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Title Page:

# Rainfall measurement from Commercial microwave links for urban hydrology in Africa: a simulation framework for sensitivity analysis.

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## Abstract (<= 250 words)

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Urban floods due to intense precipitation are a major problem in many tropical regions as in Africa. Rainfall measurement using microwave links from cellular communication networks has been proposed as a cost effective solution to monitor rainfall in these areas where the gauge network is scarce. The method consists in retrieving rainfall from the attenuation estimated along the commercial microwave links (CMLs) thanks to the power levels provided by an operator. In urban areas where the network is dense, rainfall can be estimated and mapped for hydrological prediction. Rainfall estimation from CMLs is subject to uncertainties. This paper analyzes the advantages and limitations of this rainfall data for a distributed hydrological model applied to an urban area. The case study is in West Africa in Ouagadougou where a hydrological model has been set up. The analysis is based on numerical simulations, using high resolution rain maps from a weather radar to emulate synthetic microwave links. Two sources of uncertainty in the rain estimation and on the simulated discharge are analyzed by simulations: i) the precision of the raw information provided by the operator and ii) the density and geometry of the network. A coarse precision (1 dB) in the signal provided by the operator can lead to substantial underestimation of rainfall and discharge, especially for links operating at low frequency (below 10 GHz) or short (less than 1 km). The density of the current mobile networks in urban areas is appropriate to analyze hydrological impact of tropical convective rainfall.

20

21 **Main ( < 7500 words)**

## 22 **1. Introduction**

23

24 During the last 10 years, rainfall measurement from commercial microwave link (CML) network has  
25 gradually emerged as a useful complement to traditional rainfall measurement based on gauges,  
26 weather radar or satellites. Uijlenhoet et al. (2018) and Chwala and Kunstmann (2019) provide a good  
27 review of the state of the art and the research developed since the pioneering work of Messer et al.  
28 (2006) and Leijnse et al. (2007b)The CML technique is based on the analysis of attenuation induced by  
29 rain over the radio-frequency part of the mobile network, i.e. between pairs of telecommunication  
30 antennas. The main advantage of this technique is to exploit a network already in place and well  
31 maintained by mobile operators. In developing countries where the mobile network is already well  
32 developed (Noam 1999; ITU 2004) while hydro-meteorological services have limited resources  
33 (Novella and Thiaw 2013; Dieulin et al. 2019) the prospect for operational use of the CML technique is  
34 very appealing (Hoedjes et al. 2014; Gosset et al. 2016). The telecommunication network density  
35 follows population density (i.e. the customers) and most of the antennas lay in urban areas. This means  
36 that urban hydrology and urban flood risk monitoring is a subject area that could benefit from the CML  
37 technique (Fencl et al. 2013, 2015, 2017; Stransky et al. 2018; Pastorek et al. 2019). Cities in developing  
38 countries and especially in Africa are suffering from an increase exposure to extreme weather events  
39 (Bradshaw et al. 2007; Ebi and Bowen 2016; Egbinola et al. 2017; Engel et al. 2017 ). The amount of  
40 material damages and casualties due to flooding in West Africa has increased in the last decade under  
41 the conjunction of demographical pressure and population flow towards cities on one hand, and an  
42 increase of rainfall on the other hand. The mobile communication network could potentially  
43 contribute to a better monitoring of these hydrometeorological events. With current network

44 monitoring systems (NMS) or dedicated software CML rainfall is typically monitored at time steps of 5  
45 to 15 minutes (Uijlenhoet et al. 2018; Chwala and Kunstmann 2019) which provides an interesting  
46 temporal resolution for urban hydrology. Data have been collected at even shorter time steps for  
47 some experiments (Schleiss and Berne 2010; Schleiss et al. 2013; Zinevich et al. 2009; Fencl et al. 2015;  
48 Chwala et al. 2016)

49 Most studies on CML estimation of rainfall have been based in European countries (Fenicia et  
50 al. 2012; Schleiss et al. 2013; Zohidov et al. 2016; D'Amico et al. 2016; Pastorek et al. 2019; de Vos et  
51 al. 2019; Polz et al. 2020; Graf et al. 2020; Roversi et al. 2020) and Israel (Messer et al. 2006; Zinevich  
52 et al. 2008, 2009). Most have focused on the quality of the estimate from this technique by comparison  
53 with rain gauges and/or weather radar. More recently, investigations on CML rainfall estimation have  
54 started outside Europe and Mediterranean countries (Hoedjes et al. 2014; Rios Gaona et al. 2017; Kim  
55 and Kwon 2018; Sohail Afzal et al. 2018). Doumounia et al. (2014) presented the first quantitative test  
56 of the technique in Africa, based on a single link.

