PHYSICAL ANALYSIS OF A TIDAL CHANNEL (ESPINHEIRO CHANNEL, PORTUGAL): A MODELLING STUDY

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CHAPTER SYNOPSIS

Background
The implementation of a 3D marine model to Ria de Aveiro lagoon is described in this study. The main goal of this implementation is to develop a numerical tool to research the stratification/mixing balance in one of the four main channels of the Ria de Aveiro: the Espinheiro Channel. Some of the major findings are then summarized. The simulations were performed for distinct periods where markedly tides and river discharge occurred. Tidal currents and salinity data were analyzed at the channel's mouth during several tidal cycles.

Results
A flood-ebb asymmetry was found in stratification with higher values on peak flood than on peak ebb. The cross-section structure of the channel's inlet was found homogeneous in terms of salinity, but lateral differences in current velocity were found with ebb predominance near the south margin and flood predominance near the north margin, producing a exportation (importation) of salt from the channel to the ocean near the south (north) margin.

Conclusions
All the results are consistent with observations, revealing that if adequately applied the 3D models are a suitable tool for the study and management of complex marine systems like the Espinheiro Channel.

1 INTRODUCTION

Estuarine systems are interface regions where salt water from the ocean is measurably diluted by the freshwater from land drainage [1]. These systems are highly variable and rich, supporting important economic and social activities.

Nowadays, a major motivation to implement and improve hydrodynamic models is the importance of three-dimensional (3D) localized processes in the scope of the hydrodynamic influence on water quality of estuarine areas. Observational programs often do not cover the entire study areas, therefore 3D estuarine hydrodynamic models may be used to complement observations. The set-up and development of models that describe the dynamical behavior of estuaries and coastal systems occupy much of the literature. In fact, [2] and [3] have presented a predictive model (based on ROMS) for the Chesapeake Bay and the Hudson River estuary, respectively, describing the set-up of the model for these two estuaries. GETM was applied to study transport pathways and residence time in a macrotidal estuary (Willapa Bay, Washington) [4], and to study the temporal and spatial dynamics of the North Sea using a numerical system [5] and MOHID was applied to study the dynamics of a tidal channel, located inside Ria de Aveiro lagoon (Portugal) [6]. These few examples demonstrate the importance of the set-up and application of numerical models to research estuarine and coastal dynamics.

Recent observations in estuarine regions have revealed an asymmetry in stratification and turbulent mixing over the tidal cycle. At the Columbia River estuary, a flood-ebb asymmetry was found with enhanced shear and stratification during ebb and stronger mixing and weaker stratification during flood tides [7]. It was suggested that this asymmetry is induced by a strain-induced buoyancy flux that stabilizes on ebb and destabilizes during the flood tide [8]. At Chesapeake Bay, a three-dimensional numerical model was used to investigate this issue [9] showing that the asymmetric tidal mixing causes significant variation in salinity distributions over the flood-ebb cycle. However, until recently was not performed any research about the tidal variability effects in the stratification/mixing balance along the Espinheiro channel (Ria de Aveiro).

The Espinheiro Channel is a mesotidal and shallow branch of Ria de Aveiro, a coastal lagoon located in the Northwest Portuguese coast. This channel has a great importance in the local dynamics once it connects the major source of freshwater of the lagoon (Vouga river) to the Atlantic Ocean. The channel is approximately 11 km long, has an average width of about 200 m and a mean depth along its longitudinal axis of about 10 m (Figure 1). The tides at the channel propagate from the nearby ocean and are mixed semi-diurnal, with M_2 being the most important constituent, representing more than 90% of the tidal energy [10]. The channel's dynamics is mainly controlled by the interaction of tides and incoming river flow [6, 11]. The channel's vertical structure is strongly dependent on the tidal strength and river inflow, turning from well-mixed to partially stratified [11, 12]. The channel's behavior adjusts dynamically to changes in the main forcing [13]. In the lower channel (near the mouth), tidal currents present values between 0.6 (flood) and $\sim$1.0 $\mathrm{m\,s^{-1}}$ (ebb) during neap tides. Tidal currents are higher during spring tides, ranging from 1.5 (flood) to 1.6 $\mathrm{m\,s^{-1}}$ (ebb). The Espinheiro channel presents characteristics of an ebb-dominated channel [6]. A full description of the channel can be found at [6] and [12].

A 3D baroclinic numerical model (MOHID, [14]) was used to perform hindcast simulations of the Espinheiro Channel. The simulations covered short periods of time in order to assess the channel's vertical structure under different tidal and river inflow conditions. In this work, the effect of tidal variability on stratification is described at the lower channel (located near the channel's mouth). Moreover, the cross-sectional characteristics of this zone are also studied in terms of its hydrography and velocity patterns. The effect of river inflow in the hydrography and residual circulation patterns at the channel's mouth is also investigated.

