# Modelling Hydrodynamic and Sedimentation Processes in Large Lowland Rivers: An Application to the Paraná River (Argentina)

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**ABSTRACT:** In the last decade 1D, 2D and 3D numerical models have been extensively used to simulate river-floodplain hydraulics and sediment deposition processes in floodplains. Large river-floodplain ecosystems in lowland areas show characteristic reach lengths of the order of hundred of kilometers, floodplain widths of the order of tens of kilometers and river widths of the order of a few kilometers. The floodplain itself shows also a very complex geomorphology. Computationally intensive water flow and sediment transport models cannot take into account these peculiarities, and particularly the large time and space scales involved. On one hand, 1D models are not appropriated because the one-dimensional flow description is not representative of the complex flow pattern; on the other hand, higher dimensionality models, even if they can provide the necessary level of processes representation at small spatial scales, cannot be applied over large time and space scales due to the computational demands. An alternative to high resolution models is the implementation of quasi-2D models which can capture the fundamental characteristic of water flow and sediment dynamics in those situations. Thus, a compromise between computational costs and processes representation can be achieved. In this work a quasi-2D model, suitable for the time-dependent water and sediment transport processes simulation in large lowland river systems, including their floodplain, is presented. Water flow and sediment equations are represented by means of the interconnected irregular cells scheme. Different simplifications of 1D Saint Venant equations are used to represent the discharge laws between fluvial cells. Spatially-distributed transport and deposition of fine sediments throughout the river-floodplain system are simulated. The model is applied over a 208 km reach of the Paraná River between the cities of Diamante and Ramallo (Argentina) and involving a river-floodplain area of 8100 km². After calibration and validation, the model is applied to predict water and sediment dynamics during synthetically generated extraordinary floods of 100, 1000 and 10000 years return period. The potential impact of a 56 km long road embankment constructed across the entire floodplain was simulated. Results with and without the road embankment show that upstream water levels, inundation extent, flow duration and sediment deposition increases in the presence of the embankment.

**KEY WORDS:** Fluvial hydraulics, Numerical modelling, Floodplain sedimentation, Lowland rivers, Paraná River.

## 1 INTRODUCTION

Periodic inundation cycles of floodplains ecosystems in large lowland rivers are crucial to maintain biodiversity and ecological integrity of these areas. Human interference in these systems can change the magnitude, frequency and duration of floods. As a consequence, the exchanges of water, sediments, nutrients and biota between river channels and floodplain can be modified (Thoms et al., 2005). Moreover, floodplains play an important role in river flood attenuation; thus, it is important to understand floodplain inundation dynamics in order to make decisions on flood risk management (Bates et al., 2006). In addition, due to long-term deposition and consolidation processes, floodplains can become sinks of sediments and particulate-associated contaminants (Walling et al., 1996).

These issues have promoted the development and application of different computational models to study river-floodplain hydraulics and sedimentation processes in floodplains. In the last decade 1D, 2D and 3D numerical models have been implemented to simulate either river-floodplain hydraulics (Horrit and Bates, 2002; Nicholas et al., 2006; Werner et al., 2005; Bates et al., 2006; Wilson et al., 2006) or suspended sediment transport and deposition processes (Stewart et al., 1999; Hardy et al., 2000; Asselman and van Wijngaarden, 2002; Nicholas, 2003; Nicholas et al., 2006; Yang et al., 2012). 1D and 2D models have been applied to reproduce observed hydrographs, to derive water extent inundation maps and to estimate sedimentation rates along 5-60 km river reaches, with floodplains less than 3 km in width, and without the presence of an important hydrographic network of floodplain channels. In addition, 3D models have been applied at reach scales of the order of a kilometer.

Large river-floodplain systems in lowland areas show characteristic reach lengths of the order of hundred of kilometers, floodplain widths of the order of tens of kilometers and river widths of the order of some kilometers. Flood events can last several months and data are scarce. The floodplain itself shows a very complex morphology with a network of permanent channels, interconnected lagoons, natural levees, road embankments, different vegetation types, etc. In this context, the computational-intensive water flow and sediment transport models cannot adequately represent these peculiarities over large time and space scales. On one hand 1D models are not appropriated because the 1D flow description is not representative of the real flow pattern; on the other hand, the computational demands of full 2D depth averaged models and 3D models preclude their application over large space and time scales.

