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Mathematical modelling of salt water intrusion in a northern Portuguese estuary

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Abstract Salinity intrusion is a key issue for estuarine water quality management. Aquatic ecosystem sustainability is highly dependent on salinity concentration dynamics and must be studied for each particular environment. Salinity intrusion into the estuary of the River Lima, in the northwestern region of the Iberian Peninsula, was studied based on a two-dimensional hydrodynamic and mass transport model. Tide heights and river discharges are the major causes affecting salinity intrusion, and have been analysed by means of estuarine circulation simulation for different scenarios. The upstream propagation of the salinity front under unfavourable conditions reaches a river section located at about 12 km upstream of the river mouth. The model developed constitutes a powerful tool for evaluation of the salinity intrusion pattern in the River Lima estuary, and an auxiliary instrument for decision making in river basin water management.

Key words hydrodynamics; mathematical modelling; salt intrusion

INTRODUCTION

The study of estuaries is very difficult since these water systems usually involve complex geometries, hydrodynamics, and transport patterns. In fact, the interface between fresh and salt waters forced by river discharges, tides and wind presents specific characteristics that affect the mixing properties of the estuarine water masses. There is great variability in estuaries depending on the differences in the tides, river discharges and the way these factors interact with topography (Dyer, 1997).

The salinity distribution within the estuary is commonly used for classification purposes (Pritchard, 1955; Cameron & Pritchard, 1963, cited in Dyer, 1997). However, an estuary's salinity structure can be modified by alterations of the river discharge regime caused by dam construction and bathymetric changes due to either sediment flux variation or sand removal. These modifications can significantly impact established water uses such as agricultural, domestic and industrial supply.

The extent of salinity intrusion depends on the balance between freshwater discharges and saltwater flow from the sea. This phenomenon can be reasonably predicted using mathematical models supported by monitored data. These tools can be used to quantify how much freshwater is required to counterbalance salinity intrusion at the upstream water intakes.

In the River Lima estuary, located in the northern region of Portugal, hydro-informatic tools are being used for assessing the salinity intrusion in this water body. The tools include two main components: a hydrological model of the river basin, and a hydrodynamic/transport model (WES-HL, 1996, 2000) of the lower section of the river. This paper presents preliminary results of mathematical modelling of the second modelling component. Salinity spatial distribution is characterized for a set of scenarios established according to the key processes affecting the extent of salinity intrusion. Moreover, these results will be used to define a monitoring program to collect data for model calibration and validation.

METHODOLOGY

Mathematical formulations

Saltwater intrusion analysis must be based on a fully dynamic model description. In the absence of stratification, the RMA2/RMA4 software (WES-HL, 1996, 2000) packages are an excellent tool for predicting salinity intrusion. If vertical stratification prevails, a two-dimensional vertical modelling approach or a three-dimensional (Pinho, 2001) approach must be applied.

Different criteria, such as the *flow ratio* or the *estuary number* (Dyer, 1997) for anticipation of stratification conditions can be used. These criteria are generally based on the ratio of both river and tidal flows. For the River Lima estuary salinity intrusion studies, the application of the above mentioned criteria leads to a classification of either stratified, partially mixed and well mixed conditions, depending on the river flow regime considered. However, stratified conditions are always confined to the lower estuary and well mixed conditions occur when the most severe salinity intrusions take place associated with extreme low flow events. Given these preliminary results, well mixed conditions for the estuary were assumed, since the most unfavourable salinity intrusion scenarios correspond to low river discharges.

Hydrodynamic model

The two-dimensional in the horizontal plane (2DH) hydrodynamic model was implemented using the RMA2 software that is based on the finite element method (WES-HL, 1996). This model can be applied for situations where the water flow does not exhibit a significant vertical variation, as mentioned above. It solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the solved equations are:

$$\frac{\partial \eta}{\partial t} + \frac{\partial[(h+\eta)U]}{\partial x} + \frac{\partial[(h+\eta)V]}{\partial y} = 0 \tag{1}$$

$$\begin{aligned} \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} &= +fV - g\frac{\partial \eta}{\partial x} - \frac{g}{\rho}\frac{\partial \rho}{\partial X}\frac{h+\eta}{2} + \\ &+ \frac{\rho_a k W_v^2 \cos\varphi}{h+\eta} - \frac{gU\sqrt{U^2+V^2}}{(h+\eta)C^2} + \frac{\varepsilon}{\rho}\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) \end{aligned} \tag{2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-fU-g\frac{\partial \eta}{\partial y}-\frac{g}{\rho}\frac{\partial \rho}{\partial y}\frac{h+\eta}{2}+ \qquad (3)$$

