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# Urban Flood Control, Simulation and Management - an Integrated Approach

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## 1. Introduction

History shows that places near rivers were attractive as sites for ancient civilisation development. Mesopotamia, China, Egypt and Rome are some examples. Fertile lands, transportation and water supply were main factors. During the industrial revolution, however, stormwater started to be considered as a great matter for urban life. Urban floods started to increase in magnitude and frequency. Street gutters were used to convey stormwater and wastewater as well. Diseases spread around the industrial city and waters had to be discharged as faster as possible. As a consequence, urban drainage started to play an important role in cities life.

It is possible to say that urbanisation is an inexorable trend. The urban population has been increasing significantly in the last two centuries, since industrial revolution took place. The consequences of this process incurs in great changes of the natural environment. Urbanisation process tends to substitute natural vegetation for impervious surfaces, thus reducing infiltration. It also tends to eliminate natural detention ponds, to rectify river courses, among other actions, that greatly interfere with superficial flows. In general, floods in urban areas present greater runoff volumes and flow velocities, resulting in higher flow peaks and water stages. This way, urbanisation aggravates floods and, as it could be seen in cities development, it was not always possible to accomplish urban growing with the adequate infrastructure, especially in developing and poor countries. Even in wealthy countries, urban growth stresses the existing infrastructure.

Urban floods disrupts social systems and cause significant economic losses. Among the impacts produced, there are health hazards and losses of human lives, flooding of housing, commercial and industrial properties, flooding of streets and intersections, causing traffic delays, disruption of services such as water supply, power supply and sewerage.

Flood control is, thus, one of the major issues with which urban planners must deal nowadays, once floods play a dramatic role in the cities. Additionally, the lack of planning frequently worsens this situation. Many times, the absence of systemic design tools capable to represent the problem in an integrated approach leads to a decision process in which local solutions may be inadequate for the whole system needs. An important tool to be considered refers to the mathematical modelling of hydrologic and hydraulic processes.

The concepts applied to stormwater control measures design have changed a lot in the past decades. The traditional approach focused on the drainage net correction, by canalising and rectifying watercourses, in order to improve conveyance. More recent developments tend to search for systemic solutions. New concepts focus on flood risk management aspects, concerning a multidisciplinary approach that considers aspects of prevention, mitigation and recovery of the hazard prone area. Cities are faced with the challenge to find a sustainable way in order to equilibrate harmonic growing with built environment.

In this context, the aim of this chapter is to present a comprehensive and up-to-date review on issues related to flood control and mathematical modelling, integrated with urban planning policies and strategies.

The topics covered by this chapter comprise a general frame of urban drainage problems and their interaction with urban planning; a basic review on historical aspects of the evolution of urban flood control; a presentation of structural and non-structural flood control measures, including modern sustainable drainage techniques; and a broad discussion on hydrologic and hydrodynamic urban flood modelling techniques, illustrated with some case studies applied to the State of Rio de Janeiro, Brazil.

## 2. Urbanisation and Floods

Floods are natural and seasonal phenomena that play an important environmental role. However, human settlements interfere with flood patterns, majoring their magnitude and frequency of occurrence, turning higher the associated level of risk regarding people, buildings and economic activities. Urban floods range from localised micro-drainage problems, inundating streets and troubling pedestrians and urban traffic, to major inundation of large portions of the city, when both micro and macro-drainage fail to accomplish their basic functions. These problems can lead to material losses to buildings and their contents, damage to urban infrastructure, people relocation, increased risk of diseases, deterioration of water quality, among others.

Considering it in a simple way, when rainfall occurs a portion of the total precipitation is intercepted by vegetal canopy or retained at surface depressions, another part infiltrates and the rest of it flows superficially over the terrain, conveying to channels and lower areas. The main modification introduced by the urbanisation process to the water budget refers to an increase of superficial runoff production, as can be seen in figure 1. Table 1 summarises the different impacts of urbanisation over a river watershed. Studies held by Leopold (1968) showed flood peaks majored about six times, when compared to floods in natural conditions.

The fact that must be faced is that the city can influence runoff pattern changes and the state of ecological systems not only within itself but also in the whole river system downstream, including its surroundings. This fact, historically, resulted in shifting the traditional conveyance approach in stormwater management, during the 1970s, to the storage approach with a focus on detention, retention and recharge. Later on, the evolution of this concept, during 1980s and 1990s, made stormwater to be considered as a significant source of pollution, and the goals of stormwater management shifted again in order to protect natural water cycle and ecological systems by the introduction of local source control, flow attenuation measures and water quality treatment systems such as retention ponds, wetlands and others (Niemczynowicz, 1999).

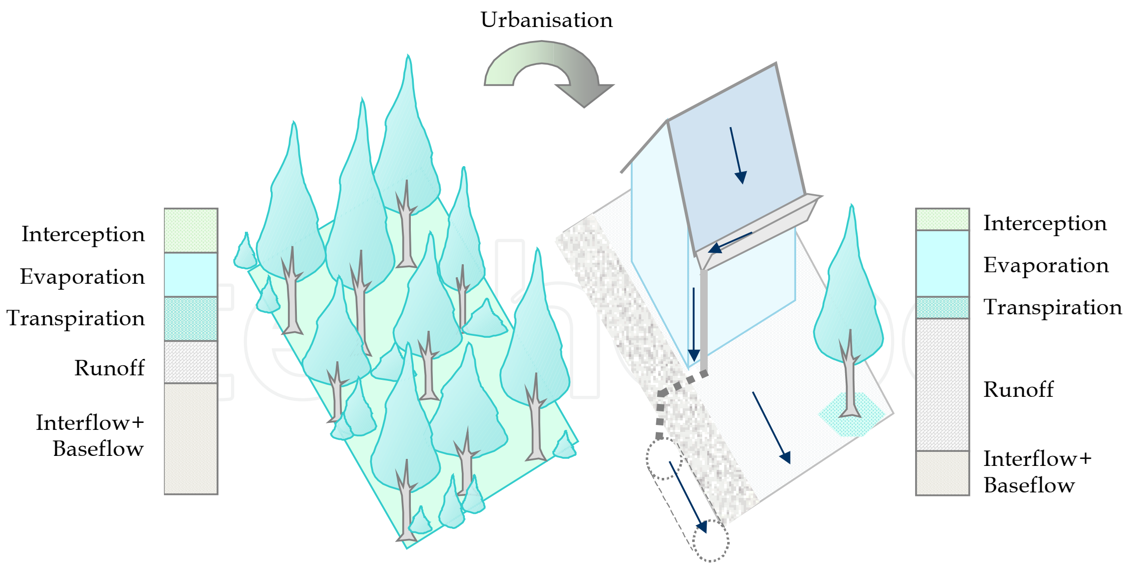


Fig. 1. Schematic picture of urbanisation changes in the water balance

| Causes | Effects |
|---|---|
| Natural vegetation removal | Higher runoff volumes and peak flows; greater flow velocities; increased soil erosion and consequent sedimentation in channels and galleries. |
| Increasing of imperviousness rates | Higher runoff volumes and peak flows; less surface depressions detention and greater velocities of flow. |
| Construction of an artificial drainage net | Significant increasing of flow velocities reduction of time to peak. |
| River banks and flood plain occupation | Population directly exposed to periodic inundation at natural flooded areas; amplification of the extension of the inundated areas, as there is less space to over bank flows and storage. |
| Solid waste and wastewater disposal on drainage net | Water quality degradation; diseases; drainage net obstruction; channel sedimentation |

Table 1. Urbanisation impacts over floods

Flood control concepts are evolving continuously, accompanying historical demands of urbanisation and its consequences. When a city starts to grow near a river, at a first moment, this city can only be inundated in extreme events, when natural floods occupy larger portions of floodplain. Urbanisation, however, changes landscape patterns, aggravating floods by increasing surface runoff flows. In this way, floods become greater in magnitude and time of permanence, occurring even more frequently.
The traditional approach for this problem focused on the drainage net itself, arranging channels and pipes in an artificial flow net system, with the objective to convey the exceeding waters away from the interest sites. At this initial moment, the canalisation solution is able to deal with floods in a certain area, transferring waters downstream with no major consequences.  As time passes, urbanisation grows and more areas of the watershed turn impervious. Upstream development stresses the system as a whole and the drainage

net fails once again. By this time, it becomes difficult to depend exclusively on improving channels conveyance capacity to try to adjust the system behaviour.

Urbanisation itself limits river canalisation enlargement. Streets, buildings and urban facilities now occupy banks and the original flood plain. Upstream reaches of the main river cannot be canalised without aggravating downstream problems, where the former city area lays. Focus now must be moved to a systemic approach, where the whole basin must be considered. Distributed actions spread around the basin comply with the drainage net in order to control generation of flows. Spatial and temporal aspects must be considered together in a way that the proposed set of solutions may reorganise flow patterns and minimise floods. In this context, not only water quantity is important, but also water quality is an issue to be considered. Distributed interventions over the urbanised basin can also act on the control of diffuse pollution from watershed washing. Here arises the concept of sustainable drainage, which states that drainage systems have to be conceived in order to minimise impacts of urbanisation over natural flow patterns, joining quantity and quality aspects, meeting technical, social, economic and political goals, without transferring costs in space or time.

In order to illustrate the interaction between urban development and flood control, as discussed above, table 2 pictures a schematic frame of a hypothetical basin urbanisation process. Knowing the sequence of facts presented in this table, it is possible to say that it would be easier to imagine another course of actions, working in a preventive way and avoiding undesirable flooding. Planning in advance, mapping of flood hazard prone areas, developing environmental education campaigns, establishing adequate legislation, in order to restrict runoff generation, among other measures, would configure a set of procedures that could allow a rational coexistence of human settlements with natural floods.

However, it is impossible to prevent everything, as it is impossible to go back in time. The historical aspects of urban development lead to all sort of established situations, where urban floods occur. There is not one best answer for this problem. Each basin has to be considered with its own characteristics, particularities and historical background, once the diversity involved may arise lots of differences from case to case. However, many studies have been developed in order to propose new concepts and alternatives.

Macaitis (1994) edited a book for American Society of Civil Engineers, where it is presented the concept of urban drainage rehabilitation. This book showed a series of studies that focused on identifying urban drainage functioning, defining maintenance procedures and proposing complementing structures (as ponds, by-passes, flood-gates, etc), in order to allow system operation to minimise flood impacts. Hunter (1994), in a paper presented at this book stressed that it is important to maintain channel conveyance capacity, by treating flood causes and not its consequences. A drainage system working as designed can be able to sustain nearby communities safety and health.

Coffman et al. (1999) proposed a design concept of low impact development (LID). LID design adopts a set of procedures that try to understand and reproduce hydrologic behaviour prior to urbanisation. In this context, multifunctional landscapes appear as useful elements in urban mesh, in order to allow rescuing infiltration and detention characteristics of the natural watershed.

In a similar way, recent trends involve the use best management practices (BMP) in drainage systems design. Best management practices work in a distributed way over the watershed, integrating water quantity and water quality control.

