International Conference on Estuaries and Coasts
November 9-11, 2003, Hangzhou, China

FINITE VOLUME, VARIABLE DENSITY SHALLOW WATER STUDY OF INTERACTIONS BETWEEN MORPHOLOGY AND SALINE INTRUSION OF THE RIO MAIPO ESTUARY IN CENTRAL CHILE

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Abstract: The Río Maipo discharges into the Pacific Ocean at 33° S, draining a 15,140-km^2 catchment, which includes the entire Metropolitan region of Santiago, Chile's largest city. Both the fluvial and morphological dynamics of the Maipo are of interest, as they have the potential to affect both the water quality within the estuary and the expansion plan for the Port of San Antonio, Chile's largest port. To study the relationship between the fluvial morphology and the saline intrusion, a numerical model based on the finite volume MUSCL-Hancock method was used to solve the 2D equations of motion, with salt transport coupled to the momentum equations via the Boussinesq approximation, which permits the simulation of baroclinic secondary circulation. Field measurements made from the period 2000-03 have provided perspective into the variability of the littoral sandbar that restricts flow at the rivermouth, which grows and decays on both an episodic and seasonal basis. A large winter storm (T_r = 100 years) in June 2002 provoked the complete removal of the littoral bar, resulting in a dramatic change in the saline intrusion dynamics. The results of both field measurements and model simulations confirm the importance of the sandbar in governing the saline intrusion and thus the residence time of river water within the estuary.

Key words: Río Maipo, Littoral sand bar, Well-mixed estuary, Rivermouth dynamics

1. INTRODUCTION AND SITE DESCRIPTION

The objective of this ongoing research project has been to draw conclusions about the fluvial dynamics and morphological variability that govern residence time and water quality within the tidal reach of the Río Maipo in Central Chile. Rapid urbanization within the catchment has brought about dramatic changes in both the hydrology and chemistry of the Maipo and its catchment. The headwaters provide 70% of the water supply to Santiago (Avila et al., 1999), while both industrial and residential wastewater from Copper mining and other anthropogenic activity are all discharged into the Maipo. Concern about trace mineral and particulate organic contamination have fueled several preliminary studies, which indicate the presence of both Cu and As downstream of the urban catchment (Avila et al., 1999, Caro et al., 2000). In order to determine the most relevant factors governing the estuarine circulation, a hydrodynamic model and field measurement have been used in conjunction, each to refine the design of the other, and thus provide focused insight into the dynamics of the estuary and its potential for contamination.

The hydrodynamic model used to simulate the estuary is based on the two-dimensional St. Venant equations. The Boussinesq approximation has been employed to couple salt and momentum conservation. The equations are approximated using the MUSCL-Hancock solution for hyperbolic conservations laws.

Fig. 1 Orthorectified aerial photograph of the Río Maipo estuary in San Antonio Chile

The estuarine portion of the Río Maipo is microtidal, varying just over 1.8 m between spring and neap tide. The mean annual discharge is 90 m^3/s and the surface area of the estuary is 0.768 km^2. The mean depth of flow is estimated at the order of 1-2 m, and the mean bed slope is 0.0013.

The cumulative findings of this project indicate that the estuary is well-mixed vertically and that the formation of the large sand bar at the rivermouth effectively precludes the advective transport of seawater up-estuary which is typically associated with the flood tide. During the period from 2000 thru 2003 observations of the sand bar formation and evolution have established a range for its variations, product of both seasonal changes in discharge and wave activity as well as sporadic storm events. The objective of this paper is to present a narrative summary of the simulations and field measurements to date, and to discuss the implications of what has been observed in the sand bar evolution and the estuarine circulation. These results provide a clear indication of the factors that remain poorly understood and the directions that the research must follow in order to better understand the mixing of fresh and salt water both in and outside the Maipo rivermouth.

