MODELLING THE EFFECTS OF HUMAN DISTURBANCES ON THE FLOW AND SEDIMENT DYNAMICS OF A LARGE RIVER FLOODPLAIN.

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1. Introduction

Periodic inundation cycles of floodplain ecosystems in large lowland rivers are crucial to maintaining the biodiversity and ecological integrity of these areas. Human interference in these systems can change the magnitude, frequency, and duration of floods, and as a consequence the exchanges of water, sediments, nutrients, and biota between river channels and floodplains can be modified. Moreover, as floodplains play an important role in river flood attenuation it is important to understand floodplain inundation dynamics in order to make decisions on flood risk management.

Main characteristics of large river-floodplain systems in lowland areas:

- reach lengths of the order of 100 km
- floodplain widths of the order of 10 km
- river widths of the order of 1 km
- very complex morphology with a network of permanent channels, interconnected lagoons, natural levees, road embankments, different vegetation types
- sediments are transported mainly as wash load

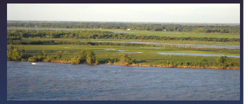

Figure 1 - Main channel and floodplain of the Paraná River, in front of Rosario.

Quasi-2D models can capture the fundamental characteristics of water flow and sediment dynamics in these areas. Large lowland river-floodplain systems have flooding duration on 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. These slow dynamics are compatible with the hypothesis on which quasi-2D models are based (Cunge, 1975) allowing for an effective compromise between computational costs and process representation.

In this poster a quasi-2D model suitable for the simulation of time-dependent water flow and fine sediment transport processes in large lowland river-floodplain systems is presented. The model implementation and application over a reach of the lower Paraná River is described. The model was calibrated, validated and applied to predict water and sediment dynamics during synthetically generated extraordinary floods. The potential impact of a 56-km long road embankment constructed across the entire floodplain was also analyzed.

2. Study Area

The model was implemented along a 208-km reach of the Paraná River, Argentina, between Diamante and Ramallo and involving a river-floodplain area of 8,100 km² (Fig. 2). The floodplain is morphologically complex, due to past episodes of sea-level rise and climate change (Iriondo, 1972). A well developed network of surface-floodplain channels, oxbow lakes, lagoons, permanent pond areas, and different types of vegetation can be observed. The floodplain width in the study area 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 station Rosario is 17,000 m³/s, while during the extraordinary floods of 1983 the maximum water discharge was approximately 60,000 m³/s with almost 30,000 m³/s flowing in the main stream, and the floodplain was completely inundated with a mean water depth of 4 m. The minimum water discharge observed at Rosario was 6,700 m³/s, in 1970. 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 varies between 1.5×10^{-5} for low water stages and 4×10^{-5} for high water stages.

The annual average total sediment transport entering the system is approximately 150×10^6 t/yr, of which 83% is composed of silt and clay transported in suspension as wash load. Sediment load entering the system is the main driver of changes in floodplain levels over long time periods. In general, suspended sediment concentrations vary seasonally, from 50 to 60 mg/l up to 500 or 600 mg/l (that occurs between March and April) in the main stream. Annual mean values are approximately within the range of 150 to 250 mg/l. The few available measurements in the floodplain indicate lower values, typically below 100 mg/l.

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

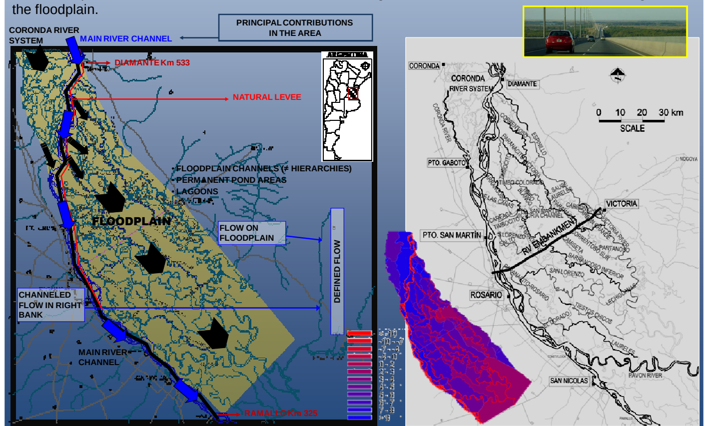

Figure 2 - Study area, MDT and main characteristics of the flow in the system.

3.CTSS8-FLUSED Model

Flow and sediment equations are discretised through an interconnected irregular cells scheme (Fig. 3), river-type cells or valley-type cells, in which different simplifications of the 1D de Saint Venant equations are used to represent discharge laws between cells (representing natural sills, levees, road embankments, culvert and bridge-like discharge laws, etc.). Spatially-distributed transport and deposition of fine sediments throughout the river-floodplain system are simulated.

