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Atmospheric Influence Over the Residence Time in the Bahia Blanca Estuary, Argentina

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Abstract

An integrated hydrodynamic and Lagrangian transport model was used to estimate the average residence time in the Bahia Blanca estuary (Argentina) for wind conditions of different seasons. The Bahia Blanca estuary consists on an elongated system of meandering bays surrounded by tidal flats and salt marshes where the tide is the principal forcing. Modelling results show that both the tidal amplitude and wind forcing affect significantly the residence time, since river discharge is very low. An increase in the wind intensity along the bays main axis causes a considerable increase in the intensity of the residual current and thus a modification of the average residence time over the model domain. In all seasons, the overall residence time ranges from 12 to 77 days. The values allow establishing a hydrodynamic performance for each of the estuary sectors over each seasonal period. These findings provide useful information to quantify the transport processes on the different sectors of the Bahia Blanca estuary necessary to understand temporal and spatial variations.

Keywords Residence time · Bahia Blanca estuary · Lagrangian transport · Hydrodynamic model · Mohid numerical model

Introduction

In recent decades, models for evaluating the water exchange in estuaries and coastal areas have received large attention (e.g., Dong and Su 1999a, b; Delhez et al. 2004; Liu et al. 2004; Fukumoto and Kobayashi 2005; Pierini et al. 2008; Ascione Kenov et al. 2012). The water exchange rate between an estuary and the open ocean plays a critical role in controlling the chemical and biological processes because of the important implication to the fate of discharged substances, and the primary production.

The time scales associated with the water exchange between the system and the open sea is a combined function of the freshwater runoff, tidal range, bathymetry (shallowness) and wind regimes and controls maximum concentrations of products discharged in the estuary, but also of products produced inside the estuary. Estuaries with a short residence time would export nutrient from upstream sources to the open ocean more rapidly than estuaries with longer transit times, reducing intensity of bloom events through nutrient limitation, but also because microalgae would stay shorter. In fact, residence times shorter than the doubling time of algae cells would inhibit formation of algae blooms (Kierstead and Slobodkin 1953; Lucas et al. 1999; USEPA 2001). Renewal time scales also characterize the exchanges between the water column and the sediment: deposition of particulate matter and associated adsorbed species depends on the particles settling velocity, water depth and particle residence time. This is particularly important for the fine fractions with lower sinking velocities (Braunschweig et al. 2003).

Highlights
A Lagrangian transport model was implemented for the Bahia Blanca estuary (Argentina).
Hydrodynamics and residence time were estimated for the Bahia Blanca Estuary
The influence of several climatic seasons on residence time was examined
Bahia Blanca bays are interconnected and exchange water following different routes.
The importance of the bio-physical processes that exist over the area was determined

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As a related concept to water exchange, the residence time is a parameter commonly used for representing the time scale of the physical transport processes (Bolin and Rohde 1973; Zimmerman 1976; Takeoka 1984). This paper describes the influence of different physical forcing on the estimation of the residence time, using a Lagrangian transport model, in order to acquire a better understanding of the Bahia Blanca estuary, Argentina. This is a part of a series of studies undertaken to improve the understanding of the hydrodynamic and transport processes within the estuary, with the overall aim of predicting the fate of contamination reaching the Bahia Blanca estuary, such as sewage, dredged material, sediment, trace metals or any other water discharges (Pierini et al. 2012; Campuzano et al. 2013).

Bahia Blanca tributaries discharge at the estuary head large nutrient loads especially during autumn and spring when the flow increases due to high rainfall in the catchment. In upper area are also located raw sewage discharges of the Bahia Blanca urban area. As a result, high nutrient concentrations in reduced forms (ammonia, nitrate and phosphate) were observed that combined with long residence times and bottom muddy sediments enhanced primary production activity (Freije and Gayoso 1998) with diatoms predominance (Gayoso 1983, 1988, 1999). The long duration of these episodes can be negative from the ecological point of view for the estuarine ecosystems.

Study Site

Bahia Blanca is a mesotidal coastal plain estuary located in the southwest of the Buenos Aires Province (Argentina). Bahia Blanca, as pointed by its name, is a bay or collection of bays with a north-west to south-east orientation, separated by islands and wide tidal flats. Their names - from north to south - are Principal Channel, where the main human settlements are located, Falsa Bay and Verde Bay (Fig. 1). The main sub-bay, Principal Channel, has a total length of 60 km, varying in width from 200 m at the head (3 m deep) to about 3–4 km at the mouth (22 m deep) where it connects to the Atlantic Ocean by a modified ebb delta.

Three freshwater streams enter the estuary: the Sauce Chico River (with a drainage area around 1.620 km^2), discharging into the Principal Channel about 3 km downstream from the head of the estuary, Saladillo de Garcia creek (with a drainage area of 830 km^2) and Napostá creek (with a drainage area around 1.260 km^2) that reaches the estuary about 1 km downstream of Ingeniero White Harbor. Averaged annual flows for Napostá Creek and Sauce Chico River are 2.68 and 5.80 $m^3\ s^{-1}$ respectively, for the 1993–1999 period provided by Aguas Bonaerenses Sociedad Anónima (ABSA) (Fig. 1).

Though the two main continental water contribution to the head of the estuary, Sauce Chico River and Napostá Grande Creek are located in the same basin (Sierras de la Ventana), their drainage network are not subjected to the same rainfall regime and they present different peaks along the year. Sauce Chico River presents two main peaks, one during autumn (Feb-Jun) and a stronger one during spring (Aug-Dec), corresponding to the rainiest period on the Bahia Blanca region. However, Napostá Grande Creek flow shows two peaks of similar intensities both in winter (Apr-Aug) and spring (Aug-Dec). Figure 2 shows the monthly averaged flow from data collected during the 1993–1999 period provided by

