Ria Formosa 3D hydrodynamic model. A contribution for the understanding of the Faro-Olhão inlet processes

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Abstract

Ria Formosa lagoon, located in Algarve, south of Portugal, is a barrier islands system that communicates with the sea trough 6 inlets. Five of these inlets are natural born and have mobility characteristics and the 6th is an artificial inlet that has been opened with the purpose of making it easier to access to the port of Faro.

In order to maintain this new inlet, two breakwaters were built, starting one in Culatra island and the other in Barreta island. The engineering works were designed to ensure self-maintenance in the navigation channel.

This purpose was in fact fully achieved but the time showed that the entrance section should have been wider. The present configuration of the breakwater is responsible for the occurrence of high velocities that put important navigation security problems. In order to try to solve these problems the port authority promoted a set of studies that could point out possible corrective measures.

In the framework of those studies a mathematical model of the system was implemented having as objectives to help in the understanding of the local processes and in the forecasting of the consequences of possible correcting solutions.

In this paper a brief description of the mathematical model characteristics and capabilities are presented and some results are discussed.

1. INTRODUCTION

The barrier islands system of Ria Formosa, located in the south of Portugal, is composed by 6 inlets which divide 5 barrier islands.

Presently the main inlet of the system is the Faro-Olhão inlet, which was artificially open. The process started in 1927 but only in 1952 the engineering works have been completed and assumed the present configuration.

Within the Ria Formosa system different and sometimes antagonic uses may be found. Part of the system is a Natural Park but Ria Formosa also plays an important role in the region economy. Beyond the tourist use the system is also the support of other economic activities like seafood farms and the port of Faro.

This latter use is the justification of the present study. In fact, the Faro-Olhão inlet was designed in a way that it could assure the self maintenance of proper depths in the access to the navigation channel. In order to fulfil this objective two breakwaters were built, starting one in Culatra island and the other in Barreta island.

Although by the time that it was designed the best knowledge has been used, time showed that the distance between the two breakwater heads was narrower that what would be necessary to accomplish the self maintenance objective. As a consequence, in front of the breakwaters an erosion process took place that led to local depths that are nowadays of the order of 40 meters.

Other consequences of the breakwaters present configuration are the occurrence of high current values (mainly in ebb conditions) that, together with the narrow entrance section and the wave action, puts important security problems in what concerns the ships movements.

In this perspective apart from the limitations of the exploitation of the port of Faro, the issues related with the inlet security are presently a major concern for all the lagoon activities.

In face of these problems, and if one intends to maintain the port operational, a solution must be found in order to prevent that a major accident may occur. The most obvious solution would be to introduce the necessary modifications in the breakwaters design in order to overcome the present limitations and risks.

Having those purposes in mind the port authority asked for the necessary studies that may lead to a satisfactory solution for the present problems.

In the framework of these studies a mathematical model of the system was implemented having as objectives to help in the understanding of the local processes and in the forecasting of the consequences of possible correction solutions.

In the following chapters a brief description of the model characteristics and capabilities will be presented and some results will be discussed.

2. MOHID MODELLING SYSTEM

MOHID modelling system is a primitive equation model based in the Navier-Stokes equations with Boussinesq and hydrostatic approximations. MOHID is formulated in a finite volume approach with a generic vertical discretization that enables the simultaneous implementation of various types of vertical coordinates.

This model was developed by the MARETEC Group of Instituto Superior Técnico (Technical University of Lisbon) and it has already shown its ability to simulate complex coastal and estuarine flows (Neves et al. 1998, Cancino & Neves, 1999, Martins et al. 2001, Coelho et al. 2001, Ruiz-Villareal et al, 2002).

2.1 Model formulation

The model uses the Navier-Stokes primitive equations with the Boussinesq and hydrostatic assumptions:

$$\frac{\partial u}{\partial t}+\frac{\partial(uu)}{\partial x}+\frac{\partial(vu)}{\partial y}+\frac{\partial(wu)}{\partial z}-fv=-g\frac{\rho_\eta}{\rho_0}\frac{\partial\eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_s}{\partial x}-\frac{g}{\rho_0}\int_z^\eta\frac{\partial\rho'}{\partial x}dz+\frac{1}{\rho_0}\frac{\partial}{\partial x}\left(\nu_h\frac{\partial u}{\partial x}\right)+\frac{1}{\rho_0}\frac{\partial}{\partial y}\left(\nu_h\frac{\partial u}{\partial y}\right)+\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\nu_v\frac{\partial u}{\partial z}\right) \quad (1)$$

