A Hydroinformatic Tool for Estuarine Water Quality Management

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Abstract Nutrient enrichment is a key factor for habitat degradation due to strong stimulation of opportunistic macroalgae growth, with the consequent occurrence of algal blooms. Residence time is broadly recognised as a key parameter to assess estuarine eutrophication vulnerability and it is related to the eutrophication gradients observed in estuarine systems. In the last two decades, the southern arm of the Portuguese river Mondego estuary was stressed by an eutrophication process due to massive nutrient loading from urbanised areas, intensively agricultural land runoff and sensitive changes on estuarine hydrodynamics induced by the silting up in its upstream area. The aims of this work were the development of a hydroinformatic tool – the *MONDEST* model – coupling hydrodynamics, water quality and *TempResid* modules, and its application to calculate residence time values, at different simulated hydrodynamic scenarios and nutrients loading characteristics. The results obtained for this estuary allow us to assess the influence of freshwater inflows and nutrient discharge characteristics on residence time spatial distribution. This work shows that the *MONDEST* model constitutes a powerful tool for enhancing systems eutrophication vulnerability assessment in order to establish the best water quality management practices for the environmental sustainability of this complex ecosystem.

Keywords Estuarine sustainable management, eutrophication, hydroinformatics, *MONDEST* model, residence time.

INTRODUCTION

The hydrology and the ecology of shallow estuarine areas are strongly influenced by the freshwater inflow and the adjacent open sea, due to tide and wind generated water exchange, creating salinity gradients, thermic stratification and assuring large transport of silt, organic material and inorganic nutrients to the estuaries. Excessive organic carbon input associated with nutrient enrichment, leading to eutrophication of coastal waters and habitat degradation, is widely recognized as a major worldwide threat (Valiela et al., 1997; Pardal et al., 2004), originating sensitive structural changes in estuarine ecosystems due to strong stimulation of opportunistic macroalgae growth, with the consequent occurrence of algal blooms. As a response to this, there has been an enormous increase in restoration plans for reversing habitat degradation, based on knowledge of the processes which cause the observed ecological changes. Biota living in the intertidal zone of macrotidal estuaries and coastal lagoons is adapted to a dynamic environment dominated by the tidal flooding and ebbing (Widdows and Brinsley, 2002). Due to the immediate changes in the physical environment (e.g. decreasing tidal currents, wave action and sediment resuspension, and settling of suspended matter) these primary producers are also biostabilisers (Flindt et al., 1999).

The influence of hydrodynamics must not be neglected on estuarine eutrophication vulnerability assessment, as flushing time affects the transport and the permanence of substances inside an estuary (Vieira et al., 1998; Duarte, 2005). Residence time (RT) values can be of paramount interest to assess estuarine eutrophication vulnerability (Meeuwig, 1998), considering the effects of tides, wind and river discharges on salinity gradients and nutrients dilution. RT is a convenient parameter representing the time scale of physical transport processes, and often used for comparison with time scales of biogeochemical processes (Jay et al., 1997; Dettmann, 2001). RT values have a strong spatial and temporal variability, so the concept of a single residence time per estuary, while convenient from both ecological and engineering viewpoints, is therefore an oversimplification. A pollutant will exert most of its effects within an estuary if its biochemical time scales are comparable to, or shorter than the residence time (Hattink et al. 2001). In fact, estuaries with nutrients residence time values shorter than the algal cells doubling time will inhibit algae blooms occurrence. The increase of estuarine flushing capacity can be seen as a management measure to mitigate or to invert eutrophication processes (Duarte et al., 2002a).

The analysis of water column and benthos field data observed in the Mondego estuary (Portugal), over the last two decades, allows us to conclude that the hydrodynamics was a major factor controlling the occurrence of this macroalgae blooms, as influential on nutrients availability and uptake conditions (Martins et al., 2001). Thus, the development of a hydroinformatic tool for hydrodynamics and transport processes characterization was obviously pertinent and useful.