2. METHODS

2.1 HYDRODYNAMIC MODEL

The generalized equations of motion are simplified to reflect the flow dynamics in a well-mixed estuary, where variation of salinity through the water column is negligible in comparison with the variability that exists in the longitudinal and lateral directions. The mass, momentum and salt conservation equations are integrated vertically to create a two-dimensional flow model. The Boussinesq approximation is used to couple the salt conservation to the hydrostatic pressure terms in the momentum equations, which permits the simulation of baroclinic circulation. The equations of flow can be written in vector form as,

$$U_t + (F(U))_x + (G(U))_y = H(U), \quad (1)$$

with vectors U, F, G, and H,

$$U=\begin{pmatrix} h \\ uh \\ vh \\ \rho h \end{pmatrix}, F(U)=\begin{pmatrix} uh \\ u^2h+\dfrac{g}{2\rho_o}\rho h^2 \\ uvh \\ \rho uh - hD_x\dfrac{\partial \rho}{\partial x} \end{pmatrix}, G(U)=\begin{pmatrix} vh \\ vuh \\ v^2h+\dfrac{g}{2\rho_o}\rho h^2 \\ \rho vh - hD_y\dfrac{\partial \rho}{\partial y} \end{pmatrix}, H(U)=\begin{pmatrix} 0 \\ -\dfrac{g}{\rho_o}\rho h(z_b)_x - \dfrac{1}{\rho_o}\tau_{bx} \\ -\dfrac{g}{\rho_o}\rho h(z_b)_y - \dfrac{1}{\rho_o}\tau_{by} \\ 0 \end{pmatrix}, \quad (2)$$

The notation $(\,)_{x_i}$ is shorthand for the partial derivative $\partial / \partial x_i$. The variable h represents the height of the water column over the variable bed z_b, while the local depth-averaged velocities along the x and y coordinates of the planar surface are u and v respectively. The local water density is expressed as ρ, and ρ_o is the freshwater reference density. The shear stress, τ_b, is calculated using a zero-order closure relation that employs Manning's coefficient, while the dispersion coefficients, D_x, and D_y are estimated using Elder's relation (Fischer, 1979).

2.2 MUSCL-HANCOCK METHOD

The conservation equations are solved on a finite volume grid of non-orthogonal quadrilaterals using the MUSCL-Hancock technique as described by (Toro, 1997; and Bradford and Katopodes, 1999). The MUSCL-Hancock technique is a 2nd order accurate upwind method, and meets the total variance diminishing (TVD) requirements when employed with a slope-limiting function (Toro, 1997). The solution is advanced iteratively using a predictor-corrector methodology to first solve the primitive form of (1) and later to solve the conservative form, having resolved the interfacial flow between finite volumes via the Riemann Problem. Detailed descriptions of the model are outlined in Loose et al. (2003), Loose and Niño (2003), and Loose (2003).

2.3 FIELD DATA COLLECTION

During the period from January 2001 through March 2003 a series of four field campaigns were conducted at the Río Maipo estuary in order to measure such parameters as the width and depth of the flow sections, terrain slope, and spatial and temporal variation in water density. Here the results of water density measurements are presented from two field campaigns; June 2001 and December 2002. In 2001 water samples were collected in polyethylene flasks and analyzed for conductivity in the Water Quality Laboratory of the Catholic University of Chile using a YSI temperature and conductivity probe. During the 2002 sampling campaign, conductivity and temperature were measured in situ, using a Hydrolabs Minisonde 4a. The conductivity probe was calibrated using a 3-point calibration, spanning the range of potential conductivity values one week prior to the field campaign.

3. RESULTS

3.1 SAND BAR EVOLUTION

The formation of a large littoral sand bar at the rivermouth is the evident product of wave activity along this portion of the coastline. The coast is directly exposed to the dominant (NW) and most frequent (SE) wave regime. Through the use of aerial photography and GPS, the seasonal and episodic evolution of the sand bar has been observed at sporadic intervals during the past 10 years. The first observation, derived from an orthorectified aerial photo taken in 1993 (courtesy of Servicio Aerofotogramétrico de la Fuerza Aérea de Chile) shows that the sand bar restricts flow to the northern most portion of the rivermouth, through a canal of approximately 100 m in width (Fig. 2, panel 1). Concern about the northward migration of the Maipo and its potential encroachment on the shipping Port of San Antonio caused the

Port to fund a bank stabilization project, which has restricted the erosive processes along the northern bank at the rivermouth along the portion indicated in Fig. 1.