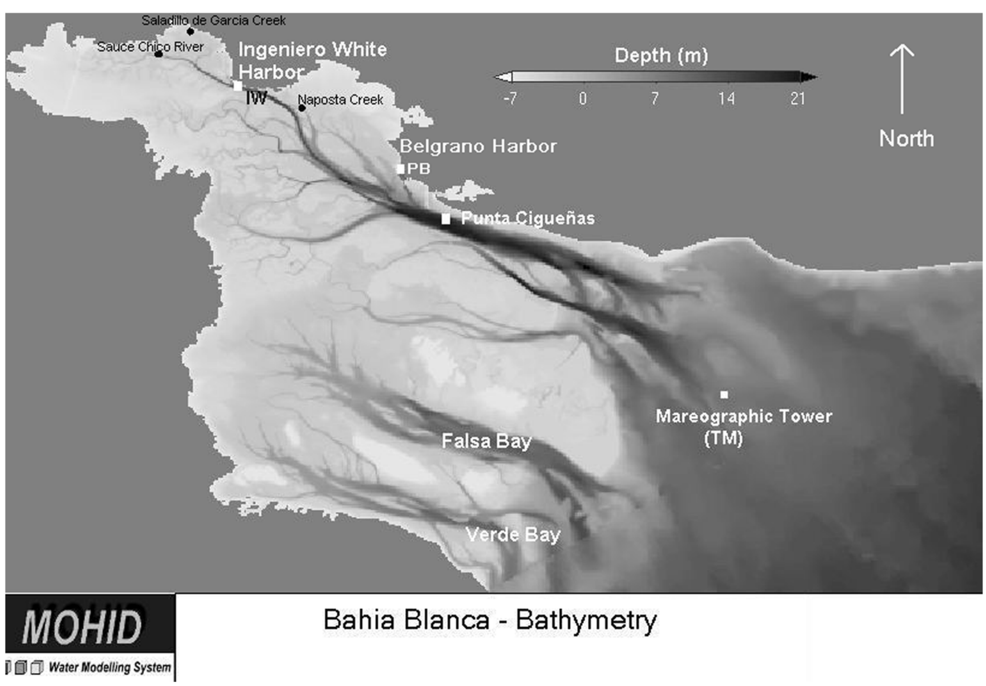

Fig. 1 Bahía Blanca estuary location and bathymetry

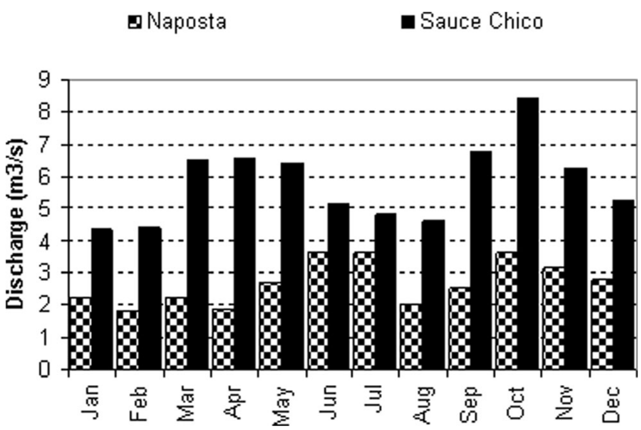

Fig. 2 Sauce Chico River and Napostá Creek monthly flow values

Aguas Bonaerenses Sociedad Anónima (ABSA). Sauce Chico presents a flow pattern very influenced by the local rain pattern on Bahia Blanca region while Napostá is more influenced by the precipitation near Sierras de la Ventana (Pierini 2007). Other artificial sources of fresh water around the Bahia Blanca estuary include the Bahia Blanca wastewater discharge with a total average flow of 0.58 m^3 s^{-1}. In any case, these freshwater inputs into such a large system are very small, and their effect on hydrodynamics is limited to the discharge area.

Climatological Conditions

The Bahia Blanca estuary location determines a typical lowland climate along with small elevations next to the Atlantic Ocean. The wind regime is dominated by northwestern (NW) winds throughout the year with the occurrence of periods of winds from the southeast (SE) quadrant associated with cold fronts crossing the coastal region of the study area. The changes in meteorological conditions observed in the Bahia Blanca estuary are usually associated with the passage, formation or intensification of cold fronts, position changes of the Atlantic and South Pacific semi-permanent anticyclones that constitute the great engines that govern atmospheric circulation in middle latitudes and determine the dominant synoptic conditions of the area. The study area is windy with prevailing winds from the N and NW with an average speed of 24 km h^{-1} and gusts often of 120 km h^{-1}. During winter, the detachment of the South Pacific high pressure and a low pressure centre in the north, along with a continental high pressure center create a SE airflow, called '*sudestadas*'. The high pressure is loaded of moist air at sea and moves into the continent with SE-NW direction. Generally from December, the North wind originates on the western edge of the South Atlantic anticyclone and generates high temperatures, low humidity and atmospheric pressure changes. On the other hand, the Pampero defined as a dry cold or fresh wind or fresh blowing from the south or southwest and that is registered with the passage of a cold front. The anticyclones migration determines the air temperature, humidity, winds and precipitation spatial and temporal variation (Capelli and Campo 2004).

In order to determine hourly wind parameter in our study area, the Mareographic Tower meteorological station (TM) installed at the Bahia Blanca estuary mouth by the Bahia Blanca Port Management Consortium (CGPBB) was used (Fig. 1). Table 1 summarizes the seasonal values of the wind at the TM tide gauge. The data analyzed correspond to the data set between 2000 and 2008. The average wind is 22.6 km h^{-1} and predominant direction of NNW (315°), NW (337.5°) and N (0°).

Model Description

The MOHID water modeling system (http://www.mohid.com) was developed mainly by the Marine Technology Research Centre (MARETEC) at the Universidade de Lisboa (Portugal) (Neves 2013). The MOHID system uses a finite volume approach (Chippada et al. 1998; Martins et al. 2001) to discretise the equations. With this approach, the discrete form of the governing equations is applied macroscopically to a volume cell, making the equation solving cell geometry independent and allowing the use of a generic vertical coordinate that minimizes the errors of the classical vertical coordinates (Martins et al. 2001). The equations are discretised horizontally in an Arakawa-C manner staggered grid. The temporal discretisation is carried out by means of a semi-implicit (ADI) algorithm with two time levels per iteration. The model has shown its ability to simulate complex coastal and estuarine flows (Pina et al. 2004). The MOHID Lagrangian module was used to assess the spatial-temporal evolution of the residence time, following the methodologies proposed in previous works (Trancoso et al. 2005; Braunschweig et al. 2003; Ascione Kenov et al. 2012). The Lagrangian module simulates the movement of Lagrangian tracer "particles" using current fields calculated by the hydrodynamic module, thus solving the equation of transport independent of momentum balance equations. The Lagrangian module derives the hydrodynamic information (current fields) from the system and updates the calculations without having the need to solve all variables at the same time (Gómez-Gesteira et al. 1999).

Table 1 Seasonal mean wind intensity and direction at the TM station (North = 0°)

Season	Intensity (ms^{-1})	Direction (°)
Spring	7.38	322.5
Summer	5.47	337.2
Autumn	5.62	345.9
Winter	6.41	334.2

Given the large horizontal dimensions (70 km) relative to the vertical (10 m) in the estuary, the vertical velocities and accelerations are small relative to the horizontal components. Thus the processes generating quantity of movement and transport occur at a different scale in the vertical and horizontal directions. Due to this fact, the circulation on these domains is mainly horizontal which implies that vertical accelerations can be ignored when compared with the gravity effect. Therefore the vertical equation of motion may be replaced by the hydrostatic pressure approximation.

Then a MOHID hydrodynamic model was used to force a two-dimensional (2D) vertically averaged domain model with a horizontal resolution of 0.002° covering from the coordinates (−61.41 W, −39.38S) to the inner estuary (−62.57 W, −38.70S). The model was forced with tides and freshwater inputs as described in following sections. Bathymetric data used to compose the model domain come from two sources, the GEBCO digital atlas, a one minute global bathymetric grid database (IOC et al. 2003) and data from the CGPBB with a waterline obtained from the evaluation of 6 sets of Landsat 5 TM and Landsat 7 ETM data resulting in a high density bathymetry (50 m × 50 m) (Pierini 2007).