57 A few studies discussed the interest of the CML rainfall for hydrological applications in Europe  
58 (Brauer et al. 2016; Smiatek et al. 2017) in particular for urban hydrology where the high spatial and  
59 temporal resolution of the rain maps is beneficial (Fencl et al. 2013, 2015, 2017; Stransky et al. 2018;  
60 Pastorek et al. 2019). These studies showed that the density of links in urban areas helps improving  
61 the simulation of the discharge dynamics compared to simulations based solely on rain gauges. They  
62 also pointed out some biases in CML rainfall estimate and their propagation in the simulated discharge.  
63 In african cities where the flood risk is very high and rainfall is due to intense convective systems, the  
64 CML technique seems particularly promising for urban hydrology. This study wishes to contribute to  
65 its development by analyzing the expected benefits.

66 The study by Doumounia et al. (2014) in Ouagadougou was part of the Megha-Tropiques  
67 satellite ground validation (MTGV) program (Gosset et al. 2018; Guilloteau et al. 2018). During this  
68 experiment a weather radar and a dense network of rain gauges were available. In order to take full

69 advantage of the CML-based rain maps when they will be available, the Institut de Recherche pour le  
70 Développement (IRD) started the development of a fully distributed hydrological model compatible  
71 with this urban context. Bouvier et al. (2017, 2018) have adapted their modeling platform ATHYS  
72 (ATelier en HYdrologie Spatialisée; Bouvier and Desbordes 1990; Bouvier et al. 2010) with a first  
73 validated set up for the city of Ouagadougou. The primary purpose of the present work is to investigate  
74 how such a distributed hydrological model can benefit from CML based rain estimation : what is the  
75 added value for hydrological prediction of the spatial information on rainfall provided by the CML  
76 network ; how does it balance with the uncertainties brought in by CML estimation ; what is the  
77 sensitivity of the predicted discharge to the CML network configuration. While CML and hydrological  
78 data is being gathered in various African test-beds (Cameroun; Niger), these questions are first  
79 investigated based on numerical simulations.

80 The proposed simulation framework is based on three components, i) the distributed  
81 hydrological model ATHYS, currently set up for the city of Ouagadougou, ii) high resolution (1 km; 5  
82 minutes) rain maps acquired with a weather radar in Ouagadougou during the MTGV campaign ; these  
83 are the reference rain fields used for the reference hydrological simulations and to generate synthetic  
84 CML measurements, and iii) the production of pseudo-CML data simulated by positioning a virtual  
85 network inside the high resolution rain fields. With this set up several aspects of CML based rainfall  
86 measurement and uncertainty propagation into the model can be investigated.

87 There are many sources of uncertainty in rainfall estimation from a network of commercial  
88 microwave links (see Chwala and Kunstmann 2019 for a recent review). In this paper we primarily focus  
89 on two aspects that are directly linked to the network itself : i) the uncertainty in rainfall estimation  
90 at each individual link due to the inaccuracy of the raw signal (digitizing step) and the length and  
91 frequency of the link, and ii) the network spatial configuration and its capacity to represent rainfall  
92 characteristics over the basin.

93 Section 2 provides an introduction to rainfall measurement from commercial microwave links  
94 (CMLs). Section 3 introduces the study area and the simulation set up, the high-resolution radar data  
95 used as input for the link simulations, the hydrological model ATHYS and the numerical experiments  
96 carried out. Section 4 presents the results from the numerical experiments, analyzing the impact of  
97 the precision in attenuation measurement and of the spatial configuration of the network inside the  
98 basins. For both topics, the impact is first analyzed on rainfall and then on the simulated discharge.  
99 Section 5 provides conclusions and perspectives.

