Analysis of hydrodynamic and transport phenomena in the 'Ría de Arousa': a numerical model for high environmental impact estuaries

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Abstract

In this paper, a numerical model for the simulation of the hydrodynamic and of the evolution of the salinity in shallow water estuaries is presented. The mathematical model consists of two coupled systems of differential equations: the shallow water hydrodynamic equations (that describe the evolution of the depth and of the velocity field) and the shallow water advective-diffusive transport equation (that describes the evolution of the salinity level). Some important issues that must be taken into account are the effects of the tides (including that the seabed could be exposed), the volume of fresh water provided by the rivers and the effects of the winds. Thus, different types of boundary conditions are considered. The numerical model proposed for solving this problem is a second order Taylor–Galerkin Finite Element formulation. The proposed approach is applied to a real case: the analysis of the possible effects of dredging *Los Lombos del Ulla*, a formation of sandbanks in the Arousa Estuary (Galicia, Spain). A number of simulations have been carried out to compare the actual salinity level with the predicted situation if the different dredging options were executed. Some of the obtained results are presented and discussed.

1 Background

Los Lombos del Ulla is a natural formation of sandbanks, lying downstream the Ulla River, within the tidal Arousa Estuary (*La Ra de Arousa*) in Galicia (northwestern region of SPAIN, EU). Figure 1 shows the whole estuary. The Ulla River

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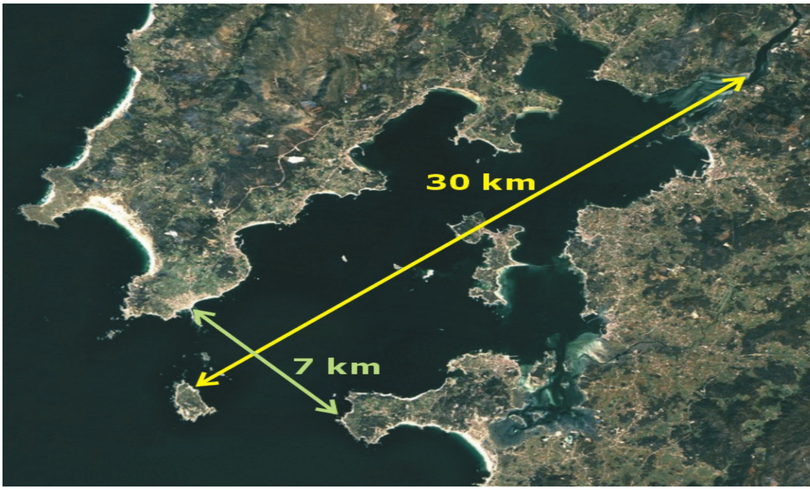

Figure 1: Satellite image of the Arousa Estuary. (Courtesy of VideaLAB, ETSICCP–UDC.)

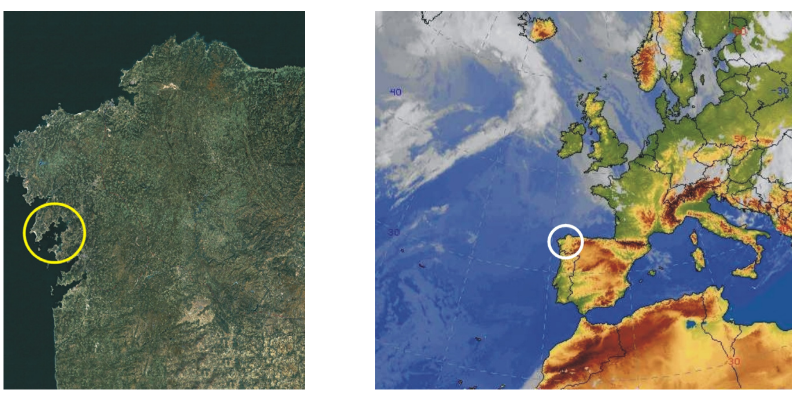

Figure 2: Satellite image of Galicia and stereographic polar image of Spain. (Courtesy of VideaLAB, ETSICCP–UDC and of *Instituto Nacional de Meteorología*.)

and *Los Lombos del Ulla* are located in the upper right corner of the image. Figure 2 shows the geographic position of the estuary.

