Estuarine hydrodynamic as a key-parameter to control eutrophication processes

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Abstract: - Estuaries and coastal lagoons are commonly subjected to intensive anthropogenic stress due to massive pollutant loading from urbanised riparian areas. Nutrient enrichment is a key-factor for habitat degradation, leading to sensible structural changes in estuarine ecosystems with the consequent occurrence of eutrophication processes. The influence of hydrodynamics must not be neglected on estuarine eutrophication vulnerability assessment. In fact, flushing time affects the transport and the permanence of water and its constituents inside an estuary, so the increase of estuarine flushing capacity can be seen as a management measure to mitigate or to invert eutrophication processes, like the one observed in the Mondego River estuary (Portugal), during the last two decades.

In this work, an integrated 2-DH water quality model was applied to calculate water residence time values, at different simulated management scenarios of the Mondego estuary. The results of the performed simulations 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, as the major driving force of the southern arm flushing capacity, as well as a spatial and temporal variability of calculated RT values.

The conclusions of this work confirm the crucial influence of hydrodynamics on estuarine water quality status and the usefulness of this hydroinformatic tool as contribution to support the design of a sustainable management plan, based on nutrient loads reduction and hydrodynamic circulation improvement. So, the proposed methodology, integrating hydrodynamics and water quality, constitutes a powerful hydroinformatic tool for enhancing estuarine eutrophication vulnerability assessment, in order to contribute for better water quality management practices and to achieve a true sustainable development.

Key-Words: - water sustainable management; estuarial modelling; eutrophication; hydroinformatics; residence time; Mondego estuary.

1 Introduction

Surface waters, as important components of the natural environment, need to be protected from all pollutant sources because man's own survival depends on their efficient use.

According to a strategic EU document [1], research and technological development play an important role in the implementation of the Water Framework Directive (WFD), in order to improve the knowledge about the pressures and ecological status of the aquatic ecosystems.

Hydrodynamics and pollutant loads dispersion characteristics are determinant factors in an integrated river basin management, where different waters uses and aquatic ecosystems protection must be considered, namely during the Strategic Environmental Assessment (SEA) of river basin planning processes, in order to preserve the cultural, natural and ecological structures and to promote a sustainable development [2]. The European Water Framework Directive (WFD) [3] establishes a scheduled strategy to reach good ecological status and chemical quality for all European water bodies.

Mathematical models are well known as useful tools for water management practices, directly or indirectly related to the implementation of the Water Framework Directive (WFD) in European countries, namely for the analysis of pressures and impacts and to support water resources monitoring. They can be applied to solve complex water management problems in river basins [4], including transitional waters (estuaries and coastal areas).

The hydrology and the ecology of shallow estuaries are strongly influenced by the freshwater inflow and the adjacent open sea, due to tide and wind-generated water exchange, creating salinity gradients, thermal stratification and ensuring large transport of silt, organic material and inorganic nutrients into the estuarine waters [5].

Related to anthropogenic activities, point and diffuse sources of pollution have driven two important water quality problems in surface waters: contamination by hazardous chemical compounds and eutrophication [6] due to an excessive organic carbon input associated with a progressive nutrient enrichment, which is widely recognized as a major worldwide threat [7, 8]. Eutrophication processes lead to sensitive structural changes in aquatic ecosystems with the consequent occurrence of episodic algal blooms. Much progress has been made in understanding eutrophication processes and in constructing modelling frameworks useful for predicting the effectiveness of nutrient reduction strategies [9] and the increasing of the estuarine flushing capacity in order to reverse habitat degradation, based on knowledge of the major processes that drive the observed ecological changes.

Estuarine water residence time (WRT) has a strong spatial and temporal variability, which is accentuated by exchanges between the estuary and the coastal ocean due to chaotic stirring at the mouth. So, the concept of a single WRT value per estuary, while convenient from both ecological and engineering viewpoints, is therefore shown to be an oversimplification [10].

Residence time (RT) values, related with the water constituents (conservatives or not) permanence inside an aquatic system, are broadly recognised as important descriptors of estuarine hydrodynamic and so, are convenient parameters to represent the time scale of physical transport processes, often used for comparison with time scales of biogeochemical processes [11]. In fact, estuaries with nutrients residence time values shorter than the algal cells doubling time will inhibit algae blooms occurrence.

The increase of primary production rate in river systems when the flows decrease can also be attributed to higher residence time values [12; 13]. Dettmann [14] used RT and a first-order biogeochemical rate coefficient on a simple two-parameter model to illustrate the relative contribution of the physical transport and biogeochemical processes in estuaries.

In the last two decades, the south arm of the Mondego River estuary was severely stressed by an eutrophication process, leading to a progressive replacement of seagrass (*Zostera noltii*) by opportunistic macroalgae. Furthermore, episodic macroalgae blooms (Fig. 1) have been observed in the southern arm of the Mondego estuary, due to the simultaneous occurrence of the water residence time increasing and a high availability of nitrogen and phosphorus, provided from oriziculture and aquaculture activities [16].