$$+\frac{\rho_a k W_v^2 sen\varphi}{h+\eta}-\frac{gV\sqrt{U^2+V^2}}{(h+\eta)C^2}+\frac{\varepsilon}{\rho}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)$$

where x and y are the horizontal Cartesian coordinates, t is the time, U and V are the vertical average of the horizontal velocity components, ρ_a is the air density, W_v is the wind velocity, φ is the wind direction, C is the Chezy coefficient and ε is the turbulent viscosity coefficient, ρ is the water density, h is water depth, η is the water surface elevation, k is an empirical wind shear coefficient and f the Coriolis parameter.

Transport model

The mass transport model, RMA4 (WES-HL, 2000) is applied to simulate depth-average advection–diffusion processes in aquatic environments. The model can be used for the evaluation of any conservative substance that is either dissolved in the water or that may be assumed to be neutrally buoyant within the water column. The model is also used for investigating the physical processes of migration and mixing of a soluble substance in reservoirs, rivers, bays, estuaries and coastal zones.

The generalized computer program solves the depth-integrated equations of the transport and mixing process. The form of the depth averaged transport equation is:

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}(UC)+\frac{\partial}{\partial y}(VC)-\frac{\partial}{\partial x}(E_x\frac{\partial C}{\partial x})-\frac{\partial}{\partial y}(E_y\frac{\partial C}{\partial y})+k_C C=0 \qquad (4)$$

where, C is the local concentration of salt, E_x and E_y are the local dispersion coefficients in the x and y direction, respectively, and k_C is the local mass transfer rate from source/sink processes. This equation is solved numerically using a modified version of the RMA4 software (Pinho, 2001).

CASE STUDY

Study area

The international River Lima basin (Fig. 1), located in the northern region of the Iberian Peninsula, is mainly used for water supply, agricultural irrigation and hydropower generation. With a total drainage area of 2496.4 km^2, (47.1% of the area in Portugal and 52.9% of the area in Spain), the River Lima basin has a mean elevation of 437 m with several peaks above 1300 m, and an average population density of 112 inhabitants per km^2 (minimum of 10 at Melgaço and maximum of 363 at Viana do Castelo). The annual mean rainfall in the Portuguese part of the basin is 2164 mm. On average, 73% of the precipitation occurs during the humid season (six months) and 27% during the dry season. The main tributaries are the rivers Lagoa de Antela, Cadones, Castro Laboreiro, Vez, Labruja and Estorãos on the right side, and rivers Faramontaos, Salas, Vade and Trovela on the left side.

