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Forecast System Implementation in the Paraná Delta

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Abstract

The hydrodynamics of the Paraná Delta is highly conditioned by the interaction of the Paraná River discharge and the tidal regime of the Río de la Plata estuary. In 2020 and 2021, the Paraná River observed one of its most significant low-flow periods in its historical record. The observed low-flows are having a significant impact on water intakes and the navigability of the waterway.

A forecasting system has been implemented to predict water levels in different cross sections at two different lead times, i.e., 4 and 15 days, corresponding to different meteorological tide inputs. The 4-day forecast model performance was assessed between 12/08/2021 and 25/1/2022 by means of the following metrics: mean absolute error (MAE), standard error (SE), and Pearson correlation coefficient (PCC), computed on modeled and observed series. The evaluation of these forecasts during 5 months show that its performance is satisfactory. The comparison between the time series of observed and simulated water levels shows that there is a good representation of the main trends, not only in time of happening but also in the magnitude of the events.

This tool has had a significant impact among users in the region in terms of its outreach, as shown by the large number of website visits to the published forecasts.

Keywords: Paraná; Hydrologic Forecast; Hydrodynamics

1. INTRODUCTION

The mouth of the Paraná River in the Río de la Plata occurs through a wide delta, caused by the deposition of sediments from its upper basin, whose current approximate width is around 50 km (Sarubbi, 2007). The Parana River Delta, with an area of approximately 17,500 square kilometers, begins at the cross section near the city of Diamante (Entre Ríos Province) and extends to its mouth in the Río de la Plata. It is crisscrossed by a complex system of canals and rivers.

The hydrodynamics of the Delta is extremely complex. It is conditioned by the discharges of the Paraná River and to a lesser extent those of the Uruguay River, generated by the rainfall in its wide basins, and by the variations in levels in the front of the Delta, a consequence of the effect of the astronomical and meteorological tides that affect the Río de la Plata estuary (Re, 2003).

Given the singular geomorphology of the Paraná River Delta, its floods are driven both by an increased river discharge from upstream or the occurrence of positive storm surges during low-flow periods. Floods are critical not only for the local population and the ecosystems present in the Delta, but also for the many stakeholders linked to its intricate commercial and productive circuits (Morale, 2018).

Some of the most important cities of the country are located on the outer banks of the Delta. Due to their number of inhabitants, the cities that stand out are Rosario (1,320,000 inhabitants), Santa Fe (391,231), Paraná (247,863), San Nicolas (133,602), Zarate (98,522) and Campana (86,860) (Figure 1).

There has been rapid urban growth for some years now, moving from existing urban areas to the floodplain, mainly due to large real estate developments in the Lower Delta section, belonging to the district of Tigre (Buenos Aires province). There are also some undertakings in other sectors such as the area adjacent to the city of Victoria (Entre Ríos province), in the Middle Delta, and the riverside sector that borders the Delta in the districts of Tigre, Escobar, Campana and San Fernando (Buenos Aires province) (Quintana, 2010).

In the Delta, due to the abundance of freshwater and many other natural resources, different productive activities are developed. In the Lower Delta, the main productive activity is forestry, with willow and poplar species that are mainly required by the pulp and paper industry. Recreational uses (tourism and nautical sports) also stand out in this sector. In the Middle and Upper Delta, on the other hand, large-scale livestock farming is one of the most important productive activities. Other traditional productive activities are beekeeping and fishing, which are carried out throughout the whole region.

