Impacts of small scale rainfall variability in urban areas: a case study with 2D/1D hydrological model in a multifractal framework

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Introduction

Basic features of hydrological processes at stake in urban hydrology flooding (rainfall, surface runoff, sewer flow, and sub-surface flow):
- Non linear
- Different characteristic spatial and temporal scales

Numerous studies suggest that rainfall variability, which is extreme over wide ranges of spatial and temporal scales, has a significant impact in hydrology and moreover in urban hydrology (greater coeff. of imper. And shorter response time)

→ What is the impact of small scale (< 1 km x 5 min, usually unmeasured) rainfall variability in urban hydrology ?
→ What should be the spatial resolution of the model used to take it into account ?

A case study :
- Kodak Catchment (1.44 km² urban near Paris)
- Two models : a fully distributed one and a semi distributed one
- One rainfall event : 9th February, 2009
The Multi-Hydro model

Overall description:

- Multi-hydro is a numerical platform developed at LEESU (v1, El Tabach et al, 2008, v2, A. Giangola-Murzyn et al., 2012) in the framework of SMARTesT. It is currently in a validation and demonstration (Heywood site, Manchester; Villecresnes site, Val-de-Marne) phase.

- It is a core that makes interact different modules, each representing a portion of the water cycle in urban hydrology.

(see Giangola-Murzyn et al. paper at this conference)

Main goals:

- taking into account small scales → fully distributed model
- physically based model (no calibration)
- easily transportable → a conversion module to generate inputs from available GIS data
- open access software packages to benefit from the feedback of a large community and frequent update.
Urban area physical processes modeled in Multi-Hydro

Surface module
- Runoffs
- Infiltration

Rainfall module
- Spatio-temporal rainfall

Soil module
- Vertical flow in the non-saturated area
- Saturation during a rainfall event

Drainage module
- Sewer flow (free surface, and loaded)
- Overflow
Kodak catchment

Kodak catchment, in Seine-Saint-Denis

C band radar of Trappes
Kodak catchment

- 1.44 km²
- Known for regular overflow
- Project to build a storm water storage basin
Multi-Hydro resolution

MH-AssimTool converts vector data in raster format for the surface. Only one land use class can be affected to a pixel of the raster format file, even though several are visible on the corresponding area (see figure below for an illustration). Therefore the order in which the various classes should be extracted must be specified.

Illustration:

In this example, if the land use class order is gully, road, house and grass, then this pixel will be considered as a gully in the raster file.

Specify the order in which the various landuse should be extracted:

Choose the category n°1 of landuse class to be extracted in the grid

Snapshot of MH AssimTool
Multi-Hydro resolution

Gully
Road
Building
Water
Wood
Grass

20 m
Multi-Hydro resolution

Gully
Road
Building
Water
Wood
Grass

15 m
Multi-Hydro resolution
Multi-Hydro resolution
Multi-Hydro resolution

Gully
Road
Building
Water
Wood
Grass

1 m
## Multi-Hydro resolution

### Example of hydrological consequences:

<table>
<thead>
<tr>
<th>Size of pixel (m)</th>
<th>% of impervious area</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>87</td>
</tr>
<tr>
<td>15</td>
<td>83</td>
</tr>
<tr>
<td>10</td>
<td>77</td>
</tr>
<tr>
<td>5</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>53</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
</tr>
<tr>
<td>1</td>
<td>40</td>
</tr>
</tbody>
</table>

How to explain these figures with a unique notion?
Fractal tools which are commonly used in geophysics can also be helpful in urban environment.

Notion of fractal dimension of a set $A$:

$N_\lambda = \text{number of boxes of size } l \text{ needed to cover the set } A \text{ of outer scale } L$

$$N_\lambda \approx \lambda^{D_F}$$

Resolution = $\lambda = \frac{L}{l}$

Fractal dimension of the impervious area:

$D_F = 1.85$ ($R^2 = 0.99$)
Kodak catchment

Multi-Hydro : 10 m resolution

- Modelled with semi-distributed 1D model Canoe (lumped model for each sub-catchment and Saint-Venant equations in the links)
- 16 sub-catchments (considered homogeneous) with size ranging from 4 to 14.5 ha
- Calibrated by DEA 93
Rainfall event of February 9\textsuperscript{th} 2009

Data: Météo-France radar mosaic

Resolution: 
1 km * 1 km * 5 min

Time evolution of the rain rate for the studied catchment

Météo-France radar mosaic, provided by Météo-France
Comparison of the simulated flow with raw radar data

For the measurement point:

- Rather similar patterns
- Significant differences in the peak flow
- Data quality?

Nash-Sutcliff
- MH 10 m: 0.40
- MH 5 m: 0.68
- Canoe: 0.78

Time (h)
Quantifying the uncertainty associated with small scale rainfall variability

Methodology: stochastic ensemble approach

(i) Generation of an ensemble of realistic downscaled rainfall fields:
   - Multifractal analysis of rainfall data
   - Downscaling with the help of discrete universal multifractals cascades

(ii) Simulation of the corresponding ensembles of hydrographs:
   - Use of operational hydrological/hydraulic urban models

(iii) Analysis of the ensembles:

Variability among the 100 samples

Uncertainty due to the unknown high resolution rainfall variability
Quantifying the uncertainty associated with small scale rainfall variability

Rainfall downscaling technique

Measured or deterministically nowcasted

Multifractal analysis → two relevant parameters of the cascade process

Stochastic spatio-temporal downscaling for each pixel

Performed with the help of discrete Universal Multifractal cascades

Two more cascade steps... → 11 m x 19 s
Quantifying the uncertainty associated with small scale rainfall variability

Rainfall downscaling technique

Temporal evolution of the avg rain rate over the studied area

Total rainfall amount:
- Raw radar: 7.34 mm
- Simulated ensemble: 7.37 ± 0.21 mm (CV=2.9%)

Potential hydrological effects are due to disparities of spatio-temporal distribution, not total amount.
Quantifying the uncertainty associated with small scale rainfall variability

Uncertainty on the simulated flow for the outlet

Multi-Hydro 10m

CV' = 15 %

Semi-distributed 1D model

CV' = 8 %

\[ CV' = \frac{Q_{0.9}(t_{PF,\text{radar}}) - Q_{0.1}(t_{PF,\text{radar}})}{2 * PF_{\text{radar}}} \]
Quantifying the uncertainty associated with small scale rainfall variability

Upstream / downstream influence

CV' = 15%

CV' = 19%

CV' = 22%

CV' = 29%

CV' = 60%
Conclusion

Quantifying the uncertainty associated with unmeasured small scale rainfall variability:
- It cannot be neglected ($CV$ reaches 60% for up-stream links and 15% for the outlet, and power law fall-off for probability distribution for both discharge and rainfall).
- A need to implement X band-radars (which provide an hectometric resolution) in urban area.

Comparison of a fully distributed model (10 m resolution) with semi-distributed one (300 m resolution):
- Much more uncertainty is unveiled with the fully distributed / Even moderate rainfalls are affected.
- Semi-distributed models would be unable to take advantage of an improved data resolution.

→ Small scale phenomenon must be taken into account in urban hydrology.

Limits / further investigations:
- Perform similar study with other inputs
- More heaviest rainfall, actually generating floods should be tested