HYDRODYNAMICS AND SEDIMENTS IN BAHÍA BLANCA ESTUARY: DATA ANALYSIS AND MODELLING

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1 INTRODUCTION

The Bahía Blanca estuary, as indicated by its name, is a bay or rather collection of bays located on the Southern part of Buenos Aires Province (Argentina) on the uppermost terrace of the Argentinean Continental Shelf (ACS), according to the bathymetric division proposed by Parker et al. (1997). The channels and bays with North-West to South-East orientation run through extensive tidal areas, namely from North to South: Principal Channel, where the main human settlements are located, Falsa Bay and Verde Bay. On the Principal Channel one of the most important deep water ports of Argentina is located, and though the harbours and the navigation channel are dredged to a nominal depth of 13 m, a tidal prediction model "is urgently required" for navigational security (Perillo and Piccolo 1991).

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). The Principal Channel ends inland in a salt flat known as Salitral de la Vidriera. Falsa and Verde bays are also funnel shaped with total lengths of around 30 km and around 4 and 6 km wide respectively. In the study area (Figure 1), average depth is around 10 m with a maximum value of around 22 m. Intertidal areas account for about 40% of the domain represented in Figure 1 and have a concomitantly large influence both on water and sediment dynamics. In the nearby coastal area the isobaths have a NE-SW orientation (Pierini 2007).

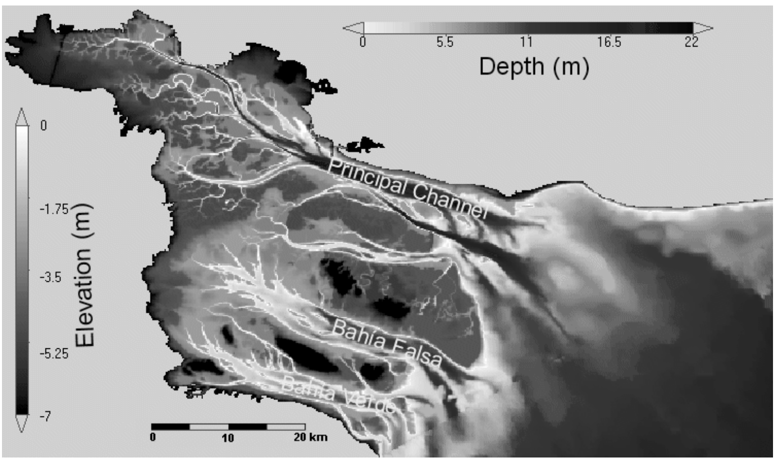

FIGURE 1: *Bahía Blanca model domain bathymetry and elevation of intertidal areas.*

Water circulation in Bahía Blanca estuary is mainly driven by tides, though it complex geometry and the prevailing winds produce deviations from the astronomical tides (Perillo and Piccolo 1991, Palma 1995, Etala 2000). Though it traditionally has been considered as an estuary (Piccolo and Perillo 1990), nowadays the only natural fresh water sources discharge into the Bahía Blanca bay innermost area (Heffner et al. 2003) at low flowrates. As such, only this inner area might be considered a true estuary.

2 GEOMORPHOLOGY

The Bahía Blanca estuary is a dynamically active system in which the main driving force that contributed to its formation is no longer present. Melo et al. (2003) described the evolution of the Bahía Blanca area from 20000 years BP when the study area was a coastal plain that the Colorado River traversed on its way to the open ocean. The freshwater inputs began to grow a deltaic front that, together with the increase in river flow and sea level rise, by 6000 years BP created the system of channels. From 5000 years BP on, the partial decrease of the mean sea level, along with the progressive migration to the South of the Colorado River and the migration North of other creeks decreased 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. The Colorado River discharges nowadays South to the Bahía Blanca estuary with an average flow of 138 $m^3\ s^{-1}$. However, it appears to have almost no influence on hydrodynamics or in sediments input into the system anymore (Cuadrado et al. 2002). Currently, the only natural fresh water sources in Bahía Blanca estuary are Sauce Chico River, Napostá Grande creek and Maldonado creek, which is formed by the junction of Saladillo de García and Dulce creeks (Heffner et al. 2003).

At present, the Bahía Blanca estuary comprises three large interconnected parallel tidal channels with a NW-SE orientation, namely from South to North: Verde Bay, Falsa Bay and Principal Channel. To these bays arrive channels of all types and dimensions, from large straight tidal channels to meandering creeks and gullies (Ginsberg and Perillo 2004). The Principal Channel is the only bay that receives freshwater discharges and near its mouth shifts from the funnel shape to a meandering channel. This main channel is connected mainly at its southern margin to other minor tidal channels. On the other hand, Verde and Falsa bays´ head act like a basin catchment where the different tidal creeks join. Nevertheless, the system is in permanent evolution as was observed by Ginsberg and Perillo (2004) who detected a lateral migration on some tidal channels at a rate of 25 $m\ yr^{-1}$.

3 HYDRODYNAMIC DATA DESCRIPTION AND ANALYSIS

3.1 Tides

In the Bahía Blanca estuary, tidal data are collected in three different stations (Table 1, Figure 2) from the open ocean to the inner area of the Principal Channel: Torre Mareográfica (hereafter TM), Puerto Belgrano Harbour (hereafter PB) and Ingeniero White Harbour (hereafter IW). Ten-minute water level timeseries for the three permanent tidal gauges were provided by the Bahía Blanca Port Consortium (CGPBB) for more than three years. The Bahía Blanca estuary is a mesotidal estuary (Piccolo and Perillo 1990, Cuadrado et al. 2002, Ginsberg and Perillo 2004), with a tidal range of 2-4 m. Averages performed on each tidal gauge water level data for the year 2000 show that the tidal range increases along the Principal channel from mesotidal to nearly macrotidal.

