EVOLUTION OF SALINITY AND TEMPERATURE IN BAHÍA BLANCA ESTUARY, ARGENTINA

J.O. PIERINI, J. MARCOVECCHIO, F. CAMPUZANO AND G.M.E. PERILLO

1 INTRODUCTION

The main driving forces of circulation in a large number of estuaries are river flow at the head of the estuary and changes in the sea level at the mouth of the estuary, which in turn determine the distribution of water properties like salinity and temperature, as well as the distribution of any other tracer. In Bahía Blanca estuary there are other forcing actions like wind stress and surface heat balance and they respond differently to these forcing actions. Bahía Blanca estuary is in Argentina and the most dynamic in terms of physical and biogeochemical processes. It is a very important ecosystem in the region where it is situated due to the intense human activity in its waters and along its margins. In the last 30-40 years the estuary was studied mainly from a biological and geological point of view.

There are not many studies or publications regarding the hydrology and physical processes of the estuary. Despite this fact, a prior physical process study (Perillo et al. 1987, Piccolo and Perillo 1990) reveals some of the main features of Bahía Blanca. Observations of water level, current velocity, temperature and salinity properties were made at several stations in the estuary during the last years. It was determined that the type of tide at the mouth of the estuary is semidiurnal and it was observed that the astronomical tide is the main forcing driving water circulation in Bahía Blanca estuary. The tidal wave propagation in the study area has the characteristics of a damped progressive wave. According to this study Bahía Blanca estuary was found to be a vertically homogeneous estuary. Nevertheless, some channels may exhibit the characteristics of a partially mixed estuary, depending on the freshwater input.

The importance of the freshwater sources in the estuary dynamics and of its seasonal effects remained a subject of study until now. The estuary has also been studied through numerical modelling. These studies were performed to investigate topics such as the tidal propagation in the estuary (Palma 1995, Etala 2000, Pierini 2007), the Lagrangian transport of particles (Pierini 2007) and studies of residual suspended sediment (Perez and Perillo 1998). The estuary has several freshwater sources, Sauce Grande River being the most important and Napostá Creek. This last freshwater source is connected to the Atlantic through a channel located in the central area of the estuary, Principal channel. This channel is only partially known in terms of temperature and salinity processes, even though it is ideal to perform this kind of studies in Bahía Blanca estuary. The description of salinity patterns provides a basis for predicting the behaviour of other soluble substances, being suitable to study since the salt is a natural tracer.

This study takes a first step to better comprehend the interaction between seawater, freshwater and temperature within this system and to the understanding of its dynamics. These studies require a large amount of field data, of salinity and water temperature, as well as the implementation of numerical models that combine hydrodynamic and transport modules. This contribution uses two complementary and interconnected approaches to study the water temperature and salinity patterns in Bahía Blanca estuary, combining field measurements with numerical modelling results.

The main purpose of this chapter is to determine the horizontal patterns of salt and water temperature in two stations along the Principal channel and to evaluate the importance of the main forcing mechanisms: tides and incoming river flow. To achieve this objective, a short description of the first annual observational program of the hydrological properties in Bahía Blanca estuary will be given. Salinity and water temperature data were measured in (Cuatreros Harbour) the harbour of Puerto Cuatreros and Ingeniero White Harbour along the Principal Channel in the inner part of estuary. These measurements have been taken weekly since 1974 to the present day. An estimation of the river flow for the survey periods was also performed. Results will be presented and discussed, that reflect the influence of superficial heat transfer and tidal forcing on the spatial and temporal distribution of the referred hydrological properties.

Another aim of this work is to implement a transport model in a 2D mode for the entire area of the estuary, with a closer look at its inner area. The model used was Mohid-Water Modelling System, a finite volume model that combines hydrodynamic and transport modules, describing its assessment through calibration and validation against several different data sets.