## 100 2. Rainfall measurement from commercial microwave links: 101 principle and known limitations

102

103 The fundamental quantity used for rainfall estimation from CMLs is the specific attenuation  $k$  (dB/km)  
104 due to the rainfall along the wave propagation path. Because both  $k$  and the rainfall intensity  $R$  (mm/h)  
105 depend on the rain drop size distribution (DSD), they are related, and their relationship can be  
106 expressed via a power law:

$$107 \quad k = a R^b \quad (1)$$

108 where  $a$  and  $b$  depend strongly on the frequency, the polarization and more mildly on other factors  
109 (DSD; temperature etc.).

110 **### Table 1 around here ###**

111 Table 1 reports values of  $a$ ,  $b$  for several frequencies typical of the range commonly used on  
112 operational mobile networks. The values of  $a$  and  $b$  were computed using the Mie scattering model  
113 (Mie 1908) and DSDs measured in West Africa (Moumouni et al. 2008).

114 Between the two ends of a CML of length  $L$  the total (or path integrated) attenuation PIA can be  
115 estimated by comparing the transmitted (Tx) and received (Rx) powers. In most cases the transmitted

116 signal Tx is constant and rainfall attenuation is detected through variations (drops in signal) of Rx  
117 compared to its *baseline* level (Overeem et al. 2011; Chwala et al. 2012; Chwala and Kunstmann 2019).  
118 The PIA is the integral of  $k$  along the path:

$$119 \quad PIA = \int_0^L k(s) ds = \int_0^L a R(s)^b ds \quad (2)$$

120 For practical purpose Eq. (2) is simplified to relate the PIA to the mean rate along the link,  $\langle R \rangle$  :

$$121 \quad PIA = \langle k \rangle L = a' \langle R \rangle^{b'} L \quad (3)$$

122 Unless rainfall is uniformly distributed along the link, or the exponent  $b$  is equal to 1,  $a'$ ,  $b'$  in Equation  
123 (3) are different from  $a$ ,  $b$  in Equation (2) (Leijnse et al. 2008, 2010). For the frequency range 18 to 40  
124 GHz (where  $b$  is close to 1, see Table 1) using  $(a, b)$  in Eq. (3) leads to little error. For short frequencies  
125 (below 15 GHz) the parameters need to be adjusted to account for rainfall variability along the link and  
126 the nonlinearity of the relation. Doumounia et al. (2014) used radar data from Ouagadougou to analyze  
127 this effect for a 29 km link operating at 7 GHz, and found an increase of 25% in the prefactor  $a'$   
128 compared to  $a$ . Similar calculations for a 5 km link gives an average increase of 3.5 % at 6 GHz and 2%  
129 at 12 GHz, and about twice these values for a 10 km link. Our data set based on 1 km radar data is  
130 however not best suited to analyze the small scale structure of rainfall.

131 Based on Eq. (3) and assuming that the parameters  $a'$  and  $b'$  are known, the rainfall estimation ( $\hat{R}$ ) is  
132 given by:

$$133 \quad \hat{R} = [PIA/a'L]^{1/b'} \quad (4)$$

134 Equation 4 and the values of  $a$  and  $b$  reported in Table 1 show that the amount of PIA for a given mean  
135 rain rate increases with the frequency and with the link length. For a given increment in PIA the  
136 equivalent rain rate is lower for higher frequencies and longer links, as illustrated in Table 1; for short  
137 links operating at low frequency the rainfall detection threshold may be high especially if the signal  
138 accuracy is coarse (1 dB). In this case low rainfall intensities will not be detected. The accuracy in the  
139 power levels provided by the operator, and the length and operating frequency of the CMLs are



140 therefore primary factors to consider in rainfall estimation and to assess the expected errors. As  
141 discussed in previous work (Leijnse et al. 2008a,b, 2010; Zinevich et al. 2010) there are several other  
142 sources of uncertainty in CMLs based rainfall estimation. One difficulty arises from the existence of  
143 fluctuations in the received power (Rx) that are not related to rainfall along the path. Attenuation by  
144 water vapor and other gas, refraction or reflection of the beam, mis-alignment of the antennas, can  
145 create such fluctuations. Drift in the electronics associated with temperature changes can also cause  
146 signal variability. These phenomena complicate the estimation of the *baseline* level during the dry  
147 periods and may cause error in rainfall detection and estimation. During and after rainfall, another  
148 source of error is the attenuation caused by antenna wetting (Leijnse et al. 2007a; Overeem et al. 2011;  
149 Chwala and Kunstmann 2019; Fencel and Bares 2019) which may lead to overestimating rainfall. There  
150 is not a simple analytical formula to relate the attenuation due to antenna wetting (in dB) at a given  
151 frequency to the rain rate, and its evolution in time. Experimental (Ostrometzky and Eshel 2018; Islam  
152 and Tharek 2000; Kharadly and Ross 2001) or theoretical (Leijnse et al. 2008a) analysis, and discussion  
153 with telecommunication engineers reveal that it depends on many factors like the material the  
154 antenna cover is made off or local wind effects. Given this complexity antenna wetting is not included  
155 in our simulations.