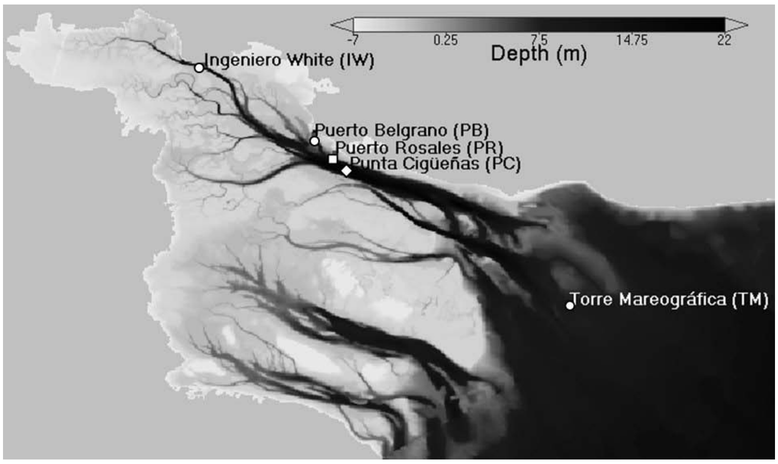

FIGURE 2: *Location of the tidal (circles), current (diamond) and meteorological (square) observation stations in the Bahía Blanca estuary.*

Harmonic analyses performed on the water level time series using the POL/PSMSL Tidal Analysis Software Kit 2000 (TASK-2000) resulted in 62 tidal components for each tidal gauge. Observed and predicted with the tidal components, water levels for each tidal gauge present a high coefficient of determination (R^2) from 0.87 for TM station to 0.91 for IW station.

Mean water level (Z_0) for the three permanent tidal stations shows a difference of 0.70 m between the two most widely separated stations (55 Km). This difference will be addressed later in the modelling chapter. The tidal components of greater amplitude are given in Table 2, the list is led in all the stations by the semidiurnal components, followed by the diurnal components whose influence decreases headwards. The Formzahl coefficient (F) provides a quantification of the degree of influence of the semidiurnal and diurnal components. It consists of 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). According to the result of the F ratio, tides can be considered diurnal ($F>3$), semidiurnal ($F<0.25$) or mixed ($0.25<F<3$). In Bahía Blanca the F ratio decreases as the tidal wave progresses up the estuary, being 0.26 at TM station and 0.19 at IW station. Tides in the Bahía Blanca estuary can thus be classified as semidiurnal. As the tide heads inland, the weight of the so-called compound tides or overtides

(M_4, MS_4 and MN_4), generated by nonlinear interactions of primary constituents, increases. This effect takes place in shallow water areas, also increasing the tidal range. These new constituents are important for turbulence, tidal asymmetry and mean water level (Wang et al. 2002).

According to Wang et al. (2002), tidal asymmetry can be assessed as a comparison of the amplitudes and phases of the dominant M_2 component with the overtide M_4. A relative phase (*phi* = $2\phi_2 - \phi_4$) between 0° and 180° indicates longer duration of the flood than ebb (flood-dominant) and vice versa. After analysing the data for the three tidal gauges in Bahía Blanca, an evolution from the flood-dominated coast to the ebb-dominated head can be observed. In Table 3 the values obtained for the years 2000-2003 analysis are summarised. The α parameter calculated as division of the M_4 amplitude by the M_2 amplitude indicates the degree of asymmetry, this parameter increases headwards due to a larger increase of the M_4 component than the M_2.

TABLE 1: *Location, observation period and source of hydrodynamic and atmospheric data.*

Station	Longitude	Latitude	Period	Source
TM	61º43'12" W	39º08'56" S	23/08/99 - 31/12/03	CGPBB
PB	62º06'15" W	38º53'48" S	23/08/99 - 31/12/03	CGPBB
IW	62º16'08" W	38º47'26" S	23/08/99 - 31/12/03	CGPBB
PR	62º04'00" W	38º53'00" S	01/01/01- 01/12/01	IADO
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 (deg/hr)	Puerto Ing. White		Puerto Belgrano		Torre Mareográfica	
		H (cm)	φ (º)	H (cm)	φ (º)	H (cm)	φ (º)
Z_O	0.000	263.544	0.000	245.635	0.000	193.273	0.000
M_2	28.984	169.123	186.072	153.523	177.906	115.864	157.094
L_2	29.528	25.475	255.364	22.471	245.987	15.977	220.692
N_2	28.440	23.983	103.593	21.080	95.833	15.239	76.690
M_4	57.968	22.764	178.277	16.141	184.234	6.396	171.968
S_2	30.000	21.589	307.350	20.632	298.669	16.843	274.215
K_1	15.041	21.151	61.178	21.481	54.527	20.345	45.066
O_1	13.943	15.528	0.701	16.186	355.431	15.426	344.967
MU_2	27.968	14.523	291.531	14.015	282.016	12.590	264.735
NU_2	28.513	10.954	137.915	9.637	130.029	7.632	113.261

3.2 Currents

The dataset collected at the Punta Cigüeñas oil pipe monobuoy (Figure 2, Table 1) by the Navy Hydrographical Service (SHN), consisting of current speed and direction every 15 minutes during 35 days, was the most representative dataset available in the Bahía Blanca estuary. The average value for the whole series is 0.64 $m\,s^{-1}$ with a maximum of 1.33 $m\,s^{-1}$ and the directions are practically opposite pointing to 295° and 115° respectively (Figure 3). Ebb tide maximum velocities are slightly higher. In order to validate and calibrate the model for different periods, the harmonic components of the dataset were obtained for each component of the velocity using the TASK-2000 software. Component U intensity of the velocity is almost double the V component, due to the orientation of the Principal Channel. The most important harmonic component for velocity is the M_2 which is responsible for more than 40% of tidal velocity, followed by the N_2 component that represents an 8% of the intensity of the currents. The tidal components are able to explain 82% of the total variability of the currents measured during the sampling period, the remainder of the variability may be due to variations in mean sea level and to atmospheric effects.

TABLE 3: *Principal tidal components for each tidal gauge (H=amplitude; φ= phase).*

	Puerto Ing. White	Puerto Belgrano	Torre Mareográfica
M_2 H (cm)	169.123	153.523	115.864
M_2 φ (°)	186.072	177.906	157.094
M_4 H (cm)	22.764	16.141	6.396
M_4 φ (°)	178.277	184.234	171.968
α	0.135	0.105	0.055
Phi	193.867	171.578	142.22

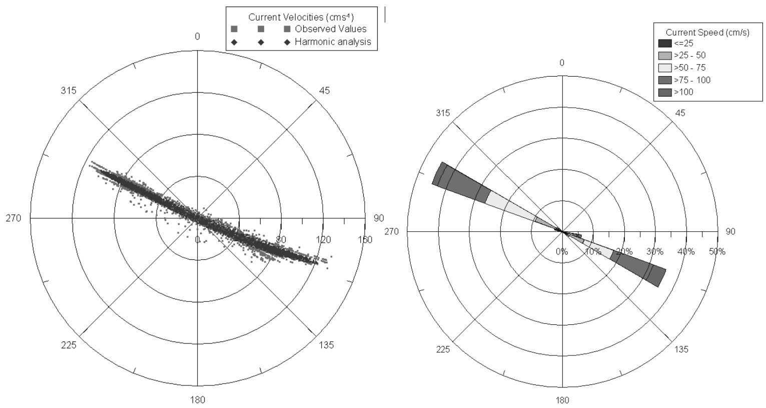

FIGURE 3: *Current intensities and directions observed and obtained through harmonic analysis for the same period (Left) and observed current values analysis (Right).*

