Methodologies to study the surface hydraulic behaviour of urban catchments during storm events

Méthodologies pour étudier le comportement hydraulique en surface de bassins versants urbains au cours d'événements pluviaux

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RÉSUMÉ

Une bonne connaissance du comportement hydraulique d'un bassin versant urbain et de ses écoulements en surface (avaloirs) représente une exigence essentielle pour garantir la sécurité du trafic et des piétons, ainsi qu'une gestion correcte du système d'assainissement. Dans de nombreux cas, la disposition des avaloirs se fait selon des critères de densité spatiale. En effet, un emplacement plus rationnel des avaloirs des bassins versants urbains doit être défini sur la base d'une analyse hydraulique précise de la relation entre les écoulements de rues et l'efficience hydraulique des avaloirs. Pour ce faire, on doit utiliser des données expérimentales et autres procédures qualifiées. De plus, nous manquons de critères de danger spécifiques en termes de hauteur d'eau et de vitesse d'écoulement maximum acceptables dans les rues sans risque pour les piétons. Cet article présente les résultats de deux campagnes expérimentales différentes. La première a été effectuée pour évaluer l'efficience hydraulique des avaloirs ; la seconde pour étudier la stabilité des piétons dans des conditions d'inondation urbaine. L'objectif était de proposer de nouveaux critères de danger. Sur la base des résultats expérimentaux, une méthodologie a été développée pour évaluer le risque d'inondation dans des zones urbaines au cours d'évènements pluvieux. Si l'on dispose d'une représentation topographique précise des zones urbaines, il est possible d'effectuer une simulation numérique 2D d'inondation urbaine au moyen d'équations complètes sur les eaux peu profondes. Grâce à cette approche, il est possible de calculer avec précision les rejets absorbés par les avaloirs au moyen de formules de rendement hydraulique. De cette manière, on peut élaborer des cartes de danger détaillées. Cet article présente une application numérique réalisée dans une rue de Barcelone.

ABSTRACT

A good knowledge of the hydraulic behaviour of an urban catchment and its surface drainage system is an essential requirement to guarantee traffic and pedestrian safety. In many cases, inlets have been situated according to spatial density criteria. Indeed a more rational location of inlets on urban catchments must be defined according to an accurate analysis of the relationship between street flow and inlet hydraulic efficiency. Moreover we lack specific hazard criteria in terms of the maximum acceptable flow depths and velocities on the streets that do not cause problems to pedestrians. In this paper the results of two different experimental campaigns are presented. The first was carried out to evaluate inlet hydraulic efficiency; the second was carried out to address the pedestrian stability in urban flood conditions, whose aim was to propose new hazard criteria. On the basis of the experimental results, a methodology was developed to assess flood hazard in urban areas during storm events. If a refined topographic representation of urban areas is available, a two-dimensional numerical simulation of urban flooding can be performed using complete shallow water equations. According to this approach a numerical application for flood hazard assessment in a street of Barcelona is shown.

KEYWORDS

2D model, hazard assessment, surface drainage systems, urban flooding

1 INTRODUCTION

1.1 Influence of the surface drainage system on the modelling of urban flooding and dual drainage

The good knowledge of the hydraulic behaviour of an urban street and its surface drainage system represents an essential requirement to guarantee traffic and pedestrian safety and, also, correct management of sewer systems. Storm sewer systems are typically designed on the assumption of near full-flowing pipes, often with little regard for how surface runoff is delivered to it (Smith, 2006; Schmitt *et al*. 2004). In reality surface runoff is almost never fully conveyed by storm sewers in case of medium or heavy rainfalls when the surface drainage system is insufficient. Even the best hydrological and hydraulic models for the management of sewer systems provide inadequate simulations under this hypothesis.

