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From hydraulic modelling to urban flood risk

André Paquier[a,]*, Emmanuel Mignot[b], Pierre-Henri Bazin[a]

[a]Irstea, UR HHLY, 5 rue de la Doua CS70077, 69626 Villeurbanne Cedex, France.
[b]Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA), CNRS-Université de Lyon, INSA de Lyon, 20 Avenue A. Einstein, 69621 Villeurbanne, France

Abstract

Urban floods cause high damages and thus mapping of flood risk is essential for protection and evacuation planning. To obtain such mapping, hydrodynamic modelling is central because it provides water depths and velocities everywhere and along the whole flood period. The case of the 1988 flood in Nîmes is presented as an example of the method to get the basis for evaluating flood risk. Once the hydro-meteorological event is selected, a lot of causes of uncertainty still exist, which are linked to either the flow processes in a complex environment or the simplifications of the 2-D models that are used for saving computation time. In order to gain information regarding the origin of such uncertainties, two series of laboratory experiments are described: one focuses on the error in the flow distribution at crossroad, the other one stresses the flow complexity in the exchange structures between the streets and the sewer network. Beyond the analysis of the causes of uncertainty, obtaining a detailed local assessment of flood risk requires a sensitivity analysis to cope with the associated uncertainty ranges; this analysis may be reduced if a relevant model is used, which means, for instance, that the processes described in the experiments are conveniently modeled.

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Keywords: urban flood; shallow water equations; risk assessment; hydrodynamic processes

1. Introduction

The origin of an urban flood is usually related to severe rains at least for cities located away from the shore, where overtopping of the protection structures by the high tides and waves may occur. The rain causing the flood may either (i) occur directly above the city, leading to high volumes of water that exceed the capacity of collection

* Corresponding author. Tel.: +33-472208775; fax: +33-478477875.
E-mail address: andre.paquier@irstea.fr

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by the designed urban structures comprising the culverts, manholes and sewer networks [1], leading to water flowing on the surface of the streets and/or overtopping out of the sewer networks or the urban rivers towards the streets, or (ii) occur on large upstream areas such as hills, fields,… where the infiltration capacity is exceeded and thus water flows on these surfaces towards the city. When simulating an urban flood scenario, a preliminary step consists in running hydro-meteorological models to estimate as fairly as possible the rain distribution over the city during the event for case (i) [2], while hydrologic or coupled hydrologic-hydraulic models are run to compute the runoff on the upstream areas for case (ii), in order to estimate hydrographs at the entrance of the city [3]. The aim of this preliminary step is to define input scenarios that are reference historical events (that have a meaning for people) or probabilistic events.

Then, within the city, the flow paths are quite complex and directly related to the topology of the city. Indeed, from a hydraulic point of view, the structure of the city is organized on the basis of networks: the hydrographic network including the rivers but also the ephemeral streams that is primarily constrained by natural topography but often distorted by urbanization, the underground sewer network that is mostly a hierarchized set of pipes, the street network that is designed for the car traffic but that is occasionally flooded and becomes a secondary network for water. Additionally, the urban environment includes build areas, themselves including buildings, walls and other obstacles to flow but also open areas such as gardens, courtyards, sport fields. All these areas strongly impact the flow dynamics and thus should be included in the calculation mesh over which the flow will be simulated. The topology and topography of these networks are complex and their fair representation requires accurate data that are usually available in the GIS (Geographical Information Systems) database managed by the city technical services. Specific models are developed to transfer such geographical data (river topography and elevation of their bank protections, street profiles, frontiers of private piece of land where bushes or low walls, topology of conduits in the sewer network, manholes, location of walls and barriers…) from these GIS models to the meshing model [4]. Nevertheless, the heterogeneity of the GIS databases from one city to another makes it difficult to develop extraction methods which automatically apply to all locations. Thus, the meshing step is still manual or only semi-automated.