An alternative to high resolution models is the implementation of quasi-2D models which can capture the fundamental characteristic of water flow and sediment dynamics in those areas. Thus, a compromise between computational costs and processes representation can be achieved. Large lowland river-floodplain systems have flooding duration of the order of several months, with a gradual and fairly slow floodplain filling due to overbank flows from the main stream and secondary floodplain channels. This hydraulic process is compatible with the hypothesis on which quasi-2D models are based (Cunge, 1975). Notably, a quasi-2D hydraulic model (CTSS8, Riccardi, 2000) applied to the Paraná River produced transverse velocity profiles similar to the ones obtained with a full 2D depth averaged model (Basile and Riccardi, 2002). Another previous application of quasi-2D hydrodynamic model at large spatial scale was reported by Wilson et al. (2007), in which the hydraulic model LISFLOOD-FP (Bates and de Roo, 2000) was used to predict floodplain inundation of the central Amazon floodplain in Brazil. Later on, Neal et al. (2009) implemented a parallel version of LISFLOOD-FP based on the OpenMP Application Programming Interface for large scale simulations. Rolim da Paz et al. (2011) implemented a 1D hydrodynamic model coupled to a 2D raster-based model in the Upper Paraguay River Basin, including the Pantanal Wetland.

In this work CTSS8-FLUSED, a quasi-2D model suitable for the time-dependent water and fine sediment transport processes simulation in large lowland river-floodplain systems, is presented. Water flow and sediment equations are represented through an interconnected irregular cells scheme. Different simplifications of 1D Saint Venant equations are used to represent discharge laws between fluvial cells. Spatially-distributed transport and deposition of fine sediments throughout the river-floodplain system are simulated. The model is applied over a 208 km reach of the Paraná River between the cities of Diamante and Ramallo (Argentina), involving a river-floodplain area of approximately 8100 km². After calibration and validation, the model is used to predict the potential effects on water and sediment dynamics of a 56 km long road embankment constructed across the entire floodplain between Rosario and Victoria.

## 2 BRIEF DESCRIPTION OF CTSS8-FLUSED MODEL

Water flow is simulated with the CTSS8 hydrodynamic model (Riccardi, 2000). The governing equations for the quasi two-dimensional horizontal time-depending flow field are represented by the well-known approach of interconnected cells (Cunge, 1975). Water continuity for the j-th cell reads:

$$A_{s\,j}\,\frac{\partial z_j}{\partial t} = P_j(t) + \sum_{k=1}^{N} Q_{j,k} \tag{1}$$

where $z_j$ is the water level; $A_{sj}$ is the surface area of the cell, t is the temporal coordinate; $P_j$ is a direct inflow into the cell; $Q_{j,k}$ is the water discharge between cells j and k and N is the number of interconnected cells to the j-th cell.

Water discharges are expressed as functions of water levels: $Q_{j,k}$=Q ($z_j$, $z_k$). Different discharge laws between cells can be used. Fluvial type links can be specified by means of kinematic, diffusive, quasi-dynamic and dynamic discharge laws derived from the Saint Venant momentum equation. In order to deal with special features of fluvial systems, weir-like discharge laws representing natural sills, levees, road embankments, etc., are included in the model. Culvert and bridge-like discharge laws are also incorporated.

The spatial distribution of model parameters and hydrodynamic variables is done through the subdivision of model domain in irregular cells, which can be specified as river-type or valley-type cells.

The sediment module FLUSED (Basile et al., 2007) incorporated into the CTSS8 model simulates transport of fine sediments and deposition processes by solving the quasi-2D continuity equation of suspended sediment. Neglecting horizontal diffusion, the continuity equation for the j-th cell reads:

$$A_{s\,j}\,\frac{\partial (h\,C_s)_j}{\partial t} = (A_s\,\phi_s)_j + \sum_{k=1}^{N} (Q\,C_s)_{j,k} \tag{2}$$

where h is the water depth in the cell, $C_s$ is the volumetric sediment concentration and $\phi_s$ is the downward vertical flux of fine sediments (deposition rate), expressed as: $\phi_s = P_d \; w_s \, C_s$, where $P_d$ is the probability of deposition; $w_s$ is the fall velocity of suspended sediment particle. The probability $P_d$ of particle remaining deposited is given by Krone (1962):

$$P_d = \begin{cases} 1-\left(\dfrac{U}{U_{cd}}\right)^2 & ; \quad U < U_{cd} \\ 0 & ; \quad U \geq U_{cd} \end{cases} \tag{3}$$

where U is the mean flow velocity and $U_{cd}$ is the critical mean flow velocity for deposition.