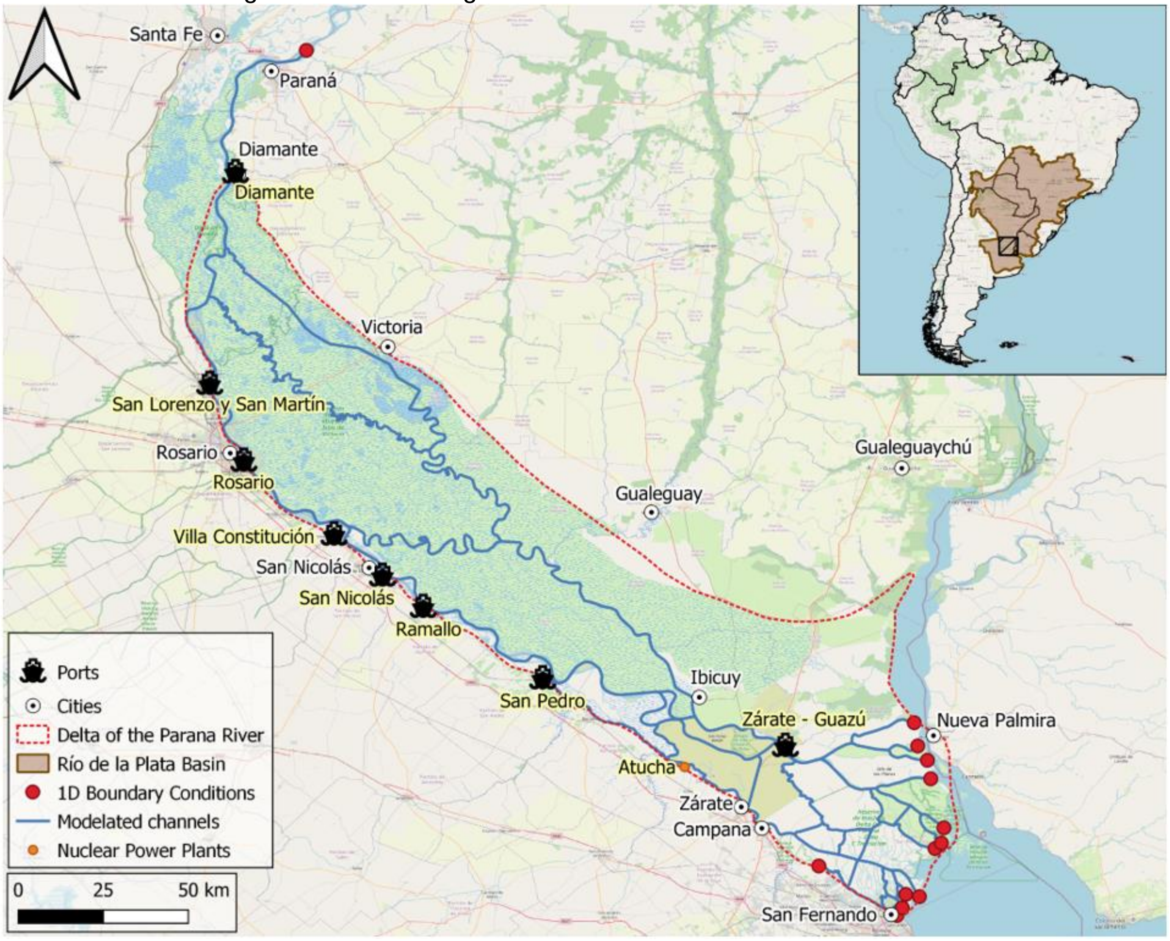

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Figure 1. Map of the Paraná River Delta area showing most important cities and ports, modeled channels and 1D boundary conditions.

The region of the Paraná River Delta is traversed by the main strategic commercial waterway for Argentina and neighboring countries. The waterway "Hidrovía Paraná-Paraguay" is one of the world's longest inland waterway (1,635 km) connecting 5 countries: Bolivia, Brazil, Paraguay, Argentina and Uruguay. Its dredged canal, which traverses the Río de la Plata, Paraná de las Palmas, and part of the Paraná rivers, allows the entrance of seagoing vessels, which carry approximately 80% of national exports and 95% of national imports according to the Ministry of Transportation. Several large ports, which have an important participation in international commercial activity, are in the Delta region. Some of them are: Zárate Guazú, San Pedro, Ramallo, San Nicolás, Villa Constitución, Rosario, San Lorenzo y San Martín, Diamante and Santa Fé. (Figure 1).

Since 1999, the dry years on record have been characterized by persistently low river levels. (Borús, 2015). In 2020 and 2021, the Paraná River observed one of its most significant low-flow periods in its historical record and the most extreme after the river became regulated due to the construction of numerous dams in the upper Paraná basin (starting in 1975). The current situation (2022) is no better and an aggravation is likely to occur (Figure 3).

The observed low flows in the Paraná river are having a significant impact on water intakes (for domestic, agricultural and industrial uses including the cooling of power plants) and the navigability of the waterway, since it makes navigation difficult and reduces operational drafts, preventing deep-draft ships from accessing ports.

In this context, an integrated modeling and forecasting framework was designed and developed, taking into account the interactions of river discharge, storm surges, waves and tides. The system is based on a one-dimensional hydrodynamic model of the Paraná Delta, a bi-dimensional model of the Río de la Plata estuary, two numerical weather prediction (NWP) models and autoregressive model schemes to further correct forecasts with observed data.

The three mentioned models were previously developed and published. This work focuses on the adaptation, automation and evaluation of the system to make forecasts in the Paraná Delta region. As a result, a forecasting system has been implemented to forecast water levels in different cross sections at two different lead times, i.e., 4 and 15 days. The outputs are issued and updated every 6 hours and made interoperably accessible via a web API.

This work is part of the project DELTA PARANA: Integrative Hydrodynamic Study of the Paraná River Delta with Multiple Purposes (https://www.ina.gob.ar/delta).

2. STUDY AREA AND MODEL DESCRIPTION

The study area is presented in Figure 2. The model framework is divided into two parts: a one-dimensional hydrodynamic model of the Paraná Delta: HIDRO-DELTA and two different bi-dimensional models of the Río de la Plata estuary: SMARA (4 days lead times) and HIDRO-RdlP (15 days lead times).

The HIDRO-DELTA and HIDRO-RdlP models were developed by the Computational Hydraulics Program (PHC) of the National Water Institute (INA), of Argentina. The first version of the HIDRO-DELTA model was published in 2014 (Sabarots Gerbec, 2014) and has been upgraded three times until today. The HIDRO-RdlP model was recently developed (Cortese, 2021) and its implementation as a forecast too is in the testing stage.

The SMARA is a set of nested storm-surge models developed by the National Meteorological Service (SMN) of Argentina and published in 2009 (Etala, 2009; Etala, 2009). The implementation in the interest area is presented in Section 3.

