MODCEL: A MATHEMATICAL MODEL FOR URBAN FLOOD SIMULATION AND INTEGRATED FLOOD CONTROL DESIGN

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ABSTRACT

Floods in urban landscapes usually make the built environment to interact and complement the drainage system, increasing the diversity of possible flow patterns. This situation is generally difficult to assess because of the complex relations established. The traditional approach for flood control design tended to focus on channel conveyance improvement. However, urbanisation itself limits river enlargements and city growth worsens the effectiveness of this approach. Canalisation practices tend to transfer problems to downstream areas in a non-sustainable way. To face this situation, a systemic approach must be addressed, considering the basin interactions as a whole. Besides, drainage systems have to be designed in order to minimise impacts of urbanisation over natural flow patterns and drainage solutions may appear distributed over the basin surface. Mathematical modelling is an important tool in this situation, in order to aid in clarify space and time relations among the different flow paths generated by the basin. This paper will present MODCEL as a model that intends to meet the requirements needed to represent urban floods phenomena. The construction of MODCEL was based on the concept of flow cells (Zanobetti et al., 1970): urban land surface is represented through a set of homogeneous compartments, which interact with each other, composing a complex flow net connected by several different hydraulic laws. Each cell also performs a rainfall run-off transformation. The mesh of cells results in a hydrodynamic looped model, in a spatial representation that covers all the basin area and links surface flow, channel flow and underground pipe flow. This arrangement can be interpreted as a pseudo 3D-model, although all mathematical relations written are one-dimensional. Several applications in urban environments have been held since 1996 and the case of Joana River basin, in Rio de Janeiro City, Brazil, is briefly presented in this text.

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1. INTRODUCTION

Floods in urban environments are generally associated with a complex scenery, involving technical, social-economic and environmental aspects. Urban development usually aggravates the flooding problem that, in turn, disrupts city life. Urban flooded areas make drainage systems structures to hydraulically interact with urban landscape features. Waters spilling out of the drainage net may cause inundation over large urbanised surfaces, encompassing streets, squares, buildings and so on. In this context, land shapes and man-made structures present on the built environment interact to increase the diversity of possible flow patterns. Another important aspect to consider in present urban drainage discussions is the changing that has been happening in flood control concepts, in the last decades. The traditional approach used to focus on channel conveyance improvement, what means, in general terms, the use of canalisation and rectifications of the watercourses. Urbanisation itself, however, limits river canalisation enlargements. Once city growth worsens flow generation, this approach tends to transfer problems to downstream reaches of the basin. This is a non-sustainable situation. To face this challenge, a systemic approach must consider the whole basin interactions. Distributed measures over the basin comply with the drainage net in order to control flow generation. Besides, drainage systems have to be designed in order to minimise impacts of urbanisation over natural flow patterns.

In this context, mathematical models arise as an important tool, in order to help in the design process of integrated urban drainage projects, allowing to control and to combine effects of the proposed measures in space and time. Traditional mathematical modelling approaches tend to simplify this situation focusing mainly on the drainage net and its hydraulic structures, in a one dimensional branched flow network representation. When dealing with urbanised catchments, however, it must be taken into account a set of features that distinguish urban flood phenomenon, which is generally a two-dimensional problem with an important role associated to the surface flow. This paper intends to show a mathematical model designed to couple with this concerns.

2. URBAN DRAINAGE TRADITIONAL DESIGN

Traditional practices of urban drainage design are based on canalisation works, in order to adapt the system to the concentrated flows. This approach equates the undesirable consequences of the process, which are the greater and faster discharges produced by the built environment.

In general terms, the urban drainage system design comprises the following steps: subdivision of the area into sub-basins; design of the network layout, integrating urban patterns, natural flow paths and topographic conditions; definition of the design rainfall, considering a time of recurrence, depending on the safety desired for the project, and a time of duration, associated with the concentration time of each sub-basin considered – calculation is made step by step, as the sub-basins are summed to compose greater areas; determination of design discharges through the

Rational Method, for example, or another hydrological method, if convenient; hydraulic calculation of each drainage network reach, using Manning or Chèzy formulas, to conduct the maximum discharge found in the previous topic. Sometimes, in the macro-drainage context, the channel design considers a maximum discharge produced by the watershed and then, with this value, the channel is calculated through backwater formulas, considering steady varied flow.

This approach greatly simplifies the real situation. In the design context, it may be not serious, once all the calculations follow a certain pre-defined order and the effects are accumulated in a controlled way. However, discharges in a drainage system are, in fact, unsteady. In a situation of flood occurrence (drainage system failure), for example, it is not recommended to work in such a simplified form. Diagnosis is something that needs a systemic approach. The combination of effects in time and space becomes crucial for the assessment of flow conditions. Besides, closed conduits introduce an even more complex element, when the system fails. Under this condition, the design discharge is surpassed and flow under pressure may occur, replacing the basic hydraulic laws of free surface flow, which guided the original project.

3. URBAN DRAINAGE DESIGN TRENDS

New trends for drainage system design seek for systemic solutions, with distributed actions over the basin, trying to recover flow patterns similar to those that happened prior to urbanisation. Methods for sustainable design and construction of urban drainage systems are presently being researched and tested (Burian and Edwards, 2002). New enterprises involve the use of the concept of low impact development-LID (Coffman et al., 1998). This concept considers the challenge of developing urban areas without changing natural hydrological patterns. Storage and infiltration measures are considered together in drainage layout proposals. Moreover, these new trends add concerns of water quality control, as well as enhance rainwater as a resource to be exploited in an integrated approach for sustainable management of urban stormwaters.