$$\frac{\partial v}{\partial t}+\frac{\partial(uv)}{\partial x}+\frac{\partial(vv)}{\partial y}+\frac{\partial(wv)}{\partial z}+fu=-g\frac{\rho_\eta}{\rho_0}\frac{\partial\eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_s}{\partial y}-\frac{g}{\rho_0}\int_z^\eta\frac{\partial\rho'}{\partial y}dz+\frac{1}{\rho_0}\frac{\partial}{\partial x}\left(\nu_h\frac{\partial v}{\partial x}\right)+\frac{1}{\rho_0}\frac{\partial}{\partial y}\left(\nu_h\frac{\partial v}{\partial y}\right)+\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\nu_v\frac{\partial v}{\partial z}\right) \quad (2)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (3)$$

Where u, *v* and *w* are the components of the velocity vector in the x, *y* and *z* directions respectively, *f* the Coriolis parameter, A_H and A_v the eddy viscosities in the horizontal and vertical directions and *patm* is the atmospheric pressure. r is the specific mass, ρ' is the specific mass anomaly and ρ_0 is the reference density ($\rho=\rho_0+\rho'$), ρ(η) represents the density at the free surface. The specific mass is calculated as a function of temperature and salinity by a simplified equation of state (Leendertsee & Liu, 1978).

If the equation of continuity (3) is integrated over the whole water column (between the free surface elevation η(x,y) and the bottom -h), the free surface equation is obtained:

$$\frac{\partial\eta}{\partial t}=-\frac{\partial}{\partial x}\int_{-h}^{\eta}u\,dz-\frac{\partial}{\partial y}\int_{-h}^{\eta}v\,dz \quad (4)$$

2.2 Numerical approach

The model uses a finite volume approach (Chippada *et a*l. 1998; Martins *et al* 2001) to numerically solve the equations. In this approach, the discrete form of the governing equations is applied macroscopically to a cell control volume. This makes the actual way of solving the equations independent of cell geometry and permits the use of a generic vertical coordinate. This procedure minimizes the errors of some of the classical vertical coordinates (Martins *et a*l. 2001).

In the horizontal, the equations are discretized using an Arakawa-C staggered grid. The temporal discretization is carried out by means of a semi implicit (ADI) algorithm with two time levels per iteration.

2.3 Boundary conditions

The model makes use of five types of boundaries: free-surface, bottom, lateral closed boundary, lateral opened boundary and moving boundary.

At the free-surface boundary the water flux across the surface was assumed null. At the bottom boundary the water flux is also assumed null and a quadratic law is used to calculate the bottom stress. The closed boundaries of the domain correspond to land. In this case an impermeable, free slip condition was adopted.

At the open boundaries the tidal signal is imposed specifying the free surface elevation of those cells.

Moving boundaries are closed boundaries whose position changes with time. This type of situation arises in domains with inter-tidal areas. In this case the uncovered cells must be tracked.

3. THE LAGOON MATHEMATICAL MODEL

A number of modelling studies have been conducted in recent years in Ria Formosa lagoon (e.g. IST, 1994, Hidroprojecto, 1997, Hidromod, 2001, Silva et al, 2001) in the framework of different projects (*e.g. India, F-Ects, Ecorudi, Faro-Olhão inlet and harbour projects)*.

All those studies and projects made use of 2DH hydrodynamic models which are, in general, suitable to describe the lagoon, well mixed, tidal flow.

However this is not the case of Faro-Olhão inlet, the most important inlet of the lagoon system, where the flow shows very complex 3D patterns. Field measurements made by the Hydrographic Institute (IH, 1981, 2001) at different inlet depths demonstrates the complexity of the local flow patterns, which show important variations of the flow intensity and direction both in the water column and across the inlet.

In order to better understand these processes a full 3D hydrodynamic model of the lagoon, based on the MOHID modelling system, was implemented. The model includes the whole west domain of the lagoon from Ancão Peninsula to the Fuzeta inlet.

The model grid in the horizontal is variable having a maximum resolution of 25x25 meters in the Faro-Olhão inlet area. In the vertical two kind of discretizations have been considered: one with just one layer (basically a 2DH model) and another with a vertical grid composed by two sigma domains. The top domain has just one layer that goes from the hydrographic zero till the free surface, and the second domain has three layers. Although it would be interesting to make the computations using more layers, the computational effort necessary does not permit it.