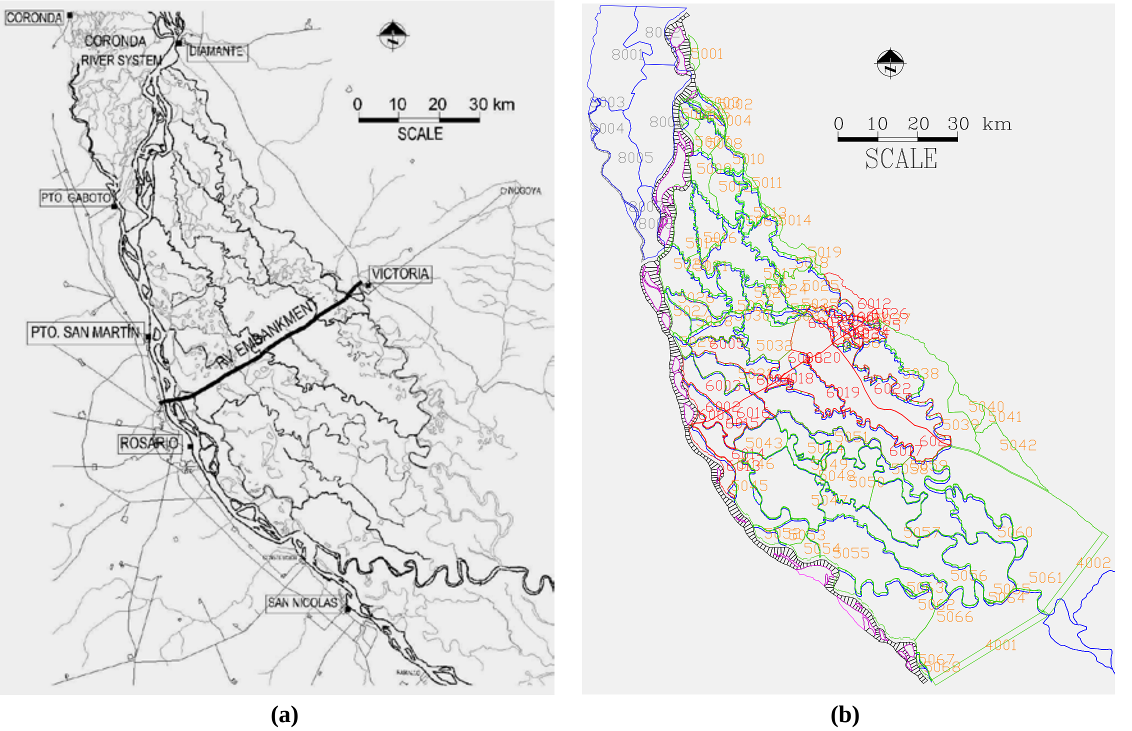
Water flow and sediment equations are solved using a finite difference numerical scheme. Water levels in each computational cell are determined by an implicit algorithm and water discharges are successively obtained by applying the discharge laws between cells. Using an implicit algorithm, suspended sediment concentration, horizontal and vertical sediment fluxes are determined. Additionally, mean and total cumulative daily, monthly and annual sediment deposition (volume and weight) as well as bed level changes are computed for each cell. The initial conditions are represented by the water levels, discharges and sediment concentrations at each computational cell of the simulated domain. Boundary conditions for water flow are represented by the hydrographs at the upstream end of the reach and by water depth-discharge relations at the downstream boundary. The incoming suspended sediment transport at the upstream end is specified.

## 3 STUDY AREA

The model was implemented along a 208 km reach of the Paraná River, Argentina, between Diamante (km 533) and Ramallo (km 325) and involving a river-floodplain area of 8100 $km^2$ (see Figure 1(a)). km identification of the stations correspond approximately to their distance along the thalweg to the mouth of the Paraná-La Plata river. The floodplain width varies between 30 and 60 km, while the width of the main channel varies from 0.5 to 3 km. The mean annual water discharge at Rosario (km 416) is 17000 $m^3$/s, while during the extraordinary flooding of 1983 the maximum water discharge was approximately 60000 $m^3$/s with almost 30000 $m^3$/s flowing in the main stream. In that occasion (maximum water level of 9.21 m IGN at Rosario) the floodplain was completely inundated with mean water depth of 4 m. m IGN stands for meters above a height datum that approximately coincides with the sea level at the mouth of the Paraná-La Plata river. The minimum water discharge observed at Rosario was approximately 6700 $m^3$/s, in 1970. Thus, considering the maximum discharge of 1983, the ratio between maximum and minimum water discharges is 9, a rather low value as in other large rivers of the world. The water surface slopes in the main stream between Puerto San Martin (km 448) and Rosario varies between a minimum of $1.5\times10^{-5}$ for low water stages (water level less than 5.5 m IGN at Rosario) and a maximum of $4\times10^{-5}$ for high water stages (water level greater than 7.2 m IGN at Rosario). The annual average total sediment transport entering to the system is approximately $150\times10^{6}$ t/year from which 83% of the total sediment load is composed by silt and clay transported in suspension as wash load (Amsler and Drago, 1999).

The main stream at macro-scale shows a morphological configuration characterized by a succession of enlargements with narrower, shorter and deeper sectors between them. Sand bars and vegeteated islands are observed at enlargements. The thalweg is sinuous and conveys approximately 60% of the discharge at a given section. The riverbed is formed by sand with $d_{50}$ varying between 0.26 mm and 0.32 mm, and geometric standard deviation varying between 1.46 and 1.85. Natural levees are observed along the main stream.