The area is very rich in seafood, specially in bivalves: clams, cockles, mussels, scallops, etc. Hence, farming of bivalves is a major economic issue and the source of an extensive complementary industry (restaurants, fish canning factories, etc.)

Sand was regularly extracted from the Ulla River in the past. However, this practice is strictly forbidden by the environmental laws since a few decades.

Figure 3: *Los Lombos del Ulla* circa 1995. (Courtesy of VideaLAB, ETSICCP–UDC.)

Thus, the ban on sand extraction could be speeding up the accumulation of sediments in the zone (see Fig. 3). The fishermen unions fear that the reducing depth due to the accumulation of sediments, with the concourse of the winds and of the high volume of freshwater provided by the river, could be slowing down the mixing, what could cause the drop of the salinity level in the zone due to the stagnation of fresh water. Recent biological studies show that a slight fall in the salinity level is associated to an expected proportional fall in the shellfish productivity. And, if further falls in the salinity level occur, most individuals in the bivalve colonies could die, although entire colonies of some species would try to migrate in search for better living conditions (letting themselves to be dragged by the flow). Therefore, the gradual accumulation of sediments in *Los Lombos* could cause a permanently low level of salinity in the area, and the consequent huge loss in the local shellfish industry.

By the early 90's, the Spanish coastal authorities considered several options in an attempt to restore the navigation conditions and to mitigate the supposedly harmful effects of the accumulation of sediments on the shellfish productivity. The proposed solution was the dredging of a channel in the direction of the main stream. However, the dredging was not entirely carried out, due to the environmental impact of some badly implemented operations and to the complaints of the affected fishermen.

In 2002 the *Xunta de Galicia* (the Regional Government) started to design a new plan for *Los Lombos del Ulla* with the following two goals: a) to preserve the shellfish productivity, and b) to restore the navigation conditions in the area. Two actions were initially considered: 1) to dredge a navigation channel (as it had been proposed about a decade before), and 2) to dredge the whole area, in order to increase the depth. In fact, the latter became an unyielding demand of the fishermen unions.

The main objective of this project was the development of a numerical model that could be used to evaluate the effect of the proposed actions on the shellfish productivity of the zone [1]. Furthermore, the information provided by this tool would be used to assess the undesirable side effects of the possible actions (changes in the hydrodynamics of the zone), to evaluate the medium-term and the long-term stability of the sandbanks (the future possible accumulation of sand), and to evaluate the environmental impact of the works (the possible stirring and dragging of solid particles of the seabed and/or their diffusion to other areas).

2 Mathematical model

In essence, two coupled models must be considered: a hydrodynamic model (to obtain the velocity field) and an advective-diffusive transport model (to predict the evolution of the salinity level). Some important issues that must be taken into account are the effects of the tides (including that the seabed could be exposed) the volume of water provided by the Ulla River and the effects of the winds.

The Arousa Estuary can be considered a shallow water domain, since the depth is small when compared to the other two spatial dimensions. Therefore the hydrodynamic phenomena can be adequately described by means of the shallow water hydrodynamic equations [2, 3]. This is a known 2D model, that is obtained by vertical integration of the Navier–Stokes equations [4]. In essence, in this approach one assumes that the vertically averaged velocity at each point can be considered representative of the velocity field in the corresponding vertical column of water.

In a similar way, we expect the vertically averaged salinity at each point to be representative of the salinity field in the corresponding vertical column of water. Thus, the transport of salt can be adequately described by means of a shallow water type transport model [2, 5, 6] that is obtained by vertical integration of the advection-diffusion equations [4].

