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Characterisation of the Bahía Blanca estuary by data analysis and numerical modelling

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ABSTRACT

The Bahía Blanca estuary is a complex system of channels and tidal flats where the most important deep water harbour system of Argentina is located. The main goal of the present work was to obtain a hydrodynamic conceptual model for the Bahía Blanca coastal area. For this reason, a combined analysis of observed data and numerical modelling has been performed for the whole area. The gained knowledge on the system hydrodynamics could aid in the decision support for navigation security, waste water discharges management, sediment dredging and rejection operations among other applications.

Due to the Bahía Blanca coastal vast area, hydrodynamic observations are scarce and located near the populated areas. In order to describe the hydrodynamics of such a complex and large system, the analysed tidal and current data from different periods have been completed through numerical modelling.

Data analysis served to determine the main processes governing the Bahía Blanca hydrodynamics, to characterise the area using general descriptors, to provide inputs for the numerical model and to aid in evaluating its performance. In addition, a 2-dimensional application was set up using the MOHID water modelling system for the Bahía Blanca estuary. This application aimed to gain a better understanding of the system dynamics, to explain and test the consistency of the observed data and to reproduce the processes taking place.

Model results were in good agreement with the analysed data and served to confirm an inconsistency found on the sea level observations. The combination of both methodologies served to further describe the hydrodynamic processes governing this coastal area and also to obtain a conceptual model for the water and property circulation in the Bahía Blanca estuary.

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1. Introduction

The Argentinean coastal area is large with a coastline of more than 5700 km. However, due to its climate and the hydrological regimes, the number of estuaries is low (Piccolo and Perillo, 1999). The Buenos Aires province has the largest number of rivers and small streams that discharge into the Atlantic Ocean, generally, through coastal plains that were once fluvial valleys. The Bahía Blanca estuary is located in the south-west coast of this province, on the uppermost terrace of the Argentinean Continental Shelf (ACS) according to the bathymetric division proposed by Parker et al. (1997).

The Bahía Blanca coastal area, as pointed by its name, corresponds to a bay or collection of bays with a north-west to south-east orientation, separated by islands and wide tidal flats. These bays are, namely from north to south, the Principal Channel, where the main human settlements are located, Falsa Bay and Verde Bay. To these bays, tidal channels of all types and dimensions arrive (Ginsberg and Perillo, 2004). The Principal Channel has an elongated shape with a total length of 68 km, being 200 m and 3–4 km wide near its head and mouth, respectively (Aliotta and Perillo, 1987). This channel ends inland in a salt flat known as Salitral de la Vidriera. Falsa Bay and Verde Bay are also funnel shaped with total lengths around 30 km and averaged widths around 4 and 6 km respectively.

The study area, Fig. 1, is characterised by its spatial homogeneity with average depths around 10 m and with a maximum value around 22 m. The intertidal areas sum around 40% of the domain, influencing significantly the water hydrodynamics. Its muddy constitution and the scarce vegetation show the constant morphological changes to which those plain areas are exposed.

The Argentinean coast have been studied using numerical models by several authors, from studies covering the continental platform (i.e. Glorioso and Flather, 1995; Glorioso and Simpson, 1994; O'Connor, 1991) to some of the major estuaries as the Rio de la Plata (i.e. Guarga et al., 1991; Simionato et al., 2006). For the Bahía Blanca estuary, there are few previous studies that have modelled the area. Palma (1995) applied the Princeton Ocean Model (POM) for a 1 km grid, while Etala

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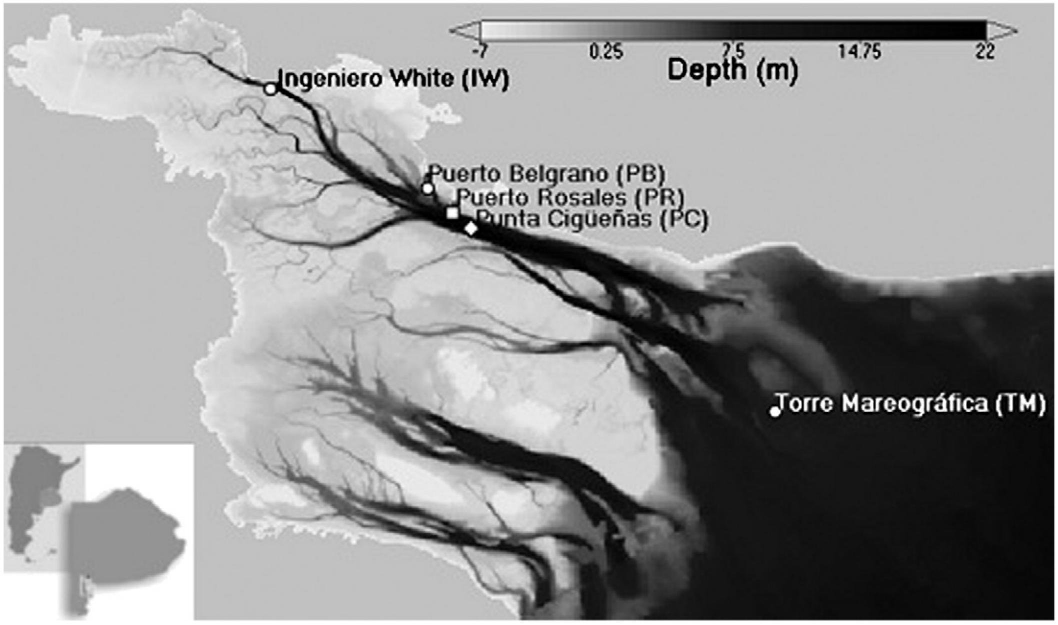

Fig. 1. Bahía Blanca estuary location and bathymetry. Location of the water level (circles), currents (diamond) and meteorological (square) observations in the Bahía Blanca estuary.

(2000) described the non-linear processes affecting a storm wave from the continental platform to the estuary.

Bearing on mind the importance of navigation in the Principal Channel, where one of the most important deep water harbour systems of Argentina is located, a tidal prediction model "is urgently required" for navigational security (Perillo and Piccolo, 1991).

2. Data analysis

Observed data in the Bahía Blanca estuary are scarce, being only available data for the Principal Channel area. In this section, river inputs and oceanographic observations in the Principal Channel were analysed in order to obtain a characterisation of the Bahía Blanca estuary hydrodynamics, to provide climatological discharges for the model input and also to aid in the numerical model verification.