3.3 Freshwater inputs

Main natural fresh water inputs in the Bahía Blanca estuary are located at the innermost part of the Principal Channel. Basically, only Sauce Chico River and Napostá Grande creeks have a considerable discharge in the study site (Heffner et al. 2003) with average annual flows of 5.80 and 2.68 $m^3\ s^{-1}$ respectively. Nevertheless, high runoff peaks have been registered, for instance in the Sauce Chico River several times discharges over 50 m s^{-1} have been observed (Perillo and Piccolo 1991). Although the source of both rivers is located in the Sierras de la Ventana mountain range, both catchment areas are not subjected to the same processes and present different discharge peaks during the year. Sauce Chico River has two main peaks, one in autumn (Feb-Jun) and a stronger one during spring (Aug-Dec). However, the Napostá Grande Creek flow shows peaks in winter (Apr-Aug) and spring (Aug-Dec), both with similar intensities. The spring peak in both rivers corresponds to the rainiest period in the Bahía Blanca region. Sauce Chico presents a flow pattern very influenced by the local rain pattern on Bahía Blanca region while Napostá is more influenced by the precipitation near the Sierras de la Ventana (Piccolo et al. 1987). Figure 4 shows the monthly average flow from data collected during the 1993-1999 period provided by Aguas Bonaerenses Sociedad Anónima (ABSA). There are other creeks flowing into the Bahía Blanca estuary, such as Galván, Saladillo de García and Maldonado creeks with an overall flow lower than the Napostá Grande creek (Piccolo et al. 1987).

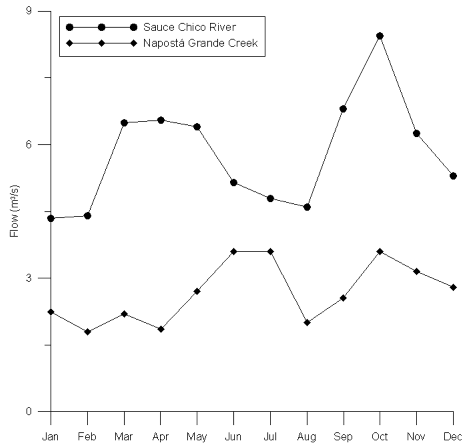

FIGURE 4: *Napostá Grande Creek and Sauce Chico rivers monthly average flow.*

3.4 Atmospheric influence

The SMN (National Meteorological Service, 1985) in Capelli and Campo (2004) described the study area as dominated by the pressure systems from the West and Southwest and the presence of a semi permanent high pressure over the South-western Atlantic centred at 30°. The circulation around the Western edge of the anticyclone results in strong winds from the NW and N. When winds blow from NW, they produce lower water levels than those predicted by the astronomical tides; on the other hand, when wind blows from SE water is piled up in the inner areas of the bay increasing the water level. This phenomenon is locally known as sudestadas. According to Perillo and Piccolo (1991) and Piccolo and Diez (2004) the predominant winds from N and NW produced an advance of the low water time, a delay on the high water time and reduced the predicted levels both for high and low tide.

Thirty minute data observed at Puerto Rosales meteorological station (Table 1, Figure 2) by the IADO for the period January-November 2001 showed prevailing winds blowing from Northern sectors, mainly from the North and Northeast. Maximum intensity recorded on this period was 23.2 m s^{-1} and an average value of 6.2 m s^{-1}. During most of the time intensities do not surpass 10 m s^{-1}.

4 HYDRODYNAMIC MODEL: SETUP AND RESULTS

The implementation of a validated hydrodynamic model would serve for applications that would aid in coastal management and would serve as a part of the DPSIR approach. The MOHID hydrodynamic model (`http://www.mohid.com/`) was used to force a Bahía Blanca 2-Dimensional domain model covering the study site. The most relevant characteristic is the order of magnitude of the horizontal and vertical dimensions. In our case study the horizontal extent is 70 km, while the average depth is 10m.

4.1 Modelling grids

To study the different hydrodynamic processes involved in Bahía Blanca, two different spatial scales covering the main area of interest were adopted with different resolutions: 0.01^o and 0.002^o horizontal step covering from the coordinates -61.41W, -39.38S to the inner estuary (Pierini 2007), hereafter referred as LoRes grid and HiRes grid, respectively. The main interests in developing different resolutions have been, on the one hand, to study different processes in diverse detail according to the available data and, on the other, to maximise the model runtime. Bathymetric data used for composing the different model domains came from the GEBCO digital atlas, a one minute global bathymetric grid database (IOC, IHO and BODC 2003) and from CGPBB data with a waterline obtained after evaluating 6 sets of Landsat 5 TM and Landsat 7 ETM data resulting in a high density bathymetry (50 m x 50 m) (Pierini 2007).

4.2 Tides

Tide enters each bay of the Bahía Blanca estuarine system by its Southern margin finding all the channels reduced in width and most of the intertidal areas emerged. As the tide advances, water starts to cover the intertidal area amplifying the submerged area. As a result of the interaction of the tidal wave with the shallow depths of the channels, overtides importance increases. Maximum tidal amplitudes are thus found at the innermost areas for each of the three different channels, and the absolute maximum was found in Principal Channel. During high tides, the connections between the three different bays reach their maximum width favouring water exchange between bays. When the tidal wave retreats, water scours from the inundated intertidal areas through tidal channels into the main channels, the time to evacuate those waters is long and so this process is still going on when a new tidal wave is already entering the system, as can be appreciated on the last image of the sequence (Figure 5). Due to the vicinity of the TM tidal gauge to the boundary of the Bahía Blanca domain, the model forcing consisted of imposing those tidal components along the entire coastal open boundary.