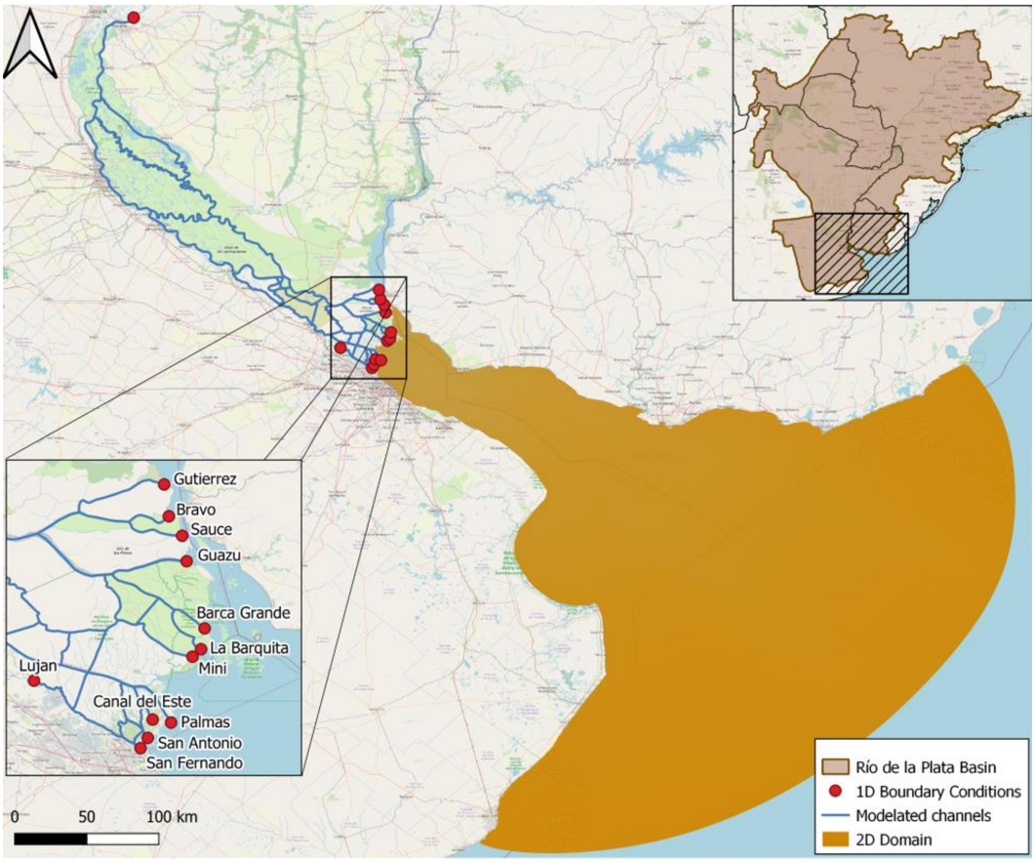

Figure 2. Map of the study area, showing the domain of the models and location of the boundary conditions.

2.1 Estuary

The Rio de la Plata is a very broad and shallow estuary, formed by the confluence of the rivers Parana and Uruguay. The main drivers of the dynamics of the Río de la Plata are the tidal wave that enters from the ocean, the discharge hydrographs of the tributaries that flow from the upper reaches of the river, and the winds that act on the entire water surface (Re, 2003).

The tides in the area are mainly semidiurnal (the M2 constituent has an amplitude of 0.27 m at Buenos Aires). However, there are significant diurnal inequalities, mostly caused by O1 (amplitude 0.15 m). The amplitude of the astronomical tide is about 1.44 m at the mouth, but in the upper reaches it decreases to 0.40 m (D'Onofrio et al., 2009).

For the forecast of levels in the Delta front, two different models were used. The first one (SMARA) has been used since October 1, 2020. The second one (HIDRO-RdlP) was developed and implemented during the year 2021 and is subject to improvements. The following subsections describe the models used, their domains and forcing. For more information, referenced publications can be consulted.

SMARA: 4-day lead time. (Etala, 2009; Etala, 2009)

Tides and storm surges in the sea shelf and estuaries are simulated by bi-dimensional models, based on the depth-averaged hydrodynamic equations. The sea shelf is represented at a spatial resolution of 1/3º lat. x 1/3º lon. Tidal harmonic constants at the open boundaries are interpolated from global models (Carrere, 2015). A higher resolution model for the Rıo de la Plata is nested at 1/20º lat. x 1/20º lon. resolution. The tidal constants at the open boundary are interpolated from the Naval Hydrographic Service (SHN) of Argentina harmonic analyses for two stations located on both shores at the mouth, by following a Kelvin wave shape along the boundary.

The Center for Storm Surge Prevention of the Rıo de la Plata at the Naval Hydrography Service (SHN) receives real-time water level data from tide gauges along the Rıo de la Plata south-western coast and the Atlantic coast. This information, in conjunction with forecasted winds, provides the input to an empirical model.

Ocean wave hindcasts are driven by the National Centers for Environmental Prediction (NCEP) global 10-m wind fields acquired four times daily. The NCEP's T382 gaussian grid is considered as a 0.313º x 0.312º regular grid. The shelf and RP 96-h wave and surge forecasts are driven twice daily by the 10-m wind and SLP fields from the mesoscale Eta model at the National Weather Service (SMN) at a 1/3º lat./lon. resolution.

HIDRO-RdlP: 15-day lead time (Cortese, 2021)

The hydrodynamic model for De La Plata River has been developed using the modeling suite Delft3D, by Deltares (version 1.4.6). A curvilinear orthogonal grid has been used for the model to adjust the spatial resolution over the domain (Figure 2), which covers from the Parana Delta Front in the north to a concave curve over the South Atlantic Ocean that connects Mar del Plata city with Cabo Polonio on the Argentina and Uruguay shores, respectively. On the north side of the model, the narrowest section of the river, the spatial resolution is almost 200 m, while on the south border it is about 1 km.

