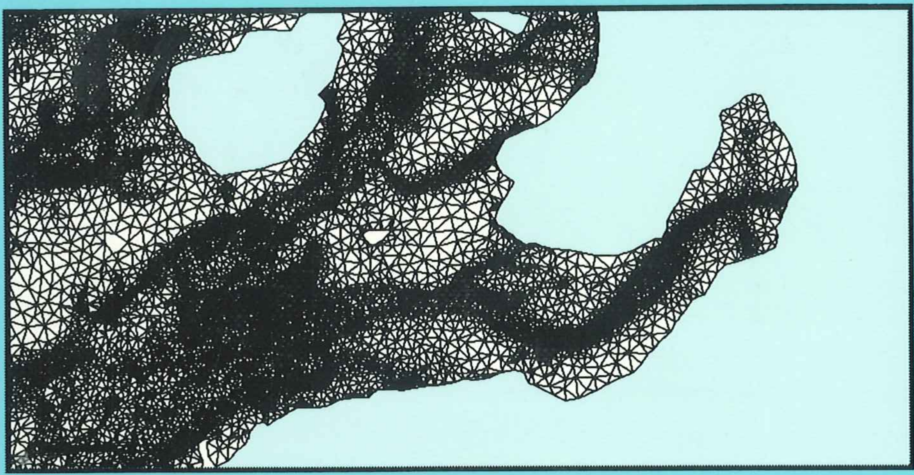
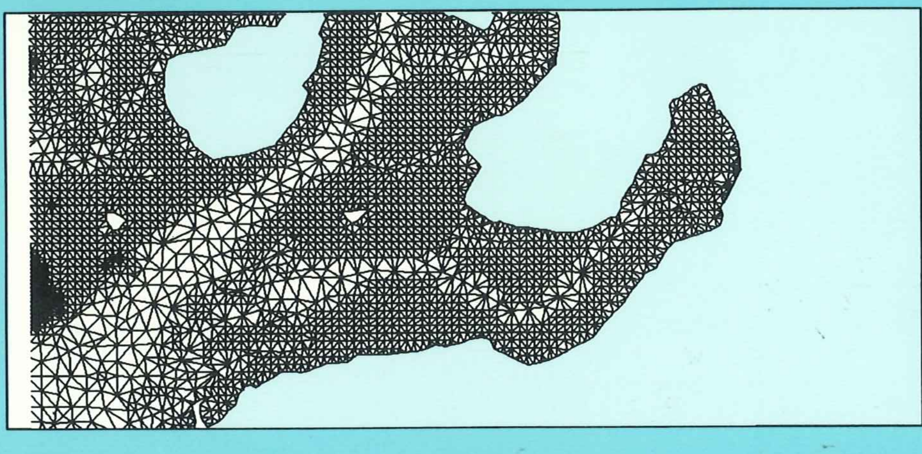
Coastal Environment

Environmental Problems in Coastal Regions

Editors: A.J. Ferrante and C.A. Brebbia





Computational Mechanics Publications

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Numerical modelling of tidal fluxes and passive pollutants concentration in Ria de Aveiro, Portugal

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Abstract

Ria de Aveiro is a shallow lagoon in the North of Portugal, extremely polluted, mainly as a consequence of the big chemical industries located in its neighbourhood.

The purpose of this work is to predict tidal flow fields as well as passive pollutants transport processes in the lagoon, to better understand its normal behaviour and the consequence of the discharges of pollutants *in situ*.

A two-dimensional finite difference numerical model, capable of predicting depth averaged tidal flow fields in estuarine waters has been adapted and extended to this area. The partial differential equations governing the conservation of mass and momentum in an incompressible turbulent flow are included in a depth-integrated form in the model.

The results reveal that bathymetry and coastal morphology strongly influence the circulation patterns and the pollutants concentration distribution in Ria de Aveiro. It is also possible to conclude that the dynamics of Ria de Aveiro is predominantly governed by the tidal wave which spreads the pollutants through almost all the lagoon.

1 Introduction

Estuaries and lagoons are areas of great importance in several ways: biologically, they can be considered as being rich in nutrients and organic mater, and as highly productive environments; they provide good natural conditions for harbour, navigation and recreation facilities and provide a source of fresh water for domestic and industrial uses as well as a place for receiving domestic and industrial wastes; they also offer good conditions for agricultural development along its borders.