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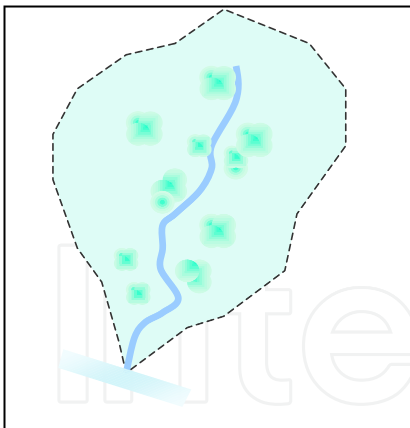
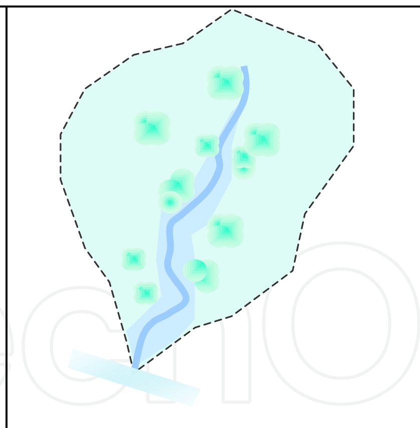
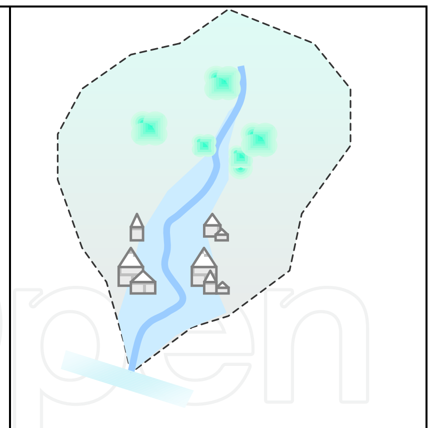
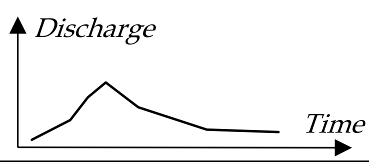
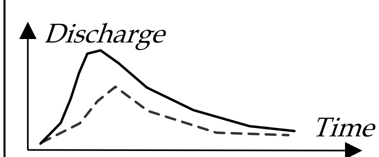
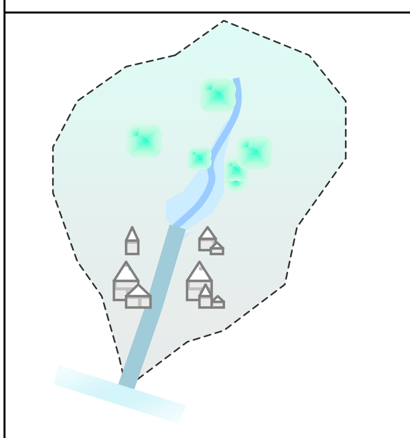
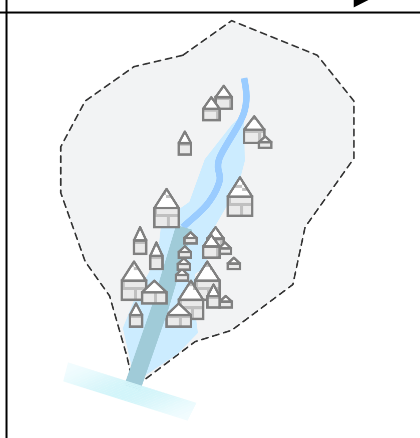
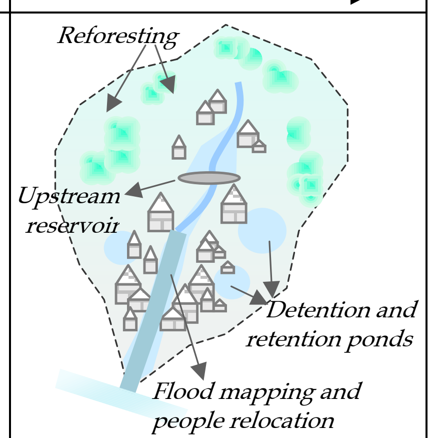
|  |  |  |
| Natural watershed, with its original land cover, without any occupation. | Natural floodplain.   | Initial urban settlement: runoff and peak discharge increase   |
|  |  |   |
| Traditional approach: canalisation and downstream flood transfer. | Urbanisation growth: greater and generalised floods. Simple focus on channel conveyance does not solve the problem. | Sustainable Drainage: distributed actions over the basin, integrating drainage net and typical urban features, ranging from on-site source control to large structural measures. |

Table 2. Schematically evolution of urbanisation and urban drainage solutions

This discussion leads to an important point: understanding how urbanisation interferes with flow patterns is necessary to develop strategies for stormwater management and urban floods control. Urban drainage planning must consider a broad set of aspects and has to be integrated with land use policy, city planning, building code and legislation. It is possible to say that urban flood control demands the adoption of a varied set of different measures of different concepts. Among these measures it is possible to distinguish two greater groups of possible interventions: the structural measures and the non-structural measures. Structural measures introduce physical modifications on the drainage net and over urban basin landscapes. Non-structural measures works with environmental education, flood mapping,

urbanisation and drainage planning for lower development impacts, warning systems, flood proofing, and other actions intended to allow a harmonic coexistence with floods.
Structural measures are fundamental when flood problems are installed, in order to revert the situation to a controlled one. Non-structural measures are always important, but are of greater relevance when planning future scenarios, in order to obtain better results, with minor costs.

## 3. Flood Control Measures

### 3.1 Structural Measures

Basically, structural flood control measures compose the most traditional set of interventions on a basin and can be classified as intensive and extensive (Simons et al., 1977). Intensive control measures refer to main drainage net modifications, including river canalisation and rectification, dredging and dike construction, as well as river in line damping reservoir applications, among others. Extensive measures, by their turn, appear spread around watershed surface, acting on source, in order to control runoff generation.
Classical drainage design concepts are intensive methods that focus on improving conveyance. More recent techniques focus on storage and infiltration measures. In the next few lines, some concepts will be presented in order to illustrate flood control alternatives.

*(a) Detention Basins*

Flood damping is an effective measure to redistribute discharges over time. Increased volumes of runoff, which are resultant from urbanisation, are not diminished, in fact, but flood peaks are reduced. Damping process works storing water and controlling outflow with a limited discharge structure. Figure 2 shows a flood control reservoir (SEMADS, 2001).

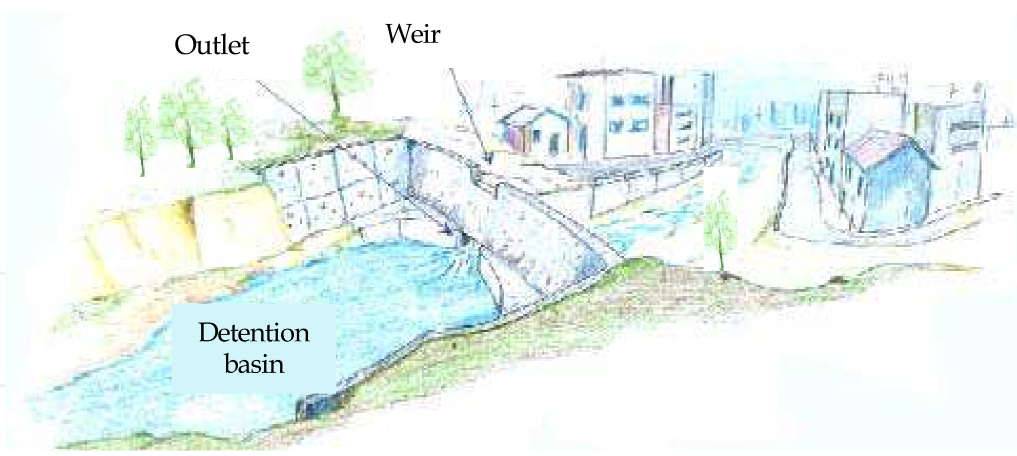



Fig. 2. Detention basin illustration (SEMADS, 2001)

There are several possibilities of application of this kind of measure. Detention ponds may be placed in line with rivers, controlling great portions of the basin, upstream the urbanised area, where occupation is lower and there is more free space to set larger reservoirs. Public parks and squares, as well as riverine areas may be used as detention ponds, opening the possibility to construct multifunctional landscapes (Miguez et al., 2007). Parking lots can also be used, in order to provide temporary storage for flood control. Another possibility, taking into account a smaller scale, on-site detention tanks may be planned as source control

measures. Alternatively, it is possible to consider roof detention for the same purpose. In order to illustrate this set of measures, figures 3, 4, 5, 6 and 7 are presented. Figure 3 pictures a reservoir proposed for upper reach of Guerenguê River, in Rio de Janeiro/Brazil, as part of an integrated project of flood control and environmental recovering of the watershed, showing its damping effect (COPPETEC, 2007). Figure 4 shows a detention pond proposed for a public square in Rio de Janeiro/Brazil (COPPETEC, 2004). Figure 5 shows a public square functioning as a multifunctional landscape, also in Rio de Janeiro. It is important to say that this square, called Afonso Pena, was not planned to act this way, but, in practice, when local drainage fails, it acts as a reservoir, avoiding street flooding at its surroundings. Figure 6 shows an on-site detention pond. Figure 7 shows a roof top garden and a roof detention (Arizona, 2003; Woodworth Jr., 2002).
It is important to say that, although providing a local attenuation effect, detention reservoirs must be spatially planned and distributed in an integrated arrangement in order to adequately combine effects for a general positive result.

