Urban Drainage: System Modelling for Integrated Catchment Management

Aradas R.D., Ivanissevich Machado L., Mauriño M., Norton M.R.

Abstract

The need to apply an integrated approach to catchment management is vital to the success in the implementation of sustainable solutions to resolve issues such as the provision of water supply and sewerage, power generation, drainage and river flooding. In recent years, the increasing awareness of the scarcity of water resources, indications of likely climate variability, and the increasing pressure to use the available fresh water sources for human consumption have together reinforced the need to look at infrastructure solutions with due regard to environmental considerations and social impacts, present and future. Furthermore, in developing countries, the economic situation often means that there is need to look at solutions which strike a balance between capital, operational and maintenance expenditure and expected benefits. Such an approach is key to sustainability and can facilitate access to international funding. This paper reviews the modelling work carried out in a major urban drainage project: the development of the Integrated Master Plan for the catchments of all the watercourses that cross the city of Buenos Aires (30.000ha and 3.5million inhabitants). This city is a very dense and consolidated urban city with a complete culverted drainage network that dates from 1919/1940 (existing trunk culverts are 20m wide and 4m height). The rapid increase in population (mostly fed by internal migration from the interior of the country) coupled with the associated development of paved roads, has produced a dramatic increase in the runoff from rainfall, resulting in severe flooding in more than 30% of the city area for events with a frequency as low as two years. InfoWorks CS was the modelling package selected to simulate the flow in more than 8000 streets and 2000 sewers. The results obtained were later processed in a GIS system to produce flood extent maps for events of different magnitudes. This approach permitted the development of a robust conceptual understanding of the system, as well as quantitatively supporting the baseline studies, and the subsequent identification of economically, socially and environmentally sustainable mitigation measures that form part of the Master Plan.

Introduction

The concept of integrated catchment management, or Integrated Water Resources Management (IWRM), is today widely used and recognized as essential in order to guarantee that all natural resources are managed in a sustainable manner. Various authors have supported this approach over the last thirty years, for example: Leopold and Dunne (1978), Saha and Barrow (1981), Mitchell (1989), Gardiner (1991), Serageldin and Steer (1995) and Newson (1997), which when added to other publications by European research bodies and organizations (in the form of frameworks, manuals and review studies), constitute a vast amount of material to set the topic as the key water management agenda in this century. This concept is equally applicable to resolve potentially conflicting issues such as the provision of water supply and sewerage, power generation, drainage and flooding. In recent years, the increasing awareness of the scarcity of water resources, evidence of climate variability, and the increasing pressure to use the available fresh water sources for human consumption (under a scenario of growing population and intensified urbanisation); have together reinforced the need to look at infrastructure solutions with due regard to environmental considerations and social impacts, present and future.

Turning the concept of integrated catchment management into practical and implementable solutions generally implies the development of an integrated master plan to express in time and space a set of structural, non structural and institutional measures to address issues such as flood mitigation. However, the integrated viewpoints of the different disciplines normally encountered in the development of a master plan would not converge on the common objective of reaching sustainability unless a clear unified methodological approach is devised to value the different objectives -often conflicting- encountered in the planning exercise at a basin level. A cost-benefit analysis seems to be a way to establish the relative importance of the different issues involved but has the drawback of having to assign cost and benefits to environmental effects and assets (HR Wallingford, 2002). The need for a cost benefit analysis is crucial in developing countries, where the economic situation means that there is need to strike a balance between capital, operational and maintenance expenditure, and expected benefits. Such an approach is key to sustainability and can facilitate access to international funding.

The preparation of a successful master plan must be also preceded by a sound diagnostic study supported by a robust identification of the mechanisms that generate flooding in the city. This in turn leads to the definition of the different hazard descriptors, such as flood depth and extent, duration and velocity. The complexity and magnitude of the flooding issue is characterized by rapid surcharge of the underground sewers, the appearance of water on the surface (forming deep and fast moving bodies of water), and the transfer of water across catchment boundaries. The analysis of all these mechanisms requires the development of a complex model integrating the simulation of the overland flow processes as well as the flow of water in the underground sewer system.