The floodplain is morphologically complex and five different morphological units can be observed (Iriondo, 1972). A well developed network of surface-floodplain channels, oxbow lakes, lagoons, permanent pond areas and different types of vegetation are observed. The sediments in the alluvial valley are made up of approximately a 30 m thick layer of sandy material with sparse patches of clay and silt. The top soil layers 1 to 3 m thick of the floodplain and islands are formed by very fine sediments in the silt and clay range.




(a) (b)

**Figure 1** (a) Study area; (b) Model constitution.

## 4. MODEL RESULTS

### 4.1 Hydrodynamic simulations of observed floods

The topological constitution of the mathematical model involved several steps. First, a DTM was developed using existing data gathered from topographic surveys conducted in the alluvial valley, bathymetric data of the main stream and floodplain channels, and satellite images and aerial photos of the area at various river stages (low, medium and high water). The topological discretization was carried out by selecting stream cells, floodplain cells and by defining the different type of links between cells to represent special topographic features (natural levees, roads embankment, bridges, etc.). In Figure 1(b) the final constitution of the model is presented. Currently, the model has 1413 stream cells that represent the main stream, secondary surface-floodplain channels and the Coronda river tributary and 140 floodplain cells representing the alluvial valley and islands, with 4248 links between the different cells.

Between 1997 and 2003 a road embankment 56 km long connecting Rosario and Victoria (RV embankment, see Figure 1(a)) across the entire floodplain was built. The embankment included a bridge over the main stream and 12 minor bridges in the floodplain. The RV embankment was also incorporated in the model.

The hydrodynamic component of the model was first calibrated for low, medium and high water stages with hydrological events registered previous to the construction of the RV road embankment. For low water stages the hydrograph of the year 1968 was considered, with a mean annual discharge of 10130 $m^3/s$. For medium water stages the hydrograph corresponding to the year 1994 (mean annual water discharge 17042 $m^3/s$) was selected. 1994 is a typical hydrological year, and displays the real hydrograph that is closer to the average statistical hydrograph. For high water stages, the extraordinary flooding events of 1982-`83, 1992 and 1997-`98 (approximately 40, 70 and 90 years return period respectively), where peak flows in main stream exceeded approximately 30000 $m^3/s$, were considered. Next, the model was validated by considering two periods of ten consecutive years of discharges corresponding to 1980-`89 and 1990-`99.

The calibration procedure consisted of ensuring that calculated daily water level series matched the corresponding observations in different stations like Diamante, Puerto San Martín (PSM), Rosario, San Nicolás, Victoria, Coronda and Puerto Gaboto and water discharges in the main stream at PSM. Water discharges at the upstream boundary at Diamante and Coronda and depth–discharge relationships at the downstream end were specified. Roughness coefficients along main stream, surface floodplain channels and floodplain cells, as well as, discharge coefficients between special cell links were varied during calibration. The adjusted values of Manning`s roughness coefficients varied between 0.029 $s/m^{1/3}$ and 0.074 $s/m^{1/3}$ for main stream cells, between 0.030 $s/m^{1/3}$ and 0.035 $s/m^{1/3}$ for surface floodplain channels cells and floodplain values of n ranging from 0.05 $s/m^{1/3}$ to 0.10 $s/m^{1/3}$. Discharge coefficients that simulate the existing weir or bridge links between different cells varied between 0.1 and 0.5.

In Figure 2 the comparison between observed and calculated water levels, for the validation period 1990-`99, is presented. The adjustment obtained is very satisfactory with average error lower than of 10% in all stations. In order to evaluate the efficiency of the modeling results, the coefficient of Nash-Sutcliffe (1970) was used for water levels. This coefficient E can vary between -∞ and 1, E=1 corresponding to a perfect adjustment between calculated and observed values. In Table 1 the values of E for all the simulations are presented, where it can be observed that without the RV embankment almost 90% of the values are equal or higher than 0.8 for calibration and 75% are equal or greater than 0.9 for validation.