2.1. Freshwater inputs

The Bahía Blanca estuary is a system dynamically active, some of the driving forces that contributed to the formation of this system are nowadays absent. Melo et al. (2003) described the evolution of the Bahía Blanca area, 20,000 years BP; the studied area consisted of a coastal plain that the Colorado River crossed on its way to the open ocean. This freshwater input began to grow a deltaic front that along with the increase on river flow and the mean sea level rise, by 6000 years BP, created the system of channels. From 5000 years BP, the mean sea level decrease along with the southern migration of the Colorado River and the northern migration of other creeks decreased globally the fresh water inputs into the Bahía Blanca system. Those losses were compensated by the entry of oceanic water that led the system to the present situation.

Nowadays, the main natural fresh water inputs in the Bahía Blanca estuary are located at the innermost part of the Principal Channel. Only the Sauce Chico River and Napostá Grande Creek have a considerable discharge in the study site with average annual flows of 5.80 and 2.67 m^3s^{-1} respectively. However, high runoff peaks have been registered with discharges over 50 ms^{-1} in the Sauce Chico River (Perillo and Piccolo, 1991). There are other sources of fresh water flowing into the Bahía Blanca estuary, as Galván, Saladillo de García and Maldonado creeks with an overall flow lower than Napostá Grande Creek itself (Piccolo et al., 1987) and some artificial sources that include the Bahía Blanca wastewater discharge near the Napostá Grande Creek mouth with values around 0.5 m^3s^{-1}.

For these reasons, the Bahía Blanca coastal area, though generally referred as an estuary, in terms of hydrodynamics could be regarded as an elongated bay, where only the innermost part of the system would be a true estuary.

2.2. Tidal data analysis

Bahía Blanca estuary water levels are permanently registered at three tidal gauges along the Principal Channel (Table 1, Fig. 1). From the open ocean to the inner area are: Torre Mareográfica (hereafter TM), Puerto Belgrano harbour (hereafter PB) and Ingeniero White harbour (hereafter IW). Ten-minute water level records for the 2000–2003 period were provided by the Bahía Blanca Port Consortium (CGPBB) for each station.

The Bahía Blanca estuary has been described in the literature as a mesotidal estuary (Cuadrado et al., 2002; Ginsberg and Perillo, 2004; Piccolo and Perillo, 1990) which corresponds to areas with a tidal range comprised between 2 and 4 m. The analysed data showed that the average tidal range increases along the channel from 2.41 m at TM station, 3.20 at PB station and 3.60 m at IW station with a standard deviation higher than 0.40 m for all the stations. The former ranges could be increased by variations on atmospheric pressure and on wind direction and intensity. Tidal amplitudes also presented a marked difference between spring and neap tides.

A harmonic analysis performed on the water level series using the TASK-2000 software (POL/PSMSL Tidal Analysis Software Kit 2000) resulted on 62 tidal components for each tidal gauge. In Table 2 the tidal components of greater amplitude are listed. In all the stations, the semidiurnal components led the list, followed by the diurnal components which influence decreases headwards. As the tide heads inland

Table 1
Location, observed period and source of hydrodynamic and atmospheric data.

Station	Longitude	Latitude	Period	Source
TM	61°43′12″ W	39°08′56″ S	23/08/99–31/12/03	CGPBB
PB	62°06′15″ W	38°53′48″ S	23/08/99–31/12/03	CGPBB
IW	62°16′08″ W	38°47′26″ S	23/08/99–31/12/03	CGPBB
PC	62°03′09″ W	38°56′40 ″S	17/03/97–21/04/97	SHN

Table 2
Principal tidal components for each tidal gauge (H = amplitude; φ = phase).

Tidal component	Speed	IW		PB		TM	
	(°/h)	H (cm)	φ (°)	H (cm)	φ (°)	H (cm)	φ (°)
Z_0	0.00	263.54	0.00	245.64	0.00	193.27	0.00
M_2	28.98	169.12	186.07	153.52	177.91	115.86	157.09
L_2	29.53	25.48	255.36	22.47	245.99	15.98	220.69
N_2	28.44	23.98	103.59	21.08	95.83	15.24	76.69
M_4	57.97	22.76	178.28	16.14	184.23	6.40	171.97
S_2	30.00	21.59	307.35	20.63	298.67	16.84	274.22
K_1	15.04	21.15	61.18	21.48	54.53	20.35	45.07
O_1	13.94	15.53	0.70	16.19	355.43	15.43	344.97
MU_2	27.97	14.52	291.53	14.02	282.02	12.59	264.74
NU_2	28.51	10.95	137.92	9.64	130.03	7.63	113.26

the so-called compound tides or overtides (M_4, MS_4 and MN_4) generated by the nonlinear interactions of primary constituents become increasingly important. This effect takes place in shallow water areas increasing the tidal range and influencing the turbulence, tidal asymmetry and mean water level (Wang et al., 2002). The correlation coefficients obtained between the observed levels and the harmonic tidal components were around 0.9 being able to explain most of the water levels variation, Table 3. The mean water level (Z_0) between the two most apart stations, distant 55 km, showed a difference of 0.70 m. This difference will be discussed later in this paper.

The Formzahl coefficient, or F ratio, consists in the division of the sum of the two main diurnal tidal components (K_1 and O_1) by the sum of the two main semidiurnal components (M_2 and S_2) and provides a quantification of the degree of influence of the semidiurnal and diurnal components. According to the result of the F ratio, tides could be considered diurnal ($F > 3$), semidiurnal ($F < 0.25$) or mixed ($0.25 < F < 3$). In the Bahía Blanca estuary, the F ratio decreases headwards being 0.26 at the TM station and 0.19 at the IW station. Thus, tides in the Bahía Blanca estuary could be classified as semidiurnal being this fact stronger as the head of the estuary is approached.

According to Wang et al. (2002), tidal asymmetry could be assessed by comparing the amplitudes and phases of the dominant M_2 component with the overtide M_4. A relative phase (phi = 2φ2–φ4) comprised between 0° and 180° indicates the longer duration of the flood, being then classified as flood-dominant, and when comprised between 180° and 360° could be classified as ebb-dominant. In Table 3, the obtained values show an evolution from the mouth, where tide is flood-dominated, at the TM station, to the head of the estuary where is ebb-dominated, at the IW station. The α parameter indicates the degree of asymmetry and is calculated as the division of the M_4 amplitude by the M_2 amplitude, this parameter increased headwards due to the higher values of the M_4 component compared to the M_2,thus resulting in a more asymmetric tide at the head of the bay.