Due to the estuary´s complex geometry and the number of calibration stations used, this goal constitutes a very challenging task. The model was calibrated using as a first approach a qualitative comparison of the temporal evolution of sea surface elevation (SSE) data measured in 1999/2003 at three locations. When a good match is obtained for all stations, the model's accuracy is evaluated through the determination of the root mean square (RMS) error and also through the comparison between amplitude and phase of the main tidal constituents determined from harmonic analysis of the observed and computed data. The validation procedure was performed using two independent data sets, which includes observations of current velocities (1997 data) and SSE values.

A mathematical model is by definition an attempt to approximate and reproduce real phenomena. The approximations and parameterizations used for the synthesis of the model lead to discrepancies and deviations of model results from observations. The optimization of the model performance is a complicated task and before using a model for operational applications the model should be verified, calibrated and validated. However, there is no widely accepted procedure for carrying out these tasks. Model calibration and validation appears in various forms, dependent on data availability, characteristics of water body, and most of all, the perceptions and opinions of modellers (Hsu et al. 1999). The aim of this paper is to present the calibration and validation of the salt and the temperature for Bahía Blanca estuary.

2 STUDY AREA

A map of the Bahía Blanca estuary location is shown in Figure 1. Principal channel is located in the middle of complex area of Bahía Blanca estuary, a mesotidal and shallow (mean depth of about 1 m relative to the local datum) estuary situated in the southeast of the Buenos Aires province, in Argentina. The study area from the mouth of the estuary to the head is approximately 79 km long, has an average width of about 200 m and a mean depth, along its longitudinal axis, of about 10 m. The tides are semidiurnal, with M2 as the most important constituent, representing more than 90% of the tidal energy. The estimated tidal prism for the estuary head at extreme neap and extreme spring is $6{,}5 \times 10^9$ m^3 and $1{,}0 \times 10^{10}$ m^3, respectively, with an average value of $8{,}4 \times 10^9$ m^3. The total estimated freshwater input for the estuary is very small (about $4{,}4 \times 10^4$ m^3 during a complete tidal cycle) when compared to the tidal prism both at the mouth or at the beginning of Principal channel.

In spite of the small contribution of the rivers in terms of water input, when compared to the tidal prism, they may have a long-term influence on the residual transport. Previous studies by Perillo and Piccolo (1991) and Pierini (2007) revealed that the tide is strongly distorted as it progresses upstream from the mouth towards the end of the channels of the estuary, due to changes in channel's geometry and bathymetry. The general characteristics of the tidal wave are those of a damped progressive wave. Nevertheless, in shallow areas the tidal wave assumes the main characteristics of a standing wave. From a dynamical point of view, Principal Channel may be considered the most important area of the estuary, because the strongest currents are observed here, reaching values higher than 2 $m\ s^{-1}$. The estuary's other channels are mainly shallow and tidal flat areas, contributing to a strong damping of currents.

3 MODEL CONFIGURATION

The MOHID - Water Modelling System (Leitão et al., ReferencesMOHID) is a barotropic finite volume model, designed for coastal and estuarine shallow water applications, like Bahía Blanca estuary where flow over complex topography, flooding and drying of intertidal areas, changing mixing conditions are all important. MOHID allows an integrated modelling approach of physical and biogeochemical processes. A complete description of the model's physics can be found in several works by Martins et al. (2001) or Leitao (2003).

MOHID has been configured for the Bahía Blanca estuary. The bathymetry of the estuary is extracted from data obtained by the Bahía Blanca Port Consortium. More recent bathymetric data, obtained from recent dredging operations in several channels and remote sensor images, were also used (Pierini 2007). Bathymetry is probably the most important among many factors that affect the flow properties in shallow systems like Bahía Blanca estuary. Previous modelling experience indicates that bathymetry controls the spatial variability of current magnitude and direction. Thus, an accurate bathymetric representation is one of the most important and fundamental requirements for successful modelling (Pierini 2007). This is particularly true

