Journal of Hydrology 559 (2018) 315–326

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Hydrodynamic modelling of a tidal delta wetland using an enhanced quasi-2D model

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A R T I C L E I N F O

Article history:
Received 2 May 2017
Received in revised form 1 February 2018
Accepted 7 February 2018
Available online 8 February 2018
This manuscript was handled by T. McVicar, Editor-in-Chief, with the assistance of Shengping Wang, Associate Editor

Keywords:
Hydrodynamic modelling
Wetlands
CTSS8
Lower Paraná Delta

A B S T R A C T

Knowledge about the hydrological regime of wetlands is key to understand their physical and biological properties. Modelling hydrological and hydrodynamic processes within a wetland is therefore becoming increasingly important. 3D models have successfully modelled wetland dynamics but depend on very detailed bathymetry and land topography. Many 1D and 2D models of river deltas highly simplify the interaction between the river and wetland area or simply neglect the wetland area. This study proposes an enhanced quasi-2D modelling strategy that captures the interaction between river discharge and moon tides and the resulting hydrodynamics, while using the scarce data available. The water flow equations are discretised with an interconnected irregular cell scheme, in which a simplification of the 1D Saint-Venant equations is used to define the water flow between cells. The spatial structure of wetlands is based on the ecogeomorphology in complex estuarine deltas. The islands within the delta are modelled with levee cells, creek cells and an interior cell representing a shallow marsh wetland. The model is calibrated for an average year and the model performance is evaluated for another average year and additionally an extreme dry three-month period and an extreme wet three-month period. The calibration and evaluation are done based on two water level measurement stations and two discharge measurement stations, all located in the main rivers. Additional calibration is carried out with field water level measurements in a wetland area. Accurate simulations are obtained for both calibration and evaluation with high correlations between observed and simulated water levels and simulated discharges in the same order of magnitude as observed discharges. Calibration against field measurements showed that the model can successfully simulate the overflow mechanism in wetland areas. A sensitivity analysis for several wetland parameters showed that these parameters are all influencing the water level fluctuation within the wetlands to varying degrees. The enhanced quasi-2D model has the potential to accurately simulate river and wetland dynamics for large wetland areas and help to understand their hydrodynamics.

1. Introduction

Wetlands are one of the most valuable ecosystems for mankind (Acreman and Holden, 2013); providing many ecosystem services like flood attenuation, pollutant uptaking, recharge of groundwater and habitat for biodiversity (Tsihrintzis et al., 1998). Special attention has been given to the study of their hydrological regime (Maltby and Acreman, 2011) since it determines the physical, chemical and biological properties of wetlands (Mitsch and Gosselink, 2000). Alteration of the catchment hydrology, including abstraction of surface and groundwater, impoundment or diversion of rivers and land use changes can have a significant impact on wetlands and the ecosystem services they provide. There is an increasing need to develop models to assess wetland impacts, evaluate risks and develop restoration plans (Acreman and Miller, 2007). Being a particularly urgent issue for the world's largest deltas, as the intensification of human activity deeply modifies the tidal river-wetland interaction by changing coastal morphology and reducing wetland extent by filling or dredging (Hoitink et al., 2016, 2017).

The choice of the modelling approach depends, besides the modelling objectives, on both scientific and technical aspects as well as on the resources available. These aspects include, among others, the scale of the simulation domain, topography, hydrological and topographical data available, the complexity of the hydraulic regime

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https://doi.org/10.1016/j.jhydrol.2018.02.014

Table 1
Summary of relevant research useful for modelling deltaic wetland hydrodynamics (the current paper is added for completeness).

Study	Objectives	Location/study size	Model used/model type//spatial domain-topology
Zanobetti et al. (1968a,b,c), Zanobetti et al. (1970)	Predict impacts of damming Tonlé Sap river on the Mekong Delta	Delta of the Mekong river 50,000 km^2	SOGREAH Quasi 2D Topological network of irregular cells: channel-river and islands as nodes, river and weir type links
Haines (2013)	Wetland restoration ecology	Hexham Swamp, Australia 30 km^2	TUFLOW hydrodynamic model 2D, free surface Ground elevation data derived from light detection and ranging (LiDAR).
Schumann et al. (2013)	Evaluate flood inundation forecasting capabilities in large data-scarce regions	Zambezi River Delta, Mozmbique 3000 km^2	LISFLOOD-FP hydraulic model coupled with VIC-WM hydrology model 2D Grid of rectangular cells with topobatimetric data and subgrid for channel routine
Gu et al. (2014)	Simulate water quantity distribution to supplement wetland conservation area	Yellow River Delta, China	SOBEK 1D
Garcia et al. (2015)	Assess effect of road embankment on observed floods and simulate time-dependent water and fine sediment transport processes in a large lowland river,	Upper Parana Delta, Argentina 8100 km^2	CTSS8-FLUSED quasi 2D Topological network of irregular cells: river and set of floodplain islands as nodes, river and weir type links
Popescu et al. (2015)	Use hydroinformatics approaches to support decision-making and planning. Predict dry area during low waters.	Sontea-Fortuna wetland area, Danube Delta, Romania. 5800 km^2	DDNI hydrodynamic model based on calibrated Delft 2D morphological model 2D model of the wetland area and a 3D model of the Fortuna Lake. Grid of rectangular cells with topobatimetric data
Marsooli et al. (2016)	Model flow–vegetation interactions to simulate the larger-scale impacts of wetlands on coastal circulation and storm tides	Laboratory experiments and applied to intertidal salt marshes of Jamaica Bay, adjacent to the New York Harbor, USA	sECOM-Enhanced hydrodynamic module of Stevens Institute of Technology Estuarine and Coastal Ocean Model, 3D, free surface, hydrostatic Arakawa C-grid with terrain-following (sigma) vertical coordinate and orthogonal curvilinear horizontal coordinate
Bricheno et al. (2016)	Inland tidal penetration	Ganges-Brahmaputra-Meghna (GBM) delta in the northern part of the Bay of Bengal, Bangladesh and India	FVCOM (finite volume community ocean model) 3D, baroclinic triangular mesh of up to date bathymetry in both wt and dry season
Haque et al. (2016)	modelling sea water inflow, volumetric flow analysis for fresh water resource availability, understanding of the flow and sediment dynamics and distribution patterns in estuarine deltas,	Ganges-Brahmaputra-Meghna (GBM) delta in the northern part of the Bay of Bengal, Bangladesh and India	Unsteady version of HEC RAS and Delft 3D 2D topographic data and 3D data from river cross sections, sea bathymetry, Mannings roughness co-efficient
Wester et al. (this contribution)	Simulate wetland hydrodynamics from river and tidal floods	Lower Delta Parana River, Argentina, 2000 km^2	CTSS8 quasi 2D Topological network of irregular cells: River-distributaries, natural levee, inner wetland and tidal creeks as nodes; river-river, river-levee, levee-inner, inner creek, creek-river type links

and computational costs. Modelling hydrological and hydrodynamic processes of wetlands is challenging mainly due to data availability. In comparison to rivers, there is a lack of systematic monitoring of water levels in wetlands (Okruszko et al., 2011). The hydraulics within wetland systems are often neglected or simplified in modelling studies (Mao and Cui, 2012). For floodplain wetlands, the extent, vegetation heterogeneity and flat topography prevent field surveys and hydrological monitoring networks from providing a detailed representation of the propagation and characteristics of floods across the floodplain (Ogilvie et al., 2015). Thus, remote sensing products are increasingly being used to provide detailed surface topography for 2D and 3D hydraulic models (Leauthaud et al., 2013; Haines, 2013; Grimson et al., 2013) and flood extent maps to calibrate or evaluate the performance of the models. (Grings et al., 2006; Grings et al., 2009; Salvia et al., 2009).