The registers of salinity in *Los Lombos* show that the vertical distribution is almost uniform, with a very weak stratification in the area of interest. Hence, it seems that there is no need to implement a multiple-layer model in this case.

Thus, for each point (x, y), at each time step t, the unknowns to be computed will be the depth $h(x, y, t) = z(x, y, t) - z_b(x, y)$, where $z(x, y, t)$ is the sea surface height and $z_b(x, y)$ is the seabed height, the velocity vector $\boldsymbol{v}(x, y, t) = [v_x(x, y, t), v_y(x, y, t)]^T$ (vertical average of the horizontal velocity) and the salinity $c(x, y, t)$ (vertical average of the salt concentration). Then, the whole set of shallow water equations (hydrodynamic and transport) can be written in a conservative form [2, 4] as

$$\frac{\partial \boldsymbol{u}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} = \boldsymbol{R}^S + \frac{\partial \boldsymbol{R}_x^D}{\partial x} + \frac{\partial \boldsymbol{R}_y^D}{\partial y}, \quad \boldsymbol{u} = \left\{ \begin{array}{c} h \\ hv_x \\ hv_y \\ hc \end{array} \right\}, \tag{1}$$

being the so-called source term

$$\boldsymbol{R}^S = \left\{ \begin{array}{c} 0 \\ fhv_y + g(h-H)\frac{\partial}{\partial x}H + \tau_x \rho^{-1} - n^2 g h^{-1/3} |\boldsymbol{v}| v_x \\ -fhv_x + g(h-H)\frac{\partial}{\partial y}H + \tau_y \rho^{-1} - n^2 g h^{-1/3} |\boldsymbol{v}| v_y \\ 0 \end{array} \right\}, \tag{2}$$

being the so-called inviscid flux terms

$$\boldsymbol{F}_x = \begin{Bmatrix} hv_x \\ hv_x^2 + \frac{1}{2}g(h^2 - H^2) \\ hv_xv_y \\ hcv_x \end{Bmatrix}, \ \boldsymbol{F}_y = \begin{Bmatrix} hv_y \\ hv_xv_y \\ hv_y^2 + \frac{1}{2}g(h^2 - H^2) \\ hcv_y \end{Bmatrix}, \qquad (3)$$

and being the so-called diffusive flux terms

$$\boldsymbol{R}_x^D = \begin{Bmatrix} 0 \\ 2h\mu\rho^{-1}\frac{\partial}{\partial x}v_x \\ h\mu\rho^{-1}\left(\frac{\partial}{\partial x}v_y + \frac{\partial}{\partial y}v_x\right) \\ h\gamma\frac{\partial}{\partial x}c \end{Bmatrix}, \ \boldsymbol{R}_y^D = \begin{Bmatrix} 0 \\ h\mu\rho^{-1}\left(\frac{\partial}{\partial x}v_y + \frac{\partial}{\partial y}v_x\right) \\ 2h\mu\rho^{-1}\frac{\partial}{\partial y}v_y \\ h\gamma\frac{\partial}{\partial y}c \end{Bmatrix}. \qquad (4)$$

In the above expressions, f is the Coriolis' coefficient, g is the gravity acceleration, H is the average depth at each point (bathymetry), $\boldsymbol{\tau} = [\tau_x, \tau_y]^T$ is the tangential stress due to the wind friction, ρ is the water density, n is the Manning's coefficient (modelling the energy losses due to the seabed friction), μ is the dynamic viscosity and γ is the total diffusivity (that includes the combined effect of the molecular diffusion, the turbulent diffusion and the dispersive diffusion [6]). The Coriolis' coefficient f is defined in terms of the latitude of the place ϕ and of the angular velocity of rotation of the Earth Ω as $f = 2\Omega\sin(\phi)$. Furthermore, the tangential stress due to the wind $\boldsymbol{\tau}$ is computed from the wind velocity $\boldsymbol{v}_w$ by means of the well known Ekman's formula

$$\boldsymbol{\tau} \;=\; \kappa|\boldsymbol{v}_w|\boldsymbol{v}_w, \quad \text{with} \quad \kappa \;=\; 3.2\;10^{-3}\,\mathrm{N\,s^2/m^4}, \qquad (5)$$

and the total diffusivity γ is obtained from the depth h and the velocity $\boldsymbol{v}$ by means of the Elder's formula [6]

$$\gamma \;=\; 0.6\,h\,|\boldsymbol{v}|. \qquad (6)$$

With regard to the boundary conditions, we have three different situations.

