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Cross-sectional and Stratification Patterns Induced by Tidal and River Discharge Changes in a Tidal Channel: A Modelling Study

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ABSTRACT

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A 3D baroclinic model (Mohid) was used to perform hindcast simulations in a tidal channel – the Espinheiro Channel (located within Ria de Aveiro, north coast of Portugal) – in order to study the effect of tidal variability and river inflow on the hydrography of the lower portion of the channel, near its inlet. 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. 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 shore and flood predominance near the north shore, producing a exportation (importation) of salt from the channel to the ocean near the south (north) shore. A marked difference in time between sea level, velocity and salinity was also found. These differences are highly variable, strongly depending on the river inflow. All the results are consistent with observations, making the use of 3D models a suitable tool for the study and management of a complex system like the Espinheiro Channel.

ADDITIONAL INDEX WORDS: *Current velocity, Salinity, Espinheiro Channel*

INTRODUCTION

Estuarine systems are interface regions where the salt water from the ocean is measurably diluted by the freshwater from land drainage (Dyer, 1997). These systems are highly variable and rich, supporting important economical and social activities.

Recent observations in estuarine regions have revealed an asymmetry in stratification and turbulent mixing over the tidal cycle. At the Columbia River estuary, Jay and Smith (1990) found a flood-ebb asymmetry with enhanced shear and stratification during ebb and stronger mixing and weaker stratification during flood tides. Stacey and Ralston (2005) suggested that the asymmetry is induced by a strain-induced buoyancy flux that stabilizes on ebb and destabilizes during the flood tide. At Chesapeake Bay, Li and Zhong (2007) used a three-dimensional numerical model to investigate this issue and found that the asymmetric tidal mixing causes significant variation in salinity distributions over the flood-ebb cycle. In contrast to these investigations at those estuaries, no observations of tidal variability have been made in 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 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 are mixed semi-diurnal, with M_2 being the most important constituent, representing more than 90% of the tidal energy (Dias *et al.*, 1999). The channel's dynamics is mainly controlled by the interaction of tides and incoming river flow (Vaz *et al.*, 2009). The channel's vertical structure is strongly dependent on the tidal strength and river inflow, turning from well-mixed to partially stratified (Vaz and Dias, 2008). The channel's behavior adjusts dynamically to changes in the main forcing as revealed by MacCready (1999). In the lower portion of the channel (near the mouth) during neap tides, tidal currents present values between 0.6 (flood) and ~1.0 ms^{-1} (ebb). At spring tides, these values are higher, ranging from 1.5 (flood) to 1.6 ms^{-1} (ebb). The Espinheiro channel presents characteristics of an ebb-dominated channel (Vaz *et al.*, 2009). A full description of the channel can be found at Vaz and Dias (2008) and Vaz *et al.* (2009).

In this work, the effect of tidal variability on stratification is investigated in one station, at the lower portion of the channel (located near the channel's mouth). Moreover, the cross-sectional characteristics of this site are also studied in terms of its hydrography and velocity patterns, pointing out the phase difference between water level, salinity and longitudinal velocity. The effect of river inflow in the hydrography of the channel's mouth is also investigated.

A 3D baroclinic numerical model (Mohid, Martins *et al.*, 2001) 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. However, no effort was made until now, to understand how intra-tidal variations of tidal flow affect stratification.

THE ESPINHEIRO CHANNEL'S MODEL

The Espinheiro Channel's predictive model is an implementation of Mohid (Martins *et al.*, 2001, 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 allow an integrated modelling approach of physical and biogeochemical processes. A complete description of the model's physics can be found in several works by Martins *et al.* (2001) and Leitão *et al.* (2005).

Mohid has been configured to be implemented in the Espinheiro Channel. Bathymetry in the channel is extracted from data obtained by the Hydrographic Institute of the Portuguese Navy in 1987/1988. More recent bathymetric data, obtained from recent dredging operations in several channels (1998) and close to the lagoon's mouth (2002), were also used. Figure 1 shows the model bathymetry. 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, Burchard *et al.*, 1999). Coefficients of horizontal viscosity and diffusivity are set to 2 m^2s^{-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 (Pawlowicz *et al.*, 2002) of data measured at a tidal gauge located close to the lagoon's mouth in 2002. At the landward boundary freshwater inflow was imposed and at the arrow marked boundaries water inflow/outflow, salinity and temperature fluxes were also prescribed. The solution imposed at the arrow marked boundaries was computed using a 2D model application for the 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 Vaz *et al.* (2005, 2007). On the offshore open boundary and at the river boundary constant values of salinity and water temperature were prescribed (S_{Sea}=36 psu.5 and S_{River}=0 psu, water temperature varies from run to run).