Flows in wetlands can be characterized as shallow flows where the horizontal dimensions are much larger than the vertical ones (Arega, 2013). The description of flow dynamics in wetlands therefore requires the use of a hydraulic model to capture the interaction between river discharge and moon tides. The wetlands of tidal dominated deltas of large rivers present additional challenges due to the very different boundary conditions upstream and at the coastal front. Many studies have successfully performed hydrologic and hydrodynamic simulations of tidal wetlands in deltaic regions with varying degrees of spatial detail and using different modelling approaches (Table 1). 3D models generally show a good performance and are reliable, but depend on very detailed bathymetry and land topography. Therefore, these models can only be applied to smaller areas or only address the dynamics of the distributary channels. Lower dimensional models are often preferred for large deltaic systems. However, many 1D and 2D models of river deltas highly simplify the interaction between the river and wetland area or simply neglect the wetland area. The first quasi-2D hydraulic model was developed for the large tidal delta of the Mekong river by Preissmann and Cunge (Zanobetti et al., 1968b; Cunge et al., 1980). A quasi-2D model is a compromise between a 1D and a 2D model. The main rivers are connected to separated river branches that represent the floodplain, thereby creating the illusion of a 2D model. Although this type of model is able to deal with the temporal scale that is needed to capture the rapid dynamics of tides, it is more commonly applied to river-floodplain dynamics (Cunge et al., 1980; Riccardi, 1997; Bates and de Roo, 2000; Riccardi et al., 2013), as it can accommodate less detailed data and performs well compared to other 2D models (Beck, 2016). Quasi-2D models have been used for modelling tidal deltas and wetland systems. By introducing an improvement to the spatial configuration of a wetland system, a quasi-2D model can also become suitable for modelling the flow processes in tidal delta wetlands. The proposed method of modelling requires a minimum amount of data and therefore has the potential to become a generalizable approach to help us understand the hydrodynamics of tidal delta wetlands around the world.

Given this background, the objective of this study is to calibrate and evaluate a quasi-2D model to simulate water flows in a test case using a spatial configuration which enables the explicit modelling of distributaries and island wetlands in a tidal delta wetland.

The CTSS8 model (Riccardi, 2000) is chosen for this study. This quasi-2D model has successfully been applied to wetland systems around the world (Garcia et al., 2007; Sandy Rojas et al., 2014; Garcia et al., 2015). Flow equations in the model are discretized through interconnected irregular cells, which allows for introducting a new spatial structure to the model based on the ecogeomorphology in complex estuarine deltas. This in turn allows for the simulation of the complex flow processes in the tidal wetland system.

2. Study area

The test case used in this study is the Lower Parana River Delta, in the east of Argentina, which is a typical case of a tidal delta wetland (Fig. 1). The study area is part of the growing portion of the Lower Delta, covering an area of 2500 km^2 between Parana Guazú and Paraná de Las Palmas rivers (Fig. 2).

The Paraná River system belongs to the Rio De la Plata basin, the second largest basin in South America after the Amazon, runs through Brazil, Paraguay and Argentina, where it flows into De la Plata estuary forming the Parana Delta. The Delta region is a fluvial-coastal complex (Iriondo, 2004), which extends along 300

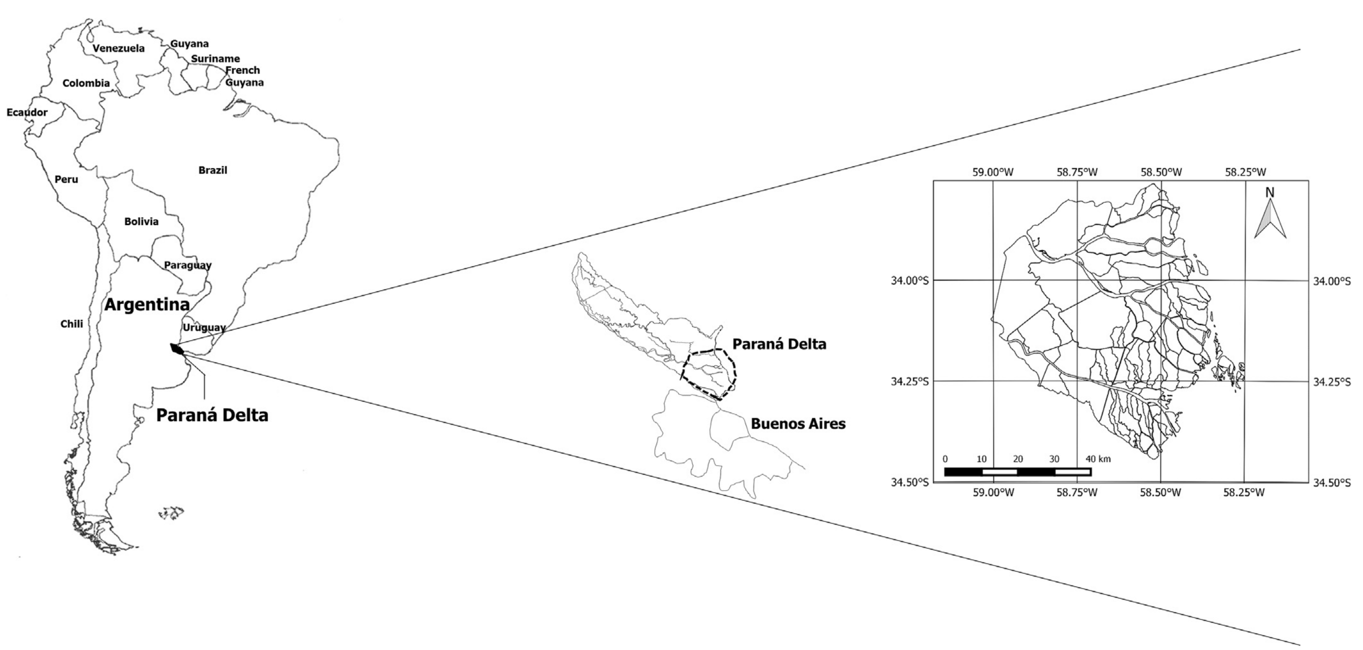

Fig. 1. Location of the Paraná Delta and the delineation of the study area. The left map shows the location of the Paraná Delta in South-America. The middle map shows the location of the study area with respect to the Paraná Delta. The right map shows the study area.