In the last years, several authors attempted to elaborate a more detailed methodology to simulate urban flooding (Aronica and Lanza 2005; Boonya-Aroonnet *et al*., 2007; Costanzo and Macchione 2006). According to these studies, an accurate analysis of urban flooding caused by surcharged sewers in urban drainage systems requires dual drainage modeling. A detailed dual drainage simulation model is described based upon hydraulic flow routing procedures for surface flow and pipe flow. Moreover, the knowledge of the hydraulic behaviour of surface drainage structures is absolutely necessary for these types of studies. In fact the hydraulic efficiency of surface drainage structures governs at the same time the rate of water removal from the gutter and the amount of water that can enter into the storm system. In this frame, it is obvious that the general problem of urban drainage cannot consider the following two distinct components separately: (1) the surface (or “major”) system composed of streets, ditches, and various natural and artificial channels and (2) a subsurface storm sewer network (or “minor system”) (Smith, 2006).

One of the first mentions of dual drainage is found in the design manuals of the city of Denver, Colorado (Wright-Mc Laughlin, 1969) where the design criteria describe the connection between the major and minor systems. Later Kidd and Helliwell (1977) described the urban runoff process as a two phase phenomenon, incorporating a surface phase with an underground phase. They recognized the complexity of the interactions between these two phases by stating: ‘Unfortunately, there is no clear-cut interface between the two phases’. Surface drainage systems represent this interface, but to date the lack of knowledge about the hydraulic behaviour of these types of structures (inlets, macro-inlets, continuous grates, etc.) have not been fully overcome. In the eighties, some municipalities of Canada required maximum flow depths and velocities in the major system in case of storms. This required a separate calculation for the major and minor systems. OTTSWMM (Wisner and Kassam, 1983) was one of the first examples of a computer model design to provide this type of calculation.

1.2 General aspects related to the flow modeling in urban areas

Flow modeling in urban areas is very difficult due to the complexity of the topography and the peculiarity of the flow characteristics (very low flow depths and high velocities). A detailed and full flood hazard assessment requires a local knowledge of the flow parameters over the entire domain under study. In order to fulfill these requirements, powerful tools and very detailed topographic data represent the only way to calculate locally flow parameters (flow depth, flow velocity, flood duration, Froude number, etc.) and often this unique method represents the most expensive as well method.

The problem of floods in urban areas caused by heavy storms has been analyzed by several authors using one (1D) and two-dimensional (2D) models (Hsu *et al*. 2000; Aronica and Lanza 2005; Costanzo and Macchione 2006), or linking 1D-2D approaches in order to simulate the “two phases” of the urban drainage (Boonya-Aroonnet *et al*., 2007; Chen *et al*., 2007) or to analyze some real cases employing various techniques for urban flood simulations (Aronica and Lanza, 2005; Gómez *et al*. 2009; Russo *et al*., 2005). In particular, the potential flooding associated with the failure of a number of inlets in the system was investigated by Aronica and Lanza (2005) by means of a flood propagation model specifically designed for areas with complex topography and applied herein to the urban environment. The studies carried out to date confirm that 2D analysis of the surface flow is very adequate for local estimation of the flow parameters. In this case, specific tools able to solve 2D Saint Venant equations are required, at the same time detailed topographic data are necessary. Nowadays, LIDAR (Light Detection and Ranging) technology has become a reference in the field of Remote sensing. Remote

sensing is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device that is not in physical or close contact with the object (such as by way of aircraft, spacecraft, satellite, etc.). Actually topography combination of aircraft-based LIDAR and GPS has evolved into an important tool to produce extremely accurate elevation models for terrain. Unfortunately, this technique is expensive and commonly used for well-defined and limited domains. For these reasons, 2D studies are generally carried out on specific areas where one-dimensional approaches or historical information have previously indicated possible critical points of the analyzed catchment. In this case the concept of a gradual methodology considering different approaches (varying in terms of accuracy and domain extension) becomes more interesting.