Regarding the boundary conditions, the following time series were used over every open boundary: along the Delta Front, fluvial discharges are imposed for the tributaries of the Paraná River. Along the South border the boundary condition consists of a time series of water levels, defined by the astronomical components (obtained from the global model FES2014); The points on which the boundaries have been imposed were defined by discretizing the border in seventeen 40-km long sections.

To train the model, simulations considering both tides, astronomical and meteorological, were made, using for the atmospheric input wind and surface pressure provided by the Reanalysis model, by NCEP, with a time step of an hour and a spatial discretization equal to 0.25°x0.25°.

2.2 Paraná

The catchment area of the Parana river is 3,100,000 km^2 and covers large parts of five countries (Argentina, Paraguay, Brazil, Bolivia and Uruguay) (Figure 2). Its average discharge is 18,000m^3/s, and throughout its history, floods of 60000 m^3/s and low-flow of 8000 m^3/s have been recorded.

As the upper boundary condition for the one-dimensional models the observed daily mean flow rates in the Paraná-Santa Fe cross section was used. A regression analysis on that variable was performed in order to obtain predicted values for the forecast lead time. The values at each 1-day step of the forecast horizon (t+1, t+2, ... t+n days) were regressed against the observations at t, t-1, t-2, … t-(m-1) days at the same site and at an upstream cross section (Corrientes), giving a total of n linear models with 1+2*m parameters each. The calibration period was 1985-02 to 2010-01 and the validation period was 2010-10 to 2022-01. With a forecast lead time of n=15 and a looking-back period of m=20 a total of 15*(1+2*20) = 615 parameters were obtained using the method of ordinary least squares.

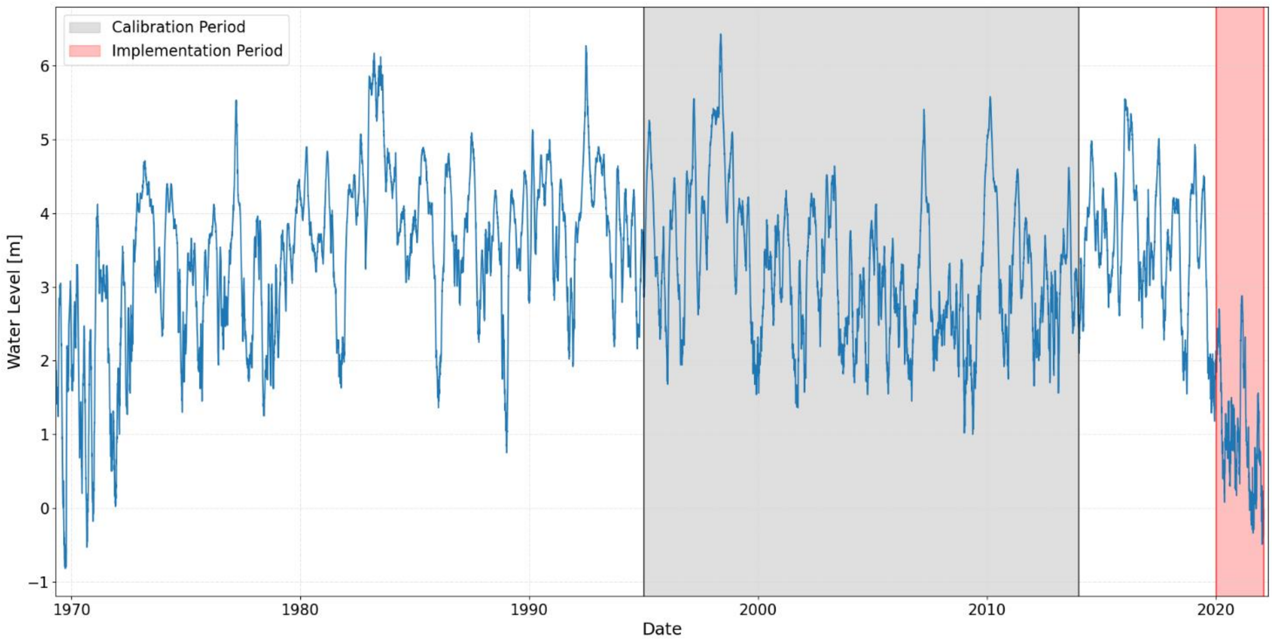

Figure 3. Historical water level observations in Rosario city (1975 break and 2020-2021 low-flow).

2.3 Delta

A one-dimensional model was implemented for the hydrodynamic modeling of the Paraná River Delta; it arises from a geometric update presented by Re et al. (2015). It was originally based on the one proposed by Sabarots Gerbec (2014), which includes the Upper Delta and the Middle Delta. The incorporation of the Lower Delta was taken from the representation of Bombardelli et al. (1994). Details of the geometric implementation can be found in Bombardelli et al. (1994) and Sabarots Gerbec (2014). In addition, the model was used to generate level statistics in the Paraná River Delta (Re et al., 2015) and for the characterization of minimum levels in the waterway (Borus et al., 2015)

This model solves the one-dimensional hydrodynamics of the Paraná, Victoria, Paraná Pavón, Paraná Ibicuy, Paraná de las Palmas, Paraná Guazú, Pasaje Talavera, Barca Grande, Paraná Mini, Sauce, Bravo and Carabelas Grande rivers, and the Gobernador de la Serna, Gobernador Arana, Irigoyen, Laurentino Comas, 4, Seoane and Zanja Mercadal channels. Figure 1 presents the modeled domain.

