THE FLOOD PROPAGATION MODELLING FOR THE MANAGEMENT OF DEVELOPMENT ON FLOOD PLAINS OF ROSARIO REGION, ARGENTINA

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Abstract

River flood plains are being subjected to intense urbanization processes in big cities of the world. These human actions on the environment have incresead the floods besides the urban drainage in a continuously incremented hydro-environmental risk. These problems could have not been solved only with structural works. Therefore, non-structural actions would be established. The mapping of risk zones by mean of mathematical modelling is a technical tool to carry out control policies of soil usage and occupation. In this work a two-dimensional mathematical model and the determination of inundation risk maps on two flood plains of Rosario region are exposed. The model can simulate both, free surface and close conduits flow over rural and urban zones. The mappings were made for floods of return periods of 50, 100 and 500 years. The studied zones embraced a superficial extent of 70 km2, with a population of 500000 inhabitants. Based on the results, state and local governments have planned non-structural rules with the associated legislation for the future urbanization processes. The flood propagation modelling has shown to be a necessary tool for the planning and control of water resources for a sustainable development.

1. INTRODUCTION

The Rosario region, is located at the south of the Santa Fe state, Argentina. It is crossed by several rivers and channels. The headwaters of these water courses are located in a rural zone with non-defined beds. Downstream, they flow by more defined beds and permanent drainage. The flood plains include big inhabited cities as Rosario. The overflows result into both material and human being losses. To solve this problem, regional governments have built several structural works (a retention dam, canalization, conduits, etc.). Later, the definition of non-structural rules was necessary to define the legislation that allows both flood plain occupation and appropriated use. The laws will contribute to the regional planning of the water resources. In this context, it was proposed to configure inundation risk maps associated with return periods by means of flow simulation mathematical modelling. With that objective a two-dimensional mathematical model of cells was developed and implemented. It is capable for subcritical and supercritical flow simulation with superficial propagation, over river and flood plain. Concerning to urban zones routing, the model was developed to simulate flood propagation both on streets (major system of urban drainage), and inside close conduit networks (minor system). Also on the water courses are possible to simulate in simplified form the transport of bed sediment.

2. MODEL FORMULATION AND GOVERNING EQUATIONS

The model hypotheses agree with the flow characteristics in the regional water courses, where rivers and streams are constituted by a main permanent bed and a temporarily occupied flood plain.

This hydric configuration allows to divide it in several interconnected cells. Moreover, the model uses a numeric resolution algorithm in which it doesn't exist any type of restrictions relating to the links between the cells. Therefore, the model provides any alternatives of both topological and hydraulic discretization. The equations that govern the model are those of the continuity and those of discharge between linked cells.

2.1 Continuity equations

It is supposed that the whole cell **i** corresponds to a characteristic water level $\mathbf{z_i}$ that is assumed in the cell center (Fig. 1). Also, it is assumed that the water surface is horizontal between the borders of the cell and it is z_i. The two fundamental hypotheses are:

(1) The volume $\mathbf{V_i}$ of water stored in cell **i** is directly related to its water level $\mathbf{z_i}$: $\mathbf{V_i = V(z_i)}$

(2) The discharge $\mathbf{Q^n_{i,i+1}}$ between two adjacent cell **i** and **i+1** at one time given $\mathbf{n\ \Delta t}$ is a function of the energy levels: $\mathbf{z^n_i + \alpha_i V^2_i / 2g}$ and $\mathbf{z^n_{i+1} + \alpha_{i+1} V^2_{i+1} / 2g}$

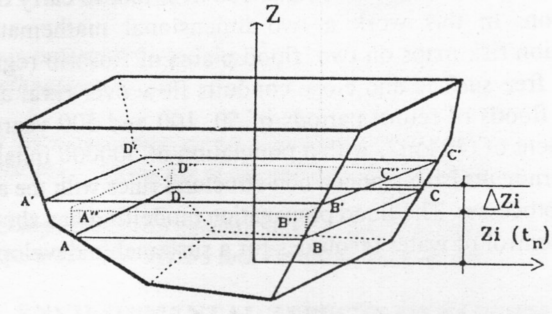

Figure 1. Continuity equation of a cell.