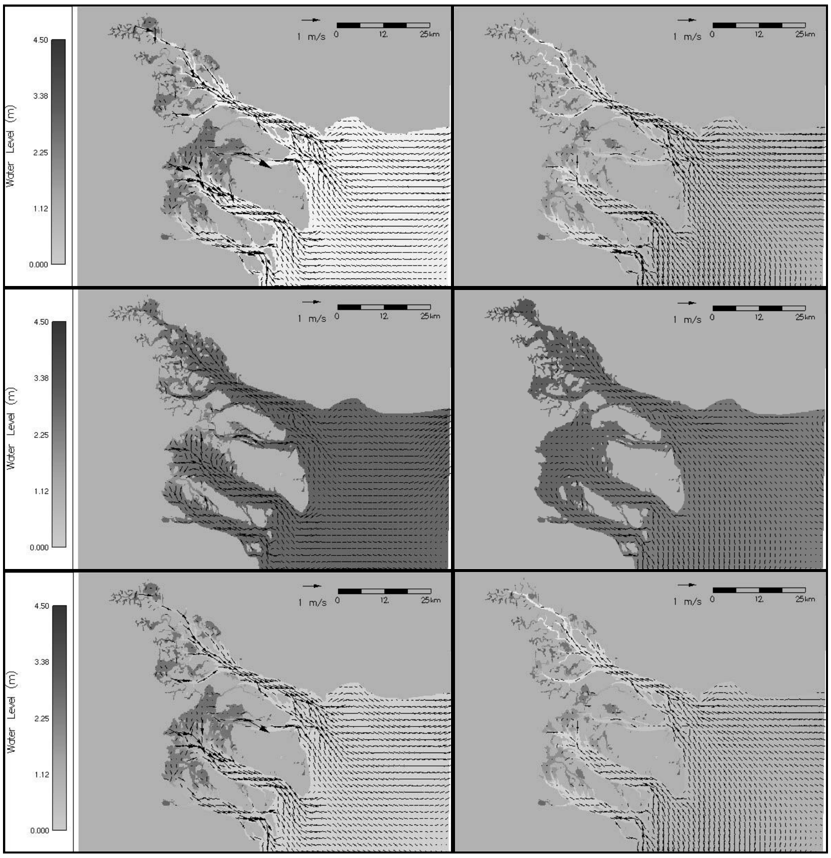

FIGURE 5: *Water levels for the HiRes domain during a period of 12 hours.*

The Bahía Blanca Estuary Principal Channel mean sea level, as stated in the data analysis, presented a permanent sea level difference of 70 cm between the most distant tidal gauges. That tidal amplification could not be explained by the increase of mean sea level due to tidal dumping. Using simultaneous validation of the water levels and the current intensities at Punta Cigüeñas (PC) station, it was concluded that using the mean sea level of the outermost station, TM, the right quantity of water was not entering the system, as the obtained currents at that station were reduced compared to the observations. On the contrary, when adding these 70 cm to the mean sea level of the TM station, both water levels and current intensities at PC station presented a high coefficient of determination.

Applying these conditions to the model, correlations between the expected water levels due to astronomical tides and model results obtained were performed obtaining correlation coefficients above 0.93 (Table 4). To further evaluate the comparison between the observed tidal levels obtained through harmonic analysis with the predicted levels obtained through modelling, the additional indicators suggested by Willmott (1982) were assessed (Table 4).

TABLE 4: *Model performance indicators at each tidal gauge.*

Station	Torre Mareográfica	Puerto Belgrano	Puerto Ing. White
Correlation (r)	0.985	0.987	0.966
Coef. Determination (r^2)	0.971	0.974	0.933
MB	-0.048	0.104	-0.054
RMSE	0.162	0.220	0.369
Skill	0.992	0.991	0.981

Mean bias (MB) indicates the average difference between the observed and predicted values. Predicted amplitudes vary in (bias/total amplitude*100) 1.37, 2.35 and 1.08% of the total amplitude at TM, PB, and IW stations, respectively. Root Mean Square Error (RMSE), or standard deviation, is the square root of the variance which represents that 95% of the model predictions do not differ (in absolute value) from the observations by more than 2xRMSE. The skill index is intended as a descriptive measure, and is both a relative and bounded measure which can be widely applied to make cross-comparisons between models. It provides similar information to the coefficient of determination, in the sense that it gives a measure of model performance, but it penalises models with greater bias. If the skill index is 1, the model presents an optimal predictive skill. Skill values for each station are close to 1, indicating a high degree of model performance.

4.3 Currents

Currents on Bahía Blanca estuary are mainly caused by tides. In addition, the importance of the geomorphology for the tidal asymmetry is reflected in the residual currents. Tidal currents at the mouth of the estuary are the result of the cumulative processes of the outer general circulation and the distortion produced by the estuary hydrodynamics. Flood velocities are generally larger than the ebb velocities outside the estuary due to the direct relationship between velocity and depth.

4.3.1 Instantaneous currents

The Principal channel, according to Piccolo et al. (1987), is dominated by ebb currents, maximum surface values are 0.80 $m\ s^{-1}$ and 1.40 $m\ s^{-1}$ for flow and ebb currents, respectively. Very similar values were obtained by Gómez et al (1996) integrating vertically the observations, with values of 1.05 $m\ s^{-1}$ and 1.30 $m\ s^{-1}$ for flow and ebb respectively. 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 $m\ s^{-1}$ being exceeded for more than 30% of the time (Cuadrado et al. 2002).

Model results (Figure 6) present an ebb-dominated inner estuary in opposition to a flood-dominated coastal area in agreement to both the relative phase values (phi) obtained in Section 3.1 and Cuadrado et al. (2002). In Verde Bay maximum values are found near its mouth due to the channelling of the ebbing waters; in Falsa Bay, in addition to the mouth, it presents maximum values near its head in the region where water from the surrounding intertidal area scours and in the Principal Channel values are high along the main axis of the channel.

During flood, the high intensities on the three bays are located along each main channel slowly covering the intertidal areas where velocities relax. During ebb along the main axis of the Principal Channel values range between 0.7 m s^{-1} and 1.4 m s^{-1}, the maximum values being found near the upper reaches; maximum values of similar intensity are observed in Falsa Bay near its head and near the mouth of Verde Bay. On the three bays, velocities during ebb tide are higher than during flood. Low intensities are mainly found in the higher reaches of the intertidal areas. During flood, water piles up in the entry of the channels, with speeds of nearly 1 m s^{-1} being observed in the mouth and average speeds along the channel axis of 0.4 m s^{-1} on average. Peak velocities observed in the model on the intertidal areas during flow are generally below 0.3 m s^{-1}. It can be concluded that the model reproduces the principal features described in the literature.