Ria de Aveiro is a lagoon connected with the Atlantic Ocean, with geographic characteristics that lead to the existence of big industries and more than 300000 people around its channels, which are responsible by several environmental problems. The study of these problems must be based upon an understanding of the biological, chemical and geological processes, which are highly dependent on the lagoon's hydrodynamics, and implies the existence of an extensive data base on quite a number of water quality and physical parameters. In what concerns Ria de Aveiro such a data base does not exist. Therefore, the development of a numerical model of complex dynamics has become a necessary field of research to better understand those processes.

Such model must be able to combine sophisticated physics with high spatial and temporal resolution, fast computational speed and efficient data storage. With the declining cost and wider availability of computer resources, numerical modelling of natural hydrodynamic systems, combined with observation studies, should become an efficient tool for understanding the physics of these systems and to predict the impact and need of human intervention.

In the present study, an enhanced version of the 2-D time-dependent numerical model by Leendertse[1,2] was used to predict tide induced water level, depth mean velocity and passive pollutants concentration in Ria de Aveiro.

2 Topographical and physical characteristics of Ria de Aveiro

Ria de Aveiro is a shallow lagoon in the North coast of Portugal (38°5'N, 8°44'W), with a very irregular and complex geometry (Fig.1) characterised by narrow channels and connected with the Atlantic through an artificial channel, opened in the beginning of the XIX century in the sand bar separating it from the sea.

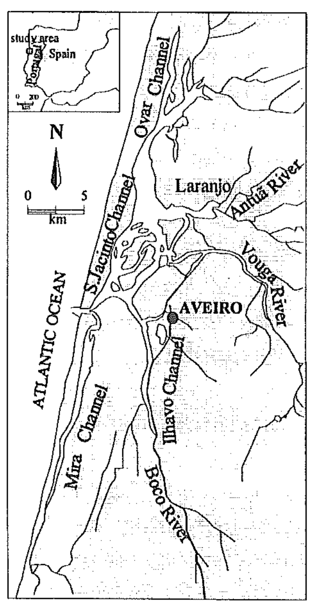

Figure 1: Geographic map of Ria de Aveiro.

Morphologically Ria de Aveiro is a typical bar-built estuary, having experienced incision during an ice age and subsequent inundation, but recent sedimentation has equilibrated the inundation.

There are three main branches radiating from the sea entrance. Mira channel, which runs to the south and is long, narrow and shallow. S.Jacinto channel, running northwards, begins by being wide and deep but changes form and character as it extends to the north, giving a complex network of bays, channels and dead arms of variable depth and shape. Finally, there is a third channel running eastwards towards the town of Aveiro, which is dredged to a depth of about 7 m to allow ship movements associated with the port activity. Ria de Aveiro has a mean depth smaller than 1 m with zones of tidal flats (Fig.3), except in navigation channels where dredging operations are carried out. Due to the small depth and depending on the tidal wave amplitude there are zones which are alternately wet and dry during each tidal cycle. With maximum length and width of 45 Km and 10 Km respectively, the lagoon covers an area of 47 Km^2 at the highest tide which is reduced to 43 Km^2 at the lowest tide.

Vouga and Antuã rivers, located on the east side, are the main sources of fresh water input into the lagoon. The input of salt water occurs through the main channel by the penetration of the tidal wave which propagates from south to north along the west coast of Portugal.

The tides are predominantly semi-diurnal. They have a mean range of 1.8 m at the mouth and propagate as progressive waves coming from the continental shelf, generating tidal currents with maximum speeds of about 1.0 m/s. Non-tidal contributions to the circulation include wind-driven currents during small periods and gravitational flow due to gradients of density formed by fresh runoff water and seawater. The resulting flow is modified by the frictional drag due to bottom roughness and by the channels geometry.