In the part of the boundary that corresponds to the mouth of the Ulla River we can suppose that the flow is super-critical (what precludes the conditions in the estuary to influence the upstream flow). Thus, we prescribe the flux and the salinity as

$$h\,\boldsymbol{v}^T\boldsymbol{n} = -h\,\frac{Q_R}{A(h)} \quad \text{and} \quad c = 0 \quad \text{on the river}, \qquad (7)$$

where Q_R is the known volume of flow in the river, $A(h)$ is the area of the wet section of the river and $\boldsymbol{n}$ is the external normal to the boundary. The salinity c is prescribed to be null, since the river flows fresh water into the estuary.

In the part of the boundary that corresponds to the sea we can suppose that the flow is sub-critical. Thus, we prescribe the depth and the salinity as

$$z = z_S(t) + \Delta z_S \quad \text{and} \quad c = c_S \quad \text{on the sea,} \tag{8}$$

where $z_S(t)$ is the prescribed depth due to the tide harmonics and Δz_S is the so-called meteorological tide. The meteorological tide is the rise or the fall of the surface level during a storm (due to the wind that blows on the whole fetch). It can be obtained from the corresponding measures and records of the seaports authorities.

Finally, we can state that both the flux of water and the flux of salt are null in the direction $\boldsymbol{n}$ of the normal to the shore, what gives

$$h\, \boldsymbol{v}^T \boldsymbol{n} = 0 \quad \text{and} \quad h\, \boldsymbol{grad}^T(c)\, \boldsymbol{n} = 0 \quad \text{on the shore.} \tag{9}$$

3 Numerical model

The above stated problem must be solved numerically. In order to do so, we will use the Finite Element Method. More specifically, we will solve the problem by means of a second order Taylor–Galerkin approach [2, 4, 7, 8].

In essence, at each time step the following linear system of equations is solved (space integration)

$$\sum_I [M_{JI}]\, \boldsymbol{w}_I(t_n) = \{\boldsymbol{f}_J\}\,|_{t=t_n}, \quad \text{with}$$

$$[M_{JI}] = \left[\iint_{(x,y)\in\Omega} \phi_J\, \phi_I\, d\Omega \right] \quad \text{and}$$

$$\{\boldsymbol{f}_J\} = \left\{ \iint_{(x,y)\in\Omega} \left[\phi_J\, \boldsymbol{b} + \underset{\sim}{\boldsymbol{A}}\, \mathbf{grad}(\phi_J) \right] d\Omega - \int_{(x,y)\in\partial\Omega} \phi_J\, \underset{\sim}{\boldsymbol{A}}\, \boldsymbol{n}\, d\partial\Omega \right\}. \tag{10}$$

Then, the solution is updated (time integration) by neglecting third order errors, what gives the second order accurate expression

$$\boldsymbol{u}_I(t_{n+1}) = \boldsymbol{u}_I(t_n) + \Delta t\, \boldsymbol{w}_I(t_n). \tag{11}$$

The coefficients matrix in system (3) is the so-called ‘mass matrix’. This linear system can be solved by using a Diagonal Preconditioned Conjugate Gradient algorithm without assembling the global matrix. Alternatively, the solution to (3) can be approximated by using the so-called diagonal lumped mass matrix [2]. This has been the procedure that was finally used in this project.