This work presents a 2D-H water quality model for Mondego estuary (*MONDEST model*), which was developed in order to simulate its hydrodynamic behaviour, salinity and residence times spatial distributions, at different simulated scenarios and discharge characteristics. This model, combining hydrodynamics, water quality and *TempResid* modules, was calibrated and validated using data obtained from the sampling carried out over the past two decades. Some hydrodynamic simulation results are presented to illustrate the strong asymmetry of flood and ebb duration time at the inner sections of this estuary, a key parameter for a correct tidal flow estimation, which is the major driving force in the southern arm of the estuary affecting its flushing capacity. The conclusions of this and other studies allowed us to support successful mitigation and restoration measures (Howarth, 2000), based on nutrient discharges reduction, river Pranto local discharge change and hydrodynamic circulation improvement. After the implementation of those restoration measures, no macroalgal blooms were observed in this system.

METHODS

Study area and sampling program

The Mondego river basin is located in the central region of Portugal. The drainage area is about 6670 km^2 and the annual mean rainfall is between 1000 and 1200 mm. The Mondego river estuarine system (Fig. 1.a) is about 29 km long, between river mouth and Formoselha bridge (upstream tidal river section) and was under severe environmental stress due to human activities: industries, aquaculture farms and nutrients discharge from agricultural lands of low river Mondego valley.

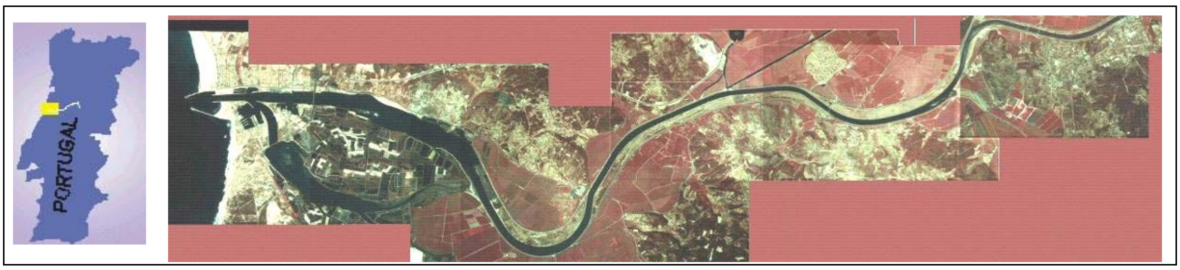

Figure 1.a Location and aerial view of river Mondego estuarine system.

The Mondego estuary zone, defined by saltwater intrusion limit, is only about 10 km long and 3 km across at its widest part and comprises a northern and a southern arm, separated by the Murraceira island, covering 6,5 km^2 (Fig. 1.b).

Figure 1.b Aerial view of Mondego estuary arms.

The Mondego estuary bathymetry shows a strong irregularity: the northern arm is deeper (10 m during high tide) and constitutes the main navigation channel of the Figueira da Foz mercantile harbour and receives the majority of freshwater input (from Mondego river), while the southern arm is shallower (2 to 4 m) and is almost silted up in the upstream area (Fig. 2). Consequently, the southern arm estuary water circulation is mainly forced by tides, wind and the usually small freshwater inflow from Pranto river, a tributary artificially controlled by sluices, that can discharge to both arms, and regulated according to the water level of rice fields in the Mondego Valley.