To perform the study of the mixing processes in the Espinheiro Channel, a 3-dimensional baroclinic model was used. The model has the ability to simulate flooding and drying of tidal flats. The model was first implemented for the entire lagoon, in a two-dimensional mode (depth-integrated), with a closer look to the central area (where Espinheiro Channel is located), in order to study the dependence of the thermohaline horizontal structure with the tidal regime and freshwater inflow.

Although this kind of applications reveals some of the main features of the horizontal thermohaline structure, mixing processes within the lagoon are driven not only by freshwater discharge and the barotropic component of the pressure gradient due to tides, but also by its baroclinic component due to salinity gradients (horizontal and vertical). Due to the shallowness and complex geomorphology of the lagoon, as well as to the existence of large intertidal areas

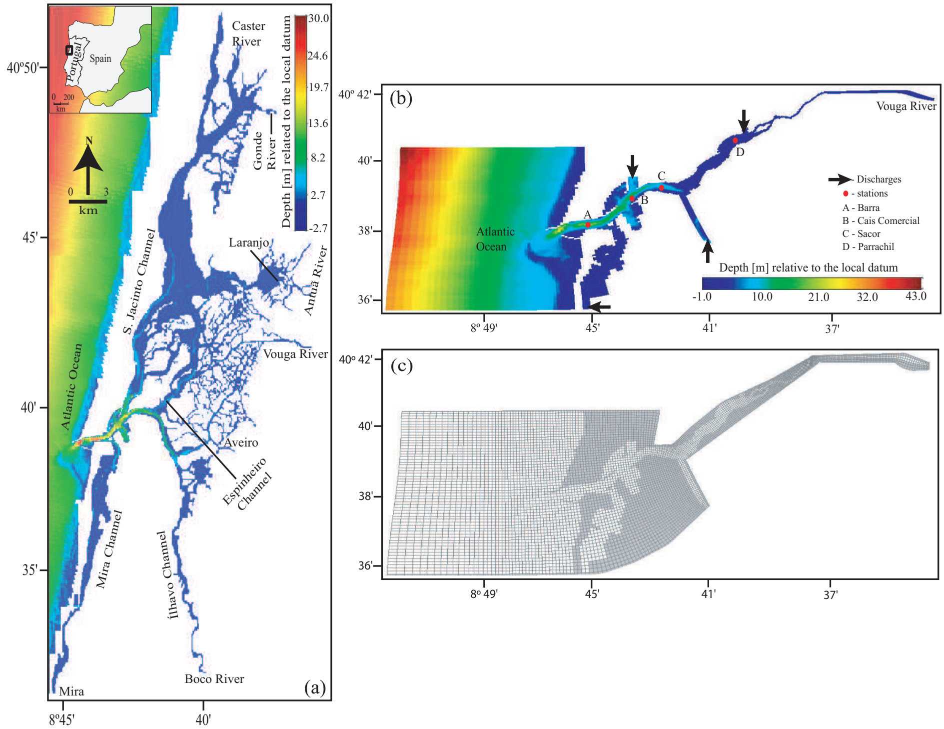

Figure 1. *(a) Bathymetry of the Ria de Aveiro lagoon and adjacent coastal area. Major tributaries are marked; (b) Bathymetry of the Espinheiro Channel with the discharge points (marked with arrows) and its major freshwater tributary. The location of the stations used in the hydrodynamic calibration procedure is marked. Depths are in meters (over the local datum); (c) Horizontal curvilinear coordinate system [6].*

it is not advisable the study of the entire system in a three-dimensional mode. In order to overleap this difficulty, a high resolution three dimensional application was developed for the Espinheiro Channel.

Ria de Aveiro has four main channels, and due to their unique characteristics each one of them may be considered as an independent estuary connected to a common inlet. The hydrology of each channel is determined by different tidal prisms and freshwater inputs.

2 THE STUDY AREA

Ria de Aveiro is a shallow mesotidal lagoon located in the Northwest coast of Portugal (40°38' N, 8°44' W). It has a very irregular geometry (see Figure 1) being characterized by narrow channels and by the existence of intertidal areas, namely mud flats and salt marshes. The lagoon has a maximum width and length of 10 and 45 km, respectively. In spring tide covers an area of 83 km^2 at high tide reducing to 66 km^2 at low tide [15]. The averaged depth of the lagoon is 1 m, except in its navigation channels where dredging operations are often carried out. One single inlet at the western boundary allows the water exchange between the Atlantic Ocean and the lagoon. This inlet has about 20 m deep, 1.3 km long and 350 m wide.