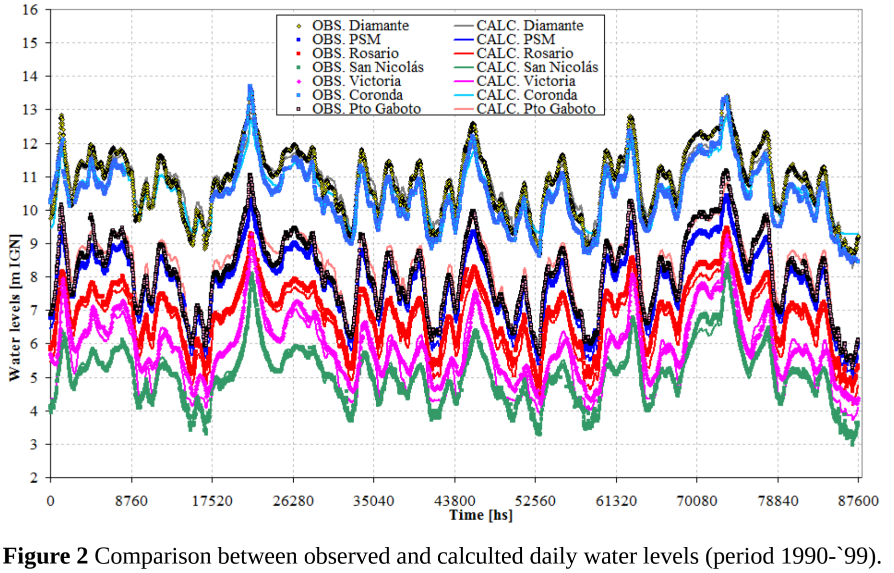



**Figure 2** Comparison between observed and calculted daily water levels (period 1990-`99).

The model was also calibrated and validated with hydrological events registered after the construction of the RV road embankment. The obtained results are also very satisfactory, with an average error between calculated and observed daily water levels lower than of 10% in all stations. Moreover, the Nash-Sutcliffe coefficients obtained for calibration (period 2007-2010) and for validation (period 2000 - 2010) indicate an adequate model performance (Table 1).

Figure 3 shows a river-floodplain cross section between Rosario (right bank) and Victoria (left bank) together with observed and calculated water levels during peak discharges of two different flood events. For the medium water stage (results with relative errors less than 4%, and minor differences up to 0.27 m), it is observed that the natural levee in the main stream is not overtopped and the floodplain is inundated, especially the lower valley areas nearby Victoria. During the high water stage (results with relative errors less than 2%, and minor differences up to 0.15 m), the valley is completely flooded. Both situations are extremely well reproduced by the model.

Simulations were performed using a time step of 360 s and model results were printed every 24 hours. CPU time for a one year simulation was approximately 8 hours on a computer with Intel Core 2 Quad 2.4 GHz CPU and 2 GB of RAM.

**Table 1** Nash-Sutcliffe coefficients for calibration and validation, without and with RV road embankment.

| | Model without RV | | | | | | | Model with RV | |
|---|---|---|---|---|---|---|---|---|---|
| | Calibration | | | | | Validation | | Calibr. | Valid. |
| **Station/Year** | **´68** | **´82-´83** | **´92** | **´94** | **´97-´98** | **´80-´89** | **´90-´99** | **´07-´10** | **´00-´10** |
| Diamante | 0.93 | 0.65 | 0.81 | 0.83 | 0.88 | 0.90 | 0.92 | 0.73 | 0.73 |
| PSM | 0.83 | 0.99 | 0.99 | 0.95 | 0.99 | 0.98 | 0.97 | 0.98 | 0.94 |
| Rosario | 0.83 | 0.95 | 0.90 | 0.80 | 0.91 | 0.94 | 0.90 | 0.93 | 0.75 |
| San Nicolás | 0.89 | 0.93 | 0.93 | 0.95 | 0.94 | 0.96 | 0.97 | 0.95 | 0.82 |
| Victoria | 0.71 | 0.89 | 0.97 | --- | 0.91 | 0.79 | 0.85 | 0.92 | 0.65 |
| Coronda | --- | 0.74 | 0.85 | 0.71 | 0.92 | 0.88 | 0.87 | 0.80 | 0.75 |
| Pto Gaboto | --- | --- | 0.90 | 0.89 | 0.94 | 0.91 | 0.95 | 0.90 | 0.87 |
| QPSM | 0.99 | 0.93 | 0.96 | 0.99 | 0.96 | 0.98 | 0.98 | 0.97 | 0.95 |