156

### 157 **3. Study area, data and simulation setup**

158

#### 159 *a. Study area*

160 The area of Ouagadougou (12.3° N; 1.5°W) in Burkina Faso was selected as an illustrative test bed for  
161 the present sensitivity study for several reasons. Ouagadougou is representative of african cities  
162 exposed to increased flood risk as illustrated by several recent extreme events (Engel et al. 2017). In  
163 addition, all the information needed for the simulations is available for this city: i) Ouagadougou hosted

164 the first quantitative experimentation in Africa of rainfall measurement based on CMLs. This  
165 experiment, presented in Doumounia et al. (2014) was based on a single link, rain gauges and used  
166 data from the radar presented in section 3.b. The operator provided meta-data on the network lay  
167 out (Figure 1) which has been included in some of our simulations ; ii) Doumounia et al. (2014)  
168 experiment was part of the larger Megha-Tropiques Ground Validation program (MTGV ;  
169 <http://meghatropiques.ipsl.polytechnique.fr/the-ouagadougou-super-site/> ; Gosset et al. 2018;  
170 Guilloteau et al. 2018) during which a weather radar was deployed for 2 years, providing high-  
171 resolution rain maps (see section 3.b) representative of african squall lines iii) a distributed  
172 hydrological model, well suited for flood prediction at the scale of a city and setup to use spatially  
173 distributed rainfall information was developed and calibrated for Ouagadougou (Bouvier et al. 2018)  
174 as presented in section 3.c.

175 Figure 1 displays the domain used for simulations (1250 km<sup>2</sup>) and the layout of the CML network used  
176 for some of our simulations. For this urban network (one of several in Ouagadougou where more than  
177 one cellular phone company operates) all 75 links operate at 13 Ghz, their lengths range from 0.3 to  
178 26 km over the domain. In our experience this density and size distribution is quite typical of what is  
179 found in other african cities, but there is a variety among countries, operators and depending on when  
180 the network was installed. In Niamey in Niger or Douala in Cameroun where we work with another  
181 operator, the number of links available over the urban areas are respectively 190 and 227; with  
182 frequencies ranging from 8.5 GHz to 23 GHz and lengths from 0.16 km to 6.59 km. Discussion with  
183 technical teams reveals that these networks are evolving with a tendency towards higher frequencies  
184 in the future.

185 The urban part of Ouagadougou is seen in the center (grey) of Figure 1 and the basins that drain water  
186 into the city are displayed. The two basins where rainfall estimation and discharge simulation are  
187 analyzed are highlighted. Their two outlets are respectively outlet 1060 (drainage area 448 km<sup>2</sup>) in the  
188 northern part of the city and outlet 1074 (drainage area 139 km<sup>2</sup>) more south. In each basin smaller

189 sub-basins are also used for testing, with outlet Ri1 and Ri3 (drainage area resp. 84 km<sup>2</sup> and 193 km<sup>2</sup>)  
190 in the northern basin, and Sa1 (74 km<sup>2</sup>) in the South.

191 #####. Fig 1 around here

192

193 *b. High resolution rainfall maps from weather radar*

194 The main data as input to the simulations is high resolution rain maps from a weather radar located in  
195 Ouagadougou in 2012 and 2013. The radar is an X-band polarimetric radar from which 5 minutes, 1  
196 km<sup>2</sup> rain maps were produced using an algorithm based on the polarimetric specific differential phase  
197 shift ( $R-K_{dp}$ ) as in Matrosov (2010), Kacou (2014) and Koffi et al. (2014).