Vouga river is the main source of fresh water supplying about 65% of a total mean discharge (in a tidal cycle) of 1.8×10^6 m^3 into the lagoon (Vicente[3]). The mean tidal volume flux entering through the mouth is 60×10^6 m^3 (Vicente[3]); therefore, the ratio of tidal to fresh water volume flux reflects the relatively low level density stratification in Ria de Aveiro, placing it in the well mixed category following Pritchard classification. The hydrodynamics of the lagoon is affected by river runoff only in flood periods of Vouga river, in Winter months.

3 The numerical model

The flow in estuaries and lagoons is time-dependent and three-dimensional. However, except when large river runoff occurs, the water column in Ria de Aveiro can be considered well mixed. The salinity results presented by Queiroga[4] confirms this assumption. Considering that the thickness of the fluid layer is small compared with any horizontal length scale the 3D mathematical problem can be reduced to a 2D one, and the computation of the water movement is made solving the shallow water equations.

3.1 The governing equations

In the hydrodynamic model, the differential equations governing the conservation of mass and momentum in the horizontal plane were obtained by depth integration of the Navier-Stokes equation, considering the fluid incompressible, the equilibrium locally hydrostatic and neglecting vertical velocities and accelerations:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-fV+g\frac{\partial \zeta}{\partial x}+g\frac{U(U^2+V^2)^{1/2}}{C_z^2 H}-\frac{\tau_{sx}}{\rho H}=0 \quad (1)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+fU+g\frac{\partial \zeta}{\partial y}+g\frac{V(U^2+V^2)^{1/2}}{C_z^2 H}-\frac{\tau_{sy}}{\rho H}=0 \quad (2)$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (HU)}{\partial x}+\frac{\partial (HV)}{\partial y}=0 \quad (3)$$

where U, V represent the vertically averaged velocity components in the x (west-east) and y (south-north) directions respectively, ζ the surface water elevation, H=h(water depth)+ζ, τ the wind stress at the surface, g the acceleration due to gravity, C_z the Chezy coefficient, ρ the water density and f the Coriolis parameter.

The Chezy value is not constant, but weakly dependent on the depth. The bottom roughness is introduced as a Manning's coefficient (n) and the Chezy value is computed after each 30 time steps by use of:

$$C_z=\frac{1}{n}H^{1/6} \quad (4)$$

The wind stress components are defined as:

$$\tau_x^s=\rho_a C_D W^2 \sin\varphi; \qquad \tau_y^s=\rho_a C_D W^2 \cos\varphi \quad (5)$$

where ρ_a is the air density, C_D the wind stress coefficient (0.0026), W the wind speed measured 10 m above the water level and φ the wind direction with North.

The equation governing the transport of a passive contaminant is:

$$\frac{\partial HC}{\partial t}+\frac{\partial (HUC)}{\partial x}+\frac{\partial (HVC)}{\partial y}-\frac{\partial (HD_{ij}\frac{\partial C}{\partial x_i})}{\partial x_j}-HP=0 \quad (6)$$

where C is the average concentration of a given contaminant, P the source or the sink of contaminant, and D_{ij} $(i,j=1,2)$ the turbulent dispersion coefficient for a completely mixed media with $x_{i=1,2}$ =x,y :

$$D_{i,i}=\frac{(K_i U_i^2+K_j U_j^2)H}{\|\vec{V}\|C_Z}\sqrt{g}; \qquad D_{i,j\neq i}=\frac{(K_i-K_j)U_i U_j H}{\|\vec{V}\|C_Z}\sqrt{g} \quad (7)$$

where $U_{i=1,2}=(U,V)$, $K_i = 5.93$ the longitudinal dispersion coefficient , $K_j = 0.23$ the transversal dispersion coefficient, according to Fisher[5].

An alternating direction implicit finite-difference scheme, based on Leendertse[1,2] model for a regular Cartesian coordinate system, has been developed for solving the presented equations. This scheme employs the following space-staggered grid:

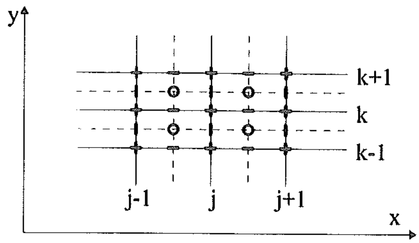

Figure 2: Space staggered grid: + water level (ζ); o water depth (h) and concentration (C); -U velocity (u); ı V velocity (v).