Fig. 2. Schematization of the study area. The names belong to the streams and the main islands are numbered from 10 to 27. The black points show the locations of the six water level measurement stations. The discharge stations are located at Brazo Largo and Zarate. The black triangle shows the location of the field measurements.

km from 32°5′ S near the city of Diamante in Entre Rios Province, to 34°29′ S near the city of Buenos Aires, covering an area of 17,000 km^2 (Baigun et al., 2008). The Parana River Delta is one of the largest coastal wetlands systems of Argentina with a complex estuary delta (Parker and Marcolini, 1992) and a large wetland influenced by fresh water tides (Kandus and Malvárez, 2002). The Lower Delta is the deltaic front, which extends from the bifurcation of the Parana River into the Parana Guazú and the Parana de Las Palmas Rivers. The Parana Guazú sub-front has not considerably advanced due to the Uruguay River currents which push the sediments to the other sub-front (average of 0–25 m/year,Boulanger et al., 2008). The Parana de las Palmas sub-front is actively growing parallel to the coast, near the city of Buenos Aires (50–100 m/year average, Pittau et al., 2004).

The Parana River drains an area of 2.3×10^6 km^2, with a mean annual discharge of 18,500 m^3/s at Parana city near the Delta apex, with peak discharges up to 60,000 m^3/s (Jaime and Menendez, 2002). The Parana River has multimodal and unpredictable flood peaks from different sources: high flows of the upper Parana river, local rainfall, flows from minor tributaries, moon tides, storm surges, and even ocean wave surges coming from De La Plata Estuary (Kandus et al. 2006; Baigun et al., 2008). The main floods in the Delta are driven by the Paraná River which has one discharge peak in the austral late summer (February-March) and another in the austral winter (July). The Rio de la Plata is also responsible for flooding in the downstream region of the Paraná River, in the Lower Delta. De la Plata Estuary has semidiurnal tides with a microtidal regime, with amplitudes less than 1 m in the delta which can temporarily reverse the flow of the distributaries (Prario et al., 2011). The influence of the tide on the upstream part of the river depends on the Paraná water level. If strong winds from the southeast persist for several days, the storm surge can block the outlet of Paraná waters and increase water levels by 3 m or more. The whole system shows seasonal, but also interannual fluctuations (Grings et al., 2006). Water level fluctuation is also clearly visible in wetland areas on satellite images (Fig. 3) and is of main importance to their physical properties.

The Parana Delta exhibits a rich mosaic of heterogeneous wetland landscapes that are interconnected by fluvial corridors with different drainage patterns. Marshes, known locally as pajonales, are the main landcover type (Baigun et al., 2008) covering the lower topographic positions of the islands. Cortadera (*Cyperus giganteus*) and junco (*Schaenoplectus californicus*) marshes make up to 45% of the vegetation in the Lower Paraná Delta (Grings et al., 2006). Forestry and cattle ranching have been the traditional landuses, but agriculture and urban development are rapidly expanding on the islands (Baigun et al., 2008; Blanco and Mendez, 2010). These land uses require the development of infrastructural works, including deepening of navigation channels, diking, island filling and construction of artificial drainages and water diversions, resulting in a disconnection between the rivers and distributaries and their flood and tidal plains (Brinson and Malvarez, 2002). The impact of this disconnection on the Parana Delta wetlands has not been assessed yet.

3. Methods

3.1. Model description

The CTSS8 quasi-2D model is a hydrologic-hydraulic model (Riccardi, 2000) developed to allow for continuous simulation of

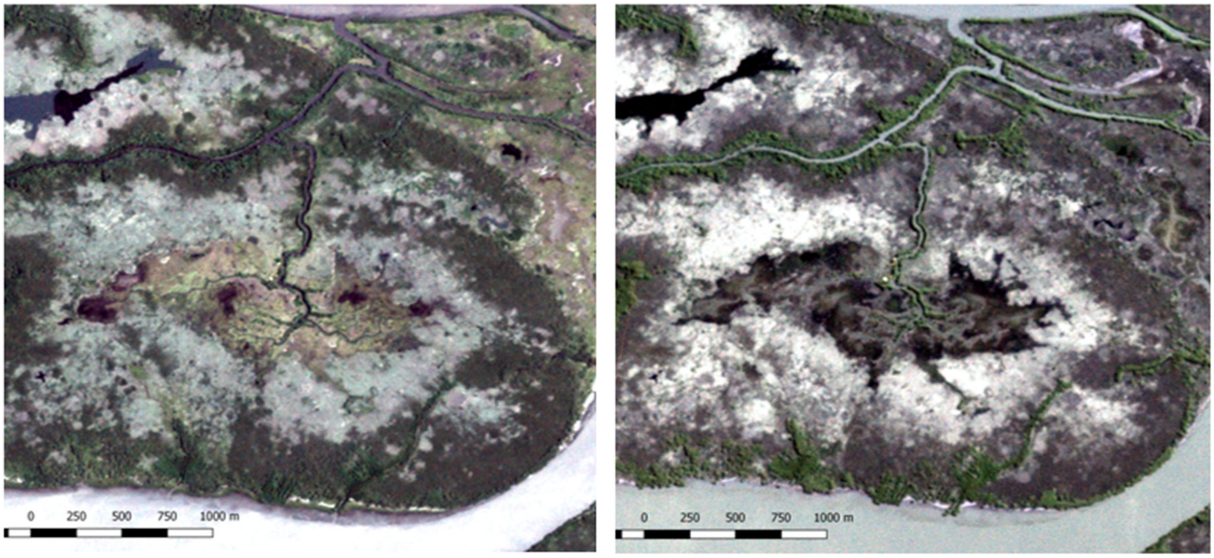

Fig. 3. On the left a satellite image from a wetland area near Braga station during a high water situation (23–09–2016). On the right a satellite image from the same wetland during a low water situation (01–12–2017). Images courtesy of Planet Team (2017). Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. https://api.planet.com.

flow regimes and flooding patterns along floodplains. The model focus is on horizontal flows but there is also an option to incorporate vertical flows, sediment transport and vegetation effects. It can simulate quasi-2D flow in a single layer and flow in two interconnected layers. Flow equations are discretised through a network of interconnected cells (Cunge 1975; Cunge et al., 1980). In order to deal with specific features of fluvial systems, equations are used to represent different discharge laws between cells. The governing equations are the St. Venant equations for continuity and different simplifications of the momentum equation. The model structure allows the representation of reality with different levels of detail, enabling the maximum possible subdivision of the physical components with geometrical and hydraulic parameters consistent with the available data. It has been successfully applied in Argentina to model rainfall-runoff processes in transformed lowland areas (Riccardi, 1997; Riccardi, 2000) and flood evolution in floodplain systems along the Parana River (Garcia et al., 2015; Rojas et al., 2014). In Australia, the model was used to simulate flows in the Hunter estuary to study mangle and saltmarsh dynamics with rising sea levels (Sandy Rojas et al., 2014). This model is considered to be an alternative to the traditional 1D/2D MIKE FLOW model to simulate flows and flooding patterns throughout the Macquarie Marshes and to assess the impacts of different management schemes on the wetland habitats (Trivisonno et al., 2014).