4. MATHEMATICAL MODELING AS A SUPPORT AID

Urban drainage models usually lay on the drainage net simulation, what may lead to a bare representation of the physical reality, when dealing with significant flooded areas, where superficial flows may play a major role in the process. The occurrence of floods, with channel overflowing and surcharging of storm galleries, makes urban structures start to work, in order to supplement the network that failed. Streets begin to act as channels and these flows may gain independent paths. Transpositions may occur from a sub-basin to another, changing the patterns expected on the original drainage system project. Overflowing discharges may pass through several drowned inlets until they finally find a chance to return to the network. Flooded squares and public spaces start to act as reservoirs, damping flows and also changing drainage patterns originally planned. This situation happens in an undesirable way, once houses may be flooded in this process and several losses may occur. Eventually, lack of maintenance of micro-drainage can cause flooding, with harmful consequences, even when macro-drainage still presents capacity of flow.

The diversity related to the urban flooding process makes this phenomenon difficult to assess. The possibilities of effects combinations in space and time are not trivial. The interaction between the drainage system and the urban structures, which eventually acquire hydraulic functions in a complementary way, produces another operational drainage network distinct from the one that was originally designed. Flow patterns developed on this new complex system is not known in advance. Thus, it is neither possible to simply sum effects nor to compose a step by step calculation. Local solutions can lead to undesirable effects, transferring flood problems. Apparently good solutions for distinct places may negatively combine their effects due to the temporal composition of the hydrographs generated. Sometimes, different interventions just superimpose concurrent results. On the other hand, it is possible to generate better results, with extra benefits, when proposing adequate combinations of measures capable to join efforts in the desired direction.

In this situation, mathematical models may be able to assist in the design of integrated flood control projects, because of the possibility of conducting a systemic evaluation of the basin and prospecting various scenarios of combined interventions and future development hypothesis. Many models, with different characteristics, may be cited, in order to illustrate the discussion on how to treat flood problems. Among these models, some free options are the SWMM - Storm Water Management Model, developed by the United States Environmental Protection Agency (EPA), and the Hydrologic Modelling System (HEC-HMS), developed by US Army Corps of Engineers (USACE). This paper will present MODCEL (Miguez, 2001; Mascarenhas & Miguez, 2002; Mascarenhas et al., 2005), which is another free model, with academic characteristics that is being developed in the Federal University of Rio de Janeiro (UFRJ) since 1990, in various versions. This is a distributed mathematical model capable to represent systemic hydrologic and hydraulic characteristics of the basin, intending to meet the requirements for urban floods simulation.

5. MODCEL

The construction of MODCEL is based on the concept of flow cells (Zanobetti et al., 1970). It was constructed to represent urban surface through a set of homogeneous compartments, integrating all the basin area, and making it interact through cell links, using various different hydraulic laws. Each cell also performs a rainfall run-off transformation. Simple hydrologic models are available to fulfill this task. The mesh of cells composes a hydrodynamic looped model, in a spatial representation that links surface flow, channel flow and underground pipe flow. This arrangement can be interpreted as a hydrologic-hydraulic pseudo 3D-model, although all mathematical relations written are one-dimensional. The main hydraulic link for superficial flows refers to the dynamic Saint-Venant equation. When drowned, storm galleries allow the occurrence of surcharged flows, using Bernoulli equation. Pseudo 3D representation may be materialised by a hydraulic link taken vertically to communicate two different layers of flow: a superficial one, corresponding to free surface channels and flooded areas; and a subterranean one, related to free surface or surcharged flow in galleries. Figure 1 illustrates MODCEL features, in a schematic basin. The mass conservation principle is written for each cell. Different types of cells and links give versatility to the model. This versatility allows the representation of on-site problems, on the plot scale, as well as the simulation of the entire basin.