2.3. Current data analysis

Due to the geomorphologic variability across the Principal Channel, from intertidal areas to deep central areas, currents measured at different points of the same reach could present different magnitudes. Current observations in the study area are very scarce, being most of the data measured only on the Principal Channel and near the coast for very specific studies, i.e. dredging operations. For this reason only some of the historical datasets could be taken as representative of the system or used for validation purposes.

Table 3
Coefficient of determination (R^2), flood/ebb domination (α) and tidal asymmetry (phi) parameters.

Parameter	IW	PB	TM
R^2	0.87	0.90	0.91
α	0.14	0.11	0.06
Phi	193.87	171.58	142.22

The current dataset collected at Punta Cigüeña (hereafter PC), an oil pipe monobuoy located at the centre of the Principal Channel (Table 1, Fig. 1), could be regarded as the most representative of all the available datasets in the Bahía Blanca estuary. The observations, performed by the Navy Hydrographical Service (SHN), consisted in currents collected every 15 min for a 35 day period in the spring of 1997. The average intensity for the whole series was 0.64 m s^{-1} and the maximum record was 1.33 m s^{-1}. Flow and ebb tides presented similar intensities, though ebb velocities were slightly stronger, heading in practically opposite directions 295° and 115° respectively (Fig. 2).

In order to reproduce these currents for different periods, a harmonic analysis was performed for each velocity component. Tides were able to explain 82% of the total variability of the currents found during the sampling period. The analysis showed that component U intensity almost doubled the V component, due to the Principal Channel orientation. The most important harmonic component for velocity was the M_2 that explained more than 40% of the tidal velocity followed by the N_2 component that represented 8% of the current intensity.

3. Numerical modelling

Traditionally, 2-dimensional vertically averaged models have been used to simulate the hydrodynamic features of estuaries (i.e. Kenov et al., 2012). In our study area, the horizontal extent is around 70 km while the average depth is around 10 m. Thus, the processes generating quantity of movement and transport occur at a different magnitude in the vertical and horizontal directions. Due to this fact, the circulation on the Bahía Blanca domain is mainly horizontal which implies that vertical accelerations could be ignored when compared with the gravity effect. The hydrostatic distribution of pressure hypothesis has been proved even for fluxes flowing over a seabed with high vertical irregularities (Koutitas and O'Connor, 1981).

The Bahía Blanca model application consists of a domain covering from the coordinates (−61.41 W, −39.38 S) to the inner estuary (Fig. 1) with a horizontal resolution of 0.002°. The MOHID water

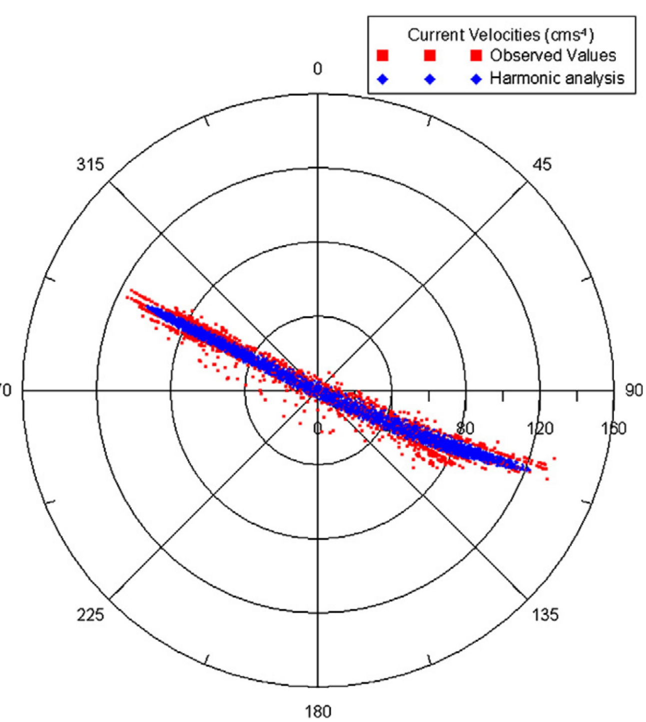

Fig. 2. Current intensities and directions observed and obtained through harmonic analysis for the same period.

modelling system (http://www.mohid.com) was used to simulate the Bahía Blanca 2-D hydrodynamics. The model was forced with tides and freshwater inputs as described in following sections.

The bathymetric data used for composing the model bathymetry came from two sources; the one minute global bathymetric grid database GEBCO digital atlas (IOC et al., 2003) and data from the CGPBB along 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).

3.1. Modelled river discharges

Though the Sauce Chico River and Napostá Grande Creek springs are located in the same mountain range, Sierras de la Ventana, both catchments areas present different peaks along the year. The Sauce Chico River presents two main peaks, one during autumn (Feb–Jun) and a stronger one during spring (Aug–Dec). However, Napostá Grande Creek flow shows peaks in winter (Apr–Aug) and spring (Aug–Dec), both with similar intensities. The spring peak on both sources corresponds to the rainiest period on the Bahía Blanca region. Sauce Chico presents a flow pattern most influenced by the local rain pattern, while Napostá is more influenced by the precipitation around Sierras de la Ventana (Piccolo et al., 1987). Fig. 3 shows the monthly averaged flow obtained from data collected during the 1993–1999 period provided by the water utility Aguas Bonaerenses Sociedad Anónima (ABSA) that were imposed in the model.

