Quasi-2D modeling of hydro-sedimentological processes in large lowland river-floodplain systems

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C: Morphodynamics of alluvial plains

ABSTRACT: In this work a quasi two-dimensional model called CTSS8_FLUSED, suitable for the time-dependent water and fine sediment transport processes simulation in large lowland river systems, including their floodplains, is presented. Water flow and sediment equations are represented by means of the interconnected cells scheme. Different simplifications of the Saint Venant momentum equation are used to represent the discharge laws between fluvial cells. Spatially-distributed transport, deposition and erosion processes of fine sediments throughout the river-floodplain system can be simulated. The model is particularly appropriated for simulations at large space scale and for both short and long-term scale. The hydrodynamic module of the model is applied along a 205 km reach of the Paraná River, Argentina, and involving a river-floodplain area of nearly 8000 km^2. Hydraulic processes in the main stream-floodplain system were simulated. The numerical simulations were carried out for both low and mean river water stages and satisfactory results were obtained during model calibration and validation.

1 INTRODUCTION

The role of floodplains as sinks for fine sediments and particulate-associated contaminants has promoted the development of different measurement techniques and computational models to study overbank sedimentation processes. Floodplain sedimentation processes presents a high spatial variability (Walling et al., 1996). As a result, spatial distribution of sedimentation in morphological complex floodplains cannot be represented by simple one-dimensional lateral overbank deposition models based on analytical equations (e.g. Pizzuto, 1987; Howard, 1992). Moreover, one-dimensional hydrodynamic model combined with a settling tank model (e.g. Asselman et al., 2002) and two and three-dimensional numerical models have been implemented to simulate river-floodplain hydraulics (Horrit et al., 2002; Nicholas et al., 2004; Bates et al., 2006; Wilson et al., 2006) and suspended sediment transport and deposition processes in floodplain (Stewart et al., 1999; Hardy et al., 2000; Nicholas, 2003; Nicholas et al. 2006).

The one and two-dimensional models cited above 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 surface-floodplain channels. In addition, the three-dimensional models have been applied at space scales of the order of a kilometer.

Large river-floodplain systems in lowland areas shows 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. The floodplain itself shows also a very complex morphology with a network of permanent channels, interconnected lakes, natural levees, different vegetation type, etc. Due to the significant floodplain areas involved, the rainfall over inner watersheds play also a very important role in the water flow dynamics of surface-floodplain channels. In this context, the computational-expensive water flow and sediment transport models that have been implemented in river-floodplain simulations until now cannot adequately represent these kind of peculiarities over rather large time and space scales. In fact, from one hand 1D models are not appropriated because the one-dimensional flow description is not representative of real flow pattern. On the other hand, the computational demands of full 2D depth averaged models and 3D models preclude their application over large time and space scales.

An alternative to high resolution models is the implementation of quasi two-dimensional 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 achived. In effect, in large lowland river-floodplain systems flooding duration is of the order of several months. In particular, the floodplain filling due to overbank flows from the main

main stream and secondary channels is gradual and evolve fairly slowly. This hydraulic process is totally compatible with the hypothesis on which the quasi two-dimensional models are based (Cunge 1975, Cunge et al., 1980). In effect, the quasi-2D hydraulic model CTSS8 (Riccardi, 2000) applied to Paraná River have showed a capability of reproduction of transversal velocity profiles similar to the obtained ones with a full two-dimensional depth averaged model (Basile & Riccardi, 2002).

In this work a quasi two-dimensional model called CTSS8_FLUSED, suitable for the time-dependent water and fine sediment transport processes simulation in large lowland river-floodplain systems is presented. The hydrodynamic module of the model is applied along a 205 km reach of the Paraná River, Argentina.

2 BRIEF DESCRIPTION OF THE MODEL

The governing equations for the quasi two-dimensional horizontal time-dependent flow and sediment transport field are represented by the well-known approach of interconnected cells. Water continuity equation for the j-th cell reads:

$$A_{s\,j}\frac{dz_j}{dt} = \left(A_s\,P(t)\right)_j + \sum_{k=1}^{N} Q_{j,k} \qquad (1)$$

where z_j is water level; A_{sj} is surface area of the cell, t is time; P_j is rainfall intensity; $Q_{j,k}$ 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.

Quasi-2D continuity equation for fine sediments (d<62 μm) in the j-th cell reads:

$$A_{s\,j}\frac{d\left(h\,C_s\right)_j}{dt} = \left(A_s\,\phi_s\right)_j + \sum_{k=1}^{N}\left(Q\,C_s\right)_{j,k} \qquad (2)$$

where h is water depth, C_s is the sediment concentration and ϕ_s is the net vertical sediment flux. For sedimentation in floodplain cells, the vertical sediment flux is expressed by the sum of two terms, one representing particle settling and the second term representing entrapment of sediment by vegetation. Instead, for stream cells only particle settling is considered. In Equation (2) only advection is considered because suspended sediment transport on natural floodplains is dominated by advection rather than diffusion (Middelkoop et al., 1998; Nicholas, 2003).

Water flow and sediment equations are solved by means of 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. Instantaneous and mean annual sedimentation rates are computed for each cell. 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. A computational platform for model running, geovisualization, pre and post-processing in Windows© was developed (Stenta et al., 2005).