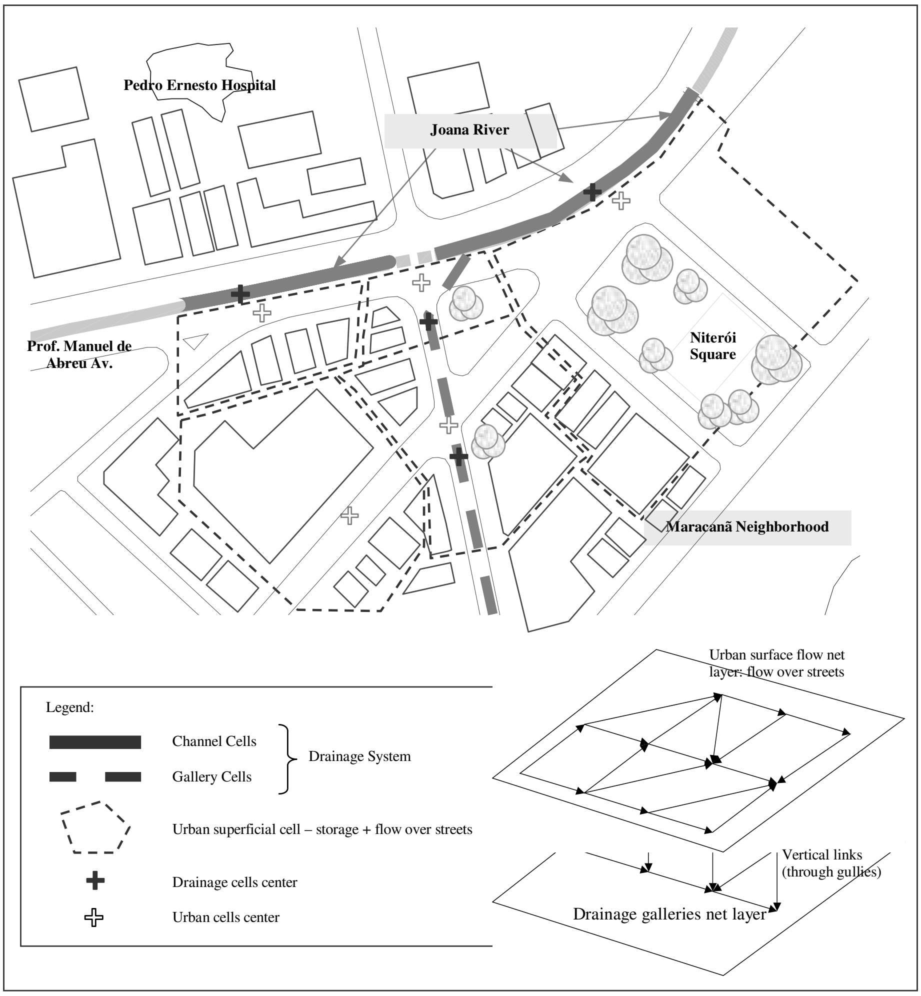

Figure 1 - Schematic representation of a portion of a basin divided into cells, showing different interactions and flow patterns modelled by MODCEL.

1.1 HYDROLOGIC MODEL

Rainfall-runoff separation is represented in MODCEL considering two different approaches:

- Using the Rational Method and applying a runoff coefficient, considered according to land use characteristics in each cell. Thus, for a given time interval, the effective rainfall in any cell can be obtained by multiplying its runoff coefficient by the rainfall occurred in that time interval.
- Applying a simple hydrological model to represent infiltration, vegetal interception and depressions retention, being the two latter considered in a combined way in an abstraction parcel. Abstraction losses occur until this reservoir gets full. On the other hand, the infiltration can occur as long as there is water accumulated over the surface of the modelled cell. At every time step, the calculations related to the hydrologic model routines are performed and then routing is done through the hydrodynamic routines.

1.2 CELL TYPES AND MASS STORAGE

- River or channel cells – these cells are used to model the main free open channel flow, in which the cross section is taken as rectangular shape and may be simple or compound;
- Underground gallery cells – act as complements to the drainage net;
- Urbanised superficial cells – used to represent free surface flow over urban floodplains, as well as to represent storage areas linked to each other by streets. This kind of cell presents different bottom levels, equivalent to a compound rectangular cross section, in order to represent a certain pre-defined urban pattern where streets, sidewalks and buildings are considered, as shown in figure 2.

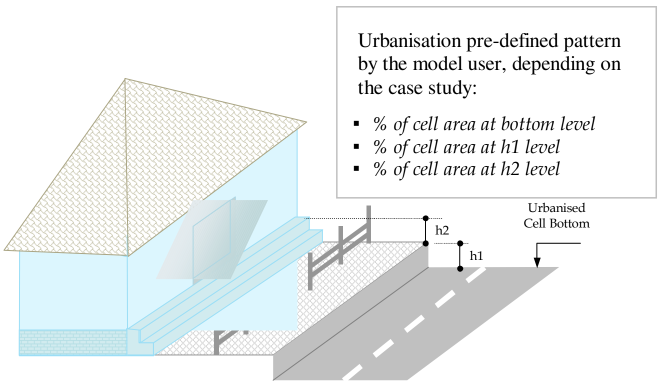

Figure 2 - Pre-defined urban pattern introduced in a MODCEL simulation.

- Natural superficial cells – these cells are similar to the preceding ones, however presenting a prismatic shape, without considering any urbanisation pattern. Both natural and urbanised superficial cells may have a storage area associated to them that differs from the total area, where rainfall occurs.
- Reservoir cells – used to simulate water storage in a temporary pond or reservoir, presenting a curve for the elevation versus surface area.

1.3 HYDRODYNAMIC MODEL

The hydrodynamic model uses the conservation mass law and hydraulic relations as the main components of the core engine of MODCEL. A detailed deduction of flow equations may be found on Cunge et.al (1980). The water level variation in a cell *i*, at a time interval *t*, is given by the continuity equation applied for that cell as stated in equation (1).

$$A_{Si}\frac{dZ_i}{dt} = P_i + \sum_k Q_{i,k} \qquad (1)$$

Where: $Q_{i,k}$ is discharge between neighbours cells i and k; Z_i is the water surface level at the centre of the cell i; A_{Si} is the water surface area for the cell i; P_i is the discharge related to the rainfall over the cell; and t is an independent variable related to time.