1.3 Flood hazard characterization in case of storm events in urban areas

The hazard degree related to floodwater is commonly related to flow depth (y) and velocity (v), so several authors proposed different relationships between these two parameters in order to express the hazard level in case of floods (Abt *et al*., 1989; Reiter, 2000). Mostly these studies were carried out for the river flooding due to heavy rains or dam break accidents. In these cases very high discharges and flow depths occur (Macchione and Viggiani 2004; Macchione and Rino, 2008) so that “flood hazard” is defined as the flood conditions that cause people to be swept away. Some of these experimental studies suggest that the safe limit (for adults) is a product of depth (meters) times velocity (meters per second) in the range of 0.5 to 1.0, even though many of these expressions concern floods in river and floodplain so they are not very adequate to be used in urban areas for floods produced by heavy storms and surcharged sewer systems. In fact when river floods occur in rural and urban catchments, high flow depths (up to some meters) are combined with flow velocity values up to 1-2 meters per second during medium-long duration. On the other hand, urban floods due to heavy rains (generally convective and orographic storms) produce situations in which flood onset is sudden (flash floods) and where there is no warning. Urban flash floods are sudden phenomena normally characterized by short flooding durations and devastating effects due to the high concentration of goods and properties located in urban areas. In these cases of flooding heavy and medium storms events (sometimes because of inadequate surface drainage systems) generate large uncontrolled amounts of surface runoff that circulate on urban streets determining a significant hazard for pedestrian and vehicular circulation. Moreover, urban flooding produced by the excessive amount of runoff, not entirely conveyed into the sewer systems and circulating on urban streets, may be exacerbated by the simultaneous overflows of significant amounts of stormwaters discharged by the sewer manholes coming from surcharged trunks of the underground sewer systems. Furthermore the low roughness of the impervious surfaces causes circulating urban surface runoff with very low flow depths (often less than 10-15 cm) combined very high flow velocity (up to 3 or 4 meters per second). If dragging flow criterion is considered, it is possible to observe that drag force is directly proportional to the flow depth, while it results a function of the squared flow velocity (Nanía, 1999). Therefore the importance of the velocity parameter in studies concerning the flood hazard assessment in urban areas is clear. Notwithstanding the importance of the flow parameters for the flood hazard assessment, no specific criterion concerning this parameter combined with low flow depths (some centimeters up to the curb height) was found.

2 HYDRAULIC PERFORMANCE OF SURFACE DRAINAGE STRUCTURES

2.1 Hydraulic efficiency: definition

The hydraulic performance of a surface drainage structure depends on its geometry, the characteristics of the gutter flow as well as on the geometric characteristics of the street. The hydraulic efficiency of these types of elements can be defined as the ratio of the discharge intercepted by the structure to the total discharge approaching to it:

$$E = \frac{Q_{\text{int}}}{Q} \qquad [1]$$

where E is the hydraulic efficiency, Q_{int} is the discharge intercepted by the surface drainage structure, Q is the circulating discharge approaching the surface drainage structure.
The flow that is not intercepted by the structure, *carry-over* (Guo, 1997) or *bypass discharge* (Nicklow and Hellman, 2004) is defined as follows:

$$Q_b = Q - Q_{\text{int}} \quad [2]$$

where Q_b is the carry-over discharge.

Actually many procedures concerning the hydraulic efficiency of surface drainage structures are based on specific results of experimental campaigns and its use is limited exclusively to previously tested drainage structures. Only a few methodologies for predicting the hydraulic efficiency of untested inlets have been identified at the present time (Spaliviero *et al.*, 2000).

2.2 Experimental campaigns carried out at the UPC hydraulic laboratory

Considering the framework discussed above, in 1997 the Flumen Research Group of the Technical University of Catalonia (UPC) started a new line of research in the field of surface drainage structure hydraulics. The first experimental campaign concerned the hydraulic characterization of several inlets commonly used in Barcelona. With this aim a physical model was designed and built in the hydraulic laboratory of the UPC (fig. 1). Tests were made in a 1:1 scale model of a roadway measuring 3 meters wide and 5.5 meters long. The platform is able to simulate lanes with transversal slope of up to 4% and longitudinal slope of up to 14%. According to the system capacity, it is possible to test drain inlets and study their hydraulic capacity for a large set of flows (0–200 l/s). The intercepted discharge by the inlet is conveyed to a v-notch triangular weir and the flow measurement is carried out through a limnimeter with an accuracy of 0.1 mm. Flow depth measurements on the platform are obtained directly with a thin graduated invar scale.