3.2. Modelled water levels

Due to the vicinity of the TM tidal gauge to the Bahía Blanca domain boundary, the followed modelling approach was to impose that station tidal components along the entire open boundary. Fig. 4 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 Bahía 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 the 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

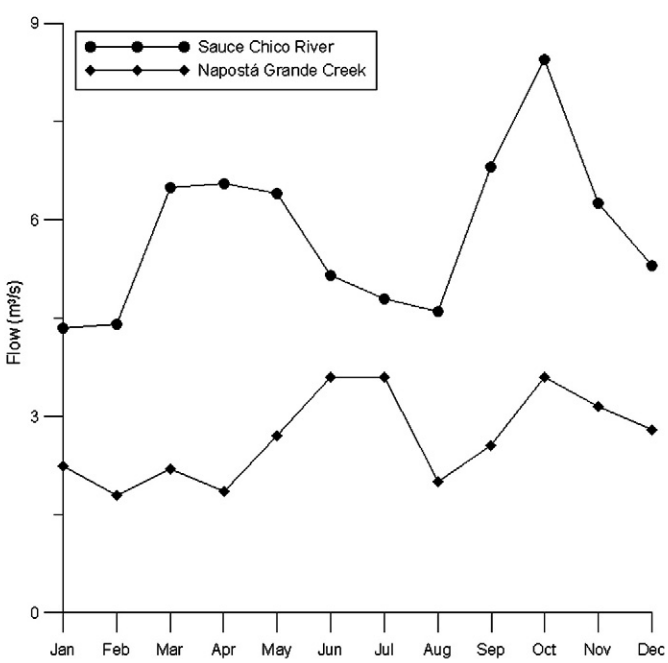

Fig. 3. Napostá Grande Creek and Sauce Chico river monthly averaged flow.

tidal amplitudes are thus found at the innermost areas, for each of the three different channels, being the absolute maximum in the Principal Channel. During high tides, the inter-channel connections increase favouring 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 Bahía Blanca channel hydrodynamics.

3.3. Modelled currents

Fig. 5 shows the current intensities and directions for the same tidal cycle described on the section above. 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 current velocities. On the three bays, ebb velocities were higher than flooding velocities. 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 ms^{-1}. Maximum current intensities were observed along the channels. 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 comprised between 0.7 ms^{-1} and 1.4 ms^{-1}, being the maximum values near the upper reaches.

These range of values were in agreement with the observations registered by several authors: Piccolo et al. (1987) registered maximum superficial values around 0.80 ms^{-1} and 1.40 ms^{-1} for flow and ebb currents respectively; Perillo and Sequeira (1989) observed that the overall peak values on flood and ebb range were 0.27 ms^{-1} and 0.87 ms^{-1} respectively and Gómez et al. (1996) who integrated vertically their observations obtaining values of 1.05 ms^{-1} and 1.30 ms^{-1} for flow 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 had maximum velocities of 0.6 ms^{-1} with velocities over 0.3 ms^{-1} that surpassed more than 30% of the time (Cuadrado et al., 2002). These intensities are similar to the ones obtained through modelling (Fig. 5).

4. Model validation

The mean sea level between the most distant tidal gauges, as described on the data analysis, presented a permanent difference of 70 cm. That tidal amplification could not be explained by the increase of mean sea level due to tidal damping. In order to find a possible explanation for this difference, simultaneous comparisons were performed between the model results and the values obtained from the reconstruction of the current intensities at Punta Cigüeña buoy (PC) and the water levels at the tidal stations from their corresponding harmonic constituents (Table 1, Fig. 1).

When using the original mean sea level (Z_0) of the outermost station (TM), the simulated currents at PC station were less intense than those obtained from the harmonic constituents thus implying that the right quantity of water was not circulating in the system. When 70 cm was added to the original TM mean sea level, model results were compared with the values obtained through the velocity harmonic components for

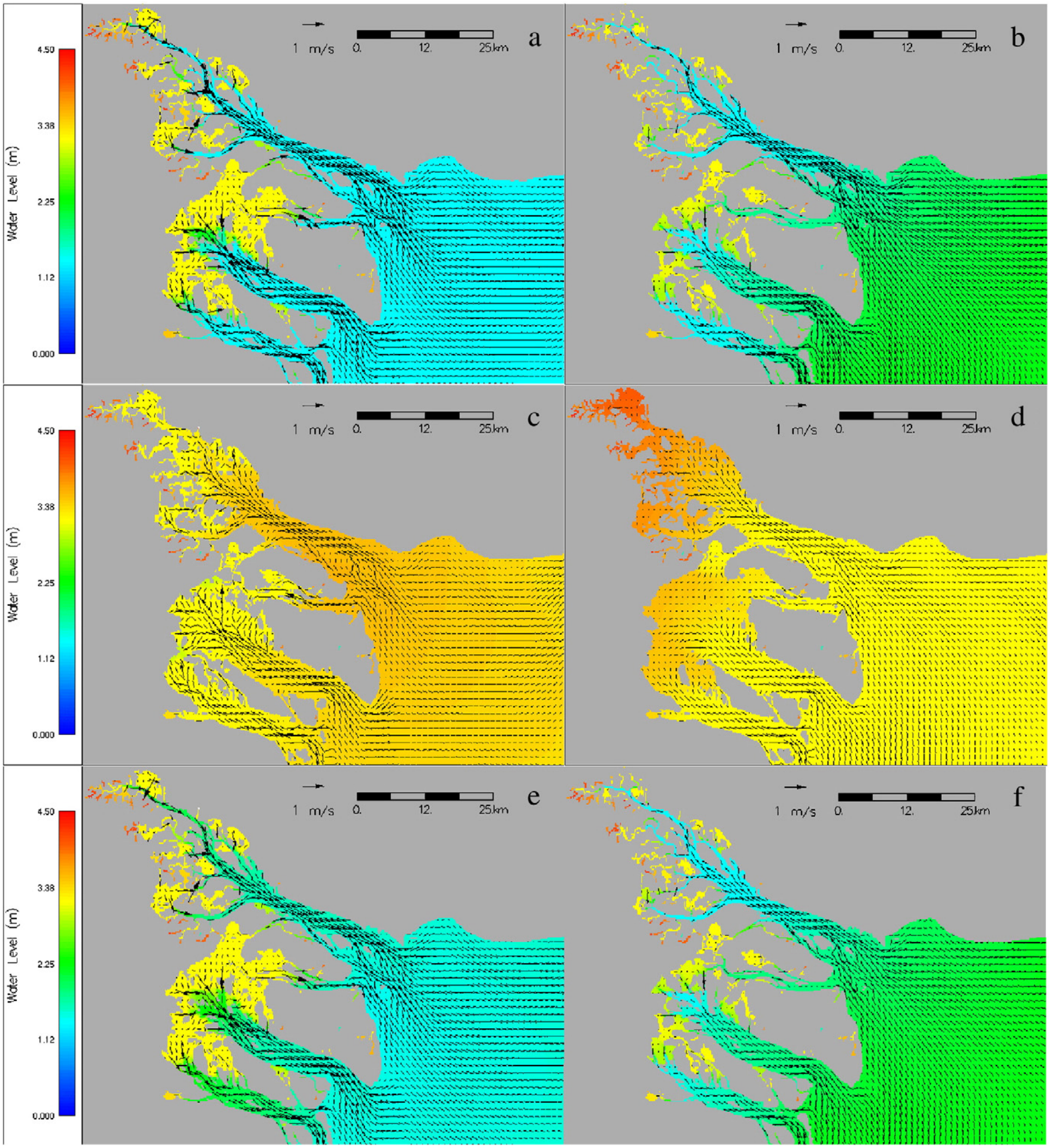

Fig. 4. Water levels for the Bahía Blanca estuary with a 3 hour interval: a) 07 h, b) 10 h, c) 13 h, d) 16 h, e) 19 h, and f) 22 h of the 7th of April 2002.

