Influence of rainfall spatial variability on hydrological modelling: case study on two urban catchments

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1 Introduction

The influence of rainfall spatial variability on the modelling of a catchment response to rainfall forcing has long been a concern for hydrologists. This subject has been a motivation of the research effort devoted by hydrologists to radar rainfall measurement. The significant improvement in radar images, combined with the spread of semi-distributed and distributed hydrological models needed to take the spatial variability of rainfall into account has resulted in an increasing number of studies (Gires *et al*., 2012; Zoccatelli *et al*., 2010). Despite this research effort, the added value of considering rainfall spatial variability in hydrological modelling remains an open question from both scientific and operational points of view. This study addresses this topic through the modelling of two urban catchments of different characteristics ("Boucle de Boulogne" and Saint-Etienne catchments) using weather radar images with a high spatial resolution (250 m x 250 m radar pixels). In this study, we have made a sensitivity analysis in order to evaluate if working with 250 m radar images give different modelling results than working with 1 km images.17 rainfall events of different rainfall typology and, thus, displaying different spatial variability have been considered.

2 Rainfall events

2.1 Radar data

Radar data are provided by the C-band weather radar of Treillières with a 3 dB beam width of 1.25 deg. This radar is located 10 km north of Nantes, south of Brittany (France). Its scanning strategy consists of three successive volume scans. Each volume scan lasts 5 min and is constituted of four elevation angles. The PPI operated at the three lowest elevation angles: 0.4 deg, 0.8 deg and 1.5 deg are contained in all three scans and are therefore repeated every 5 min. The polar measurements are projected into a Cartesian grid of 128 km x 128 km with a spatial resolution of 250 m x 250 m. Data of each radar pixel are instantaneous. Radar data have been processed from ground clutter, isolated pixels and partial beam blocking. For each scan, a static making of the measurements of each elevation angles is done. The measurement of the lowest elevation angle (which is not a ground clutter) is used. Finally, reflectivity is converted to rainfall rate according to the Marshall-Palmer Z-R relationship (*i.e.* $Z = 200\ R^{1.6}$, with Z the radar reflectivity in mm^6/m^3 and R the rain rate in mm/h).

For this study, two different rainfall spatial resolutions have been considered: measured radar data (resolution of 250 m x 250 m), taken as reference, and radar data averaged at 1 km x 1 km.

2.2 Rainfall events

A meteorological analysis conducted by Emmanuel *et al*. (2012), using the Treillières radar data, has highlighted, at the mesoscopic scale, three categories of meteorological situations: warm sectors, tail end of low pressure systems and fronts. Those meteorological situations give four different types of rainfall fields:

- Light rainfall (related to warm sectors)
- Showers (related with tail end of low pressure systems)
- Storms less organized (related with fronts)
- Storms organized in rain bands (related with fronts).

A total of 17 rainfall events have been selected in 2009 (5 events) and 2012 (12 events) on a zone of 40 km x 50 km (Figure 1) based on a visual analysis of radar images, such that each selected rainfall event is homogeneous in terms of rainfall field type. Table 1 lists the characteristics of these rainfall events relative to duration and rainfall field type; these events last between 01h35 and 16h20. An image of each rainfall field type is shown in Figure 1.

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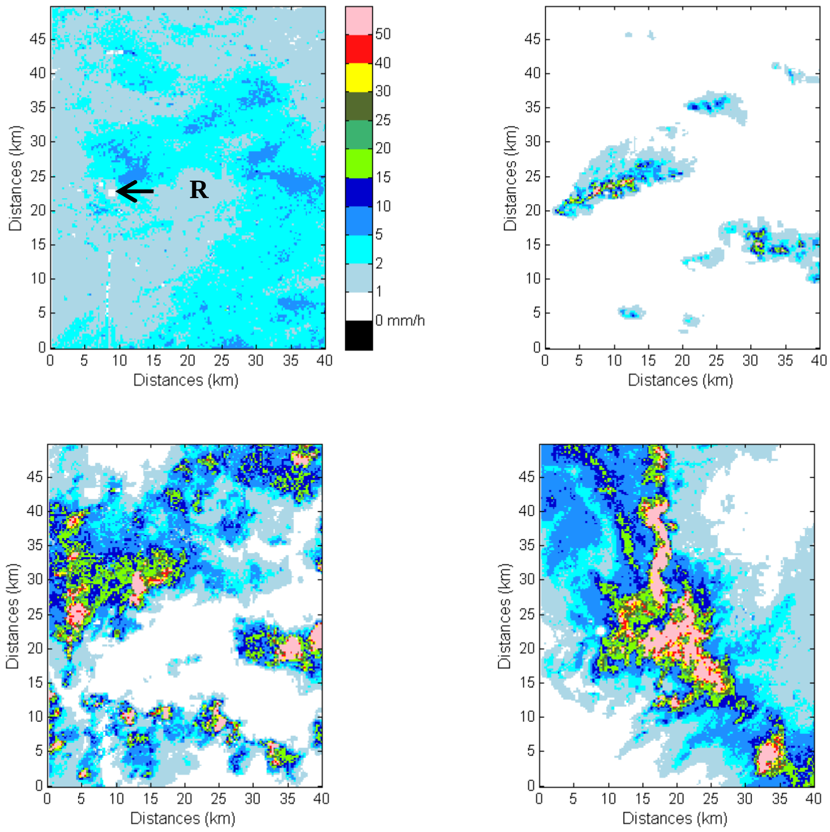