The forces originated in the local acceleration are neglected. It is possible arrive to the continuity equation written under the differential form used by the model (Cunge, 1975):

$$A_{S_i} \frac{dz_i}{dt} = P_{i_{(t)}} + \sum_i^k Q^{(n)}_{i,i+1} \left(z_i^{(n)}, z_{i+1}^{(n)}\right) \qquad (1)$$

There are many equations (1) as well as cells **i** in the model and, also as well as unknown water levels $\mathbf{z_i(t)}$. The solution to this system exists and is unique if the set of initial conditions $\mathbf{z_i(t=0)}$ is prescribed (Cunge, 1975). Once this set is known, the functions $\mathbf{z_i(t)}$ and $\mathbf{Q_{i,k}}$ may be computed numerically. Moreover, the boundary conditions varying in time must be prescribed.

2.2 Laws of discharge between the cells

2.2.1 Simple river type links

The $\mathbf{Q_{i,k}}$ expression is deduced by discretization of the momentum equation for flow with inertial forces negligible and considering the Strickler-Manning resistance formula:

$$Q_{i,i+1}^{(n)} = sign\,(z_{i+1}^{(n)} - z_i^{(n)}) \frac{K_{i,i+1}^{(n)}}{\sqrt{\Delta x}} \sqrt{|z_{i+1}^{(n)} - z_i^{(n)}|} \tag{2}$$

where: z_i and z_{i+1} are the water level in the cells, $K_{i,i+1}$ is the conveyance coefficient, defined by $K_{i,i+1} = k\, A_{i,i+1}\, R_{i,i+1}^{2/3}$ with k: roughness coefficient of Strickler $(1/\eta)$, $A_{i,i+1}$: cross-section, $R_{i,i+1}$: hydraulic radius and Δx is the fixed distance between the cell centers.

2.2.3 Kinematic type links

These links are used only when the hydrodynamic information is propagated towards downstream. This physical case may be presented over the high cells of the modelled zone. The idscharge is computed in function of the upstream cell level : $Q_{i,i+1} = f\,(z_i)$.

2.2.4 Complete river type links

The deduction of the discharge expresion is based on the complete momentum equatios:

$$a\, Q_{i,k}^{\;2} + b\, Q_{i,k} + c = 0 \tag{3.1}$$

$$a = a_1 \pm a_2 \qquad a_1 = \frac{\theta}{\Delta x\, A_{i,i+1}^{(n)}} \qquad a_2 = g\,\theta\, \frac{\theta\, A_{i,i+1}^{(n)} + (1-\theta)\, A_{i,i+1}^{(n-1)}}{\theta\, K_{i,i+1}^{(n-1)^2} + (1-\theta)\, K_{i,i+1}^{(n)^2}} \tag{3.2}$$

$$b = \frac{1}{\Delta t} \tag{3.3}$$

$$c = -\frac{Q_{i,i+1}^{(n-1)}}{\Delta t} + \frac{\theta}{\Delta x}\left[-\left(\frac{Q^2}{A}\right)_{i-1,i}^{(n)}\right] + \frac{(1-\theta)}{\Delta x}\left[\left(\frac{Q^2}{A}\right)_{i,i+1}^{(n-1)} - \left(\frac{Q^2}{A}\right)_{i-1,i}^{(n)}\right] +$$

$$\frac{g}{\Delta x}\left[\theta\, A_{i,i+1}^{(n)} + (1-\theta)\, A_{i,i+1}^{(n-1)}\right]\left[\theta\,(z_{i+1}^{(n)} - z_i^{(n)}) + (1-\theta)\,(z_{i+1}^{(n-1)} - z_i^{(n-1)})\right] +$$

$$+\, g\,(1-\theta) \frac{\theta\, A_{i,i+1}^{(n)} + (1-\theta)\, A_{i,i+1}^{(n-1)}}{\theta\, K_{i,i+1}^{(n)^2} + (1-\theta)\, K_{i,i+1}^{(n-1)^2}} \left(Q_{i,i+1}^{(n-1)} |Q_{i,i+1}^{(n-1)}|\right) \tag{3.4}$$

$$Q_{i,i+1}^{(n)} = -b + \frac{\sqrt{b^2 - 4(a_1 + a_2)c}}{2(a_1 + a_2)} \quad si\ c < 0 \qquad Q_{i,i+1}^{(n)} = -b - \frac{\sqrt{b^2 - 4(a_1 - a_2)c}}{2(a_1 - a_2)} \quad si\ c > 0 \qquad (3.5)$$