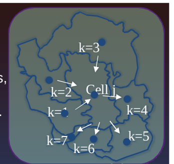

Figure 3 – Scheme model cells and links

CTSS8 Hydrodynamic Model (Riccardi, 2000)

- Flow field are represented by the approach of interconnected cells (Cunge, 1975). Water continuity for the j-th cell reads:
- Water discharge is function of water level z: $Q_{j,k}=Q(z_j, z_k)$.

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

FLUSED Sediment Module (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):

$$A_{sj}\frac{\partial (hC_s)_j}{\partial t} = (A_s\phi_s)_j + \sum_{k=1}^{N} (QC_s)_{j,k}$$

$$P_d = 1-(U/U_{cd})^2, \text{ if } U<U_{cd}$$

C_s: volumetric sediment concentration
ϕ_s: deposition rate, $\phi_s = P_d\, C_s\, w_s$
w_s: fall velocity of suspended sediment particle
P_d: probability of deposition (Krone, 1962)
U: mean flow velocity, U_{cd}: critical mean flow velocity for deposition

- Mean/total cumulative sediment deposition, bed level changes → computed for each cell
- I.C.: water levels, discharges and sediment concentrations at each cell
- B.C. water flow: hydrographs + incoming suspended sediment transport at the upstream end / water depth-discharge relations at the downstream boundary

4. Implementation and Application of the model

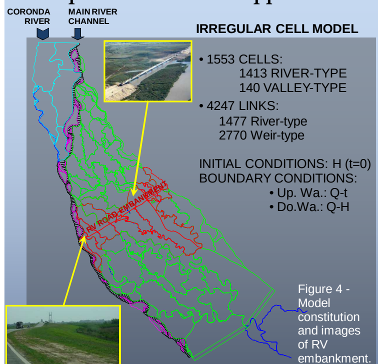

Figure 4 - Model constitution and images of RV embankment.

The topological discretisation was carried out by selecting river cells and valley cells, and by defining the different type of links between cells to represent special topographic features (natural levees, road embankments, bridges, etc.) (Fig. 4).

Two configurations of the model were created: one for the system before the construction of the RV embankment and another for thereafter. Calibration (for low, medium, and high water stages) and validation (for 10-year periods) results were very satisfactory, with the average error in calibration lower than of 10% at all stations and most Nash-Sutcliffe coefficients were above 0.8.

The different water stages (specially medium and high water) are extremely well reproduced by the model (Fig. 5). Generally, when discharge in the main stream exceeded 25,000 m³/s the water levels overtopped the natural levees at all stations and flow was exchanged between the main stream and the floodplain. With increasing flow rate, water levels at some stations tended to equalize (Diamante-Coronda and Rosario-Victoria) since the alluvial valley was completely inundated.

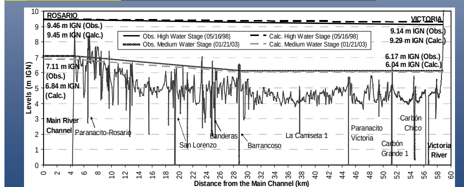

Figure 5 - River-floodplain cross section Rosario-Victoria showing main channel and secondary floodplain channels. (Calc.: calculated / Obs.: observed water levels).

Sedimentological simulations:

- 1994 - 1997 (performed)
- 1980-´89 - 1990-´99 - 2000-´10 (with and without the RV road embankment)
- Sediment Input Cs(t): at Diamante/at Coronda: synthetic sedigraph (based on available measurements), similar temporal distribution.
- Sedimentological parameters:
  - Sediment fall velocity **ws**: coarse clay (3.35 μm) - medium silt (21.2 μm)
  - Critical mean flow velocity for deposition **Ucd**: 0.15 m/s
  - Sediment Porosity p: 0.45 (1 year) - 0.44 (2 years) - 0.40 (10 years)

5. Synthetic Extraordinary Floods

Three different hydrological years were simulated with synthetic hydrographs generated for 100, 1,000, and 10,000 years return period of peak discharge, and three types of flood events were considered: long duration of maximum discharges (like the 1982-´83 flood), concentrated period of maximum discharges (like the 1992 flood), and standard (like the 1997 flood) (Fig. 6). From statistical analysis, the resulting peak water discharges for each event were 58,000 m³/s (R=100 years), 74,000 m³/s (R=1,000 years) and 89,000 m³/s (R=10,000 years).

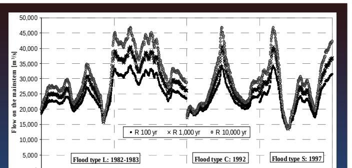

Figure 6 - Hydrographs input on main channel at Diamante.

Sediment transport and deposition simulations used the synthetic sedigraphs (determined based on available historic suspended sediment concentrations and water discharge) and sedimentological parameters (sediment fall velocity, critical mean flow velocity for deposition, sediment porosity) previously described. The incoming annual suspended transport of fine sediments for these synthetically-generated extraordinary hydrological years varied from 138×10^6 to 244×10^6 t/yr.