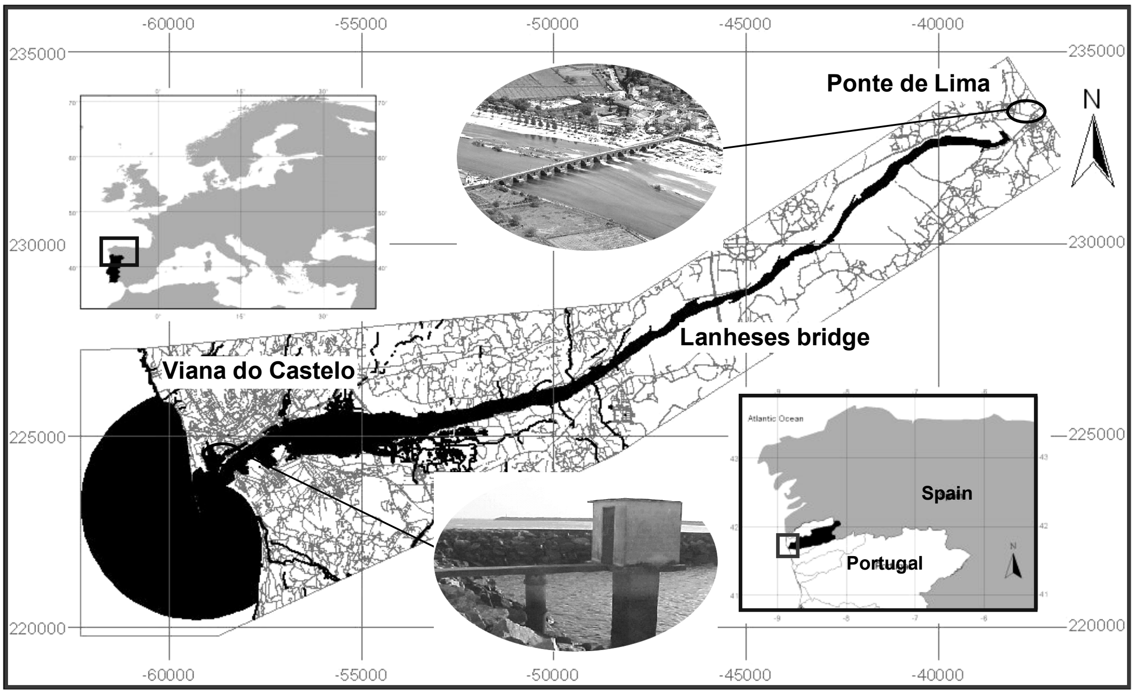


Fig. 1 Location of the study area.

Two hydropower plants (Lindoso and Touvedo) have been in operation since 1992 with an installed power of 656.0 MW. A storage volume of 274 hm^3 is possible with these two dams. This water use constitutes a determining factor that must be considered in any water management policy adopted for the salinity intrusion control.

The modelled area occupies the lower part of the river basin, where the main residential and industrial areas are located. For modelling purposes, the river reach considered in this study begins downstream of the Ponte de Lima weir and ends at the river mouth, a distance of approximately 22 km.

Model implementation

The River Lima estuary hydrodynamic and salt transport model was implemented using a finite element mesh with 6087 triangular quadratic elements (Fig. 2(b)). This mesh was generated considering a minimum interior angle of 25° and a maximum element area constraint of 10 000 m^2.

The bottom topography of the model was defined using bathymetric data collected during 2003 in the navigation channel of the Viana do Castelo harbour and related to the river profile depicted in Fig. 2(a)).

Two open boundaries were considered: an open ocean boundary at the estuary mouth (Viana do Castelo), and an open river boundary at the upstream section of the river (Ponte de Lima). At this location, the river discharges were imposed in the hydrodynamic model and a null concentration of salinity in the mass transport model. At the open ocean boundary surface tide elevations were imposed, estimated according to the