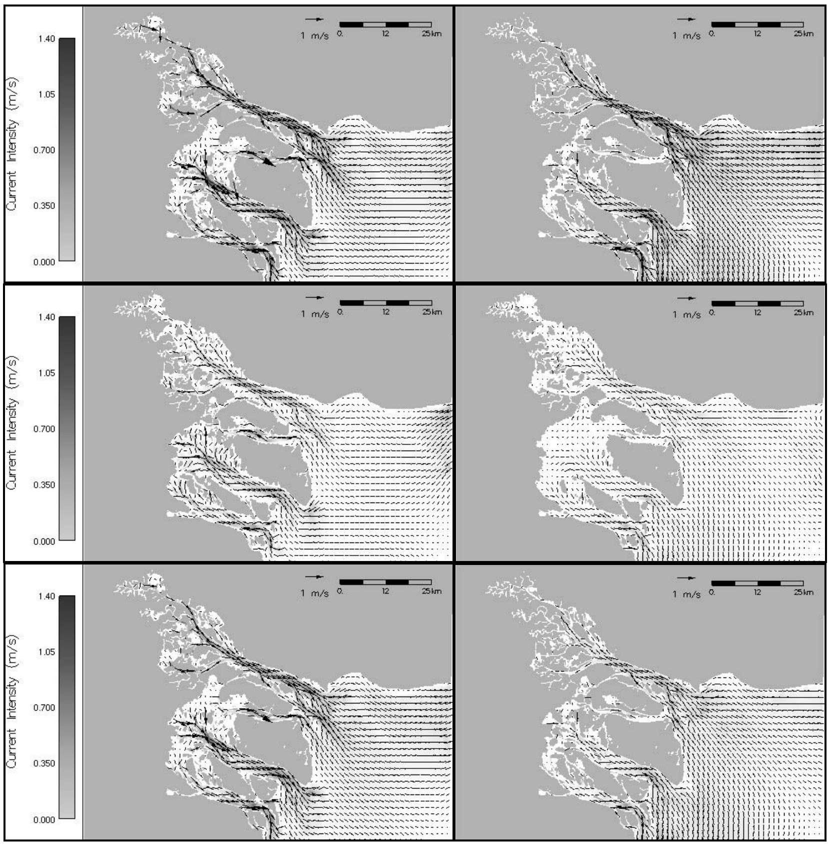

FIGURE 6: *Instant velocities for a 12 hour period in the Bahía Blanca estuary HiRes domain.*

4.3.2 Residual currents

The residual currents are a significant factor regarding the import and export of dissolved and particulate substances of the estuarine system. Two different residuals are relevant in terms of characterising the estuary, namely residual flux velocity and residual velocity. The residual flux velocity is calculated by the vertical integration of the specific residual water fluxes occurring during a defined period and is expressed in $\mathrm{m\,s^{-1}}$ and influences the transport of dissolved properties in the water column (i.e. nutrients). Figure 7 Top presents results corresponding to a month simulation average. As was pointed out by Perillo et al. (1987) and Pierini (2007) for the head of the Principal Channel, net transport in deeper areas is seawards while in shallower waters is landwards. The model reproduces this pattern. In the mouth of the Principal Channel due to its particular geomorphology with channels crossing intertidal areas, a recirculation pattern can be observed. As a consequence, the dissolved components would be transported into the intertidal areas and recirculated in the Principal Channel mouth retarding their export to the open ocean.

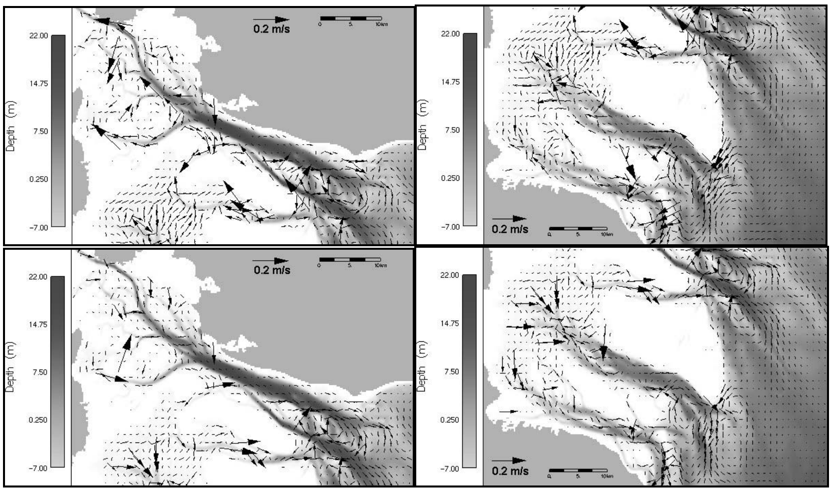

FIGURE 7: *Residual flux velocity (Top) and Residual velocity (Bottom) in the inner (Left) and the outer (Right) area of the Bahía Blanca estuary.*

The residual velocities are the net velocities obtained after balancing currents in different directions and they are of particular importance regarding particulate matter transport such as sediments. The most remarkable results (Figure 7 Bottom) are the net transport from the intertidal areas into the main channels. A recirculation pattern can also be found at the mouth of the Principal Channel. 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, although some recirculation at the Principal Channel mouth would slow down the sediments release into the coastal area (Pierini 2007).

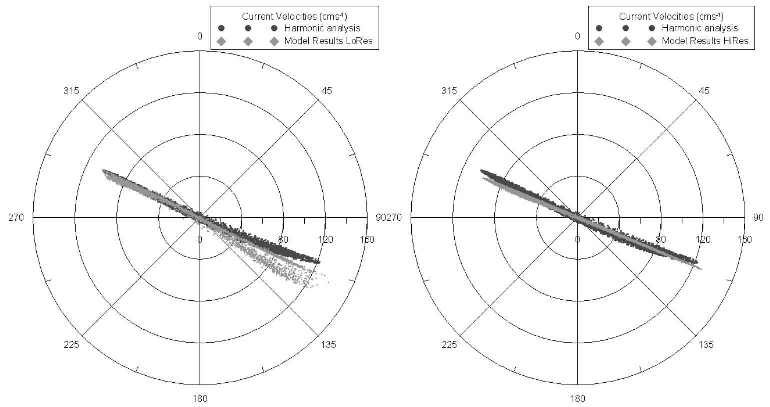

FIGURE 8: *Intensities and direction/s of the currents in Punta Cigüeñas stations obtained through harmonic analysis (dots) and modelling (diamonds) for LoRes and HiRes domains.*

4.3.3 Currents Validation

The main tidal current validation has been performed in the centre of the Principal Channel in the vicinity of the Punta Cigüeñas (PC) buoy (Figure 2, Table 1). After adding 70 cm to the mean sea level observed in TM station, it has been found that the model is able to reproduce the current intensities and directions (Figure 8). The coefficient of determination obtained when comparing both intensities is 0.72. In the HiRes domain this value increases to 80%. Model results and observed values present maximum peaks of intensity around 1.30 $\mathrm{m\,s^{-1}}$ during ebb conditions and nearly 1 $\mathrm{m\,s^{-1}}$ during flood conditions.