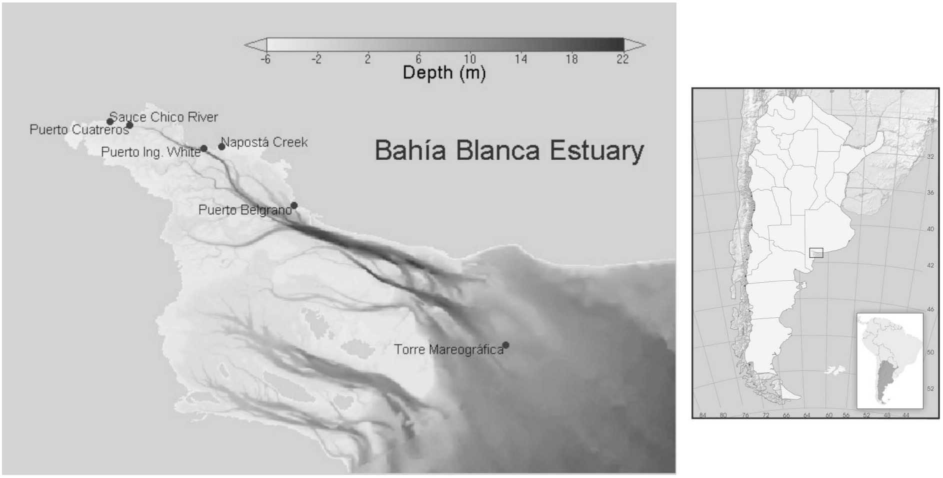

FIGURE 1: *Bathymetry, location of the tidal gauges and discharges within the estuary.*

for the Bahía Blanca estuary, where the bathymetry is very complex. Furthermore, the grid must accurately represent the bathymetric characteristics of the estuary and guarantee model stability.

The task of defining the grid-depth relations for the computational grid points can be extremely time consuming and tedious. The flow simulation in this complex domain requires the use of a high resolution grid. The model grid must be sufficiently refined to resolve the essential features of the depth and the geometry variations, but as the grid resolution is refined the total number of grid points and the computation time both increase geometrically. For this domain the ideal cell dimension would be around 50m, but the compromise solution was to develop a grid with dimensions of 200m, resulting in 119 cells in the x-direction (eastward) and 68 cells in the y-direction (northward) (Figure 1). In this case the narrowest channels had their width exaggerated, but by decreasing their depth it was guaranteed that they maintained their water volume.

Changes in the bathymetry may be expected due to sediment dynamics and to the dredging operations performed last years. The domain was designed to resolve the estuary's dynamics and not the dynamics of the near coastal ocean. Bahía Blanca estuary is an estuary where the tidal prism spreads toward the main channels and extensive tidal flats. This causes a decrease of the tidal prism through the channel affecting the dynamics of the whole study area. The Rio Sauce Chico river and Arroyo Napostá creek (Figure 1) supply fresh-water to the system. Thus, in order to simulate this inflow/outflow, the model uses as boundary conditions water flow, salinity and water temperature time series computed using a two-dimensional (depth-integrated) application of the model for all the study area.

The 2D application uses a variable spatial step Cartesian grid with higher resolution in the study area, calculating time-varying discharge, salinity and water temperature time series. The model was forced using tides (ocean open boundary) and the landward boundary was forced using river flow values typical for each run. At the oceanic and landward boundaries, the water temperature and salinity are fixed in each simulation, with typical values for each period. At the surface, heat fluxes were imposed. The model uses the heat fluxes parameterizations described by Chappra (1997). Time step is 60 seconds and the horizontal eddy viscosity is 50 $m^2 s^{-1}$. For the transport model the initial conditions are salinity and water temperature fields, obtained by interpolation of data collected in the study area. A value of 50 $m^2 s^{-1}$ was adopted for both salt and heat diffusion coefficients. The two-dimensional application is fully described in Campuzano et al. (2008). Coefficients of horizontal viscosity and diffusivity are set to 50 $m^2 s^{-1}$. Initial conditions for the hydrodynamic model are null free surface gradients and null velocity in all grid points. Initial conditions for the transport model are mean monthly values of salinity and water temperature (typical values for each run).