3.2. Model parameters

Cross-sectional data and discharge data for the main rivers and distributaries within the study area were obtained from INA (Instituto Nacional del Agua, the Argentinean National Water Institute). Discharge measurements were available for an upstream location in the Paraná de las Palmas and an upstream location in the Paraná Guazú, containing 144 records for a 22-year period for both locations.

The study area consists of 17 streams with a total length of 371.5 km. A total of 95 cross-sections were available for the study area. Water level measurement from six stations were available from the Ministry of Transport of Argentina for the period 1999–2013 for the main river branches, the Paraná de Las Palmas and the Paraná Guazú, three stations at each river. The measurements have a resolution of 20–30 min and are referenced to the IGN height reference level (Instituto Geografico Nacional, the National Geographical Institute of Argentina). The water surface slope of the main rivers is in the order of 10^{-5} m/m and the mean river widths range from 600 to 2500 m and depths from 5 to 16 m (Guerrero and Lamberti, 2013). The river bottom elevations of the river cells in the Paraná de Las Palmas and Paraná Guazú were approximated assuming steady flow, where the river bottom slope is equal to the water slope. The average water level slope was estimated by calculating the mean water levels of the measurement stations over an 18 year time period. The elevations of the other river cells were estimated by assuming a constant slope for every river and channel.

All six original water level series contain a significant number of outliers and missing values. The outliers are first filtered out from the data series with an absolute threshold and a slope threshold. Small data gaps in the cleaned series are filled up by using linear interpolation. Data from a donor station are used to fill the larger gaps of a given station. The donor is the measurement station with the highest correlation with the station presenting gaps. The water level data of the donor station are scaled in time and amplitude to maximize correlation with the original station and to smoothly fill in the original gap. After interpolation, only 2% of the data series are missing values. The boundary conditions are determined by measurements at four locations: Buenos Aires, Brazo Largo, Desembocadura and Zarate (Fig. 2). Buenos Aires station is linked to the Paraná de las Palmas in the model by a channel with dimensions which are approximated. The water level measurements are interpolated to create equal 10 min intervals for all stations. This is the largest time step that can combine the series with a 20 and 30 min interval without deleting measured data. The calculation interval of the model is also 10 min. For larger intervals the simulation becomes unstable. The initial water levels are set to two meter for all cells, except for the levee cells. This creates a stable situation that needs limited spin-up time. The initial water depth for the levee cells is zero. There is no overflow in the initial situation.

3.3. Improvement spatial configuration model

Our quasi 2D modelling strategy divides the study area in channels and islands with different connection mechanisms. The main

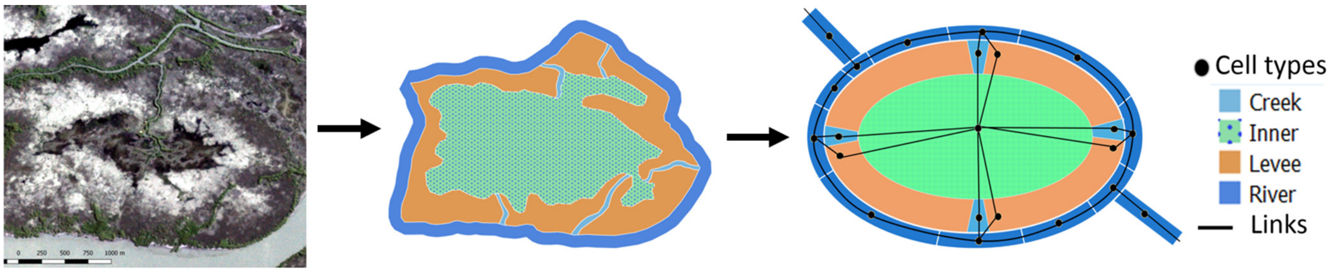

Fig. 4. Schematization of the modelling of islands.

rivers and distributaries are modelled as a series of connected channel (river) cells with river-river links. For the islands, we introduce an improvement of the spatial structure, based on the ecogeomorphology of islands in complex estuarine deltas such as the Parana River, which is presented in Fig. 4. An island has an outer natural levee with an interior shallow marsh wetland, connected to distributary streams or rivers by means of one or more tidal creeks which breach or cut across the levee. An island is modelled by an inner cell surrounded by levee cells which in turn are surrounded by distributary river cells (streams or main rivers) (Fig. 4). The inner cell represents the middle or center of the island covered with pajonal marsh. The inner cell is surrounded by levee cells and creek cells which link to the river cells. The inner cell is directly connected to the river cell by means of one or more creek cells. The number of levee and creek cells matches the actual number of adjacent rivers of the island. The creek cell is always filled with water. Flow through the levee cell is only possible when the water level is higher than the levee height.

Island areas were estimated from GIS data available from IGN. The islands are shown in Fig. 2 and indicated by the numbers 10 till 27. Inner cells represent about 40% of the total island area based on estimates from satellite imagery. The relative area of creek cells compared to that of levee cells is set to 0.02 being a rough estimation based on field observations. The levee height is set to 1.54 m above the IGN reference level added to the river bottom elevation. This number is derived from field measurements that have been done near Arroyo Las Casas (Fig. 2).

3.4. Model calibration and evaluation

The model was calibrated by means of an objective function consisting of two components. The first component is the Nash Sutcliffe Efficiency (NSE) coefficient (Nash and Sutcliffe, 1970). This is the most widely used criterion for calibration and evaluation of hydrological models with observed data, but there has also been a long and vivid discussion about the suitability of NSE. The main concern about NSE is its overestimation of model skill for basins with high seasonal variability (Gupta et al., 2009). Although the water levels in the study area are subject to seasonal variation, the variation is not exceptionally large: water levels vary between -1 and 3 m. The NSE equation is formulated as follows:

$$NSE = 1 - \frac{\sum_{t=1}^{n}(x_{s,t} - x_{o,t})^2}{\sum_{t=1}^{n}(x_{o,t} - \mu_o)^2}$$

where n is the total number of time-steps, $x_{s,t}$ is the simulated water level at time step t, $x_{o,t}$ is the observed water level at time step t and μ_o is the mean observed water level. The NSE is calculated at Carabelitas and Las Rosas. The average NSE serves as input for the objective function.