Ria de Aveiro has four main channels, and due to their unique characteristics each one of them may be considered as an independent estuary connected to a common inlet. The hydrology of each channel is determined by different tidal prisms and freshwater inputs. The Ria receives freshwater mainly from two rivers, the Antuã (5 $m^3\,s^{-1}$ average flow) and the Vouga (50 $m^3\,s^{-1}$ average flow) [10, 16]. Vouga River is responsible by approximately 2/3 of the freshwater input into the lagoon [10]. The other rivers have negligible flow, except the freshwater source in the south end of the Mira Channel, which consists of a small system of ponds and rivers with a poorly known flow.

The estimated tidal prism for the lagoon's mouth at extreme spring and extreme neap is 136.7×10^6 and 34.9×10^6 m^3, respectively [15]. Near station C ($\sim$4 km upstream) it is about 40×10^6 at extreme spring and 15×10^6 m^3 at extreme neap tide [15]. The total estimated freshwater input for the lagoon is very small (about 1.8×10^6 m^3 during a complete tidal cycle [16]) when compared to the tidal prism at the mouth. The small ratio between the freshwater input and the tidal prisms indicate that the circulation is mainly induced by tides. However, the combination of these two factors (tidal regime and freshwater inflow) highly influences the thermohaline horizontal patterns [17]. A prior hydrological characterization led to the conclusion that Ria de Aveiro can be considered vertical homogeneous during dry seasons. However, after important rainfall the stratification becomes important near the freshwater inflow locations [10, 17].

The Espinheiro Channel has a low ratio between tidal amplitude and depth, revealing an ebb-dominated channel [15]. The channel is very dynamic, presenting current velocity maximums higher than 2 $m\,s^{-1}$ [15]. The longitudinal salinity differences lie between 20 and over than 30 psu, depending on the freshwater input [17]. The channel can be divided into three distinct regions: (a) a marine or lower estuary dominated by ocean waters, (b) a middle estuary where the mixing between the fresh and salt water occurs and (c) an upper or fluvial estuary characterized by freshwater, but subject to a daily tidal action [12]. This delimitation is dynamic and can change seasonally (or in lower time scales) due to tides, winds or freshwater inflow. Residence times lower than 2 days were computed for the whole study area [18], revealing a good water renewal. A full description of the channel can be found at [6] and [12].

3 NUMERICAL MODEL

The Espinheiro Channel's predictive model presented in this study is an implementation of MOHID ([14], www.mohid.com). The model is a baroclinic finite volume model, designed for coastal and estuarine shallow water applications, like Ria de Aveiro, where flow over complex topography, flooding and drying of intertidal areas, changing stratification or mixing conditions are all important. MOHID allows an integrated modelling approach of physical and biogeochemical processes. A complete description of the model's physics can be found in several works [14, 19].

A complex application of MOHID has been configured to study the Espinheiro Channel dynamics, consisting in a local 3D application supported by a general 2D model of the entire Ria de Aveiro. Bathymetry in the channel was extracted from topohidrographic data obtained from a general survey performed by the Hydrographic Institute of the Portuguese Navy in 1987/1988. To define Ria de Aveiro bathymetry this topohidrographic data was complemented with more recent data resulting from dredging operations in several channels (1998) as well as with results from surveys performed by the local harbor administration close to the lagoon's mouth (2002) (Figure 1).

An orthogonal curvilinear coordinate system was designed to follow the general orientation of the channel including its major tributaries and the near coastal ocean. The grid spacing is less than 100 m in the longitudinal and about 50 m in the cross channel direction. High resolution is used in order to properly resolve the physical features of the channel. The total number of grid points is 200×200 and in the vertical direction the model uses 10 sigma layers. The domain was designed to resolve the channel's dynamic and not the dynamics of the near coastal ocean.

At the bottom, the 3D model uses shear friction stress imposed assuming a velocity logarithmic profile. The vertical eddy viscosity and diffusivity are computed using a turbulence model (GOTM, [20]). Coefficients of horizontal viscosity and diffusivity are set to 2 $m^2\ s^{-1}$. Initial conditions for the hydrodynamic model are null free surface gradients and null velocity in all grid points. Initial conditions for the 3D transport model are constant values of salinity and water temperature (typical values for each run). At the ocean open boundary the model is forced by the tide determined from 38 tidal constituents obtained after harmonic analysis [21] of data measured at a tidal gauge located close to the lagoon's mouth in 2002.