3.1 Model implementation and validation

The necessary bathymetric data to implement the model was obtained from surveys made by IH and the Portuguese port authority (IMP) between 1975 and 2001. The most recent surveys of 2001 only cover the main navigation channel and a few secondary channels. Only the surveys made between 1975 and 1978, which included a general bathymetric survey complemented with aerial photography for the salt marshes areas, covers the whole lagoon. The most recent information of the inlet bathymetries (exception for Faro-Olhão) remounts to surveys made by IMP between 1990 and 1994.

The model validation was based in the result of field measurement campaigns of currents and levels (cf. Figure 1) made by IH (1981, 2001).

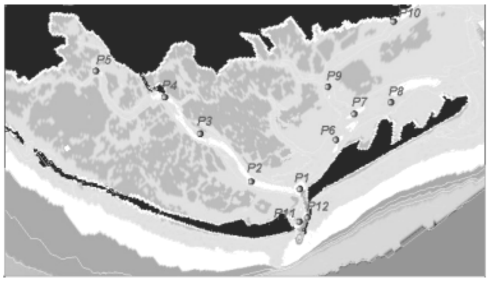

Figure 1: Measuring points used to validate the model

The computed results were compared with the available measures and, in general, a good agreement was obtained (cf. Figure 2). It was also observed that, the cases where the agreement between the measures and the computed results were less satisfactory, it was always related with less accurate bathymetric data.

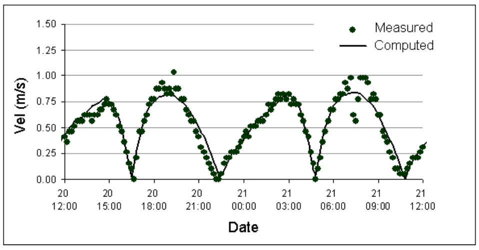

Figure 2: Comparison of measured and computed depth averaged velocities at point 3.

In the area of the Faro-Olhão inlet it was also possible to compare the model results with field data at different depths. By this way it was possible to evaluate the real importance of a 3D model to describe the flow in this region and how the model compares with what was observed (cf. Figure 3).

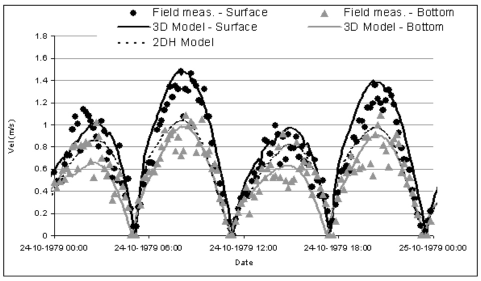

Figure 3: Comparison of measured and computed velocities at 2 depths in point 12.

4. FARO PORT PRESENT SITUATION

The access to the port of Faro is made trough a navigation channel with an extension of about 5 km. This channel is quite sinuous with a variable section having a minimum with of about 80 meters and a minimum depth of about 6 meters.

The inlet section has a navigable width of about 100 meters which is considered insufficient taking in consideration the characteristics of the ships that use the port and the adverse conditions of the local currents and wave climate.

Also the course between the inlet and the beginning of the navigation channel includes a curve that makes 90 degrees which is an extra contribution to the navigation problems.

The port of Faro is essentially a commercial port, being fuel one of the main transported products. In accordance with the region economy, the port activity also shows a significant seasonality with a peak of activity in the summer season. In these months the number of ships that seek the port may reach the double of the number of ships during winter times.

The average number of ships that used the port during the last years was about 150-170 per year. These ships have maximum lengths in the order of 100 - 120 meters. Due to the navigation restrictions the longer ships (transporting fuel) are not able to enter completely loaded.

5. PROJECT OVERVIEW

As referred above, the main objectives of the present study were: for one side understand the local hydrodynamic and transport processes and, for another side, evaluate the impacts of different engineering solutions that could contribute to solve the present problems.

Once the main problems are related to the narrow entrance section, the correction of these problems should, in principle, consider the modification of the breakwaters geometry.