The second component is a discharge ratio. This ratio is obtained as follows:

$$R_Q = \max\left(\frac{\overline{Q_s}}{\overline{Q_o}}, \frac{\overline{Q_o}}{\overline{Q_s}}\right) - 1$$

where Q_s is the average simulated discharge, Q_o is the average observed discharge and R_Q is the discharge ratio. The interval between two consecutive observed discharges is about two months. This interval is too large to compare observed and simulated discharges on every time step. Therefore, the average observed discharge during the calibration period is compared to the average simulated discharge during the same period. This component of the objective function, therefore, guarantees that the simulated discharges have the same order of magnitude as the observed discharges. The discharge ratio is calculated for Zarate and Brazo Largo, the two upstream boundary conditions. Both discharge ratios are calculated separately and then averaged. The resultant is the second component of the objective function. A discharge ratio of zero is perfect.

The full objective function is formulated as follows:

$$Objective\ function : \alpha|\overline{NSE} - 1| + (1 - \alpha)\overline{R_Q}$$

The NSE is reduced by 1. The absolute value of the resultant forms the first component of the objective function. This first component is minimized for a perfect NSE of 1. Parameter α is introduced to manually set the relative importance of NSE and RQ. This value is set to 0.95 based on expert judgement and gives more importance to an accurate NSE than an accurate RQ. An automatic calibration local optimization algorithm, based on the Nelder-Mead method (Nelder and Mead, 1965), was used to estimate the parameter values for Manning coefficients, creek/levee ratio, mean levee height, mean height of the island inner cell and the length of the channel between Buenos Aires and the river mouth of the Paraná de las Palmas. Since the water levels showed regular behavior, we used a spin-up period of one week.

The period 1 September 2001–31 August 2002 is chosen as the most suitable calibration period, because it is representative for an average hydrological year in terms of water levels with a small number of irregularities, such as sudden jumps in water level or no fluctuation for a couple of days. The model performance is evaluated for the average year September 2007–31 August 2008, the extreme dry period December 2008–February 2009 and the extreme wet period December 2009–February 2010, all with a spin-up period of 1 week. A period of 3 months is selected for the extreme periods, because for a period of one year extremes would be filtered out. The values of the calibration parameters obtained after calibration are used for the selected evaluation periods.

Manual calibration was conducted to optimize the simulation of wetland flows. The calibration period spans over 22 days for the period between 9 June and 1 July 2016. The Manning coefficients of the river-levee, river-creek, creek–inner and levee-inner links are used as calibration parameters. There are four overflow situations during the calibration period. Two overflow situations

Table 2
Calibration parameters for river cell links.

Calibration parameter	Values
Manning coefficient Paraná de las Palmas	0.0188 s/m$^{1/3}$
Manning coefficient Paraná Guazú	0.0109 s/m$^{1/3}$
Manning coefficient other streams	0.0164 s/m$^{1/3}$

occurred within the first two days of the field measurements. It is therefore chosen not to use a spin up period and to use a calculation interval of 6 s to minimize instabilities. The objective function is based on the NSE values calculated at Rio Capitan (river cell), Arroyo Las Casas (creek cell) and the pajonal. These three NSE values are averaged. Multiple local minima of the objective function are searched to find an optimal solution.

Las Rosas and Carabelitas stations are used for calibration purposes and evaluation of the model performance. Given the lack of gauge data for the wetlands, two measurement stations were installed in June 2016 inside and outside a wetland located in the center of the study region, near Arroyo Las Casas (34° 20.6′ S, 58° 33.5′ W (creek cell) and 34° 21′ S, 58° 33.2′ W (inner cell)), to be able to calibrate the wetland parameters of the model. These stations measured the water level every minute and captured four overbank flows during the measurement period.

Evaluation of the model performance for simulating flow mechanisms in wetlands is done by visual interpretation of the results for the field measurement period. A sensitivity analysis is conducted to quantify the effects of changing wetland parameters on flow dynamics in wetlands. This sensitivity analysis helps us understand the flow processes in the tidal wetland. One of the simplest and most common approaches for a sensitivity analysis is to change one factor at a time and analyze its effect on the output (Cariboni et al., 2007). This method is selected in this study, because of its simplicity and robustness. The ratio area creek cells/area levee cells, the levee height and the Manning coefficients of the wetland links are changed one at a time and the change of the average water level, the variation of the water level, the levee overflow and the delay between river and inner cells is assessed.

4. Results

4.1. Model calibration and evaluation

4.1.1. River flows

Table 2 presents the calibration parameters obtained for river cell links (main Parana branches and distributaries). The calibration process for rivers stopped after 52 iterations. The Manning coefficients are comparable with values found in the literature (Biancamaria et al., 2009; Chow, 1959; Piedra-Cueva and Fossati, 2007).

Table 3 presents the results for calibrating with a normal year and the evaluation for different hydrological conditions (normal, extremely dry and extremely wet periods). The objective function gave lower but acceptable values for the evaluation periods than for the calibration period. The simulation during the extreme dry period was more accurate than during the extreme wet period. In terms of the discharge ratio, the obtained results for the NSEs are highly satisfactory, with nearly perfect simulations for both stations.

Fig. 5 presents the observed and simulated water levels at the calibration stations for January, an average month in terms of hydrology, for the calibration and evaluation periods. Fig. 5a presents the observed and simulated water levels for the calibration. At Carabelitas the simulated water level shows an almost perfect match with the observed counterpart, while at Las Rosas station the simulations consistently show higher water levels during low tide. The NSEs are above 0.80 and the simulated average discharges differ less than 20% from the observed average discharges For the evaluation periods, the model generally underestimates at Las Rosas for low tides and slightly overestimates at Carabelitas for peak flows (Fig. 5b–d). The simulation during the extreme dry period (5c) was more accurate than the simulation during the extreme wet period (5d).

4.1.2. Wetland flows

Table 4 presents the calibration parameters obtained for the island cell links (distributary, levee, creek and inner cell). Manual calibration of the wetland dynamics was stopped when changes of the calibration parameters did not result in improvements of more than 0.01 in the NSE. The final value of the averaged NSE is 0.67. The hydraulic roughness is significantly higher for levees than for creeks as expected, which can be explained by the presence of vegetation on levees and the lack of preferred flow patterns.

Fig. 6 presents an overflow situation which was correctly captured by the model. Fig. 6a shows the complete period with field measurements. Fig. 6b zooms into the overflow situation on June 27th, 2016. The water level in the pajonal marsh rises due to high river water levels, which causes high water levels in the creeks and levee overflow. The peak water level reaches the pajonal marsh with some delay, and is lower than the peak level measured in the Arroyo Las Casas creek. The outflow as a function of time is comparable to the inflow process until the water level reaches the levee height. Next, the outflow is slowed down, because water can only flow through the creeks. This can be seen both in the measurements and the simulations.

