One-dimensional modelling of the interactions between heavy rainfall-runoff in an urban area and flooding flows from sewer networks and rivers

G. Lipeme Kouyi, D. Fraisse, N. Rivière, V. Guinot and B. Chocat

ABSTRACT

Many investigations have been carried out in order to develop models which allow the linking of complex physical processes involved in urban flooding. The modelling of the interactions between overland flows on streets and flooding flows from rivers and sewer networks is one of the main objectives of recent and current research programs in hydraulics and urban hydrology. This paper outlines the original one-dimensional linking of heavy rainfall-runoff in urban areas and flooding flows from rivers and sewer networks under the RIVES project framework (Estimation of Scenario and Risks of Urban Floods). The first part of the paper highlights the capacity of Canoe software to simulate the street flows. In the second part, we show the original method of connection which enables the modelling of interactions between processes in urban flooding. Comparisons between simulated results and the results of Despotovic et al. or Gomez & Mur show a good agreement for the calibrated one-dimensional connection model. The connection operates like a manhole with the orifice/weir coefficients used as calibration parameters. The influence of flooding flows from river was taken into account as a variable water depth boundary condition.

Key words | One-dimensional modelling, Canoe software, manhole operation, urban flooding

INTRODUCTION

Urban flooding may be due to various causes: overland flows on streets, flooding flows from rivers and overflows or surcharges from sewer networks. In some cases, one of those phenomena causes more damage than the other two phenomena. In other situations, urban flooding is due to the complex interactions between the three phenomena.

The hydraulic models used to understand various processes during urban flooding can vary from one dimensional (1D) to two dimensional (2D) to combined 1D/2D models with differing data requirements to schematise the rivers, street networks and/or the sewer systems.

Many investigations are carried out to develop models which allow the linking of complex physical processes involved in urban flooding. The modelling of the interactions between overland flows on streets and flooding flows from rivers and sewer networks is one of the main objectives of recent and current research programs in hydraulics and urban hydrology (Djordjevic et al. 1999; Chen et al. 2007). The understanding of these complex processes represents major challenges for many urban designers or managers in order to reduce the impacts of urban flooding.

This paper outlines the original one-dimensional linking of heavy rainfall-runoff in urban area and flooding flows from rivers and sewer networks under the RIVES project framework (Estimation of Scenario and Risks of Urban Floods; El Kadi Abderrezzak et al. 2007). The 1D linking has two main advantages, among others:
(i) the simplification of the street and the sewer network schematization, and
(ii) a significant decrease in the computation time.

In the first part of paper, we assess the capacity of the one-dimensional Canoe software to simulate street flows. In the second part, we show the original method of connection which enables the modelling of interactions between processes in urban flooding.

METHODS

Simulation of street flows

Presentation of the street network

In order to check the capacity of the Canoe software to simulate street flows, the virtual street network developed in Hy2ville project (hydraulics and hydrology in urban areas, France) was used. The virtual street network layout is shown in Figure 1.

This street network was chosen to represent dense urban areas in cities like Paris, Lyon or Montpellier in France. It is a virtual physical model covering an area of 1,000 m × 1,000 m. There are two scales of street: small and big streets which are 10 m and 25 m wide respectively. Its well defined geometry facilitates its use as a benchmark for different numerical models. It also allows comparison with local elements which are well documented elsewhere, for example, four branch crossroads (Mignot et al. 2008).

Simulation of the street flow

The Canoe 1D and SW2D software packages were used to simulate the distribution of flows through the virtual overland flow network from north (with \( H_{\text{north}} \) as the upstream hydraulic head) to south (with \( H_{\text{south}} \) as the downstream hydraulic head) in order to check the capacity of 1D model to represent surface flows. Figure 2 identifies the boundary conditions for the 1D simulations.

The Canoe software is based on the Barré de Saint Venant equations for continuity and momentum which in the \( x \)-direction are:

\[
\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}
\]

\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + g \frac{\partial h}{\partial x} = g(S_0 - S_f) + (e - 1)q \frac{U}{S} \tag{2}
\]

where \( S \) is the cross-sectional area, \( Q \) is the discharge, \( q \) the lateral flow rate per unit of length, \( U \) is the mean velocity in the \( x \)-direction, \( g \) is the gravitational acceleration, \( h \) is the water depth, \( S_0 \) is the bottom slope, \( S_f \) is the energy loss and \( e \) represents the lateral momentum transfer coefficient. In our study the lateral effects due to lateral flows was neglected.