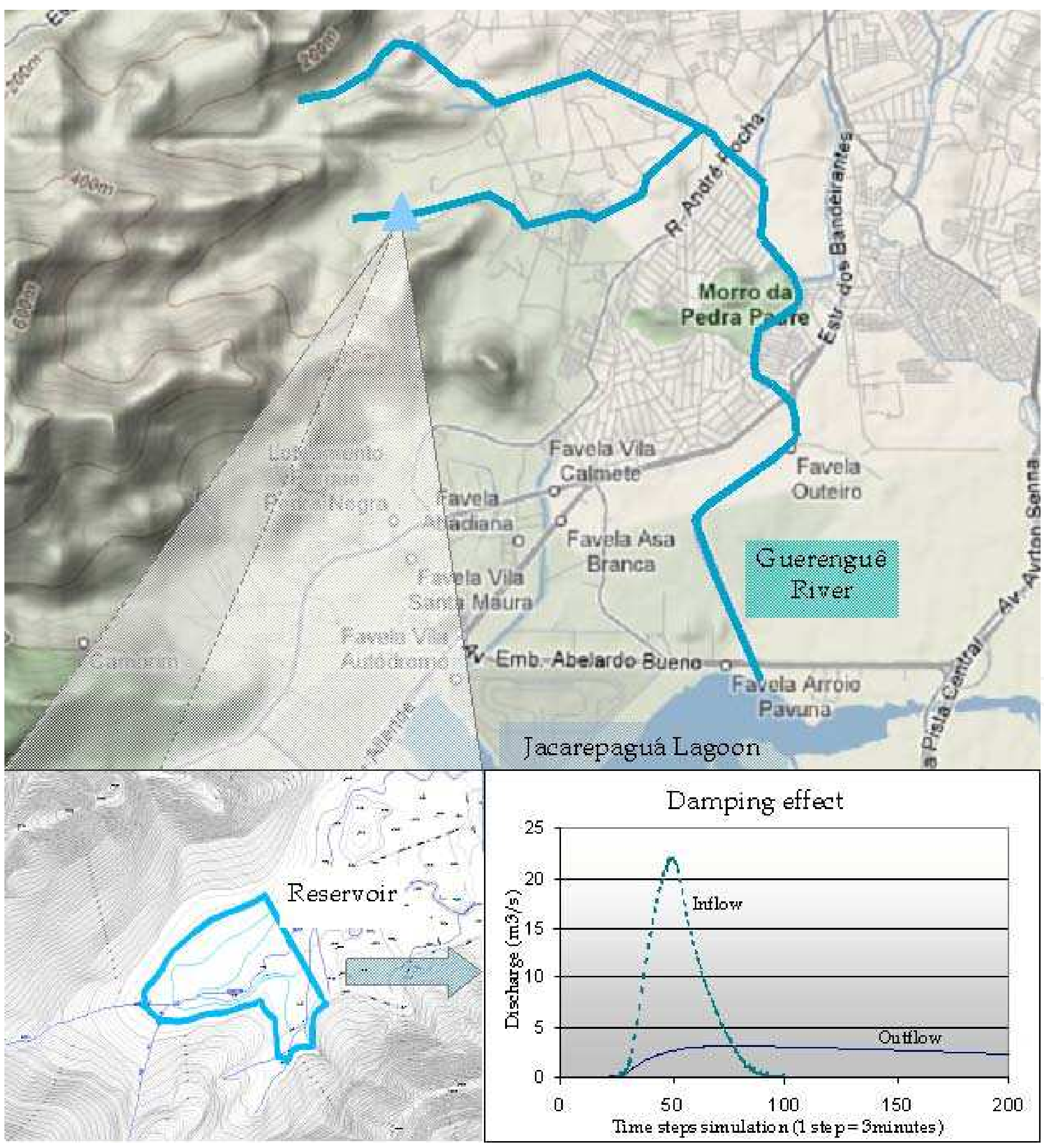



Fig. 3. Detention basin proposed to the upper reach of Guerenguê River Basin – RJ/Brazil

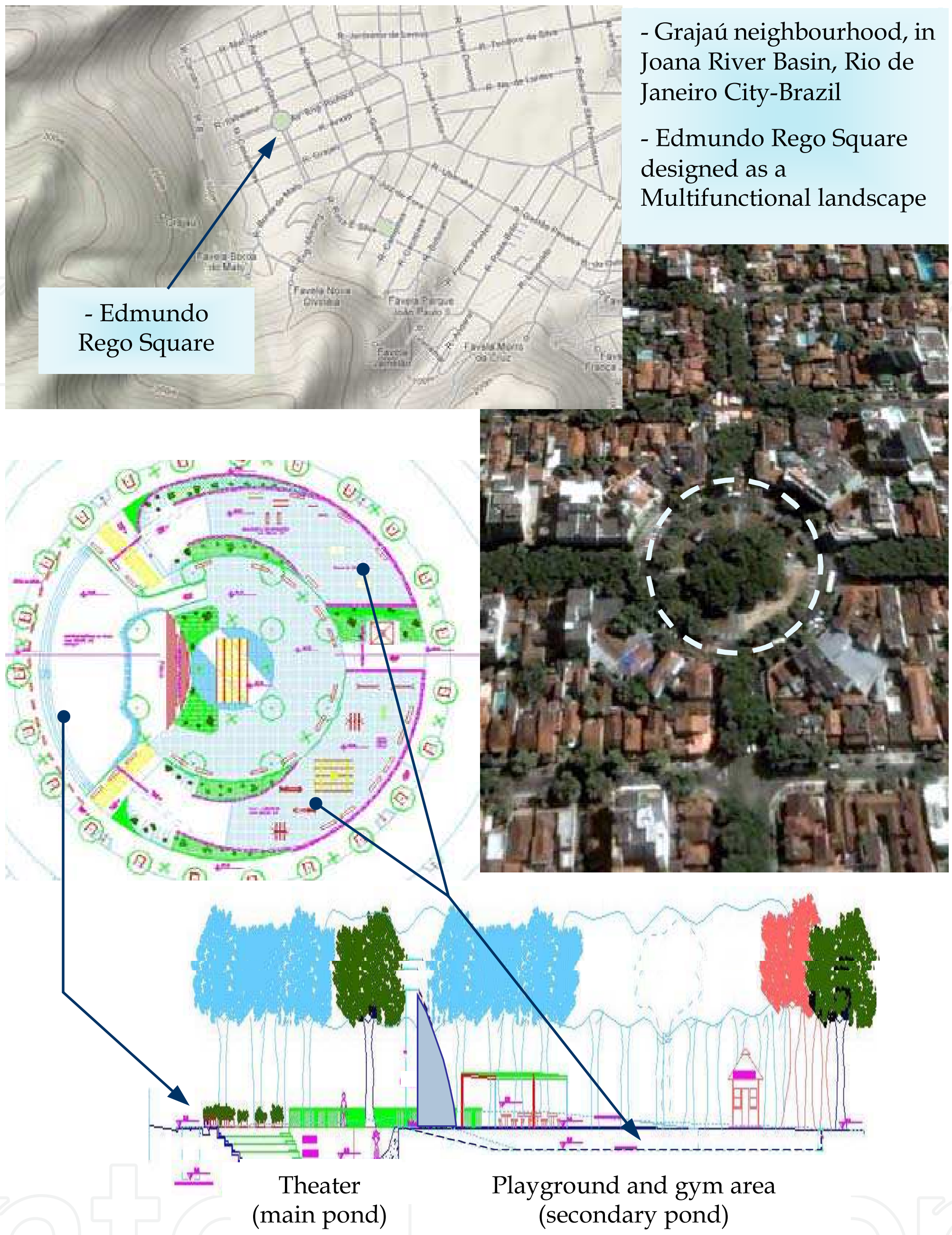



Fig. 4. Edmundo Rego square, at Joana River Basin, designed as a multifunctional landscape

Fig. 5. Afonso Pena Square, acting non-intentionally as a detention pond – RJ/Brazil

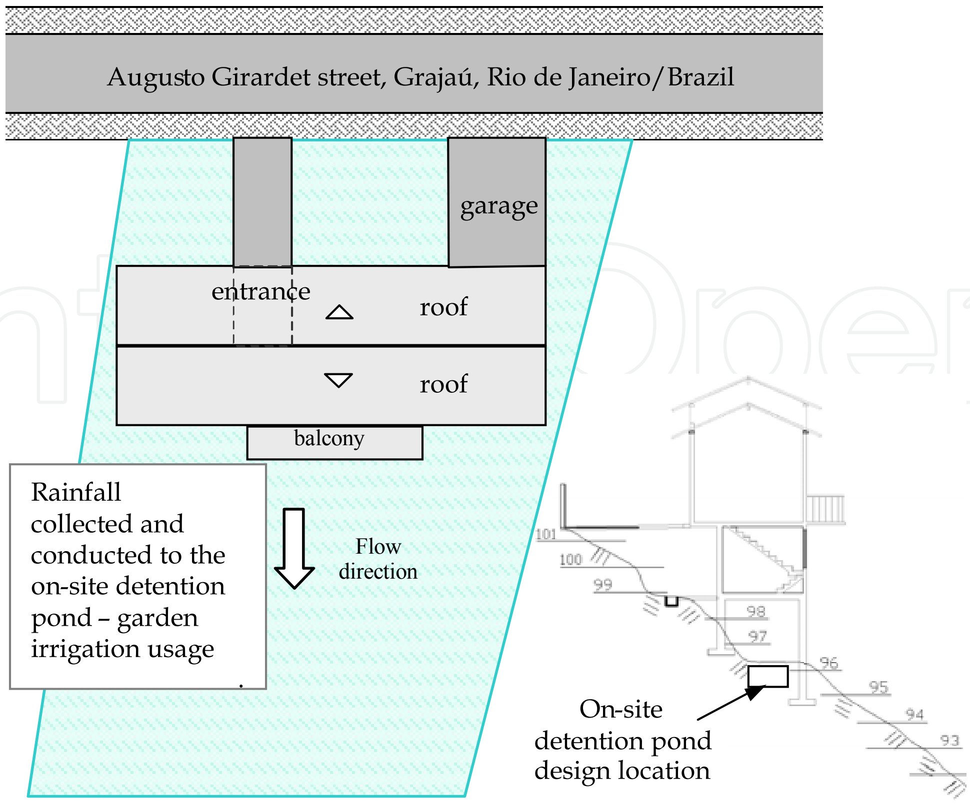
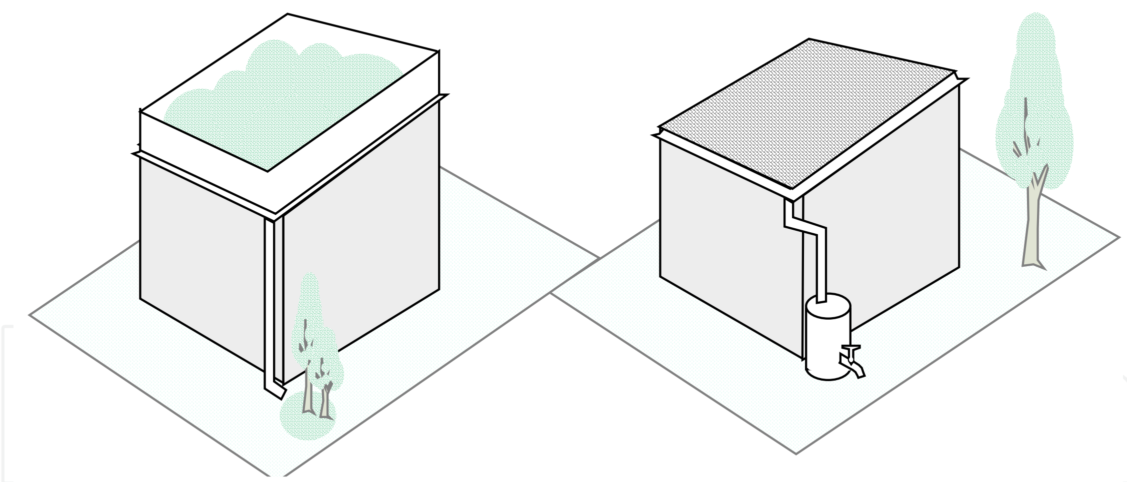



Fig. 6. On-site detention pond, collecting rainfall from the house roof



(i) roof top garden, disconnected from drainage net.

(ii) rain barrel, collecting roof top runoff.

Fig. 7. Alternative measures for roof top runoff

*(b) Retention ponds*

A permanent pool characterises retention ponds. This kind of pond has two main objectives: the first, and most important, is water quality control; the second is water quantity control, although in a minor scale, when compared to the detention ponds. The permanent pool acts allowing the deposition of sediments, helping in diminishing pollutant concentration. Time of permanence of water inside the retention pond is determinant to their efficiency.