4.2. Sensitivity analysis

Fig. 7 presents the results of the sensitivity analyses for the Manning coefficients for the links between creek and inner cells (Fig. 7a) and river and creek cells (Fig. 7b), the creek/levee ratio (Fig. 7c) and inner cell elevation (Fig. 7d) for a typical island during January 2008. For most inner cells similar variations were found, although some only showed minor variations in water level because of their larger size. The water level fluctuation in the inner cell is generally smaller than the water level fluctuation in the river cells. A lower Manning coefficient results in more water level fluctuation. Water level fluctuations in the wetland inner cell are more influenced by the Manning coefficient of the creek-inner cell link and the creek/levee ratio than the Manning coefficient of the river-creek link and the island elevation.

Table 3
Results of the calibration and the evaluation.

Simulation	Objective function	NSE Las Rosas	NSE Carabelitas	Qs/Qo Zarate	Qs/Qo Brazo Largo
Calibration (Sept. 2001–Aug. 2002)	0.0371	0.93	0.99	1.00	0.98
Evaluation Normal Period (Sept. 2007–Aug. 2008)	0.1263	0.82	0.93	0.81	0.96
Evaluation Extreme Low (Dec. 2008–Feb. 2009)	0.0907	0.84	0.97	0.85	0.93
Evaluation Extreme High (Dec. 2009–Feb. 2010)	0.1626	0.72	0.95	0.91	1.15

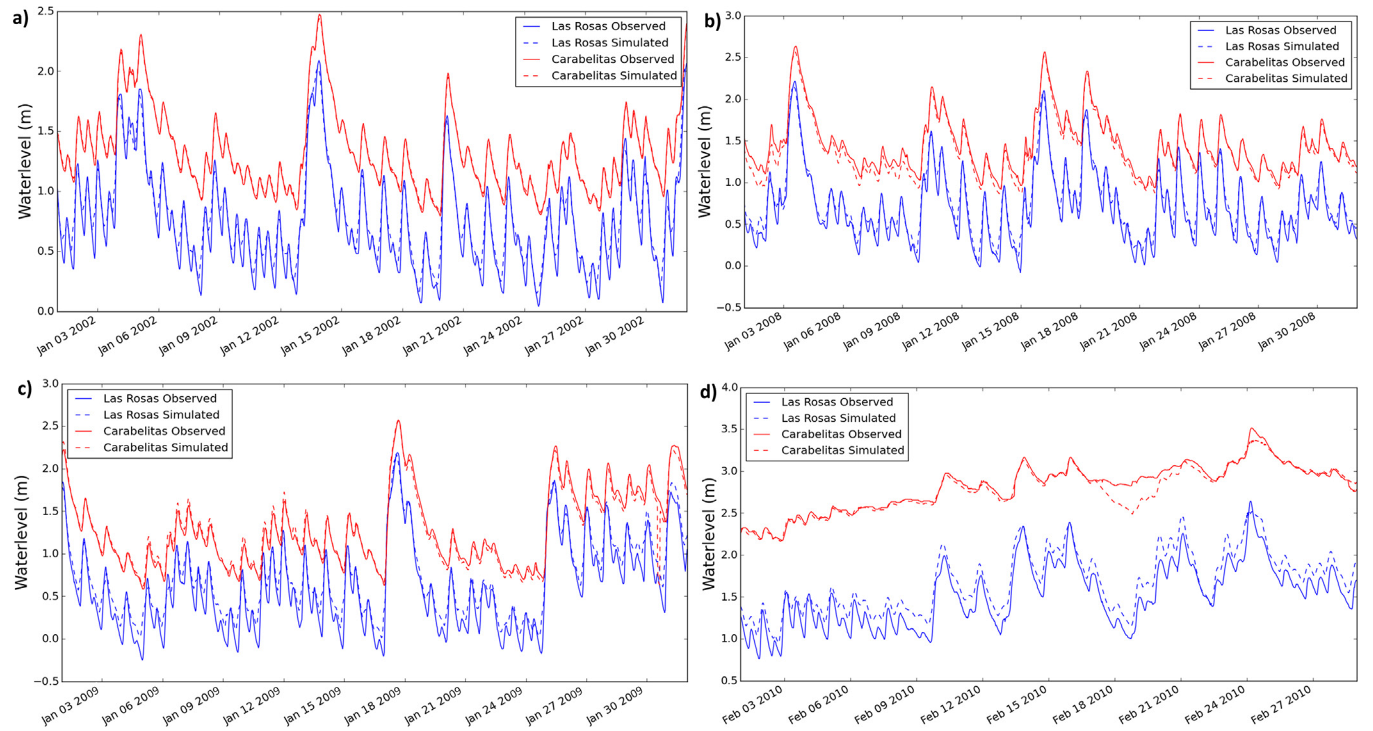

Fig. 5. The observed and simulated water levels at Las Rosas and Carabelitas are shown for the calibration and the three evaluation periods. The water levels during January 2002 in the calibration period are shown in the top left plot (a), the water levels during January 2008 in the evaluation period are shown in the top right plot (b), the water levels during January 2010 in the extreme dry evaluation period are shown in the bottom left plot (c) and the water levels during February 2010 in the extreme wet evaluation period are shown in the bottom right plot (d).

Table 4
Calibration parameters obtained for island cell links (distributary river, levee, creek and inner wetland).

Calibration parameter	Values
Manning coefficient River–Levee	1.3908 s/m$^{1/3}$
Manning coefficient River–Creek	0.0343 s/m$^{1/3}$
Manning coefficient Creek–Inner wetland	0.3322 s/m$^{1/3}$
Manning coefficient Levee–Inner wetland	1.7241 s/m$^{1/3}$
Manning coefficient downstream rivers	0.0098 s/m$^{1/3}$

Fig. 8 shows the sensitivity of the water level of the inner wetland cell to the value of the levee height. The water level in the river cell fluctuates significantly more than the inner cell as would be expected. A lower levee corresponds with more variation and an overall higher water level in the inner cell. For an intermediate levee height (2.0 m), the water level shows a sudden bending point when the water level surpasses the levee, after which the outflow slows down, because there is no longer levee overflow. All water flows out via the creek and that slows down the outflow process. The figure shows that the model can capture overflow processes and flow from the river to the inner wetland through creeks.