3 MODEL APPLICATION

3.1 *Brief description of the study area*

The model was implemented along a 205 km reach of the Paraná River, Argentina, between Diamante (km 530) and Ramallo (km 325) and involving a river-floodplain area of nearly 8000 km^2. The floodplain width varies between 40 to 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 17,000 m^3/s, while during the extraordinary flooding of 1983, the maximum water discharge was approximately 60,000 m^3/s with 27,500 m^3/s flowing in the main stream and 32,500 m^3/s, with mean water depth of 3 m, in the floodplain.

The main stream at macro-scale shows a morphological configuration of braided river, while the thalweg is very well defined and presents a meandering configuration. The riverbed is formed by quasi uniform sand with d_{50} varying between 0.26 to 0.32 mm. The annual average total sediment transport at Rosario is approximately 98×10^6 t/year from which 81% is composed by silt and clay transported as wash load. The floodplain is morphologically complex. Five different morphological units can be observed (Iriondo, 1972). It is crossed by a well developed network of channels with natural levees along both main stream and secondary surface-floodplain channels. Also, oxbow lakes, 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, silt or clay with silt over Tertiary claystones. The top soil layers of the floodplain and islands are formed by very fine sediments in the silt and clay range.

3.2 *Model implementation*

The topological constitution of the model had a gradual development. First, the DTM was developed using existing data gathered from topographic surveys conducted in the alluvial valley, bathymetric data of the main stream and surface-floodplain channels, satellite images and aerial photos of the area, in different states of the river (low, mean and high water stages). The topological discretization was made by selecting stream cells, floodplain cells and by defining the different type of links between cells to represent special topographic features. A two dimensional rectangular grid formed by cells of 500 × 500 m was specified. Currently, the model has 6636 elements that represent the main stream and secondary surface-floodplain channels (stream cells) and 23,220 elements representing the alluvial valley (floodplain cells).

Water depth – discharge relationships in the downstream end cells of the model were specified. Roughness coefficients along main stream and surface-floodplain channels were specified and discharge coefficients in the weir type links were assigned. A number of model runs were performed by considering only the hydrodynamic module of the model. Preliminary tests were performed with constant water discharge to control the connectivity between cells and the correct functioning of the model. The model was running with a constant discharge of 17,000 m^3/s until the water level in all cells was steady.

In order to analyze the dynamic behavior of the system, with stream flow only, hydrographs that did not generate any noticeable water transfer from the main stream and surface-floodplain channels cells towards the floodplain cells were considered. Such events were characterized by low and mean water stages. For low water stages the hydrograph of the year 1968 was considered. It is a hydrological year with a mean annual discharge of 10,130 m^3/s. For mean water stages the hydrograph corresponding to the year 1994 was considered. It is a typical hydrological year which represents the real hydrograph that better is adjusted to the average statistical hydrograph corresponding to 1967-1996 period. The mean annual water discharge for the year 1994 was 17,042 m^3/s. The model was calibrated by considering the event of 1968. Several model runs were carried out and roughness coefficients and discharge coefficients in weir type links between main stream cells and surface-floodplain channels cells were adjusted. After that, with the coefficients obtained in the calibration process, the model was validated by considering the 1994 hydrological event. The obtained values of the Manning roughness coefficients varied between 0,033-0,040 $s/m^{1/3}$. On the other hand, the discharge coefficients, that simulate the existing links between the main stream cells and secondary channels cells in the floodplain, varied between 0.2 and 0.5 depending on the direction of the incident flow from the main stream.

3.3 *Evaluation of results*

The simulations showed how the water is distributed in the surface-floodplain channel network during low and mean hydrological years. The water enters to the floodplain channels mainly through (i) several connections along the left bank of the main stream in the northern part of the floodplain, from Diamante until Oliveros; (ii) the connection of the old navigation channel to Victoria and (iii) the Pavón stream in the southern part of the floodplain. In the northern part of secondary surface-floodplain channel network, a trend of increased flow in NO-SE direction is observed, that is, towards the denominated plain of temporary activation, which is a region with permanent pond areas in the left bank of the floodplain. The simulations showed that the model adequately describes the stream flow pattern dynamics in floodplain channels. With regard to the calibration procedure, it consisted in ensuring the better agreement between calculated daily water level series and the corresponding observed ones in different sections along the main stream. The roughness coefficients varied in a limited range and the obtained values are physically reasonable. Also, likely values of discharge coefficients in weir-type links were assigned. In order to evaluate the efficiency of the modeling results, the coefficient of Nash-Sutcliffe (1970) was used. This coefficient can vary between $-\infty < E \leq 1$, E=1 corresponds to a perfect adjustment between calculated and observed water levels. The values of E in three stations varied between 0.92 to 0.96 for the year 1968 and between 0.81 to 0.91 for the year 1994. The obtained adjustment is very satisfactory. A slight but not significant diminution of E for model validation run with mean water stages is observed.

4 CONCLUSIONS

The CTSS8_FLUSED quasi two-dimensional water flow and fine sediment transport model was applied to simulate the hydrodynamics of a Paraná River reach including its floodplain, particularly in conditions of low and mean water stages. The model is suitable for simulations at large space scale and satisfactorily represents the stream flow dynamics in the main stream and secondary floodplain channels system.

5 REFERENCES

Asselman N.E.M. & Wijngaarden, M. 2002. Development and application of a 1D floodplain sedimentation model for the River Rhine in The Netherlands. *Journal of Hydrology* 268: 127-142.

Basile, P.A. & Riccardi, G.A. 2002. A Quasi-2D Hydro-Morphological Mathematical Model: An Application to the Argentinean Paraná River. *International Journal of Sediment Research* 17 (1): 20-30.