This paper reviews the modelling work carried out in the development of the Integrated Master Plan for urban drainage for the city of Buenos Aires: a World Bank funded project executed by a Joint Venture between Halcrow (UK), Harza (USA) and Iatasa and Latinoconsult (Argentina) for the Government of the City of Buenos Aires. InfoWorks CS was the modelling package selected to simulate both flow processes in the drainage network; those above and below ground. The resulting water levels on the surface were later processed in a GIS system to produce flood extent maps and flood damage assessments for events of different magnitudes. This approach permitted the development of a robust conceptual understanding of the system, as well as quantitatively supporting the baseline studies, and the subsequent identification of mitigation measures that form part of the Master Plan.

Buenos Aires and its Flooding: A Recurrent Hazard.

At the beginning of the past century, a series of natural and open watercourses (Ao.Medrano, Ao.Vega and Ao.Maldonado) crossed Buenos Aires in a South West to North East direction then discharged to the La Plata River. The Southern area of the city was also characterized by the presence of short and relatively steep streams (Ao. Cildañez, Ao. Erézcano, Ao. Ochoa and Ao. Elía) that discharge to the Riachuelo River. The catchment of these streams, together with that of the arroyos Medrano, Maldonado and Cildañez, extend beyond the limits of the city and have their upper contributions in the Province outside the administrative boundaries of Buenos Aires. Since 1940, the City undertook a drastic change in its urban architecture and all the natural streams within the limits of Buenos Aires were culverted, coinciding with the construction of the present drainage network of trunk and secondary sewers. The drainage network of the Buenos Aires is a separate system except in the old and central area where a combined sewage and storm network is in place, accounting for only 8% of the total catchment area. Each of the three most important catchments (Maldonado, Medrano and Vega) are drained by a large trunk sewer that follows the alignment of the former watercourses; typical dimensions range from 15m to 20m wide and 3m to 4m height with an internal supporting structure of columns and beams that results in a significant interaction with the flow system.

The construction of the drainage network was subsequently followed by a rapid increase in population and urbanization that lead to the current situation where over 3.5million people occupy the area of all catchments of the city (30,000ha). Only 10% of the city is open and green area. Figure 1 presents the location of the City of Buenos Aires and its relevant watercourses through a 3D view of the Digital Elevation Model.

Figure1: **Left: Location of Buenos Aires Province – Argentina**
Right: Satellite View of the City of Buenos Aires – Buenos Aires Province
Bottom Corner: Natural Landscape of Buenos Aires. 3D View.

Although the city does not have sufficient rainfall stations to enable a definitive description of its temporal and spatial rainfall pattern, it is possible to say that Buenos Aires suffers from the occurrence of intense storm events, most of them of convective type during the summer. The statistical analysis of daily rainfall in the two stations available yields the conclusion that the total amount of rainfall falling on "rainy days" (i.e. those with more than 20mm of rainfall during that day) account for 50% of the total for a year, whereas the same quotient but for days with more than 50mm of rainfall is 20%. This means that the proportion of storms in a year is double that of typical Europe cities with approximately the same amount of rainfall in a year.

The occurrence of severe intense storm events can be traced back to the first decades of the last century. The most important events are summarized in the following Table 1 together with the amount of rainfall derived from a statistical analysis of annual series of 3hours duration (considered the critical duration for most of catchments of the city).

Rank	Rainfall (mm)	Year	Duration (hours)
1	308	1985	+/- 20
2	147	2001	+/- 3
3	146	1959	+/- 24
4	141	1945	+/- 12
5	130	1968	+/- 12
6	126	1963	+/- 12

Return Period (years)	Rainfall (mm)
2	52
5	69
10	81
20	93
50	110
100	123

Table 1: **Left: Historical Observed Storm Events (Villa Ortúzar)**
Right: Storm Events for Different Return Periods.