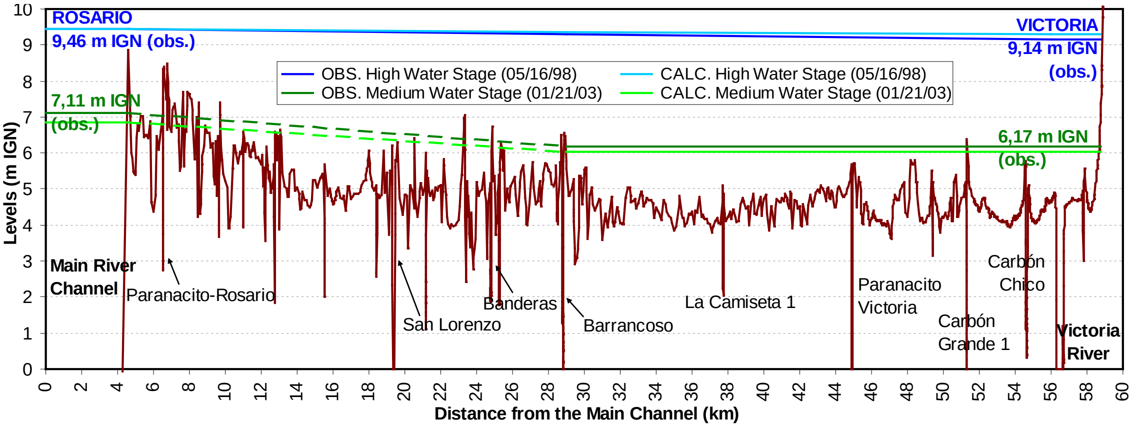



**Figure 3** River-Floodplain cross section Rosario-Victoria. Comparison of calculated and observed water levels.

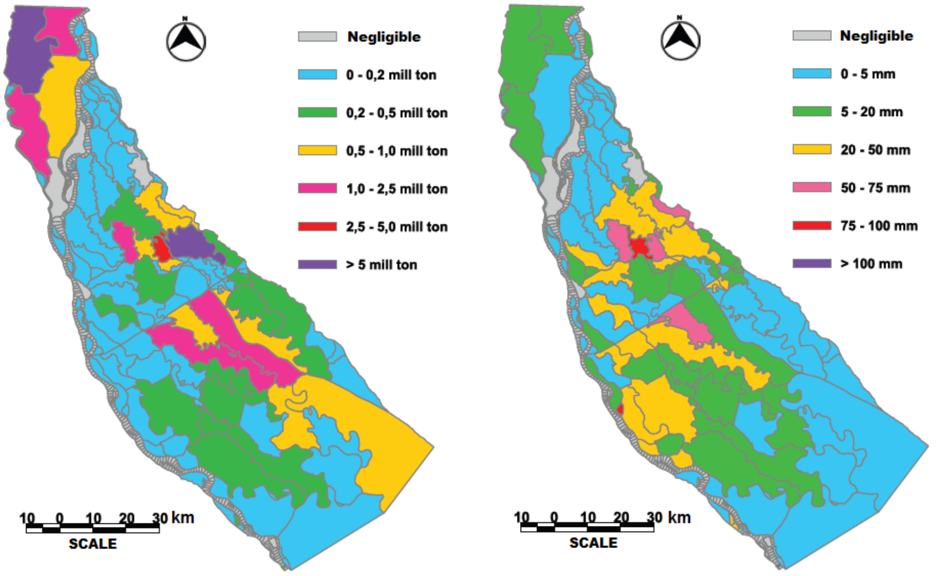
## 4.2 Sedimentological simulations of observed floods

The sedimentological simulations were performed for 1994 (medium water stage), 1997 (high water stage), 1980-´89, 1990-´99, and 2000-´10, this last period with and without the RV road embankment.

Regarding sediment input at Diamante (upstream boundary), a synthetic sedigraph was determined based on available suspended sediment concentrations and water discharge measurements at Corrientes (approximately 75 km upstream). The resulting sedigraph has a maximum suspended sediment concentration of 497 mg/l (March), a mean value of 182 mg/l and a minimum value was 60 mg/l, and accounts for the lag between Corrientes and Diamante. The annual suspended transport of fine sediments for the registered hydrological years varied from $105\times10^6$ t/year to $135\times10^6$ t/year. The suspended sediment input at Coronda shows a similar temporal distribution but, according to measurements reported in Amsler et al. (2007), the maximum concentration is about 195 mg/l and the total annual input varies between $4.7\times10^6$ t/year to $8.6\times10^6$ t/year.

In order to define sedimentological parameters such as sediment fall velocity ($w_s$) and critical mean flow velocity for deposition ($U_{cd}$), plausible ranges from measurements performed on the floodplain were considered (Mangini et al., 2005). Measurements indicate that $U_{cd}$ varies between 0.1 m/s and 0.2 m/s and $w_s$ between $1\times10^{-5}$ (m/s) and $4\times10^{-4}$ (m/s). These values of $w_s$ correspond to coarse clay (3.35 μm) and medium silt (21.2 μm), respectively when the equivalent diameter is calculated using Stokes law. A value of $U_{cd}$=0.15 m/s was specified and three values of $w_s$ within the observed range were adopted. For sediment porosity the following values were assigned, which account for different levels of compaction: 0.45 for annual simulations, 0.44 for biannual simulations and 0.40 for long term simulations (10 years). In Figure 4, a gvSIG visualization of the spatial distribution of deposited sediments expresed in millions of tonnes (Figure 4a) and in terms of total bed level variation in mm (Figure 4b) is observed, which corresponds to the simulation of year 1997 by considering $w_s$ = 0.0001 m/s and $U_{cd}$ = 0.15 m/s. Higher deposits are observed in cells corresponding to lagoon areas where the flow velocity is very low. In Table 2 a summary of results for the entire simulation set is presented.

Simulations were performed using a time step of 3600 s and model results were printed every 24 hours. Average CPU time of ten-year periods was between 10-12 minutes, working on a computer with Intel Core 2 Quad 2.4 GHz CPU and 2 GB of RAM.