During the flood inside the city, water fluxes are exchanged from one - previously listed - network to the others. Firstly, exchanges take place between the surface flows and the underground flows [5] (mainly in the sewer network) and thus exchanges between these latter flows occur through vertical exchange structures (manholes, metro or mall stairs, aeration conduits…) [6]. Secondly, surface flow is shared between the hydrographic and street networks and the available open areas (private areas and larger parking areas, parks, etc.). In the streets and streams, the flow velocity is relatively high with a flow mainly directed along the axis of the stream or of the street. Nevertheless, in the streets, the relatively shallow flow perturbed by the obstacles leads to local changes from subcritical to supercritical flow regimes and conversely [7]. This flow complexity leads to a strong variation, in time and space, of the hydraulic parameters (water depth, velocity…), which means that the local exposure to flood is varying a lot along the event. In the available open areas at the surface of the city, the velocities often remain low but complex recirculating flows develop. Finally, in the sewer network, the maximum flow capacity of the pipes can be locally exceeded leading to an alternation of free surface and pressurized conditions, the conditions being modified at each of the multiple junctions or other structures of the network.

Finally, after computing one flood event, the last step usually consists in establishing risk maps [8]. Nevertheless, the vulnerability to flood of a given city or district may vary a lot because of the type of buildings, the use of the buildings or of the streets, the time and day of the flood. In order to define flood risk accurately, the flood hazard should be mapped at a local scale [9]. Finally, for application by the city technical services, the risk level must be included in the GIS database as a new information layer. Then, the efficiency of the protection and evacuation measures can be investigated for several types of flood event scenarios one by one; often, a frequency estimate is associated to each scenario in order to obtain a probabilistic estimate of the global risk. In any case, in order to compare the efficiency of two technical solutions or to perform a cost benefit analysis, the uncertainty of the hydrodynamic results together with the one of the vulnerability parameters should be estimated [10].

In the following section, this paper aims at introducing the major causes of uncertainty linked to the hydrodynamic processes taking place in a flood and to the numerical models used for establishing a flood risk map for a selected inflow scenario. The case of the French flood of the city of Nîmes in 1988 is considered herein and all the steps from the rain event to the risk map estimations are detailed. Then two specific flow configurations which are likely to introduce a high level of uncertainty in the urban flood simulation are detailed: the presence of obstacles in the streets near the crossroads and the presence of manholes with flow exchanges between the surface and underground flows. Recommendations for dealing with these sources of uncertainties are also discussed.

2. The 1988 flood event at Nîmes

The specificity of the city of Nîmes is its location downstream from seven hills located on the north of the urban area. Since the first registered data in 1350, the strong rain events on these hills always produced damages in the city because the water infiltration in the surrounding area is not sufficient and runoff tends to concentrate the surface water towards the city. The decrease of both the infiltration rate of the soils and the capacity of the natural watercourses related with the development of urbanization is likely to increase the peaks of the hydrographs at the upstream border of the city. In 1988, a particularly severe rainstorm took place in this region with a cumulated rain of up to 420 mm occurring within 8 hours [11]. The analysis presented here below and detailed by [7] aims at estimating the flooding risk in one particular district: the Richelieu district located at the North-East of the city center.

The water accumulated in the small and usually dry valleys before flowing towards the city. In absence of open-channel watercourse through the city, the inflow consists mainly in the surface flow in the streets and secondarily in the flow inside the rapidly saturated sewer pipes. In comparison, the volume brought by the rain over the city itself during the event remained low, so that this local rain process can be neglected. The hydraulic model requires hydrographs at each entrance of the city, which provide the time evolution of the water discharge entering the city. The Richelieu district comprises two entrances below a railway embankment: one corresponding to the Eastern hills and the other one to the Western hills. Consequently, two hydrological calculations are performed [12], one for each entrance, in order to estimate the hydrographs at the outlet of each basin as a function of the rain falling on the basin, recorded by pluviographs, and of the topography and land use of the basins. The final results are the two hydrographs shown in Fig. 1, which show two peaks, respectively between 4 and 5 hours and between 8 and 9 hours after the beginning of the event.