*(c) Infiltration Measures*

Infiltration measures allow to partially recovering the natural catchment hydrologic behaviour. However, it is generally not possible to restore pre-urbanisation conditions, when higher taxes of urbanisation and imperviousness occur. Infiltration measures may be divided into some different categories, depending on how they work. Infiltration trenches, which are very common infiltration devices, are linear excavations backfilled with stones or gravel. The infiltration trench store the diverted runoff for a sufficient period of time, in order to have this volume infiltrated in the soil (AMEC, 2001). Vegetated surfaces are other type of infiltration measure. Two common types of this kind of structure refer to swales and filter strips. Swales are shallow grassed channels used for the conveyance, storage, infiltration and treatment of stormwater. The runoff is either stored and infiltrated or filtered and conveyed back to the sewer system. Filter strips are very similar, but with very low slopes and designed to promote sheet flow (Butler & Davies, 2000). Rain gardens are an especial type of garden designed to increase infiltration potential, presenting also a landscape function. Porous or permeable pavements are a type of infiltration measure where superficial flow is derived though a pervious surface inside a ground reservoir, filled with gravel (Urbonas e Stahre, 1993). Porous pavement upper layer consists of a paved area constructed from open structured material such as concrete units filled with gravel, stone or porous asphalt. Another possibility refers on concrete units separated by grass. The depth of the reservoir placed beneath the upper layer determines the capacity of the measure in minimising runoff. Soil infiltration rates and clogging over time will interfere with the effectiveness of this type of device (Butler & Davies, 2000). Figures 8 and 9 illustrate different types of infiltration measures.

(i) (ii)

Fig. 8 and 9. Example of rain garden (i) and examples of pervious pavements (ii)

*(d) Reforesting*

The process of replacing plants in a area that has had them cut down, because of unplanned urban growth, irregular land use occupation or other motives, like economic use of trees, is a very important measure to recover natural flow patterns. Reforestation prevents soil erosion, retains topsoil and favours infiltration. Runoff volumes are reduced and drainage structures keep working efficiently, once a minor quantity of sediments arrives at the system. Renewing a forest cover may be achieved by the artificial planting of seeds or young trees. Figure 10 shows a degraded area in a hill, at Rio de Janeiro City, Brazil, where there was originally a forest reserve.

Fig.10. Degraded hill area – slum occupation substituting a forest

*(e) Polders and dikes*

The conception of a polder, as illustrated in figure 11, allows protecting a riverine area from the main river flooding, by constructing a dike alongside the channel. Inside the protected area, there are needed a temporary storage basin and an auxiliary channel to convey local waters to this reservoir. Usually, flap gates are responsible for discharging this reservoir when main river water level falls below temporary inside storage water level. Another possibility lays on the use of pumping stations to complement flap gates discharge capacity.

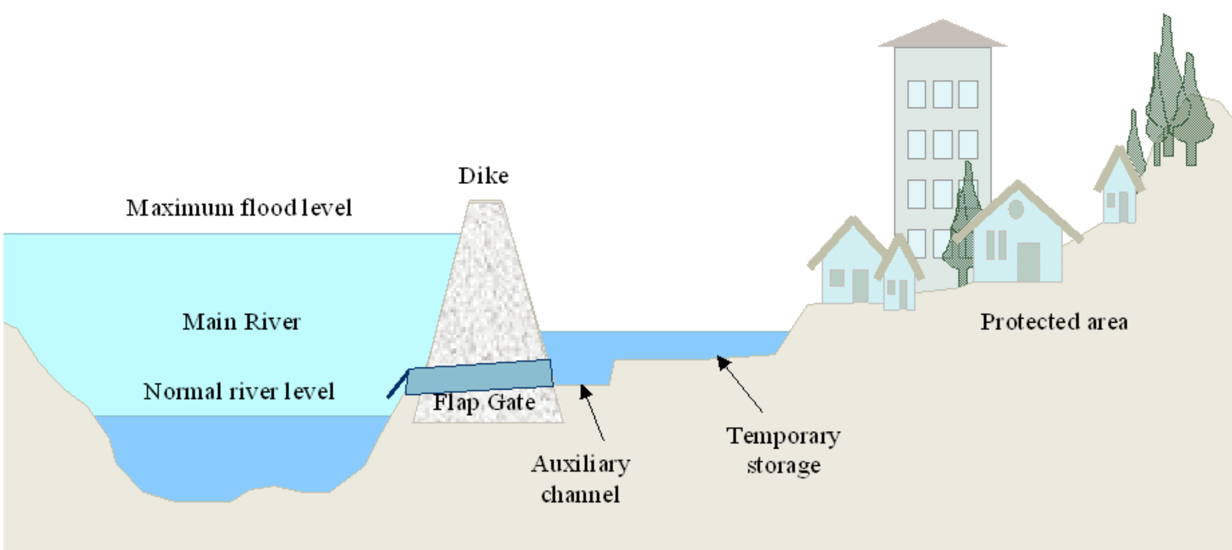



Fig. 11. Illustrative view of a generic polder area

*(f) Canalisation*

Canalisation is the most traditional measure in drainage works. It is obtained by removing obstructions from riverbed, straightening river course and fixing river banks, resulting in an increased conveyance. Figure 12 shows an example of a canalised river.

Fig.12. Canalised Joana River stretch, in Rio de Janeiro City, Brazil

### 3.2 Non-structural Measures

Unlike structural works that physically act on the flood phenomena, the aim of non-structural measures is to reduce the exposure of lives and properties to flooding. A wide set of possible actions, ranging from urban planning and zoning to flood proofing of constructions compose this type of measures. The following paragraphs highlight some issues regarding this concept.

#### 3.2.1 Floodplain Management and Regulation

The most important of all non-structural measures is to avoid or restrict the occupation of floodplains. The periodical flooding of riverside areas is a natural process of great environmental relevance. In urban areas, the encroachment of flood plains constitutes a serious problem. The population usually exerts pressure for the occupation of these lands, especially in cases in which there is no recent flooding record or where land use control is ineffective, a common situation observed in poor and developing countries.

Conceptually, floodplain regulation should be based on flood mapping, identification of flood hazard prone areas and establishment of land use criteria. It should also be developed integrated with urban planning activities. In fact, it is extremely desirable that urban zoning and master plans consider aspects related to the regulation of riverine land.

It is common to divide the floodplain into two different zones. The first is called floodway and is associated with areas subject to frequent flooding. The other is the flood fringe, which constitutes regions that may be flooded during more severe storms, although presenting only storage effects. In general, the boundaries of these zones are defined with the aim of flood mapping. Each of these limits is determined according to floods of a given return period. Often, the floodway is related to a 20-year return period flood while the floodplain is associated with more rare events, for instance a 100-year return period flood. Figure 13 illustrates a cross-section of a river basin with the representation of these two zones.

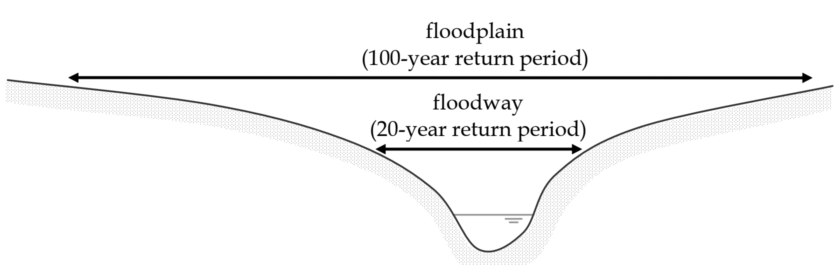



Fig. 13. Illustration of floodway and floodplain zones

Avoiding the encroachment of the floodway is extremely important and that is why building in this area is forbidden in many countries. These areas are more suitable for the development of public parks, which can act as multifunctional landscapes, or environmental conservation zones and can be managed in order to become greenways along the city.

In general, the occupation of the flood fringe is allowed, although sometimes with restrictions such as requiring the base floor level to be above the base flood (100-year return period, for instance) maximum water stage plus a certain safety margin freeboard or designing and constructing in accordance with flood-proofing building codes.

Flood zones can be represented as maps which should be considered as basic information for several urban planning and management activities. The development of these maps can be supported by GIS techniques and the resulting products should be available for free public access. A trend observed since the last decade is the development of combined packs joining hydrodynamic and hydrologic simulation programs with features provided by GIS software. Kraus (2000) shows some benefits concerning the use of GIS StreamPro to calculate and represent flood maps for the American National Flood Insurance Program (NFIP). According to Dodson & Li (2000) the time taken to produce flood maps with the aid of GIS based programs can be reduced in 66% compared to traditional approaches.

In the USA, the Federal Emergency Management Agency (FEMA) defines flood zones on its flood insurance rating map (FIRM). This is an example of a desirable integration between floodplain management and the NFIP.

Public authorities can also purchase and demolish properties in flood risk areas. In these cases, affected people and properties need relocation. This is a very common frame noticed in poor and developing countries. In Brazil, part of the money assigned to major drainage works is frequently destined to floodplain acquisitions and relocation of households.

#### 3.2.2 Master Planning

Flood management master plans (FMMP) consist of a set of strategies, measures and policies arranged together in order to manage flood risk and guide the development of drainage systems.

One basic concept regarding master planning is that is should apply to the river basin as a whole. Additionally, this plan should be carried out integrated and harmonically with other urban planning and management instruments, regulations and related laws. In some countries, especially in wealthy ones or in cities with combined sewers systems, it is also frequent that part of the FMMP studies account for water pollution and soil erosion control. In the other hand, poor countries still face enormous difficulties regarding flood risk reduction and in these cases, generally, aspects related to water pollution and erosion control assume minor relevance.

Basically, a FMMP include different studies, data collection and programs, such as (adapted from Andjelkovic, 2001):

- the definition of goals and objectives that should be fulfilled in a foreseeable future;
- inventory of all drainage and flood control infrastructure;
- gathering hydrologic data regarding rain and river gages as well as past flood records;
- a diagnosis of flood problems and its causes;
- analysis of existing stormwater practices and its inadequacies;
- flood zoning studies in order to determine land use restriction;
- proposal of feasible structural and non-structural measures;

- design and cost estimate of proposed works and measures;
- benefit/cost analysis and comparative evaluation of alternative solutions;
- definition of drainage facilities design criteria;
- water pollution and soil erosion control program; etc.

### 3.2.3 Flood Forecasting and Warning

Early warnings can save lives and significantly reduce tangible and intangible losses due to natural hazards. In developed countries, the use of flood forecast and warning systems, such as those implemented for the Danube and the Mississippi river basins, represents one of the main trends in terms of non-structural flood control measures and has shown highly effective in reducing flood losses (Smith, 1996).

Some case studies authors claim that, in theory, flood damage reduction can reach up to two thirds of total losses. Actually, the reduction of economic losses effectively achieved through this kind of measure is about half of this estimate (Smith, 1996).

Flood forecasting in large basins is much simpler than in small ones, which are usually affected by flash floods. This is mainly due to the difficulties and uncertainty regarding the forecast of storms with short duration and concentrated in small areas.

One factor that substantially affects flood damage reduction is the warning lead time. Penning-Rowsell et al. (2003) developed curves relating flood warning lead time and flood damage reduction.

The expect benefits of a warning system depends not only on an efficient communication strategy to the people living in prone areas, but also rely on the level of preparedness of the affected community. The development of educational actions focusing on an increase of people awareness and preparedness can strengthen local community to face floods. This action can be carried out through public workshops and hearings, as well as using web communication or even on paper leaflets to be distributed (Andjelkovic, 2001). Emergency response teams can also take advantage of flood warning systems.

Another concern regarding the functioning of these systems relates to the uncertainty of the forecast. Fake alerts usually tend to reduce the population's reliability in the warning system and community coping with flood reduction strategies.