Figure 1: Radar images characteristic of each rainfall field type. The radar images are shown at the level of the study zone (40 km x 50 km). The radar is identified by the R.

2.3 Rainfall events variability

2.3.1 Methodology

In order to study the events rainfall spatial variability, a geostatistical approach has been adopted. Different studies have shown that this approach was efficient to analyze rainfall field variability (Berne *et al.*, 2004; Emmanuel *et al.*, 2012). The spatial variogram, γ, enables to characterize the spatial structure of the random function Z of which the rainfall field is a realization.

$$y(d) = \frac{1}{2}E[(Z(x) - Z(x+dx))^2] \qquad (2)$$

with *E* the mathematical expectation and *dx* the distance increment.

The spatial variogram gives information on the data continuity and the cofluctuation in function of their spatial distance. When the random function has a defined variance, the variogram reaches a sill at a given range. In this case, the sill is equal to the variance. It then becomes possible to normalize the variogram, by the respective variance of each realization, and ultimately to average this normalized variogram over all realizations. This variogram is known as the climatological variogram (Berne *et al.*, 2004) and is characterized by a sill equal to one; moreover, it yields a structure representative of a set of realizations displaying a similar structure by assigning an equivalent weight to each realization. The range corresponds to the decorrelation distance, *i.e.* the distance from which two measurement points exhibit independent statistical behavior. To complete this information, the study of the d50 (distance for which the variogram reaches 50% of its sill) enables to obtain an indication on the small scale variability.

A rainfall field is composed of the alternation of a zone where it rains (*i.e.* the zone of non-zero rainfall) and a zone of zeros where it does not rain. In this study, we have focused on the non-zero variogram: each point used to compute this variogram has an intensity strictly higher than 0 mm/h. Therefore, for each rainfall event, the climatological spatial non-zero variogram has been studied through its shape, range and d50.

2.3.2 Results

Figure 2 gives an example of the obtained spatial variograms for the rainfall events 0 (light rain), 5 (shower), 16 (storm less organized) and 13 (storm organized). Those variograms are representative of the obtained variograms of the other rainfall events of same rainfall type. Table 1 summarizes the values of the computed ranges and d50 per rainfall event.

Variograms of light rain events present a unique structure with a range between 25 km and 30 km. Variograms of shower events have a range of about 5 km, which means that for showers, two points 5 km apart exhibit independent behavior. Less organized storms variograms feature two main structures and decrease after the second sill. The first structure corresponds to a 7.5-9 km range, while the second corresponds to a 26-30 km range. Finally, organized storms variograms reach a maximum value at about 13 km, after which variability decreases. Moreover, all variograms are characterized, by a very fast rise (d50 less than 4 km). Those observations had also been made by Emmanuel *et al*. (2012).

This study confirms that the studied rainfall events are of different types and display different spatial variability.