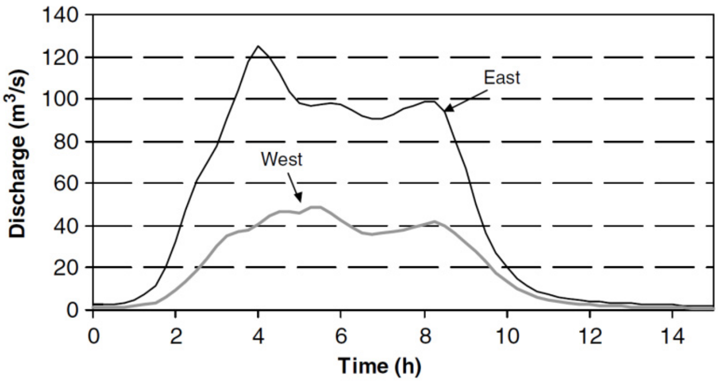

Fig. 1. Hydrographs computed by the hydrological model at the entrance of the Richelieu district

As a second step, the water propagation within the urban area is computed. In the Richelieu district, the sewer network is rapidly saturated at the beginning of the raining event and its capacity (about 2 m^3/s in 1988) can be neglected compared to the surface hydrographs and, consequently, the flow in the sewer network is not computed herein. The Richelieu district is a highly urbanized area and thus the water mostly flows within the streets, crossroads and some open areas such as a hospital and a military barrack (see Fig. 2). In a first step, the introduction of water within these two major open areas is neglected, its effect being analyzed further in the paper. Thus, the basic mesh comprises the streets and crossroads of the Richelieu district, delimited by the railway at the entrance, walls and a hill to the Eastern and Western sides of the domain respectively and finally to 11 streets at the outlet through which the water leaves the calculation domain. The mesh is based on local measurements of the topography of the city with nine measured elevation points in each street, comprising the sidewalks, the gutters and the mid-point of the street section. A regular space step of about 10 meters is selected along the streets axis leading to typical horizontal cells of about 10 m by 1 m (and about 1 m by 1 m in the crossroads). Due to its shallowness (much higher street length and width than water depth) the flow in the street network is mainly horizontal and the vertical velocities remain limited so that a shallow water equations (or de Saint-Venant equations) model can be selected. Moreover, as explained above the flow in the streets in mainly 1-dimensional directed along the street axis but in the crossroads and open areas, the flow is complex and takes place along the two horizontal directions. For these reasons, the hydrodynamic model selected to simulate the 1988 flood event is a 2D-shallow water equations model. This set of equations is solved by a finite volume numerical scheme (detailed in [13]) that permits to calculate the flow through complex topographies during flash floods. The initial conditions (at t=0) are dry streets and the boundary conditions are the hydrographs in the two entrance streets, walls on the sides and a free outlet condition for the outlet streets. The results of the model are the time evolution of the water depth and of the velocity components in each cell, which is a very fine spatial distribution of flow characteristics.

Then, a map of the maximum water depths (Fig. 2) and a map of the maximum velocity magnitudes are established as hazard maps and can be delivered to the rescue services (here the Technical services of the city of Nîmes) to be included in the rescue system.