### 3.2.4 Flood Proofing

Flood proofing consists in the use of permanent, contingent or emergency techniques to prevent flood water from reaching buildings and its contents, as well as infrastructure facilities, or to minimise flood damage (Andjelkovic, 2001). Basically, the design of flood proofed constructions must consider floodwaters forces due to flooding depth, flow velocities and debris impact potential. There are several types of flood proofing techniques, as shown in figure 14. Some of the adjustments that may be necessary to ensure flood proof of a building are: anchoring it to withstand flotation, lateral movements and collapse; installation of watertight closures for door and windows; reinforcement of walls; installation of check valves to prevent entrance of stormwater or sewage through utilities; location of electrical, mechanical and other damageable equipment above expected flood level; floodwalls, small levees, berms or other kinds of barriers; among many other possible actions (FEMA, 1993).

Urban policies or floodplain regulations can require new constructions in the floodplain zone to comply with a flood proofing building code. Existing building can also be retrofitted in order to improve its flood protection level.

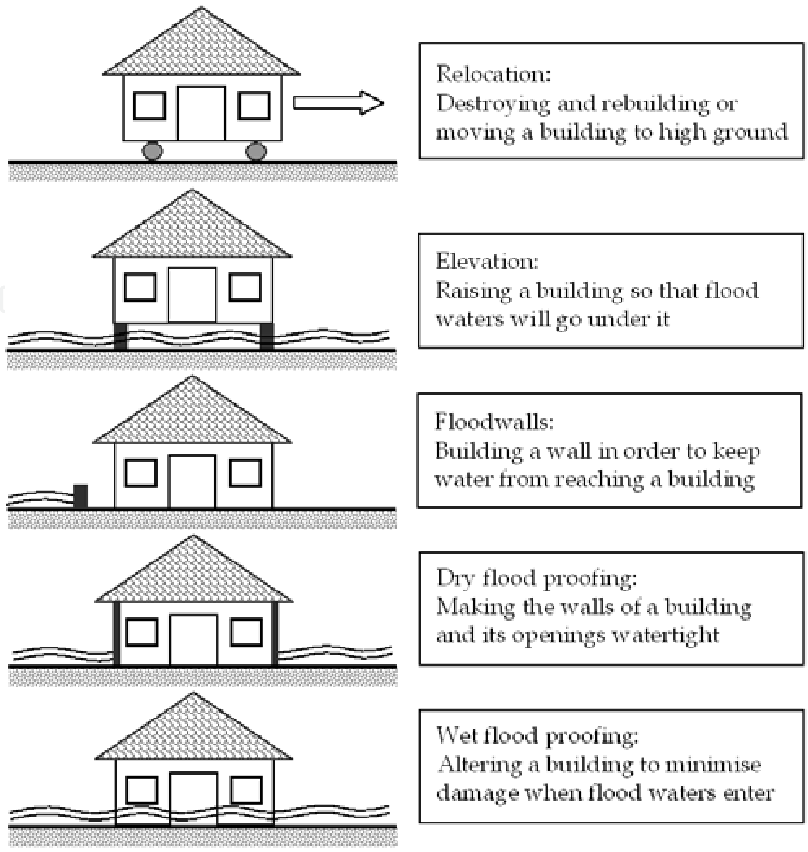


Fig.14. Examples of flood proofing measures (adapted from UNESCO, 1995)

#### 3.2.5 Other Measures

Besides those non-structural measures previously listed, there are several other possibilities of application of this kind of measure. Environmental education activities and the establishment of a flood insurance program are other examples of non-structural flood risk management alternatives.

## 4. Urban Flood Models

Mathematical modelling of physical processes is a valuable tool to understand their systemic behaviour and the interactions among their individual components. However, practical solutions for mathematical models demand the introduction of a set of simplifications to be considered. Natural phenomena, because of their diversity, are generally not simple to model. Depending on the hypothesis considered, one given model may be suitable for certain situations, but may not be applied to other conditions. Although the choice of an adequate model may be difficult, models must be an active part of planning or design solutions, especially where the considered problem demands a systemic approach or when future scenarios must be analysed. The predictive capacity of a mathematical model is one of its most distinguishable characteristics to be valued (Cunge et al., 1980).

When dealing with floods, there are complex aspects related to spatial and temporal flow variations. At urbanised basins, topography and man-made landscapes interact to increase the diversity of possible flow patterns. Urban floods may become a difficult challenge, when drainage net fails and surcharged pipe flow occurs, jointly with open channel flow and flow over streets, composing a complex picture where hydraulic structures and typical structures of urban landscape interact to redefine a practical drainage net, not planned and not desired. This situation leads to great flooded areas with lots of losses of different kinds. Flood solutions must consider the whole system interactions, not transferring problems downstream nor combining undesirable effects. It is important to maintain track of what is happening in different parts of the watershed, in order to avoid peak combination of floods coming from different sub basins.

Integrated projects for urban flood control have to identify how to optimise benefits of different individual measures considered together, and these are difficult questions that can be treated with the aid of mathematical models. In this context, it is important to recognise that choosing an adequate model is the first task when dealing with systemic problems.

The basic needs associated to an adequate urban flood model may be resumed below:

- The correct identification and characterisation of the problem, in order to understand main causes of the process and to choose suitable simplification hypothesis for a sound modelling formulation;
- Sometimes, when designing drainage net, one-dimensional modelling can be applied, once it is expected that there will be no overflow for the design discharge adopted. Other times, even when overbank flow occurs, if the flooded area is confined alongside river course, it is possible to use one-dimensional model, extrapolating calculated channel water levels. However, when inundation of great areas leads to flow patterns dictated by topography, with little relation to channel flow, or when an urban area suffers from lack of adequate micro-drainage and flooding begins with overland flow accumulation, two-dimensional or pseudo two-dimensional models are more suitable;
- On the last case mentioned in the previous item, it is important to consider that the proposed model must be able to join drainage net with urban landscape, as it is possible that streets will act as channels, squares, parks, parking lots and buildings will act as undesired reservoirs, walls and roads will be barriers to the flow, at lower levels, but will become to act as weirs, when flooding levels rise;
- Considering the diversity of a urban drainage system, it is important that the model can be able to simulate different hydraulic structures, as weir, orifices, pumps, flap gates, etc.

### 4.1 Hydrologic Aspects

Hydrology studies are necessary in order to determine peak flow rates or the design hydrograph, depending on the type of study carried out. The focus of hydrologic flood modelling is to represent rainfall-runoff transformation. It is also often necessary to determine a design rainfall, as it is the basic input considered in this process.

One of the main issues with which engineers must deal in order to develop urban flood studies is the definition of the hydrologic approach to be used. Choosing a suitable methodology depends on physical characteristics of the catchment and also on the available data and the study goals. Ponce (1989) proposes a simplified scheme that presents adequate approaches according to basin size, as seen in figure 15. As shown in this figure, the rational method meets the requirements needed in small catchment applications (usually limited to 2,5km$^2$ areas), unit hydrograph techniques suits better midsize watersheds and routing methodologies are suitable for large basins simulation.

The representation of the hydrologic cycle or part of it is the basis of engineering hydrology methods. Due mostly to the time scale of urban floods, some components of this cycle can be neglected. Evaporation, transpiration and groundwater flows variations are slow processes that have no significant effect on flood hydrographs. Therefore, the most important phenomena are precipitation, infiltration, vegetal interception and depression storage (which are usually considered combined and denoted as initial losses or abstraction) and surface runoff.

| Method or approach \ Catchment scale | Small | Midsize | Large |
|---|---|---|---|
| Rational method | Usually | Not applicable | Not applicable |
| Unit hydrograph | Not applicable | Usually | Not applicable |
| Routing tehcniques | Not applicable | Not applicable | Usually |

Fig.15. Suitable methodological approaches according to basin size (Ponce, 1989)

The representation of the hydrologic cycle or part of it is the basis of engineering hydrology methods. Due mostly to the time scale of urban floods, some components of this cycle can be neglected. Evaporation, transpiration and groundwater flows variations are slow processes that have no significant effect on urban flood. Therefore, the most important phenomena are precipitation, infiltration, vegetal interception and depression storage (which are usually considered combined and denoted as initial losses or abstraction) and surface runoff.

Hydrologic models consist of a set of mathematical equations arranged in order to describe relevant phases of the hydrologic cycle and can be classified according to different features. Some of the main types of models are:

- physical or mathematical – the first depends on a physical representation of the prototype and, in practical hydrology, is almost never used, while the second is based on mathematical equations and constitutes more common tools;
- theoretical, conceptual or empirical – a theoretical model is based on general governing physical laws, an empirical model is based on equations using parameters determined from data analysis and conceptual models are based on either theoretical and empirical equations in order to try to represent system behaviour;
- single-event or continuous streamflow simulation– the model can represent the catchment hydrologic response for only a single storm event or determine streamflow regime in a continuous basis;
- lumped or distributed – lumped models can describe rainfall and flow rate temporal variations but cannot represent spatial variations, while distributed models are capable of describing both of them (Ponce, 1989);
- deterministic or stochastic – the difference between these kind of models is that the response of a determinist model to a given input data is always the same, while the relation between input and output in a stochastic model depends on random properties of the time series.

The continuous development of computers over the last decades has been stimulating the use of mathematical models. This happens due to the ever increasing availability of computers and the progress of computer sciences and processing capability.
The most common type of model used in flood hydrology applications is the simple, single-event, rainfall-runoff simulation model. The primary interest of these models is the determination of the flood hydrograph.
The basic set of information needed to develop a flood hydrology study is:

- rainfall and streamflow data;
- rain gages intensity-duration-frequency equations;
- rainfall depth-area-duration curve for the region (not applicable for small catchments);
- topographic mapping of the catchment;
- land use mapping;
- soil types mapping;
- unit hydrograph (if available, otherwise it is possible to use synthetic hydrographs).

Applications based on distributed models are more complex and usually need a large amount of data for its calibration. However, frequently there is no availability of the required data, as its collection is expensive and difficult. This kind of models also face scaling challenges, due to the difference of field measurements, which are representative of a point or a local scale, and the computational grid used to represent hydrologic processes (DeVries & Hromadka, 1993).
The following paragraphs present a simple description of a typical hydrologic design sequence for flood peak calculation in midsize basins using synthetic precipitation and hydrographs. For a broader discussion on the available methods, their characteristics and its limitations it is suggested that the reader refer to specific books such as Linsley et al. (1984); Ponce (1989); Hromadka II et al. (1987) ; Urbonas & Roesner (1993); among others.
The time of concentration is usually defined as the period necessary for the runoff produced in the most remote point of the catchment to reach a given point or cross-section. It is frequent to consider rainfall critical duration as equal to the catchment time of concentration. This hypothesis is suitable for small watersheds, reasonable for midsize catchments, but not applicable to large basin. In theory, the time of concentration is composed by two different parts: time to equilibrium and time of travel. There are several equations developed to calculate the time of concentration in catchment with different characteristics. Some of it focus mainly in overland flow representation (which is associated to time to equilibrium), while others are concerned mostly with the account of the time of travel. In small catchments the time to equilibrium is the preponderant parcel and, in the other hand, the time of travel is the most important in large basins. Hence, it is important to know the applicability limits of each formulation aiming to choose a suitable approach.
In order to determine a design storm it is necessary to define a return period associated with this event. High return periods lead to a lower risk of flooding and to higher costs of the necessary flood control works.
It is common to calculate the design storm using an intensity-duration-frequency curve, which refers to a specific rain gage. The frequency is related to the storm return period. Higher return periods implies in higher precipitation depths and intensities. Rainfall duration affects this curve in a different way. Higher storm intensities are achieved with lower duration, while total rainfall depth increases with duration.