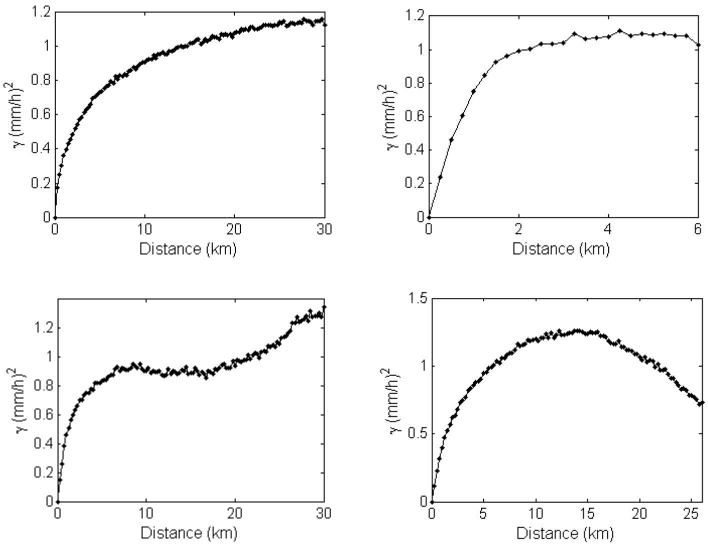

Figure 2: Example of the obtained spatial variogram for events 0 (up, left), 5 (up, right), 16 (down, left) and 13 (down, right)

Table 1: Rainfall events characteristics in terms of duration and rainfall field type

Name	Duration	Rainfall type	Range (km)	d50 (km)
EV0	16h20	Light rainfall	30	3.5
EV1	04h00	Light rainfall	30	3.5
EV2	08h00	Light rainfall	25	3.5
EV3	04h50	Light rainfall	30	3.75
EV4	08h20	Light rainfall	30	3
EV5	04h00	Shower	5	0.5
EV6	04h35	Shower	5	1
EV7	10h10	Shower	5	0.75
EV8	03h25	Shower	5	1
EV9	03h15	Storm less organized	9-27	1.5
EV10	02h50	Shower	6	1.25
EV11	04h30	Shower	5	1
EV12	10h30	Storm less organized	7.5-26	1
EV13	03h00	Storm organized	13	2
EV14	01h35	Storm organized	13	2
EV15	01h45	Storm organized	14	2.5
EV16	03h40	Storm less organized	8.5-30	1.25

3 Method

3.1 Presentation of the studied urban catchments

The study was conducted on two different catchments of combined sewage systems: the “Boucle de Boulogne” and Saint-Etienne Metropolis (Figure 3).

The “Boucle de Boulogne” is located in the southwestern of Paris region, in “Hauts-de-Seine” department, on the right bank of a meander of the Seine River. This 5.6 km² catchment has a relatively flat morphology (slopes ranging from 0.03% to 2%) and an urban land cover.

Saint-Etienne Metropolis is located in the southeast quarter of France, in the “Loire” department. The studied sewer system drains a catchment of 42 km² area with sub-catchments which have different characteristics. For this study area, the slope is much stronger with a maximum vertical drop of 176 m. The sub-catchments located upstream are peri-urban with a steep morphology. Further downstream, sub-catchments present an urban land cover with more or less steep areas.