Considering equation (1) in discrete terms, it turns into equation (2).

$$A_{si}^{t}\frac{Z_i^{t+1} - Z_i^{t}}{\Delta t} = P_i^{t+1} + \sum_k Q_{i,k}^{t+1} \qquad (2)$$

The discrete time interval $(n+1).\Delta t$, represented by the index $t+1$, is taken as the calculation time, when the variables are unknown. On the other hand, at the discrete time $n\,.\,\Delta t$, index *t*, all variables are known, because they were already calculated or prescribed as initial conditions. The water surface area of the cell, A_{Si}, which appears in equation (2), is taken as a function of the known water level Z_i^t, implying that a first order approach, $(\Delta A_{Si}/A_{Si}) << 1$, is adopted. P_i is a known value, since the rainfall is considered a given entry for all time intervals. Z_i^{t+1} and $Q_{i,k}^{t+1}$ are unknowns and the numerical scheme is fully implicit. In order to solve this equation, the unknown discharges may be written as a function of the water levels in the cell i considered and all its k neighbours. Thus, in order to avoid the presence of a non-linear term in equation (2), it is possible to develop $Q_{i,k}^{t+1}$ in Taylor series, taking only the first order terms, as in equation (3).

$$Q_{i,k}^{t+1} = Q_{i,k}^{t} + \frac{\partial Q_{i,k}^{t}}{\partial Z_i} \Delta Z_i^{t+1} + \frac{\partial Q_{i,k}^{t}}{\partial Z_k} \Delta Z_k^{t+1} \tag{3}$$

Taking into account the previous discussion, equation (2) may be re-written as seen in equation (4).

$$A_{S_i}^{t} \frac{\Delta Z_i^{t+1}}{\Delta t} = P_i^{t+1} + \sum_k Q_{i,k}^{t} + \sum_k \frac{\partial Q_{i,k}^{t}}{\partial Z_i} \Delta Z_i^{t+1} + \sum_k \frac{\partial Q_{i,k}^{t}}{\partial Z_k} \Delta Z_k^{t+1} \tag{4}$$

The variables ΔZ_i^{t+1} and ΔZ_k^{t+1} are related respectively to the water levels Z_i^{t+1} and Z_k^{t+1}, that appear in equation (4) written for each cell, and are the only unknowns. They refer to the considered cell and to its adjacent neighbours. The system resulting from the application of the continuity equation is capable of solving the problem, since the mathematical relations introduced to represent the discharges between cells, $Q_{i,k}^{t}$, can always be written for values of Z_i^{t} and Z_k^{t}.

The typical discharge links between cells can be expressed through known hydraulic laws. The possibility of introducing different hydraulic laws inspires the use of the cell model to represent the urban floods in all of its diversity. The kind of links considered in this study are presented and briefly discussed in the following topics.

- River/Channel Link –This link is related to river and channel flows. It may eventually also be applied to flow on the streets. More specifically, it corresponds to the free surface flow represented by the Saint-Venant dynamic equation. Equation (5) results from the consideration of rectangular cross section and fixed bottom.

$$\frac{1}{A_{i,k}} \frac{\partial Q_{i,k}}{\partial t} - \frac{Q_{i,k}}{A_{i,k}^2} \frac{\partial A_{i,k}}{\partial t} + \frac{Q_{i,k}}{A_{i,k}^2} \frac{\partial Q_{i,k}}{\partial x} - \frac{Q_{i,k}^2}{A_{i,k}^3} \frac{\partial A_{i,k}}{\partial x} + g \frac{\partial Z}{\partial x} + gS_f = 0 \tag{5}$$

Where: $B_{i,k}$ is the surface flow width between cells i and k; $A_{i,k}$ is the wetted flow cross-section area between cells i and k; S_f is the energy line slope; $R_{i,k}$ is the hydraulic radius of the flow cross-section between cells i and k; n is Manning's roughness coefficient; and x and t are independent space and time variables. The parameters n, $A_{i,k}$ and $R_{i,k}$, representative of the flow section between cells i and k, are evaluated through a weighting procedure between the water levels of cells i and k, here assigned as Z_p.

Multiplying equation (5) by $A_{i,k}$, and using the traditional form of the continuity equation to substitute $\frac{\partial Q_{i,k}}{\partial x}$ by $-\frac{\partial A_{i,k}}{\partial t}$, equation (6) may be written:

$$\frac{\partial Q_{i,k}}{\partial t} - 2\frac{Q_{i,k}}{A_{i,k}}\frac{\partial A_{i,k}}{\partial t} - \frac{Q_{i,k}^2}{A_{i,k}^2}\frac{\partial A_{i,k}}{\partial x} + gA_{i,k}\frac{\partial Z}{\partial x} + gA_{i,k}S_f = 0 \tag{6}$$

Remembering that the discharge was open in a Taylor series, in order to have its representation in the time $n \,.\, \Delta t$, it is needed to obtain an expression to evaluate this discharge explicitly, providing the entrance required in the modified continuity equation (4). Thus, turning equation (6) into discrete terms, equation (7) may be written, considering cell *i* in an upstream:

$$\frac{Q_{i,k}^t - Q_{i,k}^{t-1}}{\Delta t} - \frac{2Q_{i,k}^t}{A_{i,k}^t}\frac{A_{i,k}^t - A_{i,k}^{t-1}}{\Delta t} - \left(\frac{Q_{i,k}^t}{A_{i,k}^t}\right)^2 \frac{A_k^t - A_i^t}{\Delta x} + gA_{i,k}^t\left(\frac{Z_k^t - Z_i^t}{\Delta x}\right) + gA_{i,k}^t \cdot S_f = 0 \tag{7}$$

S_f, by its turn, may be approximated by expression (8):

$$S_f = \frac{Q_{i,k}^2 n^2}{A_{i,k}^2 R_{i,k}^{4/3}} \tag{8}$$

Combining equation (7) and (8), considering the adopted hypotheses , the term $Q_{i,k}^t$ is the focus of interest: all information on time *t-1* is available and all water levels in time *t* are known. In order to explicit this term and obtain a direct solution for this equation, the quadratic terms were "factored", in a numerical simplification as it can be seen in expression (9).

