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# Impact of seasonal bathymetric changes and inlet morphology on the 3D water renewal and residence times of a small coastal stream

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**ABSTRACT**

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The sustainable management of small, intermittent coastal systems is a challenging task due to the strong morphological dynamics of their inlets, which causes hydrodynamics, morphodynamics and water renewal to be highly variable, at both seasonal and shorter time scales. This strong variability makes these coastal systems very sensitive to pollution events because the consequences of these events may differ significantly depending on the bathymetry at the time they occur. Here, a 3D modeling-based study of the water renewal variability of a small coastal system, the Aljezur stream, is presented, targeting 1) the impact of different measured bathymetric conditions, different seasonal forcings and processes included in its water renovation, and 2) the confirmation of the small role of light in the decay of fecal coliforms on the stream. The analysis is conducted for 4 distinct scenarios, including two real settings, using a 3D baroclinic model and an associated particle model. Results confirm the major role of bathymetry on the residence times of the Aljezur stream, leading to 100% differences. Wind is shown to have a significant impact on the water renovation, as well as the instant of particle release within the tidal cycle. A low permanence of particles in the upper layer of the water column, defined through laboratory experiments using the stream water, confirmed the small importance of light in promoting fecal bacteria decay in this stream.

**ADDITIONAL INDEX WORDS:** *Aljezur stream, Baroclinic model, Fecal contamination*

## INTRODUCTION

The downstream areas of coastal streams contain small estuaries and lagoons of complex behavior, due to the strong morphological dynamics of their inlets. This morphological dynamics often leads to the inlet closure, as a result of the action of waves, wind, tides and intermittent river flows. Hydrodynamics, morphodynamics and water renewal are thus highly variable, at both seasonal and shorter time scales, which hampers the monitoring, the forecasting and, ultimately, the management of these systems. This strong dynamics makes the intermittent coastal streams very sensitive to contamination/pollution, as contaminated discharges may have very different consequences depending on the specific capacity of water renewal of the system at that time (Oliveira et al., 2007).

The research project MADyCOS aims at improving the current understanding of the hydrodynamics, morphodynamics and potential for fecal contamination of intermittent coastal streams, through an interdisciplinary study that integrates field data acquisition, laboratory research and high-resolution numerical modeling. In the present paper, we aim at improving the current understanding of the impact of seasonal inlet morphology and bathymetric changes on the pollutant permanence on these small coastal systems, based on the application of a 3D baroclinic hydrodynamic model, calibrated and validated (Rodrigues et al., 2011), to force particle simulations.

The small dimensions of the Aljezur coastal stream make it an ideal testbed for this study. It is located on the Southwest coast of Portugal, drains a 182.9 $km^2$ basin (Gama-Pereira, 2005) and is connected to the ocean through a very dynamic inlet located on the southern end of Amoreira beach (Figure 1a). This system is located in an environmentally protected area and has several recreational and bathing spots, being simultaneously affected by several contamination sources (wastewater plant disposal, marginal pasture use and aquaculture disposal). Maintaining the high standards of water quality, for both ecological and recreational purposes, has been a growing concern for the management authorities, as any increase in anthropogenic pressure may increase the pollution loads, with potentially damaging consequences for the ecosystem and the quality of bathing waters at the two official beaches. Evaluating the impact of this anthropogenic pressure requires the detailed knowledge of the inlet's morphological evolution, which depends on the relative strength of each forcing, and of the evolution of the fecal contamination plumes for variable environmental conditions.

The behavior of this lagoon-estuarine environment is highly seasonal, since its circulation is driven by river flows, waves and wind, besides tides. A preliminary analysis, using a 2D depth-averaged model forced by tides and waves, showed that wave-induced currents sweep away materials coming out of the estuary, while wave-induced set-up has a profound effect on tidal propagation, water levels and velocities in the estuary, promoting the upstream transport of pollutants (Oliveira et al., 2010). The impact of these processes is expected to be stronger on small,