The software used was HEC-RAS (Hydrologic Engineering Center - River Analysis System). The temporal discretization of the model is t = 30 min and the spatial one is x = 5000 m.

Regarding the forcing of the system, the model has 13 boundaries conditions. One in Paraná (Entre Ríos), one in Luján (Buenos Aires) and 11 distributed on the front of the Delta between San Fernando (Buenos Aires) and Nueva Palmira (Uruguay) (Figure 2).

A time series of flow rates was provided at the upstream boundary node in Paraná. A reliable rating curve is available for the Paraná-Santa Fe cross section, which transforms the water stages observed in the Paraná hydrometric station. The total discharge of this cross-section results from the sum of the discharges of the main stream channel (Underwater Tunnel), the Colastiné river and the Leyes-Setúbal system. The validation of these discharge values was made by comparing them with the discharge of the Chapetón cross section (Re et al., 2015; Borus et al., 2015).

Unlike previous versions, the current model does not take a single time series of water levels for the entire Delta front. Taking advantage of the fact that hourly data is available in quasi real time in San Fernando (Argentina) and Nueva Palmira (Uruguay), a linear interpolation of the water level is performed between these two points (Figure 1). In this way, each of the eleven boundary conditions in the front has its own series of water levels.

3. INTEGRATED SYSTEM

The Hydrological Information and Warning Systems Division (SIyAH) of the National Water Institute (INA) receives real-time data from water-level gauges along the Rıo de la Plata and Paraná rivers. Also, wind forecasts are downloaded and stored in the INA database (DB). This information provides the input to the models.

Figure 4 shows a flow chart of the HIDRO-DELTA integrated structure. The workflow was implemented using an open-source programming language and may be scheduled for automatic execution. First, it downloads the input data from the DB and transforms it into required formats. Then, the models of the Río de la Plata estuary are run. These models give downstream boundary conditions to the one-dimensional Delta model which is subsequently run to provide forecasts at two different lead times, 4 and 15 days. Finally, the output data from the models is saved to the database for later use as input data for other models or to create graphics for the website.

The astronomical tide heights, past and future, were provided by the Naval Hydrography Service (SHN) in the eleven boundary nodes in the Delta front. The tide and storm wave model of the Naval Hydrography Service (SMARA) provides the correction to the astronomical tide height due to meteorological effects. It is updated every 6 hours and its output is stored in the DB. Combining the astronomical tide height and the correction to this height due to meteorological effects, the hydrometric level is obtained.

For the HIDRO-RdlP model, the discharge series are downloaded from the DB, while the wind fields are taken from the Global Ensemble Forecast System (GEFS), provided by the National Centers for Environmental Information (USA). Once all the recently downloaded data is transformed into the Delft3D required format, a simulation is carried out. As the time needed for the model to reach dynamic equilibrium on each run is not an issue, initial conditions are taken from the last simulation instead of simulating a warm-up time window. The system allows running up to 15 days ahead with a maximum refresh interval of 6 hours (this is limited by the wind forecast update frequency).

The one-dimensional model simulation period goes from 60 days before the execution date (current date) to 4 or 15 days ahead, depending on which model the forecast data is taken from: SMARA or HIDRO-RdlP respectively.

Before using the simulated series generated by bi-dimensional models in the estuary as input to the one-dimensional model, a correction is made, both in San Fernando and Nueva Palmira. This correction aims to improve the match between the data observed in the Delta front and the data predicted by the bi-dimensional models. Once again, the quasi-real-time hourly data available in the database is used. In this case, the relationship between the simulated astronomical and meteorological tides (independent variables) and the observed water level (dependent variable) is estimated through a multiple linear regression. This correction is updated in each run, taking the last 60 days of observed data and the forecasts generated during these days.