$$\left(Q_{i,k}^t\right)^2 = Q_{i,k}^{t-1} \cdot Q_{i,k}^t \tag{9}$$

From this discussion, equation (10) for river discharge link is obtained and may be used in the mass conservation balance:

$$Q_{i,k}^t = \frac{Q_{i,k}^{t-1} - g \cdot A_{i,k}^t \cdot \Delta t \cdot \dfrac{\left(Z_k^t - Z_i^t\right)}{\Delta x}}{1 - 2 \cdot \dfrac{\left(A_{i,k}^t - A_{i,k}^{t-1}\right)}{A_{i,k}^t} - \dfrac{Q_{i,k}^{t-1}}{A_{i,k}^{t-1} \cdot A_{i,k}^t} \cdot \dfrac{A_k^t - A_i^t}{\Delta x} \cdot \Delta t + g \cdot A_{i,k}^t \dfrac{Q_{i,k}^{t-1} \cdot n^2}{A_{i,k}^{t-1} \cdot A_{i,k}^t \left(R_{i,k}^{t-1} \cdot R_{i,k}^t\right)^{2/3}} \cdot \Delta t} \tag{10}$$

- Surface Flow Link - This link corresponds to the free surface flow without inertia terms, as presented in Zanobetti et al (1970). MODCEL uses this link frequently to represent flow between superficial natural or urbanised cells. Latter case may be able to simulate flow over streets, joining inundated areas.

- Gallery Link - This link represents free surface flow in closed conduits, as well as under pressure flow conditions for drainage galleries, after they became drowned. Free surface flow is modelled in this case exactly as it is in surface links, using simplified Saint-Venant dynamic equation. On the other hand, when galleries become full, pressure flow conditions are given by energy conservation law considerations. MODCEL considers the gallery linked by gullies to a street above it (figure 3). In this situation, flow over the street occurs with free surface and the water level associated to this flow can be considered equal to the pressure flow line level for the gallery-drowned flow. Thus, departing from Bernoulli equation (11), equation (12) was developed from the situation shown in figure 3, considering cell *i* in the upstream position.

$$Z_i + \frac{v_i^2}{2g} = Z_k + \frac{v_k^2}{2g} + S_f \Delta x \tag{11}$$

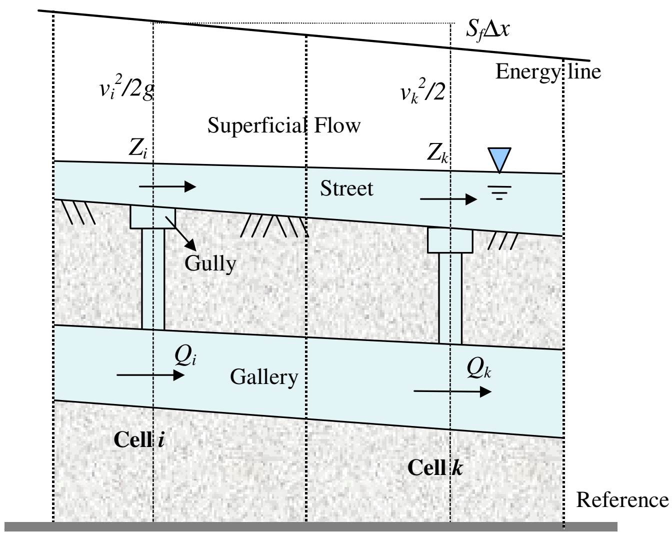

Figure 3 - Representation of flow under pressure in drowned gallery.

$$Q_{i,k} = -\left[\frac{2g(Z_k - Z_i)}{\frac{1}{A_i^2} - \frac{1}{A_k^2} - \frac{2gn^2\Delta x}{A_{i,k}^2 R_{i,k}^{4/3}}} \right]^{1/2} \tag{12}$$

An important model feature to be stressed is that if the cell *i* is located upstream, drowned, and the downstream cell *k*, also drowned, has a water elevation at he surface cell, Z_k, greater than the elevation Z_i, the flow may be forced gallery upwards.

It is also important to detail how the model manages the flow transition from free surface to under pressure flow. At a gallery stretch, while it does not become drowned, the river and channel flow equations apply. When the water level evaluated by those equations indicates a value greater than that referred to the top of the gallery, the calculated exceeding water is returned to the surface cell, through the associated gully link. From this moment on, and until the gallery is drowned, the relationships developed for under pressure flow become to be valid. It must also be noticed that after the drowning of a cell gallery, the gullies related to it stop to contribute with inflow. Actually, once the mass balance is done, if a drowned stretch receives more water from upstream than that released to downstream, this discharge difference is sent to the surface, through the modelled gullies, for the plain cell which contains the street above the gallery and which communicates with it.