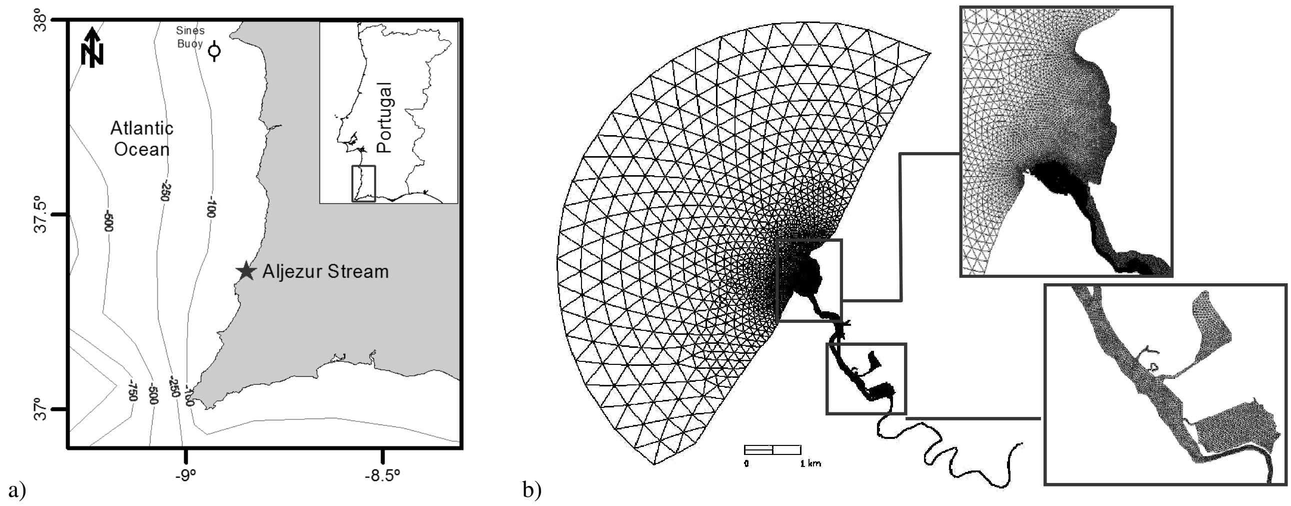


Figure 1. a) Aljezur coastal stream location; b) computational horizontal grid, with 40000 nodes.

shallow systems, relative to large estuaries, as the importance of the wave set-up on the total depth can be significant due to the small depths of their inlets, leading to a major effect of waves on tidal propagation and distortion.

Guerreiro (2010) studied the impact of floods on the inlet and beach configuration and their corresponding recovery time, using a 2D morphodynamic model. Results show that even relatively small floods can enlarge the inlet severely and potentially flush contaminants from the system. However, the impact of seasonal forcings (wind, river flow) and correspondent bathymetric settings on water renewal is yet to be determined.

A 3D baroclinic circulation analysis, including forcing by wind, showed that salinity and temperature in the stream are very sensitive to the river flow and wind forcing (Rodrigues et al., 2011). This analysis showed that a larger propagation of summer spring tides relative to neap tides might have a positive effect in the water renewal upstream and, consequently, in the water quality of these areas. This phenomenon can increase the water renewal during summer, when fecal contamination loads are higher due to population increase. The impact of density gradients and wind circulation on the water renewal and residence times remains however to be investigated.

The goal of the present analysis is to complement the work of Oliveira et al (2010) by analyzing the impact of 3D baroclinic circulation on the water renovation and residence times, forced by tides, river flow, wind and density gradients, based on the circulation analysis of Rodrigues et al. (2011). The paper is divided in 3 sections besides this Introduction. Section 2 presents the methodology and set-up of the two models. Residence time and permanence results are shown and discussed in Section 3. The paper closes with a summary of the major conclusions.

## METHODOLOGY AND MODEL SETUP

Residence time, water age and other tracer indicators have become well-established links between physical and water quality processes in well-mixed coastal systems (e.g., Oliveira et al., 2006, Monsen et al., 2002). The adaptation of these concepts for stratified and generally 3D flow fields has been based on 3D circulation models (Rueda and Cowen, 2005) but its usefulness can be further extended if particle models are forced by the circulation results. Indeed, further understanding is needed towards linking 3D physical and water quality processes.

The present analysis starts with the methodology of Oliveira and Baptista (1997) and Oliveira et al. (2006), by producing residence time analyses of water masses, released throughout the stream at the surface at four instants in the water cycle (high water, low water, mid-flood and mid-ebb).

In the second analysis, the vertical mobility of water masses is assessed and compared with the behaviors of relevant fecal organisms. In particular, the impact of light on the organisms' mortality is assessed in this system by comparing the light extinction depth for this system (17 cm, J. Menaia, personal communication) and the average depth at which particles are located.