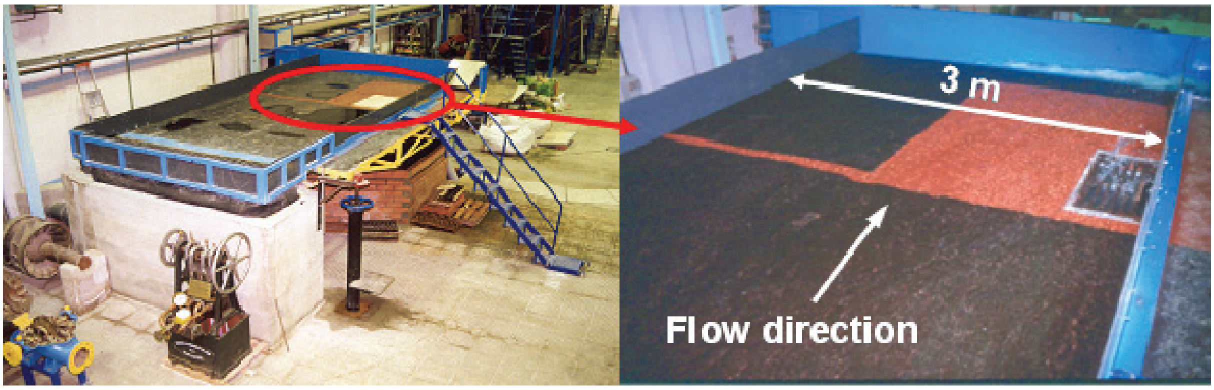

Figure 1: UPC platform and testing area.

One of the most important goals achieved in this phase was the implementation of a specific methodology for the estimation of inlet hydraulic efficiency on the basis of the approaching flow circulating in the gutter and the geometry of the grates. Particularly the following power law expression was proposed:

$$E = A\left(\frac{Q}{y}\right)^{-B} \quad [3]$$

where E is the hydraulic efficiency of the inlet, Q is the discharge approaching to the inlet (m^3/s), y is the flow depth measured at the curb immediately upstream from the inlet, A is an empirical coefficient of the inlet grate, B is an empirical coefficients of the inlet grate.

Moreover specific coefficients A and B were related to the geometry of the grates (such as void area, number and type of the bars, etc.), so it was possible to estimate hydraulic efficiency for a specific inlet on the basis of the gutter flow without the necessity of previous experimental tests. Further tests allowed to increase the number of tested inlets and the valid range of the achieved expressions, while theoretical studies were carried out to compare the developed methodology to those employed in other countries (Gómez and Russo, 2005) and to generalize the procedure for different types of street geometry with a uniform triangular gutter (Russo *et al.,* 2007)

More recently further experimental campaigns concerning other types of surface drainage structures such as continuous transversal grates, macro-grates and unconventional structures (Fig. 2) are underway.

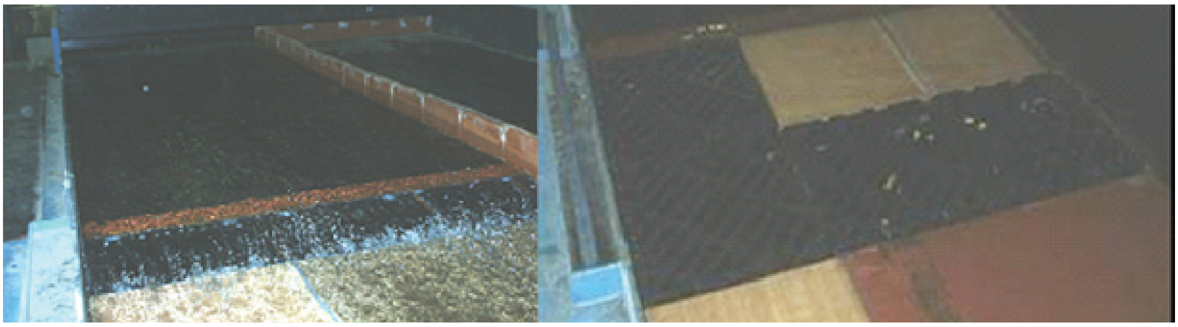

Figure 2: Other surface drainage elements during the tests.