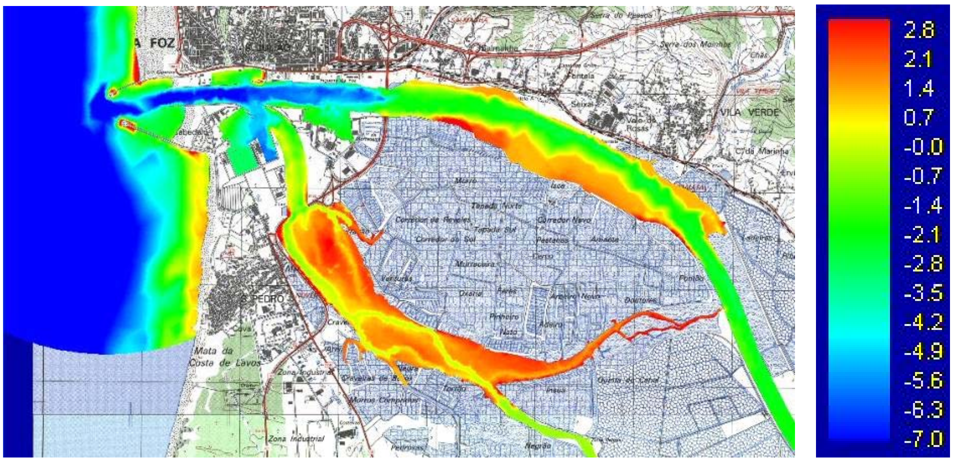

Figure 2 Bathymetry of the Mondego estuary (high tide).

The southern arm is also characterised by large areas of intertidal flats exposed during low tide, corresponding to more than 75% of the total southern arm area (2,3 km^2). These areas are a strong influence on its hydrodynamic behaviour leading to a big asymmetry on flooding and ebbing times at the inner areas (Duarte, 2005).

In this arm, eutrophication has triggered serious biological changes, which led to a progressive replacement of seagrass (*Zostera noltii*) by opportunistic macroalgae. Green macroalgal blooms have been observed in the southern arm due to: (i) the simultaneous occurrence of the water residence time increase, related to its progressive upstream silting up process (Duarte et al., 2001); (ii) the sunlight and temperature favourable conditions; (iii) and the high availability of nitrogen and phosphorus discharged by oriziculture and aquaculture activities. This situation may result on anoxic system collapse, with the development of hydrogen-sulphide conditions, lethal to rooted macrophytes such as *Zostera spp*..

So, it became crucial to obtain better information about the major mechanisms, like hydrodynamics and nutrients annual balance, which can regulate the abundance of opportunistic macroalgae and identify the most vulnerability zones to the eutrophication processes.

A sampling program was carried out during the past two decades at three benthic stations and at three other sites (river Pranto mouth, Armazéns channel mouth and Gala bridge) for water column monitoring. The choice of benthic stations was related to the observation of an eutrophication gradient in the south arm of the estuary, involving the replacement of eelgrass, Zostera noltii by opportunistic green algae such as *Enteromorpha spp*. and *Ulva spp*. (Pardal, 1998). Water level, velocity, salinity, temperature and dissolved oxygen were measured *in situ* and water samples were collected for physical and chemical system characterization and also for nutrients annual balance estimation (Fig. 3).

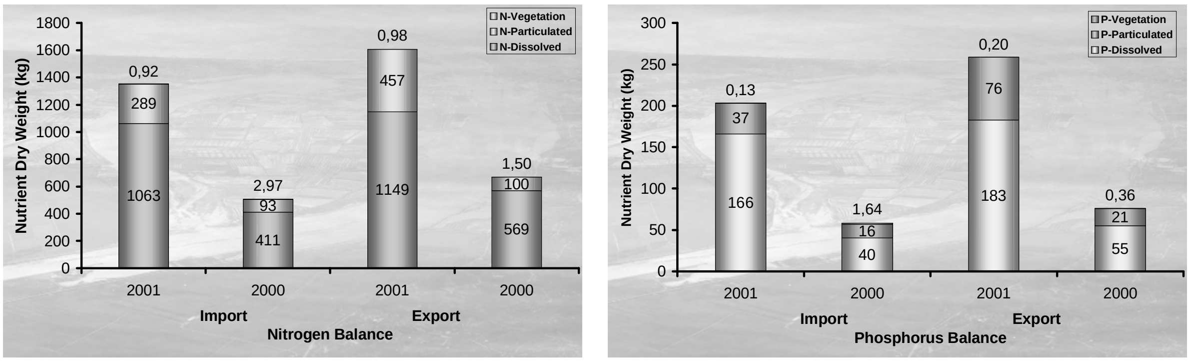

Figure 3 Annual nutrients (N, P) balance estimation (2000 and 2001) in Mondego estuary southern arm.