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 72:74m^3s^{-1} (November 2003), and for the neap simulations was 2.0 (July 2004) and 143.16m^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^3s^{-1} and 2 m^3s^{-1}, respectively. Details about these simulations can be found at (Vaz *et al.*, 2009).

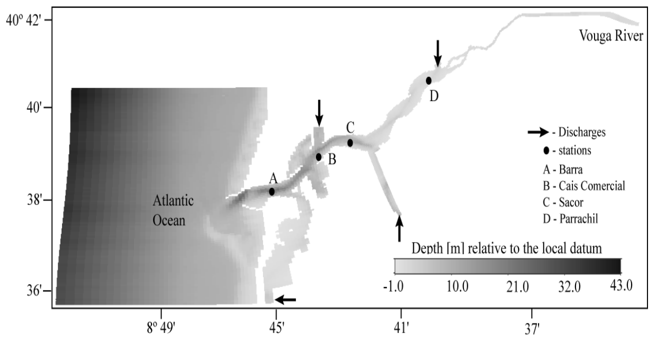

Figure 1. Bathymetry of the Espinheiro Channel with the discharge points (marked with arrows) and its major freshwater source.

The hydrodynamic was spun up from rest over 2 days (~ 4 tidal cycles). This is considered a fair adjustment period for the hydrodynamic. The spin-up period is not included in the results and the initial state of a run refers to the end of the spin-up period.

RESULTS

Flood-ebb asymmetry

In order to study the effects of tidal flow on stratification it is important that the model accurately predicts tidal heights and tidal currents in the channel. In a previous study, Vaz *et al.*, (2009) show that the model accurately predicts tidal heights in the channel. The skill coefficient between data and model outputs is of the order of 0.9 in the four stations marked at Figure 1.

Then, it was analyzed the flood-ebb asymmetry during a neap and a spring tide. The simulated results are 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 its location) and

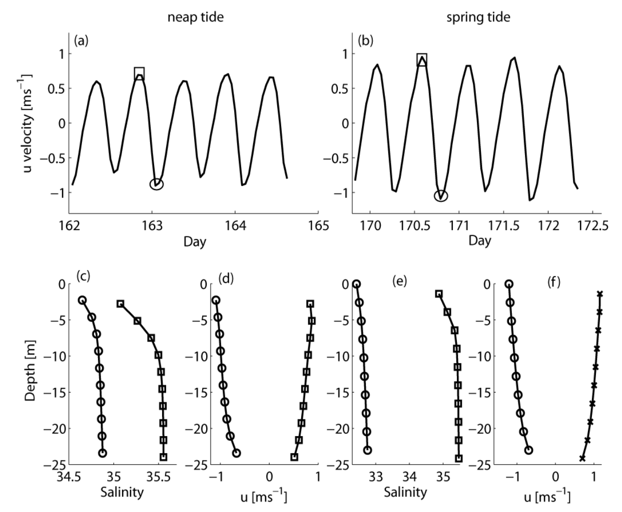

Figure 2. (a, b) Time series of along-channel depth-averaged velocity (*u* component) at station A at neap and spring tide for June 2004; (c, d). Vertical profiles of salinity and current velocity at the peak flood (squares) and peak ebb (circles) at neap tide and (e, f) spring tide.

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 values about 30% (10%) higher than the flood one at neap (spring) tide. In Figures 2c-f, it were compared the vertical profiles of salinity and current velocity between the peak flood and ebb tides.

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 tidal velocities on ebb tide that increases turbulent mixing which causes a decrease on stratification. At neap tide, the peak flood velocity profile shows a subsurface maximum (~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.