Freshwater inflow was imposed at the landward boundary and at the arrow marked boundaries water inflow/outflow, salinity and temperature fluxes were also prescribed. The solutions imposed at the arrow marked boundaries were computed using a 2D model application for the entire Ria de Aveiro lagoon. This 2D model computes sea surface height, current velocity, salinity and water temperature which are then imposed to the 3D model. Details about this 2D application can be found in previous works [11, 17]. On the offshore open boundary and at the river boundary constant values of salinity and water temperature were prescribed (S_{Sea} = 36 psu and S_{River} = 0) psu, water temperature varies from run to run, accordingly to the local climatology).

A set of simulations, covering spring and neap tide periods of 2003 and 2004 was performed. Two of the simulations include two spring tide periods with low and high river inflow (26/09/2003 and 25/11/2003) and two neaps also with high and low river inflow conditions (29/01/2004 and 25/07/2004). The river inflow imposed at the landward boundary was 2.06 (September 2003) and 72.74 $m^3\ s^{-1}$ (November 2003), and for the neap simulations was 2.0 (July 2004) and 143.16 $m^3\ s^{-1}$ (January 2004). Another period was simulated – June 2004 – when the river inflow ranges from medium-to-low, with maximum and minimum freshwater discharges of the order of 20 $m^3\ s^{-1}$ and 2 $m^3\ s^{-1}$, respectively. Details about these simulations can be found in a previous work [6]. The hydrodynamic was spun up from rest over 2 days ($\sim$4 tidal cycles), which is considered a fair adjustment period. The spin-up period is not included in the results and therefore the initial state of a run refers to the end of the spin-up period.

4 RESULTS

4.1 Flood-ebb asymmetry

To study the effects of tidal flow and river discharge on stratification/mixing processes along the Espinheiro Channel, the model should accurately predict tidal heights and tidal currents in the channel. This evaluation was previously performed [6], showing that the skill coefficient between data and model outputs is of the order of 0.9 in the four stations marked in Figure 1. Consequently the results show that the model accurately predicts tidal heights in the channel.

Then, the model was applied to research the flood-ebb asymmetry for a neap and a spring tide during June 2004. It was selected a station in the lower portion of the channel (Station A, see Figure 1 for location) and were chosen two instants during the tidal cycle: one representing the peak flood and the other representing the peak ebb. As shown in Figure 2a and 2b, the depth-averaged current oscillates at the semi-diurnal frequency. The barotropic current presents ebb intensities about 30% (10%) higher than the flood values at neap (spring) tide. The vertical profiles of salinity and current velocity between the peak flood and ebb tides are compared in Figure 2c and 2f, respectively.

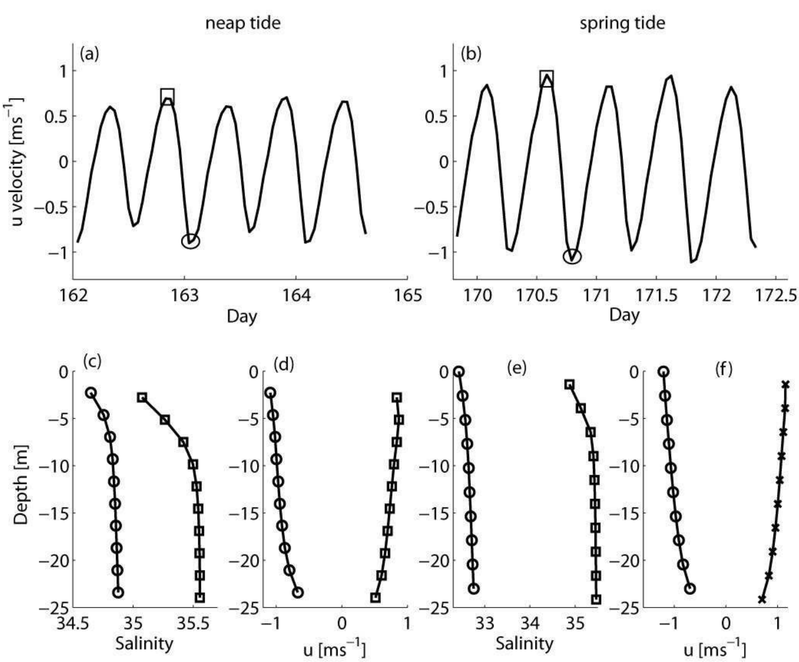

Figure 2. *Time series of along-channel depth-averaged velocity (u component) at station A at neap and spring tide for June 2004; (c, d). Vertical profiles of salinity and current velocity at the peak flood (squares) and peak ebb (circles) at neap tide and (e, f) spring tide. (From [22])*