the same period. The model was able to reproduce the current intensities and the direction. Current orientation was WNW–ESE (Fig. 6, left) as they are conditioned by the Principal Channel geomorphology. The coefficient of determination obtained when comparing both intensities was 0.80, which implies that model results are able to explain the 80% of variability on intensity due to tides.

In Fig. 6 left, model results were represented along values obtained from the harmonic analysis of the current components showing maximum peaks of intensity around 1.30 ms^{-1} during ebb conditions and nearly 1 ms^{-1} during flood conditions. The model results agreed with the relative phase values (phi) obtained in Table 3 that concluded that stations within the system were ebb-dominated increasing this character with distance from the estuarine mouth. In Fig. 6 right, the current values for the reconstituted time series with the harmonic analyses (A) and the modelled 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, their root-mean square difference, 12.80 in our case, and their standard deviations, 28.31 for the reconstructed values and 27.16 for the modelled values. In this diagram

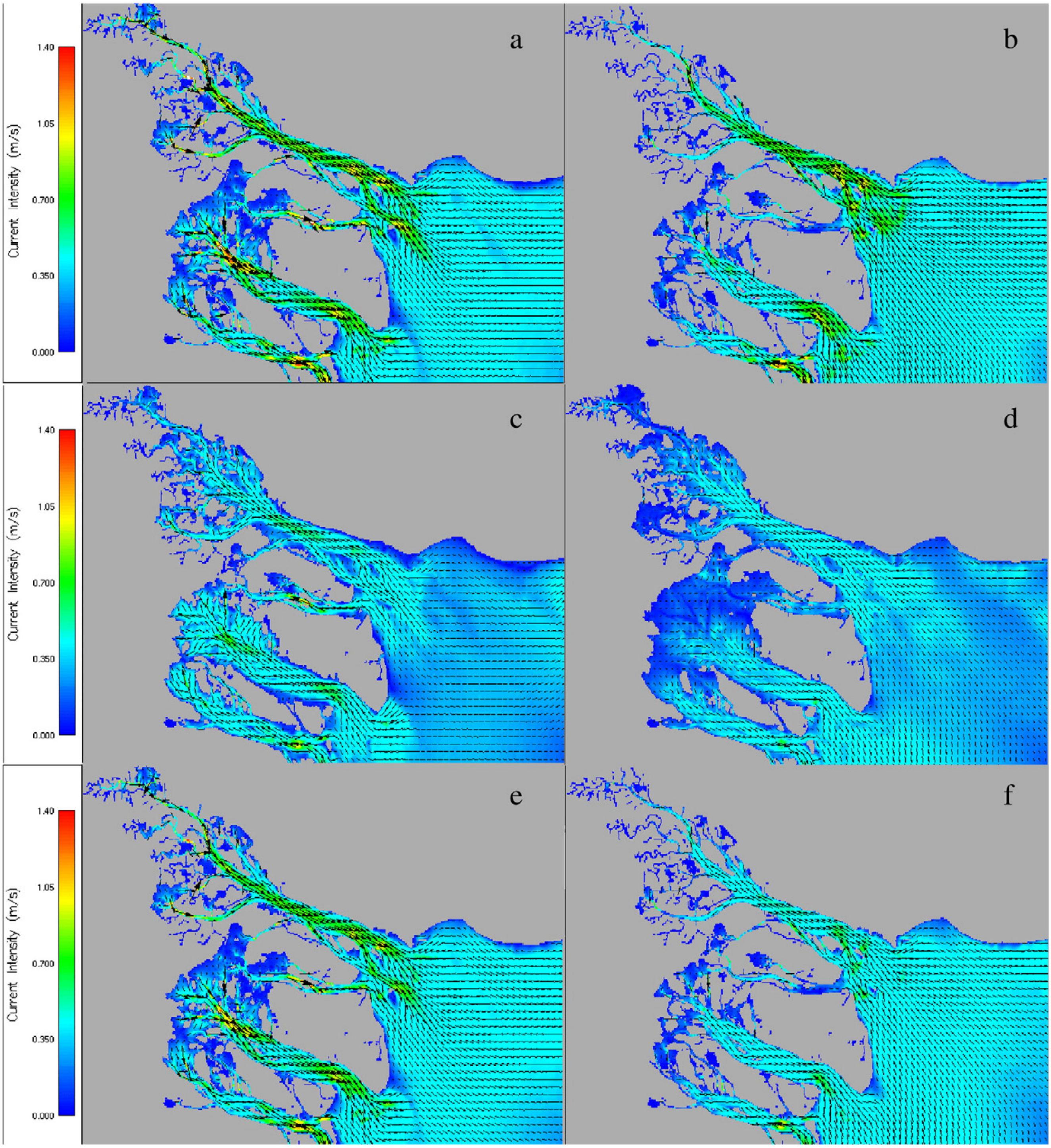

Fig. 5. Instant velocities for the Bahía Blanca estuary with a 3 hour interval: a) 07 h, b) 10 h, c) 13 h, d) 16 h, e) 19 h, and f) 22 h of the 7th of April 2002.

the closer the stations are the more similar they are. The correlation is very high between both stations and they also present a similar standard deviation and a low root-mean square difference.