5. Discussion

A model capable to simulate flood dynamics in a large fluvial-coastal tidal delta should be able to represent hydrologic and hydraulic processes in a distributed way, integrating the main drainage system with the different types of surface flows and their interactions which take place in the deltaic island landscape. Another requirement for modelling complex flows is giving primary importance to the physical interpretation while maintaining data needs as simple as possible, so topographic and hydraulic

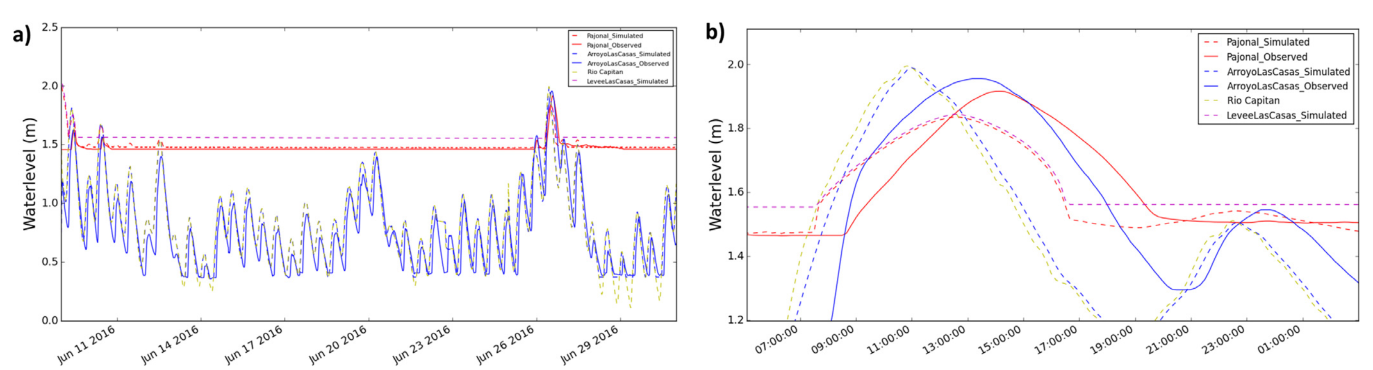

Fig. 6. Results of the calibration of the wetland flow processes with field measurements. The left plot (a) show the total calibration period. The right plot (b) is zoomed to the overflow situation on 27 June 2016.

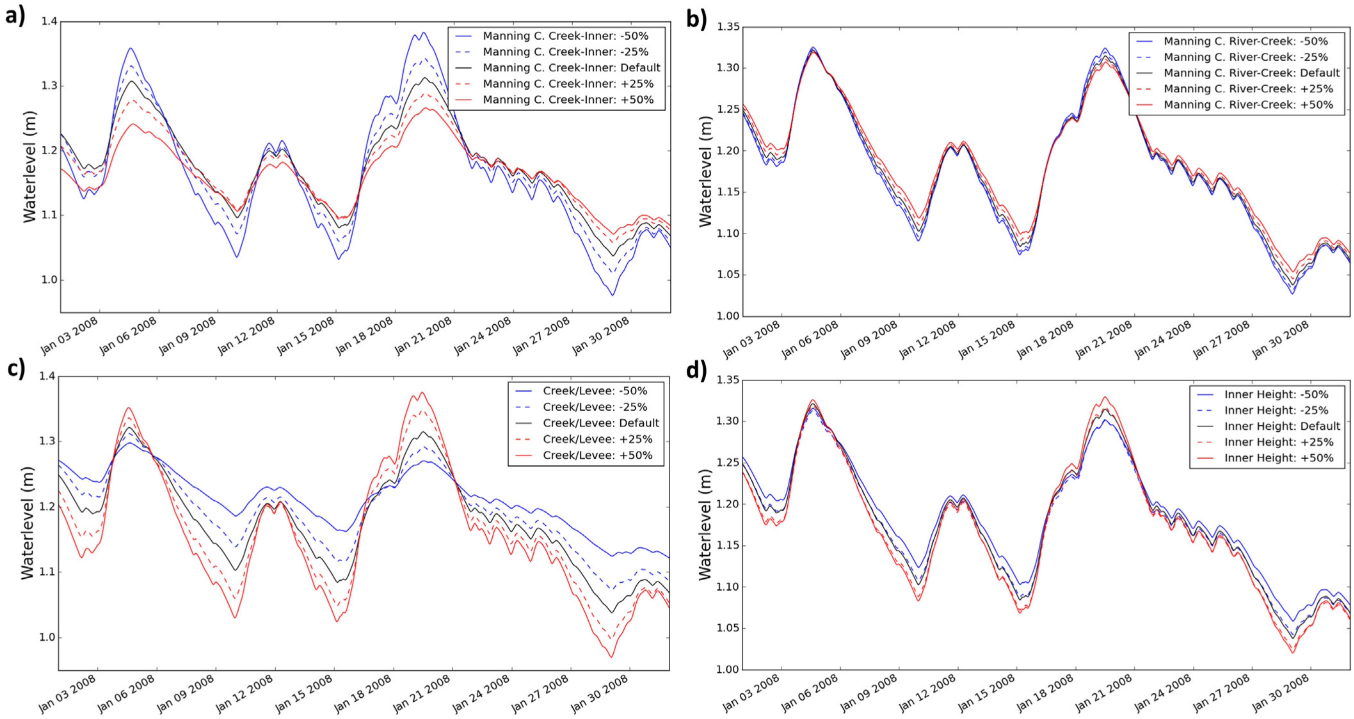

Fig. 7. Results of the second sensitivity analysis. The changes in water levels are displayed for the changes in four different wetland parameters. The top left plot (a) shows the changes in the creek-inner Manning coefficient, the top right plot (b) the changes in river-creek Manning coefficient, the bottom left plot (c) the changes in creek/levee ratio and the bottom right plot (d) the changes in inner height.

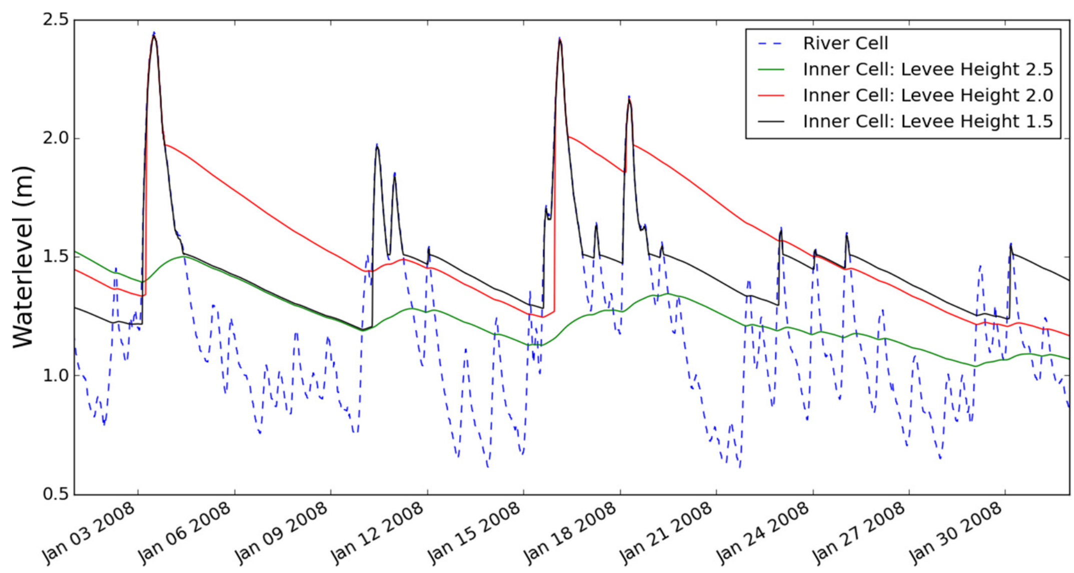

Fig. 8. Water level fluctuation within island 10 during January 2008 for different levee heights.

representations of the physical reality are the two core elements needed to simulate flood dynamics (Gomes Miguez et al., 2017).