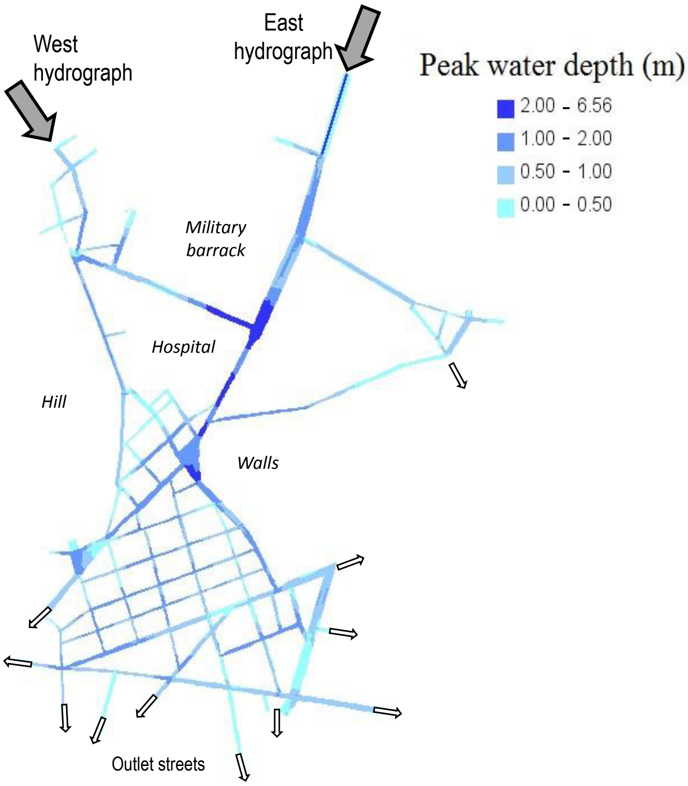

Fig. 2. Distribution of peak water depths computed in the Richelieu district.

The calculation of the flow characteristics comprises numerous sources of uncertainty, which complicates the calibration of a numerical model. For instance, the comparison of calculated peak water depths to 99 observed flood marks for the 1988 flood event provides a standard deviation of the difference of water levels remaining equal or above 0.48 m [7] for all tested configurations within the sensitivity analysis that was carried out. From this sensitivity analysis, it also resulted that the uncertainties attached to the inflow hydrographs (as a result of the hydrological calculation) have direct effects on the water depths: it remains the main cause of uncertainty in Nîmes because without flow measurement upstream from or within the city, the error in volume and peak flow in Fig. 1 can be estimated as high as 50%. Now, the rain over the city and the presence of open storage areas are involving much smaller volumes (less than 1%) and thus can reasonably be neglected although locally the effect can increase. On the other hand, the interactions with the sewer network, that were neglected, are obviously weak during the flood peak because of the under-dimensioned sewer network in 1988 (this capacity was increased since then) but it might not be the case during smaller floods or during the periods of low flows of the 1988 flood. Finally, the calibration of the friction coefficient in the streets is a challenging task as it should integrate the effects of obstacles in the streets and crossroads (which were not explicitly represented for sake of simplification) because it implies a local calibration performed usually without enough information. Among these sources of uncertainty, the following sections aim at investigating two processes that were not previously investigated in the studies about Nîmes flood [7] (because wider simplifications were performed and thus dominated the uncertainty range): the flow disturbance by obstacles in the crossroads and the flow exchanges between the streets and the underground sewer network.

3. Uncertainty related to obstacles in the crossroads

In the calculation of Nimes flooding event in [7], the obstacles such as the bus stops, newsstands, parked cars, trees were neglected. While in junctions (with two incoming and one outing streets), the impact of obstacles remains limited to the area around the obstacle with slightly higher or lower local water depths and velocities, in forks (with one incoming and two outing streets) the obstacles may modify the discharges to both downstream streets and thus to the whole downstream area of the domain. In order to investigate the impact of such neglecting, experiments were performed in idealized subcritical 3-branch forks with 14 flow configurations with and without obstacles [14].

Selected obstacles are square-shaped of width 5 cm, which is 1/6 of the street width. 7 obstacle layouts are considered with obstacles 1 and 2 located in the incoming street, 3 and 4 in the lateral branch street, 5 and 6 in the main outlet street and 7 in the middle of the crossroad (Fig. 3).

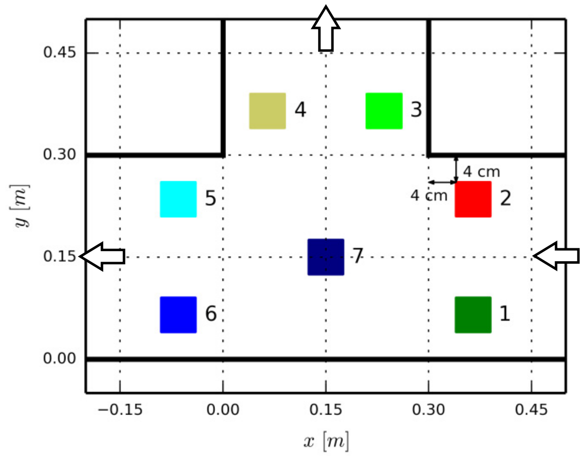

Fig. 3. Location of all tested obstacles in the crossroad

The first observation reported by [14] is that the impact of each obstacle strongly depends on its location with regards to the crossroad:

- obstacles located within the upstream street (1 or 2) increase the streamwise flow velocity and thus make it more difficult for the flow to turn towards the lateral branch due to the increased centrifugal force and thus they tend to reduce the lateral and increase the downstream discharge.
- obstacles located within the crossroad or the downstream street (5, 6 or 7) tend to block the flow in this street and thus to reduce the downstream discharge while increasing the lateral discharge.