- Inlet gallery Link - This link acts accordingly with computed flow conditions at every time step. If there is a free surface flow at the entrance of the gallery, this link acts as a channel link, with a local head loss, associated to the contraction of flow, when passing from a channel to a gallery. If the entrance is drowned, then Bernoulli equation is used.
- Outlet gallery Link - This link is analogous to the previous one, but here the model deals with a possible expansion of the flow leaving the gallery and returning to an open channel flow.
- Gallery Discharge into an Open Channel Link - This link allows a gallery to discharge into an open channel in a condition different from a junction. In MODCEL, junctions are treated as special cells with “Y” shape, where mass balance equilibrates inflows and outflows. This link is associated to galleries that arrive at a level higher than that of the river bottom, acting as free broad crested weirs, drowned weirs, or orifices, depending on water level in the channel.
- Inlet Link - This link promotes the interface between surface and storm gallery cells. When not drowned, it acts as a weir conveying flow from streets to galleries. This weir has the length of the perimeter of the gully multiplied by the number of gullies along the street modelled by the considered cell. When drowned, this link considers flow occurring through a certain number of orifices associated to the gullies in the street.
- Broad crested weir Link - This link represents the flow over broad-crested weirs. It is used, mainly, to represent the flow between a river and its margins. The classic formula of flow over broad-crested weirs is used here; however, the coefficients of discharge must be adjusted, because the flow, in this case, occurs laterally to the main channel. Flow over a weir may be free or drowned.
- Orifice Link - This link represents the classic formula for flow through orifices.

- Reservoir Link -This link combines an orifice, as the outlet discharge of a reservoir, with a weir, that can enter or not in charge, depending on reservoir operation. It is useful to simulate the damping effect of a reservoir, in the design condition, and to verify reservoir functioning in more severe conditions (those in which the weir can start to be used).
- Stage-Discharge Curve Link -This link corresponds to a mathematical relation calibrated for hydraulic structures in a laboratory and basically relates discharges with water levels.
- Pumping Link - This link allows discharges pumped from a cell to another departing from a starting pre-defined operation level.
- Flap gate Link -This link simulates flows occurring in the direction allowed by the flap gate opening, and can be found, normally, in regions protected by polders.

6. CASE STUDY

Several applications in urban environments have been held with MODCEL since 1996. One of these cases is presented in this text, for Joana River basin, in Rio de Janeiro City, Brazil. In this case, MODCEL was used to simulate and design local and systemic intervention, ranging from a volume assessment of on-site detention tanks to a detention reservoir in an open public square, as a local drainage solution, and a set of integrated measures for minimising floods on the plan areas of the basin outfall.

Joana River drains an urbanised watershed with approximately 11km², comprising the districts of Grajaú, Andaraí, Vila Isabel and Maracanã, in the northern region of Rio de Janeiro. Joana and Maracanã Rivers are the main rivers of the Mangue Channel basin, an important city reference, located at the city port zone. In this basin, there are some of the most critical flooding points of the city, including Bandeira Square and the surroundings of Maracanã Stadium and Rio de Janeiro State University.

Analysing this basin, some important points should be stressed: the basin is highly urbanised; the existing macro-drainage net presents reaches of stormwater galleries flowing under buildings, in places difficult to access, with sharp angle curves, galleries present points of sudden cross section reductions and other types of constraints; a significant portion of the slope areas (about 50%) is occupied by slums; water quality parameters values are similar to those found in wastewaters, although the area is provided with a separate sewer system; floods are relatively frequent and occur because micro and macro-drainage failure. Considering the flooding levels observed at the basin, damping storage measures were assumed as essential ones. Zones located near the base of slope areas, where there is still a sparse occupation, were considered adequate places to settle damping reservoirs. These structures aim to act on upper river basin contributions, decreasing water peaks arriving at flood-prone zones. Reforestation of slope areas is also considered as a desirable measure – although its application may be very difficult in the areas occupied by slums. Regarding the lower and more urbanised zones of the basin, squares and public parks were considered as appropriate locations for possible detention reservoirs, in a spatial arrangement distributed over the basin. Although the use of temporary reservoirs at squares can suffer resistance from the surrounding community, this can be an opportunity for urban renewal of these areas, which assume multifunctional landscapes characteristics. On-site measures can be very useful due to flow control at plot level, what leads to the proposition of on-site detention tanks, especially at the medium portion of the basin. At last, additional flood control measures were considered important, either due to the presence of constraints on the flow sections, or because of the existence of canalisation projects proposed in the context of a city municipality public program called "Rio-Cidade".

In this context, a preliminary choice of interventions was produced, but the choice considered in this paper should not be taken as definitive. Further, this study may be evolved in order to reach an economic and practical solution for the watershed flood problem.

From the brief discussion presented, the following interventions were chosen and modelled to face the urban flood problem at the considered basin: reforestation; on-site detention; detention reservoirs at squares/parks; reservoirs at the base of slope areas; traditional canalisation and by-passes.

Figure 4 shows a plan view of Edmundo Rego Square and the design of the detentions ponds projected to this square, at Joana river basin, in a portion located at the Grajaú district. Edmundo Rego Square was supposed to be lowered at different levels. These different levels would allow a selective flooding according to the recurrence of the rainfall, until reaching the top of these proposed reservoirs for the design rainfall of 20 years of recurrence time. In this way, frequent floods would not interrupt the usage of the square. More important floods would require a clean up maintenance plan, to be put in practice right after the rainfall event. Fig. 5 shows the hydrograph with the damping effects resultant for Edmundo Rego Square detention pond. Figure 6 shows the whole set of interventions tested for flood control purposes on the Joana River Basin. This set of measures encompasses: the implementation of 4 detention reservoirs near slope areas and 11 detention ponds in squares and parks of the basin; the widespread adoption of the concept of on-site reservoirs on the plots of the middle portion of the basin, in a residential area; the geometry correction of a channel reach and a new canalisation for another strangled reach; and also reforestation actions, recovering slope hill areas presently occupied by irregular slums. Several combinations of these measures were tested and figure 7 shows the results obtained for a scenario simulation at a downstream reach of Joana River main course, near its outlet, where inundation is a serious problem This simulation considered the use of the slope reservoirs, the square ponds and the on-site detentions.