The experimental results achieved showed that equation [3] can be used for these types of elements too, while for other types of structures it is no possible. Specifically a new empirical expression was developed for continuous transverse grates in which hydraulic efficiency is related to the flow conditions upstream from the grates and to two specific coefficients depending on the grate geometry (Gómez and Russo, 2009b):

$$E = \alpha \cdot \left(Fr \cdot \left(\frac{y}{L^*} \right)^{0.812} \right) + \beta \qquad [4]$$

where, in addition to the other previously defined parameters, *Fr* is the Froude number upstream the grate, *α* and *β* are two coefficients which depend exclusively on the geometric characteristics of the grates, L^* is the length of the minimum rectangle including the void area in the flow direction, $\frac{y}{L^*}$ is the normalized water depth related to L^* and calculated immediately upstream of the grate.

The experimental campaigns did not consider the possibility of clogging. At the moment, no empirical experience has been carried out on the clogging phenomenon, that could reduce significantly the hydraulic efficiency of the inlets.

3 FLOOD HAZARD ASSESSMENT IN URBAN AREAS DURING STORM EVENTS

3.1 A specific physical model to assess flood hazard in flooded streets

To date, the experimental campaigns addressing the stability of human subjects in flood conditions have been carried out in some hydraulic laboratories through the construction of channels reproducing natural streams in real scale, in order to avoid scale effects (Abt *et al.*, 1989; ARMC, 2000). No reference concerning human stability in flooded streets was found in the literature. Due to the peculiarity of the flow circulating on the streets during storm events, a different physical model was developed in order to reproduce, at the maximum and possible level, the human subject conditions when a flooded street has to be crossed during storm events.

In order to reproduce a flooded street, a model essentially made up by a platform (for testing) and an upstream regulation tank was planned and built in the UPC “Physical Model Laboratory”. Particularly the platform presents two sidewalks to reproduce the entrance of the human subject into the flooded gutter and a roadway with its own transverse slope. The platform can rotate in order to achieve several longitudinal slopes (and, consequently, very high flow velocity values) up to the maximum value of 10%. The maximum discharge capacity of the laboratory pumps is 500 l/s. Due to this important limitation, in order to have enough flow circulating on the model and to achieve high velocity values, it was decided to consider a platform with one street layer 2.60 m wide and 5 m long. According to the Barcelona Sewer System Master Plan, a transverse slope value of 2% was set for the lane of the platform. Moreover the height of the curb was fixed to 15 cm on the one side of the lane (Gómez and Russo, 2009a). According to the established testing protocol, human subjects crossing the platform were tested with a large range of circulating flows and several geometric configurations (Fig. 3). In this

way human stability in a flooded urban street was studied for a large spectrum of flow conditions as well as considering a wide range of people characteristics (weight, height, etc.). Finally 834 tests regarding 23 human subjects were carried out considering different lighting conditions (in some cases, subjects had restricted vision due to dark glasses, trying to reproduce night conditions). Hazard conditions were classified into three groups (low, medium and high) and parameters at which these conditions occurred were recorded. The results obtained showed that for a human subject weighting between 50 and 60 Kg, few centimeters of flow with a velocity of 1.5-2 m/s can generate a loss of stability due to phenomena of dragging or overturning. The results of the experimental campaign demonstrated that the actual hazard criteria elaborated for the hazard characterization in floodplains are not adequate for urban flooded areas characterized by low flow depths and high velocities.

Figure 3: Human subject during the tests in the hydraulic department of the UPC.

According to the adopted definitions, *high hazard condition* occurred when an individual indicated a clear loss of stability (individual could not longer remain stable in a standing or walking position or was dragged away by the flow) or when an individual indicated a clear loss of maneuverability (individual could not carry out testing protocol correctly). Flow parameters corresponding to *medium hazard* conditions were also recorded when an individual showed significant loss of stability (individual moved unsteadily making a big effort to remain stable in a walking position, or when an individual showed significant loss of maneuverability); in these cases the individual showed clear difficulties in carrying out and finishing the testing protocol. Finally flow conditions that caused *low hazard* to the human subjects during the tests were recorded when an individual grasped the rope unintentionally or an individual balked upon entry onto the platform or, when more simply, an individual showed few problems of stability and maneuverability. Moreover, in order to propose practical flow velocity values to characterize the hazard produced by a flood event in a simple way, 95% percentiles of the population data concerning low, medium and high hazard situations were calculated. Finally the following values of flow velocity were achieved:

- *Low hazard (95% percentile): 1.51 m/s*
- *Medium hazard (95% percentile): 1.56 m*
- *High hazard (95% percentile): 1.88 m/s*

As shown by these results, medium and low hazard levels are very similar. Moreover flow conditions that could generate low and medium hazard are more subjective than others related to high hazard, so it seems appropriate to propose for the hazard levels the ranges of velocity reported in Table 1.