where $0.5 \leq \theta \leq 1$

2.2.4 Weir type links

This link type is used to represent links between cells with a physical limit. Cells separated by highway embankments, roads, bridges, links between main course and flood plain, etc. For the discharge calculation the expression of the wide crest weir is used, with μ_1 and μ_2 as the coefficients discharge and **b** the effective weir width:

$$Q_{i,i+1}^{(n)} = \mu_1\ b\ \sqrt{2g}\ (z_i^{(n)} - z_w)^{3/2} \qquad \textit{Free flow weir} \qquad (4.1)$$

$$Q_{i,i+1}^{(n)} = \mu_2\ b\ \sqrt{2g}\ (z_{i+1}^{(n)} - z_w)\ \sqrt{z_i^{(n)} - z_{i+1}^{(n)}} \qquad \textit{Floodedflow weir} \qquad (4.2)$$

2.2.5 Loss energy type links

These links are capable for flow singularities with energy losses due to abrupt changes in the cross-section. Those are present usually in sewers, collectors mouths, junctions box, etc. Considering to **k** as the portion of velocity energy loss, the $\mathbf{Q_{i,i+1}}$ expression in a contraction (eq. (5.1)) and expansion (eq. (5.2)) are defined as:

$$Q_{i,i+1}^{(n)} = \sqrt{2g}\ \sqrt{\frac{z_i^{(n)} - z_{i+1}^{(n)}}{\left(\frac{1+k_{i+1}}{A_{i+1}^2} - \frac{1}{A_i^2}\right)}} \qquad (5.1)$$

$$Q_{i,i+1}^{(n)} = \sqrt{2g}\ \sqrt{\frac{z_i^{(n)} - z_{i+1}^{(n)}}{\left(\frac{1}{A_{i+1}^2} - \frac{1-k_i}{A_i^2}\right)}} \qquad (5.2)$$

2.2.6 Frictional conduit type links

These links are used for connection between cells of close conduits. The discharge is similar to river links exposed above. The difference from those is given for the cases that the conduit works under pressure. In 0these cases the Preissmann slot (Cunge, 1980) is used in the continuity equation:

$$A_{s_i} = \frac{g\, A_{i_0}}{a^2}\, L_i \qquad (6)$$

where A_{i0}, a and L_i are the cross-sectional area, the propagation speed of the elastic weave and the lenght of cell.

2.3 Transport of bed sediment

The model can simulate the transport of bed sediment. The solid transport **G = G (Q,h,S)** can be resolved by the Engelund-Hansen, Einstein, Meyer-Peters and Richards formulations (Vannoni ,1975) . The process can be simulated over cells with permanent flow.

3. NUMERICAL FORMULATION AND BOUNDARY AND INITIAL CONDITIONS

An implicit method of finite difference for the numerical resolution is ured (Cunge, 1975) :

$$A_{s_i} \frac{\Delta z_i}{\Delta t} = P_i + \sum_1^k Q_{i,k}^{(n)} + \sum_1^k \frac{\partial Q_{i,k}^{(n)}}{\partial z_i} \Delta z_i + \sum_1^k \frac{\partial Q_{i,k}^{\,n}}{\partial z_k} \Delta z_k \qquad (7)$$

where $\mathbf{A_{Si}}$, $\mathbf{P_i}$ and $\mathbf{Q_{i,k}}$ are known in the time $\mathbf{t= n\ \Delta t}$ and the increments $\Delta \mathbf{z_i}$ and $\Delta \mathbf{z_k}$ are unknown.

The model uses a matrixial resolution algorithm based on the Gauss-Seidel's methcd. The solid load transported **G** is resolved by uncoupled solution.

There are three types of boundary conditions that the model may simulate : **(a)** Level given as a function of time; **(b)** discharge given as a function of time and **(c)** Relationship is given between level and discharge. Also, the model requires the specification of water levels in all cells at initial time.

4. DESCRIPTION OF THE MODELLED ENVIRONMENTS AND APPLICATIONS

The region of Rosario city is denominated Pampa Ondulada Argentina. The River Ludueña and River Saladillo basins belong to that region.. Both hydric systems flow towards River Parana.