The dissolved matter fraction in the nutrients transport showed to be the most representative fraction of matter and is also an important factor on the eutrophication process, since it represents the nutrients kind immediately accessible to the macroalgae tissues incorporation on the growing process Analysis of the available data allowed us to conclude that the occurrence of green macroalgal blooms is strongly dependent on the flushing conditions, salinity gradients and nutrient loading characteristics (Duarte et al., 2002b).

MONDEST model

The Mondego Estuary Model (*MONDEST*) is a 2D-H water quality model based on the finite elements method (FEM), with an eulerian formulation, and was conceptualized (Fig. 4) by coupling mesh generation, hydrodynamic, constituents transport and residence time (*TempResid*) modules, based on different generic package models, like *RMA2* and *RMA4* (WES-HL, 1996) and adapted to this specific estuarine ecosystem. Pre and post-processing work was carried out using several informatics tools, namely *SMS* (BOSS SMS, 1996).

The hydrodynamic module provides flow velocities and water levels for the water transport module, which acts as an input to the *TempResid* module, feeding constituents (tracer, nutrients) concentration over the modelled aquatic system and allowing estuarine dispersive behaviour characterization. *TempResid* module was integrally developed in this work as a new approach for RT values calculation for each constituent over all the system and allows us to map RT spatial distribution at different simulated management scenarios (Duarte, 2005). The permanence of a constituent into any elementary volume of the modelled domain can be calculated as the time range which its concentration remains above the concerning reference conditions (blank or residual concentration).

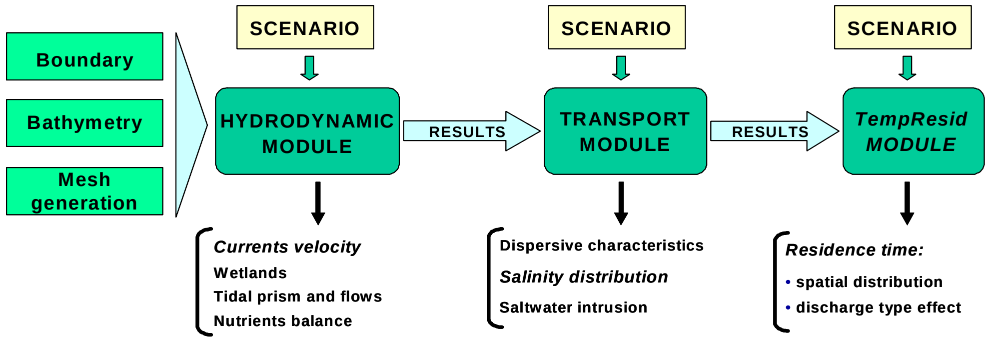

Figure 4 The *MONDEST* model conceptualization.

The velocities and water levels field data, obtained from a comprehensive sampling program at three different stations, were used to calibrate, validate and define the boundary conditions of *MONDEST* hydrodynamic module for different tidal regimes, freshwater inflows and sampling stations. Figure 5 shows calibration and validation procedures for surface water level at Gala station (S1) and Armazéns creek station (S2) and different tidal regime (spring and neap tides).