Subsequent to the time of the aerial photo a large winter storm in June 2002, estimated as a 100-year return period rain event within the Maipo catchment, caused extreme flooding and morphological change to the region of the Maipo estuary. The most dramatic of these changes was the complete removal of the littoral sand bar at the rivermouth. Following this June 2002 storm, the entire rivermouth was exposed to the ocean, a state that, according to local fishermen, had not occurred since 1983. Observation of the changes that occurred after the sand bar removal included short period water level changes of up to 50 cm resulting from ocean swell propagation into the estuary as well as the presence of larger diameter sand and sediment grains overlying the previous deposits of silt and loam.

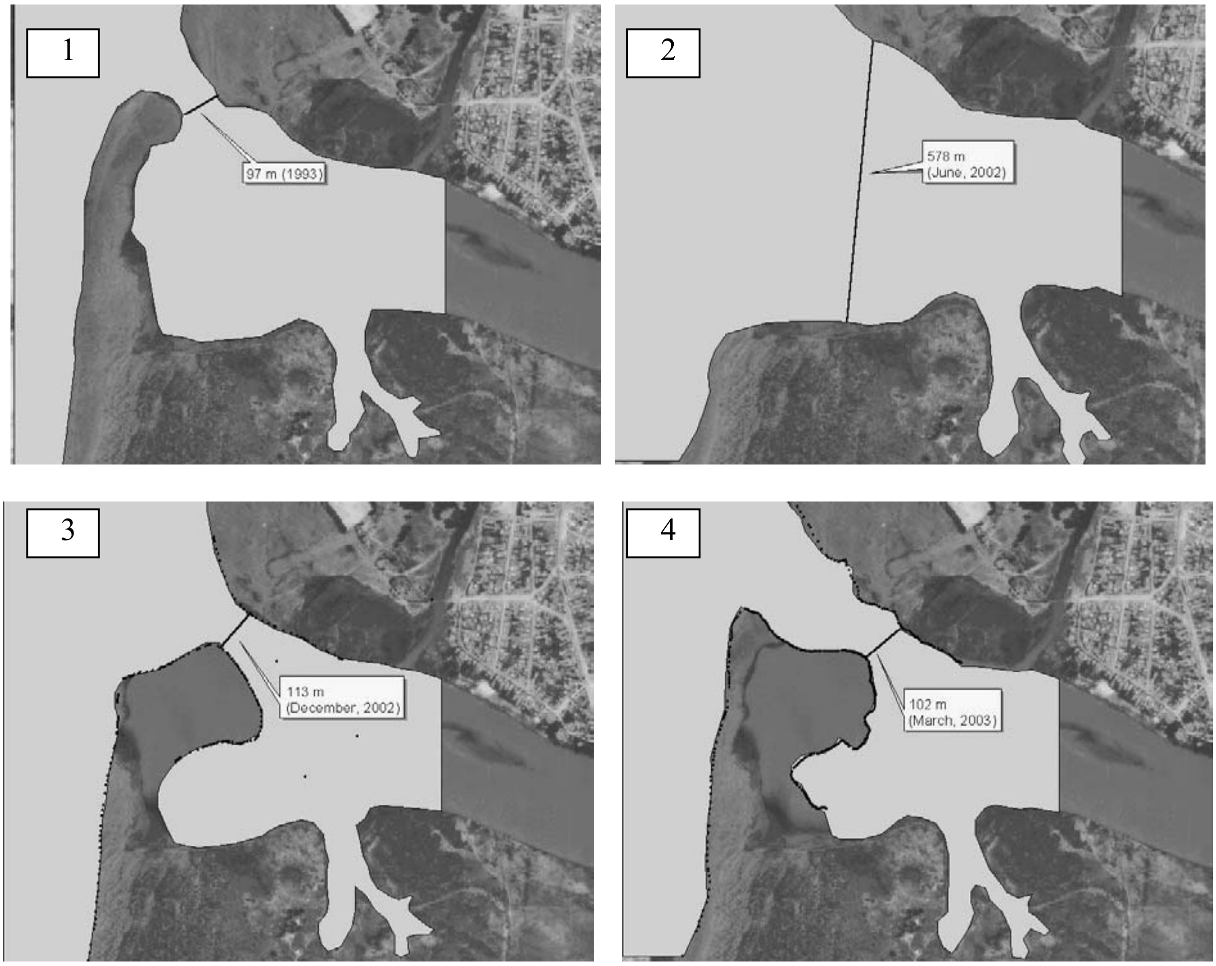

Fig. 2 Evolution of the littoral sand bar at the Río Maipo rivermouth during a decadal period (1993 – 2003)