The goal of the studies were to analyse the hydraulic behaviour and determinate maps with inundation risk both for a natural stage (without works) and a projected work stage (with structural works). Those maps were determined for 50, 100 and 500 years return periods. The results for: 50 years of return period without works, and 500 years of return period with works are presented in Figures 4 to 9. It can see the inflow from the high catchment (Figs. 2 and 4), the profiles of maximum water elevations (Figs. 3 and 5) and the inundation maps of the studied zones (Figs. 6 and 7). The return period events were selected on upstream boundaries.

4.1 River Saladillo

This river drains a 3000 km^2 basin area. The reach studied divides two cities (Fig. 6) : Rosario and Villa Gobernador Gálvez. The reach length is seven km, beginning in rural zone and ending in a cascade of 15 m in height. The bottom medium slope is 0.7 o/oo. The flood plain includes a total surface of 20 km^2 , a 70 % is rural zone, 15% is semiurbanized and the 15% is fully inhabited. The area studied has a population of 200000 inhabitants. There are seven bridges with lengths of them vary from 43 m to 145 m, being shorter ones contractions of the flow. Near the cascade there is a second outflow constituted by a paleostream that flow downstream of the cascade. Embankments normally to the stream are barricades for the flow due to its height, establishing "storage cells".

In this application the structural works analysed were: cross section increment, embankment construction and works to avoid the movement of the cascade towards upstream.

The model configuration resulted in 88 cells, being 30 type rivers and 58 type valleys. Conveyance coefficients of river links were calculated with a preliminary Manning coefficient of 0.030. Flow coefficients of bridges were calculated according to Chow methodology. Boundary conditions were water level at upstream free fall law at the two outlet points downstream. Near the zone of the cascade there is a critic regime, routing its influence towards upstream. River and valley cells were 250 m lengths. The adjustment was made by mean of previous overfloods, firstly April 1986 one (1200 m^3/s peak flow, an inundation map available). The parameters adjusted were Manning coefficients in beds and valleys, weir discharge coefficients and corrective bridge factors. By means of statistical studies was defined a flow peak of 1280 m^3/s for 50 years of return period, 1488 m^3/s for 100 years and 1950 m3/s for 500 years. The lag of maximum overfloods is 44 h and base time of the hydrograph is larger than 100 h.

4.2 River Ludueña

This area studied embraces Rosario city and Funes village (Fig. 7). The river drains a 800 km^2 basin area. The lengths of river and its tributaries are 19 km, with 1.2o/oo medium slope. In the main course, overflow it presents for 80 m^3/s. The flood plain in study includes a total surface of around 50 km^2. A 75% of it is rural zone, a 15 % semiurbanized and the 10% is fully inhabited. There are around 300000 inhabitants. In a reach of 1.5 km of length the water course is piped in five conduits. These conduits have a cross section 73.3 m^2, and drain in the River Parana flowing by a channel of 0.8 km of length. The discharge maximum capacity of the conduit network is 350 m^3/s. A retention dam has been built recently in the upstream boundary.

The topological and spatial discretization was satisfied with 202 cells and 311 links. Fifty-four cells corresponded to open channel flow; 43 to conduit networks; 95 to flood plains of rural and semiurban zone and 10 to urban zone. Topographical information was considered over a grid of points of 100 m average distance, this information was digitalized for a precise determination of 0.25 m contour maps. The hydraulic parameters considered in preliminary form: roughness, efficiency coefficients, etc. was taking in account for previous simulations (Riccardi, 1994). The model was calibrated in function of different floods and mainly with one measured in 1986 of 40 years of return period. It was carried out the mapping for the probably maximum flood (PMF) as catastrophe event. The values of the discharge peaks were 500 m^3/s for 50 years of return period, 700 m^3/s for 100 years, 1000 m^3/s for 500 years and 1700 m^3/s for the PMF.

