solution 1 and solution 2 compared with the reference scenario, suggest the following remarks:

- Proposed dredging strategies minimizes flood dominance and maximize ebb dominance as required.
- Proposed guideline wall prevent inlet movements to the south and contributes for the safety of the local houses.
- In Bom Sucesso branch it will be expected an increasing in the RT by about 40% compared with the reference scenario. This could be an unfavorable result for this particularly area, due to its biologic activity.

LITERATURE CITED

AIRES, J.P., NOGUEIRA, J., MARTINS, H., 2005. Survival of sardine larvae off the Atlantic Portuguese coast: a preliminary numerical study. *Journal of Marine Science* 62, 634-644.

BRAUNSCHWEIG, F., MARTINS, F., CHAMBEL, P., NEVES, R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus estuary case. *Ocean Dynamics*, 53, 137-145.

DANISH HIDRAULIC INSTITUTE, DHI, 1997. *Hydraulic and Sedimentologic Studies design of a Dike/Channel System*, Relatório realizado no âmbito do Projecto para a Fixação da Aberta da Lagoa de Óbidos, INAG, pp.112.

FORTUNATO, A.B. and OLIVEIRA A., 2007a. Improving the stability of a morphodynamic modeling system. *Journal of Coastal Research*, 50 pp. 486-490.

FORTUNATO, A.B. and OLIVEIRA A., 2007b. Case Study: Promoting the Stability of the Óbidos Lagoon Inlet. *Journal of Hydraulic Engineering*, 133 (7), pp. 816-827.

FORTUNATO, A.B. and OLIVEIRA A., 2004. A modeling system for tidally driven long-term morphodynamics. *Journal of Hydraulic Reasearch*, 42 (4), pp. 426-434.

LEITÃO, P., COELHO; H., SANTOS, A., NEVES, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*,10 (4), pp. 1-42.

Le PROVOST, C., LYARD, F., MOLINES, J. M., GENCO, M. L., RABILLOUD, F., 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set. *Journal of Geophysical Research-Oceans,* 103, pp. 5513-5529.

LABORATÓRIO NACIONAL de ENGENHARIA CIVIL, LNEC, 2002. *Análise da Implementação do Plano de Gestão Ambiental da Lagoa de Óbidos: Simulação de Alternativas de Gestão,* Relatório, LNEC.

MALHADAS, S.M., LEITÃO, P.C., SILVA, A., NEVES, R. Effect of coastal waves over the sea level in Óbidos Lagoon. *Continental Shelf Research (accepted).*

MALHADAS, S.M., 2008. *Modelação do impacte de emissários submarinos em zonas costeiras-caso da Foz do Arelho*. Msc. Thesis for the Msc. degree in environmental engineering. Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisboa, Portugal, 95 p.), published (in Portuguese).

MARTINS, F., LEITÃO, P.C., SILVA, A., NEVES, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta*, 24 (1), pp. 551-562.

NEVES, R.J.J, LEITÃO, P.C, BRAUNSCHWEIG, F., MARTINS F., COELHO, H., SANTOS, A. and MIRANDA, R., 2000. The advantage of a generic coordinate approach for ocean modeling. *In Proceedings of Hydrosoft 2000 Conference*, Lisbon.

SANTOS, M., NEVES, R., LEITÃO, P.C., PEREIRA, P., PABLO, H., FERNANDES, L. D., CARVALHO, S., ALVES, C., 2006. Qualidade da água da lagoa de Óbidos: Que futuro? *In Proceedings of 12º Encontro nacional de Saneamento Básico*, 24-27 Outubro, Cascais. ISBN:978-972-95302-8-9.

SARAIVA, S., PINA, P., MARTINS, F., SANTOS, M., NEVES, R., 2007. Modelling the influence of nutrient loads on Portuguese estuaries. *Hydrobiologia* 587, 5–18.

SILVA, A.J.R., LEITÃO, J.C. and ABECASIS C., 2004, Improving the navigability and safety conditions in Douro estuary inlet, *In Proceedings of ICCE 2004, ASCE*, Ed. by Billy Edge, pp. 3277-3289.

SMITH, J. M., SHERLOCK, A.R., and RESIO, D.T., 2001. STWAVE: Steady-state wave model user's manual for STWAVE, V3.0. ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS: http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/downld/erdc-chl-sr-01-11.pdf).

VAN RIJN, L.C, 1989. *Sediment Transport by Currents and Waves Handbook*. Delft Hydraulics, Report H 461 p.

VÃO–Arquitectos Associados, 1991. *Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia*. Vols. I, II and V (in Portugese).

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