198 In Ouagadougou as in most West Africa the rainfall season is associated with organized convective  
199 systems characterized by a front of convective cells followed by a stratiform trail (Moumouni et al.  
200 2008; Depraetere et al. 2009; Alcoba et al. 2016) and propagating mostly westwards. Figure 2 displays  
201 the rain maps over Ouagadougou while a convective system recorded by the radar on 2012 August 4th  
202 is crossing the area. The front of heavy rainfall associated with the convection arrives first followed by  
203 more widespread and lower rain rates. Altogether three rainfall events that lead to heavy  
204 precipitations and were well sampled by the radar are used for the simulations. Figure 3 displays the  
205 hyetogram (rain rate versus time) of these events and the frequency distribution of rain intensities.  
206 The values are typical of African squall lines, with most of the rainfall accumulation due to the  
207 convective front which lasts about one hour, and only 20 to 30% of the event accumulation due to the  
208 stratiform trail that lasts several hours. The heavy convective rainfall, with peak intensities well above  
209 50 mm/h is the main driver for the floods and needs to be monitored. The spread in the value of the  
210 percentiles in Figure 3 illustrates the spatial variability of rainfall over the domain, especially during  
211 the convective front. The ability of the CML network to capture this variability is crucial as discussed in  
212 section 4.

213 #####. Fig 2 and Fig 3 around here

214

215 *c. Simulation setup*

216 The objective of the simulations is to analyze the capacity of the CML network to reproduce the  
217 characteristics of the rain field that are needed to simulate the discharge. The benchmark is the  
218 hydrological model forced by the high-resolution radar rain maps; they provide the reference  
219 simulation.

220 CML-like data, mimicking various network configurations are generated from the radar maps. The  
221 quality of these synthetic-CML rainfall estimates is first compared with the original rainfall maps. Then  
222 these rainfall estimates are used as forcing to the hydrological model, and the simulated discharges is  
223 compared to the reference (i.e. the model forced by the high-resolution rain map).

224

225 1) CML SIMULATION FROM RADAR DATA

226 The CML simulation is based on calculating the interception between the links and the radar maps. The  
227 lines in Figure 2 display simulated links with their colors representing the mean rainfall over the link  
228 path.

229 For each radar image, the mean rainfall over each link  $R_{link}$  is computed as the weighted average of the  
230 rain rates over all radar pixels intercepted by the link:

231 
$$R_{link} = \frac{\sum_{i=1}^n l_i R_{pix_i}}{\sum_{i=1}^n l_i} \quad (5)$$

232

233 with  $n$  the number of radar pixels intercepted by the link,  $l_i$  is the length of link intercepted by the  
234 pixel,  $R_{pix_i}$  the rain intensity on the radar pixel  $i$ , and the link length is  $L = \sum_{i=1}^n l_i$ .

235 Similarly, the PIA is calculated based on the specific attenuation of each pixel,

$$236 \quad PIA_{link} = \sum_{i=1}^n l_i k_{pix_i} \quad (6)$$

237 where  $k_{pix_i}$  is related to  $R_{pix_i}$  through Eq. (1) with the parameters  $(a, b)$  suited for the frequency  
238 of the simulated link. The simulated PIA can be altered by adding a measurement noise or considering  
239 other sources of errors. A rounding error of 1 dB or 0.1 dB can be considered as in section 4.1 to  
240 account for the coarse precision of the raw data provided by the operator. The rainfall estimated from  
241 the link  $\hat{R}_{link}$  is then computed using Eq. 4. A range of values of the coefficients  $(a, b)$  can be tested  
242 in Eq. 4 to account for the uncertainty in the k-R relationship.

243 From the principle above a variety of CML network configurations can be tested by varying the  
244 frequency, length, position and orientation of the links. Several sources of uncertainty can be included  
245 in the simulations.