As a result of the occurrence of severe intense storm events, flooding becomes the most serious environmental problem that affects the normal life of the citizens of Buenos Aires, causing extensive and frequent damages to urban infrastructure, commercial and industrial activities, transport services, social distress and, to a lesser extent, posing a threat to life. The continuous increase in the degree of impermeability in the city (coupled with other physical interventions) has altered the normal functioning of the sewerage network and, today, the system cannot convey the runoff generated for a storm event for even 2 years return period. A quantification of the social and physical impact of different storm events is presented in the Table 2 below and Figure 2 shows pictures that show the effect on normal life in the city.

Affectation to:	**Return Period of the Storm Event (years)**		
	2	**10**	**100**
People (No)	330,000	660,000	1,100,000
Area (ha)	2260	5400	7600
Houses (No)	125000	250000	375000
Commerce (No)	6500	14000	22000
Industries (No)	1700	3800	6000

Table 2: Social and Physical Impact of Flooding in Buenos Aires

Figure 2: A view of flooding in Buenos Aires. Maldonado Catchment, 1985.

Buenos Aires is also affected by an increase in the level of the La Plata River as a consequence of the incidence of strong winds blowing from the South East. This results in an impact localized in the low lying areas near the La Plata and Riachuelo rivers. Although a high water level in these rivers imposes a constraint on the capacity of the sewers discharging into them, hydrological studies have shown that the occurrence of severe storm events and strong winds from the South East are independent events and therefore the flooding problems are not generally worsened (CAI, 1995).

Modelling of Storm Water System - Concepts

From the 19th century, the design of storm drainage systems for urban areas was dominated by the Rational Method (Mulvaney, 1850; Kuichling, 1889; Lloyd-Davies, 1906). Although the simplicity of this method was the reason for its widespread use throughout the world, doubts have often been expressed on the applicability of its simple concepts to the complex interaction of social and structural city development with the urban flow processes. During that century, the larger cities of America and Europe started to consider the necessity of planning their drainage systems and for many decades, the provision of piped sewerage and flood-free streets was regarded as essential for the quality of urban life. However, even in those large cities, the dimension of sewers calculated using the Rational Method was affordable given the fact that the proportion of impermeable area was still within reasonable limits.

At the beginning of the 20th century, the rapid development of cities and the associated increase in the proportion of impermeable areas had immediate hydrological consequences: an increase on the peak and volume of the runoff, leading to estimation of very large sewer dimensions. This triggered designers and researchers to assess the need to incorporate in the design process physical aspects not accounted for by the Rational method for the design of sewerage networks, such as storage routing and surcharged flow. This need was further intensified after the Second World War, when European cities had to be reconstructed and optimization in the design was necessary in order to accommodate investment within public expenditure. This was the origin of the spread of simulation models that were developed to predict the flow in a given drainage system under a defined rainfall event.

One of the concepts that has emerged in the last 20 years in Urban Drainage Management is the importance of maximizing the use of the "major" and "minor" systems to manage the resulting excess runoff originated during a storm event. It needs to be pointed out that the term "management" comprises the concepts of "conveyance", "storage" and "infiltration" of the excess water rather than the traditional idea of developing systems to convey the runoff as fast as possible to the receiving water bodies. The development of solutions that make use of the physical aspects of both "major" and "minor" systems implies examination of the integral capacity of the underground network of assets as well as the network above ground; the latter comprising roads, inlet works, and any feature of the physical infrastructure that could interfere with (and thus alter) the movement of the water. This opens up the number of variables to be examined in a diagnostic study and at the same time widens the criteria to be used when evaluating flood control and mitigation measures. This means that the capacity of the integral system can no longer be assessed as the maximum capacity of the critical underground sewers but must also consider the capacity of the inlet structures (gullies) and the capacity of the above-ground flow paths. Accordingly, the mechanisms which generate flooding can be grouped as (see Figure 3):

- flooding due to insufficient capacity of the inlet devices when the piezometric level of the underground sewer remains below ground level; and
- flooding due to insufficient capacity of the underground sewer when the piezometric level is above ground level.