In this first phase of the project two main restrictions were considered: 1) the new inlet geometry should not contribute for a significant modification of the tidal prism neither for a significant modification of the flow distribution between Olhão and Faro channels in order to avoid as much as possible unpredicted system reactions; 2) the solution should contribute in an effective way for a significant reduction of the ebb currents in order to make easier the local navigation.

5.1 Basic alternative solutions

In a first evaluation process, two kinds of generic solutions were considered: the modification of the East breakwater or the modification of the West breakwater (cf. Figure 4 and Figure 5).

In a first sight, both solutions show advantages and disadvantages. The main advantage of a solution based on a modification of the East breakwater would be no direct conflicts with the barrier islands. The main disadvantage would be, in principle, the cost.

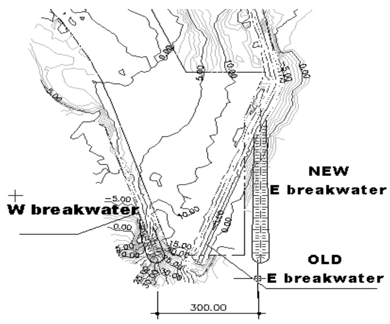

Figure 4: East breakwater type solutions

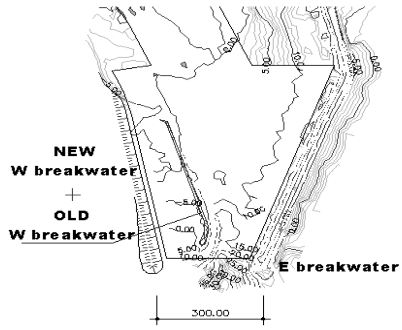

Figure 5: West breakwater type solutions

A solution based on a modification of the West breakwater would be, in principle cheaper, but it would be necessary to cut a small piece of the Barreta island.

A first guess of the equilibrium section may be done on the basis of the approaches of Jarrett (1976) who reviewed the previously established relationships for inlet stability and performed a regression analysis on data from 108 Pacific, Atlantic, and gulf coast inlets in various combinations in an attempt to determine best-fit equations.

Results of his analysis indicated that the tidal prism-inlet (P) cross-sectional area (A) relationship is not a unique function for all inlets, but varies depending on inlet location and the presence or absence of jetties. Jarrett confirmed the original relationship established by O'Brien (1969) for inlets with two jetties:

$$A = 4.69 \times 10^{-4} P^{0.85} \qquad (5)$$

In the case of the Faro-Olhão inlet, if one considers a spring tidal prism of about 70 million cubic meters, the above formulations point to an equilibrium section of the order of 4000 m^2.

Considering the fact that presently the inlet section has about 3000 m2, one may also conclude that the natural trend will be for the maintenance of the erosive process that has been observed in the past.

6. MODEL RESULTS

The analysis of the lagoon water flows shows that Faro-Olhão and Armona inlets are responsible for over 80% of the water going in and out of Ria Formosa.

Faro-Olhão acts as an ebb inlet while Armona acts like a flood inlet. This behaviour is responsible for a residual flow directed from Armona to Faro-Olhão (cf. Figure 6). This behaviour may also be confirmed trough the analysis of the available field measurements.

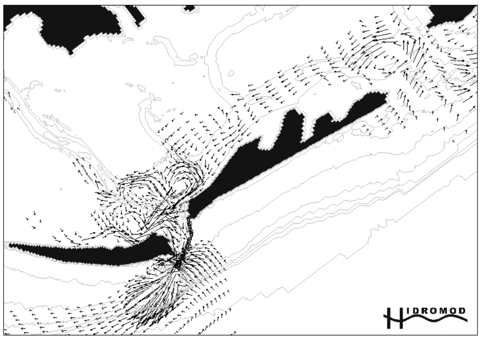

Figure 6: Residual flow between Armona and Faro-Olhão inlets

6.1 Analysis of the tidal prisms

Having in mind the restrictions that should be considered in what concerns the modification of the tidal prisms, it is important to evaluate what has been the recent evolution of the lagoon inlet system.

In this perspective different situations based on bathymetric surveys from different years have been simulated. Three cases have been considered: the oldest situation corresponds to the general survey of the seventies, the second situation corresponds to the inclusion of the nineties surveys and the last situation corresponds to the inclusion of the 2001 IH survey.

The analysis of the results led to the conclusion that, from the seventies until now, it can be observed a continuous trend of increasing water volumes in Faro-Olhão inlet and a more regular behaviour of the water volumes in Armona inlet (cf. Figure 7).