There are some methods that can be used to determine an average precipitation over an area, such as: Thiessen polygons method; isohyetal method; and average rainfall method (as kwon as arithmetic method). As catchment area grows, it becomes necessary to correct rainfall through a depth-area-duration adjustment curve.
Rainfall can be represented in three different ways: constant in both space and time; constant in space but varying in time; and, varying in both space and time. The first approach is suitable for small catchments, while the second and third hypotheses are adequate to midsize and large basins, respectively (Ponce, 1989). A distributed model is required in order to represent spatial variations.
Once the design rainfall is defined, the next step is to calculate runoff depth, or precipitation excess. There are many methods that can be used for this purpose, such as: the rational method; the Soil Conservation Service (SCS) method; the use of phi-index method; the use of potential infiltration curves, such as the Horton formula, for instance; among others. Some of these methods are more suitable for small watershed, while others are more indicated to larger catchments.
Finally, the last step to determine a flood hydrograph can be carried out with the aid of synthetic unit hydrograph methods. These methods assume that the catchment behaviour is linear, which implies that if the basin response for a unit rainfall is know, one can determine its response for any rainfall. There are several synthetic unit hydrographs methods such as, in example, the SCS method or the Snyder method.

### 4.2 Hydrodynamic Aspects

Hydrodynamic aspects of urban flood modelling encompass various typical aspects of general flood modelling. The hydrodynamic model must use the mass conservation law and hydraulic and hydrodynamics relations as the core engine. The Saint-Venant equations are usually used to represent flow conditions in the main channel net. This system of equations may appear in a one-dimensional form, a two-dimensional form or in a pseudo two-dimensional form, where a spatial region is divided into an integrated mesh of cells, linked by one-dimensional equations, although composing a two dimensional flow net.
An alternative way to represent flow mass balance, appropriated to a cell flow model representation, considers that 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).

$$A_{S_i} \frac{dZ_i}{dt} = P_i + \sum_k Q_{i,k} \tag{1}$$

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; $A_{S_i}$ is the water surface area for the cell i; $P_i$ is the discharge related to the rainfall over the cell; and $t$ is a independent variable related to time.
River and channel flows, as well as flow over the streets, may be represented by the Saint-Venant dynamic equation. Taking into account a rectangular cross section and a fixed bottom result in equation (2) (Cunge et al., 1980).

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

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 $x, t$ are independent space and time variables.

The diversity involved in the detailed representation of the urban watershed may require various other hydraulic laws, in order to represent different types of flow.

One question that must be emphasised is that the whole basin must be represented. This consideration allows a systemic modelling with a comprehensive approach that may simulate the integrated consequences of acting over different parts of the basin, inside and outside drainage net. This is what makes a model really useful, especially in flood control planning. Representing the whole basin, however, can reveal a very difficult task, depending on the scale of interest. When parts of a watershed do not present any special interest, it is possible to substitute these parts by boundary conditions that concentrate the effects of the outer parts of the basin at the interface between modelled area and outside areas. Boundary conditions may represent, discharge series, water level series or discharge vs. water levels relations. Figure 16 pictures a region schematically modelled, showing an arrangement of cells, where mathematical equations are applied and boundary conditions substitute parts of the basin not modelled. In this example, upstream boundary conditions represent the discharges of upper basin reaches, while downstream condition represents water levels showing tidal influence at a hypothetical bay.

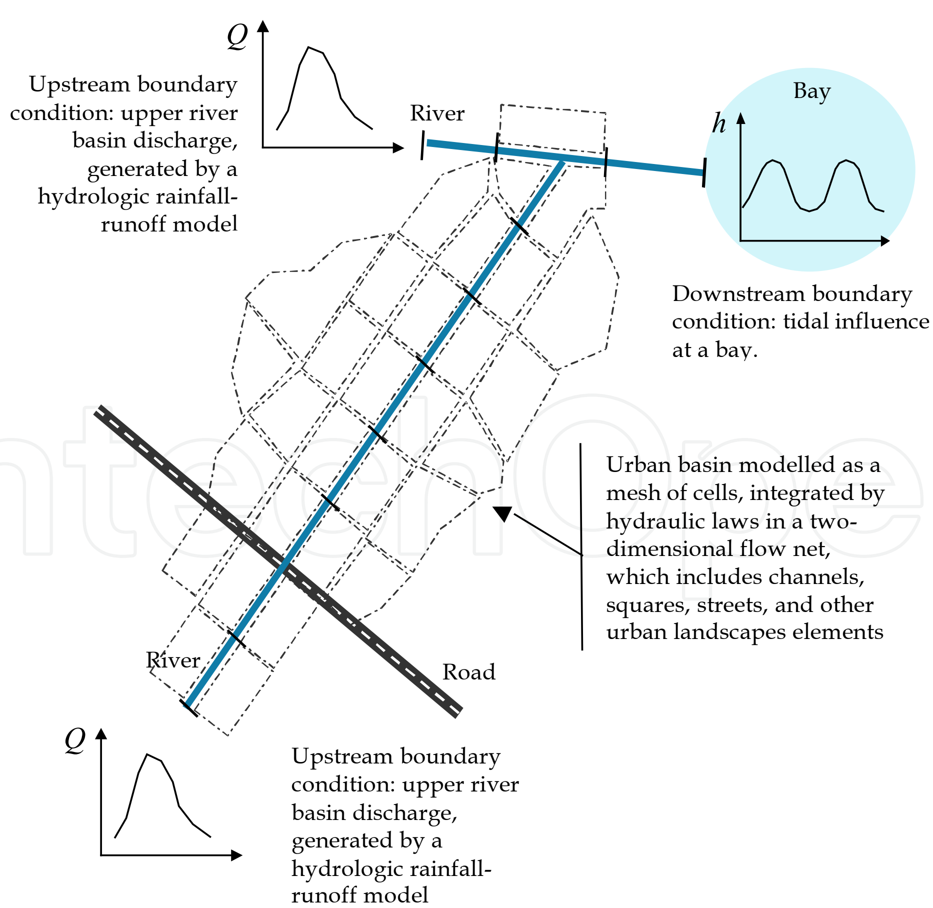



Fig. 16. Hypothetical mathematical modelling of an urban basin

### 4.3 Illustration of a Set of Typical Urban Flood Model

Urban flood modelling is increasing in interest, once urban floods appear as one of the most frequent, serious and costly problems that cities must face. Many models, with different characteristics, may be cited. In order to illustrate the discussion held in this chapter, some of the most common programs used for urban flood simulation will be mentioned in the following paragraphs.

MIKE FLOOD is a comprehensive modelling package, developed by DHI, covering the major aspects of flood modelling. MIKE FLOOD integrates flood plains, streets, rivers and sewer/storm water systems into one package. In order to achieve this objective, MIKE FLOOD join three widely used hydrodynamic models namely MIKE 21, MIKE 11 and MIKE URBAN into one package. This way, a 1D model and a 2D model are coupled with a sewer model, enabling analysis of flooding and assessment of the consequences of planned solutions The philosophy adopted allows an appropriate spatial resolution, so that. pipes and narrow rivers are modelled using one-dimensional solvers whereas the overland flow is modelled using two spatial dimensions. Some characteristics of MIKE FLOOD are: coupled one and two-dimensional flow, integration of hydraulic structures in 2D grids, effective mass conserving flooding/drying routine, accurate and physically based simulation of flow splits (DHI, 2008).

The United States Environmental Protection Agency (EPA) developed Storm Water Management Model (SWMM), which is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, among others. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Rossman, 2008).

SWMM was first developed in 1971, and has undergone several major upgrades since then, being used for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. The current edition is SWMM 5.

The Hydrologic Modelling System (HEC-HMS), developed by US Army Corps of Engineers (USACE) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be useful in a wide range of geographic areas, including large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs calculated by the program are used directly or in conjunction with other software for studies regarding water availability, urban drainage, flow forecasting, future urbanisation impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

The program is a generalised modelling system capable of representing many different watersheds. A model constructed for one watershed considers separation of the hydrologic cycle into manageable pieces and the definition of boundaries around this watershed, in the area of interest. In most cases, several model choices are available for representing each kind of problem (Scharffengerg & Fleming, 2008).

**4.4 MODCEL – An Overview**

MODCEL (Mascarenhas et al., 2005) is an urban flood model, which integrates a hydrologic model, applied to each cell in the modelled area, with 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 for the model are one-dimensional. 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 The construction of MODCEL, based on the concept of flow cells (Zanobetti et al., 1970) intended to provide an alternative tool for integrated urban flood solution design and research. The representation of the urban surface by cells, acting as homogeneous compartments, in which it is performed rainfall run-off transformation, integrating all the basin area, and making it interact through cell links, using various hydraulic laws, goes towards the goals to be achieved by the mathematical modelling of urban floods, as discussed in the previous sections. Different types of cells and links give versatility to the model. Figure 17 shows a catchment's profile, where it is possible to see a cell division and the interaction between cells.

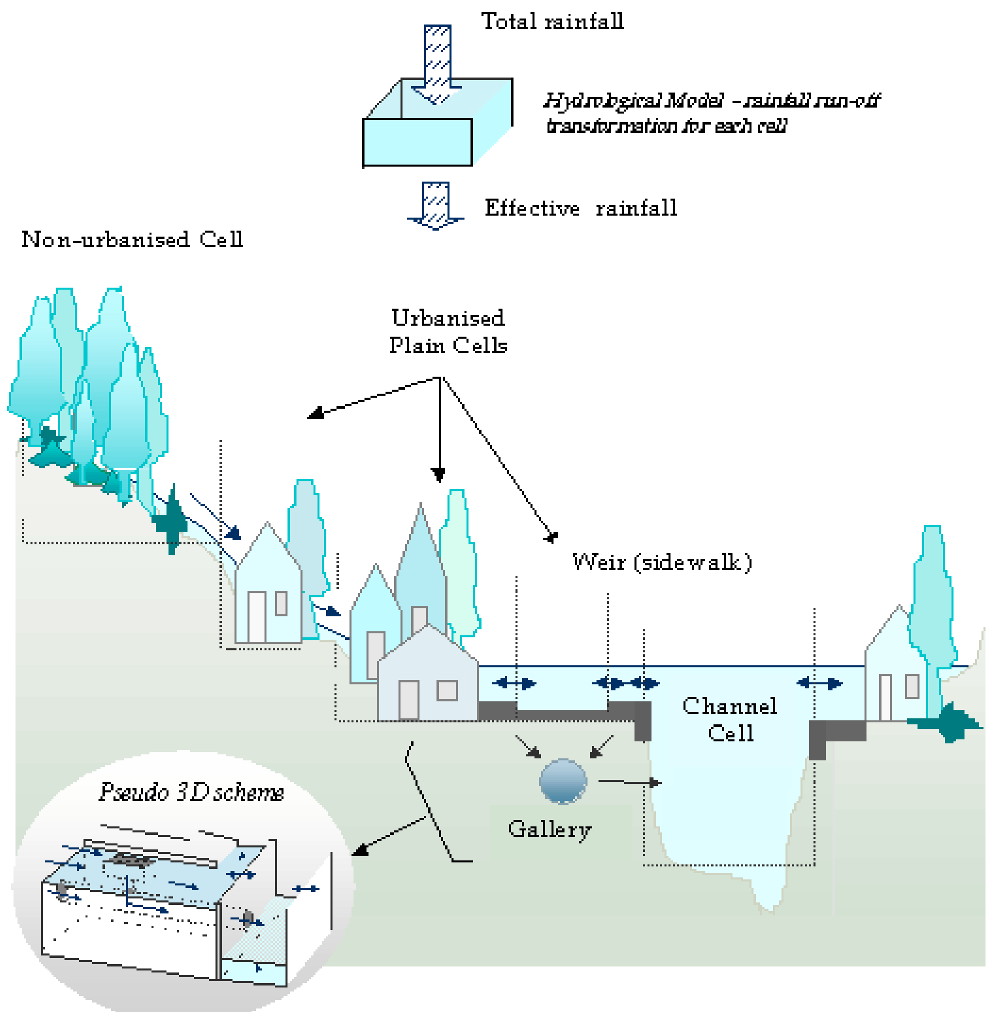



Fig. 17. Schematic vertical plane cut in an urban basin showing a cell model representation