4 Discretization and bathymetry

Although the area of interest (*Los Lombos del Ulla*) is relatively small, we are forced to analyze the whole estuary (see Fig. 1) in order to impose the sea boundary

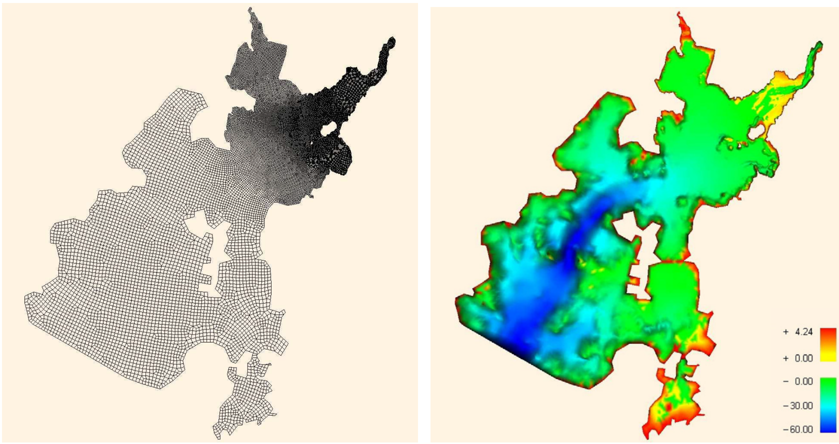

Figure 4: GEN4U discretization of the estuary (left). Actual bathymetry (right).

conditions far enough from the area of interest, and in order to take into account the influence of the whole estuary in the hydrodynamics.

The estuary was discretized by the Gen4u mesh generator [9, 10] in 30970 isoparametric quadrangular elements of 4 nodes, what yields 120424 degrees of freedom (30106 nodes times 4 d.o.f. per node) at each time step (see Fig. 4).

Approximately half of the total elements (14979) are placed in *Los Lombos del Ulla* while the rest are spread in the rest of the estuary, what is the most extensive part. The size of the elements gradually grows as we move away from *Los Lombos*. Thus, we seek more precise results in the area of interest. But, also, we try to avoid the stability conditions [2] to become excessively restrictive, since the largest elements are located in the deepest areas (where the velocity of propagation of the gravity waves is higher).

The actual bathymetry of the whole estuary was obtained from some measurements specifically made in *Los Lombos* during 2002, from the charts of the estuary and from the available topographic data of the shore [1]. The bathymetry that corresponds to the first possible action (dredging a navigation channel) was obtained from the actual bathymetry by dropping the corresponding values of the seabed height down to the level -1.5 m. The bathymetry that corresponds to the second possible action (general dredging of *Los Lombos*) was obtained from the actual bathymetry by dropping the corresponding values of the seabed height down to the level -0.5 m, but limiting the drop to 0.75 m in each point at the most [1].

5 Program of simulations

Two types of simulations were carried out: 28 days simulations in normal conditions (NC) and 2 days simulations in extreme conditions (EC) [1]. The 28 days

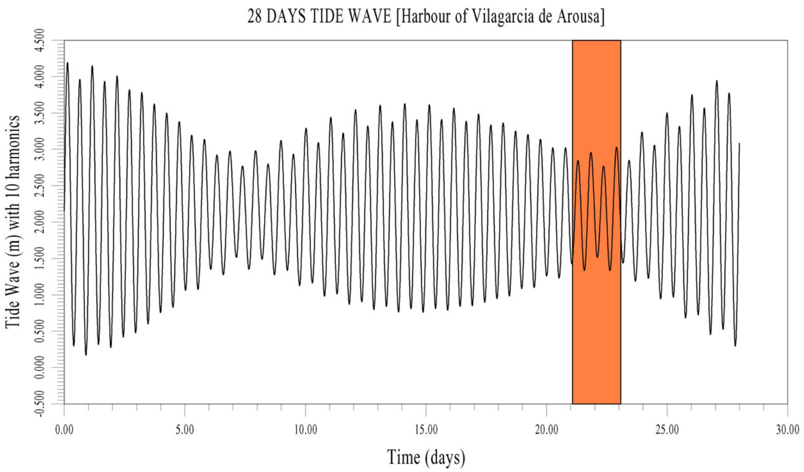

Figure 5: 28 days tide wave. The subinterval corresponds to the 2 days simulations.