The SW2D model solves the two-dimensional shallow water equations with porosity (Guinot & Soares-Frazão 2008).
(Lhomme 2006) that allow the macroscopic properties of flows in urban areas to be represented at a large scale. The classical shallow water equations, which are used as the governing equations in the present simulations, are a particular case of these equations with porosity uniformly equal to unity. The two-dimensional equations can be written in conservation form as:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} + \frac{\partial r}{\partial y} &= 0 \\
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} + \frac{gh^2}{2} \right) + \frac{\partial}{\partial y} \left( qr^2 h - \frac{gh^2}{2} ight) &= gh(S_{0,x} - S_{f,x}) \\
\frac{\partial r}{\partial t} + \frac{\partial}{\partial x} \left( qr h \right) + \frac{\partial}{\partial y} \left( r^2 h + \frac{gh^2}{2} \right) &= gh(S_{0,y} - S_{f,y})
\end{align*}
\]

(3)

where \(h\) is the water depth, \(q\) and \(r\) are the unit discharge in the \(x\)- and \(y\)-direction respectively, \(S_{0,x}\) and \(S_{0,y}\) are the bottom slopes in the \(x\)- and \(y\)-direction respectively, and \(S_{f,x}\) and \(S_{f,y}\) denote the friction slope in the \(x\)- and \(y\)-direction respectively. When the classical shallow water equations are solved, the friction slope is computed using a standard Manning-Strickler formulation. Equation (3) is discretized on grids with arbitrary-shaped cells (triangular, quadrangular or polygonal) using the Godunov (1959) approach using a finite volume form that can handle discontinuous flows such as hydraulic jumps, moving bores, etc. The mass and momentum fluxes between the computational cells are computed using approximate Riemann solvers (Guinot & Soares-Fração 2006; Lhomme & Guinot 2007) that improve the treatment of the source terms arising from variations in the porosity and/or the ground level. Three Riemann solvers known as HLL, HLLC and AS were tested. A specific higher-order reconstruction technique of the flow variables allows a robust treatment of wetting/drying fronts on arbitrary topographies (Soares-Fração & Guinot 2007).

Figure 3 shows the computational mesh for the 2D simulations. Specific attention was focused on the mesh at crossroads.
1D Modelling of interactions between sewer and street flows

Test network layout

A simplified network was used to represent the interactions between surface flows and flooding from rivers and sewer networks. Figure 4 shows this test network layout.

The shape of the street channel is shown in Figure 5. Sewer conduits are circular pipes with diameter of 1.5 m. The Strickler roughness coefficient was 70 m$^{1/3}$/s for all tests.

Presentation of the structure of connection

The interactions between street and sewer flows are achieved through a channel connection without slope to avoid numerical perturbations. The channel connection has short length (1 m long) and is very high in order to contain the hydraulic head. Exchanges between the sewer network and street networks are through orifice/weir devices as shown in Figure 6.

Tests of the numerical stability

This step aims to check the numerical stability related to the way that the interactions are simulated. Brutal and gradual inflows are set at the sewer and street networks inlets. Simultaneous inflows of different or the same hydrograph shape were tested with various downstream water depths to represent the influence of a river. Discharges which allow exchanges between the two networks were chosen. Figure 7 shows kinds of inflow hydrograph.

RESULTS AND DISCUSSIONS

Simulations of the street flows with Canoe software

Comparison between 1D and 2D distribution of discharges through the virtual network

The 1D modelling approach was to develop a quasi 2D model by representing all roads (north-south and east-west) using 1D elements that were all cross connected at crossroad intersections. The comparison of the estimated overland flow discharges using the 1D and 2D schemes are given in Table 1 and in Figure 8.

1D simulated discharges are always greater than 2D simulated discharges because the 2D modelling takes into account all lateral transfers of flow as well as the energy losses due to crossroads in the network according to the main direction of the flow. The mean ratio between 2D and 1D discharges is close to 0.70 for all simulations carried out. The best agreement was obtained with the 2D HLLC and AS solvers (refer Figure 8).

Differences between 1D and 2D discharges increase with increases in the flow rates (more than 200 m$^3$/s). This is attributed to the increasing energy losses due to increases in the flow rates.

Table 1 | Comparison between 1D and 2D north–south simulated discharges through the virtual network

<table>
<thead>
<tr>
<th>$H_{north}$ (m)</th>
<th>$H_{south}$ (m)</th>
<th>$Q_{2D}$ (m$^3$/s)</th>
<th>$Q_{1D}$ (m$^3$/s)</th>
<th>$Q_{1D}$ (m$^3$/s)</th>
<th>$Q_{2D}$ (m$^3$/s)</th>
<th>$Q_{1D}$ (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>1.54</td>
<td>30 (Q$2D$/Q$1D$ = 17%)</td>
<td>116 (67%)</td>
<td>116 (67%)</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>1.32</td>
<td>70 (28%)</td>
<td>169 (68%)</td>
<td>169 (68%)</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>1.57</td>
<td>1.09</td>
<td>99 (35%)</td>
<td>190 (67%)</td>
<td>190 (67%)</td>
<td>285</td>
<td></td>
</tr>
<tr>
<td>1.56</td>
<td>0.86</td>
<td>117 (38%)</td>
<td>198 (65%)</td>
<td>198 (65%)</td>
<td>304</td>
<td></td>
</tr>
<tr>
<td>1.17</td>
<td>1.02</td>
<td>33 (29%)</td>
<td>84 (75%)</td>
<td>84 (75%)</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>1.16</td>
<td>0.80</td>
<td>59 (41%)</td>
<td>108 (74%)</td>
<td>108 (74%)</td>
<td>145</td>
<td></td>
</tr>
</tbody>
</table>
Comparison with the experimental data