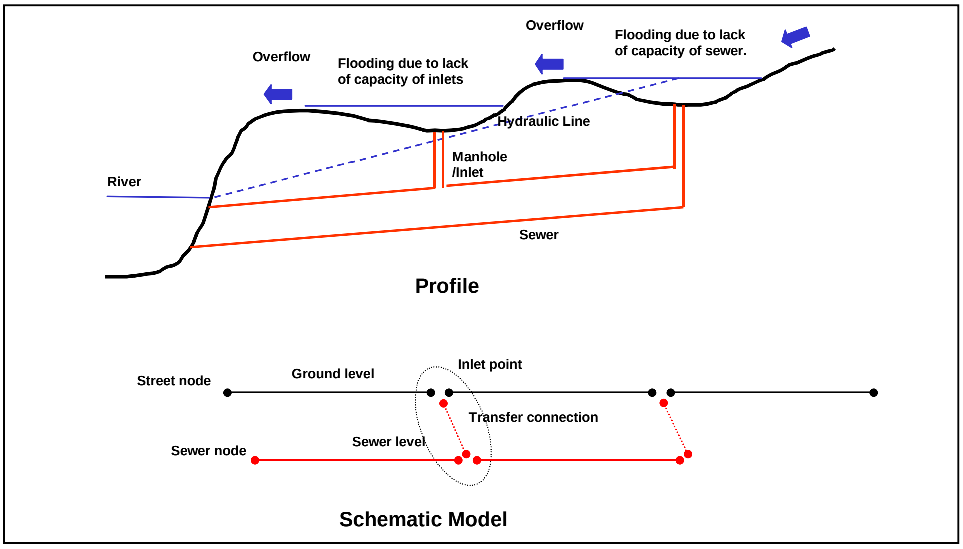

Figure3: Schematic representation of the two flooding situations.

The implementation of a modelling system capable of examining the integral complexity of the flooding process implies taking into account a number of concepts, such as:

- representation of conveyance and storage of water on the surface in order to determine water levels once the piezometric level of the underground sewers emerges to the surface. This is mainly achieved through identification and representation of the overland flow paths to convey the excess runoff to lower areas, and the inclusion of sufficient flow paths to account for the full spread of water for the most extreme event to be simulated. For a city such as Buenos Aires, the first implies the assignment of the correct slope and cross section of a conveying street whereas the latter means the inclusion of as many streets as required to cover the maximum flood extent (see Figure 4). Some approaches model the storage and conveyance effects in the surface using a cross section with a representative width; however this fails to represent the overland flow paths and transfers of water generated in the upper parts of the secondary network, which ultimately implies a potential under-prediction of the volume of water being conveyed to the lower lying area above the trunk sewer.

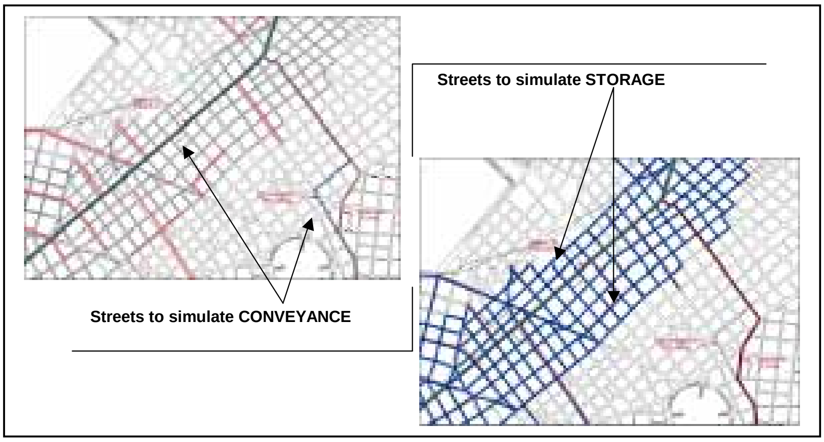

Figure 4: Schematic representation of conveyance and storage in the overland flow system.