While the removal of the littoral sand bar was dramatic and complete, the reformation of the bar was rapid. As shown in Figure 2 (panel 3), within 7 months the bar had reformed to occupy almost the entirety of the rivermouth once again. Further, the exit canal reassumed its characteristic width of approximately 100 m (Fig. 2, panels 1, 3 and 4). The change in bar morphology from spring (December) to fall (March), as shown in panels 3 and 4 (Fig. 2) indicates the tendency of the sand bar to respond to changes in the dominant wave direction. While the incident wave direction of greatest frequency is Southeast, the large winter storms which produce the most intense wave activity during June – August have an incident direction of NW to NNW.

3.2 SIMULATION: BAR VS. NO BAR

The observations of variability in the rivermouth morphology gave rise to a series of comparison model simulations. How would saline intrusion dynamics vary given the presence and absence of the littoral sand bar? Hypothetical simulations were conducted with and without the sand bar at the rivermouth under identical discharge and tide conditions. A data set of 4 days was used to force the model for the comparison, corresponding to the 2nd-5th of January 2000. River discharge was provided by the DGA, Public Works Ministry of Chile, while tidal data, recorded 5 km to the north of the rivermouth, within the Port of San Antonio (33.58° S, 71.92° W) was provided by the Hydrologic and Oceanographic Service of the Chilean Navy. The tidal elevation varied from a maximum of 1.5 m to a minimum of 0.4 m during the simulation; while stream discharge decreased from a maximum of 119 m^3/s to a minimum of 39 m^3/s (Fig. 3, bottom panel).

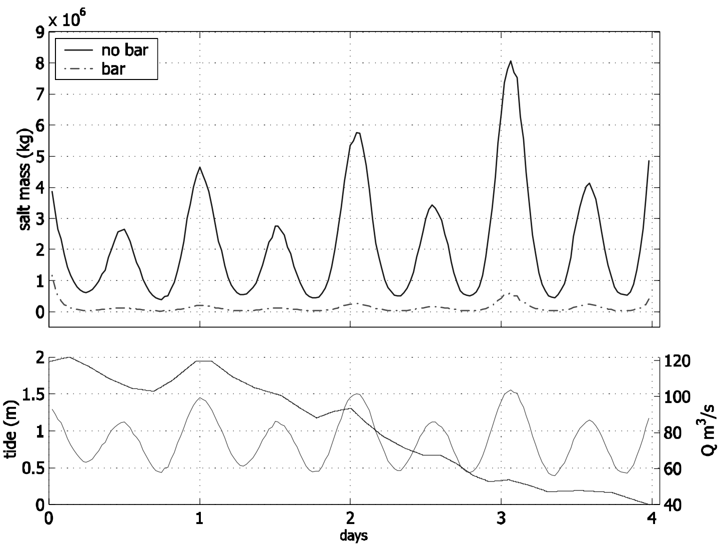

Fig. 3 Time series of salt mass within the Maipo estuary under both presence and absence of the bar at the rivermouth.

To compare the evolution of the saltwater intrusion within the estuary, a time series of the total salt mass in kg was calculated over the 4-day simulation for both the 'bar' and 'no bar' simulations (Fig. 3). While the sand bar was in place, the salt mass within the estuary was found to be less than 5% of the salt mass while the sand bar was removed. "Snapshots" of the density intrusion with the bar (right panel) and without (left panel) are shown in Fig. 4. If the extent of the intrusion is defined by the 1002 kg/m^3 isopycnal, then the intrusion reached a maximum point of approximately 850 m upstream without the bar. In contrast, the intrusion remained contained at the exit canal when the bar was present.

3.3 MEASUREMENTS OF SALINITY

Separate measurements of salinity were made during two field campaigns in an effort to confirm the result of model simulations, namely that the presence of a seawater intrusion is negligible given the presence of the sand bar. A transect of salinity was taken on June 23, 2001. On this date, the littoral bar was present, much like it is depicted in Figure 1. Samples were collected during ebb tide, longitudinally from the rivermouth towards the bridge (Fig. 1). At least two depths were sampled at each location. The results of transect are shown in Fig. 5. Second, a time series of salt concentration was taken at the rivermouth during a 22-hour period on December 6th, 2002, using a Hydrolab Minisonde 4a. Conductivity (mS/cm), temperature (°C) and sensor depth were recorded at 30-second intervals and then filtered to a two-minute interval to reduce noise (Fig. 6).