The analyses are conducted on two contrasting bathymetric settings: May and September 2008, globally representative of the end of maritime winter and the end of maritime summer, respectively. The analyses are based on two field campaigns, which provided measurements of bathymetry of the lower estuary and ocean beach, water levels, currents, salinity and temperature, as well as other quantities, in May, 6th and September, 8th.

Dynamic forcings are highly variable. Tidal conditions are distinct: spring tide in May and neap tide in September. River flow is almost zero (0.03 $m^3.s^{-1}$) in September and small (0.15 $m^3.s^{-1}$) in May. Wind conditions vary in space and time, based on results from the GFS model at the coast and data from the Aljezur meteorological station in the upper estuary (Rodrigues et al., 2011). As wind was shown to play an important role on the circulation in most of the upper estuary (Rodrigues et al. 2011), and to analyze its impact on residence times, an additional circulation simulation was set-up, based on May 2008 conditions, but without wind. Similarly, all May 2008 settings were kept in the last run, except for bathymetry. Based on the analysis of 10 bathymetric surveys (Guerreiro, 2010), the bathymetry of March 2010 was selected as representative of the severe 2009-2010 winter conditions (Figure 2). This way, a set of 4 simulations was created in order to analyze the effect of bathymetry and inlet configuration, wind and typical seasonal conditions (Table 1).

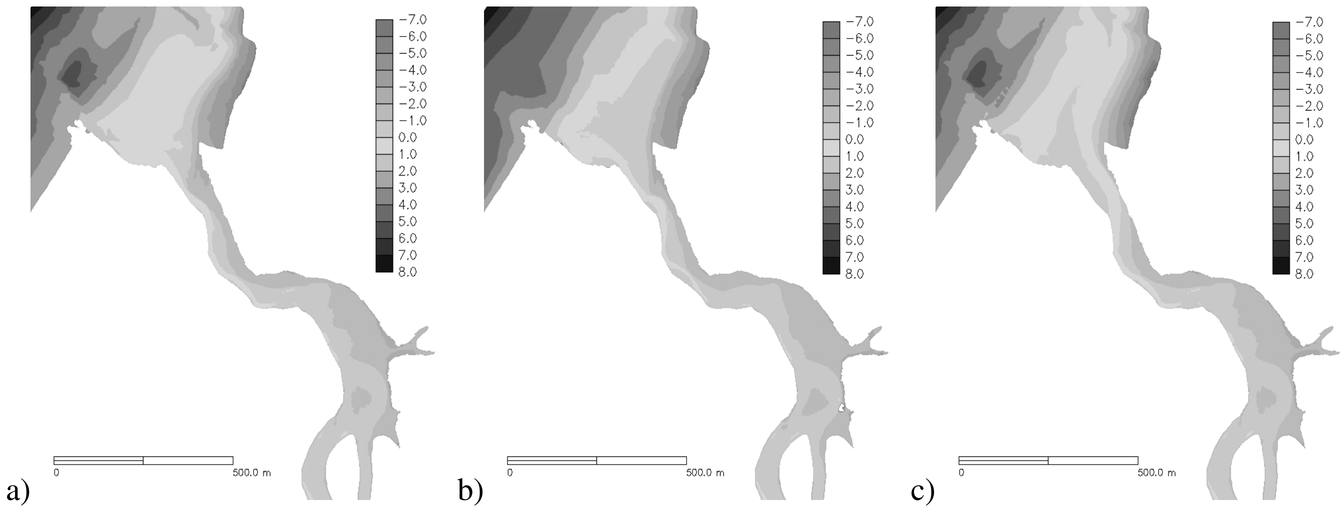


Figure 2. Bathymetry (m, MSL) in: a) May 2008, b) September 2008 and c) March 2010.

The simulations were conducted with a 3D baroclinic model (SELFE, Zhang and Baptista, 2008). River flows were forced at the upstream boundary (Table 1). The model was forced at the ocean boundary by tidal elevations from the regional model of Fortunato et al. (2002), using eleven constituents (Z0, M2, S2, N2, O1, K1, M4, MN4, MS4, MSF and K2). The waves' effect was parameterized through the Z0 constituent and was based on the results of the application of the morphodynamic model MORSYS2D to the Aljezur coastal stream (Oliveira et al, 2010; Guerreiro, 2010). Wind forcing was established based on NCEP Reanalysis Data (http://www.esrl.noaa.gov/psd/) at the coast and SNIRH database (available at http://snirh.pt) in the upper stream. The forcing conditions were used on the same computational domain, using an unstructured grid with about 40000 horizontal nodes and 11 equally-spaced vertical S levels (Figure 1b). The spatial resolution varies from 450 m in the coastal area to 2 m in the stream. Figure 3 presents the model validation results for velocities.