Hazard level	**Flow conditions**
	(for flow depths between 9 and 16 cm)
High	$v \geq 1.88$ m/s
Moderate	$1.51 \leq v < 1.88$ m/s
Low	$v < 1.51$

Table 1: Hazard levels according to flow parameters in flooded streets.

4 IMPLEMENTATION OF THE METHODOLOGY CARRIED OUT ON REAL CASES STUDIES

4.1 From simple hydrological approaches to 2D detailed approaches

The methodology carried out taking into account hydraulic characterization of surface drainage structures and the hazard conditions related to storm events in urban areas were implemented in several real cases studies considering different levels of accuracy, in order to study the hydraulic behaviour of an urban catchment in case of flooding produced by heavy storm events. The level of accuracy of the analysis often depends on the availability of topographic data or the adequacy of the computational tools.

Generally the rational method is successfully used in many urban drainage calculation procedures. Its frequent use is due to the reduced size of the basins in urban areas. Normally spacing between two adjacent drainage grates is of the order of tens of meters and sub-catchment areas are lower of one hectare, consequently if poor data are available, its use can be convenient. In this case inlets can be considered as hydrological limits of a series of sub-catchments that jointly represent the whole urban basin. In the design phase it is possible to determine the optimal spacing among inlets to fulfil the hazard criteria admitted by Public Administrations (Russo *et al.*, 2007).

The hydraulic behavior of an urban catchment formed by a series of streets may be studied through procedures considering 1D flow propagation, while the rainfall runoff transformation may be treated in different ways. If surfaces as terraces and roofs are directly connected to the sewer system, an urban catchment can be represented as a series of sidewalks and roads that compose the hydrological subcatchments. Every subcatchment should be represented through its own parameters (longitudinal and transversal slopes, wide, roughness, etc.). Each variation in term of physics or geometric parameters determines a hydrological limit between two adjacent subcatchments. Moreover each inlet represents a hydrological limit as well, such as a crossroads where hydrographs proceeding from different streets will be combined. Once an urban catchment has been divided into an adequate number of subcatchments, for each of them it is necessary to define models which simulate the rainfall runoff transformation and the flow propagation. In these cases a 1D kinematic wave approach can be used if gradients and specific gutters ensure clear one-dimensional flow behaviour (Russo *et al.*, 2005).

Often the runoff produced during a storm circulates uncontrolled on the urban surfaces due to the lack of clear thalwegs or adequate gutters capable to collect it. This phenomenon is a typical situation occurring in squares, parks, street bends or corners, etc. In these cases isolated conventional inlets result ineffective to capture, quickly, the circulating flows producing stormwater storage phenomena. So, generally, macro-grates located in sag points or continuous transverse grates are used. Moreover the runoff circulating over these areas presents a clear two-dimensional behaviour, so this type of modelling requires a 2D approach.

A specific two-dimensional code for numerical simulation of urban flooding was developed in the LAMPIT laboratory of the University of Calabria (UNICAL) (Costanzo and Macchione 2006), in order to locally evaluate the hydraulic behavior of the urban streets and the efficiency of the drainage system, and provide hazard maps related to each considered storm event. The approach proposed by LAMPIT is based on the complete two-dimensional shallow water equations:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial x}+\frac{\partial \boldsymbol{G}}{\partial y}=\boldsymbol{S} \qquad [6]$$

in which:

$$\boldsymbol{U}=\begin{pmatrix} y \\ yu \\ yv \end{pmatrix} \; ; \; \boldsymbol{F}=\begin{pmatrix} yu \\ yu^2+\frac{1}{2}gy^2 \\ yuv \end{pmatrix} \; ; \; \boldsymbol{G}=\begin{pmatrix} yv \\ yuv \\ yv^2+\frac{1}{2}gy^2 \end{pmatrix} \; ; \; \boldsymbol{S}=\begin{pmatrix} q_{rain}-q_{drain} \\ gy\left(S_{0x}-S_{fx}\right) \\ gy\left(S_{0y}-S_{fy}\right) \end{pmatrix} \qquad [7]$$