Some simulations were also carried out with the Canoe software in order to check its capacity to represent the distribution of discharges through a crossroad intersection. The Mignot (2005) experimental data was used as the benchmark. Mignot (2005) conducted an experimental study of the distribution of flows through a crossroad intersection using a small-scale physical test bench which could be adjusted to give several slopes in the $x$- and $y$-directions. Slopes along $x$- and $y$-direction are called $S_x$ and $S_y$ respectively. The distribution of the flows was checked for each couple of slopes $S_x - S_y$. Figure 9 shows the directions of flows during the experimental tests. The main experimental results are presented in Figure 10.

The results of simulation from the Canoe runs are related to the virtual network crossroad intersection indicated on Figure 2 by a circle. It can be seen in Figure 10 that the results provided by Canoe align with the experimental data obtained with $S_x = S_y = 1\%$. Indeed, this slope is related to the hydraulic gradeline (near 1\%) and not to the bottom slope of the channel which is 0\%. Those first results of comparison show the ability of the Canoe software to represent the distribution of discharges through a regular crossroad intersection. More tests should be carried out under various conditions in order to improve the capacity of the Canoe software to simulate overland flow by adding terms related to the energy losses through crossroads.

Modelling of exchanges between the sewer and overland networks

Numerical stability

The evolution of the intercepted or flooding flows is done according to the hydrograph shape. Steady state behaviour is reached after 1,000 minutes (see Figure 11). No divergences were observed during simulations.

Agreement with manhole operation

The hydraulic behaviour of the original method of connection was compared to the results found in literature like Despotovic et al. (2004) or Gomez & Mur (2004). Orifice/weir coefficients were used as parameters for the calibration of the model. The influence of flooding flows from a river has been taken into account as a variable water depth boundary condition.

There is a transitional operation of the device until the intercepted flow $Q_i$ and the approach (upstream discharge) flow $Q_a$ reach the values of 0.35 m$^3$/s and 1.5 m$^3$/s respectively (see Figure 12a). For the street flows lower than 1.5 m$^3$/s the intercepted flow rates increase quickly until the beginning of the real operation of a manhole. This may be due to the perturbations related to the weir/orifice combined operation for the low street flow rates.

Figure 13 shows the evolution of the efficiency (the ratio between the street and intercepted flow rates) according to
Figure 10 | Comparison between experimental results (Mignot 2005) and the simulated distribution of discharge through a crossroad intersection.

Figure 11 | Exchange between the sewer and street networks after brutal and gradual inflows: (a) intercepted flow after inflow at street inlet point; (b) flooding flow after inflow at sewer inlet point.

Figure 12 | Similarity between the behaviour of connection method and operations of a Manhole. (a) Simulated behaviour of the original method. (b) Manhole operations (Despotovic et al. 2004)
the ratio between the street upstream flow rate and the water depth in the street near a manhole. For the same reason as previously noted, a transitional zone was observed in Figure 13a. Figures 11, 12 and 13 indicate that the single calibrated 1D model like Canoe is able to take into account interactions between street and sewer flows. Mark et al. (2004) used as well the 1D approach to simulate urban flooding. In our case, the influence of the river flooding is integrated as water depths boundary conditions.

**CONCLUSIONS**

The purpose of this paper was to simulate the interactions between heavy rainfall-runoff in an urban area and flooding flows from rivers and sewer networks using a linked 1D modelling approach.

The Canoe 1D software package was used to simulate both street flows and the exchanges between overland flows and sewer networks. The Canoe 1D software shows good capacity to simulate street flows based on simulated distribution of discharges through a virtual street network (developed in the French Hy2ville Project) in comparison with 2D flow distributions simulated using the SW2D software and experimental data from Mignot (2005).

The method of linking the street and sewer networks gave a consistent response according to the shape of the inflow hydrograph. The connection operates like a manhole with the orifice/weir coefficients used as calibration parameters.

Some tests carried out in this study highlight similarities between the method of linking and manhole operations as assessed by Despotovic et al. (2004) and Gomez & Mur (2004).

The influence of flooding flows from river has been taken into account as variable water depth boundary condition.

It is concluded that models that are able to represent overland flows on streets, flooding flows from rivers and overflows or surcharges from sewer networks like the model outlined in this paper will allow designers and managers to better understand flooding in urban areas.

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