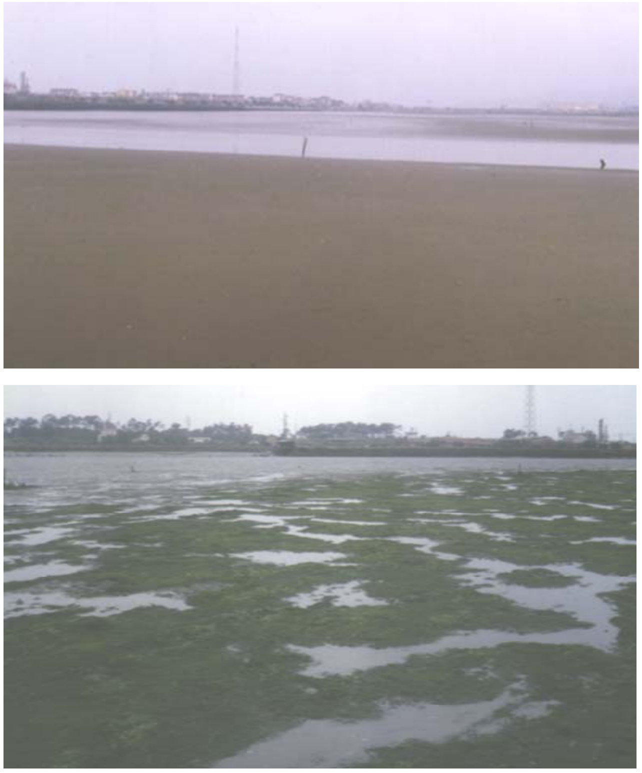


Fig. 1 Macroalgal bloom in Mondego estuary (before and after the occurrence)

This work presents a 2D-H water quality model for the Mondego estuary (*MONDEST model*), which was developed in order to simulate its hydrodynamic behaviour, salinity and residence times spatial distributions, at different simulated management scenarios.

This model was calibrated and validated using data obtained from the sampling programmes carried out over the past two decades [17].

Some results of hydrodynamic simulations are presented to illustrate the strong asymmetry of flood and ebb periods at the inner sections of this estuary, as well as a new approach for tidal prism and tidal flows estimation. The assessment of tidal regime and freshwater discharges effects on estuarine RT values spatial variation is the main goal of this work.

2 Methods

The benefits of the synergy between modelling and monitoring are often mentioned by several authors and the linkage of both approaches makes possible to apply cost-benefit measures [18].

Therefore it is essential to correlate monitoring and modelling information with a continuous feedback, in order to optimize both the monitoring network and the simulation scenarios formulation processes.

2.1 Study area

The Mondego River basin is located in the central region of Portugal, confronting with Vouga, Lis, Tagus and Douro river basins. The drainage area is 6670 km^2 and the annual mean rainfall is between 1000 and 1200 mm.

The Mondego estuary (40º08'N 8º50'W) is divided into two arms (north and south) with very different hydrological characteristics, separated by the Murraceira Island (Fig. 2).

The area covered in this study refers to the whole Mondego estuary, with 32 km long, from its ocean boundary defined approximately 3 km outward from the mouth to Pereira bridge, about 2.8 km upstream from the Formoselha bridge and its small dam that prevents tidal propagation up the river.

Fig. 2 Location and aerial view of Mondego estuary

The north arm is deeper and receives the majority of freshwater input (from Mondego River), while the south arm of this estuary is shallower (2 to 4 m deep, during high tide) and presents an extensive intertidal zone covering almost 75% of its total area during the ebb tide. The irregularity of its geomorphology and bathymetry is depicted in Figure 3.

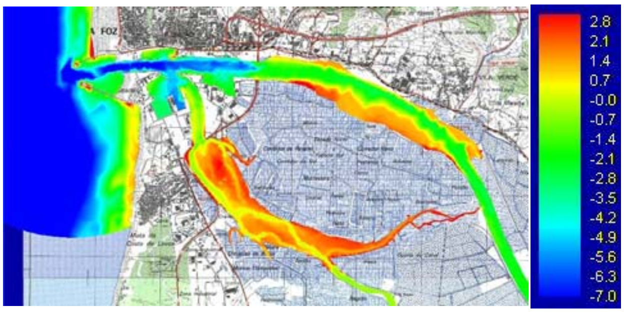


Fig. 3 The Mondego estuary bathymetry (high tide)

Consequently, the south arm estuary water circulation is driven by tide, wind and the usually small freshwater input of Pranto River, a tributary artificially controlled by the *Alvo* sluices located 1 km upstream from its mouth, originating a coastal lagoon-like behaviour.

For the eutrophication process control, it became crucial to obtain information about the mechanisms that regulate the abundance of opportunistic macroalgae and its spatial and temporal distributions.

2.2 Sampling programme

An extensive sampling programme has been carried out for the last two decades at three benthic stations (A, B, C) and at three other sites ─ Lota (LT), Armazéns creek (EA) and Pranto River mouth (RP) ─ for water column monitoring (Fig. 4).