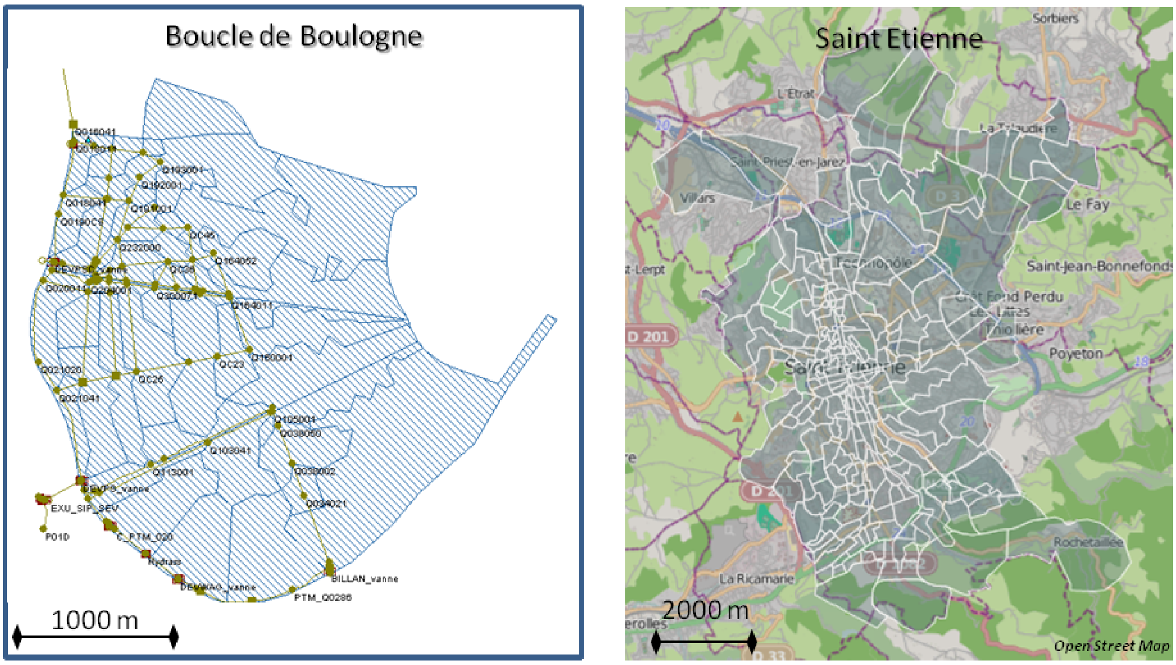

Figure 3: The two studied catchments (sub-catchment cutting is represented)

3.2 Description of the hydrological and hydraulic models

The proposed methodology is based on the coupling of a semi-distributed hydrological modeling with a hydraulic network modeling. The cycle of calculations consists of three major steps (Figure 4).

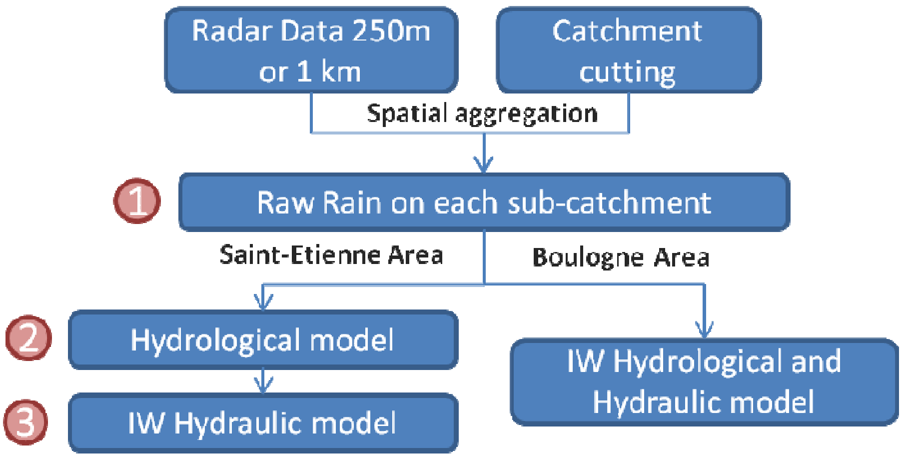

Figure 4: Summary of the cycle of calculations composed of three major steps

3.2.1 Radar data aggregation on sub-catchments

In order to obtain the raw rainfall on each sub-catchment, an assignment was made between the radar data at 250 m or 1 km resolution and each sub-catchment. This assignment was based on the sub-catchments cutting at GIS formats. This cutting takes into account the specificities of the collection system as well as the morphology of the surface land. Table 2 shows that the sub-catchments cutting give, for each studied catchments, very different characteristics of sub-catchments in terms of area. An identification of the pixels and the surface coverage was calculated for each sub-catchment. Radar data were then aggregated according to the assignment and to a weighting factor which has been computed from the surface radar coverage of each pixel.

Table 2: Catchment properties

Catchments	Number of sub-catchments	Total area (km²)	Minimal sub-catchment area (km²)	Maximal sub-catchment area (km²)	Mean sub-catchment area (km²)
Boucle de Boulogne	45	5.6	0.01	0.83	0.12
Saint-Etienne	231	42.9	0.003	2.84	0.19

3.2.2 Hydrological model

During this step, each sub-catchment hydrological response is computed from each sub-catchment raw rainfall.

For the “Boucle de Boulogne”, the hydrological model is based on predefined Infoworks® modules, namely "FIXED" production module whose parameters remain fixed over time (no integration of antecedent conditions) and the transport unit "SPRINT" module which is based on a simple linear reservoir model. This 5.6 km² catchment regroups 45 sub-catchments. The active area is of 2.6 km² for an impervious ratio of 46%. The initial losses were differentiated according to the local slope with a value of 2 mm for a slope less than 15 ‰ and of 1 mm for a slope higher than 15 ‰.