Cross-sectional structure

The model was also used to provide insight into transport of water and salt through a cross section located near the channel's inlet (near Station A, see Figure 1). The cross-section has a triangular shape with a deeper zone near the center, and may be considered representative of the lower portion of the channel. The longitudinal velocity and salinity were averaged over four complete tidal cycles in order to remove the tides and reveal the characteristic features of the estuarine circulation (Pritchard, 1952; Hansen and Rattray, 1965).

The lateral and vertical structure of the tidally averaged (or residual) salinity and longitudinal velocity component are shown in Figure 3. Positive values are referred as landward velocities and negative values as seaward values. The salinity structure presents a stratified water column but the channel may be considered as laterally homogeneous in terms of salinity. During this spring tide period, when the river inflow is high (~70 m^3 s^{-1}), the residual velocity pattern at this cross-section reveals flood currents near the north shore and ebb current on the south shore, revealing lateral differences in terms of current velocity.

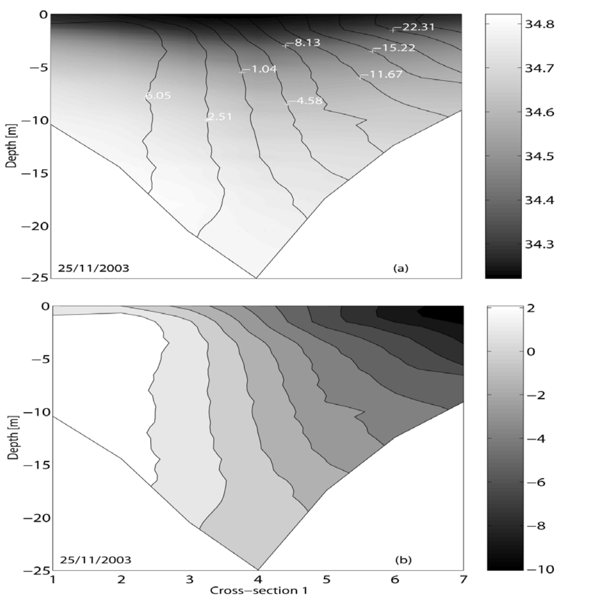

Figure 3. (a) Cross-section of tidally averaged salinity (shading, psu) and longitudinal velocity component (contour, cms^{-1}); (b) predicted tidally averaged salt transport (cms^{-1}) for cross-section 1, near the mouth of the channel. (a, b) are for spring tide and river flow of 70 m^3s^{-1}.

Near the mouth of the channel, the predicted tidally averaged salt transport corresponds to the same pattern observed in velocity, with a net up-channel flux (positive) in the proximity of the north shore of the section decreasing toward the center of the channel, and presenting a net down-channel flux (negative) from the middle toward the south shore of the channel. This is a common feature of the lower portion of the Espinheiro channel. The exception is when the river inflow is higher than 100 m^3s^{-1}, when a two-layer structure is visible (Vaz *et al.*, 2009).

Phase difference between water level, salinity and longitudinal velocity

In this channel, as in other tidal channels and estuaries, tidal elevation and velocity are not in phase, and the maximum and minimum salinity occur before or after high and low water. The use of a tested numerical model is particularly useful, not only to know the three-dimensional or longitudinal structure of a domain, but also to understand how different forcing conditions affect the occurrence of maximums and minimums of estuarine variables and the phase difference between them. In order to examine this phase lag are used vertical profiles of *u*-velocity and salinity obtained at the central axis of the channel (at the cross-section near the channels mouth, see previous section), during a complete tidal cycle for the neap tide period of January 2004.

A pronounced stratification and shear velocity at low (left panel) and high water (right panel) is noticeable from the salinity and velocity profiles. At low water, ebb currents are visible (Figure 4a). Near the surface, the longitudinal velocity present values of about -0.6 ms^{-1}, decreasing toward the channel's bed. The salinity profiles reveal some stratification, with top-to-bottom salinity difference of about 2 psu. At high water (right panel), the water is still being pushed into the channel, presenting flood