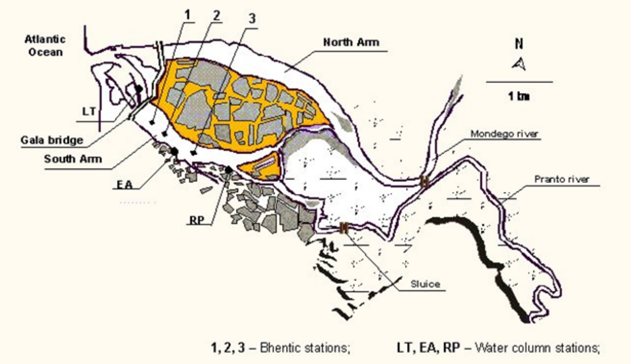


Fig. 4 Sampling points location in the southern arm of Mondego estuary'

In the beginning, the main goals of this sampling programme were: to assess annual nutrients balance in the south arm estuary; to characterize the chemical estuarine waters quality and its ecological status; and to establish a southern arm eutrophication gradient, based on biological indicators, such as the *Zostera noltii* meadows areas reduction, replaced by opportunistic green macroalgae, such as *Enteromorpha spp*. and *Ulva spp*. [19].
Water level, velocity, salinity, dissolved oxygen and water samples were collected every half-hour for physical and chemical characterization of this system. Depending on the tidal amplitude, depth, cohesiveness of algae, current velocity, wind and wave-induced vertical turbulence, plants growing in shallow areas are suspended in the water column, transported out and eventually settled in deeper areas. In this system, the analysis of available data allowed to conclude that the occurrence of green macroalgae blooms is strongly dependent on the flushing conditions, salinity gradients and nutrient discharge characteristics [20].

2.3 Mathematical modelling

Numerical modelling is a multifaceted tool to get a better understanding of physical, chemical and biological processes in the water bodies, based on a "simplified version of the real" described by a set of equations, which are usually solved by numerical methods. The models to be used for the implementation of the WFD should ideally have the highest possible degree of integration to comply with the integrated river basin approach, coupling hydrological, hydrodynamic, water quality and ecological modules as a function of the specific environmental issues to analyse [21].
The *Mondego Estuary (MONDEST) model* was conceptualized (Fig. 5) as an integrated hydroinformatic tool, linking hydrodynamics, water quality and residence time (*TempResid*) modules.

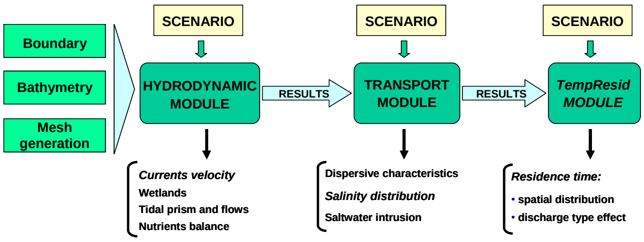


Fig. 5 The *MONDEST* model conceptualization

This model is based on generalized computer programmes RMA2 and RMA4 [23], which were applied to this specific estuarine ecosystem.
The RMA2 programme solves depth-integrated equations of fluid mass and momentum conservation in two horizontal directions by the finite element method (FEM) using the Galerkin Method of weighted residuals. The shape (or basis) functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation [22]. The RMA4 programme solves depth-integrated equations of the transport and mixing process using the Galerkin Method of weighted residuals, too [23].
In the MONDEST model, the hydrodynamic module provides flow velocities and water levels for the water quality module, whose results acts as input on the *TempResid* module, feeding the constituents concentration over the aquatic system.
The formulation of an accurate model requires the better (possible) definition of the geometry and bathymetry of the water body and the interactions with the boundary conditions.
The boundary conditions considered in the *MONDEST* model refer to the flow rates of the Mondego and Pranto Rivers and the water level rise at the ocean boundary, corresponding to the tidal signal in the vicinity of Figueira da Foz that is generated by programmer SR95 [24] for the analysed period, while considering a synthesis of the main harmonic tidal components (Fig.6).

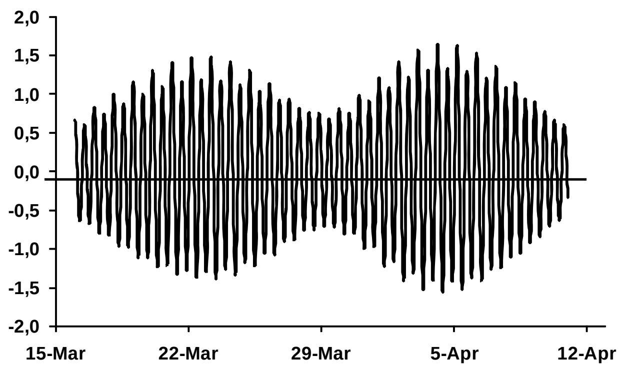


Fig. 6 Tidal harmonic signal at Figueira da Foz

The flow rates observed for the Mondego River result from the analysis conducted for the daily average values observed for 1990-2004. The following values were adopted: 15 $m^3.s^{-1}$, as a typical dry-weather flow (corresponding to the 90% percentile on the cumulative flow rate curve); 75 $m^3.s^{-1}$, as the annual average value; 340 $m^3.s^{-1}$, as the maximum flow rate for sizing the minor bed of the main channel. The values that were considered for the discharged flow rates by the Pranto River into the south arm correspond to those observed during field work, considering the flow discharge curves of the three Alvo sluices. Therefore, daily average values of 0 (closed sluices), 15 and 30 $m^3.s^{-1}$ were considered. They correspond, respectively, to discharges carried out during part of the tidal cycle and continuous discharges that are usual in periods of greater rainfall.
The size of the elements to consider in the spatial discrimination of the simulated domain of numerical models must be established as a function of larger or smaller spatial gradients than those displayed by the variables (water level and velocity) in that domain.
In the case of the Mondego estuary, since the south arm was the preferred object for studying, the network of finite elements was refined in that sub-domain, thereby reducing the maximum area of its (triangular) elements to 500 m^2 (Fig. 7).