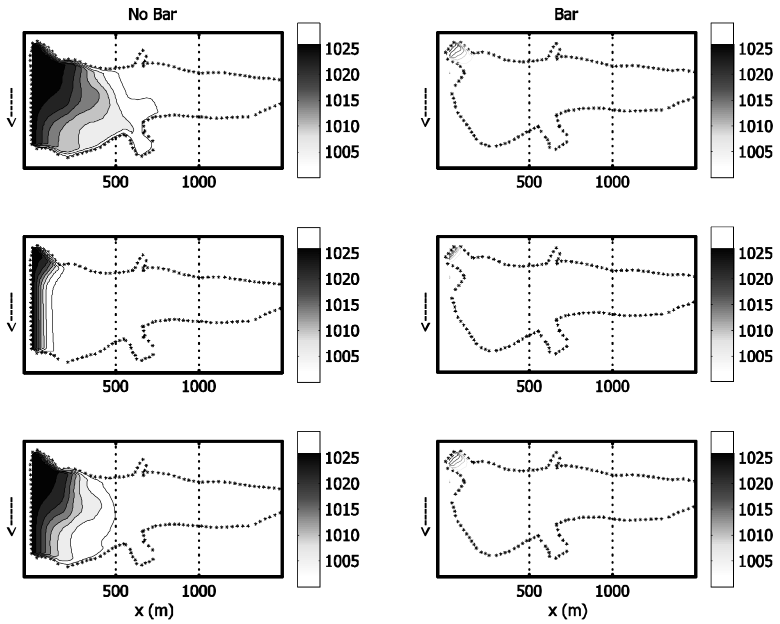

Fig. 4 Simulated density intrusion into the Maipo rivermouth with (left panel) and without bar (right panel); units are in kg m^{-3}.

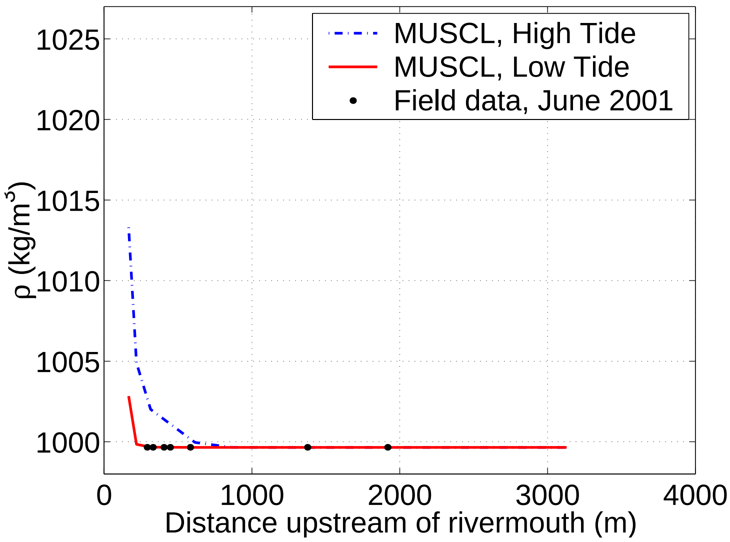

Fig. 5 Comparison of longitudinal water density calculated by model simulations (MUSCL) and by field measurements in June of 2001

The longitudinal distribution of vertical-mean density from the June 2001 sampling is presented in Fig. 5 along with simulated water density during high and low tide conditions. It can be observed that water density was that of freshwater in all sections during ebb tide; both simulations and measurements confirm this result.

In Fig. 6, the time series of water conductivity and temperature are shown in the top panel. The sampling location is indicated in Fig. 1 by a black circle. The bottom panel contains both the time series of density, calculated from conductivity and temperature, as well as the time series of sensor depth as measured by the pressure transducer. The temperature varied from 17.7 to 19.2 °C during sampling period; temperature peaked just after midnight on December 7th. This is likely an effect of diurnal heating of river water in the catchment. Water density (Fig. 5, bottom panel) varied from 998.7 to 999.1 kg/m^3; the factor most affecting the variability in water density were the changes in water temperature that occurred during the day. Water density was that of fresh water.