As a first approach, a model covering the Argentina Continental Shelves to whole estuary and surroundings ("grandfather model", Figure 2) and forced with tidal components provided by the generic tidal FES95.2 model (Le Provost et al. 1998). In order to simulate water level at the boundaries a network of "imaginary" tidal gauges fringing the model boundary is set as shown in Figure 2 for the primary model. The model automatically performs triangulations between the different "imaginary" tidal gauges to impose the tide on every cell of the boundary. At the landward boundary freshwater inflow was imposed water inflow/outflow, salinity and temperature fluxes were also prescribed. On the offshore open boundary and at the river boundary constant values of salinity and water temperature were prescribed (S_{sea} = 35 and S_{river} = 0.5, water temperature varies from run to run). The hydrodynamic was spun up from rest over 4 days ($\sim$8 tidal cycles). This is considered a fair adjustment period for the hydrodynamics. The spin-up period is not included in the results and the initial state of a run refers to the end of the spin-up period.

3.1 Temperature and Salt transport models

In most estuaries with a significant freshwater discharge, salinity may serve as an ideal natural tracer for calibration of transport processes. In these environments the tidal current, the freshwater discharge, the density circulation, as well as the turbulent mixing processes affect salinity distribution. Therefore, the salinity distribution reflects the combined results of all these processes, and in turn it controls the density circulation and modifies the transport processes. Assuming that the barotropic flows (tidal and freshwater flows) have been calibrated and validated, the procedure to calibrate the salinity transport model is to match the observed and the computed salinity time series in Puerto Cuatreros and Puerto Ingeniero White. In this calibration procedure, the analysis of predicted distributions of salinity is used to guide the adjustment of calibration constants through comparison with the typical horizontal salinity distribution observed in Bahía Blanca estuary. Once the salinity transport model is considered calibrated, the transport processes may be considered well represented by the model. Therefore, the calibration of the heat transport model is related only to the heat and radiative fluxes parameterization.

A set of salinity and water temperature data measured between 1/4/2003 and 1/8/2004 is available for comparison with model results. These data include long time series of salinity and water temperature measured weekly at Puerto Cuatreros and Puerto Ingeniero White. The freshwater continuous inflows through the upstream boundaries are not known. The imposed flowrates at the rivers boundaries resulting from mean monthly value procedure were the following (Table 1)

The freshwater was specified with salinity equal to 0.5, freshwater temperature for the Napostá Creek and Sauce Chico River as 10 °C. In the calibration of the heat transport model the sensible and the latent heat fluxes coefficients are also used as calibration parameters and were considered constant in all the simulations. It was found that the agreement between the predicted and the observed temperature is good. Figures 3 and 4 show the comparison between the predicted and observed salinity and water temperature, respectively, for 2 stations (Puerto Cuatreros and Puerto Ingeniero White). The patterns observed are essentially dependent on the tidal transport. The RMS values were computed for each station, and are presented in each plot.

The agreement between the predicted and the observed salinity may be considered good for all the stations, the salinity time evolution and amplitude variation being well represented by the model. The maximum absolute RMS value was determined for station Puerto Cuatreros, with a value of 0.125, which represents about 12% of the local salinity amplitude. The RMS value for the other station is also around 10% of the local salinity amplitude. In general there is a good agreement between the predicted and the observed water temperature values (Figure 3 and 4). The RMS values are typically about 21% of the local water temperature amplitude. From these results it may be considered that the transport processes in the Bahía Blanca estuary are well represented by the transport models. And the heat exchanges between the atmosphere and the water surface are very important processes too.

4 CONCLUSIONS

The transport models of heat and salt were successfully implemented for the Bahía Blanca estuary. Results show that the calibration of the models was successfully carried out, showing a good agreement between measurements and model results. The validation tests showed that the models can reproduce an independent observed data set. The developed and applied models to the study area appear to use an adequate bathymetry. However, differences still do exist, and they might be the result of several factors, including: inaccurate definition of the bathymetry in the model for that region; very narrow channels not well resolved by the model horizontal grid; and uncertainties in the field data. The results show that the models can accurately reproduce the barotropic flows and simulate adequately the salt and heat transport in Bahía Blanca estuary, even in conditions of freshwater inputs from the rivers and heat transfer between the atmosphere and the water surface. The models can, therefore, be considered as a new important tool for future studies of Bahía Blanca estuary dynamics and water quality.