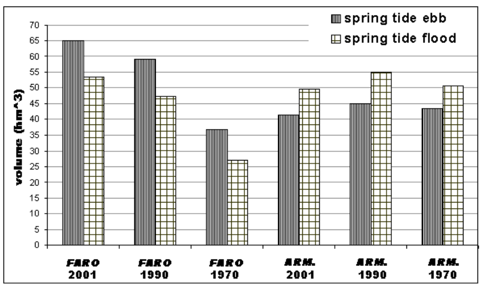

Figure 7 – Computed tidal prisms for the Faro and Armona inlets from 1970 till 2001

This conclusion is of the major importance if one intends to identify the relative importance of what would be the natural water flux transfer from Armona to Faro-Olhão and what would be the forced water flux transfer related with the modifications proposed to Faro-Olhão inlet.

The computed water fluxes were compared with field measurements made by IH (2001) and showed a good agreement both in ebb and flood conditions (cf. Figure 8 and Figure 9)

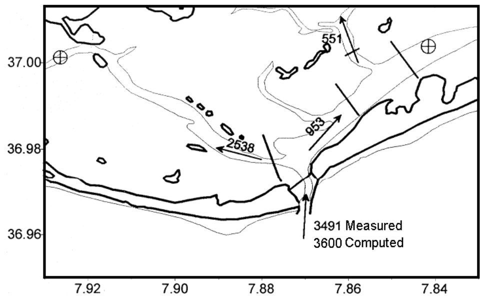

Figure 8: Comparison of the measured and computed Faro inlet water fluxes in spring tide flood conditions (after IH, 2001)

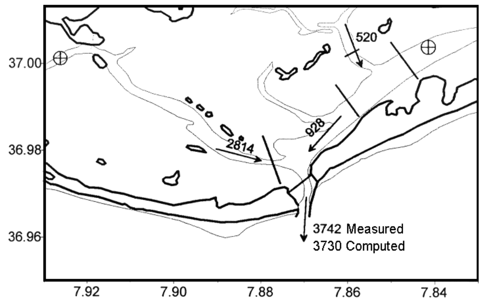

Figure 9: Comparison of the measured and computed Faro inlet water fluxes in spring tide ebb conditions (after IH, 2001)

The next step was then to evaluate the water volumes modifications due to the construction of one of the possible alternatives. The simulations made with the two alternative geometries showed that a water flux transfer movement from the Armona to Faro-Olhão will be expected (cf. Figure 10).

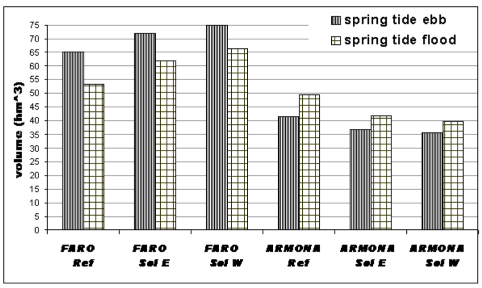

Figure 10 – Comparison of the tidal prisms for the Faro and Armona inlets considering the alternative solutions.

In what respects this aspect there were not found any important differences between the two solutions, although the solution based on a modification of the East breakwater seems to be slightly better in what respects this issue.

If compared with the natural evolution, the predicted modifications of the tidal prisms as consequence of the possible alternative solutions are of the same order of magnitude.

It must be also considered that these simulations did not had any particular concern with the optimization of any of the simulated solutions being its objective to act only as a first guess of the possible expected impacts.

6.2 Impacts on the circulation patterns

As referred before, more than 80% of the water that flows in and out Ria Formosa is passing through Faro-Olhão and Armona inlets. This means that any modification of the geometry of one of these inlets may cause, as a consequence, a modification of the lagoon circulation patterns with the associated effects on the sediment transport processes. This aspect was one of the main concerns of this study, especially in what respects the currents in Faro-Olhão inlet.

The breakwaters configuration is responsible for the flow acceleration in its heads section (cf. Figure 11) which puts important security constrains to the navigation. For this reason the proposed solution must contribute to a significant decrease of the maximum values that occur near the surface.