Both at neap and spring tide, the salinity profiles (Figures 2c and 2e) show higher stratification on peak flood than on peak ebb. This feature may be induced by the higher ebb tidal velocities that increase turbulent mixing, inducing a decrease on stratification. At neap tide, the peak flood velocity profile shows a subsurface maximum ($\sim$5 m depth) and a quasi-linear distribution on ebb tide (Figure 2d). On the flood, this slight drop of the water velocity may be caused by the non-tidal pressure gradient that reinforces the tidal pressure gradient at the deepest layers, but opposes it near the surface. On ebb, the non-tidal pressure gradient reinforces the tidal pressure gradient near the surface, but opposes it at the bottom layers, resulting in a nearly linear depth distribution of the depth-average velocity. At spring tide, the depth variation of the barotropic current is nearly linear at peak flood and peak ebb.

4.2 Residual circulation

Superimposed on the back-and-forth tidal water flow there is an averaged steady water motion, known as residual circulation. This circulation has a time scale similar to the tidal cycle time scale, and amplitude which is typically one or two orders of magnitude lower than that of the tidal currents. In spite of its small amplitude, the residual circulation can determine the long-term transport which is very important for the ecological systems dynamics.

In this study the residual circulation was determined from model results at two different levels: on the surface (Figure 3a) and near the bottom (Figure 3b). The results revealed here represent the residual flow driven by tides and freshwater inflow during the spring tides of November 25th (river flow of 72.74 $m^3\ s^{-1}$). The residual values were calculated by tidally averaging the transient solution computed by the model and are about one order of magnitude lower than the tidal currents within Espinheiro Channel. The hydrodynamic and salinity simulations cover a period of 4 days (plus spin-up). The model results were averaged for four and eight tidal cycles, however the results did not change revealing its independency from the average time.

Without freshwater inflow, the tide induced residual currents are seaward on the surface and bottom, revealing an ebb-dominated channel (not shown), in accordance with results from a previous study [16]. In that study the authors applied a depth-integrated numerical model to capture the barotropic residual circulation in Ria de Aveiro, induced by tides, river inflow and winds. The results presented in the present study are consistent with an ebb dominated channel, where the surface and near bottom currents are always directed seaward. Nevertheless, currents show some spatial variability. The surface currents are more intense, flowing out the estuary (Figure 3a). This jet-like current spreads over the full channel width for almost all the channel area. However, it intensifies near the south margin of the inlet. The bottom current is also seaward but less intense. The results presented in this section have shown that the model can qualitatively capture some of the characteristics of the tidally averaged estuarine circulation revealed in a prior study [15].

4.3 Cross-sectional tidally averaged velocity and advective salt tranport

In the frame of this investigation the model was also used to provide insight on the transport of water and salt through the channel's inlet (near station A). Simulations for January and