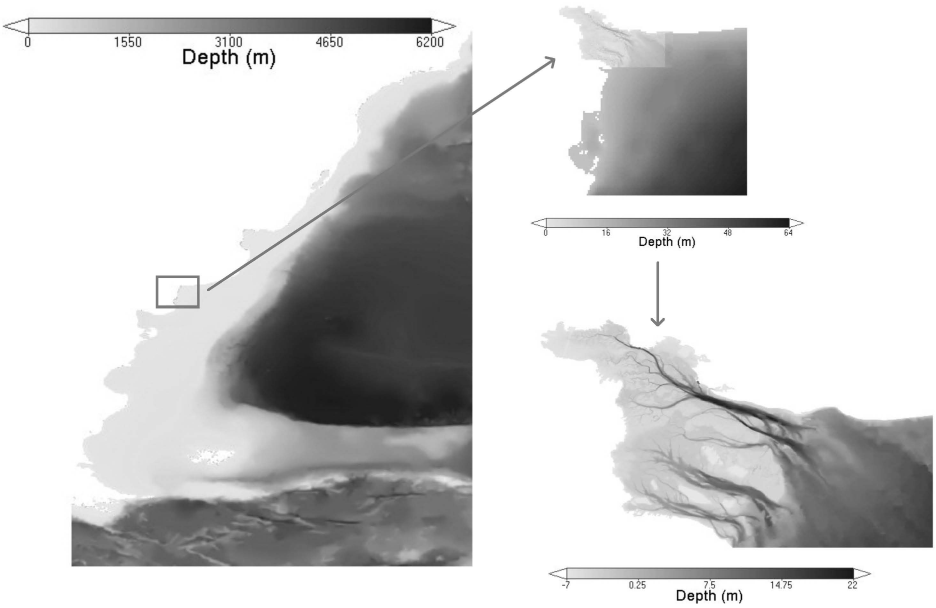

FIGURE 2: *Nested models used for Bahía Blanca Model. On the left is the primary model (Argentina model), on the right above is the secondary model (El Rincon model) and lower right is the tertiary model (Bahía Blanca model).*

TABLE 1: *Monthly mean freshwater flows*

Month	Arroyo Napostá creek (m^3s^{-1})	Río Sauce Chico river (m^3s^{-1})
January	2.25	4.35
February	1.80	4.40
March	2.20	6.50
April	1.85	6.55
May	2.70	6.40
June	3.60	5.15
July	3.60	4.80
August	2.00	4.60
September	2.55	6.80
October	3.60	8.45
November	3.15	6.25
December	2.80	5.30
Average	2.68	5.80

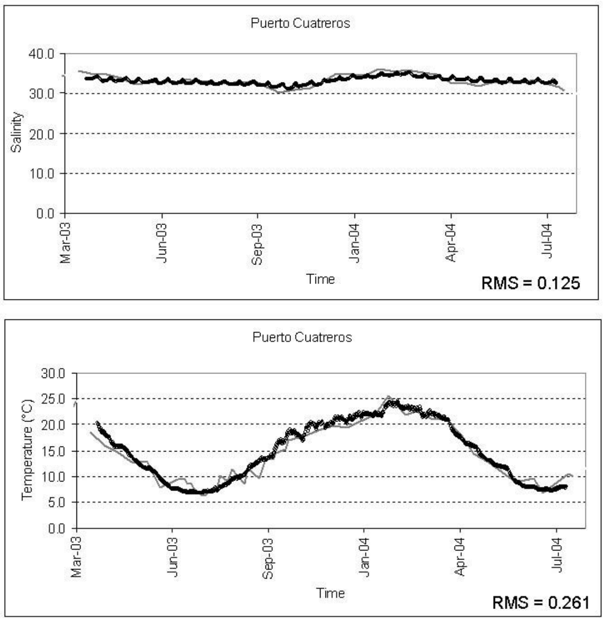

FIGURE 3: *Puerto Cuatreros salinity and temperature representation: observed (grey line) and modelled (circles).*