The covering and uncovering of the tidal flats were included in the model; several tests were done during the computations to determine if each cell of the numerical grid should be considered wet or dry. Dry cells are withdrawn from the computations, and the last values of water level calculated are kept in memory. Later they will be used to determine when those cells have to be considered again in the computations.

3.2 The numerical bathymetry

In 1987-88 the IH (Hydrographic Institute of Portuguese Navy) has carried out a general survey of Ria de Aveiro at a scale of 1/5000, resulting in a total of 93000 data points characterised by geographic coordinates and lagoon depths. The numerical bathymetry was determined using this information and the Monte Carlo method to determine the volume integrals for each cell. The resulting grid has 160 cells in the x-direction and 393 cells in the y-direction (Fig.3). The x-axis is directed eastward and the y-axis is positive northward. The numerical resolution for the lagoon is $\Delta x = \Delta y = 100$m. The grid has an open boundary in the west, connecting the lagoon with the Atlantic Ocean.

3.3 Boundary and initial conditions

The boundary conditions used in the hydrodynamic model for Ria de Aveiro include a zero normal velocity along the closed boundaries. At the open boundary the free surface elevation is specified for each time step, using the harmonic constants computed by IH, and it constitutes the main driving force. A wind speed and direction can be attributed to each cell. The initial

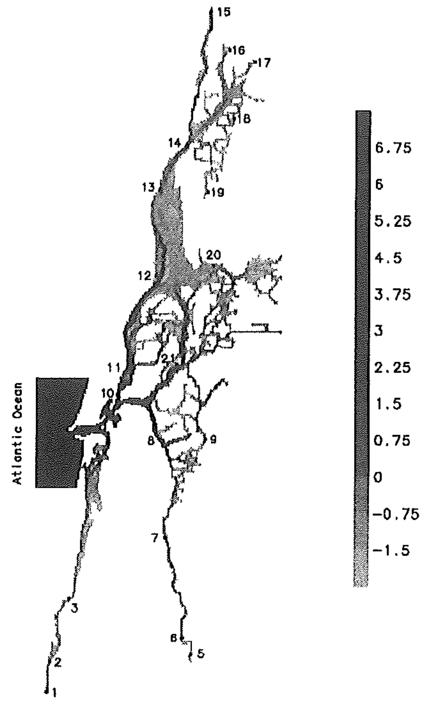

Figure 3: Numerical bathymetry, with the depth, in meters, relative to the hydrographic null (-2.00 m below mean sea level), with locations of tidal stations used in calibration and validation procedures.

hydrodynamic conditions are a constant water level and zero water velocity in all the domain

3.4 Model verification, calibration and validation

A mathematical model is, by definition, an approximative reconstruction of a real phenomenon. The abstractions, approximations and parametrisations used for the synthesis of the model are responsible for discrepancies and deviations between model results and nature. Before using the model for operational applications it should be verified, calibrated and validated.

A large number of sensitivity tests were made to verify the adopted model. The comparison between model results and analytical and typical solutions are presented in Dias[5], where the validity of the numerical solution of the model was proved. It was also determined how long the memory of the system is and the influence of the time step on amplitudes and phases of the tide.

Model calibration was conducted using simulated and measured water levels at 21 different temporary tidal stations within the lagoon (Fig.3). Unfortunately it was necessary to simulate 5 different periods in 1987-88 because the data concerning almost all the spatial dimensions of Ria de Aveiro weren't simultaneous. The bottom roughness in the lagoon is not well known and has to be found by trial and error, optimising the agreement between the amplitude and phase of the computed and the observed water levels at these positions; the parameters used in the adjustment were the depth and the Manning's number coefficient. Increasing the roughness reduced the tidal heights inland and caused a small delay in the tidal propagation. The agreement between the computed and measured results is close for all the 21 sites considered, as can be seen from the comparisons shown in Figure 4 (only for 4 significant stations).

For the validation of the model data for different periods were used in almost all the stations. The agreement between observed and computed water levels was good. As a result the transport of water in and out of the system should be well simulated.