where ***U*** is the vector of the flow variables, ***F*** is the flux in the *x* direction, ***G*** is the flux in the *y* direction, ***S*** is the source term, *t* is time, *x*- and *y*- are the horizontal coordinates, *y* is the flow depth, *u* and *v* are the depth-averaged flow velocities in *x*- and *y*- directions, *g* is the acceleration due to gravity,

q_{rain} and q_{drain} are, respectively, the specific discharges due to the rain and lost because of grates calculated by the expression [5], S_{0x} and S_{0y} are the bed slopes in *x*- and *y*- directions. As shown by these results, medium and low hazard levels are very similar. S_{fx} and S_{fy} are the friction slopes in *x*- and *y*- directions which can be calculated from Strickler's formula:

$$S_{fx} = \frac{u\sqrt{u^2+v^2}}{k^2 h^{4/3}}; \qquad S_{fy} = \frac{v\sqrt{u^2+v^2}}{k^2 h^{4/3}} \qquad [8]$$

where *k* is Strickler's coefficient.

The equations (7) have been numerically integrated by means of the upwind finite volume HLLC scheme.

Some numerical applications of the numerical code have been performed for a street having the typical geometry used in the city district of Barcelona known as the Eixample (Gómez *et al*., 2009). The longitudinal slope and the transversal slopes were set at 1%; the same slope was assumed for the sidewalks. The simulation was performed for a street reach having a length of 60 m and considering the inlets placed along the borders of the street spaced every 10 m (Fig.4). A specific inlet grate was considered and its hydraulic efficiency was calculated by the equation [3]. For the numerical simulation the reach of the street was discretised as a domain of 3120 cells with sides having lengths of 0.5 m. The 2D code was used for the flood hazard assessment of the street under the hypothesis of a storm with a return period of 10 years (the project storm used for the design of Barcelona sewer system). With this aim hazard maps concerning flow depths and velocity were elaborated (Fig. 5 and Fig. 6).

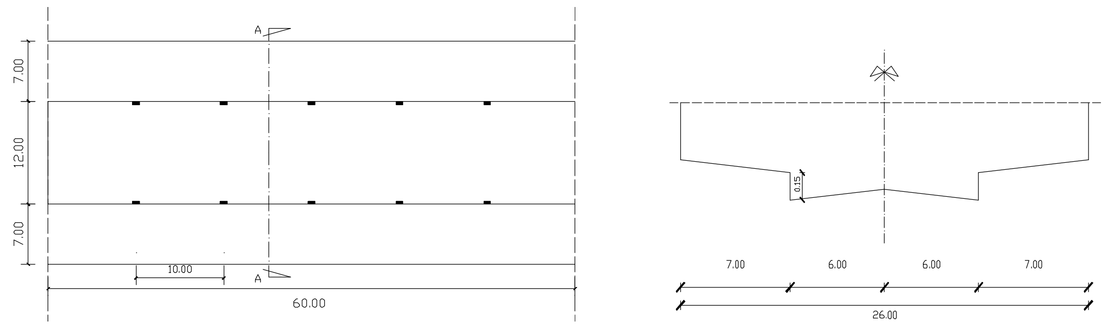

Figure 4: Geometric characteristic of the street reach analyzed.