simulations compare the results obtained for the actual bathymetry (i.e., the current situation) with the results predicted for each one of the two possible actions (dredging a navigation channel and dredging the whole area of *Los Lombos*). The second option was discarded after analyzing these results. Thus, the 2 days simulations only compare the results obtained for the current bathymetry with the results predicted for the first possible action (dredging a navigation channel). In the NC simulations we considered the average volume of water ($Q_R^{MED} = 56\ \mathrm{m}^3/\mathrm{s}$) in the Ulla River, and the average velocity wind ($\boldsymbol{v}_W^{MED} = 4.8\ \mathrm{m/s}$) blowing in the dominant direction (202° S–SW) without meteorological tide ($\Delta z_S = 0$ m). On the other hand, 5 different extreme conditions were defined: SouthWest storm (EC#1), flood condition (EC#2), SouthWest storm and flood condition (EC#3), NorthEast storm and flood condition (EC#4) and NorthEast storm (EC#5). In the EC#2, EC#3 and EC#4 simulations we considered the flood volume of water ($Q_R^{MAX} = 300\ \mathrm{m}^3/\mathrm{s}$) in the Ulla River. In the other ones (EC#1, EC#5) we considered the average volume of water (Q_R^{MED}) in the Ulla River. In the EC#1 and EC#3 simulations we considered the maximum velocity wind ($v_W^{MAX} = 15.0\ \mathrm{m/s}$) blowing in the most adverse direction (210° SW) with positive meteorological tide ($\Delta z_S = 0.15$ m). In the EC#4 and EC#5 simulations we considered the maximum velocity wind (v_W^{MAX}) blowing in NE direction (30° NE) with negative meteorological tide ($\Delta z_S = -0.15$ m). In the remaining simulation (EC#2) we considered the average velocity wind (v_W^{MED}) blowing in the dominant direction (202° S–SW) without meteorological tide ($\Delta z_S = 0$ m).

We took the following values for the physical constants of the problem: $\Omega = 2\pi/86164.09\ \mathrm{rad/s}$, $\phi = 43^\circ\ 35'\ 58''$, $g = 9.81\ \mathrm{m/s}^2$, $\rho = 10^3\ \mathrm{Kg/m}^3$,