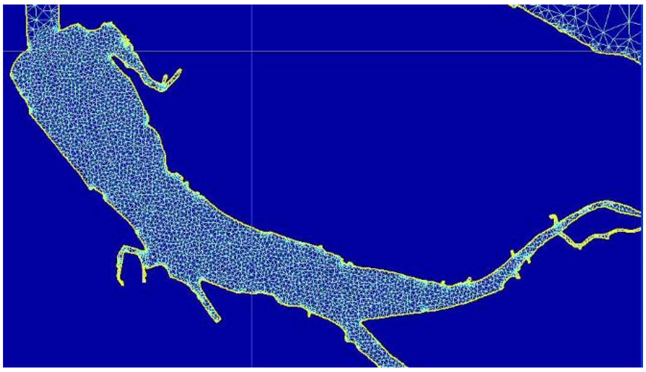


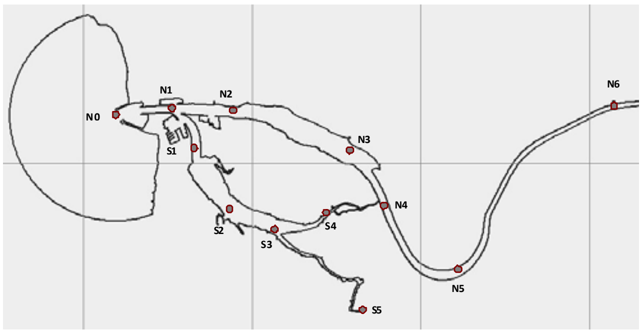
Fig. 7 Finite elements mesh adopted in MONDEST model for the estuary southern arm

The *TempResid* module was integrally developed in this study aiming to compute RT values of each water constituent (conservative or not) and allowing to map its spatial distribution over all the estuarine system, considering different simulated management scenarios [20]. For this purpose,, a wide range of management scenarios were judiciously selected considering a representative set of typical tidal amplitudes (0.60, 1.15 and 1.60 m), river flow inputs (from Mondego and Pranto), pollutant load characteristics and constituent decay rates (Table 1).

Table 1 Simulated management scenarios for estuarine residence time calculation

SCENARIO	RIVER FLOW ($m^3.s^{-1}$)		TIDE	LOAD	DECAY RATE (day^{-1})
	Mondego	Pranto			
RT 1	15	0	medium	point	0
RT 2			spring		
RT 3			neap		
RT 4			medium		1
RT 5					10
RT 6		15			0
RT 7	1	0			
RT 8	75				
RT 9	340				
RT 10	15			diffuse	
RT 11					1
RT12	75				0
RT 13					1
RT 14					0,5

Figure 8 presents the outline of the estuarine area of the Mondego River and the location of the several sections used for calibrating and analysis the results from the simulations. The legend includes the designation, section code and their distance to the mouth of the estuary.



CODE	SECTION NAME	DISTANCE (km)
N0	Estuary mouth	0.0
N1	Recreational harbor	1.3
N2	Figueira Bridge	2.8
N3	*Gramatal*	6.3
N4	*Cinco Irmãos*	7.4
N5	Maria da Mata sluices	10.0
N6	Foja Pumping Station	15.7
N7	River Arunca mouth	20.9
N8	Formoselha Bridge	28.6
N9	Pereira Bridge	31.4
S1	Gala Bridge (Lota)	2.6
S2	Armazéns creek (Negra)	4.4
S3	River Pranto mouth	5.4
S4	*Areeiro novo*	6.7
S5	Alvo sluices	8.7

Fig. 8 Control sections adopted for model calibration and simulation results analysis

3 Results and discussion

This work presents some *MONDEST* model results obtained for different simulated scenarios in order to evidence the influence of hydrodynamics (tidal regime and freshwater inflows) on estuarine residence time spatial variation, which can play a special role in estuarine eutrophication vulnerability assessment, by identifying the most sensitive areas [15].

3.1 Model calibration and validation

The velocities and water levels field data, obtained from the sampling programme were used for model calibration and validation (Fig. 9), as well as to define accurate boundary conditions to introduce on hydrodynamic and transport modules.