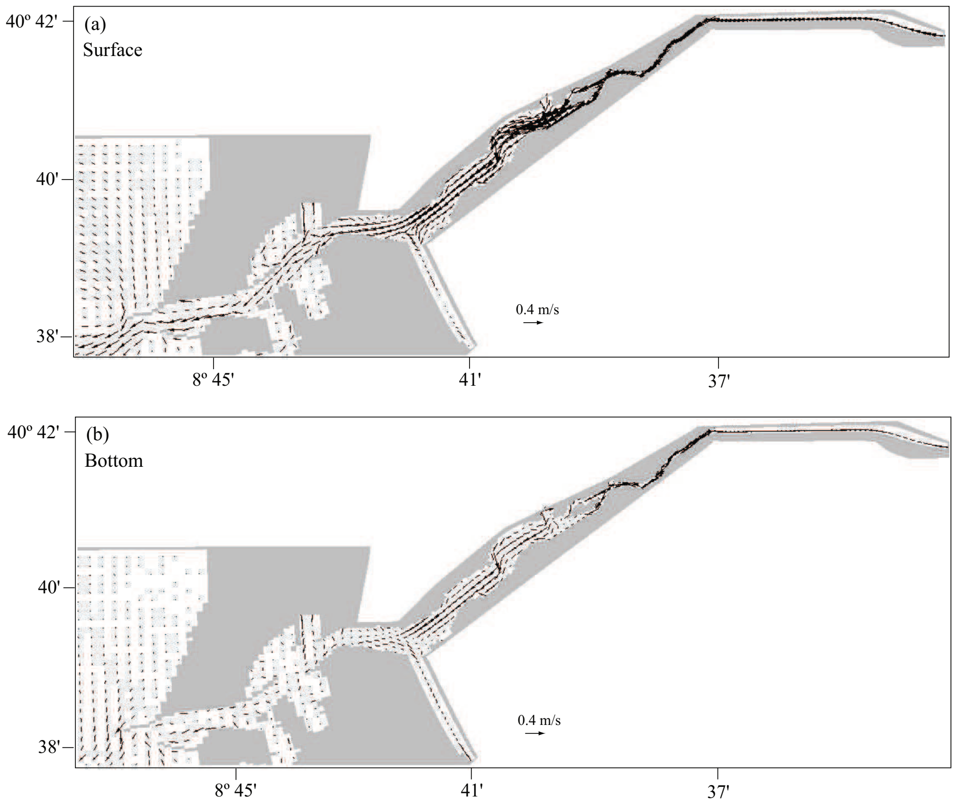

Figure 3. *Averaged residual flow: (a) surface layer and (b) bottom layer. Simulation period: 24/11/2003 to 27/11/2003. River inflow of 73* $m^3\ s^{-1}$.

July were performed and the results obtained are presented here. The cross-channel section has a triangular shape (smooth slope from the center to the margin) with a deeper zone close to the center, and may be considered representative of the lower region of the channel. At this location, the channel width is about 350 m and the maximum depth is ∼25 m. The longitudinal velocity and salinity were averaged over four complete tidal cycles to remove the tidal periodicities and reveal the characteristic features of the estuarine circulation [23, 24].

In Figure 4, the lateral and vertical structure of the tidally averaged (or residual) salinity and longitudinal velocity component is shown. Positive values are referred as landward velocities and negative values as seaward values. At the channel mouth, during low river flow periods (July simulation, river flow of $\sim 2\ m^3\ s^{-1}$), the salinity structure is nearly homogeneous, revealing a well mixed section (see Figure 4b). However, the residual velocity pattern is different, with higher ebb currents near the south margin decreasing toward the middle of the section while flood currents are found close to the north margin. During medium (not shown) and high river inflow events (January simulation, Figure 4a), the salinity structure presents a stratified water column but the channel may be considered as laterally homogeneous in terms

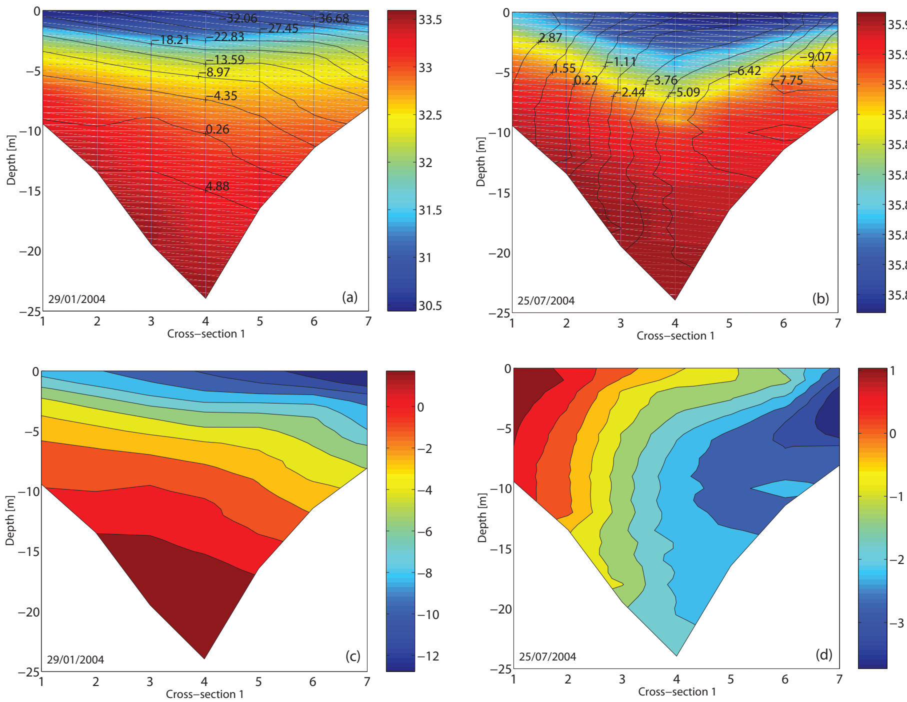

Figure 4. *(a, b) Cross-sections of tidally averaged salinity (shading) and longitudinal velocity component (contour,* $\mathrm{cm\ s^{-1}}$*); (c, d) predicted tidally averaged salt transport (*$\mathrm{cm\ s^{-1}}$*) for cross-section 1, near the mouth of the lagoon. (a, c) are for neap tide and river flow of 143* $\mathrm{m^3\ s^{-1}}$ *and (b, d) are for a neap tide and river flow of 2* $\mathrm{m^3\ s^{-1}}$*. (From [6])*

of salinity. During the January simulation, when the river inflow is high (143.16 $\mathrm{m^3\ s^{-1}}$), the residual velocity pattern, at cross-section 1 reveal flood currents near the bottom and ebb currents at mid-column and on the surface, revealing a stratified water column and nearly flat isotachs through the cross-section.