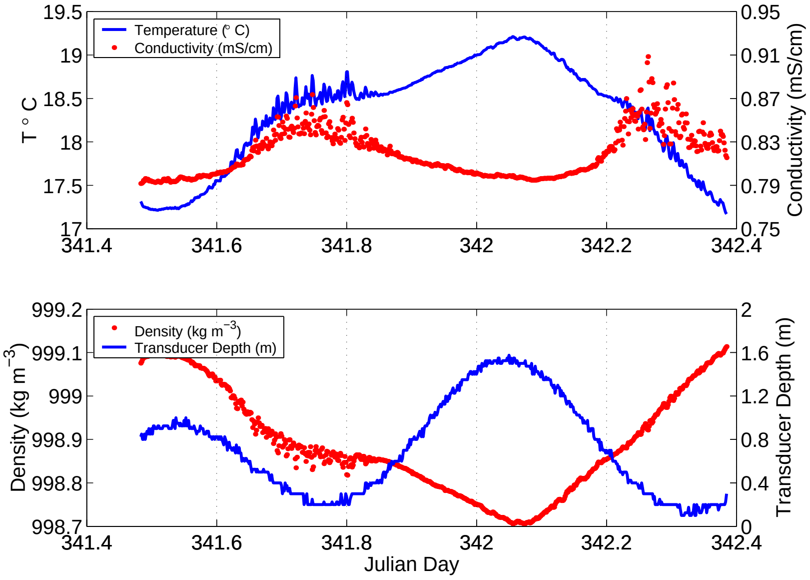

Fig. 6 Conductivity (mS/cm) and temperature (°C) measured for a 22 –hour period at the rivermouth and used to calculate density (bottom panel)

4. DISCUSSION

During the course of a 10-year period the Río Maipo estuary has experienced regular variations in the size and shape of the littoral sand bar that restricts the rivermouth. Successive field measurements and model simulations indicate definitively that the presence of the sand bar entirely precludes seawater advection up-estuary. As shown by the model simulations, the presence of the sand bar reduced salt mass in the estuary by 95 % as compared with the same conditions and the rivermouth entirely open to the ocean. Further, despite both episodic and seasonal variations in the sand bar morphology there exists a tendency for the bar to quickly reassume a characteristic shape, most easily distinguished by the width of the exit canal (~100 m in all observed cases, Fig. 2). This would indicate that the sand bar represents something of an equilibrium state between the competing fluvial and coastal processes.

The enduring presence of the littoral sand bar and its effect on seawater intrusion has potentially positive consequences for the water quality of the estuarine reach of the Maipo. The lack of both seawater and a current reversal inside the rivermouth implies that the residence time of river water within the estuary is likely to be considerably less than the typical residence time in an estuary where these two factors exist. The effect of tidal currents and density gradients induced by seawater intrusion can result in a myriad of circulation processes, which both prolong the residence time of river water and permit the sequestration of contaminants through settling, adsorption, and other physico-chemical interactions (Stumm and Morgan, 1996).

While this implication is positive for the Maipo estuary ecosystem it is potentially negative for the coastal ecosystem as those contaminants that exit the estuary pass into the littoral zone. Furthermore, this also implies that the mixing of fresh and salt water occurs just outside the rivermouth and along the surf zone. Mixing and transport of river water within the littoral zone is predominantly an effect of longshore and cross-shore coastal currents, the efficiency of which governs the residence time of river water outside the rivermouth. To further refine simulations of the river water mixing and dilution, an investigation into the longshore and cross-shore transport is necessary. An understanding of these factors would improve understanding of the fate of terrestrial contaminants as well as a refinement of the boundary conditions that govern mixing within the estuary. This is the subject of ongoing research.

ACKNOWLEDGEMENTS

Funding for this research was provided by FONDECYT Project 1010483. The authors would like to thank both the Servicio Hidrográfico y Oceanográfico de la Armada and the Dirección General de Aguas of the Chilean government for their generous donations of data.

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