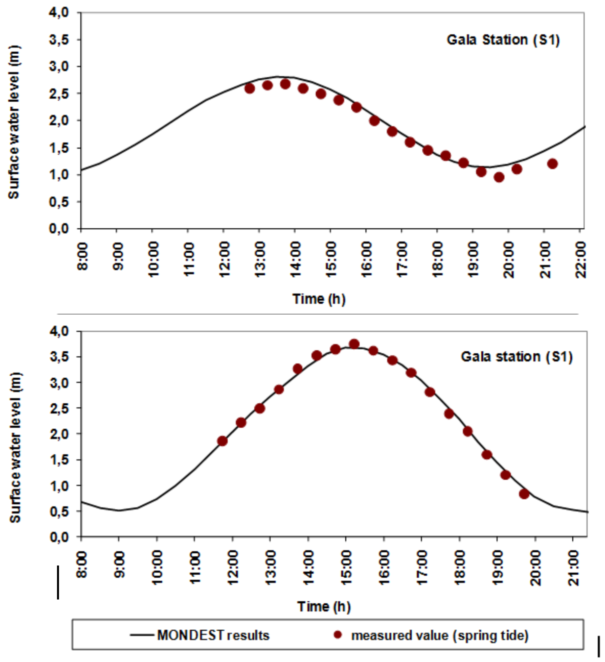


Fig. 9 Hydrodynamic module calibration (spring tide) and validation (neap tide), at Gala bridge (S1)

The transport module calibration (Fig. 10) and validation was performed with the salinity field data, in order to estimate the estuarine dispersion coefficients, which allowed the better correlation between model results and sampling data.

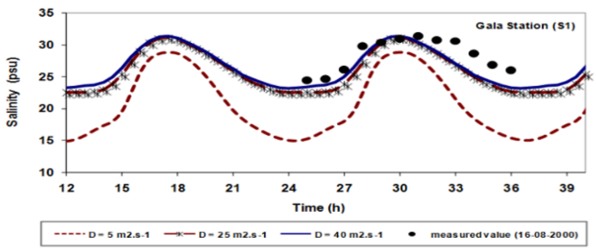


Fig. 10 Transport module calibration (Gala bridge)

3.2 Hydrodynamic modelling

The hydrodynamic modelling carried out allowed to characterize the velocity fields in both arms of the estuary as a function of the tidal regime and the variation of the Mondego and Pranto Rivers flow rates, as well as the determination of flow rates and high and low tides, by calculating the corresponding tidal prisms.

Figure 11 presents a synthesis of tidal prism values for two control points: one near the Mondego estuary mouth (N0) and the other in the south arm, downstream from the Gala bridge (S1).

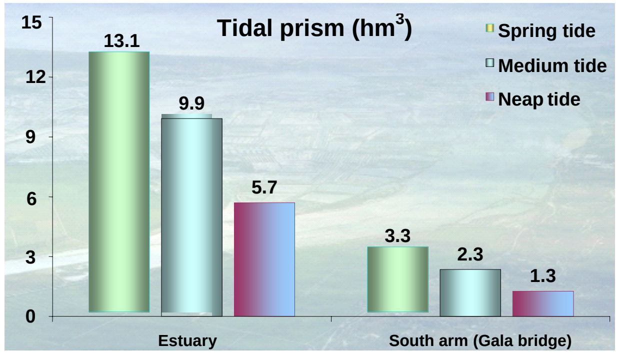


Fig. 11 Tidal prism values for different tidal regimes

These values were calculated applying the *MONDEST* hydrodynamic module to the simulation scenarios RT1, RT2 and RT3, considering the three different tidal amplitudes referred, for a typical dry-weather condition.

As seen in this graph, tidal amplitude has a great influence on tidal prism values estimated at both control points, corresponding to a water volume reduction of 56% and 61%, according to whether a spring or a neap tide is considered.

The simulation results allowed us to identify some tidal prism asymmetries in the estuary north arm, regarding the ebbing or the flooding periods. For spring and medium typical tides, the ebbing tidal prism is 9% higher than the flooding one. But, during typical neap tide, the flooding tidal prism exceeds the ebbing one by 2%. However, in the south arm these asymmetries are irrelevant, since the differences are lower than 0.3%.

The tidal prism variation (hm^3) as a function of the Mondego River flow rate is presented in Figure 12, for a tidal amplitude of 1.60 m of a typical spring tide.

The influence of the Mondego River flow rate on the tidal prism value is much less than that of the tidal regime, leading only to a 19% reduction of the ebbing prisms and a 4% reduction in its south arm (upstream from Gala bridge), respectively.

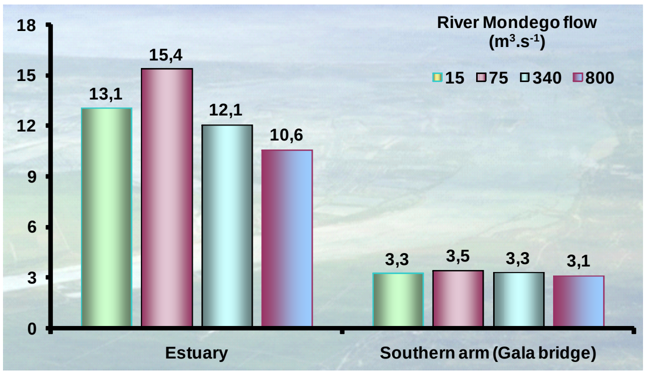


Figure 12 Tidal prism variations due to Mondego River flow increase

The obtained results lead to the conclusion that the tidal prism variation (during ebbing and flooding) does not increase proportionally with incremental values of the Mondego River flow. The trend line that is associated to the values obtained for the estuary indicates that the maximum prism, for spring tides, occurs for flow rates close to 60 $m^3.s^{-1}$.

Hydrodynamic modelling results allowed also assessing the influence of tidal regime on the currents velocity in both arms during ebbing (Fig. 13) and flooding situations.