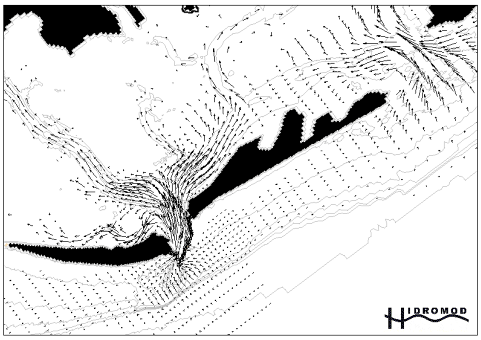

Figure 11: velocity patterns in a flood situation

Field measurements of currents made by IH shows the existence of a velocity gradient in depth which is more pronounced close to the breakwater heads section. The maximum current values may exceed 2 m/s near surface on spring tide situations.

This means that a 2DH model will not be suitable to predict the effective benefits of the solutions in what respects the navigation problems once these problems are essentially related with the flow near the surface.

Having this in mind the model was set up to run with the four layers referred before. The results were compared with field measurements at different depths and with the one layer version of the model in order to better understand the benefits of the 3D approach.

The analysis of the computed values shows that the reduction of the current values computed near the surface, in terms of the project objectives, is more significant than the reduction of the depth average velocity.

In Figure 12 it is presented an example of this situation. As it may be seen the maximum velocity near the surface in these points is about 2 m/s. The computed values show that, the implementation of a west breakwater modification type solution could be responsible to reduce this maximum velocity for values of about 1.25 m/s.

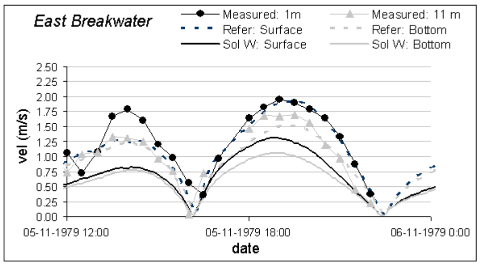

Figure 12: Comparison of measured and computed velocities at two depths, considering the reference situation and a West type solution.

If one uses a 2DH model instead, it will not be possible to reproduce the surface velocities and the evaluation of the results will point to lower benefits of the solutions in terms of the reduction of the maximum velocities.

For instance, if one compares the results of the 2DH model for the same situation represented in Figure 12 it may be concluded that the computed average velocities are much closer of the measured bottom velocities then to the measured surface velocities (cf. Figure 13).

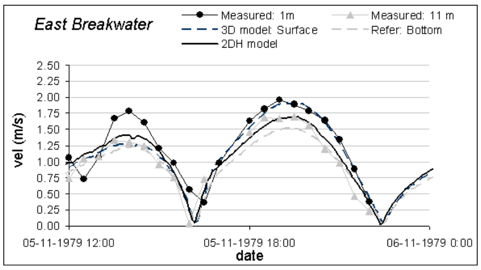

Figure 13: Comparison between the measured values, the 2DH model results and the 3D model results

It also must be taken in consideration that these differences between the depth average velocity and the surface velocity tend to increase as we approach the breakwater head section.

7. CONCLUSIONS

The present configuration of the Faro-Olhão inlet is responsible for the occurrence of high current values that are related with important navigation security concerns. In order to find a solution that may serve the navigation needs without the present risks the necessary studies are taking place.

In the framework of these studies a 3D mathematical model of the lagoon has been implemented in order to help to understand the hydrodynamic and transport processes and help in the evaluation of the impacts of possible alternative solutions.

In this paper a description of the 3D mathematical model of Ria Formosa lagoon and a discussion of the possible impacts of two different solutions for the Faro-Olhão inlet on the local hydrodynamics are presented.

The model results were analysed trough two perspectives: the impacts on the tidal prisms and the impacts on the circulation patterns.

In what concerns to the first issue it was concluded that both solutions will contribute for an increase of the tidal prism that crosses Faro-Olhão inlet. In any case, it was also shown that most probably the inlet section didn't reach yet an equilibrium stage and, even in the case that no other action will taken, the natural trend will be for an increase of the tidal prism.

In what concerns to the second issue it was concluded that any of the simulated solutions would contribute for a significant benefit in what concerns the maximum velocities that are related with the security problems.

The obtained results put also in evidence the important contribution that the models may give in the analysis of this kind of problems. They enable the integration of the local measured values transforming single point observations in pictures of the whole area, and giving the opportunity to test different solutions and evaluate their impacts at a low cost.

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