After adding these extra 70 cm to the TM mean sea level, astronomical water levels and model results were compared. 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. In this station, model results were compared with the astronomical tide obtained from this station tidal components plus 70 cm. 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 (Table 4). In PB tidal gauge, without performing any water level correction, the degree of adjustment was 0.97, similar to that obtained in the TM station. Around 20 km inland from the PB station, the IW station model results and the astronomical tide presented a coefficient of determination of 0.93. However, modelled low tides at the IW station were lower than the values obtained through the harmonic analysis. A possible explanation would be the inaccuracy on the

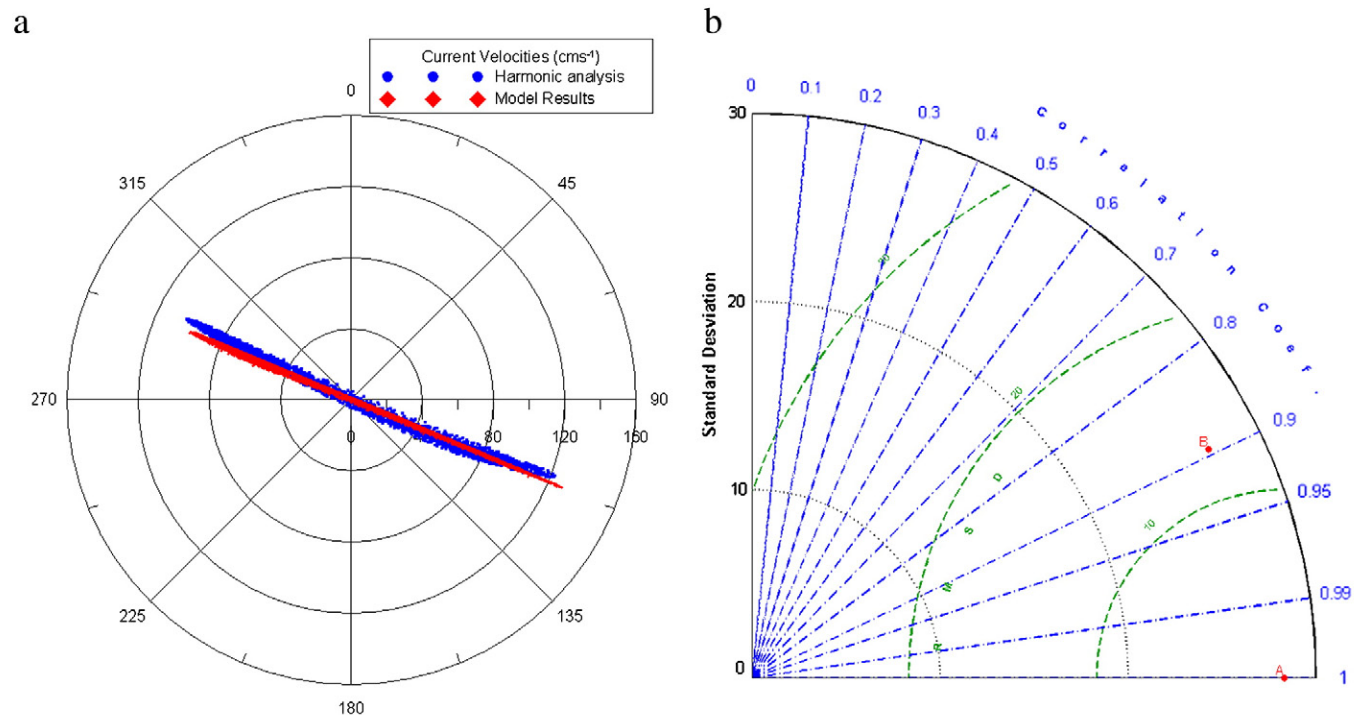

Fig. 6. Rose diagram representing the current intensities and directions obtained through harmonic analysis (dots) and modelling (diamonds) (left) and Taylor diagram for the reconstituted (a) and modelled (b) current intensities (right) for the Punta Cigüeña station.

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 Bahía Blanca estuary.

To further evaluate 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 4). 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 2× RMSE. The skill index, or index of agreement, could be regarded as the normalised model error and provides similar information than the coefficient of determination, in the sense that it gives a measure of the model performance, but it penalises models with greater bias. Skill values for each station are close to one, indicating a high degree of model performance.

5. Discussion

Once the Bahía Blanca model is validated, this tool is able to provide additional system information such as the estuarine tidal prism and the residual velocities, which are useful in determining the residence time and the import and export of dissolved and particulated properties of the estuarine system.

Table 4
Model performance indicators at each tidal gauge for the Bahía Blanca estuary model.

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

5.1. Tidal prism

The Bahía Blanca estuarine system total volume (Fig. 7), obtained by the model, ranged between $7 \cdot 10^9$ and $1.1 \cdot 10^{10}$ m^3 with an average value of $9 \cdot 10^9$ m^3. The total volume variation of the Bahía Blanca estuary due to tides was around 45% of its average volume and the differences of volume during of spring and neap tides could also be noticed on the same figure.

5.2. Residual velocity

Currents inside the Bahía Blanca estuary are tide dominated and its asymmetry is reflected on the residual currents. Two different residuals could be regarded as important in terms of describing the hydrodynamic properties of the estuary, namely, residual flux velocity and residual velocity.

The residual flux velocity, expressed in ms^{-1}, may be defined as the depth integrated residual water fluxes and its importance resides on the transport of dissolved properties in the water column (i.e. nutrients).

Fig. 8 represents the residual flux velocities for a month simulation for the Bahía Blanca estuary. Tide enters by its southern coast and propagates through the different bays and channels. The Coriolis force deviating effect is stronger in wider channels and could be clearly observed on the Principal Channel where waters enter the channel through the southern bank and exit along the northern bank of the channel. As was pointed out by Perillo et al. (1987) and Pierini (2007) for the Principal Channel head, net transport in deeper areas is seaward, while in shallower waters is landward. The model was able to reproduce this pattern, residual fluxes on the southern margin and in the channels connected to the Principal Channel indicated a net landward transport. In the Principal Channel mouth, due to its particular geomorphology, a recirculation pattern could be observed. The consequence of these residual flux velocities would be the transport of the dissolved components into the intertidal areas and some recirculation in the Principal Channel mouth, retarding their export to the open ocean.