4.4 Wind effect

In order to study the effect of wind over the water levels observed, a month was simulated with different wind conditions. According to data analysis performed by Cuadrado et al (2005), predominant directions are NW, NNW and SE with a velocity range between 5 and 10 $\mathrm{m\,s^{-1}}$. A reference simulation with no wind was used to compare with simulations forced with constant wind conditions of 10 $\mathrm{m\,s^{-1}}$ coming from different directions (N, NW, S & SE). Maximum differences occur at the higher reaches of the estuary when winds blow along the Principal Channel axis, piling up water when it blows from the South and decreasing water levels when it blows from the North. In Table 5, mean sea levels are summarised for the three tidal stations analysed in this study.

5 SUSPENDED SEDIMENT DATA ANALYSIS

Despite the relevance of sediments accretion-erosion processes in the evolution of the geomorphology and hydrodynamics, suspended sediment data for the Bahía Blanca estuary are scarce and the origin of the sediments in the water column is not well-established. From the socio-economic point of view, the importance hinges on the need to maintain a nominal depth of 13.7 m for harbours and navigational channels (Perillo and Sequeira 1989). The Port Construction and Navigational Ways National Direction (DNCPVN, its Spanish acronym) dredges around 300,000 $m^3\ yr^{-1}$ in a 2 km stretch of El Toro Channel to maintain a 10 m nominal depth.

TABLE 5: *Wind direction and resulting mean sea level for each tidal gauge.*

Wind Direction	Torre Mareográfica	Puerto Belgrano	Puerto Ing. White
No Wind	1.93	1.93	1.94
North	1.84	1.64	1.62
Northwest	1.83	1.67	1.54
South	2.03	2.22	2.34
Southeast	2.01	2.25	2.44

Sediment balance is related to accumulation or erosion processes, also connected to the residual velocities. In the same sense, Ginsberg and Perillo (2004) concluded that the duration of asymmetry controls the trend of erosion in the channel system while the velocity asymmetry is responsible for the net sediment transport. Flow asymmetries characterized by shorter flood duration and higher flood current maximum (flood dominance) induces landward directed sediment transport while shorter ebb periods and greater ebb current maximum (ebb dominance) cause net outward sediment transport (Lanzoni and Seminara 2002).

The lack of major sediment point sources in the system, due to the reduced river flow, and the small contribution of sediments from the open ocean implies that the channel margins and intertidal areas should be regarded as the main source of sediments (Perillo and Sequeira 1989, Ginsberg and Perillo 2004). They considered sediment transport controlled by the degree of tidal asymmetry and trends on erosion governed by the degree of time asymmetry. According to Perillo and Cuadrado (1990) an erosion process is ongoing in the study area, sediments are eroded from the channel margins and eventually exported to the continental shelf. The materials affected are mainly very fine sand (38%), silt (37%) and clay (25%); with the sand transported as bedload and the other fractions in suspension (Aliotta et al. 2004).

As occurs with hydrodynamics, wind direction and intensity has an effect on suspended sediments in the estuary. Perillo and Cuadrado (1990) found in the nearby coastal area, Northeast of Bahía Blanca estuary mouth, homogeneous sediment concentrations between 70 and 90 $mg\ l^{-1}$ with North wind that decreased to 10 to 20 $mg\ l^{-1}$ when the wind shifted to a SSE direction. The origin of those sediments was found related to the Bahía Blanca sediment plume.

The Austral campaign on November 1993 covered the coastal vicinity of the Bahía Blanca showing a clear sediment front along the coastal area of the Bahía Blanca estuary (Figure 9, left), also observed in recent satellite pictures (Figure 9 right). In the Austral campaign, maximum concentrations of over 60 $mg\ l^{-1}$ are related to the Principal Channel while coastal values are between 20 and 25 $mg\ l^{-1}$ in agreement with the values estimated by Cuadrado et al. (2002). According to determinations done by NEDECO-ARCONSULT (1983) referred to in Perillo and Sequeira (1989), mean values for the middle reach of the estuary are around 90 mg l^{-1}. In the vertical, sediment concentrations present a nearly homogeneous distribution, with distance from the coast being the main factor determining the observed concentrations. This implied that a 2D model could be used to simulate the sediment transport and to test different hypotheses of the origin and fate of the cohesive sediments.

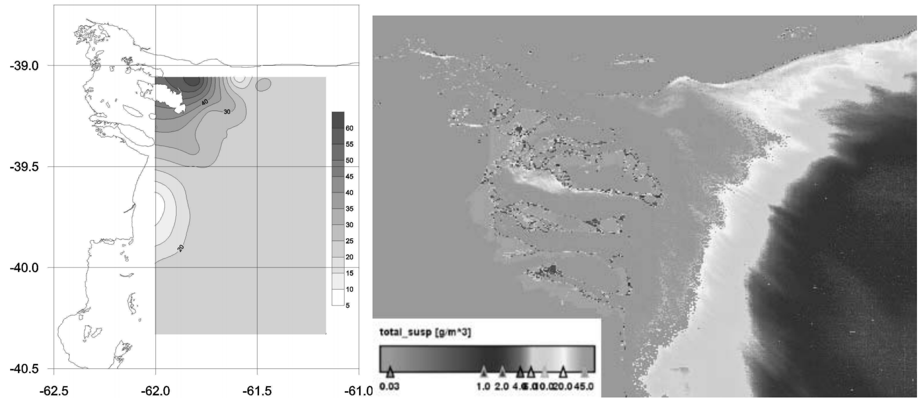

FIGURE 9: *Total suspended matter observed on the outer area of Bahía Blanca estuary measured during the Austral campaign at the surface in mg l^{-1} (left) and MERIS satellite image dated on 10/08/2004 (right).*

6 BAHÍA BLANCA ESTUARY COHESIVE SEDIMENTS CONCEPTUAL MODEL

Based on model tests, historical data and a bibliographic survey, the conceptual model to be tested assumes that water column sediments are resuspended during the high tides on the tidal flats and transported to each bay's main channel (Figure 10). In this manner, erosion is taking place due to the sediment loss into the open ocean although the erosion process is a slow process. This theory would also explain the wide ranges of values for turbidity and sediments in the inner areas of the system where tidal flats occupy larger areas in comparison with the main channel. Thus, depending on the stage of the tidal cycle when the data are collected and on the wind conditions, data would vary considerably on the inner stations with maximum values which may be up to six times larger than the minimum values observed.