Table 1: Definition of simulation conditions.

| ID | Bathymetry | River Flow ($m^3.s^{-1}$) | Wind | Tidal conditions |
|---|---|---|---|---|
| A | May 2008 | 0.15 | NCEP+SNIRH | Spring, May 2008 |
| B | Sept. 2008 | 0.03 | NCEP+SNIRH | Neap, Sept. 2008 |
| C | May 2008 | 0.15 | No wind | Spring, May 2008 |
| D | March 2010 | 0.15 | NCEP+SNIRH | Spring, May 2008 |

Currents from the four 3D hydrodynamic simulations (A-D) are used to force a Lagrangian model, integrated in the SELFE suite of models and based on backward Euler tracking, to establish the preferential pathways of conservative tracers, accounting for horizontal and vertical advective processes. Particles were released at the surface at each nodal location on flood, high-tide, ebb and low-tide. Residence times were computed as the time required for each particle to exit the inlet, following the once-through residence time concept of Oliveira and Baptista, 1997.

These 3D currents were also used to study the vertical motion of fecal bacteria in the stream which determines the processes that can affect their mortality. In the Aljezur stream, local samples and laboratory simulators indicated that light-induced mortality was unimportant in the decay of e-coli and enterococcus, relative to sedimentation and physical transport. The application and validation of a fecal contamination model (Rodrigues et al., 2011) confirmed these findings, but did not provide an explanation. Here we explore the possibility that bacteria does not remain in the light-mortality effective zone (determined as the upper 17 cm of the water column) long enough to be severely affected by this mortality source.

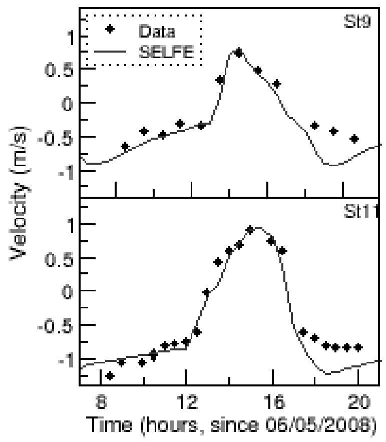


Figure 3. Velocities near the inlet in May 2008: data / model comparison.

## RESULTS

### Residence time analysis

Cumulative histograms of residence times for the four simulations reveal that variability within the tidal cycle is relevant, but bathymetric settings and seasonal conditions also play an important role on the water renewal in the system (Figure 4). Water renewal for the 10 day simulation is restricted to the lower estuary and highlights the permanence of pollutants for time scales larger than those associated to the typical decay rates. These results are consistent with local measurements of fecal coliforms in the ocean beach, which rarely present any contamination.

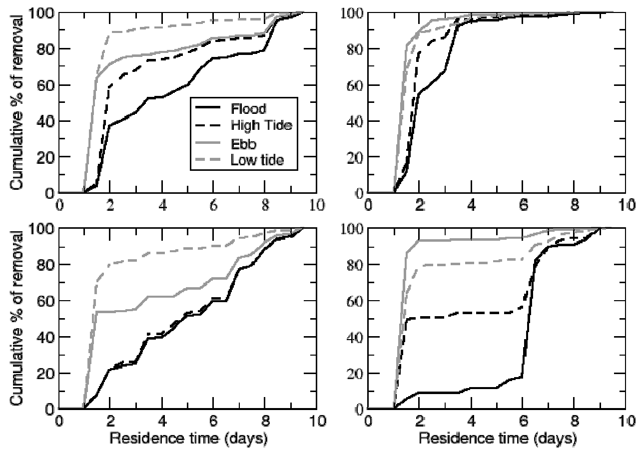


Figure 4. Cumulative histograms of residence times for the 4 release times for simulation: a) A; b) B; c) C and d) D.

Residence times were then averaged over the 4 instants in the tidal cycle and scaled for the residence times of May 2008. Results show the strong dependency of residence times on the bathymetric conditions in the lower estuary: March 2010 conditions almost double the renewal capacity of May 2008 bathymetry, when all other parameters are kept constant (Figure 5). This finding needs further support with other bathymetric settings, but current results support the need to account for bathymetric variability in water renewal in morphologically-dynamic systems.