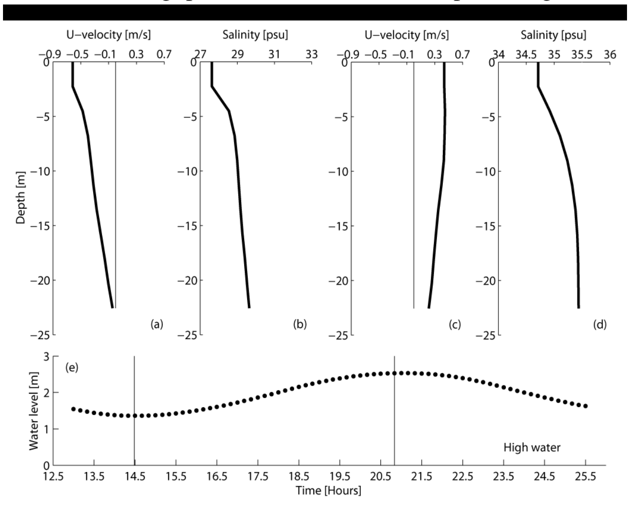

Figure 4. Computed vertical profiles of current velocity (a, c) and salinity (b, d) at a cross section near the mouth of the channel. (a, b) represents low water profiles; (c, d) high water profiles.

velocities at both cross-sections. Near the channel's mouth (Figure 4c), a typical logarithmic velocity profile is visible, with more intense values near the surface (~0.4 ms^{-1}).

In Figure 5 are depicted the vertical profiles of *u*-velocity and salinity near the channel's mouth at two different times: the beginning of the flood period and when the flood is fully developed in the entire water column.

The flood period begins 30 minutes after the low water. The water starts flowing into the channel at the bottom layer and the flood is fully developed 3h 40 min after low water (Figure 5a). This long period necessary to achieve a fully developed flood may be due to the intense freshwater inflow from the Vouga River, which enhances the ebb currents at the surface and acts like a countercurrent in opposition to the tidal intrusion. The maximum flood velocity is reached 4h 50min after the beginning of the flooding.

The salinity minimum (Figure 5b) occurs about 30 minutes after the beginning of the flooding at both cross-sections, revealing a time lag between the low water and the salinity minimum of ~1 hour. The salinity maximums occur 50 minutes after the high water. From the figure is also visible that when the minimums and maximums salinities are reached, the water column is weakly stratified. This fact may be related to the influence of the freshwater at this point and by the high velocity values, which increases turbulence and therefore increases mixing in the water column.

The Espinheiro Channel dynamics is mainly influenced by the interaction of tidal forcing and river inflow. From the simulations described in this study, it is possible to characterize the phase difference between tidal elevation, longitudinal velocity and the occurrence of salinity minimums and maximums. In fact, changing the tidal forcing from neap to spring and imposing a low-to-high river inflow, slightly modifies the phase difference between these estuarine variables. For example, for the spring tide of November 26th 2003 when the river inflow is weak (2.06 m^3s^{-1}), the time difference between the beginning of the flood and the low water is 1h 30min at cross-sections 1 (near the mouth). Increasing the river inflow (72.74 m^3s^{-1}) but keeping the tidal amplitude (spring tide simulation of November 25), this time difference is about 1h 40min at the channel's mouth. When the river inflow changes from medium-to-high, the salinity minimum is reached 30 minutes after the beginning of the flood (January 29, neap tide), and 10 minutes (after the beginning of the flood) under medium river inflow and spring tide conditions (November 25). The salinity maximums are reached 1 after high water, at the channel's mouth. During the two periods of medium-to-high river inflow, the maximum flood current is reached typically 1 hour before high water.

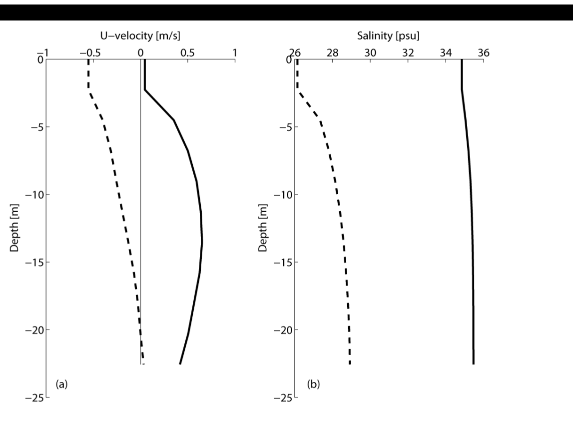

Figure 5. Vertical profiles of current velocity (a) and salinity (b) at the mouth of the channel. (a) Dashed line: beginning of the flood; solid line: fully developed flood current. (b) minimum (dashed line) and maximum (solid line) salinity profiles during the tidal cycle.