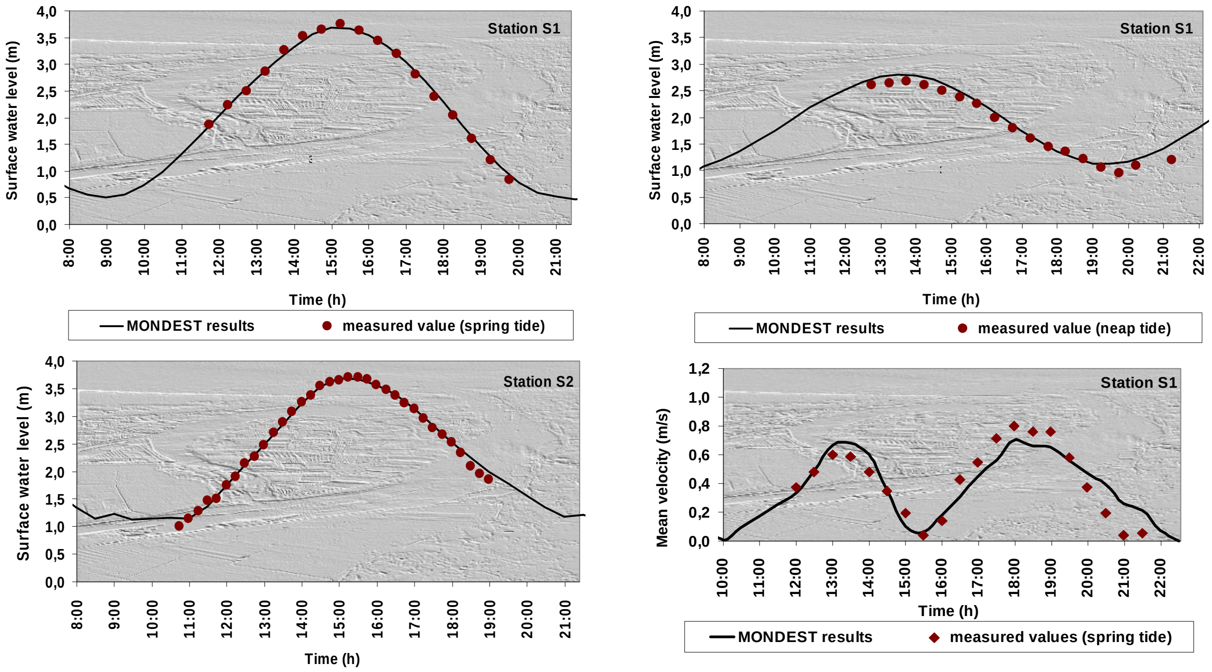

Figure 5 Hydrodynamic module calibration and validation (surface water level).

The transport module calibration and validation was performed with the salinity field data, from different sampling stations, in order to estimate the horizontal dispersion coefficients (Fig. 6).

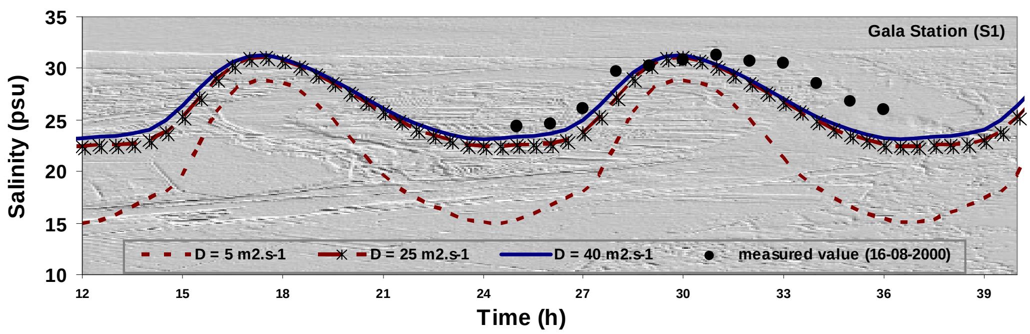

Figure 6 Transport module calibration (Gala station).

A sensitivity analysis was also carried out to assess the influence of these parameters on results variability and quality. The recommended method for *MONDEST* model application successful to estuarine water quality management is based on a wide, but judicious, range of simulation scenarios, considering representative tidal, wind and freshwater inflow regimes, as well as pollutant decay rates and discharging characteristics (location, load, time release, tidal cycle). Table 1 presents some simulated scenarios adopted for hydrodynamic influence assessment on estuarine eutrophication processes based on RT computing and sensitivity analysis (Duarte, 2005).