The cells, solely as units or taken in pre-arranged sets, are capable to represent the watershed scenery, composing more complex structures. The definition of a set of varied flow type links, which represent different hydraulic laws, allows the simulation of several flow patterns that can occur in urban areas. Therefore, the task related to the topographic and hydraulic modelling depends on a pre-defined set of cell types and possible links between cells.
The pre-defined set of cell types considered in MODCEL is listed below:

- River or channel cells – are used to model the main free open channel drainage net, in which the cross section is taken as rectangular and may be simple or compound;
- Underground gallery cells – act as complements to the drainage net;
- Urbanised surface cells – are used to represent free surface flow on urban floodplains, as well as for storage areas linked to each other by streets. Alternatively, these cells can represent even slope areas, with little storage capacity. In this case, they are designated to receive and transport the rainfall water to the lower modelled areas. Urbanised plain cells can also simulate a broad crested weir, which conduct water spilled from a river to its neighbour streets. These kinds of cells present a gradation level degree, assuming a certain pre-defined storage pattern, as shown in figure 18;
- Natural (non-urbanised) surface cells – these cells are similar to the preceding case, however having prismatic shape without considering any kind of urbanisation;
- Reservoir cells – used to simulate water storage in a temporary reservoir, represented by an elevation versus surface area curve.

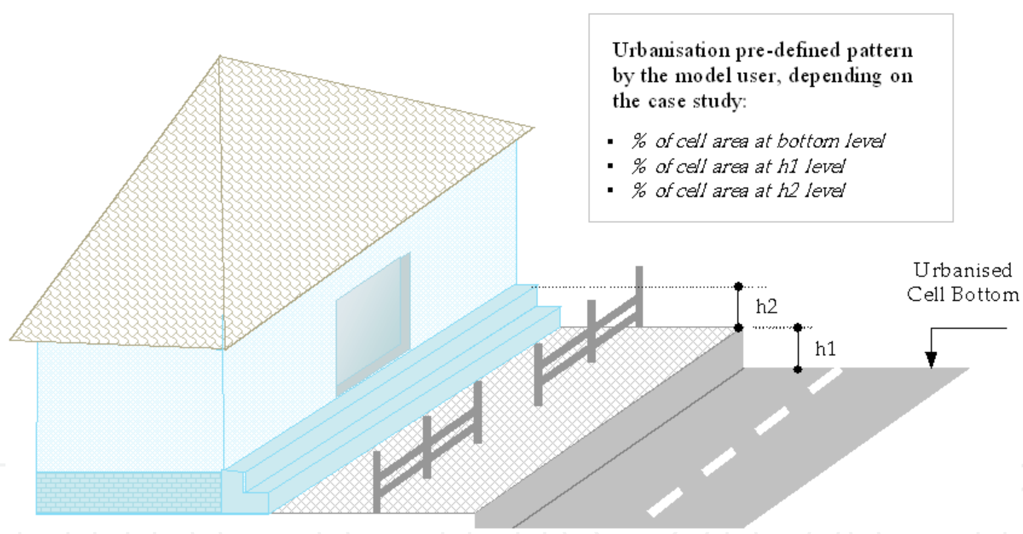



Fig. 18. Urbanisation storage pattern representation

Typical hydraulic links between cells can be summarised as shown below (Miguez, 2001; Mascarenhas et al., 2005):

- River/channel link - this type of link is related to river and channel flows. It may eventually also be applied to flow over the streets. More specifically, it corresponds to the free surface flow represented by the Saint-Venant dynamic equation;
- Surface flow link - this link corresponds to the free surface flow without inertia terms, as presented in Zanobetti et al. (1970);
- Gallery link - this link represents free surface flow in storm sewers, as well as surcharged flow conditions. Free surface flow is modelled the same way as in surface flow links, using simplified Saint-Venant dynamic equation. On the other hand, when galleries become

drowned, pressure flow conditions are given by energy conservation law; therefore, using Bernoulli equation;

- Inlet gallery link/Outlet gallery link - computed flow conditions define if the inlet/outlet is drowned or not, also considering the possible occurrence of local head losses;
- 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;
- Orifice link - this link represents the classic formula for flow through orifices;
- Street inlet link - this link promotes the interface between surface and gallery cells. When not drowned, this link acts as a weir conveying flow from streets to galleries. When drowned, this link considers flow occurring through a certain number of orifices associated to the street inlets;
- 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;
- Stage-discharge curve link - this link corresponds to special structures calibrated at physically reduced scales in laboratory and basically relates a discharge with a water level, in a particular equation;
- Pumping link - this link allows to pump discharges 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 often found in regions protected by polders.

### 4.5 Acari River Mathematical Modelling - A Case Study in a Poor Region of RJ/Brazil

The basin of the river Acari has a drainage area of about 107km², composed by densely populated neighbourhoods of the city and containing several important streets, avenues and highways. This region, however, is one of the most poor of the city and there are various informal communities established there, especially near river banks. The main river itself shows signs of heavy environmental degradation, with solid waste disposal, garbage and sediments appearing in several reaches. Flooding is one of the critical problems of the basin as well. There are inundation records of more than one meter in different places. At the critical points, there are records of almost two meters. City Hall estimates that floods on Acari river basin directly affect about 20,000 people, and more than 150,000 people are affected indirectly, because of urban infrastructure disruption during inundation. Figure 19 shows some of these problems.

Fig. 19. Scenes of Acari river basin

The solution for Acari River basin floods poses a difficult problem, combining critical flooding levels, social pressures, lack of appropriated infrastructure, sea and tidal influence. The first attempt to treat this problem, as proposed by Rio de Janeiro City Hall, referred to the traditional approach of canalisation. This design concept arose because of several detected river bed obstructions and river banks occupation, facts that suggested the need of improving conveyance. However, this proposition would probably not be able to solve the problem by itself. Tide at the outlet of the basin limit the discharge capacity and large flooded areas spread around the basin show that simple canalisation would transfer the problem to lower areas, increasing flood magnitude at these parts of the basin.
Facing this problem, Rio de Janeiro City Hall and Federal University of Rio de Janeiro joined efforts in the search of a systemic solution, balancing conveyance and storage approaches. The basin, showed in figure 20, was modelled using MODCEL. An example of the cell division, is provided in figure 21.