- in relation to the above, it is important to identify *all* the overland flow paths, noting that they do not necessarily have to follow the layout of the underground sewer, as depicted in Figure 4 (left). Some of the overland flow paths operate for the full range of storm events that generate surcharging conditions on the surface, while some only appear when the depth of water on the ground is significant. The latter are generally related to transfers between catchments like those that take place between the lower part of the Maldonado and Ugarteche catchments, between the Medrano and the White, and between the catchments along the southern part of the city. Figure 5 shows the different inter basin transfers identified in Buenos Aires, which dictated how the different subcatchment were merged for modelling purposes.

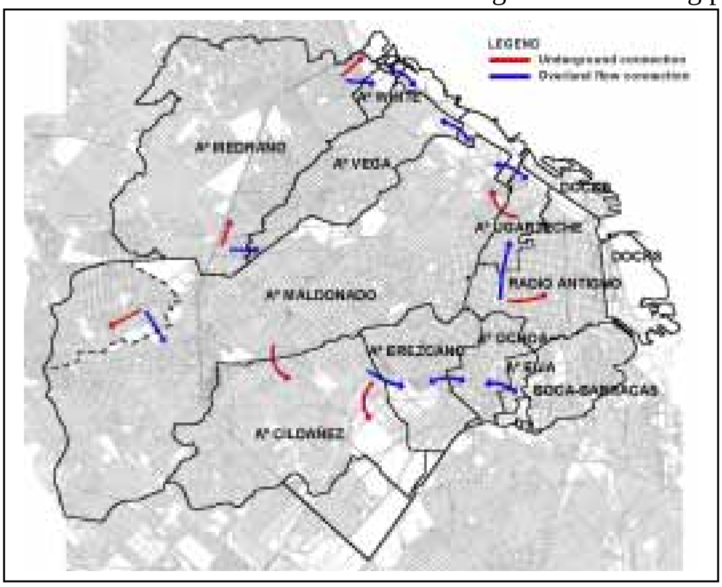

Figure 5:

Inter Basin Connections.

- an accurate representation of the functioning of inlet devices under varying circumstances. The inlets are the elements that control the flow rate between the the surface water system and the underground network. Although some models represent the gullies by assigning to them a maximum inlet capacity, the exchange of water between both systems is not realistically reproduced unless the model includes the hydraulic control that operates across a range of flow situations. During the rising part of the storm, the rate of flow entering the sewers is controlled by the length of the inlets in the surface but when the system is fully surcharged the control moves to the pipe connecting the gullies to the sewer

- it is common to find that a key criteria to decide which sewer has to be modeled is its capacity (or a surrogate, its size). However, irrespective of capacity, it may also be required to include in a model the pipes that, when surcharged, generate runoff that could impact the performance of other parts of the network.

- one of the usual applications of urban drainage models, when used as a tool to support the development of an economically viable plan, is the prediction of flood depths on the surface. The incidence of damage inside properties implies that there is some extra storage mobilized that should be taken into account in the schematization of the model. Although it is a parameter which is very difficult to estimate, the use of detailed aerial photographs can be the source to arrive at an approximate estimation of the storage inside flood-affected properties.

- the hydrographs that result from the rainfall runoff transformation for each subcatchment are applied into nodes of the overland flow system; this implies that at each node only part of the runoff enters the sewer according to the capacity of the inlet structure, the capacity of the downstream overland flow network, and the differential head between both systems at the node level.

- the runoff routing factors of the classical hydrological modules need to be examined and adjusted to take account of the potential overlap that might arise since most of the surface processes within a subcatchment are explicitly represented in the schematization of the surface water system, like storage and routing in streets.

Model Development and Applications

InfoWorks CS was the modelling package selected to simulate the flow in 1400km of sewers in the city of Buenos Aires, covering an area of 30,000ha with 7,000 subcatchments and 12,000 and 6,000 street and sewer nodes respectively (Figure 6).