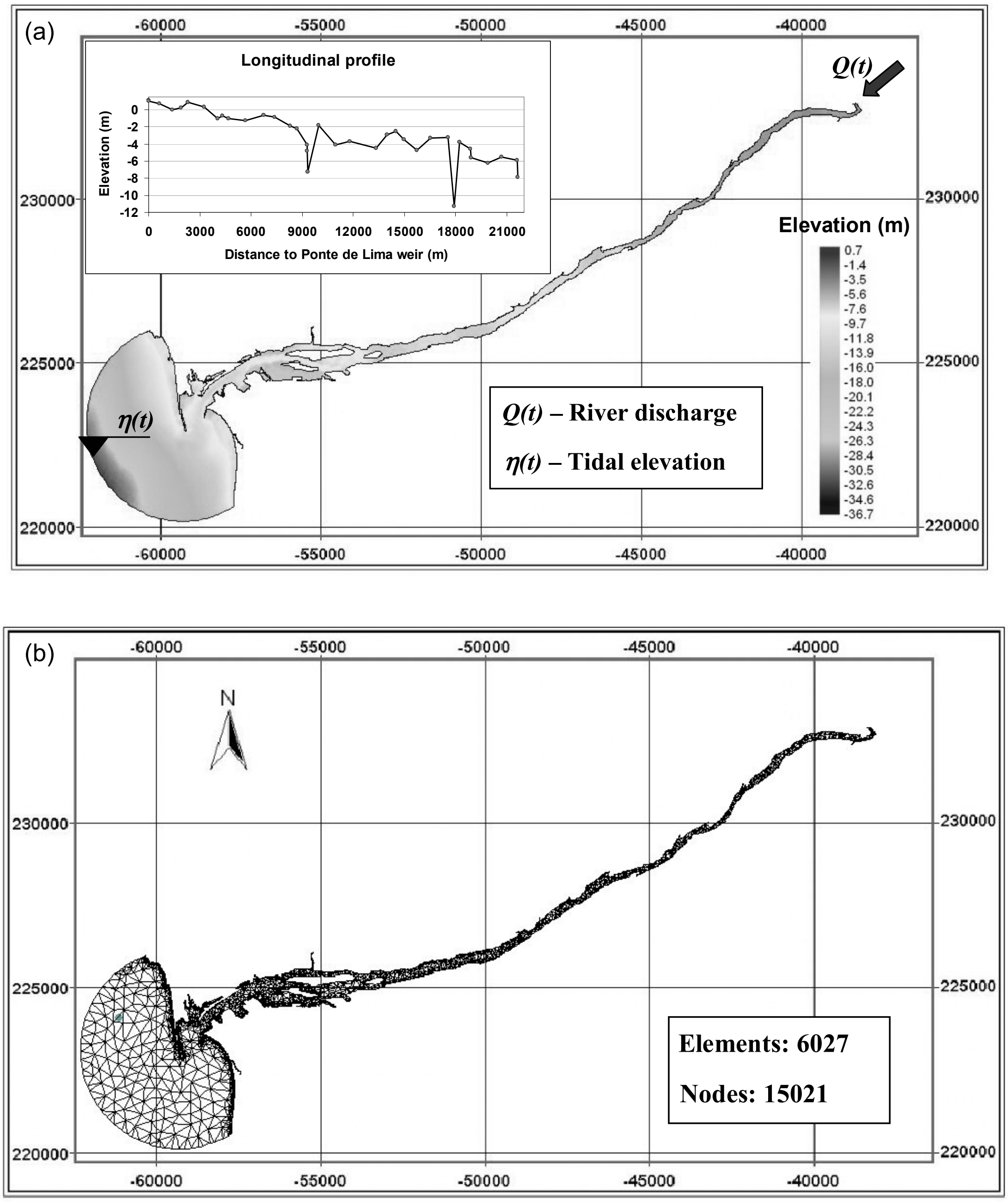


Fig. 2 Hydrodynamic and transport model: (a) bathymetry and longitudinal river profile; (b) 2DH finite element mesh.

Topex-Poseidon satellite observation data through the SR95 program (JPL, 1996). The average salinity concentration adopted at the ocean boundary was 35 psu.

Model calibration and validation

As mentioned earlier, the results obtained in this work will be used to define a comprehensive monitoring programme for collecting data for model calibration and validation. Selection of monitoring station locations for water level, current velocity and salinity concentration, as well as the choice of the most convenient field work period, will be made according to the preliminary results obtained with the hydrodynamic and mass transport model. Meanwhile, in the present work phase, model parameters were established using values determined in similar studies, available data for the Viana do Castelo tidal gauge station, and other qualitative data observed in the field. Thus, values of 40 $m^{1/3}$ s^{-1} for the Manning-Strickler equation coefficient and of 20 m^2 s^{-1} for the turbulent viscosity coefficient were adopted. Figure 3 depicts model computed (lines) and predicted (dots) tidal elevations at the Viana do Castelo tidal gauge station.

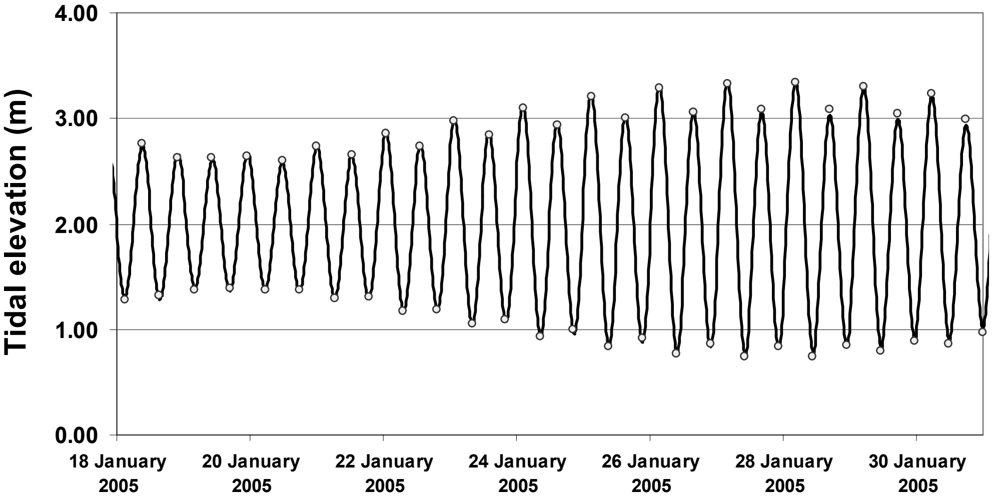


Fig. 3 Hydrodynamic model. Computed (lines) and predicted (dots) tidal elevations at the Viana do Castelo tidal gauge station.