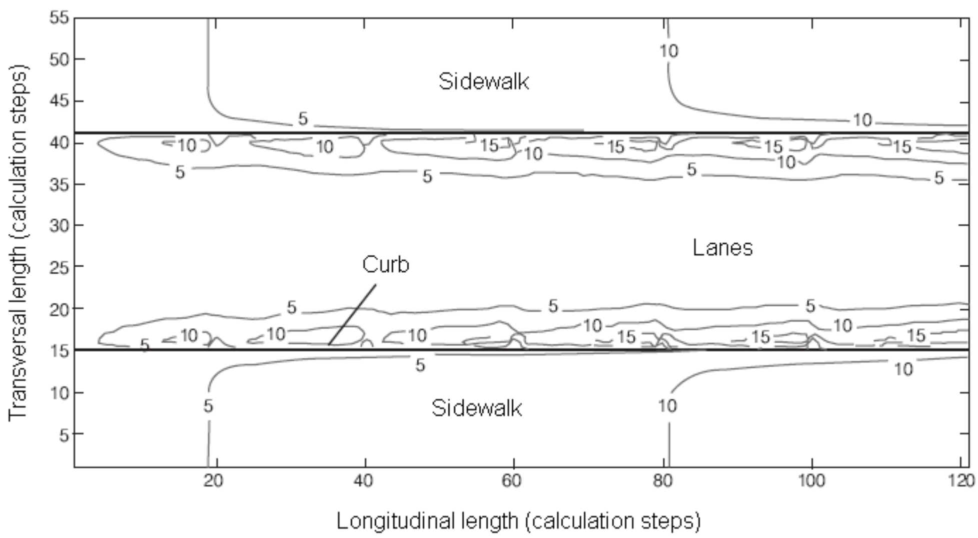

Figure 5: Map of the flow depths (mm) on a flat street.

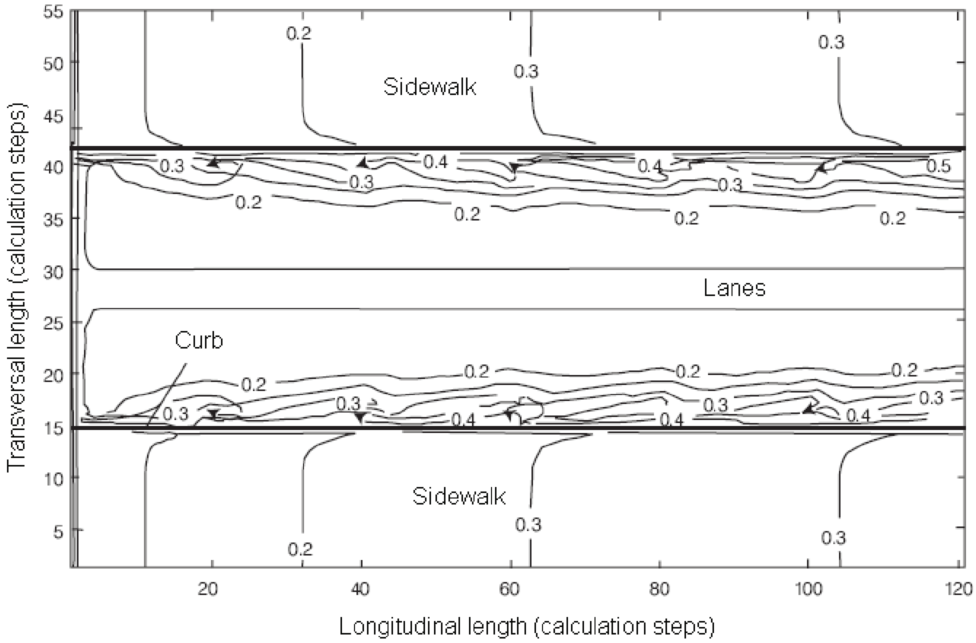

Figure 6: Map of the velocities (m/s) on a flat street.

5 CONCLUSIONS

The study of the modern planning of urban drainage systems, able to satisfy the hazard criteria for pedestrians and vehicles, requires advanced mathematical models and experimental studies for an accurate description of the main characteristics of flow over urban areas. Given the very small water depths involved in urban runoff, a very accurate topographic representation of urban areas has to be used as the basis of hydraulic calculations. Moreover realistic results cannot be obtained without the knowledge of the hydraulic behaviour of the surface drainage systems under real flow conditions. On the other hand flood hazard map assessment in urban areas should be related to hazard criteria characteristic of this type of flood. In this paper all these aspects have been treated in order to propose rigorous methodologies to study the surface hydraulic behaviour of urban catchments during storm events. This paper summarizes a line of research about the design of surface drainage systems according to hazard criteria related to flooding of urban areas carried out by the Flumen Research Group (UPC) and LAMPIT (UNICAL).

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