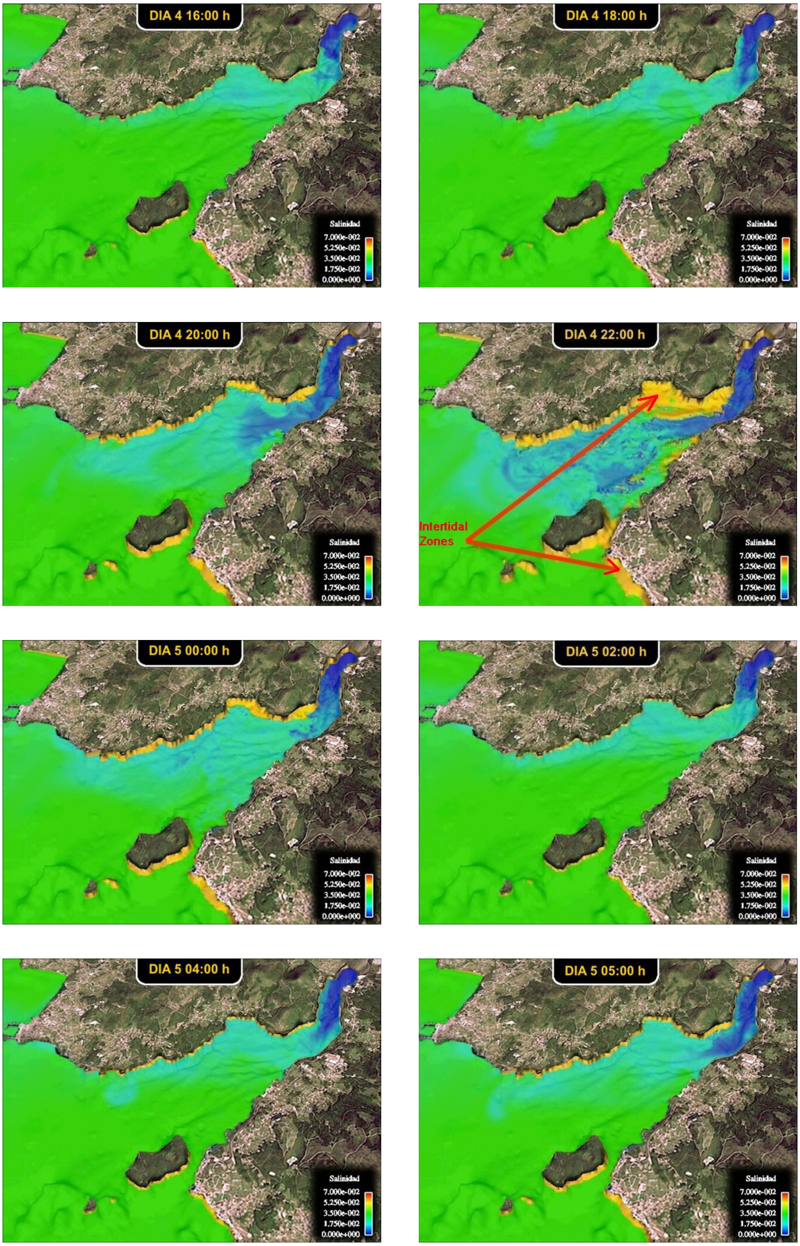

Figure 6: Evolution of the salinity in *Los Lombos* (actual bathymetry case). The salinity level is recovered during the spring tide cycles due to the periodic emptying of part of the basin and the subsequent filling with salt water.

$n = 0.0425$ s/m$^{1/3}$, $c_S = 0.035$ and $\mu = 50$ Kg/ms. Finally, the tide was modelled by adding up the first 10 harmonics of the corresponding Fourier series, as given in the Spanish seaports authority website [11]. Fig. 5 shows the 28 days tide wave and the 2 days tide wave that were used for the NC and for the EC simulations.

6 Analysis of results and conclusions

The numerical results of the model have been compared with data given by the experts in the hydrodynamics of the area, with measurements performed during the project and with computed results obtained with simpler models. The results agree with the available data and the model predicts correctly the main hydrodynamical phenomena that are observed in the estuary.

The periodic emptying (and almost complete) of *Los Lombos* due to the low tide during the spring tide cycles is the essential process that allows to maintain the average level of salinity in the area (see Fig. 6). During the neap tide cycles, the salinity level inexorably falls due to the continuous contribution of freshwater from the river. During the spring tide cycles, the salinity level is recovered due to the emptying of an important part of the basin and the periodic contribution of salt water from the sea. For this reason, we absolutely advised against a general dredging of *Los Lombos*. As it is observed in the simulations, a general dredging causes an important decrease in the average salinity level in all the area.

However, the dredging of a channel does not significantly modify the salinity level in *Los Lombos*. Thus, the shellfish production of the area would not be substantially affected, while the navigation conditions in the area could be improved.

The presented model contributes to know the marine habitat. It shows how important are the different processes involved in the hydrodynamics of an estuary. It provides useful and accurate information that can be used to predict the migration of the shellfish colonies depending on the salinity level and on the currents. And it allows to predict the effects of Civil Engineering public works and other human actions (dredging, spillings, etc.) and to evaluate their environmental impact.

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