The diffusion coefficient was automatically defined by the model after each time step, based upon a provided Peclet number, which is based upon the element size and calculated velocity within each element. This number is the non-dimensional parameter developed by taking the ratio of the advective terms to the diffusive terms in the governing equations.

RESULTS AND DISCUSSION

Simulated scenarios

Simulated scenarios were defined considering the two key actions on salinity intrusion: river discharge and tide height. The tide heights adopted are representative of the neap-spring tidal range. For river discharge, four different values were adopted: the minimum (9 m^3 s^{-1}) corresponds to the guaranteed mean discharge during the dry season (April to September) with a probability of 95%; the 54 m^3 s^{-1} value is approximately the guaranteed annual mean discharge with a probability of 50%; the value of 31.5 m^3 s^{-1} corresponds to an intermediate situation; and 300 m^3 s^{-1}, corresponding to a typical value for hydropower generation periods (hydropower plants have an installed capacity of about 250 $m^3 s^{-1}$).

The scenarios worked out are summarized in Table 1, which shows the adopted river discharge values at Ponte de Lima weir and tide height at the ocean boundary.

Table 1 Simulated scenarios.

River discharge ($m^3 s^{-1}$)	Tide height (m) Spring tide: 3.50	Average tide: 2.55	Neap tide: 1.60
9.0	S1	S2	S3
31.5	S4	S5	S6
54.0	S7	S8	S9
300.0	S10	S11	S12

These scenarios represent the most relevant situations for evaluation of the salinity intrusion. Comparison of scenarios S1, S4, S7 and S10 allows the evaluation of the river discharge effect during unfavourable tidal regimes. For each discharge it is also possible to analyse the effect of different tide heights on salinity intrusion by considering the scenarios belonging to each row of Table 1. The impact of the Alto Lindoso and Touvedo dams' discharge flows can be evaluated during spring tides (S10) and neap tides (S12). The total simulation time for all the scenarios considered was set at 96 hours in order to evaluate the effect of the different conditions on the extent of salinity intrusion.