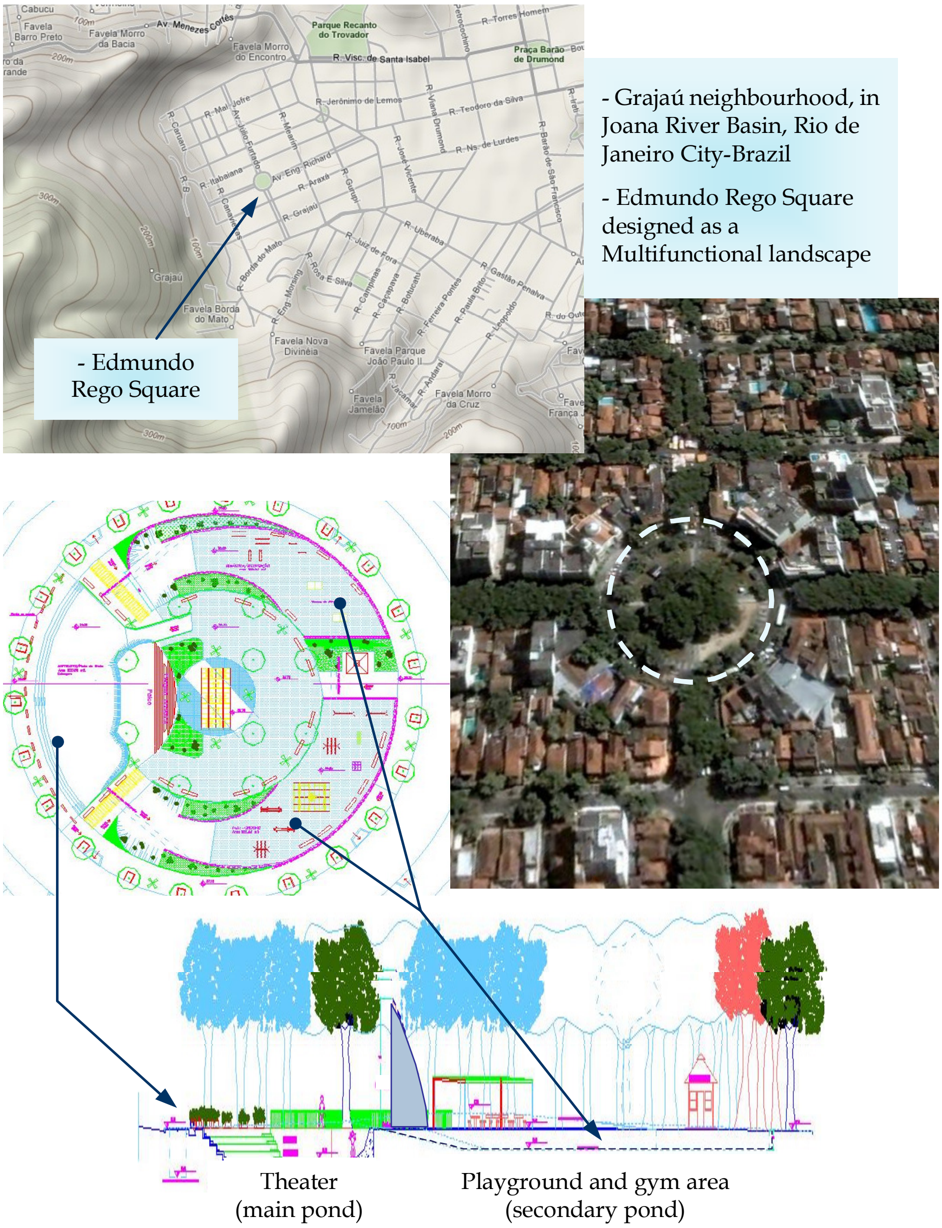

Figure 4 - *Edmundo Rego square, at Joana River Basin, designed as a multifunctional landscape.*

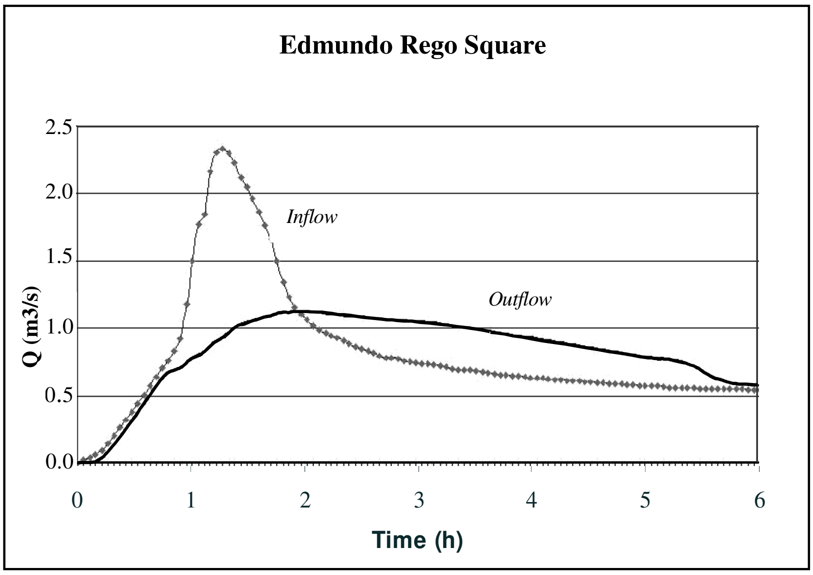

Figure 5 - Damping effect in the Edmundo Rego square detention pond.