Table 1 Simulation scenarios for Mondego estuary eutrophication process management

SCENARIO	FRESHWATER FLOW ($m^3.s^{-1}$)		TIDE	LOAD	SUBSTANCE
	Mondego	Pranto			
RT 1			medium		
RT 2			spring		conservative
RT 3		0	neap		
RT 4	15				non-conservative (k= 1 d^{-1})
RT 5				point	non-conservative (k=10 d^{-1})
RT 6		15			
RT 7	15				
RT 8	75				conservative
RT 9	340		medium		
RT 10	15	0			
RT 11					non-conservative (k= 1 d^{-1})
RT12				diffuse	conservative
RT 13	75				non-conservative (k= 1 d^{-1})
RT 14					non-conservative (k=0,5 d^{-1})

RESULTS AND DISCUSSION

Hydrodynamic results allowed the evaluation of the magnitude of currents velocity in both arms during ebbing and flooding situations, and to assess the influence of tidal and freshwater inflows regimes (Fig. 7). The higher velocity values in the southern arm occur near Gala Bridge, reaching 0.35 to 0.70 $m.s^{-1}$ (depending on tidal regime), while in the northern arm these values are lower, reaching 0.33 to 0.60 $m.s^{-1}$, at about 1km upstream the Figueira da Foz Bridge.

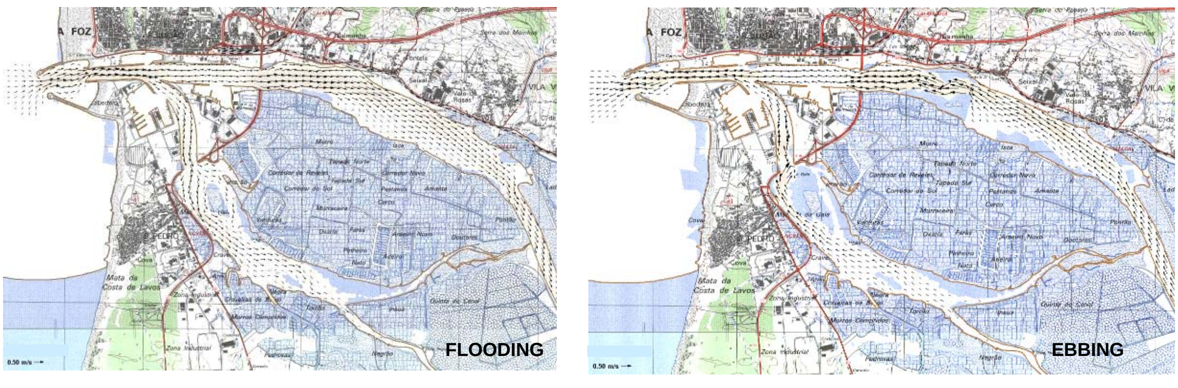

Figure 7 Maximum current velocities in the Mondego estuary (spring tide)

Hydrodynamic modelling has shown the occurrence of a delay between the flooding beginning in these two arms of Mondego estuary. Moreover, in the southern arm, the flooding time, which decreases at the inner zones, is much smaller than the ebbing time due to shallow waters and to large intertidal mudflats areas. This asymmetry is influenced by tidal regime and has a fast increase into the inner areas of this arm reaching 2.5 hours: 5 hours for flooding and 7.5 hours for ebbing time (Fig. 8).

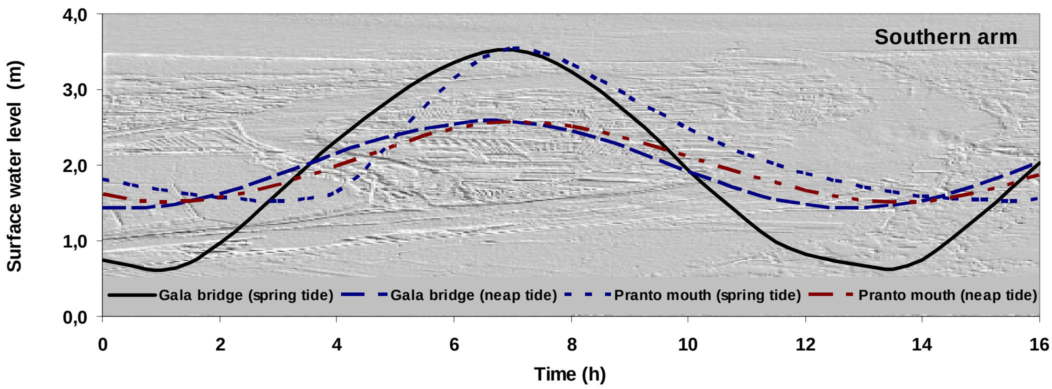

Figure 8 Effect of tidal regime on flooding and ebbing duration asymmetry

The river Pranto inflow in estuary southern arm had shown a strong influence on salinity distribution decreasing drastically its values to a range far from the most favourable for macroalgal growth, about 17 to 22 *psu*. Figure 9 allows the comparison of the opening sluices effect on southern arm salinity gradients caused by river Pranto flow discharge of 30 $m^3.s^{-1}$.