The 0.01° resolution grid was forced by the TM station tidal components taking into account the difference in the mean sea level. In the seabed, two different sources for the cohesive sediment layer were initially assumed. The intertidal area is considered as the main contributor of sediments to the water column, with a total thickness of available sediment of 0.2 m, on the other hand sediments in the channels and deeper areas were considered with a total thickness of 0.05 m that might undergo erosion and deposition processes. The sediments were also divided into a total of 15 layers; the first 8 were defined empty to allow consolidation of sediments, the next five represented each a 15% of the total sediments and the last two consisted of the 12.5% of the total sediments.

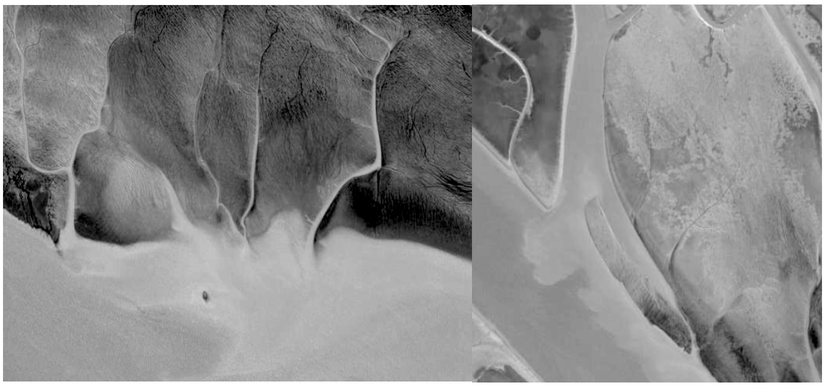

FIGURE 10: *Sediments loads from the intertidal areas into the Principal Channel of the Bahía Blanca estuary (Google Earth Captures).*

In addition, different critical shear stress profiles were considered on the intertidal and submerged areas. Sediments on the bottom of the channels were considered to be harder and also requiring higher stress intensity for resuspension. For the submerged area, an exponential increase of critical shear stress from 60 to 125 Pa was considered, while for the intertidal, a homogeneous value of 1.35 Pa was considered. The equations governing the erosion and deposition processes that would modify the original values are described in Chapter 5 of this volume.

The values assigned to the erosion and depositon parameters have been taken from those published by Perillo and Sequeira (1989) to model the cohesive sediment transport in the middle reach of the Bahía Blanca Estuary (Table 6). The settling velocity was computed by NEDECO-ARCONSULT (1983) as $1.25\text{x}10^{-3}$ m s^{-1}. Perillo and Sequeira, based on the work of Hayter (1985), calculated a value for the first centimetre of newly deposited mud of 0.225 N m^{-2}. The same authors assumed that mud characteristics were similar to those in San Francisco Bay where Mehta (1985) obtained a value of 0.1 N m^{-2}. In this study a dry density for the sediment of 2300 kg m^{-3} was used. To calibrate our model, different values for the erosion rate parameter have been evaluated, finally choosing a value of 10^{-5} kg m^{-2} s^{-1}.

Those conditions are defined for the interface of the sediment with the water, also known as the fluff layer. Under this layer, a 3D sediment model that would provide this layer of sediments when they are eroded was deployed. The model boundaries are forced by the two rivers Napostá Creek and Sauce Chico River as the unique land source of sediments with a constant concentration of 25 mg l^{-1}, and a constant value for the ocean boundary of 21.6 mg l^{-1} (Cuadrado et al. 2002). Also, an initial value of 50 mg l^{-1} was considered as the concentration in the water column for the entire system.

TABLE 6: *Parameters used to model the erosion and deposition of cohesive sediments.*

Parameter	Symbol	Value	Source
Critical shear erosion	τ_E	0.225 N m^{-2}	Perillo and Sequeira 1989
Erosion rate	E	$1{\cdot}10^{-5}$ kg m^{-2} s^{-1}	
Critical shear deposition	τ_{cd}	0.1 N m^{-2}	Perillo and Sequeira 1989
Constant settling velocity	w_s	$1.25{\cdot}10^{-3}$ m s^{-1}	Perillo and Sequeira 1989
Manning coefficient		0.020	

7 SEDIMENT MODEL RESULTS

The Bahía Blanca model, using the assumptions described above, was run for a period of five years until the bottom sediments and the water column concentrations stabilised, followed by a four year model run. A series of stations (Figure 11) running along the Principal Channel of Bahía Blanca Estuary was selected to evaluate the defined sediment model reaction to the forced hydrodynamics.

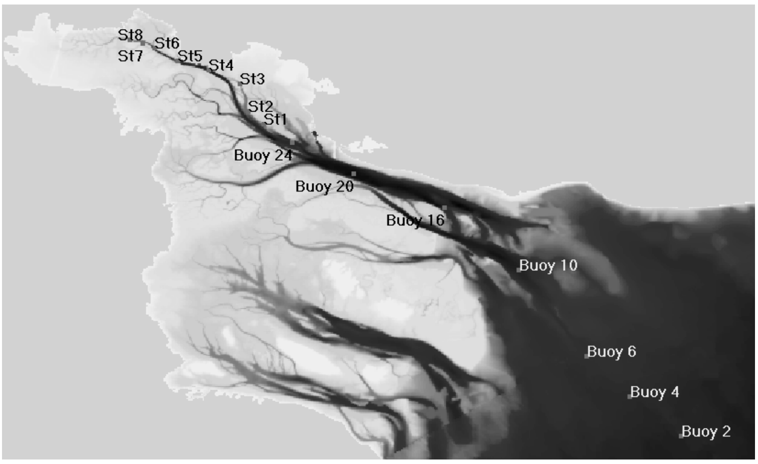

FIGURE 11: *Location of the monitoring stations in the Bahía Blanca estuary model.*

The model results show a decrease in suspended sediments from the head to mouth of each bay. Sediments are resuspended during the flood and transported through the intertidal channels into the main channels of each bay during the ebb tide. During the ebb tide, maximum concentrations are reached in the water column. During spring tides, the range of sediment concentrations on the water column is wider than during neap tides. The influence of spring and neap tides is detected even in the most distanced station Buoy 2. The transport of these sediments off each channel produces a sediment front along the Bahia Blanca coast (Figure 12). This feature was noticed in the MERIS satellite image (Figure 9, right) with similar concentrations to the observed in the model results.

The average values for the three year simulation depicted in Figure 13 follow a spatial distribution in which the innermost estuarine area cohesive sediment concentrations are stable, while seawards concentrations steadily decrease reaching constant values on the open ocean area. The maximum value is found in Station 3 due to its location in a narrow channel surrounded by intertidal areas parallel to the Principal Channel. According to our model results, the Falsa Bay, due to its particular geomorphology, presents the highest registered values. During ebbing tides, sediments from all the tidal channels converge, increasing their concentration. Unfortunately, data to calibrate and validate simply do not exist for the other bays that form the estuarine system along with the Principal Channel.