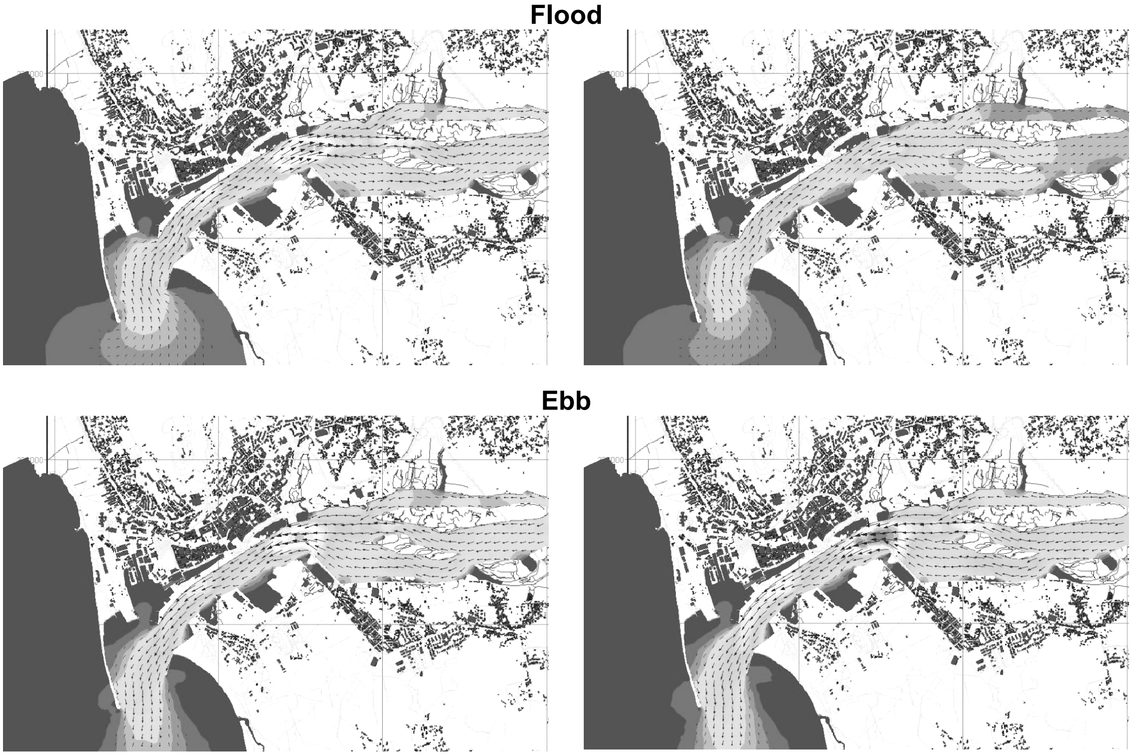
Hydrodynamics

The hydrodynamic simulations were carried out in two steps: in the first step the transient solution between a hydrostatic situation and the dynamic solution was achieved; and in the second step, two tidal periods were computed using, as initial conditions, results corresponding to the final time step of the solution previously computed. Although the model calibration process has not been yet completed it is possible to present some qualitative results (Fig. 4).

The maximum current velocities occur near the railway bridge of Viana do Castelo (Fig. 4) for the spring tide and for the lowest river discharge considered in the simulated scenarios during flood tide and for the maximum river discharge during ebb tide. The depth averaged velocity at this location varies from 84 cm s^{-1} (S1) to 62 cm s^{-1} (S10) during flood tide and from 92 cm s^{-1} (S1) to 106 cm s^{-1} (S10) during ebb tide.

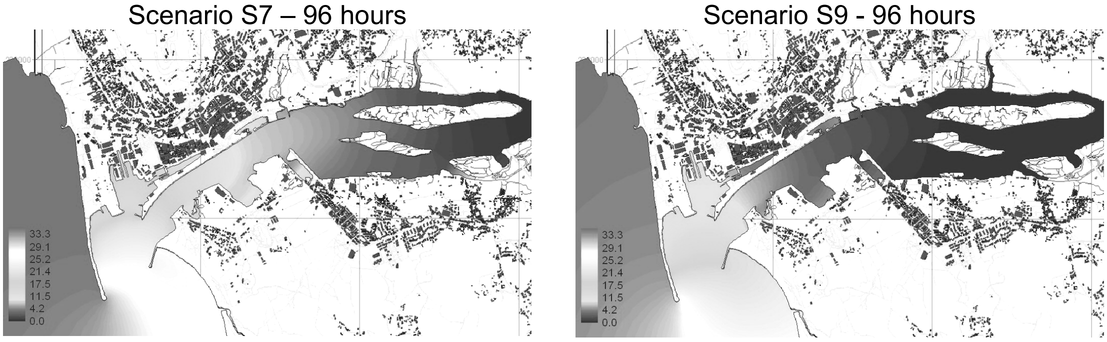
Salinity intrusion

The salinity gradient for average river discharges is limited to the estuary region located between the ocean boundary and the highway bridge (located near the right extremity of the bigger island, Fig. 5). However, it must be stressed that under these



Scenario S1 **Scenario S10**

Fig. 4 Hydrodynamic model: current velocities for the harbour zone during ebb and flood for scenarios S1 and S10.


Scenario S7 – 96 hours

Scenario S9 - 96 hours

Fig. 5 Salinity concentration for scenarios S7 and S9 after 96 hours of simulation time.

scenarios the model formulation applied (valid for well-mixed conditions) only gives a coarse approximation since stratified conditions are expected to occur. The results shown in Fig. 5 correspond to salinity concentrations for both spring and neap tides.

Definition of the maximum extent of salinity intrusion depends on the established concentration limit. For this work, a concentration of 1 psu was adopted. Moreover, the intrusion extent will be variable according to tide stage. For the most unfavourable scenario (S1) the extent variation during the last simulated tidal period is about 5600 m (Fig. 6).