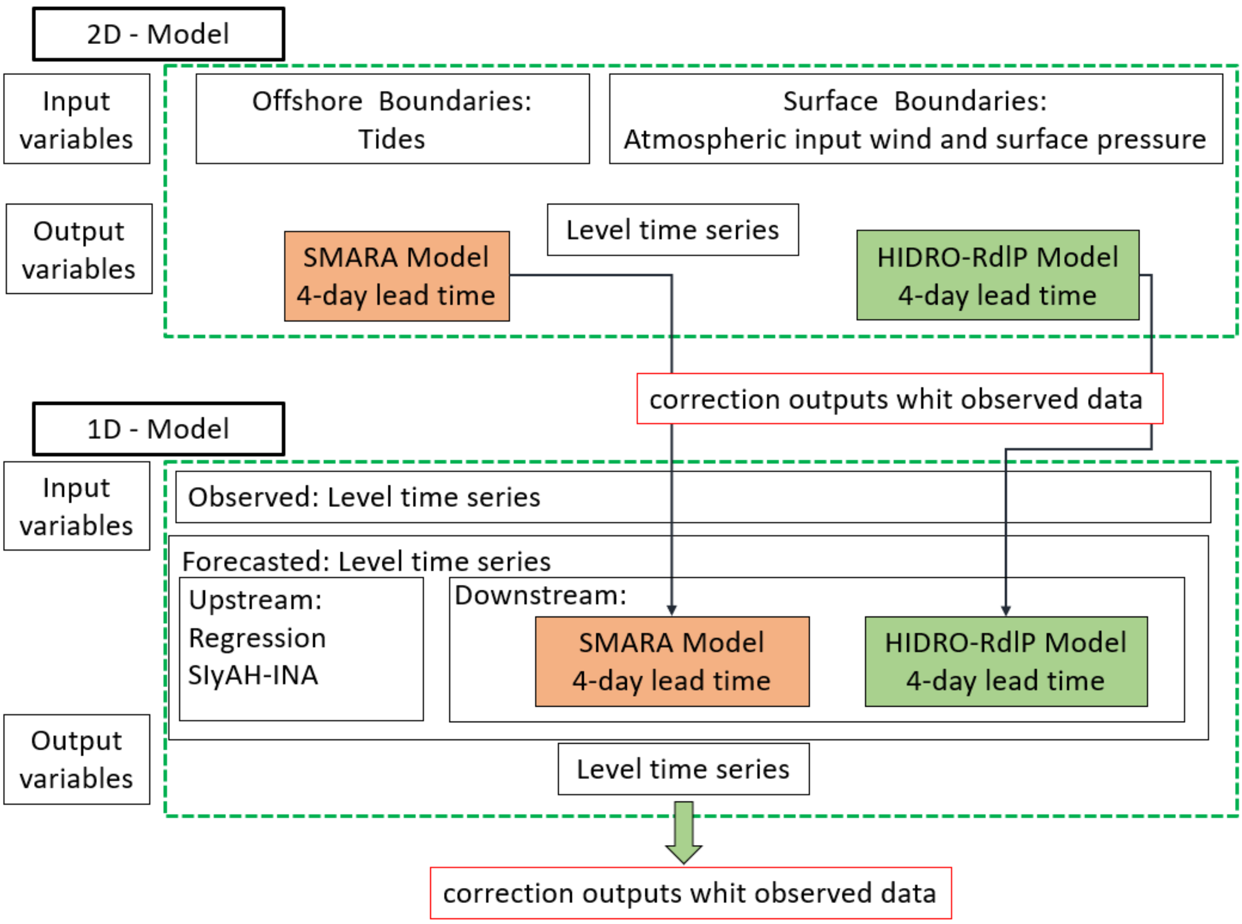

Figure 4. Flow chart of the HIDRO-DELTA integrated structure.

The one-dimensional model was calibrated for the period 1995-2014. This time period encompasses varied hydrological conditions and allows a good adjustment for high, medium and low flows (Sabarots Gerbec et al., 2016). However, the discharge values observed during the years 2020 and 2021 are considerably lower than those observed during the calibration period. In Figure 3, the levels in Rosario during the two time periods, calibration and current situation, can be observed. Given this extraordinary condition of low levels, the model outputs register a systematic error. To improve the outputs, a correction is applied, using a methodology similar to that used for the input data. It is based on a linear regression that is updated on each run, taking the last 60 days of observed data and the output generated during these days.

HIDRO-DELTA is currently running 4-day forecast every 6 hours, with computation time of 2 min on a single processor. The results are issued and made available interoperably via a web API. The programming language version used was Python 3.7. In addition, different Python libraries are used, such as: requests to make queries to the INA DB through the web API, SQLite3 to organize model input and output information in a local relational database, Pandas and Numpy for data manipulation and Matplolib and Seaborn to make plots.

4. RESULTS

The hindcast evaluation for water level was assessed by means of the following metrics: mean absolute error (MAE), standard error (SE), and Pearson correlation coefficient (PCC), computed on modeled and observed water levels series at five hydrometric stations within the Delta region: San Fernando, Nueva Palmira, Atucha, Zarate and Rosario (Figure 1).

The statistical scores computed between 12/08/2021 and 25/1/2022 for the 4-day forecast are summarized in Table 1. Figure 5 shows the comparison of the measured and calculated water levels during one week in San Fernando and Figure 6 the comparison during 21 days in Atucha.

Table 1. Statistical scores computed for the water level hindcast at several stations and lead times

lead time (days)	1			2			3			4		
Indicators:	MAE	SE	PCC	MAE	SE	PCC	MAE	SE	PCC	MAE	SE	PCC
San Fernando	0.00	0.21	0.91	0.00	0.23	0.89	0.00	0.26	0.86	-0.01	0.29	0.82
Nueva Palmira	0.02	0.15	0.92	0.03	0.15	0.92	0.03	0.17	0.90	0.02	0.19	0.87
Atucha	0.01	0.17	0.92	0.01	0.18	0.92	0.00	0.19	0.91	-0.04	0.19	0.90
Zarate	0.02	0.19	0.92	0.02	0.21	0.91	0.01	0.21	0.91	-0.05	0.22	0.89
Rosario	0.00	0.08	0.99	0.00	0.09	0.99	0.02	0.10	0.98	0.04	0.11	0.98

4-day forecast: for all lead times, an unbiased MAE was obtained. SEs of 0.21m for the 1-day lead time, gradually increasing to 0.29m for the 4-day lead time. It is observed that SE decreases upstream of the Parana river. Decreasing from 0.21 m in San Fernando to 0.08 m in Rosario for 1-day lead time. And from 0.29 m to 0.11 m for 4-day lead time. Likewise, PCCs of 0.91 at 1-day lead time, decreasing to 0.82 at 4-day lead time were attained in San Fernando.