- for obstacles located within the lateral branch street: obstacle 4 tends to block the flow in thislatter street, reducing this discharge while obstacle 3 located within the recirculation zone exhibits a very limited impact.

Moreover, the impact of an obstacle appears to increase as the Froude number of the incoming flow in the upstream street increases.

The change in the flow distribution due to an obstacle can typically reach 10% to 15% [14]. Nevertheless, this does not mean that neglecting the presence of this obstacle - as performed when simulating the 1988 flood event in Nîmes - necessarily means that the discharges in any street downstream are estimated with such high level of uncertainty. Indeed, if the crossroad is located within a quite regular street network, the flow is distributed into other parallel streets, which strongly reduces the effect of the obstacle in the downstream area but nevertheless implies a small remaining effect in a quite large area. However, if this crossroad structures the flow pattern (for instance, it is the crossing of large avenues delimiting different sub-districts), a 10% change in the flow distribution strongly influences the flooding of the whole downstream areas.

This uncertainty in the flow distribution at a crossroad due to an obstacle should also be compared to the typical error of 2-D modelling in simulating this flow distribution. [15, 16] showed that this error can be as high as 20% if there is a change in the flow regime within the crossroad, which often means that a hydraulic jump (difficult to model accurately) forms and influences the flow distribution. Oppositely, errors are much lower as the flow remains subcritical everywhere near the crossroad. In any case, [17] showed that when modelling the subcritical flows in the forks with the obstacles presented herein with the 2D model, the accuracy remains high and this confirms that, in that case, the uncertainty due to neglecting the obstacles highly exceeds that related to the use of 2-D modelling. .

4. Uncertainty related to exchanges with the sewer network

In the calculation of the 1988 Nimes flood [7], the sewer network was neglected because the discharge in the streets highly exceeded the capacity of the sewer network. For a less severe event with lower flow discharges, the exchanges with the network can however become predominant. Unfortunately, these exchange processes are not well documented [18]. In order to gain information on these exchanges, experiments were performed in Kyoto University [19] using a flume with one street (red number "1" in Fig.4) connected to an underneath pipe (5) along with 10 pairs of connection tubes (3) representing the manholes connected to the streets through boxes (2), as sketched in Fig. 4.