Ebb tide – 82.5 hours Flood tide – 88.5 hours

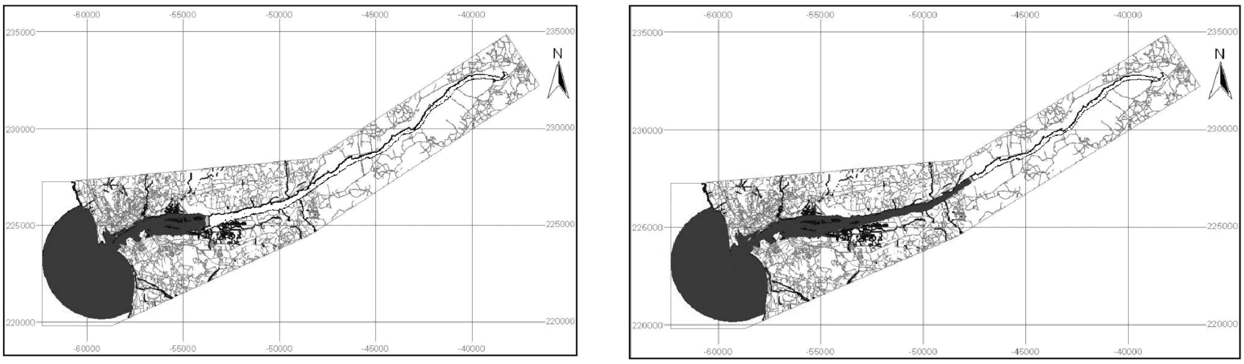
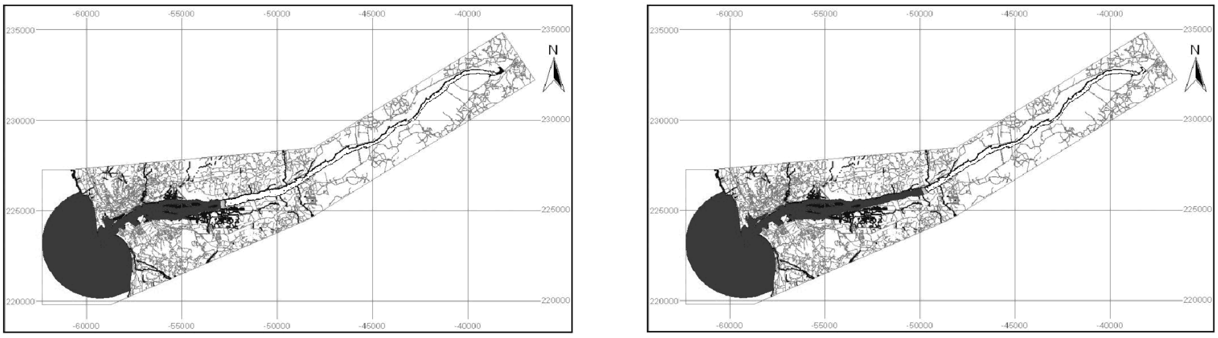


Fig. 6 Mass transport model: intrusion extent during ebb and flood under conditions of scenario S1.

Simulation time – 26.5 hours Simulation time – 26.5 hours



Simulation time – 26.5 hours Simulation time – 26.5 hours

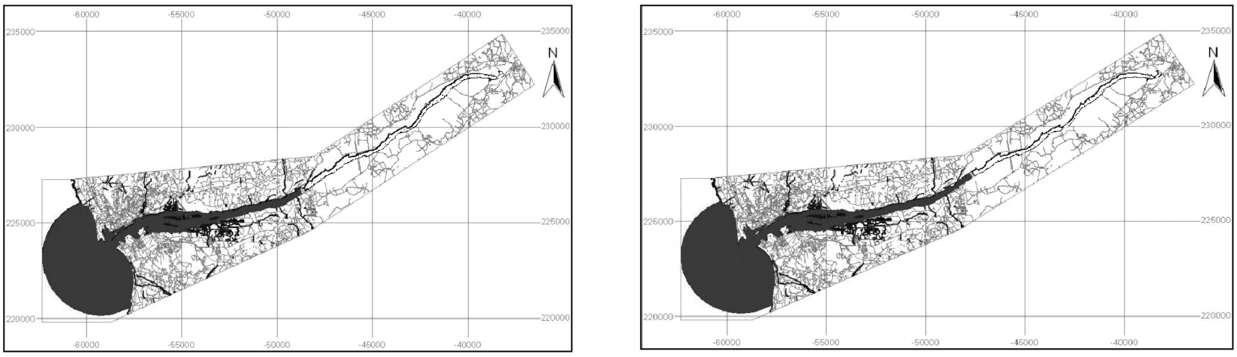
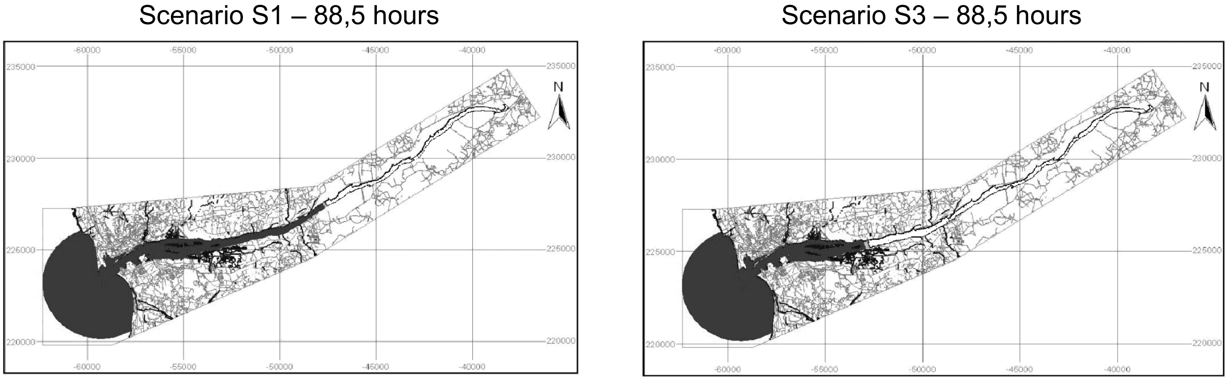