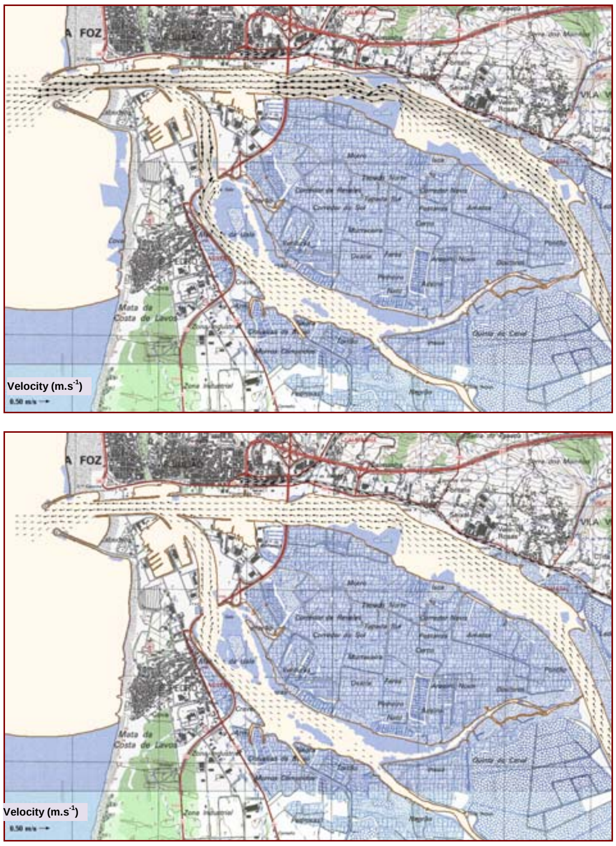


Fig. 13 Effect of tidal regime on currents velocity magnitude (ebbing and dry-weather conditions)

For the simulated dry-weather condition, the higher velocity values obtained in the southern arm occur near the Gala Bridge, reaching 0.35 (neap tide, RT3) to 0.70 $m.s^{-1}$ (spring tide, RT2), while in the northern arm these values are lower, reaching 0.33 (neap tide) to 0.60 $m.s^{-1}$ (spring tide), at 1 km upstream the Figueira da Foz bridge.

In the southern arm, the flooding time, which decreases at the inner zones, is much shorter than the ebbing time, due to shallow waters and to large intertidal mudflats areas. This asymmetry is influenced by the 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. 14).

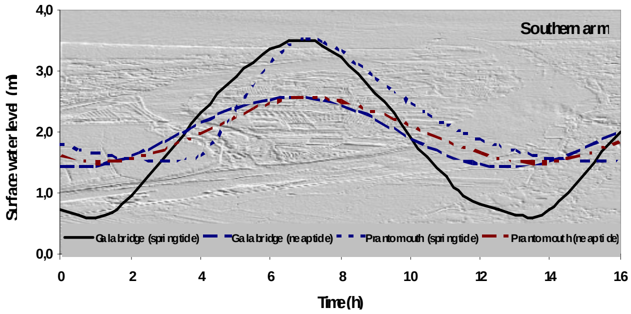


Figure 14 Effect of tidal regime on flooding and ebbing durations in the southern arm (S1 and S3)

The analysis of the salinity distribution in the estuary had, as a primary objective, the identification of the areas that, throughout the tidal cycle, present salinity values within the interval for the most favourable algal growth, 17 e 22‰.

Figure 15 presents only the estuary stretches with salinity values between 15 and 24‰ in the ebb tide (maximum salinity) and in the instant where maximum ebbing currents occur (medium salinity), taking into consideration the hydrodynamic conditions corresponding to scenarios RT1 and RT6.

It is possible to verify that, during the most part of the tidal cycle, that interval of salinity that is favourable to the proliferation of infesting macroalgae occurs precisely in the south arm stretch considered to be hypertrophic in 1998. Conversely, in the stretch upstream from Gala Bridge, which was then considered as mesotrophic, salinity values belonging to that interval were rarely seen. An area with favourable salinity also occurs in the north arm, but in this case, it coincides with a stretch where the currents are more intense. Therefore, the juxtaposition of these two effects could be a determining factor in the analysis and evaluation of the vulnerability of estuarine systems to eutrophication phenomena.