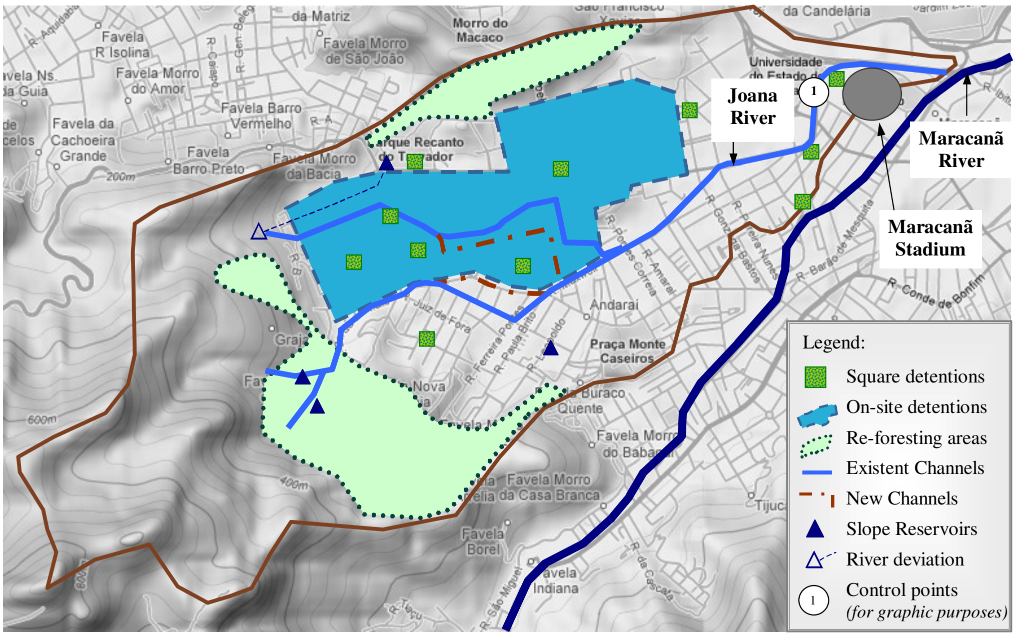

Figure 6 - Set of interventions tested for flood control purposes on the Joana River Basin.

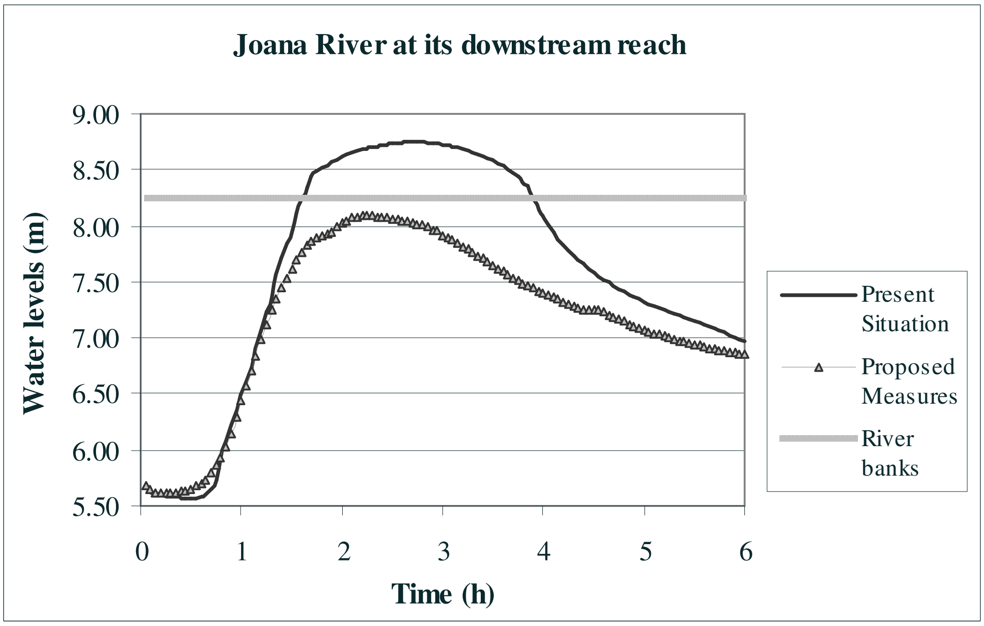

Figure 7 - Flood control obtained at the downstream reach of Joana River Basin.

7. CONCLUDING REMARKS

Mathematical modelling can provide an important tool to aid in flood control design process. Models allow the recognition of flood patterns and urban drainage behaviour, enabling the capability of creating different future scenarios of urban growth and proposed design concepts to deal with the problem. Stormwater in cities is a matter to be managed linked with land use planning.

In the case presented, MODCEL showed to be able to reproduce a great variety of hydraulic patterns in an urban landscape. Its ability to perform rainfall-runoff transformation, in a distributed way, was important to integrate hydrologic and hydraulic processes.

MODCEL seems to be a useful tool for managing drainage systems, especially where severe flood problems occur, with large inundation areas, which can hydraulically behave in a pattern distinct from that of main channels flow. As MODCEL has a set of integrated modules, it is possible to continue refining its capacity to represent hydraulic features by increasing the types of links and cells used in the model. Also, integrated projects can be developed in a more effective way, once it is possible to simulate the basin as a system.

8. REFERENCES

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