Fig. 7 Mass transport model: intrusion extent for successive tide flood events (S1).

The upstream propagation of the salinity front during a spring tide with a low river discharge can be observed in Fig. 7. The salinity intrusion, as defined before, reaches a river section located 11 800 m upstream of the river mouth (2300 m downstream of Lanheses bridge). From the simulation results obtained it is possible to estimate a front propagation average velocity of 130 m h^{-1}.

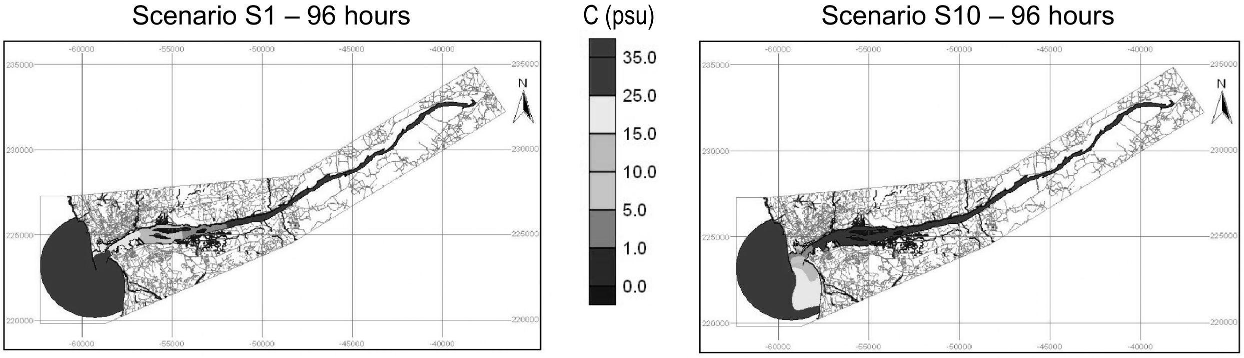
The influence of the two key actions in the salinity intrusion can be observed in Figs 8 and 9. The occurrence of spring or neap tidal conditions implies a difference in



Scenario S1 – 88,5 hours

Scenario S3 – 88,5 hours

Fig. 8 Mass transport model: intrusion extent for different tidal conditions.



Scenario S1 – 96 hours

Scenario S10 – 96 hours

Fig. 9 Mass transport model: salinity concentration gradient for the adopted extreme river discharges.

the extent of salinity intrusion of 5700 m, using the concentration limit (1 psu) previously mentioned.

River discharge flows of higher than 54 $m^3 s^{-1}$ (S7) during spring tides lead to salinity concentrations lower than 5 psu in the estuary zone downstream of the railway bridge. However, this location must be confirmed by field work or reference to a transport model capable of simulate stratified conditions.

CONCLUSIONS

The extent of salinity intrusion in the River Lima estuary was estimated using a 2DH hydrodynamic and mass transport model. Variations of the salinity front propagation with tide height and river discharges were evaluated. From the results obtained it can be concluded that the salinity intrusion reaches a river section located about 12 km upstream of the river mouth, under the most unfavourable conditions (spring tides and low flow river discharges). For greater river flows, the salinity gradients occur mainly downstream of the highway bridge (5 km from the river mouth). However, for these conditions a more accurate evaluation is required using a three-dimensional model.

The results achieved will be used as an important auxiliary source of information when selecting gauge stations for measurements of tidal water elevations, current velocity, and salinity concentrations.

Once adequately calibrated, the model developed will be a powerful tool in assessing the impacts of bathymetric alterations on the salinity intrusion. Also, it can be used to establish operational discharge schemes for the upstream hydropower plants that will safeguard the downstream water intakes.

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