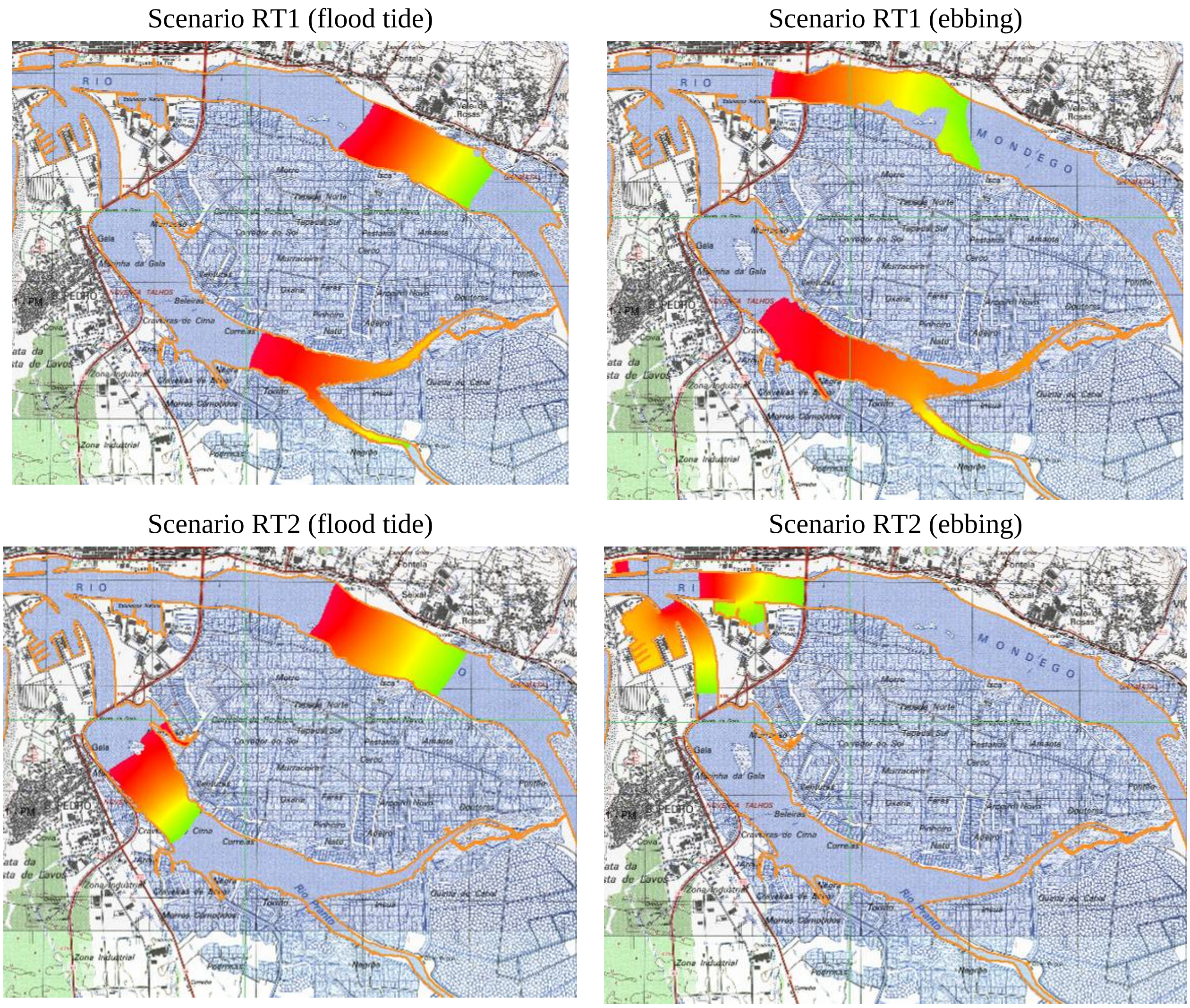


Figure 15 Delineation of areas with salinity that is favourable to macroalgae growth

The RT value of a substance was calculated for each location and instant, as an interval of time that is necessary for that corresponding initial mass to reduce to a pre-defined percentage of that value. In this work, a value of 10% was adopted for the residual concentration of the substance, attending to the fact that the effect of the re-entry of the mass in the estuary during flooding is considered (a significant effect for dry-weather river flow rates).

The determination of the RT in the various stations along the estuary, including the south arm locations (A, B and C) where the eutrophication gradient was indentified, was carried out by applying the *TempResid* programme to the results of the simulations that were performed with the transport module of the MONDEST model

Figure 16 shows an example of the *MONDEST* model transport module results for management scenario RT1, one of the most favourable to macroalgae blooms occurrence, due to low freshwater inputs and consequent reduction of estuarine waters renovation (scenario RT1). This graph presents the concentration decrease of a conservative constituent, in three control points (N0, S1 and S3), due to estuarine flushing currents, considering the well known re-entrance phenomena at the estuary mouth.

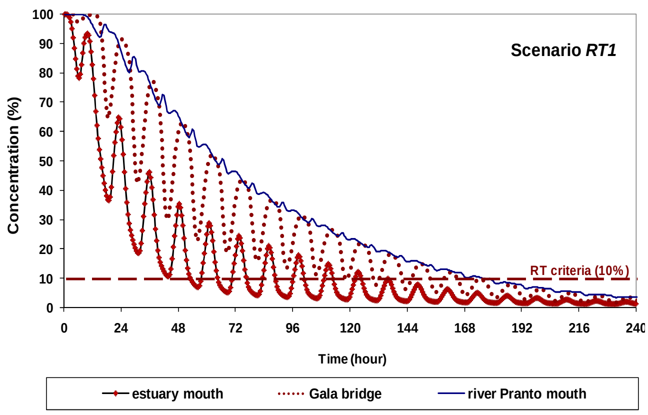


Fig. 16 Residence time computation (scenario RT1)

During the warm season (late spring and summer), the Alvo sluices are almost closed. So, the salinity and the RT in the Mondego estuary south arm are strongly influenced by tidal regime. Concerning the periodicity of tidal regime recurrence, its effect could be very relevant only on estuarine biochemical processes with a time scale lower than 6 days.