In terms of sediment erosion, a comparison in sediment height performed between the initial and last instant of the last three years simulation period shows that the Bahía Blanca estuary is under an eroding process in agreement with Perillo and Sequeira (1989). Erosion takes place mainly on the sides and heads of the tidal channels, while an area with significant deposition has not been found. In agreement with the results presented above, the head of the Falsa Bay is the area that presents a higher degree of erosion (Figure 14).

FIGURE 12: *Cohesive sediments concentration ($mg\ l^{-1}$) in the water column during flood (left) and ebb tide (right).*

8 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 due to the permanent erosion by the action of tides enhanced by the action of wind and waves. In order to evaluate the possible impacts due to dredging and the dumping of dredge spoils at the disposal areas, it is very important to gain knowledge of system dynamics. In an estuary with a high ratio of intertidal areas, hydrodynamics would be very sensitive to water level variations. Due to this importance during the present study, the sources of variations in water level have been identified, analysed and quantified for the Bahía Blanca estuary.

The main contributors to the hydrodynamics system are the astronomical tides, explaining more than 85% of the water level variation. However, other atmospheric phenomena, such as pressure and wind, can provoke modifications in water elevations.

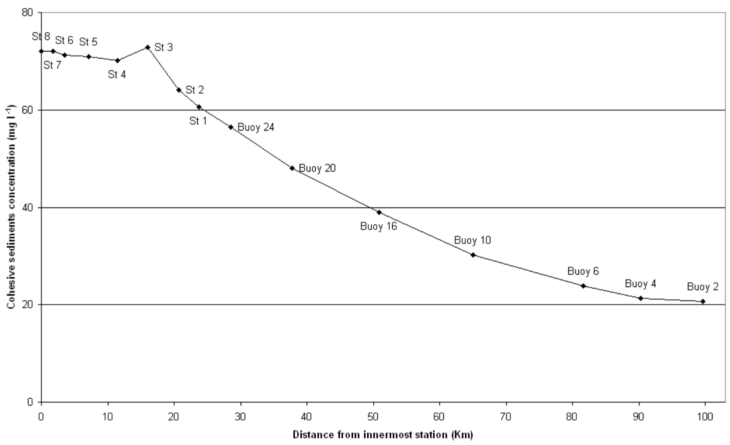

FIGURE 13: *Average values for four years simulation in each of the model monitored stations along the Principal Channel main axis.*

FIGURE 14: *Sediment height difference between the last three years simulated with an erosion rate of* 10^{-5} $kg\ m^{-2}\ s^{-1}$.

The circulation in the Bahía Blanca estuary has been described as dominated by a semidiurnal, quasi-stationary tidal wave (Perillo and Piccolo 1991) and this makes it a tide-governed estuary. The tidal wave travels from the South and enters each of the bays by the Southern margin. The particular geomorphology of the Bahía Blanca estuary produces the increase of the overtides components which produce the tidal amplitude increase. As an effect, tides evolve from the outer ocean from flood dominated to ebb dominated increasing this dominance with the distance from the mouth. As a result, higher current speeds are found during ebb for each of the bays. Maximum values during ebb tide are found near the mouth of the estuary where waters collected by the system of channels meet, and along the main axis of the channel. During flood, maximum values are found near the mouth of the bays where water entering piles up. On the other hand, minimum values are found on the elevated intertidal areas.

One of the great advantages of using modelling tools in integrated coastal zone management is that datasets collected at different periods and sampling intervals can all be integrated into one tool to reproduce periodical phenomena, i.e. tides, currents. Also, modelling allows isolating and discriminating single processes from all the available information. Data modify the conditions of the model, and model results can provide a feedback for the accuracy and consistency of the data. For these reasons, models should not be regarded as data "sink" tools only, as they are also able to test the available data consistence.

In the Bahía Blanca case, modelling served to confirm an inconsistency on the MSL used for the TM station. In this case, the simultaneous use of observed water levels and currents, although they were not from the same period, and the posterior mathematical analysis and validation through a hydrodynamical model resulted in the conclusion that mean sea levels for the tidal gauge stations needed (re)calibration. This is one of the major outcomes of the present work.

The model hydrodynamics indicates a residual circulation into the head of the tidal channel of dissolved properties; on the contrary, tidal channels export particulated matter. This fact is relevant for water quality and sediment studies. Dissolved properties would tend to accumulate in the innermost areas of the channels while sediments would be washed away. The latter phenomena would be less in the Principal Channel, due to the recirculation pattern found at its mouth. These features are also in agreement with the lagrangian test performed where tracers located in the innermost area of the Principal Channel present longer residence times.

Although more detailed work should be performed on this matter, the model appears to respond to wind forcing as the literature has described. Water levels increase in the inner areas when winds blow from the South-Southeast sector and decrease on average when they blow from the opposite direction. This effect is more intense when the wind blows along the bays main axis.

In this chapter, a conceptual sediment model has been established, in which due to the absence of external sources of sediments, the sediments found in the water column have their origin in the Bahía Blanca estuarine system. Tidal currents transport the eroded sediments from the channel flanks into the Principal channels (Perillo and Sequeira 1989). These sediments would be transported by the ebb currents and exported into the adjacent coastal shelf forming a sediment front along the Bahía Blanca coast along with the exported sediment from the other bays of the Bahía Blanca estuarine system.

Some assumptions were made in order to achieve the present results. The intertidal areas were considered the main source of sediments into the system with a higher resuspension potential of sediments than in the subtidal areas. The subtidal areas were a residual source of more compacted sediments that would need higher stresses to be eroded, while in the intertidal areas, the stress needed would be lesser and constant with sediment depth. This 3-dimensional geomorphological model was forced by a 2-dimensional vertically averaged hydrodynamical model with a resolution of 0.01°.

The results obtained through the simulations agree in general with the conceptual model and the analysed data. The model has been validated mainly in the Principal Channel of the Bahía Blanca due to the lack of data for the rest of the system. Cohesive sediment concentrations decrease steadily from the innermost area of the channel to the open ocean. The decrease in sediment concentration is mainly due to the higher proportion of intertidal areas in the inner areas of the system while the proportion of these areas is lesser mouthwards. In its mouth, the Principal Channel, Falsa Bay and Verde Bay formed a sediment and hydrodynamic front that is more intense during ebb tides and enhanced during spring tides which indicates net erosion in the system.

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