**(a)** **(b)**

**Figure 4** (a) Deposited sediments, b) Bed level variation. Year 1997 ($w_s$ = 0.0001 m/s, $U_{cd}$ = 0.15 m/s).

**Table 2** Summary of sedimentological simulation results for observed floods.

| | **Without RV** | | | **With RV (% increment)** |
|---|---|---|---|---|
| **Variable** | **Total 10 yrs** | **Mean anual** | **Tot. yearly** | **Total 10 yrs** |
| Incoming SST [$10^6$ t] | 1050 - 1260 | 105 - 126 | 105 - 135 | --- |
| Deposited sediments (entire domain) [$10^6$ t] | 150 - 465 | 14 - 47 | 16 - 54 | 0.81 - 1.66 |
| Trapping efficiency (entire domain) [%] | 14 - 37 | | 15 - 40 | 0.20 - 0.26 |
| Deposited sediments (floodplain cells) [$10^6$ t] | 70 - 215 | 7 - 20 | 6 - 28 | 0.19 -1.72 |
| Trapping efficiency (floodplain) [%] | 7 - 17 | | 5 - 21 | 0.01 - 0.12 |
| Bed level variation in floodplain cells [mm] | 10 - 100 | 1 - 10 | 0.5 - 13 | 0 - 38 |
| Simulated period | `80-`89, `90-`99, `00-`10 | | `94, `97 | `00-`10 |

### 4.3 Water and sediment behaviour prediction for synthetic extraordinary floods

The model was applied to predict the behavior of water and sediments with synthetic extraordinary hydrological events. Three different hydrological years were simulated with synthetic hydrographs generated for 100, 1000 and 10000 years return period of peak discharge. In turn, for each return period three types of flood events were considered, i.e., long duration of maximum discharges (like 1982-´83), concentrated period of maximum discharges (like 1992) and standard (like 1997 flood). Each scenario was simulated without and with the RV road embankment. Peak water discharges for each event were 58000 m³/s (R=100 years), 74000 m³/s (R=1000 years) and 89000 m³/s (R=10000 years). In Figure 5 a longitudinal profile showing water levels corresponding to flood peak discharges of different return periods without and with RV embankment are presented.

The incoming annual suspended transport of fine sediments for these synthetic extraordinary hydrological years varied from 138×10$^6$ t/year to 244×10$^6$ t/year. In Table 3 a summary of results for the most relevant sedimentological variables, considering all return periods and flood types, is presented.

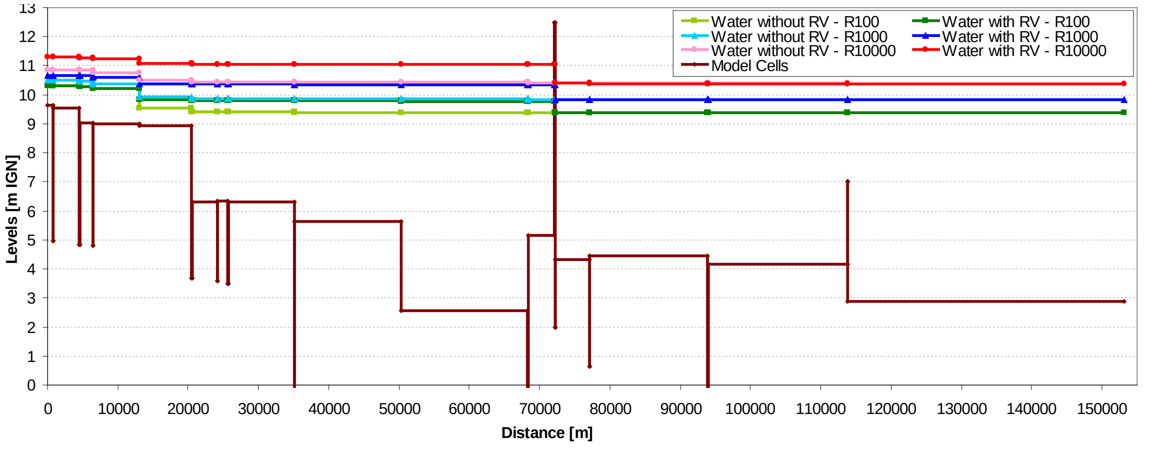



**Figure 5** Floodplain longitudinal profile and water levels for peak flood of different R, without and with RV.

**Table 3** Summary of simulation results for synthetic extraordinary floods.

| Variable | Without RV | | | With RV (% increment) † |
|---|---|---|---|---|
| | R=100 yr | R=1000 yr | R=10000 yr | |
| Incoming SST [10$^6$ t] | 138 - 180 | 148 - 210 | 160 - 244 | --- |
| Deposited sediments (entire domain) [10$^6$ t] | 31 - 95 | 35 - 126 | 40 - 156 | Less than 1.26 |
| Trapping efficiency (entire domain) [%] | 23 - 52 | 24 - 60 | 25 - 64 | Less than 0.43 |
| Deposited sediments (floodplain cells) [10$^6$ t] | 22 - 66 | 26 - 95 | 32 - 123 | Less than 3.76 |
| Trapping efficiency (floodplain) [%] | 16 - 36 | 18 - 45 | 20 - 50 | Less than 1.25 |
| Bed level variation in floodplain cells [mm] | 2 - 24 | 2.5 - 24 | 3 - 25 | 0.1 – 43.75 |

† Maximum increment considering all return periods and flood types.