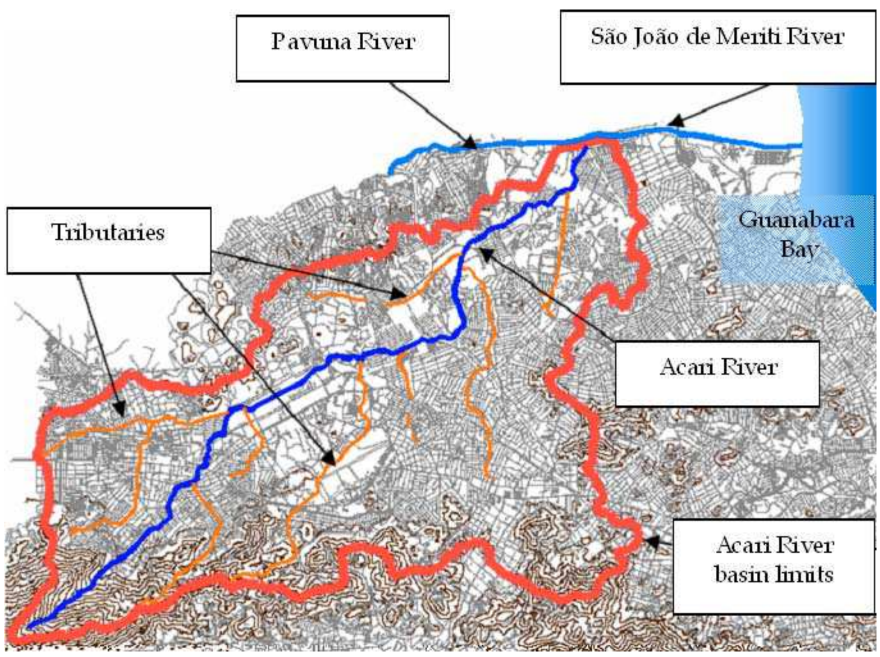


Fig. 20. Plain view of Acari river basin

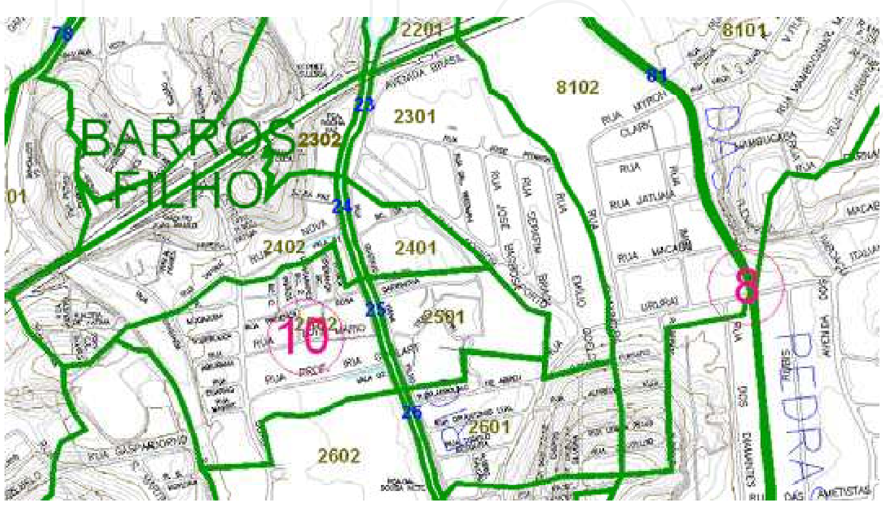


Fig. 21. Detail of the cell division for Acari River Basin Modelling

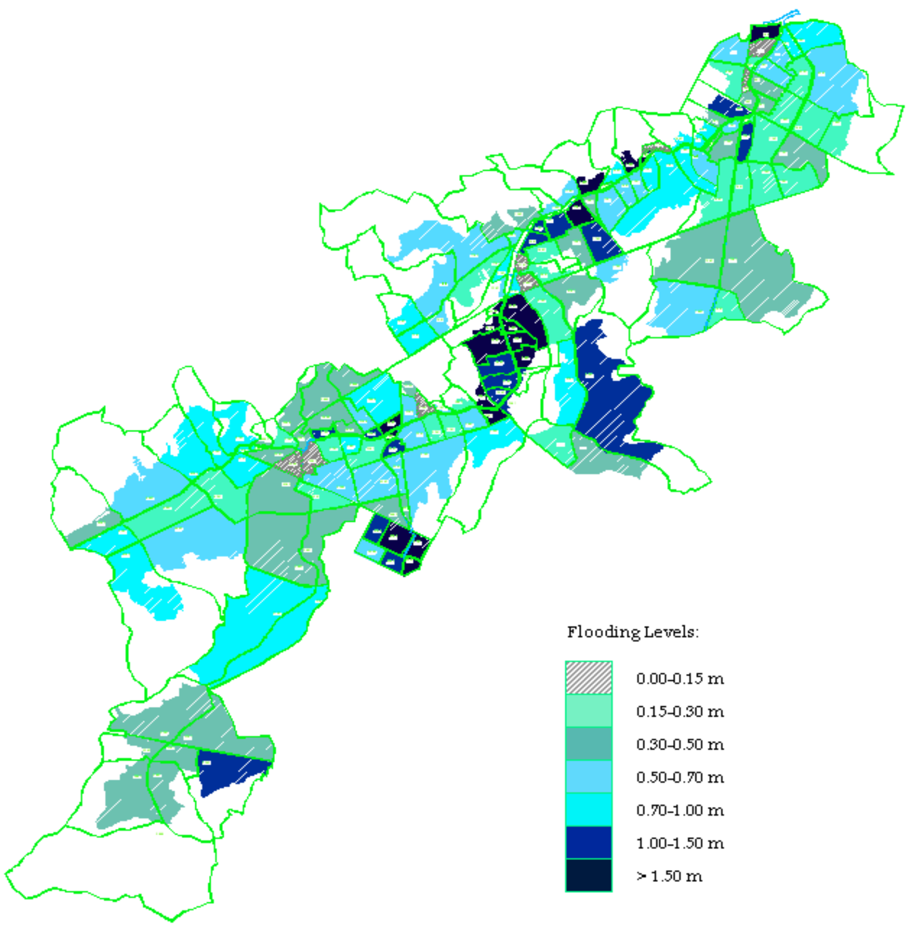



Fig. 22. Flood map for present situation

After analysing flood patters and making a diagnosis of the flooding present situation, whose flood map is seen in figure 22, a set of complementary and integrated measures was proposed as a result of prospecting scenarios generated by the model:

- canalisation was not considered necessary in a large scale, although it should be useful and recommended for specific reaches;
- it was necessary to propose an dredging of medium and low reaches of the river, in order to deal with river bed sedimentation and local obstructions, specially near bridges pillars;
- low bridge beams, working as local barriers to flood flow, must be remodelled (one of the bridges, at Luis Coutinho Cavalcanti street was considered very critical);
- the original storage capacity of the basin needs to be, at least, partially restored. In this way, a set of reservoirs was proposed, with two major reservoirs in important tributaries of Acari River. Other measures included one detention basin proposed in the left margin of the river, near a military area, and a slum area, on the right river margin, was proposed to turn into a park and to work as a multifunctional landscape, damping high discharges;
- people living in very critical areas, in the flood plains, needs to be relocated to safer areas;
- flood problems could be reduced, but there would be areas still strongly affected. It is important to understand that only a long-term work could produce better results. Sustainability needs a larger range of actions. Environmental recovery and investment in general urban infrastructure are necessary to revert the situation. Education and economic development complete the puzzle to construct the desired solution for the problem.

After considering this set of interventions, comparing flood levels at 18 control points, there was an average reduction of 30%. The higher water level reduction result showed inundation diminished by 76% (from 1.31m to 0.31m).

### 4.6 Use of soccer fields as complementary areas of a temporary storage pond in a poor community

This second case study refers to a region of Rio de Janeiro State (RJ) known as Baixada Fluminense, located at the metropolitan region of Rio de Janeiro City and occupied mostly by low-income families. This region is also characterised by low level lands naturally subject to floods caused by Iguaçu and Sarapuí rivers. Dikes have been built to prevent the flooding of this region, and as a consequence, polder areas were created. The typical arrange of these polders consists of a stormwater temporary storage pond which receives the major drainage channels and is connected to Iguaçu or Sarapuí rivers through flap gates. The use of flap gates to allow discharge of these polders has the advantage that this kind of structure is passive, robust and requires no operation. The disadvantage is that the discharge can only take place during low tides and these periods can sometimes be delayed due to the routing of floods in the Iguaçu and Sarapuí rivers and adverse climatic conditions. Pump stations could overcome these limitations, but the use of this kind of solution in such case can be considered inappropriate due to the lack of security of the facilities and high operation and maintenance costs. As a result, in order to prevent the water from rising up to a certain level that could cause uncontrolled flood of the surrounding area and consequent failure of other elements of the drainage system, a greater temporary storage volume is required.

Polder Alberto de Oliveira, which receives drainage of part of São João de Meriti and Duque de Caxias municipalities (RJ), is taken in this case study as an example of what is occurring with other polder areas at Baixada Fluminense region. Regular and irregular buildings have been occupying a portion of almost 80% of polder original area designed to work as stormwater temporary storage pond (COPPETEC, 2003). Visiting this community, it can be observed that one of the measures developed by local population, in order to prevent flood losses, was building their homes over 1.0 to 1.5 meter tall pillars. Urbanisation of the catchments also aggravates the problem, as the runoff production got higher than that estimated by the time the original pond was designed. These two factors caused the flood risk of the region to rise considerably. Recent storms and the extension of flooding areas caused a lot of public pressure over the municipalities and state governments. The response of the authorities was the creation of a program to reduce the flood risk in this area. So forth, studies have been carried out in order to determine which interventions are needed to maintain the water inside the pond, considering a maximum water level that could cause no flood hazard to the surrounding community. MODCEL (Miguez, 2001) was used to simulate the flood at the polder area and at the Sarapuí River. A 20-years return period storm was set for the polder area and a 10-year return period storm was used for the Sarapuí river basin.

The results of the mathematical simulation showed that three combined possibilities could reduce water level in the storage pond area to the desirable level (COPPETEC, 2003): a) double the number of flap gates; b) set a 8m3/s pump station close to the remaining storage area; c) reallocate part of the population that occupies the original temporary pond area. Due to the already mentioned problems concerning pump facilities this alternative has been abandoned. One demand of state authorities was the reduction of the number of families in need of reallocation. The final scenery proposed considered an increase of the number of

flap gates (60% more flow capacity) and the lowering of the ground level of two areas close to the remaining storage pond. Few families occupy one of these areas and several soccer fields occupy the other. Figure 23 shows the cell division of the region and these areas.
An interesting aspect about the behaviour of local communities in Brazil is that it is very hard to prevent the occupation of free spaces close to poor communities, but soccer field areas are almost always respected, as there is a public perception that these areas serve as leisure and sport facilities for the community. Part of the strategy was setting a multifunctional landscape at the soccer fields' area, so that it could assume a new function, flood control. The proposal was lowering this area to a ground level higher than the other new storage area which is being added to the remaining pond, so that this complementary storage volume gets used only in case of more intense storms, allowing its sportive function at most of the time. The set of measures presented in the final scenery are currently under construction.

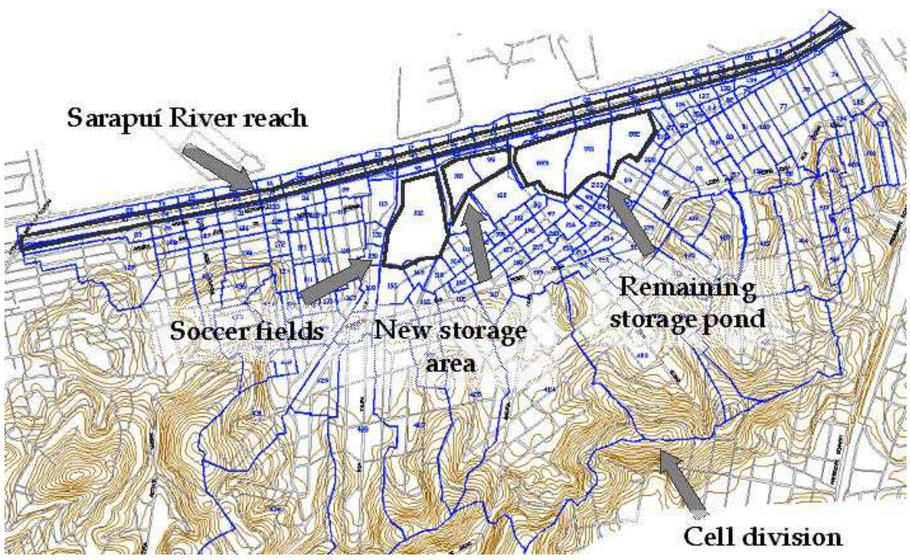



Fig.23. Cell division of the region of interest and new areas added to the remaining pond

## 5. Concluding Remarks

Flood control is one of the major questions with which urban planners must deal nowadays. According to Freeman (1999), 60% of human life losses and 30% of economic losses caused by natural disasters are due to floods. Besides, urban floods involve several different aspects in a mosaic involving climatic, technical, social, economic and environmental issues.
Technically, the urban flood problem must be understood in both spatial and temporal dimensions. In this context, city landscape diversity aggregates one more difficulty, generating a complex flow pattern.
Optimal Engineering solutions are not always possible to be achieved because of social or political and institutional constraints. However, in order to have the best possible solution, it is necessary to provide integrated, sound and efficient design alternatives.
In this context, mathematical modelling can provide an important tool to aid in the 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.

Classic site-specific planning needs to be replaced by a watershed oriented planning. Local and isolated solutions tend to transfer flood problems. The traditional canalisation approach, improving conveyance and focusing the consequences of floods, cannot face alone the flooding problem. New approaches focus on storage and infiltration measures, as well as on preventive actions, complementing the traditional ones. Therefore, the concepts applied to stormwater drainage design have been changing a lot in the past decades, pointing to a systemic approach. Structural measures, of different kinds, are being proposed to reorganise flow patterns and partially recover hydrologic conditions previous to urbanisation, while non-structural measures aim to provide rational coexistence with floods. All these changes along time and the state of art evolution detach the challenge with which cities are being faced: to find a sustainable path to equilibrate city growing with a harmonic built environment for their communities.

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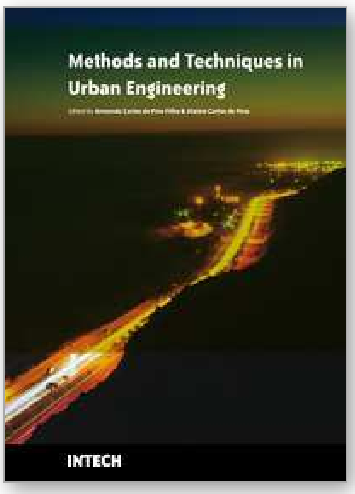


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A series of urban problems such as dwelling deficit, infrastructure problems, inefficient services, environmental pollution, etc. can be observed in many countries. Urban Engineering searches solutions for these problems using a conjoined system of planning, management and technology. A great deal of research is devoted to application of instruments, methodologies and tools for monitoring and acquisition of data, based on the factual experience and computational modeling. The objective of the book was to present works related to urban automation, geographic information systems (GIS), analysis, monitoring and management of urban noise, floods and transports, information technology applied to the cities, tools for urban simulation, social monitoring and control of urban policies, sustainability, etc., demonstrating methods and techniques applied in Urban Engineering. Considering all the interesting information presented, the book can offer some aid in creating new research, as well as incite the interest of people for this area of study, since Urban Engineering is fundamental for city development.