4 Model application

The numerical model was used to simulate the evolution of Ria de Aveiro during two tidal cycles, on 15/06/1989. This period was chosen because there was available data concerning passive pollutants concentration at Laranjo to

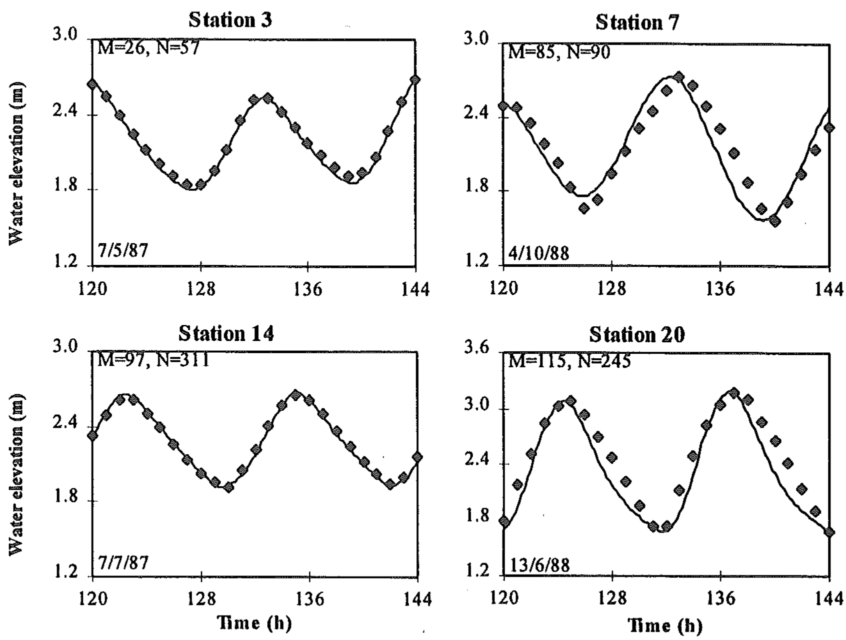

Figure 4: Comparison between computed (—) and measured (◆) water elevations (relative to the hydrographic null).

compare with model results. The model was forced only with the tidal wave (no wind conditions), which was computed at each time step using the harmonic constants. The time step was 40 s and the results presented were obtained after the simulation of 7 days, to guarantee their stability and independence relative to the initial conditions.

The tidally forced computed flow field for all the computational domain was obtained for each hour of the tidal cycle. Figure 5 shows tidal currents in an ebb and a flood situation, where their values are maximum. One sees that the strongest currents are along the deep and narrow channels, with a maximum velocity of about 1 m/s. Tidal currents decreases towards the end of the main channels, but they don't reach the null value. Therefore, the influence of the tidal wave is present in all the lagoon.

The currents in the channel connecting the lagoon with the Atlantic Ocean, which are very high, appear to be stronger in the ebbing than in the flooding. The observation of the flow patterns in this zone show that the ebb flux is similar to a jet, slightly deflected southward, while the flood flux proceeds from a wider zone, converging in the mouth of the lagoon. This difference in the flow patterns is responsible for the existence of good conditions for the renewal of the water moved between the lagoon and the sea in each tidal cycle.

In order to study the evolution of a passive contaminant in the lagoon initial conditions have been taken as high concentration at Laranjo (varying from 0.1 to 0.5μg), low concentration elsewhere (0.1μg) and high concentration at an emission point located inside Laranjo (2.0μg). Figure 6 shows that concentration follows the tidal cycle, but maximum and minimum of concentration increase progressively with time due to a continuous discharge from the emission point; comparison between measured and simulated data show a good agreement, except near the maximum. This phenomena can be explained by the fact that we haven't take into account physical and chemical interactions in our transport model and because the salinity field has been supposed constant. Actually, at ebbing tide contaminants and freshwater are carried into Laranjo and then spread throughout the lagoon, where water is more salty and less contaminated. It is well known that a decrease of salinity contribute to a desorption of contaminant from sediments and therefore an increase of dissolved contaminant (Turner[7]).

5 Conclusions

The two-dimensional model of Ria de Aveiro is able to simulate the tidally induced flow and the progression of the tide with reasonable accuracy. The model is capable of calculating the flows in shallow waters where inter-changing of land-water boundaries occur.