Complementing the analysis of Rodrigues et al. (2011) and Oliveira et al. (2010), results also highlight the importance of dominant winds in water renovation, and the need to account for its impact in residence time analysis. Results indicate that neglecting wind may reduce residence times by 25% (Figure 5).

The combination of different seasonal conditions (wind, tidal amplitude and river flow) together with the impact of the bathymetric variations over a maritime summer (from May to September 2008) suggest that the balance between increased renovation due to the maritime summer conditions and wind may not overcome the joint effect of a smaller tidal amplitude and river flow.

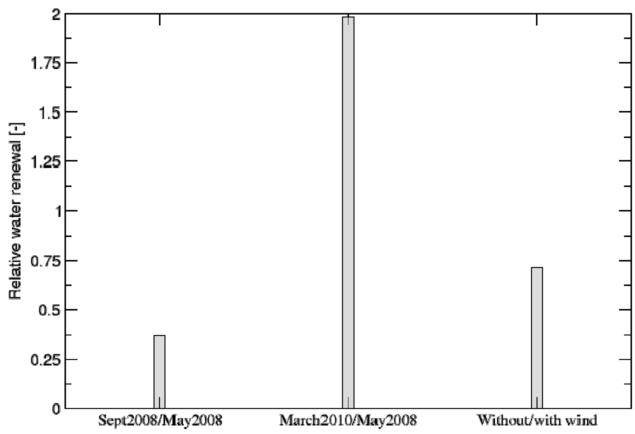


Figure 5. Tidally-averaged relative water renewal.

## Preliminary analysis of the importance of light in the mortality of fecal bacteria

The percentage of permanence in the light extinction zone for each particle was analyzed globally by examining the cumulative histograms of percentage of permanence (Figure 6). Results show that the particles are outside the light-effective zone about 50% of the time, and that particle release time has a minor impact in the vertical dynamics. Similarly, different bathymetric conditions have a small effect on permanence in the light-impacted zone, with a small increase for March 2010.

A more detailed analysis of the spatial variability of the permanence reveals that differences associated with the four scenarios simulated are local and more pronounced near the inlet (Figure 7). The salt marsh areas that border the aquaculture (mid-estuary) also present significant differences for the bathymetries tested, which are probably associated with different renovation capacities.

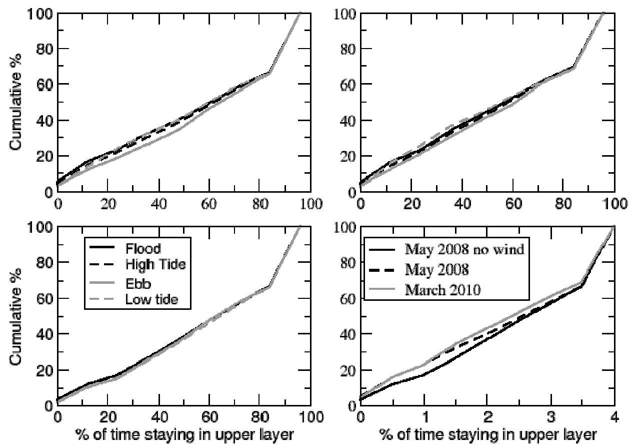


Figure 6. Variability in permanence in the light extinction decay layer: a) Simulation A, b) Simulation D, c) simulation C, d) Comparison at low tide particle release.

## CONCLUSIONS

The sustainable management of small coastal systems, which simultaneously harbor large ecological values and increasing human occupation and use, require the detailed characterization of its renewal capacity. Typically, residence times are calculated accounting only for river flows and tides.

A 3D modeling study on the circulation and water renovation of a morphologically dynamic, shallow coastal stream preliminarily identifies the strong dependency on bathymetric conditions in the lower estuary and inlet, besides other already known forcings associated with seasonal conditions (waves, river flow and wind). The study was applied to the Aljezur coastal stream, Portugal, and highlighted the need to extend traditional residence time analyses to account for bathymetric variability. The differences of water renovation can be on the order of 100%.