For Saint-Etienne metropolis, the hydrological model equations are the same as those of Boulogne’s Infoworks® model. For practical reasons of integration of the raw rainfall in the hydrological model, the computations were externalized from Infoworks®. This 42.9 km² catchment is composed of 231 sub-catchments. The active area is of 21.1 km ² for an impervious ratio of 49%. The initial losses were set at a value of 0.6 mm.

3.2.3 Hydraulic model

Hydrological results are injected into Infoworks® hydraulic model.

For both study catchments, the hydraulic model includes only the main network. Thus, 19.5 km of linear collectors are modelled for the “Boucle de Boulogne” and 124 km for Saint-Etienne. All characteristics (slope, geometry, roughness, altimetry, etc.) of collectors and structures (weirs and valves) have been described. The model solves the Saint-Venant equations (Yen, 1973) for the free surface flows. During the transition between the free surface flows and loads, Saint-Venant equations are retained but with the introduction of the principle of Preissman slot (Cunge and Wegner, 1964). Networks have several regulators (valves and thresholds) that are monitored by an automated system with different rules in function of dry or wet weather. All of these rules are integrated in the hydraulic model.

The construction, the calibration and the validation of both hydrological and hydraulic models have been realized in previous studies based on different rainfall events.

3.3 Outputs analysis

The interest of working with 250 m radar data compared to 1 km radar data has been assessed through a sensitivity analysis by comparing the hydrographs obtained from each case at the output of the hydraulic model. In order to obtain results on areas with different characteristics in terms of number and geometry of sub-catchments, results have been extracted, for both studied catchments, at an upstream point and at a downstream point of the drainage system. Table 3 presents the characteristics of each analyzed extracted point.

This table shows that the studied areas upstream of each extracted point present different characteristics in terms of sub-catchments. The last column indicates if the flow on each area can be influenced by some network facilities (weir, control valve, basin storage, etc.).

*Table 3: Extracted points characteristics (*area located downstream of the drainage system)*

Studied catchment	Extracted point Name	Number of Sub-Catchment	Total area (km²)	Minimal sub-catchment area (km²)	Maximal sub-catchment area (km²)	Mean sub-catchment area (km²)	Influenced Network
Boucle de Boulogne	Q015P02.1*	45	5.57	0.01	0.83	0.12	Yes
Boucle de Boulogne	QC26.1	10	1.38	0.05	0.23	0.14	No
Saint-Etienne	CH_20.1	23	7.00	0.02	2.06	0.30	No
Saint-Etienne	E_01A.1*	231	42.87	0.003	2.84	0.19	Yes

For each rainfall event, a statistical indicator has been computed to compare the modelled hydrographs obtained from 1 km radar data to the one obtained from 250 m radar data (taken as reference): the Relative Absolute Deviation (noted RAD) defined as follows:

$$RAD = \frac{|Qp1km - Qp250m|}{Qp250m} * 100 \qquad (2)$$

with $Qp1km$ the maximum value of the hydrograph obtained from 1 km radar data and $Qp250m$ the maximum value of the associated hydrograph obtained from 250 m radar data.

4 Interest of a detailed knowledge of rainfall spatial variability: results

Results are summarized in Table 4. Figure 5 illustrates for Event 14 (organized storm) the obtained hydrographs.

Table 4: Evolution of RAD for the four extracted points and the 17 studied events (the shades of grey differentiate each rainfall field event type)

	CH_20.1	E_01A.1	Q015P02.1	QC26.1
EV0	1%	2%	1%	4%
EV1	2%	2%	0%	1%
EV2	6%	1%	0%	1%
EV3	0%	1%	0%	1%
EV4	0%	0%	0%	1%
EV5	15%	5%	1%	1%
EV6	2%	3%	0%	5%
EV7	12%	0%	0%	1%
EV8	5%	0%	1%	1%
EV10	2%	2%	2%	2%
EV11	9%	6%	2%	2%
EV9	22%	1%	0%	2%
EV16	1%	0%	0%	5%
EV12	1%	0%	1%	18%
EV13	3%	0%	0%	2%
EV14	10%	1%	0%	14%
EV15	10%	3%	3%	6%