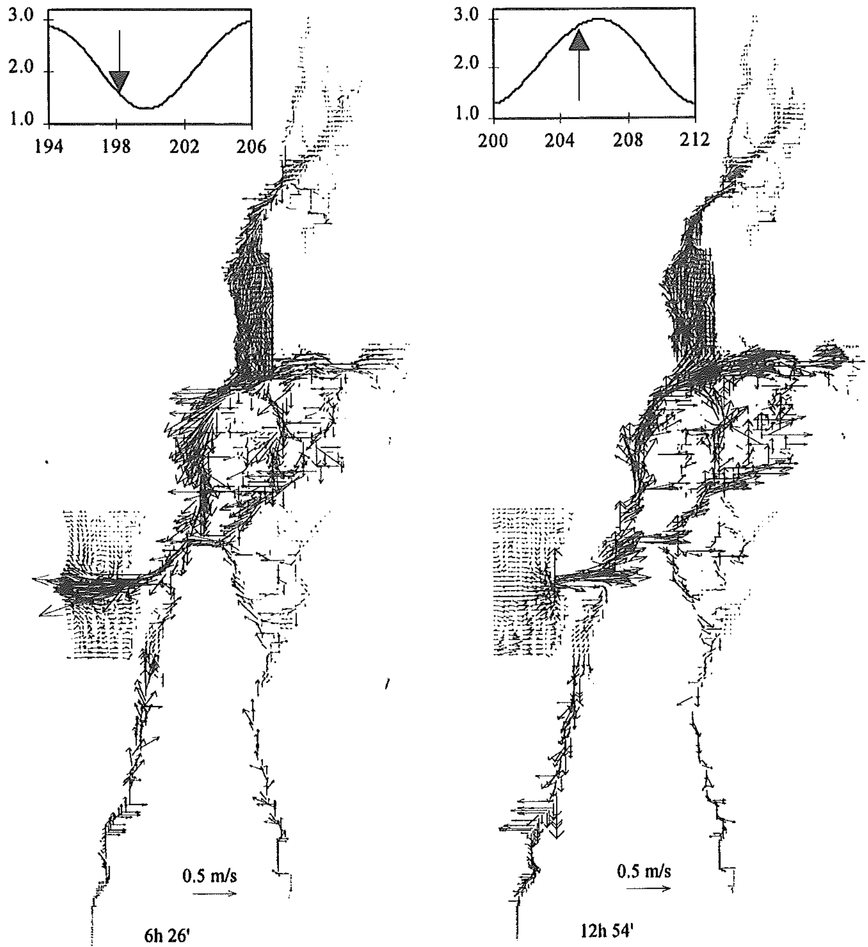

Figure 5: Computed flow field on 15/06/1989, during ebbing and flooding (⟶ free surface elevation at the open boundary).

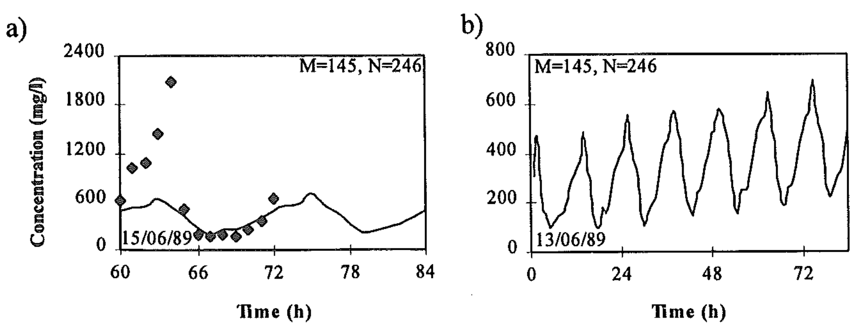

Figure 6: a) Comparison between computed (—) and measured (◆) contaminant concentration at Laranjo; b) Evolution of contaminant concentration at Laranjo.

The results of the present study reveal that bathymetry and coastal morphology determine many of the flow characteristics in Ria de Aveiro and that the effect of the tidal wave is present in all the lagoon, governing its dynamics.

Introduction of river runoff, wind conditions, and a non constant salinity field as well as the effect of sediments is necessary for a better description of different processes in the lagoon and interesting for further studies.

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