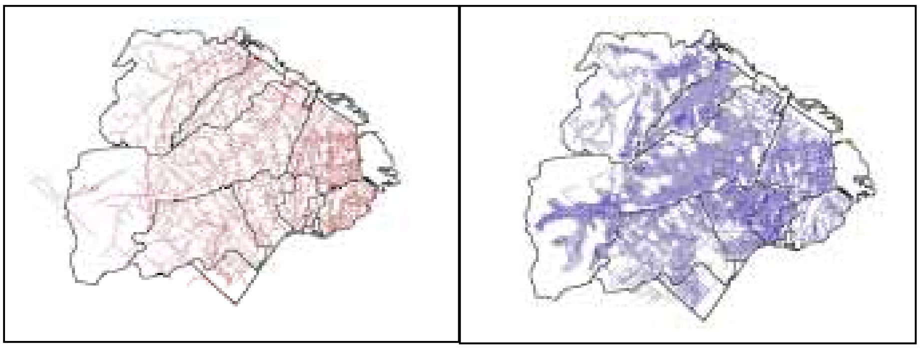

Figure 6:

Left. Schematic of the underground system

Right. Schematic of the overland flow system

The development of the model was carried out following the concepts outlined below but with a varying degree of detail in the schematisation according to the decisions to be made at each stage of the project: diagnosis and analysis of alternatives, feasibility designs and detailed design of the preferred option. The variables adjusted in the schematisation were mainly the size of the subcatchments and the extent of streets and pipes included in the model.

Data for the underground network came mostly from hard copy maps (data from the 1980s). Ground data for the construction of the overland flow system originated from restitution of aerial photographs and came in the form of spot heights along streets every 25m to 100m. The odel was calibrated using existing available data. Two exercises were carried out for in-sewer calibration of the trunk sewer of the largest catchment based on rainfall data from six gauging stations and four level recorders, and the surcharged calibration for two large flood events using flood level data on the streets gathered from surveys amongst the population affected in each basin (Figure 7). The lack of detail of observed rainfall, level and flow time series needs to be highlighted as a drawback for the calibration of the in-sewer drainage network; however, the spread of observations gathered after the flood event of January 2001 demonstrated that the performance of the model is satisfactory for the purpose of making comparative judgements between basin scale flood mitigation measures.

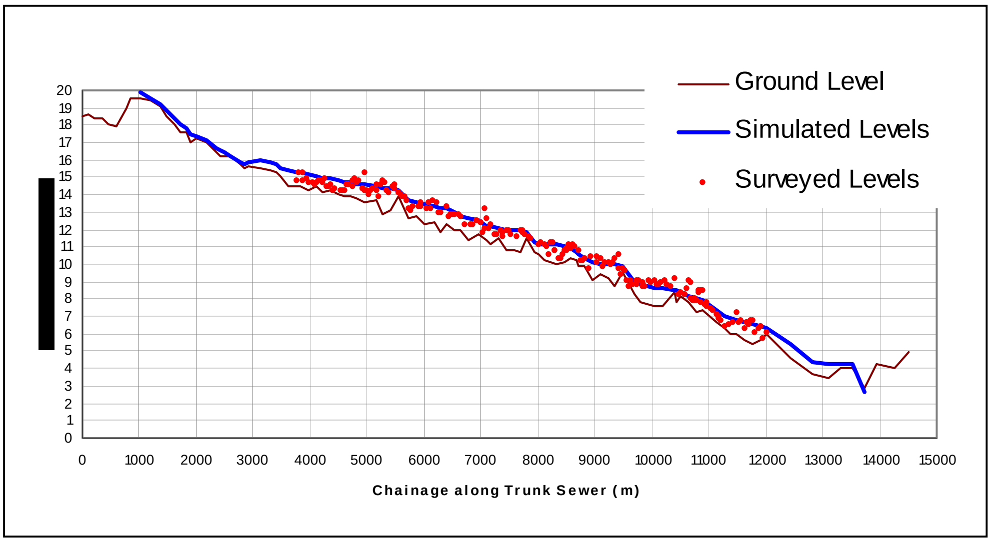

Figure 7: Model Calibration for the event of January 2001. Maldonado Catchment.