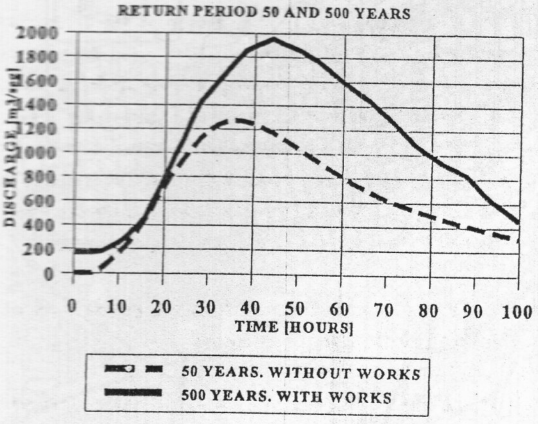

Figura 2. River Saladillo
Upstream Hydrographs.

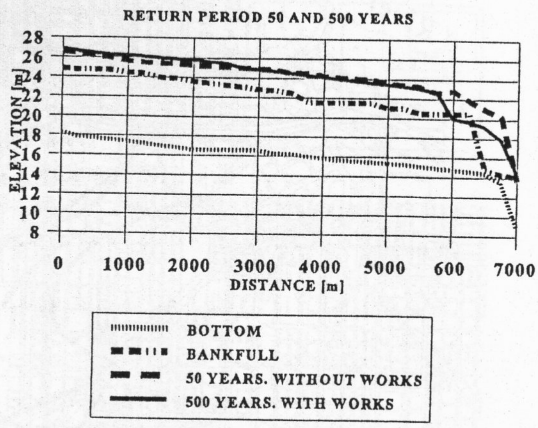

Figura 3. River Saladillo
Maximum Elevations.

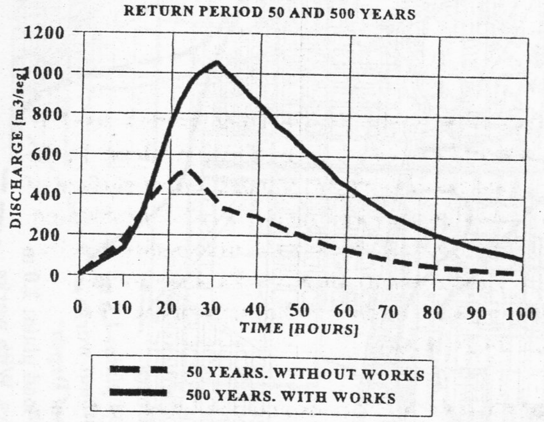

Figura 4. River Ludueña.
Upstream Hydrographs.

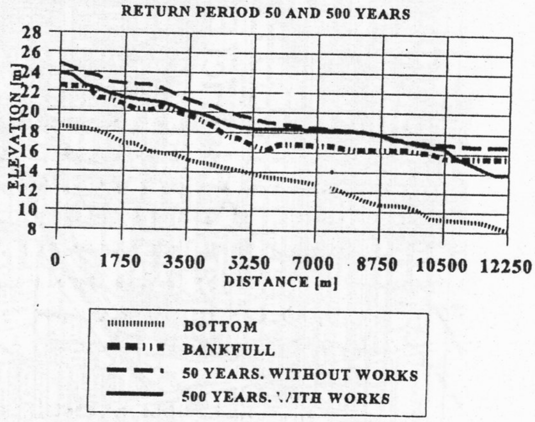

Figura 5. River Ludueña
Maximum Elevations.