Water Levels

Due to the vicinity of the TM tidal gauge (Fig. 1) to the Bahia Blanca domain limits, the approach followed was to impose the tidal components of that station along the entire open boundary to obtain robust hydrodynamics (Campuzano et al. 2008). Figure 3 shows the water levels for a tidal cycle during average tidal conditions, between spring and neap tide conditions. In that figure, it could be observed how the tide enters each bay of the Bahia Blanca estuarine system by its southern margin simultaneously finding all the channels reduced in width and most of the intertidal areas emerged. As the tide advances, water starts to cover the intertidal areas amplifying the submerged area. The interaction of the tidal wave with the shallow depths of the channels resulted in an increase of the overtides importance. Maximum tidal amplitudes are found for the three channels at their innermost areas, being the

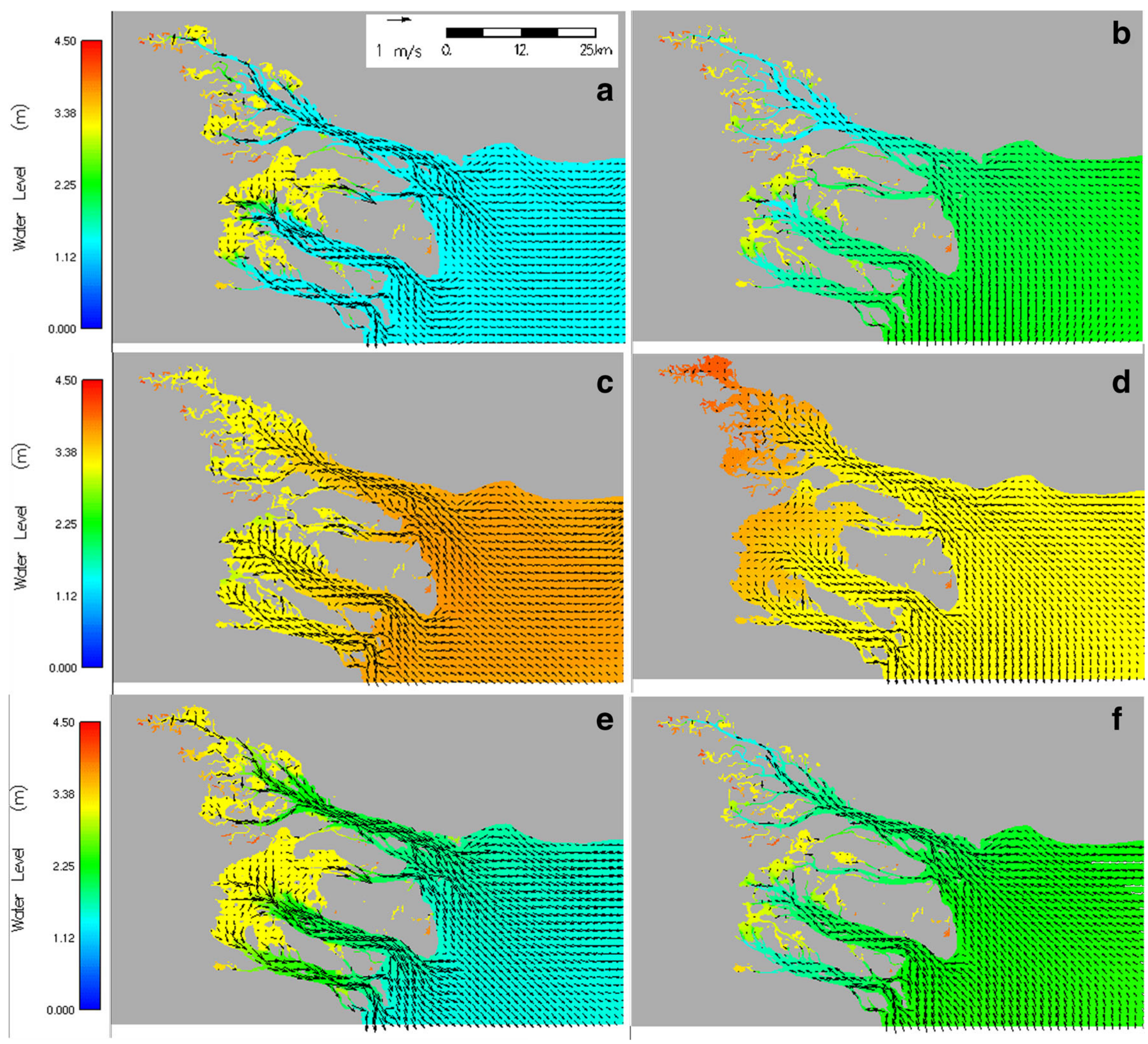

Fig. 3 Water levels for the Bahia Blanca estuary with a 3 h interval (**a**) 07 h (**b**) 10 h (**c**) 13 h (**d**) 16 h (**e**) 19 h (**f**) 22 h of the 7th of April 2002

absolute maximum located in the Principal Channel. During high tides, the inter-channel connections increase favoring water exchange between adjacent bays. When the tidal wave retreats, water flows from the inundated intertidal areas into the main channels, the ebb is still taking place when a new tidal wave is entering the system, as could be appreciated on the last image of the sequence. Water enters predominantly by the southern margin and exits with higher intensities by the central area of the channels following the channels maximum depth. Tidal currents at the estuarine mouth are the result of the cumulative processes of the outer general circulation and the distortion produced by the Bahia Blanca channels hydrodynamics.

Currents

Current intensities and directions for the tidal cycle described in the above section is given in Fig. 4. In this figure, it could be observed that once the estuary starts to be flooded and water begins to cover the large intertidal areas the space available for flooding increases and velocities reduce. The reverse process occurs on the ebb tide, water drains to the channels reduced in size increasing the currents velocities. Ebb velocities were higher than flooding velocities in the three bays. In the high reaches of the intertidal areas low intensity currents were found. Modelled peak velocities on the intertidal areas during flow were generally under 0.3 m s^{-1}.

Maximum current intensities were observed along the channels (Pierini 2007). In Verde Bay, maximum values were located near its mouth where water tends to concentrate. In Falsa Bay, maximum intensities were located also near its mouth and in its head due to the water flowing from the large surrounding intertidal areas. In the Principal Channel, ebb intensities along the main axis were comprised between 0.7 m s^{-1} and 1.4 m s^{-1}, being found the maximum values near the upper reaches.