Once built and calibrated, the modelling tool provided a wide range of results to support the different applications of the Master Plan. Flood extents were used to assess the magnitude of the problem, quantifying the elements of the physical and social infrastructure of the city exposed to the flood hazard for different return periods. These extents and the spatial distribution of flood depths were combined with a cadastral database in order to take the assessment of exposure further into the calculation of flood damage at a postcode level (Figure 8). Maps of isochrones, showing how long each area was exposed to a given flood depth, were used to assess the disruption to the transport services and its economic impact. The assessment of the flood hazard also included the estimation of the spatial distribution of the product of the overland flow velocity times the flood depth. This, together with a detailed analysis of the ground surface, provided a good insight into the dynamics of the water in the surface, highlighting the effects of the raising the level of avenues perpendicular to the main direction of the surface flow (through successive re pavements). This effect (markedly shown in the Maldonado catchment) consists of the ponding of water behind each transverse avenue, increasing flood depth in localized areas but diminishing overland flow velocities (Figure 9).

The trunk sewers of the most important catchments become surcharged for events of even two years return period, suggesting severe under-capacity of the system to carry the current excess runoff generated in the basin. Because the cover of these sewers rarely exceeds two meters, the surcharge rapidly translates into the appearance of water in the surface. Once surface flooding takes place in a generalized manner on top of the trunk sewer, its carrying capacity is primarily controlled by the hydraulic gradient on the surface which reinforces the need to model the storage on the surface across the whole flood extent. Traditional modelling approaches that do not model the overland flow component tend to generate output flow hydrographs that overestimate the peak flow and underestimate the time for recession; this is a result of the fact that results are largely dominated by the hydrological routing rules. Once flooding occurs, the ground storage in a flat area (far larger than the storage available in the underground system) rapidly balances the piezometric levels which then impose a limit on the maximum flow rate that the trunk sewer can discharge.

The coupled overland-underground flow model was also a key tool to support the process of analysis and selection of alternatives. The severe lack of capacity of the underground system imposed the need to plan the execution of large infrastructure works in the form of deep relief tunnels for the three main catchments with diameters varying from 3m to 7m and a maximum length of 10km in the case of the Maldonado. Though storage solutions were investigated, they were not generally an effective alternative to relief sewers to mitigate the large scale flooding in most catchments. In the Vega basin,.some deep off-line reservoirs were included to mitigate flooding in localized areas, in addition to the extra conveyance provided with the tunnels. All designs were carried out to a standard of 10 year return period, and adopting design criteria that trunk sewers have to operate under free flow conditions while the secondary network could be surcharged so long as streets were not flooded by more than 0,25m and the product of velocity and depth did not exceed 0,5m^2/s.