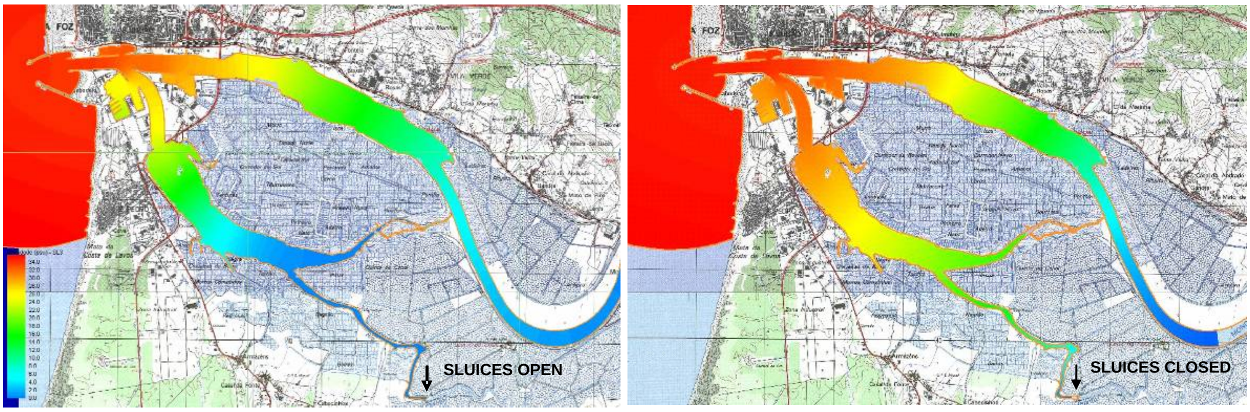

Figure 9 Effect of river Pranto flow discharge on Mondego estuary salinity distribution (high tide)

The same effect was analysed for RT values spatial distribution applying *TempResid* computing availability. The RT values near Pranto mouth station (S3) can quintuplicate when Alvo sluices are closed (Fig. 10).

Figure 10 Effect of river Pranto flow discharge on RT values distribution (dry-weather conditions)

When sluices are closed salinity and RT distributions are strongly related to eutrophication gradients observed in this system over the last twenty years, validating the applied methodology for estuarine water quality assessment.

CONCLUSIONS

Results obtained from hydrodynamic modelling have shown a strongly asymmetry of ebbing and flooding times at inner estuary south arm areas due to its complex geomorphological patterns (wetlands and salt marshes). This information allows a more accurate tidal flow calculation which is the major driving force of the southern arm flushing capacity, when Alvo sluices rest closed. Add to that, River Pranto inflow absence (a typical summer situation) increases RT values drastically in the inner estuary southern arm and, consequently, the nutrients availability for algae uptake is higher, enhancing estuarine eutrophication vulnerability.

Water quality modelling results confirm the eutrophication gradient measured in the Mondego estuary southern arm, validating the methodology applied. For non-conservative substances, like nutrients, residence time highest values are obtained, precisely, at the most eutrophied area observed in this estuarine system.

The *MONDEST* model developed and applied in this work allows us to evaluate and rank potential mitigation measures, like nutrient discharges reduction levels, dredging works for hydrodynamic circulation improvement. So, the proposed methodology, integrating hydrodynamics and water quality, constitutes a powerful hydroinformatic tool for enhancing estuarine eutrophication vulnerability assessment and providing judicious information for decision support, in order to select the most appropriate water quality management practices and to contribute for a truly sustainable ecosystems management.

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