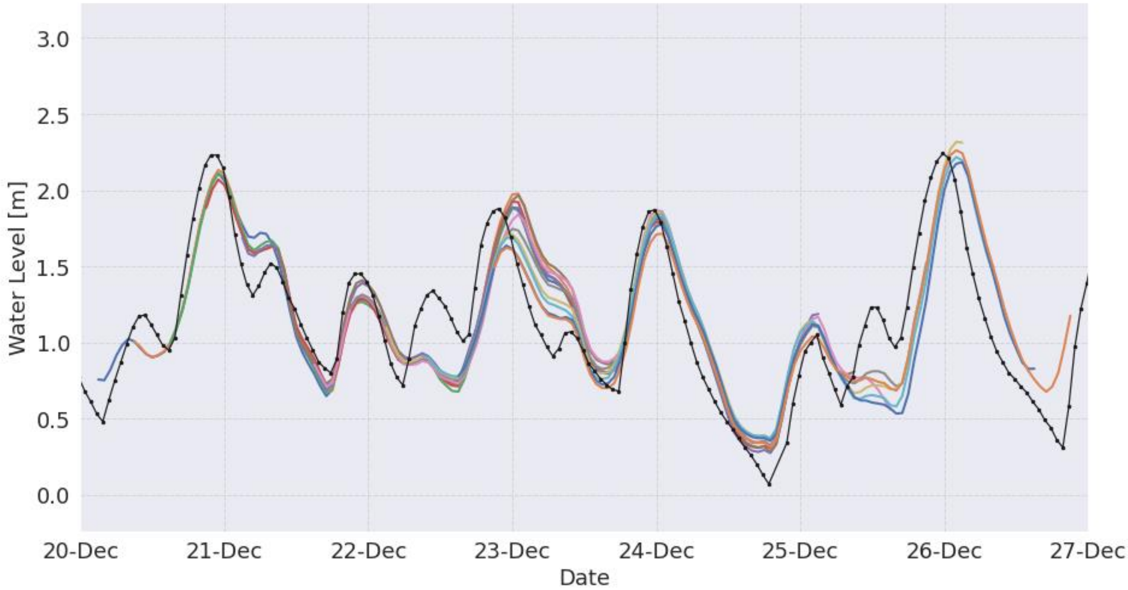

Figure 5. Shows the observed water level (black dots) and the forecasts (color lines) generated during a week for the San Fernando station.

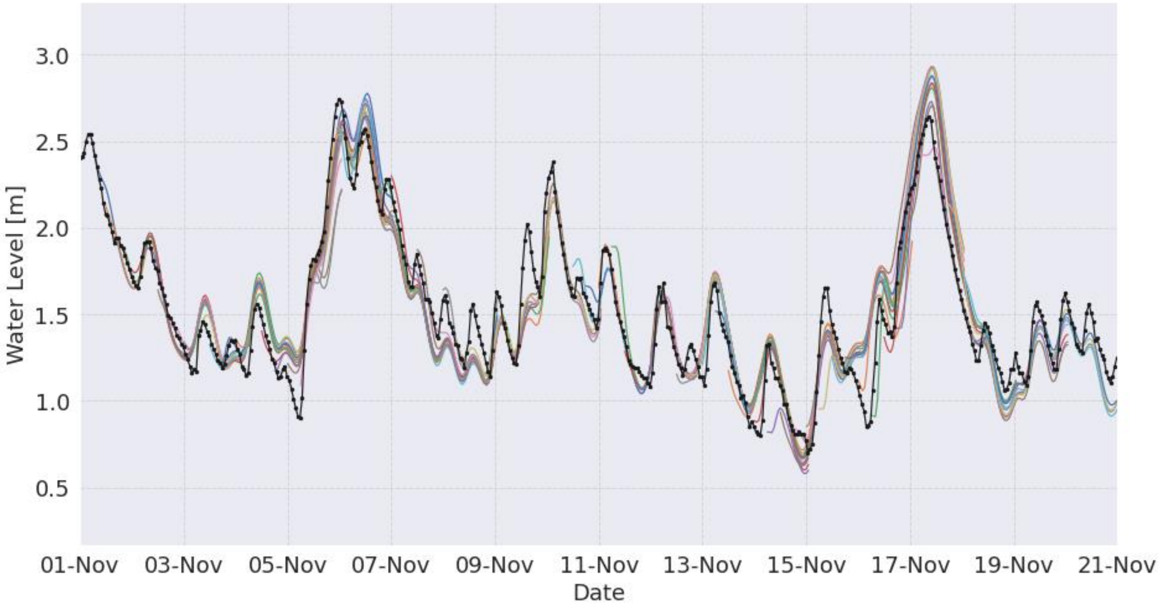

Figure 6. Shows the observed water level (black dots) and the forecasts (color lines) generated during 21 days for Atucha.

The hindcast evaluation for the 15-day forecast was assessed during the month of January 2022. In the case of the 15-day forecast model, the performance proved lower. The same performance metrics were calculated showing that the MAE was also unbiased. In San Fernando SEs go from 0.35m to 0.88m for 1 to 15 days of lead time, respectively, and the PCCs, from 0.73 to 0.22. As for the4-day forecast, it is observed that all the metrics improve upstream.

5. SYSTEM IMPACT

This tool has had a significant impact among users in the region in terms of its outreach, as shown by the large number of website visits to the published forecasts. Since it was first published on the INA website, a record of visits has been kept (Figure 7-b). During the first 8 months (brown in Figure 7-b), only the forecast for San Fernando was generated. Although it was public on the INA page, it was only distributed to a limited group of stakeholders. During this time, an average of 175 visits per week were recorded.