These range of values were in agreement with the observations reported previously for this area (Pierini 2007; Pierini

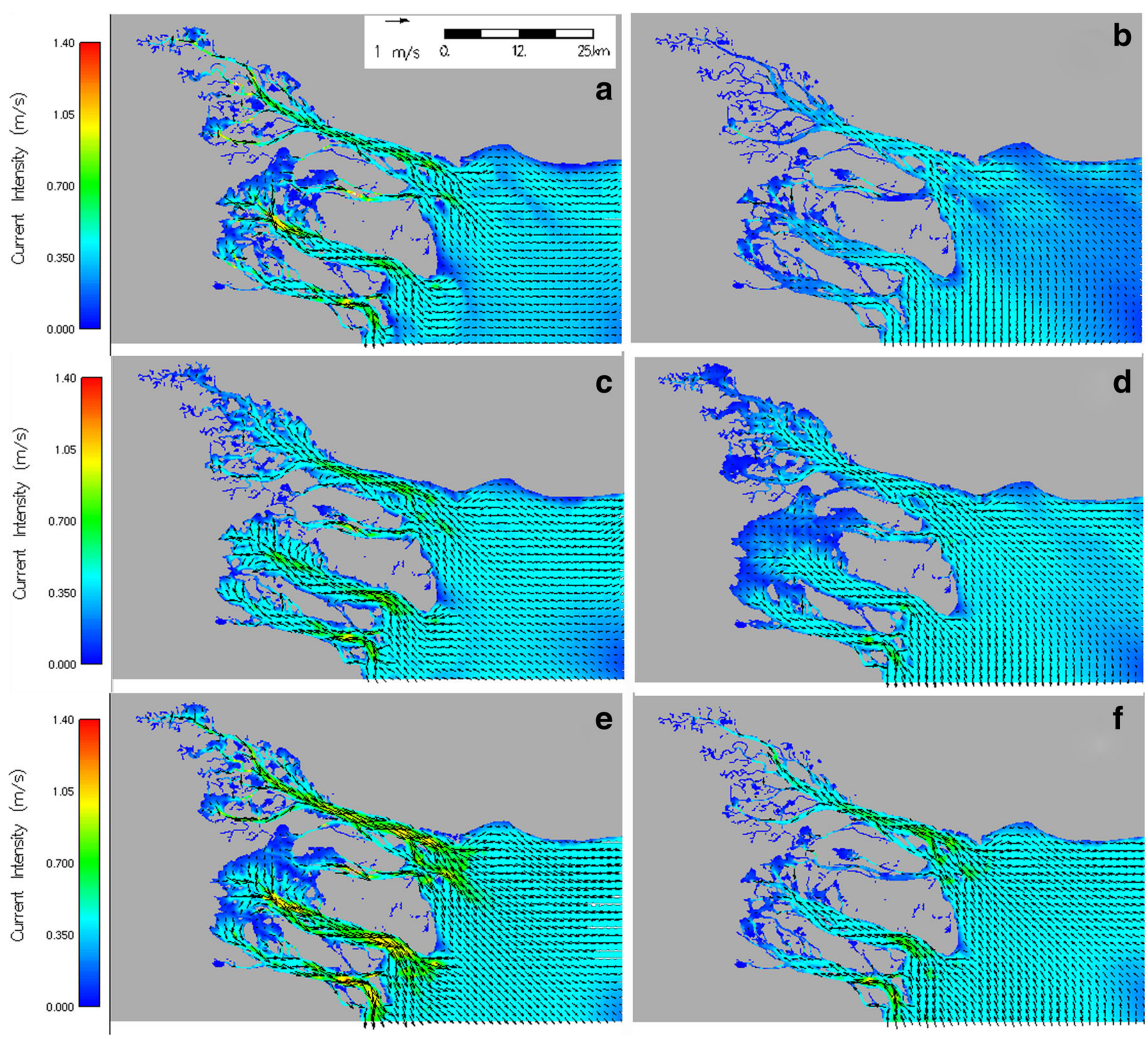

Fig. 4 Instant velocities for the Bahia Blanca estuary with a 3 h interval (**a**) 07 h (**b**) 10 h (**c**) 13 h (**d**) 16 h (**e**) 19 h (**f**) 22 h of the 7th of April 2002

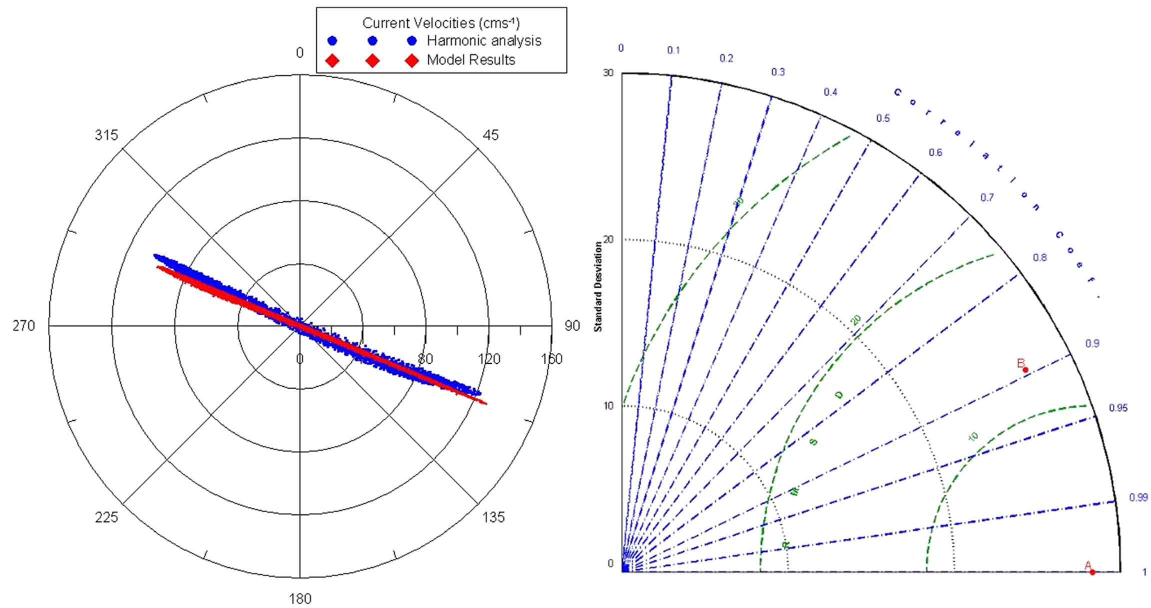

Fig. 5 Rose diagram representing the current intensities and directions obtained through harmonic analysis (dots) and modelling (diamonds) (left) and Taylor diagram for the reconstitued (**a**) and modelled (**b**) current intensities (right) for the Punta Cigüeñas station (Campuzano et al. 2014)

et al. 2008) who showed maximum superficial values around 0.80 m s^{-1} and 1.40 m s^{-1} for flow and ebb currents respectively, observed overall peak values on flood and ebb range were 0.27 m s^{-1} and 0.87 m s^{-1} respectively, and Gómez et al. (1996) that integrated vertically their observations obtaining values of 1.05 m s^{-1} and 1.30 m s^{-1} for flood and ebb currents, respectively.

Outside the estuary, flood velocities are generally larger than the ebb velocities due to the direct relationship between velocity and depth. In the coastal area, measurements obtained during the Austral campaign in 1993 observed maximum velocities of 0.6 m s^{-1} with velocities over 0.3 m s^{-1} surpassed during more of the 30% of the time (Cuadrado et al. 2002). These intensities are similar to the ones obtained through modelling (Fig. 4).

Model Validation

The calibration of the hydrodynamic model was performed by adjusting the bottom friction coefficient, through the comparison between measured and predicted time series of sea level for 3 stations along the Principal Channel. Harmonic analysis was performed in order to evaluate the model accuracy. To validate the hydrodynamic model measured and predicted sea level values were compared for 3 stations (Mareographic Tower (TM), Belgrano Harbor (PB) and Ingeniero White Harbor (IW)), as well as main flow velocities and directions at a station (Punta Cigueñas). This model was validated comparing the model results with an independent field data set. The hydrodynamic model for Bahia Blanca estuary was successfully calibrated and validated in Campuzano et al. (2014).