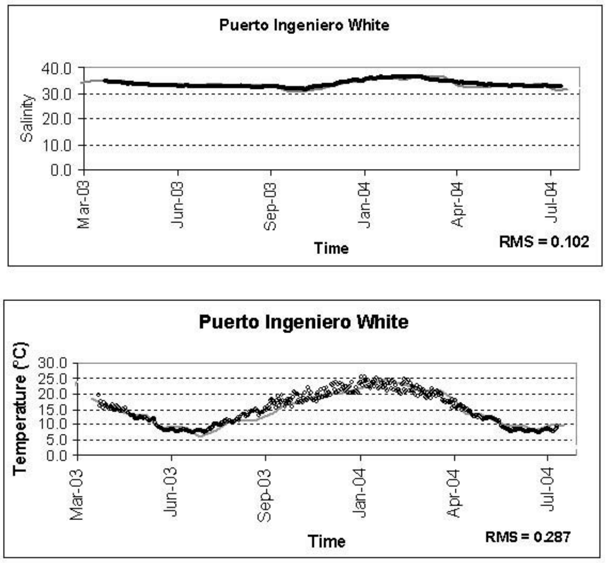

FIGURE 4: *Puerto Ingeniero White salinity and temperature representation: observed (grey line) and modelled (circles)*

REFERENCES

Campuzano FJ, Pierini JO, Leitao P (2008) Hydrodynamics and Sediments in Bahía Blanca Estuary: Data analysis and modelling, this volume.

Chapra S (1997) Surface water-quality modelling McGraw-Hill, New York, pp: 784

Etala P (2000) Modelos hidrodinámicos anidados para el cálculo de la onda de tormenta en el estuario de Bahía Blanca. Tesis Doctoral, Universidad de Buenos Aires, 131pp.

Hsu MH, Kuo AY, Kuo JT, Liu WC (1999) Procedure to calibrate and verify numerical models of estuarine hydrodynamics. Journal of Hydraulic Engineering 166-182

Leitao PC (2003) Integration of Scales and Processes in the marine Environment Modelling. Doctoral thesis, Technical Superior Institute, Lisbon, 2003. (in Portuguese)

Leitão PC, Mateus M, Braunschweig F, Fernandes L, Neves R (2008) Modelling coastal systems: the MOHID Water numerical lab, this volume.

Martins F, Leitao P, Silva A, Neves R (2001) 3D modelling in the Sado estuary using a new generic vertical discretization approach. Oceanologica Acta 24: 1-12

Palma ED (1995) Modelo matemático hidrodinámico de circulación con contorno variable. Desarrollo y aplicaciones. Tesis Doctoral, Universidad Nacional del Sur, 178pp.

Perez DE, Perillo GME (1998) Residual fluxes of mass, salt and suspended sediment through a section of the Bahía Blanca estuary. Geoacta, 23: 51-65

Perillo GME, Piccolo MC, Arango JM, Sequeira ME (1987) Hidrografía y circulación del estuario de Bahía Blanca (Argentina) en condiciones de baja descarga. 2 Congreso Latinoamericano sobre Ciencias del Mar, **II**, 95-104pp.

Perillo GME, Piccolo MC (1991) Tidal response in Bahia Blanca estuary, Argentina. Journal of Coastal Research 7: 437-449

Piccolo MC, Perillo GME (1990) Physical Characteristics of the Bahía Blanca Estuary (Argentine). Estuarine, Coastal and Shelf Science 31: 303-317

Pierini JO (2007) Circulación y transporte en zonas costeras del estuario de Bahía Blanca. Tesis Doctoral, Universidad de Buenos Aires, 225pp.

Provost C, Lyard F, Molines JM, Genco ML, Rabilloud F (1998) A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. Journal of Geophysical Research 103(C3): 5513-5529