Near the mouth of the channel, the predicted tidally averaged salt transport presents a pattern similar of that observed for velocity, with a net up-channel flux (positive) in the proximity of the north margin of the section decreasing toward the center of the channel, and a net down-channel flux (negative) from the middle toward the south margin of the channel. This feature is visible in all simulations, except for the January simulation (Figure 4c), where following the same pattern of the residual velocity, the cross-section presents a net up-channel flux near the bottom and a down-channel flux on the upper layers. During this period the gravitational circulation becomes an important mechanism for transport of salt at cross-section 1. Another feature found during the analysis is that, in general, the salinity values are higher during the flood than during the ebb, leading to a landward transport. This is the tidal cycle correlation term of the salt transport and can be important in branching and curved estuaries [4, 25]. The

September and July simulations were carried out under similar river inflow (about 2 $m^3\ s^{-1}$), showing a higher down-channel salt transport during spring tide (not shown) than during neap tide (July simulation, Figure 4d). This result is expected since the residual currents present higher values at spring tide.

4.4 Estuarine stratification

To evaluate the estuarine stratification at the mouth of the Espinheiro Channel under different conditions of tidal ranges and river inflow, the Estuarine Richardson number, R_{iE}, [1, 25] was calculated. This number expresses the ratio of the potential energy gain due to freshwater discharge to the mixing power of tidal currents, and it is defined as:

$$Ri_E = g\left(\frac{\Delta\rho}{\rho}\right)\left(\frac{Q_f}{bU^3_{RMS}}\right) \tag{1}$$

where Q_f is the river inflow, b is the width of the section where the data were collected, Δ_ρ is the density difference between sea and freshwater, ρ is the mean density and U_{rms} is the root-mean-square tidal velocity. If R_{iE} is greater than 0.8 the estuary is considered highly stratified, if it is smaller than 0.08 the estuary is considered well mixed and finally, if $0.08 < R_{iE} < 0.8$ the estuary is considered partially mixed [25]. Moreover, the water column stability was analyzed using the buoyancy frequency (N) [26], calculated at the two locations previously referred. N is defined as:

$$N = \left(\frac{g}{\rho}\frac{\Delta\sigma_t}{\Delta z}\right)^{\frac{1}{2}} \tag{2}$$

where ρ is the density, σ_t is the density at atmospheric pressure (1000 $kg\ m^{-3}$) and z is the depth measured from the surface.

In July and September, when the river inflow is $\sim$2 $m^3\ s^{-1}$, and independently of the tidal regime, the region in the vicinity of the Espinheiro Channel mouth reveals a well mixed water column, presenting a Richardson number of 0.001 (September) and 0.01 (July), respectively. This area of the channel becomes highly stratified when the river inflow is higher than 100 $m^3\ s^{-1}$ (January), presenting a Richardson number of 0.95. Under spring tide regime and river inflow of $\sim$70 $m^3\ s^{-1}$ (November), this area presents well mixed characteristics (Richardson number of 0.05) due to the high tidal currents which increase turbulence, and hence vertical mixing.

The characteristic of the whole flow has been analyzed using R_{iE}. This information can be complemented by means of the Buoyancy frequency (N). In Figure 5 the N values are depicted as a function of the layer's depth for the four simulations performed. The figure shows higher values of N on the surface layers and low values near the channel's bed (for all simulation periods), indicating a more stratified water column on the surface and more homogeneous close to the bed. The higher values of N are visible during the November and January simulations when the river flow is high. The Espinheiro Channel is a small system where the river inflow has a major role in determining the stratification patterns. Buoyancy inflow from river tends to maintain stratification in the channel. On the other hand, the friction induced by the tidal flow causes mixing.