The model was able to reproduce the current intensities and the direction. The coefficient of determination obtained when comparing both intensities (measured and modeled) was 0.80, which implies that model results are able to explain the 80% of variability on intensity due to tides. The model results agreed with the relative phase values (Phi) and showed that stations within the system were ebb-dominated with an increasing character with distance from the estuarine mouth. In Fig. 5 right, the current values for the reconstituted time series with the harmonic analyses (A) and the modeled values (B) are represented in a Taylor diagram (Taylor 2001). This diagram provides a concise statistical summary of how similar the sets of values are by providing in a single diagram their correlation, 0.90 in our case, the root-mean square difference, 12.80 in our case, and their standard deviations, 28.31 for the reconstructed values and 27.16 for the modeled values. In this diagram, the closer the stations the more similar they are. The correlation is very high between the two stations and they also present a similar standard deviation and a low root mean square difference (Campuzano et al. 2014).

Table 2 Model performance indicators at each tidal gauge for the Bahia Blanca estuary model (Campuzano et al. 2014)

Station	TM	PB	IW
Correlation (r)	0.985	0.987	0.966
Coefficient of determination (R^2)	0.971	0.974	0.933
MB	−0.048	0.104	−0.054
Bias / total amplitude * 100 (%)	1.37	2.35	1.08
RMSE	0.162	0.220	0.369
Skill	0.992	0.991	0.981

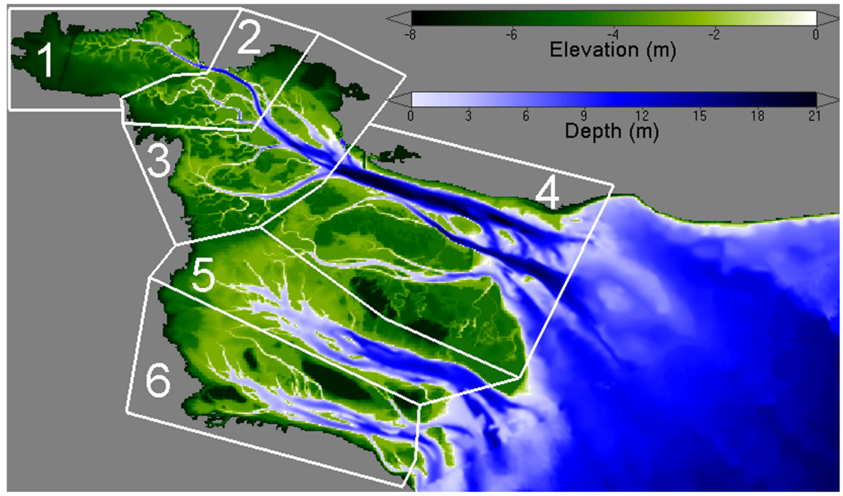

Fig. 6 Defined boxes for calculating residence time in the Bahía Blanca estuary

From the open ocean to the inner area, water levels at the TM station were very close from the model results as its tidal components were the ones used to force the model, differences were mainly due to the distance travelled by the wave until reaching the validation station. The linear regression between both series shows that water levels in both series were comprised in the same range of values and the coefficient of determination was very high 0.97 (Campuzano et al. 2014). In PB tidal gauge, the degree of adjustment was 0.97, similar to the obtained in TM station. Around 20 km inland from PB station, IW station model results and the astronomical tide presented a coefficient of determination of 0.93. However, modelled low tides at IW station were lower than the values obtained through the harmonic analysis. A possible explanation would be the inaccuracy on the bathymetry as it was obtained from a combination of different sources. In any case, the results obtained would model with high accuracy the tidal processes taking place inside the Bahia Blanca estuary.

As mentioned in the Campuzano et al. (2014) paper the comparison between the observed tidal levels obtained through harmonic analysis with the predicted levels obtained through modelling, the indicators suggested on Willmott (1982) were assessed (Table 2). Mean bias (MB) indicates the averaged difference between the observed and predicted values, modelled amplitudes deviate a low percentage of the total amplitude at all stations. Root Mean Square Error (RMSE), is the square root of the variance indicating that 95% of the model predictions do not differ, in absolute value, from the observations by more than 2xRMSE.

The skill index, or index of agreement, could be regarded as the normalized model error and provides similar information than the coefficient of determination, in the sense that gives a measure of the model performance, but it penalizes models with greater bias. Skill values for each station are close to one, indicating a high degree of model performance.

Residence Time

To estimate the residence time in the Bahia Blanca estuary, the methodology proposed by Braunschweig et al. (2003) was applied. In this methodology the estuary is divided into subregions "boxes" (Fig. 6). The water inside each box is divided into parcels, "particles", and the average residence time of each box particles is calculated. In the case of the Bahia Blanca estuary a set of six boxes were defined and filled with volume particles of 1.1 10^5 m^3 each as defined in Table 3 in a way that the total volume associated to the particles matches the total volume of the estuary. The boxes were defined in order to evaluate exchanges between the three different bays: Verde, Falsa and Principal Channel. The Principal Channel has been divided into a set of four boxes to calculate the residence time of the different areas of the channel.

Several simulations were performed using observed wind data at different year periods and one in the absence of wind to calculate the tracer evolution within the estuary. Figure 7a depicts the original situation of these tracers and a snapshot of their location after a month simulation, in the latter it can be observed that particles are able to travel through the intertidal channels and along the estuary (Fig. 7b).

From the modelling results, it can be drawn a conceptual model where the different bays are interconnected and exchange water by different routes. Verde Bay

Table 3 Particles originally contained on each defined box

Box	1	2	3	4	5	6
Initial Volume (m^3)	6.94E+07	1.56E+08	4.60E+08	2.93E+09	1.45E+09	7.61E+08
Number of Particles	631	1418	4182	26,636	13,182	6918

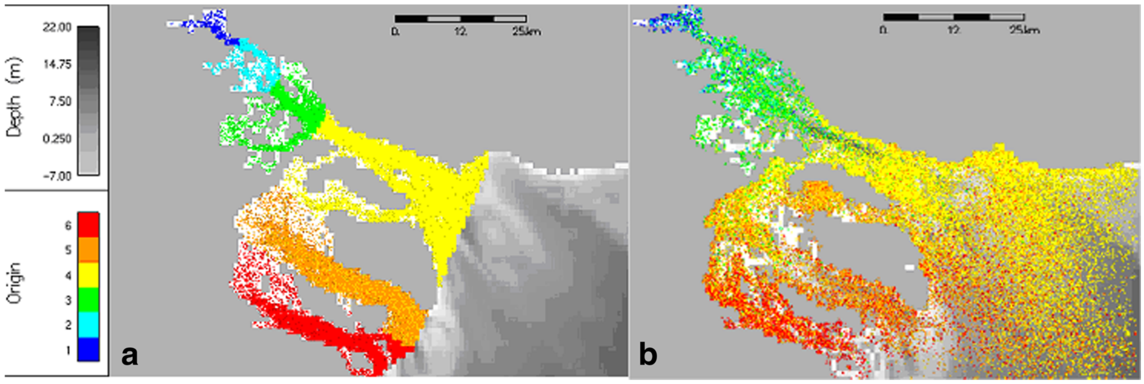

Fig. 7 Particles at the beginning (**a**) of the run and after (**b**) one month

exports water to the open ocean that is reincorporated by Falsa Bay due to the general current that travels north, the same process takes place between Falsa Bay and the Principal Channel. On the other hand, the three bays are connected by inner parts following inverse transport scheme where water from the Principal channel enters Falsa Bay head and continue to Verde Bay. This recirculation system is broken only by water exports from the Principal Channel to the open ocean (Pierini 2007; Campuzano et al. 2008, 2014).