Most hydrologic and hydrodynamic models neglect the wetland dynamics or highly simplify wetland areas (Sassi and Hoitink, 2013; Gu et al. 2014). Garcia et al. (2015) simplified the non-tidal upper Parana Delta by considering valley cells to represent complex alluvial valleys with islands. Bolgov et al. (2014)used several storages to prevent large errors, because wetland dynamics was not accounted for in their model. Our quasi 2D modelling strategy uses a spatial network of cells of irregular size connected to each other by links, in a fashion similar to that proposed by Cunge and used to model hydrodynamics in deltaic and floodplain regions (Zanobetti et al. 1970; Cunge et al., 1980). We introduced an improvement, based on the observed ecogeomorphology of islands in complex estuarine deltas such as the Parana River. The main rivers and distributaries are modeled as a series of connected river cells with river-river links. The islands are modeled by an inner wetland cell surrounded by levee cells which in turn are surrounded by river cells (streams or main rivers). The inner cell is connected to the river cell by means of one or more creek cells. Levee cells only transfer water when their height is surpassed by the water level in the river cells. This improved strategy allows to simulate flow and overflow processes in one large scale model, without having complete 3D information on the terrain and a high density of gauging stations.

Despite having scarce data, our model does not neglect the wetland dynamics. The simulations presented in Section 4 show that this spatial modelling strategy is being able to capture the distributary and wetland dynamics and their interaction. Actual flow processes are simulated instead of introducing compensation measures. These flow processes contain valuable information about the hydrodynamics that is linked to the physical and biological properties of wetlands.

The model accurately simulates water levels and the average simulated discharges are in the same order of magnitude as the observed average discharges. The results of the simulations during the extreme wet period are slightly worse than the results for the other evaluation periods. During the extreme wet period there is more overflow than in the other periods and therefore more interaction between the river and wetland system. Hence, the uncertainties in the proposed values for the wetland parameters are significantly more influencing the model outcomes than during average conditions. Several assumptions had to be made to be able to carry out wetland simulations (e.g. assuming elevations for the different parts of the area and assuming a constant width for the creeks that connect the inner wetland with the river). However, since the wetland dynamics has limited effect on the river water levels during average conditions, these assumptions have limited effect on the evaluation of the model performance at the measurement stations. Incorporating wetland dynamics in the model does therefore not lead to significant better or worse river water levels simulations. The assumption of constant river slopes, based on the difference between the average water levels at measurements stations, does influence the simulations in the river because elevation is a main parameter in hydrodynamic models. The water level simulations showed a consistent overestimation of the low water levels at Las Rosas in the Paraná de las Palmas, probably due to incorrect river slope estimation and elevations. A higher elevation in the Paraná Guazú than in the Paraná de las Palmas damps the effect of low water levels in the Paraná de las Palmas, because water will flow from the Paraná Guazú in the Paraná de las Palmas during low water levels. The model might overestimate this dampening, because of too large differences between elevations in both rivers. The model performance could only be evaluated at two locations in the main rivers and for one wetland area.

Model calibration and evaluation have mainly been carried out based on observed water levels, because of a lack of other data. The upper and lower boundary conditions of the model are also prescribed by observed water levels. As a result, the model has a few degrees of freedom and one could argue that it is fairly easy to get good calibration and evaluation results. While this is partly true, it should be mentioned that the upstream and downstream boundary conditions are influenced by different flow processes (tides, river flow, wetland flows, etcetera), which are not equally important at all gauge stations. Simulating the water levels correctly therefore is not a straightforward interpolation. A denser network of measurement stations, each measuring multiple flow parameters, would enable a more thorough evaluation of the model. It would also enable the formulation of new boundary conditions and calibration criteria, which in turn will enhance the overall model performance. It would also allow for the evaluation of the manual calibration of the wetland flow processes. The model has successfully simulated tidal delta wetland flow processes for the presented case study. Now the question arises what this entails for tidal delta wetland systems around the world. The results can not simply be extrapolated to other catchments around the world. However, if another catchment meets the requirements of the proposed method and model, a similar study can be conducted to learn more about the hydrodynamics of this catchment. Since the used method of this study is based on limited data requirements, it is applicable to many other similar study areas.

6. Conclusion

This paper presents the application of the CTSS8 model to a study area in the Lower Paraná Delta (Argentina). An enhanced strategy was used to spatially represent the wetland area in the study area. The model was calibrated against water levels in the main rivers for the hydrological year September 2001–August 2002 with a 10 min interval and on field measurements in a wetland area for June 2016. The obtained values of the Manning coefficients after calibration comply with values found in the literature. The model was evaluated for an average hydrological year (September 2007–August 2008), an extreme dry period (December 2008–February 2009) and an extreme wet period (December 2009–February 2010). Water level simulations were successful for all periods at the two measurement locations in the main rivers. The simulated discharges at two upstream locations have the correct order of magnitude. The influence of the wetland area on water levels in the main rivers is negligible in the presented model set-up. However, the river dynamics do influence the wetland dynamics and wetland parameters also influence wetland dynamics. Calibration of the model against field measurements showed that the model can successfully simulate the overflow and outflow mechanisms in the wetland area. A next step would be to gather more water level measurements in the distributaries and wetland areas to evaluate the model performance more thoroughly. The used model and method can also be applied to other tidal delta wetland systems around the world to learn more about their hydrodynamics and the functioning of tidal delta wetlands in general.

Acknowledgements

This work was mostly carried out at 3iA-UNSAM, Argentina, within the framework of Sjoerd Wester's master thesis project at the University of Twente, the Netherlands. S. Wester received a student scholarship for his stay in Argentina from the University of Twente. We would like to acknowledge the support of Gerardo Riccardi and his staff from the Department of Hydraulics of the Universidad Nacional de Rosario by providing the CTSS8 model and valuable user information, of Subsecretaria de Puertos y Vias Navegables (Secretaría de Transporte de la Nación Argentina) regarding the data from the measurement stations, and of Martin Sabarots Gerbec from Instituto Nacional del Agua by providing spatial data. Additional funding for meetings with Riccardi's group in Rosario, and construction and setup of measurement devices in Las Casas creek in the lower Parana Delta were provided by grant FONCyT PICT-2014-0824 to P. Kandus, R. Grimson and P. Minotti. We would also like to acknowledge the work of the two anonymous reviewers and the editorial team of Journal of Hydrology.

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