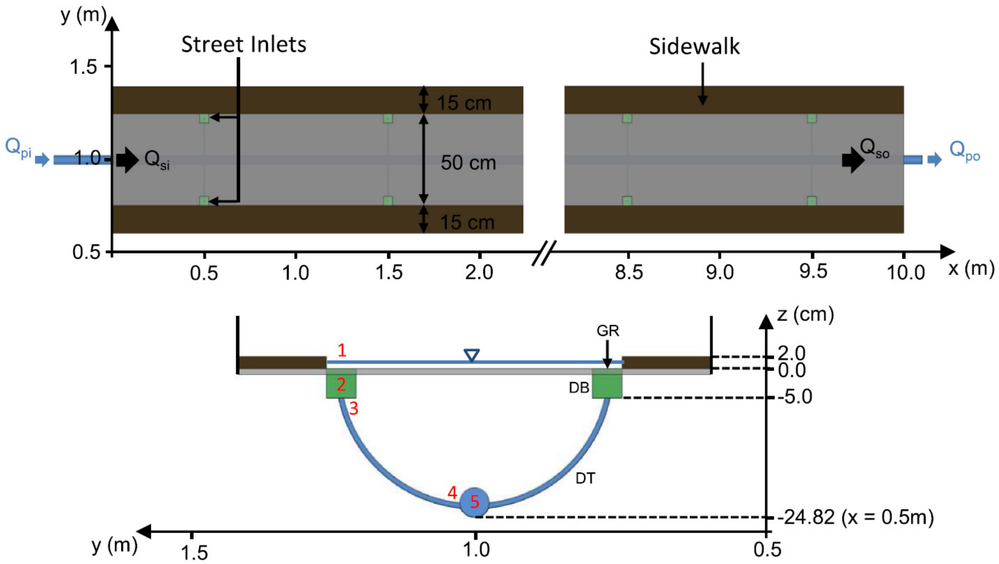

Fig. 4. Scheme of the experimental street surface and underneath sewer pipe at Kyoto University with a top view (top) and a side view (bottom)

Several flow scenarios with increasing head in the pipe and water elevation in the street were carried out, measuring exchange discharges in each case in order to investigate the various flow patterns and quantify the exchange discharges that may occur in the exchange structure. At the location of a manhole if the head in the street exceeds that in the sewer network, the flow is collected from the street to the pipe underneath while if the head in the pipe exceeds that in the street, the water overflows from the pipe towards the surface. Moreover, two configurations were observed which require specific types of modelling method: if the head of the pipe flow exceeds the elevation of the street, the flow in the exchange tube (manhole) is saturated and the exchange discharge (collecting or overflowing) can be computed solving the Bernoulli equation; oppositely if the head in the pipe is lower and that the collecting flow from the surface to the pipe is low, air remains in the exchange tube, which makes the calculation of the exchange discharge much more complicated.

The general method to calculate both the flow on the two layers can include [19]: the calculation of the surface flow using a 2D shallow water equations model (as used in Nîmes calculations), the calculation of the flow in the sewer system using a 1D shallow water equation model and finally the calculation of the exchange discharges by solving the Bernoulli equation and using the head loss coefficients from empirical formulas proposed by [20] for which the coefficients are more and less accurate depending of the flow conditions but provide suitable results (less than 5% error) for the configurations of the experiments considered here. For the same experiments, [17] showed that the error in the exchange discharge obtained by simpler methods that use a standard orifice equation, can be as high as 50 % because the head losses are distributed along the exchange structure and depend of various parameters. Additionally, in the field, parameters such as the deposits that prevent water from entering the exchange structure are secondary causes of uncertainty; the drainage capacity of the pipes can also be questioned for the same reasons.

5. Conclusions

Urban floods cause high damages and mapping of flood risk has become essential for protection and evacuation planning. This mapping requires an accurate calculation of the flow characteristics (water depth and velocity) during the event, which is achieved solving 2-D shallow water equations (eventually associated to 1-D shallow water equations for the sewer network) providing that enough detailed inputs are available. In order to evaluate the remaining errors - or uncertainties – in the urban flood calculation, two experiments and corresponding numerical simulations were performed. They focus, on the one hand, on the effect of obstacles at crossroads on the flow distribution towards the downstream streets and, on the other hand, on the exchanged flow patterns in the structures linking streets and sewer pipes and the possibilities to calculate them using applicable models. We showed that in these two cases, slight improvements of the basic 2-D modelling methods permits to provide accurate results, at least in experimental conditions. In the field conditions, other causes of uncertainty were identified and quantified for the case of the 1988 Nîmes flood.

Even if uncertainty can be reduced using refined and complex models and/or through calibration based on the available urban flood registered flood marks or extension maps, a sensitivity analysis is still necessary because linking the hydro-meteorological inputs to the flood risk at a local scale remains a challenging task. Indeed, the deviations at the crossroads, the obstacles (eventually moving as cars), the exchanges with the sewer network or private properties, … can change the local water depth and/or velocities by a few percent and this small change may imply strong consequences if a damage threshold is reached, as for instance as the water level reaches the elevation of a building entry or as the flow velocity locally exceeds the velocity magnitude carrying away pedestrians [21, 22]. Thus, the integration of local flood parameter uncertainty is necessary to evaluate flood risk at the relevant scale, which should lead to elaborating mitigation measures at both individual and municipality scales.

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