The water fraction (f) inside the box at each time step is calculated by the following expression:

$$f_{i,j}(t) = \frac{V_{i,j}(t)}{V_{i,j}(0)}$$

With $V_{i,j}(t)$ being the volume of tracers from box j, contained in the box i at a time t, and $V_{i,j}(0)$ the original volume contained by the box i at the beginning of the simulation. When $V_{i,j}(t)$ (volume of tracers) equals to zero implies that all the original volume of water ($V_{i,j}(0)$) has been replaced by new water and thus t would be the residence time of that water mass, only if $V_{i,j}(t)$ equals $V_{i,j}(0)$ which means that $f_{i,j}(t) = 1$.

Eventually during the simulations a small fraction of the tracers can remain confined within a box for a prolonged period of time, leading to high residence time. Due to this phenomenon, the residence time, in this study, has been defined as the time needed to evacuate 90% of the original volume of water (T90). The remaining volume within the estuary generally tends to describe a logarithmic relationship with time, the regression coefficients and formulas are detailed on Table 4 (Fig. 8).

The water released in the boxes is sometimes strongly recirculated. In fact, the time to evacuate the 50% of the original volume of the three first boxes, corresponding to the inner part of the Principal Channel, could be longer than 2 years ($R^2 = 0.82$). This value is consistent to the one found in Pierini (2007) and Campuzano et al. (2013).

Wind Influence over Residence Time

Prevailing winds of TM station are NW-N for over 41% of the time, while SE-S winds occur ~9% of the time. These wind directions are important because they blow parallel to the main channels. Wind is a major factor in the Bahia Blanca estuary dynamics since it produces strong delays or advances of the tidal wave and large differences between the real and the predicted astronomical tides (Pierini 2007).

As the dominant winds come from the NW, Boxes 1 and 2 particles (Fig. 6) would tend to leave the area faster due to the wind influence, thus reducing the residence time. Similarly, it can be observed that the Box 4 is the responsible of the estuarine water flow to the open ocean and its residence time would depend on the wind direction. While the Box 3 is a transition zone where the retention time is smaller in any case studied.

Using the same initial conditions and amount of particles from the previous study, the model was forced with hourly wind conditions obtained at the TM station (Fig. 9), to study the different seasonal hourly wind intensities and directions and to represent realistic situations instead of constant winds with a persistent direction.

Considering hourly wind values different simulations were performed starting at a random day for each season. All

Table 4 Logarithmic equations for residence time, determination coefficient and T_{90}

Box	Formula	R^2	T_{90}
1	y = −6.3942Ln(x) + 48.779	0.67	430
2	y = −8.0620Ln(x) + 57.073	0.84	343
3	y = −7.6277Ln(x) + 50.039	0.87	190
4	y = −14.057Ln(x) + 81.327	0.95	160
5	y = −9.5548Ln(x) + 55.308	0.84	115
6	y = −7.8002Ln(x) + 52.371	0.95	229

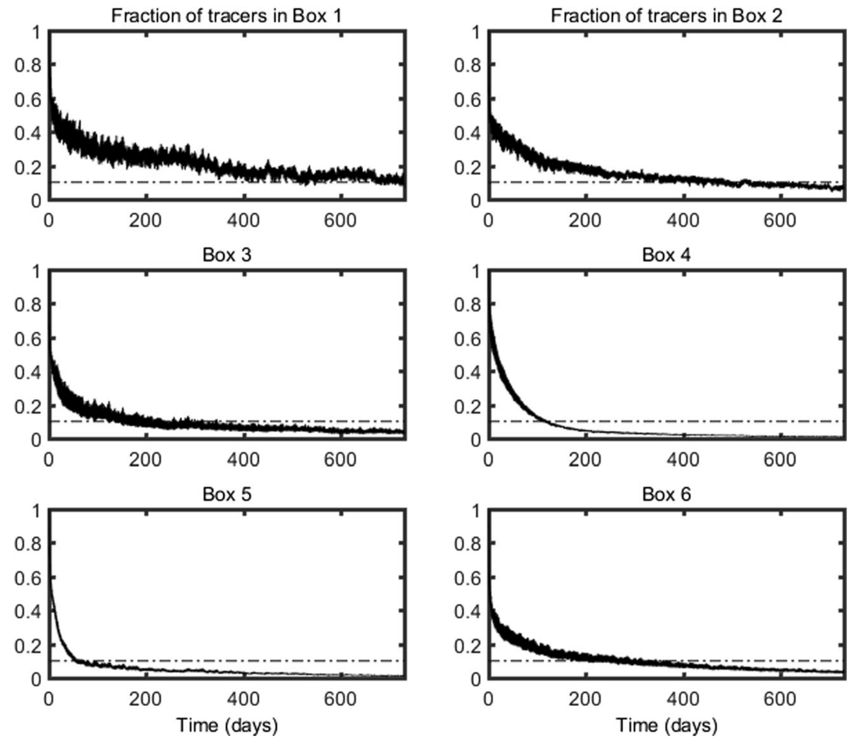

Fig. 8 Fraction of tracers over Bahía Blanca estuary without wind, dates comprised between 01/05/2002 and 01/06/2004

simulations initiated and completed within the season of the year evaluated and the residence time obtained is the average of the simulations performed (Table 5). Although here we are not showing the hourly wind time series, for sake of brevity, the graphical results of the frequency distribution and wind direction for each season of the year are shown in Fig. 10.

Tidal currents when combined with the wind action changes the estuarine circulation pattern. In this case, the circulation generated by meteorological forcing promotes the mixture of the water masses in the estuary and especially over the shallow areas. As illustrated through the results, residence time decreases in the inner part of the estuary (Table 5).

However, the wind does not influence significantly the water circulation in Box 4, indicating that the wind effect is stronger in the shallower parts of the estuary.

Throughout all simulations, the difference on the residence time has been found insignificant when using maximum and minimum average flow for the Sauce Chico River and Napostá creek, due to the poor water contribution when compared with the tidal prism of the Bahía Blanca estuary.