6. Results

Effect of the presence of RV road embankment on observed floods

Comparison of the simulation results of recorded floods corresponding to the 2000-'10 period, without and with RV road embankment, show that upstream values of both water levels and water residence time in floodplain cells increased due to the embankment. The biggest difference in water levels was about 0.65 m and the backwater extent during peak flood was approximately 53.5 km. Results show that upstream water residence time increased due to the presence of the embankment from 5% to 50%, depending on the flooded area.

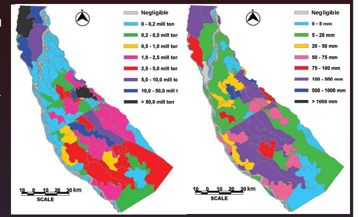

Figure 7 – Left: Deposited sediments; Right: Bed level variation. Decade ´80s (ws = 0.0001 m/s, Ucd = 0.15 m/s)

Sedimentological simulations of observed floods

The results are presented in Table 1. Fig. 7 shows the spatial distribution of deposited sediments and the corresponding bed level variation for the simulations of the period 1980-´89 (decade ’80s) and considering ws = 0.0001 m/s and Ucd = 0.15 m/s. Higher deposits were observed in cells corresponding to lagoon areas in which the flow velocity was very low, and also in cells where the floodplain widened. Practically no deposition occurred in the main stream.

Table 1 - Summary of sedimentological simulation results.

	OBSERVED FLOODS			SYNTHETIC EXTRAORDINARY FLOODS			
	Without RV		With RV (% increase)	Without RV			With RV (% increase)
Variable	Total 10 yr	Mean annual	Total 10 yr	R=100 yr	R=1,000 yr	R=10,000 yr	
Incoming SST [10^6 t]	1,050 – 1,260	105 - 126	---	138 - 180	148 - 210	160 - 244	---
Deposited sediments (entire domain) [10^6 t]	154.3 – 465.8	14.5 – 46.6	0.81 - 1.66	31 - 95	35 - 126	40 - 156	Less than 1.26
Trapping efficiency (entire domain) [%]	13.8 – 37.3		0.20 - 0.26	23 - 52	24 - 60	25 - 64	Less than 0.43
Deposited sediments (floodplain cells) [10^6 t]	71.3 – 212.6	6.7 – 21.3	0.19 -1.72	22 - 66	26 - 95	32 - 123	Less than 3.76
Trapping efficiency (floodplain) [%]	6.4 – 16.9		0.01 - 0.12	16 - 36	18 - 45	20 - 50	Less than 1.25
Bed level variation in floodplain cells [mm]	6.4 – 98.7	0.6 – 9.9	0 – 38	2 - 24	2.5 - 24	3 - 25	0.1 – 43.75
Simulated period	`80-`89, `90-`99, `00-`10		`00-`10	synthetic extraordinary floods			

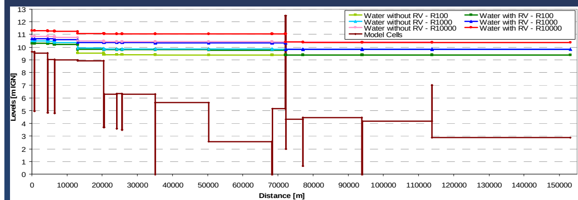

Figure 8 - Floodplain longitudinal profile and water levels for peak flood of different return periods (R), without and with RV embankment

Water and sediment behaviour prediction for synthetic extraordinary floods (without RV embankment)

- Maximum capacity of the main channel: 30000 m³/s
- Remanent flux: enter by OVERFLOWING to floodplain
- MAXIMUM water levels > Levels EVACUATION (even R=100 years)
- Flood with > flooded areas: type P
- Mean annual sediment deposition attain values above the range observed for simulated recorded floods.

The behavior of water and sediments on the Floodplain (with RV embankment)

- induced an increase in upstream water levels of 0.5 m to 0.7 m.
- the backwater extent (peak flood) upstream is ≈ 61.3 km (R=100 years), 65.5 km (R=1000 years) and 72.5 km (R=10000 years).
- For a given R, the upstream water levels generated are coincident with those simulated without the embankment, but for a return period an order of magnitude greater.
- Increases in water residence time are 20% - 35% in upstream cells and the increase is up to 1.2% in downstream cells.
- Annual sediment range entering the system is in the range of what can be deposited in the floodplain during a decade (see Table 1).
- The long duration floods (type L) produced the largest deposits, with the standard floods (type S) also producing significant deposits but not as large and the deposition from the long duration flood is more evenly distributed. Concentrated floods (type C) had the smallest deposits and they were concentrated in a few cells. These patterns remained unchanged for the different recurrence, but they were reinforced with increasing discharges.
- The differences in deposited sediment were driven by increases upstream of the RV road embankment and on the left margin, because of water level increases and redistribution of flow to this sector.

7. References

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