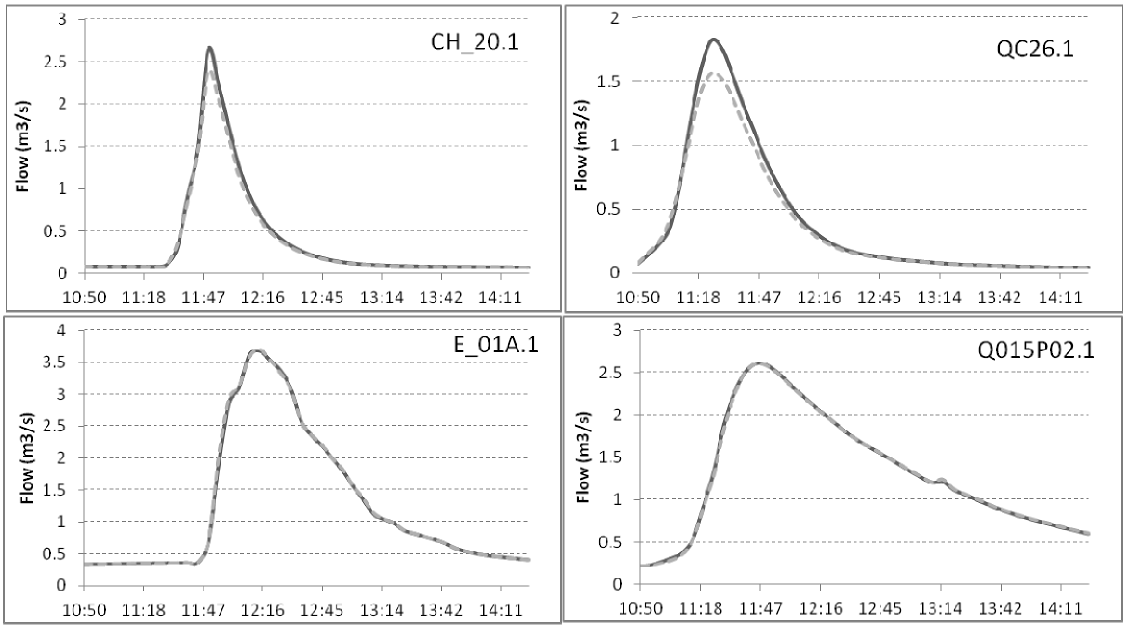

Figure 5: Hydrographs obtained for Event 14 from 250 m radar data (black) and 1 km radar data (dot grey) for the "Boucle de Boulogne" catchment (right) and Saint-Etienne catchment (left) for the upstream (up) and downstream (down) extracted points.

For light rainfall, RAD remains lower than 6% whatever the extracted point which means that 250 m radar data do not engender modelled hydrographs different from those obtained with 1 km radar data. This can be explained by the fact that light rainfall events are the less variable and thus, for those events a 1 km radar knowledge do not differ much from a 250 m radar knowledge.

For showers and storms, values of RAD depend of the studied extracted point. For the downstream points, RAD remains also lower than 6%. However, for upstream points, values of RAD are much more variable and vary from 1% to 18% for the "Boucle de Boulogne" case and from 1% to 22% for the Saint-Etienne case. For variable rainfall events, 250 m radar data appear to give, for some events, different information than 1 km radar data. Downstream points seem to filter those differences as both hydrographs remain very similar, whereas upstream points appear more sensitive to those differences. The filtering observed for downstream points could be partly explained by the fact that the studied points are influenced by some network facilities.

Those results represent a first analysis and the subject will be explored more deeply to understand why, for events of a same rainfall typology, results vary so much for the upstream extracted points.

5 Conclusion

The interest of working with 250 m radar data compared to 1 km radar data for hydrological modelling has been studied on two different catchments: the "Boucle de Boulogne" and Saint-Etienne Metropolis. Those catchments present different characteristics in terms of area (respectively 5.6 km² and 42.9 km²) and location. A hydrological model and a hydraulic model, which were already calibrated, have been used. The influence of rainfall spatial variability has been studied through a sensitivity analysis by considering two rainfall inputs: the measured radar data with a resolution of 250 m x 250 m and the associated averaged radar data at 1 km. The obtained associated hydrographs have been compared by computed the Relative Absolute Error. 17 events of different rainfall types (from light rainfall to showers and storms) and thus displaying different spatial variability have been considered. For both catchments, results have been studied at two different points: an upstream and a downstream point of the drainage system. Results are varied and depend on the rainfall event type and on the location of the extracted point. For light rainfall event and for downstream points, 250 m and 1 km radar data give very similar hydrographs. However, for upstream points associated with showers and storms events, hydrographs obtained from 1 km radar data can be different from those obtained from 250 m data (the error can reach up to 22%).

The presented work is a first analysis and needs to be explored more deeply to better understand the varied obtained results.

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