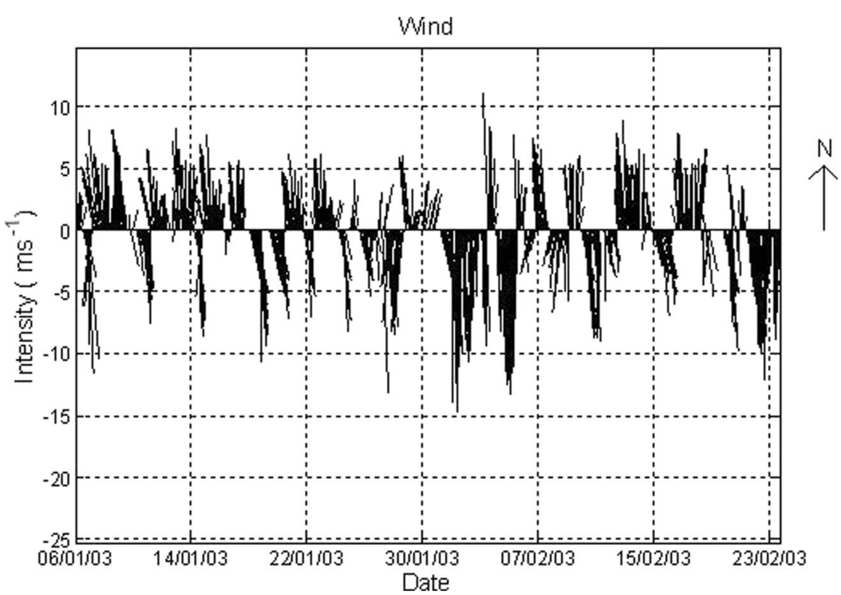

Fig. 9 Stick plot of hourly wind intensity and direction of weather station located at Torre Mareografica (TM) during some days in 2003. Wind stick point in the direction "from" which the wind is blowing

Table 5 Mean Residence Time (T_{90}) with real wind data

Box	Summer	Autumn	Winter	Spring
1	20	25	18	15
2	48	25	15	28
3	16	15	12	18
4	77	28	22	57
5	60	28	17	35
6	25	20	18	22

Discussion and Conclusion

The Bahía Blanca estuary is the most important deep water harbour system of Argentina and to maintain its navigability it needs periodical dredging. It is very important to gain knowledge of system dynamics in order to evaluate the posible impacts due to the dredging and the rejection at the disposal areas, navigation security, waste water discharge trajectories and other applications. In an estuary composed with a high ratio of intertidal areas, hydrodynamics would be very sensible to the water level variations. The Bahia Blanca estuary consists of a set of three parallel bays, namely from south to north Verde Bay, Falsa Bay and Principal Channel. They are interconnected through large intertidal areas crossed by smaller creeks and gullies that collect water into the main channels during the ebb.

The main contributor to the system hydrodynamics are the astronomic tides explaining more than 85% of the water level variation while the fresh water sources are scarce in flow. However other atmospheric phenomena as pressure and wind can provoke modifications in water levels (Campuzano et al. 2014).

The model hydrodynamics indicate a residual circulation of dissolved properties into the head of the tidal channel and on the contrary, export of particulate matter through tidal channels. This fact is relevant for water quality and sediment studies. Dissolved properties would tend to accumulate on the

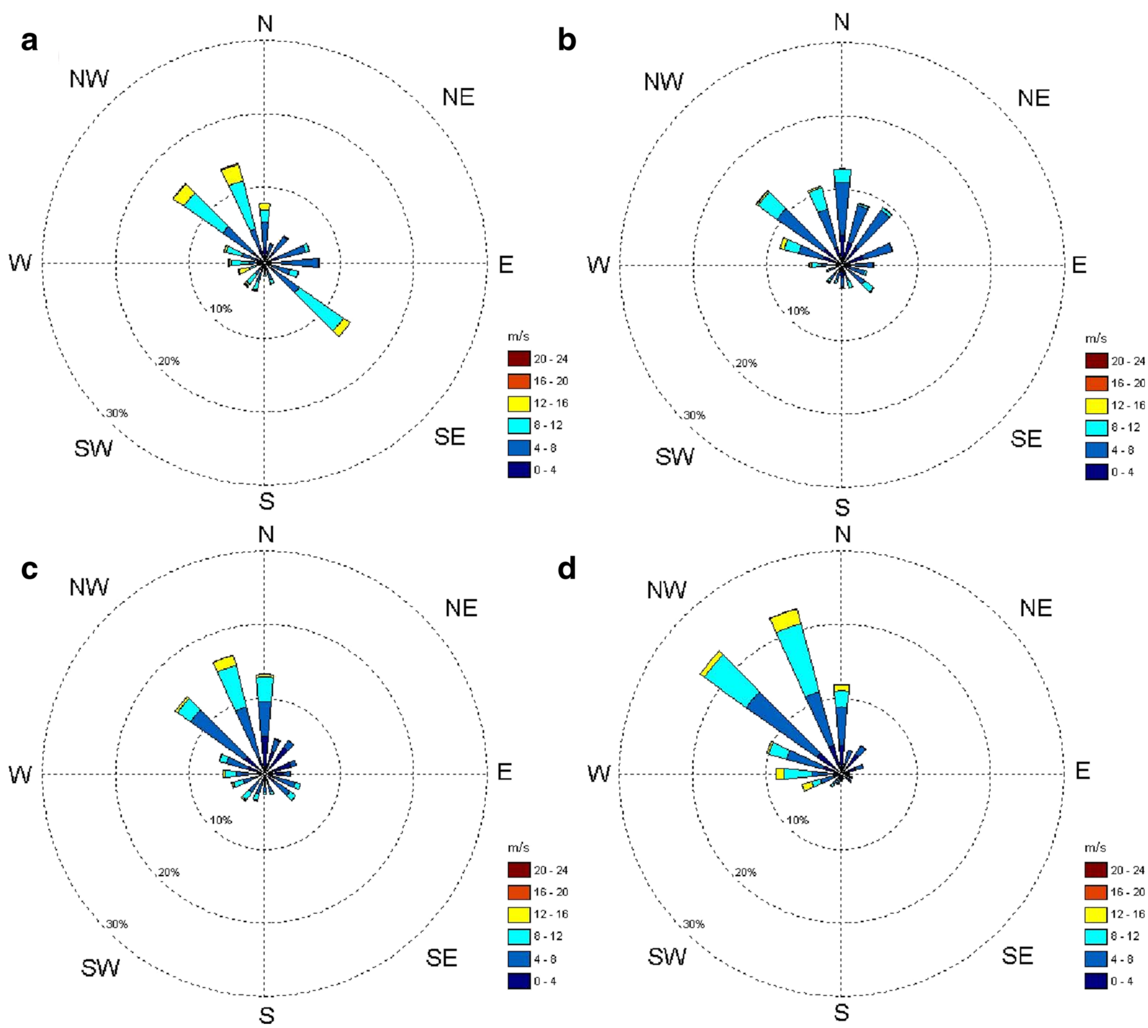

Fig. 10 Wind roses for the different seasons of the year at the TM station (**a**) Spring (21/9 to 21/12) (**b**) Summer (21/12 to 21/3) (**c**) Autumn (21/3 to 21/6) (**d**) Winter (21/6 to 21/9)

innermost areas of the channels while sediments would be washed away. The latter phenomena would be relaxed in the Principal Channel due to the recirculation pattern found at its mouth. These features are also in agreement with the Lagrangian results where tracers located in the innermost area of the Principal Channel presents longer residence times.