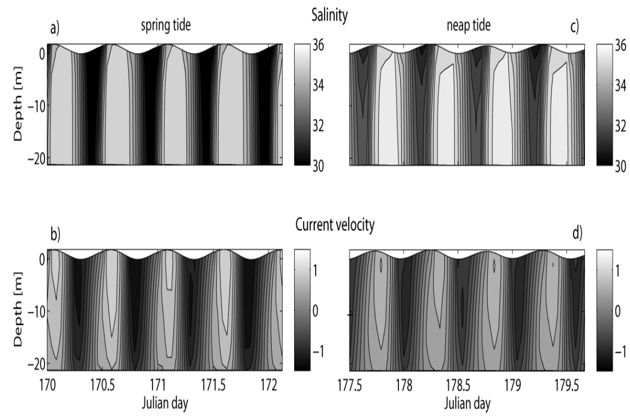

Figure 6. Time evolution of salinity (a, c) and tidal currents (ms^{-1}) (b, d) at a station located near the mouth of the channel. The left panels represent a spring tide and the right panels represent a neap tide. The river inflow is lower than 10 m^3s^{-1} for both periods.

Time evolution of tidal currents and salinity

Tidal currents and salinity time evolution are analyzed at a station located near the channel's inlet (station A, see Figure 1). This station is located at the channel axis, and Figure 6 depicts the results for four tidal cycles during a spring and a neap tide (June 2004).

During the spring tide period, the salinity presents lower values at the end of the ebb tide (Figure 6a). In fact, values of 31 psu are found at this location near the channel's inlet. On neaps, the salinity values at the end of the ebb tide are higher than in spring, presenting values of about 34 (31) psu on the surface (bottom) (Figure 6c). At the end of the flood period, values of 35 psu are found for both spring and neap tides. The tidal currents are higher on spring tides, presenting values ranging from -1.4 ms^{-1} during ebb and 1 ms^{-1} during the flood period (Figure 6b). During neaps, tidal currents presents a lower range, with values of -1 ms^{-1} during ebb and flood values of about 0.9 ms^{-1}. These velocity values explain the salinity values found at this location. Due to the intense tidal velocity, more low saline water (during spring tides) is advected toward the mouth of the lagoon, which decreases the concentration of salt at this location.

The water column, presents higher stratification during the neap tide period and on peak flood, which is consistent with the results presented in Figure 1. In fact, during the spring tide, the intense ebb currents induce a well mix water column at this location. In neaps, the stratification is higher, with a bottom-to-surface difference of about 3 psu, and the water column is partially stratified.

CONCLUSIONS

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 the results found by Jay and Smith (1990) for the Columbia River estuary.

The cross-sectional structure of the channel's mouth may be considered homogeneous in terms of salinity, but presents lateral differences in the tidal-averaged velocity, with ebb predominance near the south shore and flood predominace in the north shore of the channel. This result is consistent with that reported by Vaz *et al.* (2009).

The model was also used to evaluate the phase difference between sea level height, current velocity and salinity. Near the channel's mouth, the time difference between velocity and sea level is higher than 3 hours under an intense river inflow regime (higher than 100 m^3s^{-1}).

Near the channel's mouth, the tidal currents are high and induce large turbulent mixing, generating well-mixed conditions, except during high river runoff events when this area is considered partially stratified. In this channel, the turbulence generated by the large tidal currents is 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.

The analysis of the results was focused on the study of the lower portion of the channel, near its mouth. The main conclusions are:

- This region changes its physical characteristics in short time scales (one tidal cycle).
- Stratification reduces from peak flood to peak ebb, induced by changes in the local velocity.
- Near the channel's mouth, the circulation is highly complex due to the phase difference between the tidal elevation and current velocity, which induces changes in the salinity distribution according to the type of tide and river discharge.
- All the results are consistent with observations, making the use of a 3D model a suitable tool to study a complex system as the Espinheiro Channel.

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