The residual velocities are the net velocities obtained after balancing currents in different directions and their importance resides on the

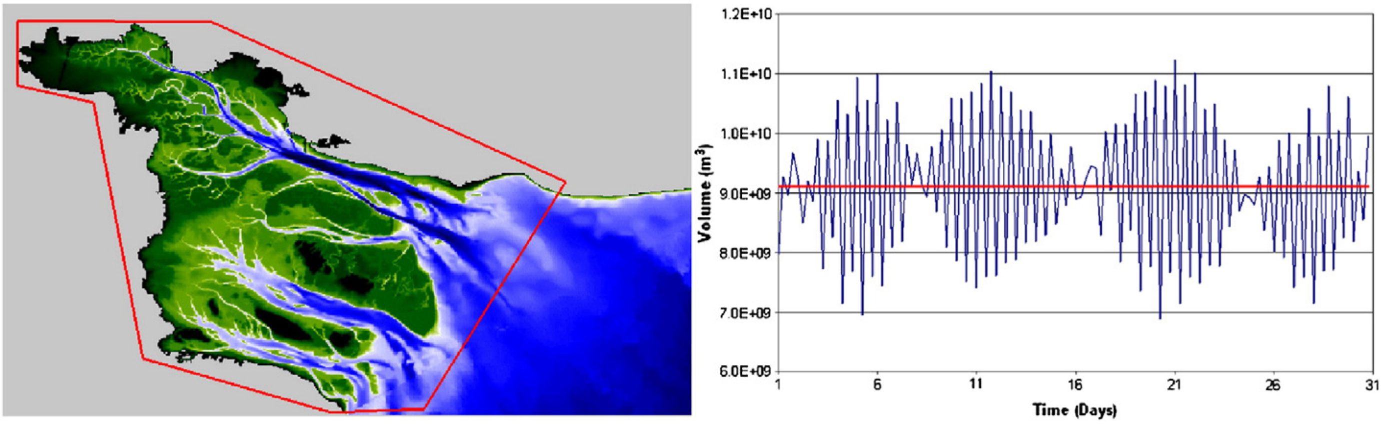

Fig. 7. Volume variation of the area that comprised the red polygon during a month of simulation forced by TM tidal components.

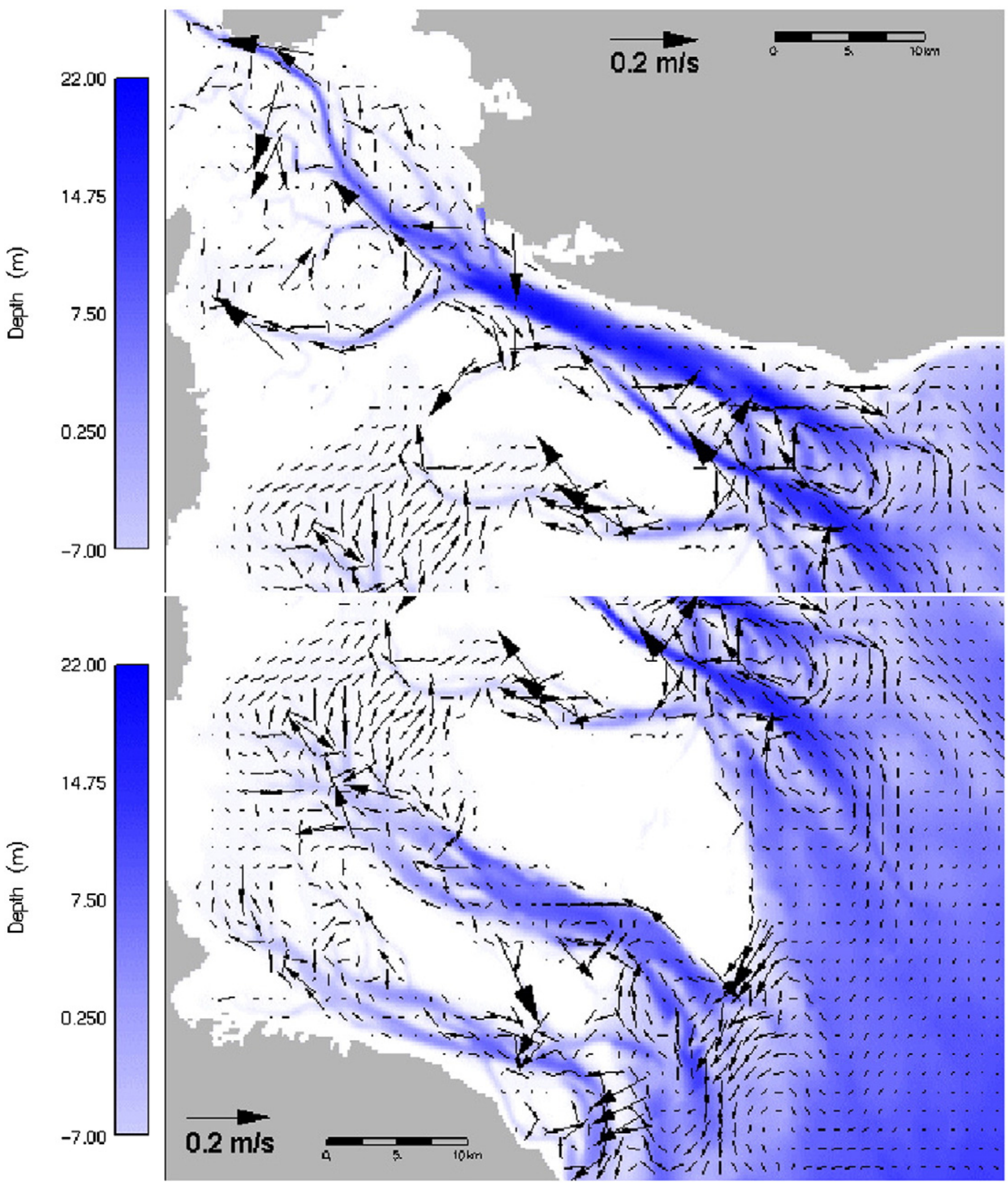

Fig. 8. Residual flux velocities in the inner (top) and the outer (bottom) area of the Bahía Blanca estuary.

transport of particulate matter such as sediments. Fig. 9 shows the existence of a net transport from the intertidal areas into the main channels. A recirculation pattern at the mouth of the Principal Channel could also be observed. According to these results, the intertidal channels would be exporting sediments and other particulate matter into the main channels favouring erosion processes in the intertidal areas, though some recirculation at the Principal Channel mouth would slow down the sediments' release into the coastal area (Pierini, 2007).