246

## 247 2) HYDROLOGICAL MODEL

248 A distributed hydrological model is needed to analyze the impact of rainfall spatial variability and to  
249 assess the ability of the CML network to reproduce rainfall characteristics that are important for the  
250 hydrological response. This work concentrates only on sensitivity analysis, by comparing the simulated  
251 response for various rainfall forcing. The purpose is not to evaluate the model output against real  
252 discharge data as these were not available when the radar was operating. The model was however  
253 setup and compared with real data in some areas of Ouagadougou, using rain gauge data, as described  
254 in Bouvier et al. (2018). The model is based on the open source platform ATHYS ( [www.athys-soft.org](http://www.athys-soft.org)  
255 ; Bouvier and Desbordes 1990; Bouvier et al. 2010). The model has been used for flood modeling in  
256 many areas, especially for small catchments. Recently Bouvier et al. (2018) proposed a version of the  
257 model suited for the analysis of urban floods in African cities. The motivation was to propose a  
258 distributed gridded model operating over the whole city, with small computation time allowing real-

259 time forecasting. ATHYS distributed event-based parsimonious model, with Soil Conservation Service  
260 Lag-and-Route (SCS-LR) formula for runoff production and propagation is well suited for these  
261 constraints. As detailed in Bouvier et al. (2018) the model was setup over a 1000 km<sup>2</sup> domain which  
262 includes the city of Ouagadougou as represented in Figure 1. The hydrographic network was defined  
263 using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) elevation  
264 model. This defines the 'natural' network in the rural area while the flux is forced by the street layout  
265 provided by the OpenStreetMap ([/www.openstreetmap.org](http://www.openstreetmap.org)) data base for the built areas. The runoff  
266 is calculated based on the SCS formulation on elementary grid cells of resolution 10 m, and then  
267 propagated through the connected grid cells downstream using a 'lag and route' formula. The velocity  
268 of propagation over a given grid cell is parameterized by the slope at this grid point and by the drainage  
269 area upstream that grid. This is a simplified version compared to Bouvier et al. (2018) who also  
270 considered hydraulic propagation (kinematic wave) in some parts of the network. Another  
271 simplification is that the SCS parameters are uniform for the whole area (the interception parameter  
272  $S$  is equal to 100 mm, in the range used by Bouvier et al. 2018) as the purpose here is to analyze the  
273 relative impact of various rain products, rather than the discharge simulation itself.

274 In this study rainfall is provided each 5 minutes, either on the radar grid (1 km resolution) for the  
275 reference simulation, or at the position of the links (center of each link) when testing the various  
276 network configurations. Inside ATHYS, the rainfall is interpolated at each grid point based on the  
277 Thiessen polygons method (Thiessen 1911).

278

### 279 3) REFERENCE SIMULATION

280 The reference simulations are based on the model above with the high-resolution rainfall maps (1 km  
281 resolution; 5 minutes time step) as forcing. A reference simulation is provided for each 3 rainfall events  
282 displayed in Fig.3. The discharge is calculated in 1078 intermediary points within the simulated area.

283 In the next sections the discharge sensitivity to the rain forcing is analyzed specifically at the outlets of

284 the two main basins in Fig.1 (1060 and 1074) and their sub-basins (Ri1, Ri3 and Sa1). Part of the  
285 northern basin (outlet 1060) lays in rural areas which are poorly observed by the telecommunication  
286 network (Fig 1), while the southern basin (outlet 1074) is located mostly in the urban area, thus better  
287 covered by the mobile network.

288

## 289 **4. Analysis of CML Rainfall uncertainty and propagation in** 290 **discharge simulation**

291

292 The simulation framework is used in this section to analyze uncertainties in rainfall estimation based  
293 on CMLs and its impact on the hydrological simulations. The reference simulation is based on the full  
294 resolution (1 km) rain maps. Synthetic CML rainfall estimates are produced using the link simulations  
295 introduced in section 3c for several network configuration.

296 First the impact of the precision of the attenuation data provided by the operator is tested in section  
297 4a. For this experiment the links are positioned and oriented as in Fig. 1 and the impact of the rounding  
298 error on attenuation (0.1 or 1 dB) is analyzed considering several frequencies and link lengths. The  
299 impact is first analyzed on the retrieved rainfall distribution and then on the simulated discharge over  
300 the 2 main outlets 1060 and 1074.

301 Section 4b concentrates on the spatial configuration of the network and its ability to sample rainfall  
302 variability within the basin. As above the analysis is first focused on the uncertainty on rainfall  
303 estimation over the basins and then on the simulated discharge. Several sub-basins of various size and  
304 shape are used.