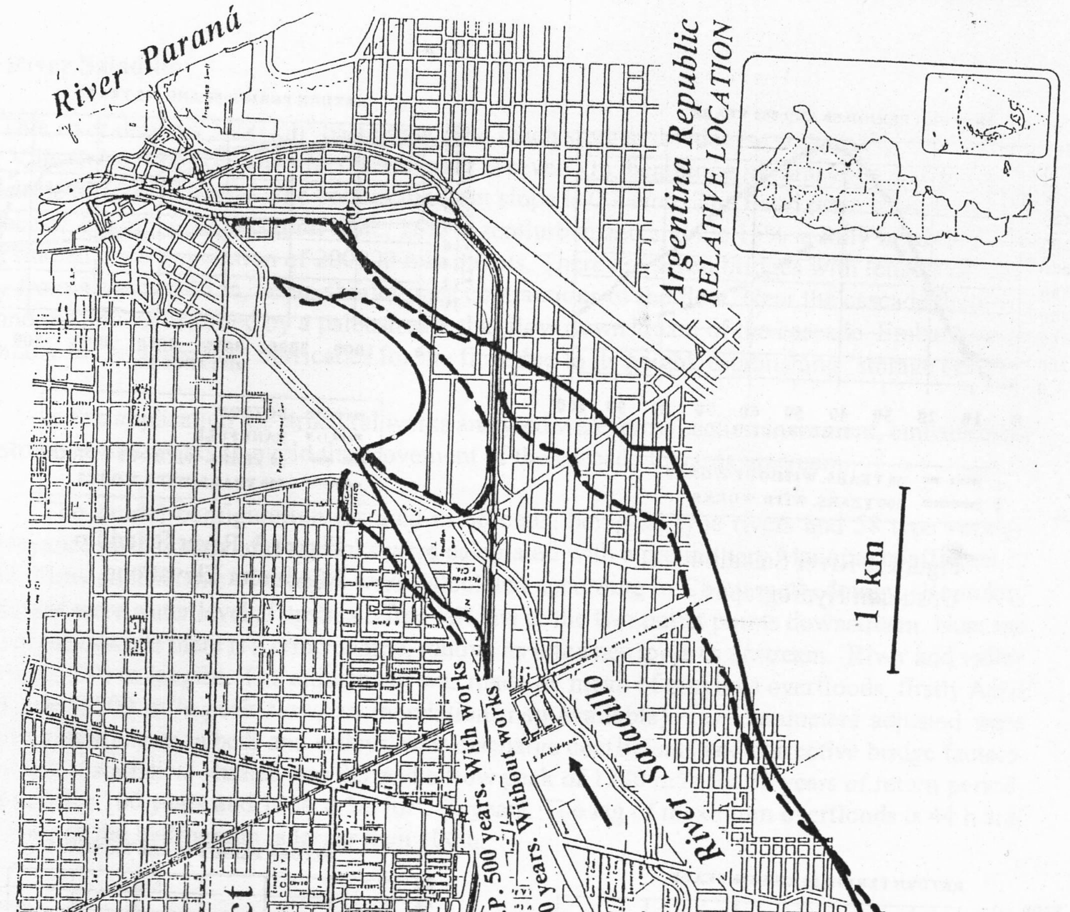

Figure 6. Inundation Map River Saladillo.

Figure 7. Inundation Map River Ludueña.

5. USE OF RESULTS

Based on the risk area delimitations described in this paper, state and local government have planned the non-structural rules and they are developing the associated legislation. The projected legislation proposes severe restrictions of soil use and occupation for the risk zone of 100 years of return period. The inundation map of 500 years return period was considered as the minimum risk zone (Fig. 8). Variable restriction rules in the intermediate zone have been proposed. These rules diminish towards the limit of the inundation map of 500 years return period, according to conditions of velocity and depth maximum (Fig. 9).

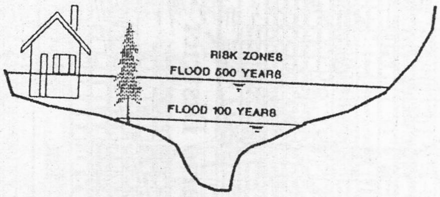

Figure 8. Inundation Risk Zone.

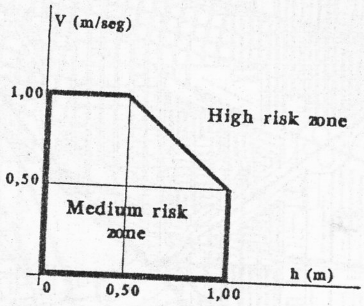

Figure 9. Criterion for 500 years inundation risk zone.

6. CONCLUSIONS

The model developed has resulted completely capable for flow simulation with twodimensional characteristic. It simulates with satisfactory approach the flow propagation by beds, flood plains, underground conduit networks and major system of urban zones. The results of applications have shown a very good approximation to the real phenomenon. The adjustment process and the first order uncertainty analysis of the variables have demonstrated the reliability and precision of the model results. It is corroborated the capaility of cell models for the simulation of different flow alternatives. Also these model applications have been able to incorporate a powerful technological tool to the managment of development on regional flood plains, allowing delimitation of zones with inundation risk by mean of computed results. These actions should be included in strategies of sustainable development and hydroenvironmental equilibrium.

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