In the month of July 2021 (light blue in Figure 7-b), the forecast is extended to different locations in the Delta region: Rosario, Villa Constitución, San Nicolás, Lima (Atucha on the map), Zárate, Campana, Escobar and Nueva Palmira. Figure 7 shows how the number of visits increases. It went from 175 to 920 weekly visits. It also matches with low water levels due to severe drought conditions in the upper basin (Figure 7-c).

The figure shows a correlation between the demand for information and the intensity of extreme events (circled on the graph). In particular, during the month of January 2022 (green in Figure 7-b), a series of southeasterly events were forecast, one reaching 3.5 meters (Evacuation Level) in San Fernando. During this week a peak of 2600 visits was reached.

Although the number of visits to the website is known, there is uncertainty in the actual number of stakeholders that make use of this forecast system. It is estimated that the amplification factor is, at least, 3 to 4 times the web-access counts. This information dissemination takes place by less formal, yet effective, communication ways, as WhatsApp groups administered by other government agencies or decision makers.

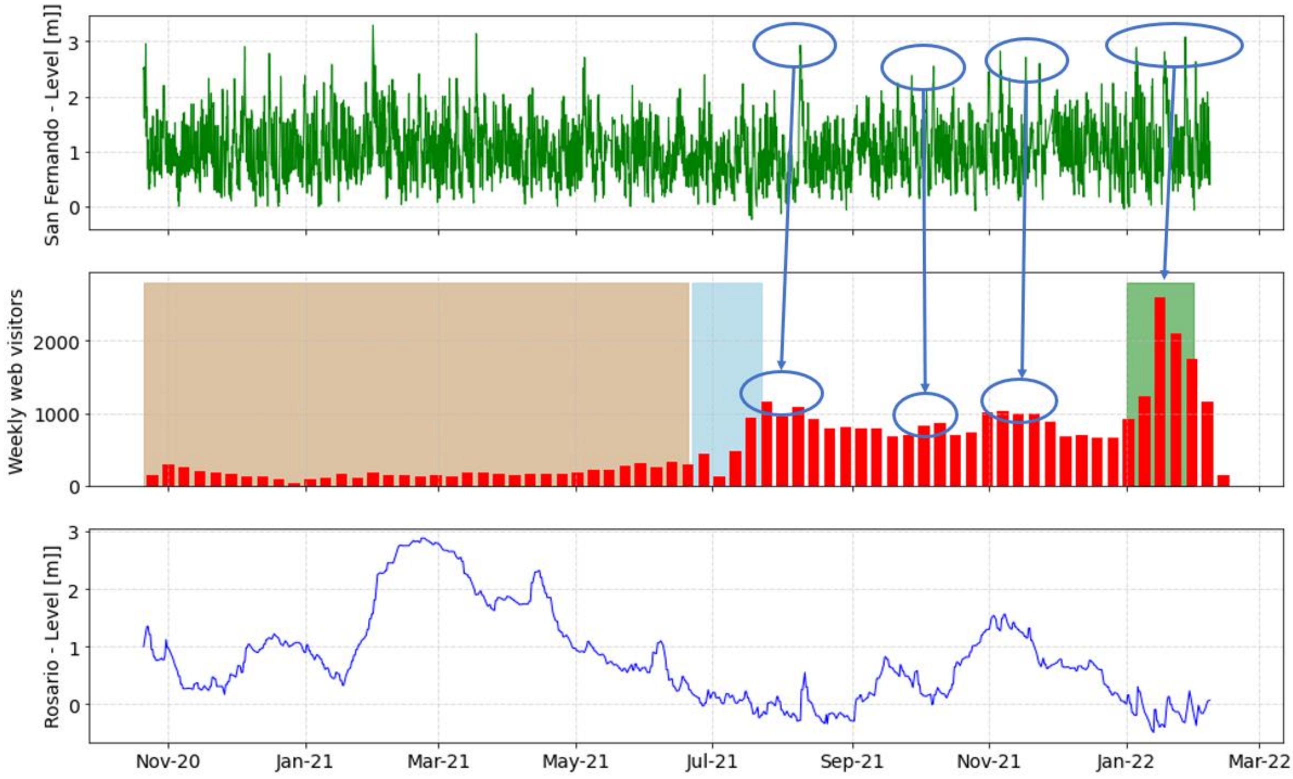

Figure 7. a) water level observations in San Fernando. b) weekly web visitors to Delta Forescast. c) water level observations in Rosario city.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

This publication presents the implementation of a water level forecasting system for a number of cities and ports of the Paraná river Delta region. This system links hydrological models with coastal ocean models by passing boundary conditions between the models. It is based on a one-dimensional model of the Delta area and two different models for the Río de la Plata estuary which provide the boundary conditions to the first model.

The evaluation of these forecasts during 5 months shows that its performance is satisfactory. The comparison between the time series of observed and simulated water levels shows that there is a good representation, not only in time of occurrence but also in the magnitude of the events (Figure 5 and 6).

Currently a new one-dimensional model of the Delta is being upgraded. This model extends the network of modeled streams and updates the geometry with bathymetry for 2019, 2020 and 2021. Furthermore, the topographic information is being updated to improve the representation of the floodplain.

Finally, as part of the project DELTA PARANA: Integrative Hydrodynamic Study of the Paraná River Delta with Multiple Purposes, since 2017 hydrometric stations have been installed at different locations of interest within the Delta. So far, 5 stations have been installed, which send information in real time. Survey and gauging campaigns are also undertaken on a regularly. All this information is used to update the geometry of the model and calibrate it. During the implementation stage, the real-time information is used to monitor the model's performance.

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