6. Conclusions

The Bahía Blanca estuary circulation has been described in the literature as dominated by a semidiurnal, quasi-stationary tidal wave (Serman, 1985 in Piccolo and Perillo, 1990; Perillo and Piccolo, 1991). However, modelling results show that it corresponds to a tide governed estuary, though its complex geometry and the prevailing winds could produce deviations from the astronomical tides (Etala, 2000; Palma, 1995; Perillo and Piccolo, 1991). The tidal wave travels from the south and enters each of the bays by its southern margin. When moving to the head of the estuary, the overtide components augment due to the geomorphology increasing the tidal amplitude. As a consequence, tides evolve from the outer ocean from being flood dominated to ebb dominated increasing this dominance with the distance from the mouth. The tide evolves along the Principal Channel from mesotidal to nearly macrotidal at the upper reaches. Macrotidal estuaries correspond to estuaries where processes are mainly tide dominated and where rivers present low flows. The former description agrees with the features described for the innermost part of the Bahía Blanca estuary.

Though the Bahía Blanca estuary has been traditionally regarded in the literature as an estuary (Piccolo and Perillo, 1990), the only superficial natural fresh water sources are located on the innermost part of the Principal Channel (Heffner et al., 2003) and its flow is not significant compared to the system water volume. As such, only the area where rivers discharge could be considered as a true estuary and their influence to the hydrodynamics are very localised.

The model residual currents indicate the recirculation of dissolved properties in the head of the tidal channels. On the contrary, tidal channels seem to export particulated matter. This finding could be relevant

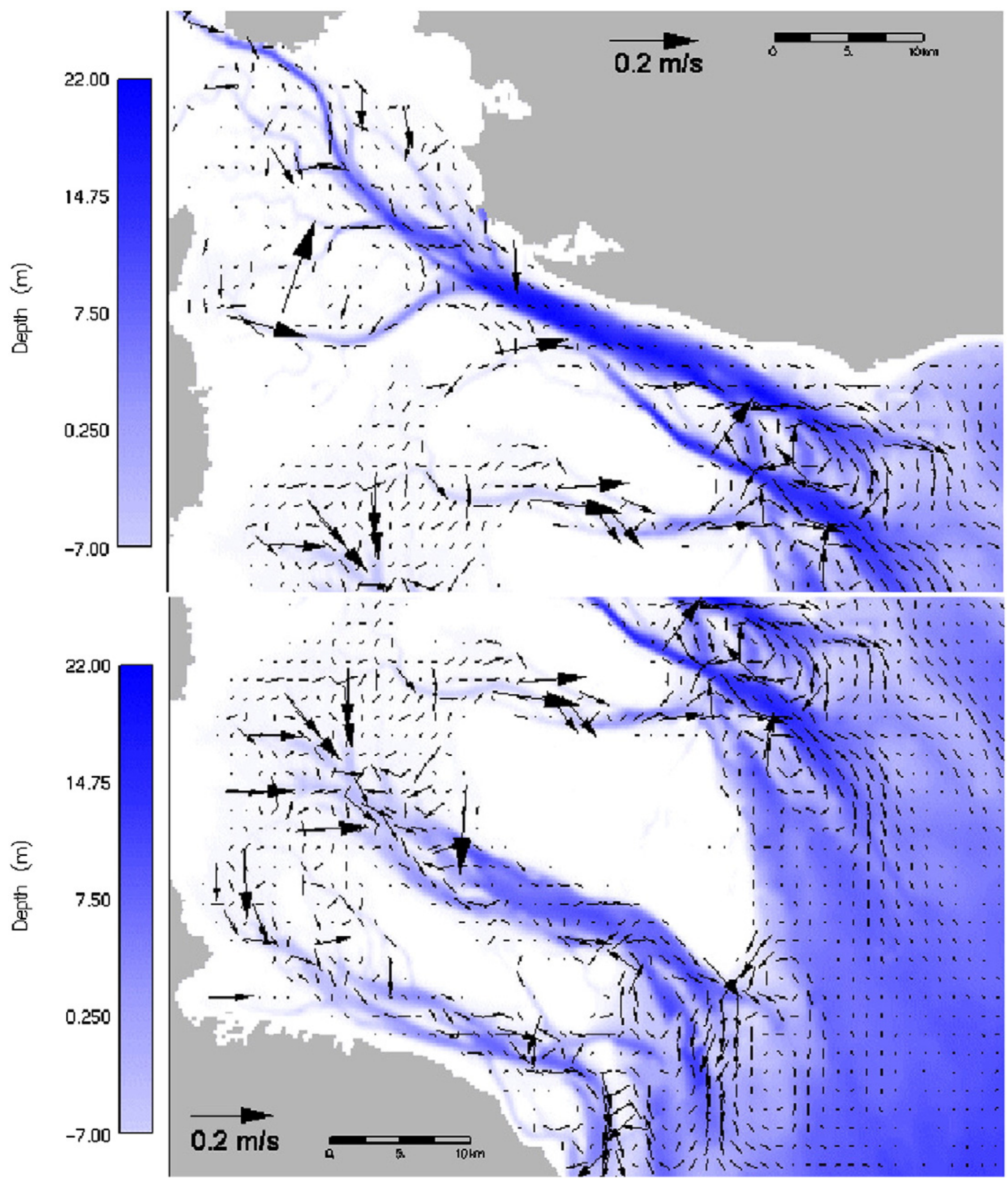

Fig. 9. Residual velocities in the inner (top) and the outer (bottom) area of the Bahía Blanca estuary.

for water quality and sediment studies. Dissolved properties would tend to accumulate on the innermost areas of the channels while sediments would be washed away. The latter process would be relaxed in the Principal Channel due to the recirculation pattern found at its mouth.

The combination of data analysis and numerical modelling allow a more comprehensive conceptual model of the Bahía Blanca estuary hydrodynamics that could aid in decision-making to local managers (Campuzano et al., 2013). One of the greatest advantages of using modelling tools in integrated coastal zone management is that datasets collected at different periods and sampling intervals could be all joined in a tool to reproduce periodical phenomena, i.e. tides, currents, and to analyse and obtain different system descriptors such as the tidal prism or the residual currents. Numerical modelling also allows the isolation and discrimination of single processes and can aid with data accuracy and consistency.

In the Bahía Blanca study case, the modelling exercise was able to confirm an inconsistency on the MSL used for the TM station. In this case, the simultaneous use of observed water levels and currents, though they were not collected at the same period, and the posterior mathematical analysis and validation through a hydrodynamic model resulted on the conclusion that tidal gauge stations' mean sea level need to be recalibrated. This could be regarded as one of the major outcomes of the present work.

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