Another interesting outcome of the modelling exercise in terms of water quality is the water transport between the different bays that form the Bahia Blanca estuarine system. According to the model results water that leaves Verde Bay (Box 6) through its mouth would be transported to Falsa bay (Box 5) and consecutively to the Principal Channel. The opposite sense would occur in the inner connections of the bays. This fact indicates that water quality affecting one of the different bays would influence the other bays water quality. According to the modelling results, the main export of the system would take place in the Principal Channel mouth where water would leave the system transported by the general circulation to the North. Water levels increase in the inner areas when winds blow from the south-southeast sector (increasing the residence time) and decrease on average when they blow from the opposite direction (decreasing the residence time) (Pierini et al. 2008). This effect is more intense when the wind blows along the bays main axis, varying the residence time as a function of the persistence and intensity. This study is the first water residence time carried out in the Bahia Blanca estuary and establishes the importance of the physical and biological processes that exist within the study area.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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References

Ascione Kenov I, Garcia A, Neves R (2012) Residence time of water in the Mondego estuary (Portugal). Estuar Coast Shelf Sci 106:13–22

Bolin B, Rohde H (1973) A note on the concepts of age distribution and transit time in natural reservoirs. Tellus 25:58–62

Braunschweig F, Martins F, Leitão P, Neves R (2003) A methodology to estimate renewal time scales in estuaries: the Tagus estuary case. Ocean Dyn 53:137–145

Campuzano FJ, Pierini JO, Leitão PC (2008) Hydrodynamics and sediments in Bahia Blanca estuary: data analysis and modelling. In: Neves R, Baretta J, Mateus M (eds) Perspectives on integrated coastal zone Management in South America. IST Press, Lisbon, pp 483–503

Campuzano FJ, Mateus MD, Leitão PC, Leitão PC, Marín VH, Delgado LE, Tironi A, Pierini JO, Sampaio AF, Almeida P, Neves RJ (2013) Integrated coastal zone management in South America: a look at three contrasting systems. Ocean & Coastal Management 72:22–35

Campuzano FJ, Pierini JO, Leitão PC, Gómez EA, Neves RJ (2014) Characterization of the Bahia Blanca estuary by data analysis and numerical modelling. J Mar Syst 129:415–424

Capelli, A., Campo, A.M., (2004). Climatología, in: M.C., P., M.S., H. (Eds.), Ecosistema del Estuario de Bahia Blanca. IADO, Bahia Blanca, pp. 87–90

Chippada S, Dawson CN, Martinez ML, Wheeler MF (1998) A Godunov-type finite volume method for the system of shallow water equations. Comput Methods Appl Mech Eng 151:105–129

Cuadrado D, Picolo C, Perilo E (2002) Hydrography of the inner shelf offshore Bahia Blanca estuary. Argentina Thalassas 18:45–56

Delhez EJM, Heemink AW, Deleersnijder E (2004) Residence time in a semi-enclosed domain from the solution of an adjoint problem. Estuar Coast Shelf Sci 61:691–702

Dong LX, Su JL (1999a) Numerical study of the water exchange in Xiangshangang Bay. Part one: advection-diffusion tidal exchange model. Oceanologia et Limnologia Sinica 30:410–415

Dong LX, Su JL (1999b) Numerical study of the water exchange in Xiangshangang Bay. Part two: model application and water exchange study. Oceanologia et Limnologia Sinica 30:465–470

Freije RH, Gayoso AM (1998) Producción primaria del estuario de Bahia Blanca. Informes UNESCO Ciencias Marinas 7:112–114

Fukumoto T, Kobayashi N (2005) Bottom stratification and water exchange in enclosed bay with narrow entrance. J Coast Res 21: 135–145

Gayoso AM (1983) Estudio del fitoplancton del estuario de Bahia Blanca (Buenos Aires, Argentina). Studia Oecologica 2:73–88

Gayoso AM (1988) Variación estacional del fitoplancton en la zona más interna del estuario de Bahia Blanca (Argentina). Gayana, Botánica 45:241–248

Gayoso AM (1999) Seasonal succession patterns of phytoplankton in the Bahia Blanca estuary (Argentina). Bot Mar 42:367–375

Gómez EA, Ginsberg S, Perilo G (1996) Geomorfología y sedimentología de la zona interior del Canal Principal del Estuario de Bahia Blanca. Asociación Argentina de Sedimentología Revista 3(2):55–61

Gómez-Gesteira M, Montero P, Prego R, Taboada JJ, Leitão P, Ruiz-Villarreal M, Neves R, Perez-Villar V (1999) A two-dimensional particle tracking model for pollution dispersion in a Coruña and Vigo rias (NW Spain). Oceanol Acta 22:167–177

IOC, IHO, BODC, (2003). Centenary edition of the GEBCO Digital Atlas. Published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans; British Oceanographic Data Centre, Liverpool

Kierstead H, Slobodkin LB (1953) The size of water masses containing plankton blooms. J Mar Res 12:141–147

Liu Z, Wei H, Liu G, Zhang J (2004) Simulation of water exchange in Jiaozhou Bay by average residence time approach. Estuar Coast Shelf Sci 61:25–35

Lucas LV, Koseff JR, Monismith SG, Cloern JE, Thompson JK (1999) Processes governing phytoplankton blooms in estuaries. II. The role of horizontal transport. Mar Ecol Prog Ser 187:17–30

Martins F, Neves R, Leitão PC, Silva A (2001) 3D modeling in the Sado estuary using a new generic coordinate approach. Oceanol Acta 24: S51–S62

Neves, R., (2013). The mohid concept, in: M., M., R., N. (Eds.), Ocean modelling for coastal management - Case studies with MOHID. IST Press, pp. 1–11

Pierini, J.O., (2007). Circulación y transporte en zonas costeras del estuario de Bahia Blanca. Ph.D. thesis. University of Buenos Aires

Pierini JO, Marcovecchio JE, Campuzano FJ, Perillo GME (2008) Evolution of salinity and temperature in Bahia Blanca estuary, Argentina. In: Neves R, Baretta J, Mateus M (eds) Perspectives on integrated coastal zone Management in South America. IST Press, Lisbon, pp 505–513

Pierini JO, Streitemberger E, Baldini M (2012) Evaluation of faecal contamination in Bahia Blanca estuary (Argentina) using a numerical model. Rev Biol Mar Oceanogr 47(2):193–202

Pina, P., Martins, F., Leitão, P.C., Braunchweig, F., Neves, R., (2004). Development of an integrated system for coastal waters, in: MERIS user workshop, Frascati, Italy, 10–13 November, ESA SP-549

Takeoka H (1984) Fundamental concepts of exchange and transport time scales in a coastal sea. Cont Shelf Res 3:311–326

Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. Journal Geophysical Research 106:7183–7192

Trancoso A, Saraiva S, Fernandes L, Pina P, Leitão P, Neves R (2005) Modelling macroalgae using a 3D hydrodynamic-ecological model in a shallow, temperate estuary. Ecol Model 187:232–246

USEPA, (2001). Criteria Development Guidance - Estuarine and Coastal Waters EPA-822-B-01-003. Technical Report. U.S. Environmental Protection Agency

Willmott CJ (1982) Some comments on the evaluation of model performance. Bull Am Meteorol Soc 63(11):1309–1369

Zimmerman JTF (1976) Mixing and flushing of tidal embayments in the western Dutch Wadden Sea part I: distribution of salinity and calculation of mixing time scales. Neth J Sea Res 10:149–191