## 5 DISCUSSION

The simulation results of recorded floods, corresponding to the 2000-2010 period, without and with RV road embankment, show that upstream values of both water levels and water residence time in floodplain cells increases due to the embankment. The biggest difference in water levels is about 0.65 m and the backwater extent, during peak flood, is approximately 53.5 km. Water residence time increases from 5% to 50%, depending on the accumulated flooded area.

The simulation results for all observed floods, without the influence of the RV road embankment, show that the floodplain retains annually between 5% and 21% approximately of the total incoming suspended sediment transport (Table 2). The total amount of sediment input represents plausible values, according to the available measurements upstream. Moreover the simulated suspended sediment concentrations in the main stream show an acceptable agreement with the available measurements downstream. It is estimated that the accumulated annually sediment deposits generate an average increase of floodplain bottom level ranging between 0.5 mm/year to 13 mm/year, depending on time evolution of flooded area. This is consistent with observations made in some dredged trenches within the floodplain. The simulations including the RV road embankment shows that in 10 years the presence of the embankment induces an increase in bed level variation of floodplain cells up to 38% .

Generally, when discharge in the main stream exceeds 25000 m³/s the corresponding water levels overtop the natural levees in all stations and flow is exchanged between river and floodplain. Moreover, by increasing the flow rate (i.e. incresing return period), there are stations that tend to equalize water levels (Diamante with Coronda and Rosario with Victoria, see Figure 3), since in these situations the alluvial valley is completely inundated. The simulations including the RV road embankment show that the presence of the embankment induces an increase in upstream water levels of 0.5 m to 0.7 m. The backwater extent, during peak flood, upstream of the embankment is approximately estimated as 61.3 km (R = 100 years), 65.5 km (R = 1000 years) and 72.5 km (R = 10000 years). It is noted that, for a given return period, the upstream water levels generated by the RV road embankment are coincident with those simulated without the embankment but for a return period an order of magnitude greater (see Figure 5). Increases in water residence time by the RV road embankment, for all return periods and flood types, are between 20% and 35% in upstream cells and the increase is up to 1.2% in downstream cells.

For synthetic extraordinary flood simulations without the RV road embankment, the mean annual sediment deposition (Table 3) attain values above the range observed for simulated recorded floods. The annual sediment range entering the system in those events (138 to 244 million tonnes, Table 3) is in the range of what can be deposited in the floodplain during a decade (70 to 215 million tonnes, Table 2). The largest sediment deposits are verified during long duration floods. Trapping efficiency in the floodplain varies between 16% and 50%, according to the flooding type and return period considered. Bed level of floodplain cells, independently of synthetic floods recurrence, increases from 2 to 25 mm. For the simulation incorporating the RV road embankment during synthetic extraordinary floods, floodplain bed levels variations increased up to 43.75% compared to the condition without the embankment.

## 6 CONCLUSIONS

A quasi-2D model CTSS8-FLUSED was implemented and applied to simulate time-dependent water and fine sediment transport processes in a river-floodplain area of approximately 8100 km² of the Paraná River. The model was calibrated and validated for low, medium and high water stages. The model reproduces adequately the water flow and sediments dynamics in the main stream and in the floodplain with low computational demand. The effect of a road embankment across the whole floodplain was also simulated. The main changes induced by the embankment are observed upstream. An increment of water levels of up to 0.65 m, greater inundation extent and longer flow durations were observed.

Floodplain sedimentation processes were evaluated. The obtained results for recorded floods show that floodplain sediment deposition varies between 6 and 28 millions t/year and floodplain trapping efficiency varies between 5% and 21%. This induces an average deposition rate ranging between 0.5 mm/year and 13 mm/year. For the entire reach, including floodplain channels and the Coronda river tributary, the sediment deposition varies between 16 and 54 millions t/year, that is, approximately 15% to 40% of the total incoming sediments.

Furthermore, hydro-sedimentological effects during synthetic extraordinary flooding events were also simulated. Comparing the results, without and with the RV road embankment, it was noted that upstream water levels, inundation extent and flow duration increases up to 35%. Regarding sediment processes, sedimentation in the entire domain can vary between 31 and 156 millions t/year and trapping efficiency vary between 23% and 64%.

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