Figure 17 illustrates the gradient of RT spatial distribution, which was mapped applying the *TemResid* module computing availability for management scenarios RT2 and RT3.

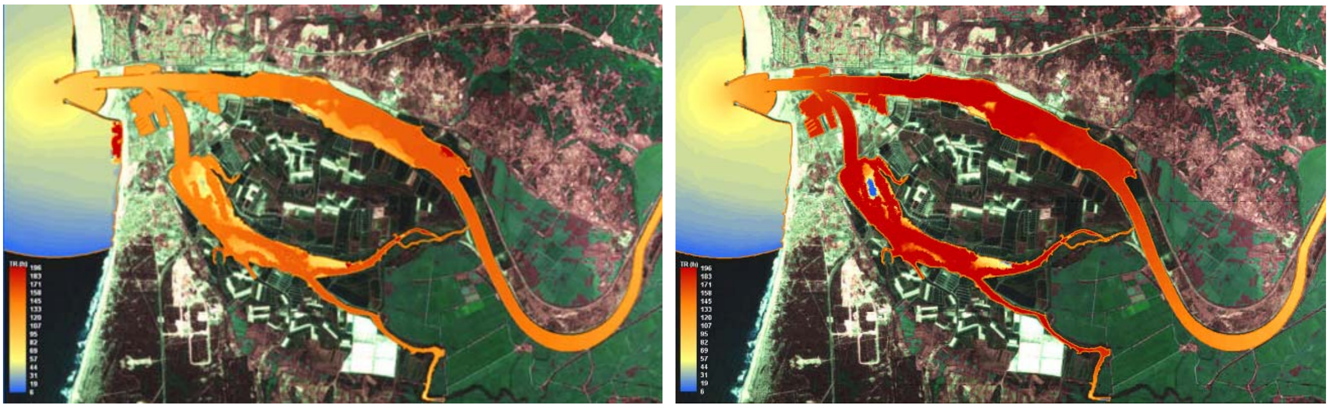


Fig. 17 Effect of tidal regime on RT values distribution (neap and spring typical tides)

Simulation results for these two tidal scenarios showed a RT values increase of 50% for a neap tide, when compared with a spring tide, both in south arm and in the north arm reach, between N1 and N2 control points.

This increase is smoothed in northern arm inner areas, with de lowest increase (only 17%) at the Mondego estuary mouth. The minimum RT values (3.2 days) occurred in the Mondego estuary mouth (N0) and in the mesotrophic wetland zone of the south arm (station A).

The maximum RT values (9.5 days) were obtained for the strongly eutrophicated zone (station C) of this estuary arm, near the Pranto River mouth.

The Pranto River inflow in estuary southern arm has shown a strong influence on RT values that can quintuplicate at the Pranto mouth station (S3) when the Alvo sluices are closed (Fig. 18).

Fig. 18 Effect of Pranto River flow absence in RT values distribution (scenarios RT1 and RT6)

In this management scenario, RT values spatial distribution are strongly related with eutrophication gradients observed in this system over the last twenty years, validating the applied methodology for estuarine water quality assessment.

For dry-weather flow conditions, the tide constitutes the most important transport mechanism in both arms and it is practically dominating in the south arm, as long as there are no discharges from the Pranto River.

When there are discharges in the Pranto river (RT6 scenario), the contribution of the two fluvial flow rates (Mondego and Pranto) increases from 30 to 96%. This fact reveals that the discharge of the Pranto River has a decisive effect in the flushing capacity of the south arm that is similar to the one produced by a Mondego River flow rate close to 50 $m^3.s^{-1}$.

4 Conclusions

Results obtained from hydrodynamic modelling have shown a strong asymmetry of ebbing and flooding times at inner estuary south arm areas due to their complex geo-morphological patterns (wetlands and salt marshes). This information allows for a more accurate tidal flow calculation, which is the major driving force of the southern arm flushing capacity, when the Alvo sluices rest closed.

From the analysis of the results obtained, it is possible to conclude that in both arms of this estuary, the tidal prism volumes are influenced by the bathymetry (extensive wetland areas), tidal regime and freshwater inputs. However, the influence of the tidal regime on the tide prism values is much greater than that of the fluvial flow rate, and it is possible to verify that those values do not increase proportionally to the incremental values of the Mondego River flow rate.

The analysis of the results obtained in the performed simulations allows the confirmation that there is a significant influence of bathymetry in the spatial variation of the RT along the Mondego estuary and consequently, the definition of typical (unique) values for each one of its arms becomes inadequate if they are not associated to local and specific hydrodynamic scenarios.

For medium typical tide, drought conditions and conservative constituents, simulation results showed that estuarine RT values range between 6 days (at both arms) and 4 days in the downstream reach of its two arms confluence (control point N1).

The Pranto River inflow absence (a typical summer situation) increases RT values drastically in the inner estuary southern arm and, consequently, the availability of nutrients for algae uptake is higher, enhancing estuarine eutrophication vulnerability.

The MONDEST model developed and applied in this work allowed the evaluation and ranking of potential mitigation measures (like nutrient loads reduction or 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, in order to contribute for better water quality management practices and to achieve a true sustainable development.

Acknowledgments

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