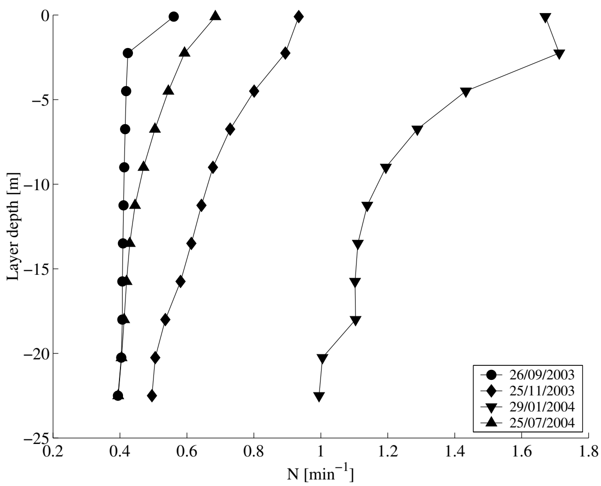

Figure 5. *Buoyancy frequency, N* (min^{-1})*, as a function of layer depth (m). (From [6])*

Due to the small length of the channel, even close to the channel's mouth, which is the deepest area of the channel, the river inflow is confined to the surface and tends to maintain stratified a small portion of the water column (3.0 – 5.0 m, depending on the river inflow). At this location, the tidal velocities are high, and tend to activate turbulent mixing, producing the well mixed portion of the water column. In general, these model results do not illustrate the existence of a visible pycnocline. Instead, a monotonic decrease of *N* toward the channel's bed is visible. This fact may indicate an overestimated mixing of the water column. This feature was also observed in the study of Ria de Ferrol (NW Spain) [27], where under low river inflow is not visible the pycnocline. In the Espinheiro Channel, only under high river runoff (January simulation) is visible a pycnocline at a depth of $\sim$2.5 m. In this case, the maximum buoyancy frequency is 1.71 min^{-1}.

5 CONCLUSION

A 3D baroclinic numerical model (MOHID) was used to perform hindcast simulations of the Espinheiro Channel covering short periods of time in order to assess the channel's vertical and cross sectional structure under different tidal and river inflow conditions. The flood-ebb asymmetry was examined at a station located near the channel's mouth. At this location, the barotropic velocity oscillate at the semi-diurnal frequency, and the water column show higher stratification on peak flood than on peak ebb, which is consistent with results found for the Columbia River estuary [7].

The residual currents were also examined. The general characteristics within the domain are those of an ebb dominated channel, revealing a more intense current near the surface due to the freshwater inflow. This feature is common to other estuaries like the Galician Rias or Chesapeake Bay where surface residual currents enhanced by the river inflow are visible. Another feature revealed from the analysis of the residual circulation at the entrance channel of Ria de Aveiro, is that in the vicinity of the north margin of the inlet channel's the residual currents present positive (inward) values, and close to the south margin the residual currents present negative (outward) values. This may suggest that, at the entrance channel of the lagoon, the water flow during the flood period has a preferential path near the north margin and during ebb the preferential path is near the south margin of the channel's entrance. These preferential water flow paths may be related to the existence of two long jetties which induces, during the flood period, a water movement close to the north margin of the channel's inlet. The preferential path during the ebb period may be related to the channel's curvature which induces a flow path close to the south margin of the lagoon's inlet.

The tidally averaged cross-sectional and vertical structure of the channel were examined. Under low-to-medium river runoff the channel is laterally homogeneous in terms of salinity. However, the residual velocity structure is different, presenting landward velocities near the north margin of the channel and seaward velocities at the south margin. When the river inflow is high (higher than 100 $m^3\,s^{-1}$), the channel presents a typical estuarine behavior, with landward residual currents near the bottom and seaward currents at the top layers.

The tidally averaged salt transport follows the same patterns found for the residual currents, presenting landward salt transport at the north margin and seaward salt transport at the south margin under low-to-medium river runoff. When the river flow is high, the landward salt transport was found near the channel's bed, being seaward at the top layers.

It is well known that the river flow, which causes an inflow of buoyancy, tends to maintain stratification, and that the tidal flow induces mixing due to the turbulence generated by friction effects. At the channel's mouth, tidal currents are higher activating turbulent mixing, and generating well mixed conditions, except during high river runoff events when this area is partially stratified. In general, at the channel's mouth, the stratification found in the model results tends to extend throughout the water column, revealing no distinctive pycnocline. This pattern was also observed in a ROMS application for the Hudson River estuary [3]. At the Espinheiro Channel, a visible pycnocline is found when the freshwater runoff is higher than 100 $m^3\,s^{-1}$, revealing a more stratified surface layer. In this channel, the higher tidal currents are frequently able to homogenize the water column. Near the channel's mouth, the water exchange is mainly due to the tide, except under high river flow events when the freshwater extends its influence from the channel's head to its mouth.

In summary, the Espinheiro Channel is a very dynamic estuarine region. The lack of a consistent and permanent monitoring program for this zone turns necessary the use of numerical models to study in detail its dynamics. The results obtained with this study points to the inevitability of future application of pre-operational methods to successfully monitor this channel.

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