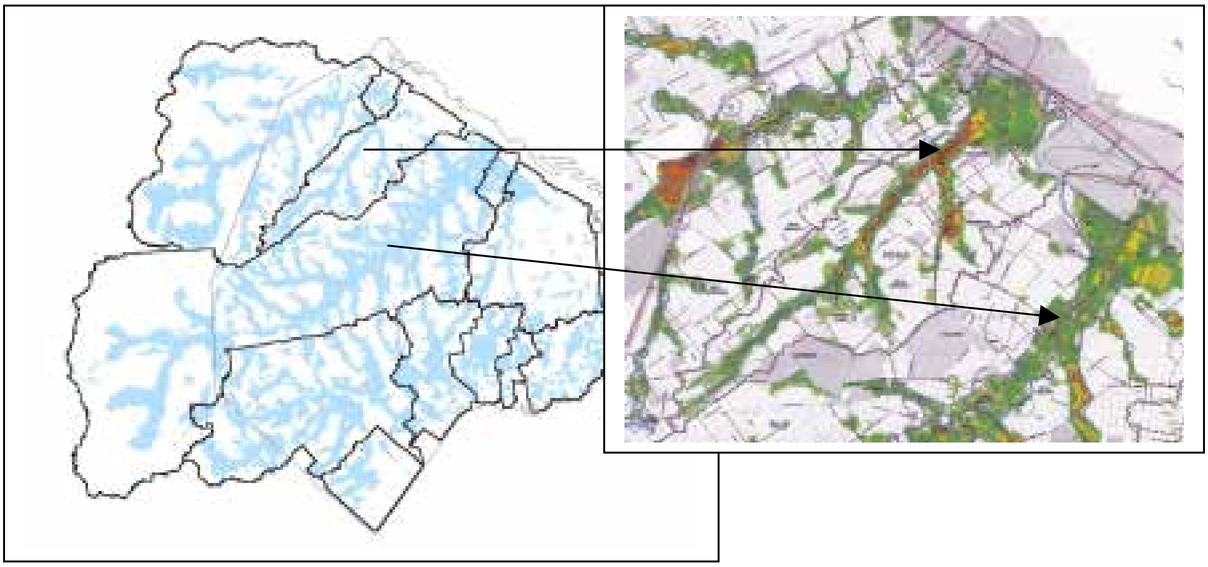

Figure 9:
Left: Flood extent obtained with the model for a 100 years event.
Right: Map showing the product of velocity x depth of surface water
(Red and green indicate highest and lowest values of this product respectively)

The Way Forward: *Turning Models into Operational Tools*

One of the key findings of this project is the appreciation that models cannot only serve as a tool during the design phase but also they can perform an effective role in the day-to-day management of the storm drainage system. The integrated model will form part of various subsystems of the Sectoral Management System that will provide the technical basis of the daily management and implementation of the measures of the proposed Master Plan. The main role of the model will be to support a flood warning system; although the response time of the city to storm events (of the order of 2 to 3 hours) is faster than what would be manageable in a real time modelling system, the model will be used to predict the flood extent in advance of the storm as rainfall predictions are made available from the future hydrometeorological network. Also a set of customized interfaces were designed to facilitate the simulation and analysis of results of different scenarios by allowing changes in boundary conditions and rainfall data without modifying the structure of the model and to support the calculation of flood damage and the quantification of the affected infrastructure in the city after each flood event. Finally the database that supports the simulations of the model will be linked to the asset database of the city so that any changes in one system can be easily transferred to the model database.

Conclusions

A comprehensive overland-underground flow model for all the catchments of the city of Buenos Aires was built and calibrated using the InfoWorks CS package. The model covered the simulation of over 1000km of sewers and 20,000 streets, covering ten catchments and 30,000ha, increasing significantly the existing capabilities in the Government of the city to analysis its drainage system.

The coupling of very detailed ground level mapping with less detailed records of the underground network proved to be sufficient to construct this model for diagnosis and design purposes, taking into account the predominance of the overland flow processes in relation to the severe under-capacity of the existing sewers. More fieldwork will be required to verify the model once the proposed works are in place and the flow in the underground network will be more important across a wider range of storm events. On the other hand less data will be avilable for the calibration of the out-of-sewer model.

A first impression of the level of detail comprised in the model may pose the question of whether the effort required balances the benefits of the development. The experience and results gathered throughout the execution of the master plan proved that, if a careful balance is maintained between the degree of detail in the schematization and the type of decisions to be made at each stage of the project, then a tool of this type can provide invaluable support in the identification of problem areas and solutions. In particular, the model helps to consider flood alleviation measures that integrate the functioning of both the overland and the underground network, permitting evaluation against criteria of tolerability of floodwater for people and infrastructure. Furthermore the question of worthiness can be substantiated if the model is developed to be later integrated as part of asset management systems that include the day-to-day operation of the drainage system.

Acknowledgements

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