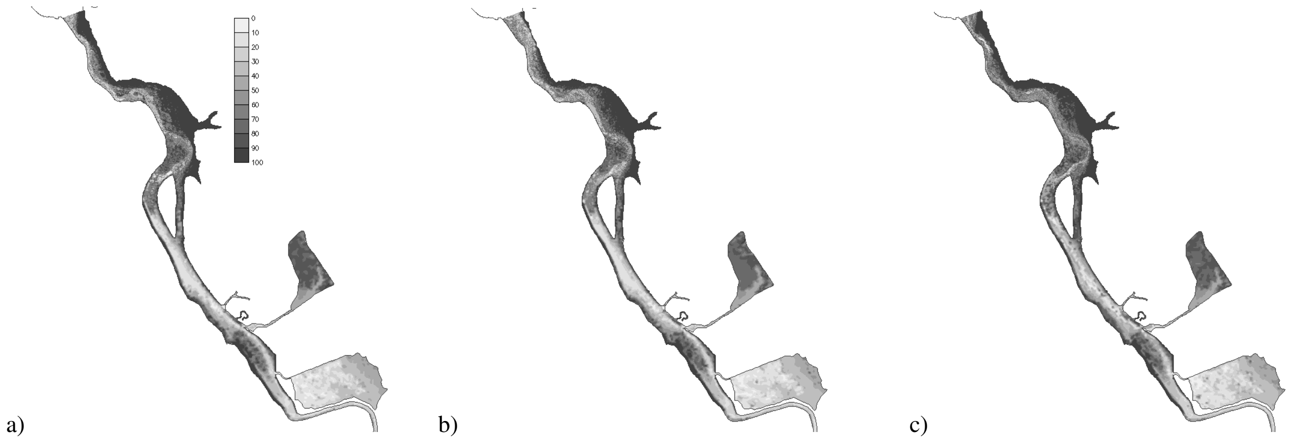


Figure 7. Percentage of time staying in light extinction layer: a) May 2008, b) March 2010 and c) May 2008, no wind.

The modeling study also supported the weak dependency of fecal coliforms decay on light, identified in a thorough laboratory study (Menaia et al., 2010). The modeling analysis showed that about 50% of the particles only stay in the light extinction depth area 50% of the time. This value is an underestimation of the real permanence of fecal bacteria as aggregation and sedimentation processes were not included in the analysis. Accounting for these processes would further decrease the potential for fecal bacteria mortality due to light.

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## LITERATURE CITED

Gama-Pereira, C (2005) Dinâmica de sistemas sedimentares do litoral ocidental português a sul do Cabo Espichel. PhD thesis, Universidade de Évora, Portugal.

Guerreiro, M. 2010. Morphodynamic modeling of the Aljezur stream. Aveiro University, M.Sc. thesis, 58p.

Menaia, J, Cravo, A., Napier, V. (2010). Evolution of enterobacterial populations along the Aljezur Costal Stream as correlated to the occurring physical-chemical characteristics of the water, Water Research Conference 2010, 113.

Monsen, N.E., Cloern, J.E., Lucas, L.V., and Monismith, S.G., 2002, A comment on the use of flushing time, residence time, and age as transport time scales: Limnology and Oceanography, 47(5), 1545-1553.

Oliveira, A. and Baptista, A.M. 1997. Diagnostic modeling of residence time in estuaries. Water Resources Research , 33/8, 1935-1946.

Oliveira, A., Fortunato, A.B., and Rego, J.R.L. 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos lagoon (Portugal). Continental Shelf Research, 26/8: 917-942.

Oliveira, A., Fortunato, A., Rodrigues, M. and Azevedo, A. 2007. Integration of physical and water quality models. Houille Blanche, 4: 40-46. DOI: 10.1051/lhb:2007045

Oliveira, A., Fortunato, A.B., Guerreiro, M., Bertin, X., Bruneau, N., Rodrigues, M., Taborda, R., Andrade, C., Silva, A. M., Antunes, C., Freire, P., Simões Pedro, L., Dodet, G., Loureiro, C., Mendes, A., 2010. Effect of inlet morphology and wave action on transport and sediment dynamics in a coastal stream. ICM11-11th Estuarine and Coastal Modeling, ASCE, Spaulding et al (eds), 601-620.

Rodrigues, M., Oliveira, A., Guerreiro, M., Fortunato, A.B. (2011). Modeling fecal contamination in the Aljezur coastal stream. Ocean Dynamics (in press).

Rueda, F.J. and E.A. Cowen, 2005. Exchange between a freshwater embayment and a large lake through a long, shallow channel, Limnology and Oceanography, 50/1, 169-183.

Zhang, Y-L, Baptista, AM (2008) SELFE: A semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation. Ocean Modeling, 21(3-4): 71-96.