305

306 *a. Impact of PIA rounding error*

307 As discussed in section 2 (Table 1) the accuracy of rainfall estimation from Eq. 4 depends on the  
308 precision of the PIA measurement itself, on the frequency (through the parameters  $a$  and  $b$ ) and on  
309 the link length  $L$ . The most recent network monitoring systems (NMS) provide Tx and Rx with 0.1 dB  
310 or better, but more basic NMS provide only 1dB precision (Leijnse et al. 2007b; Fencil et al. 2015; Kim  
311 and Kwon 2018). The relative effect of PIA precision is stronger for the lowest rain rate and sets the  
312 lower limit of rainfall detection. According to Table 1 for instance the theoretical limit of detection for  
313 a link of 1km operating at 12 GHz and with a coarse accuracy of 1 dB is  $22 \text{ mm}\cdot\text{h}^{-1}$ ; rainfall below this  
314 threshold cannot be measured with such a link. For the highest end of the rainfall spectra (and specially  
315 for intense convective rainfall as in Africa) the relative error due to PIA is low (Leijnse et al. 2008a).

316 In order to analyze the impact of PIA precision on rainfall and subsequently discharge simulation,  
317 synthetic CML networks with precision 1 or 0.1 dB, and a range of frequency and length are simulated.

#### 318 1) NUMERICAL EXPERIMENT

319 For this experiment the links' center position and their orientation are those provided by the operator  
320 meta-data in Ouagadougou for the 75 links shown in Figure 1 but the links' length, operating frequency,  
321 and the PIA precision can be changed. Three link lengths: 1, 5 and 10 km; five frequencies: 6, 12, 18,  
322 24 and 30 GHz; and two rounding errors on the PIA: 0.1 and 1 dB, are considered. For each experiment  
323 the network is homogenous (same length, frequency and precision for all links).

324 The values of  $a$  and  $b$  used to simulate the PIA and the estimated rainfall at each link are those  
325 from Table 1. The only source of uncertainty in the simulation is the rounding error of the PIA.

#### 326 2) ANALYSIS OF THE ERRORS IN RAINFALL ESTIMATION

327 #####. **Fig 4 around here**

328 Figure 4 illustrates the error in the frequency distribution of the rainfall rates due to the rounding error,  
329 for links of size 1 km and the indicated frequencies. The calculation is done considering all three rainfall  
330 events. The curves in Fig.4 show the mean rainfall accumulation per link and per event, as a function



331 of the rain intensity class. The blue line is for a link with perfect precision (where the retrieved rainfall  
332 is exactly the mean link rainfall as in Eq.5), the other curves show the degradation as function of  
333 precision (0.1 or 1 dB) for the various frequencies. Figure 4 is consistent with the numbers displayed  
334 in Table1. A 1 km long link operating at 6 GHz would miss a substantial amount of rainfall, because an  
335 intensity above 26 mm/h is needed to create a 0.1 dB shift in attenuation, and 150 mm/h to create a  
336 1 dB shift. Fortunately, short links (common in urban areas) usually operate at higher frequency, and  
337 a 10 km long 6 GHz link would have better detection (cf Table 1). As expected from Table 1, the  
338 distribution of rain intensity is better reproduced for higher frequencies and for all frequencies the  
339 errors are relatively lower for higher rain rates. This last point is important when considering the  
340 impact of the highest rain rates on floods. For 1 dB precision the overall bias on the mean event rainfall  
341 is small (about 10 %) from frequency 24 GHz and above. For a precision of 0.1 dB all the frequencies  
342 from 12 GHz and above provide a good reproduction of the rain rates, with biases below 5 %. The  
343 rendering would be better for longer links (and worse for shorter links) following Eq. (4).

344 It is worth stressing again that our simulations do not account for the wet antenna effect. Antenna  
345 wetting would typically increase the measured PIA by about 1dB (this is indicative; the range of values  
346 reported in the literature and by engineers is wide), with a risk of overestimating rainfall and creating  
347 false alarms. The existence of this positive bias can in practice counterbalance (compensating errors)  
348 some of the negative bias due to missing low rain rates with a coarse precision. Other effects such as  
349 the non-linearity of the attenuation-rainfall relationship (as discussed in section 2) tend to add a  
350 positive bias for long links (above 5 km) and frequency below 15 GHz if they are not accounted for in  
351 the retrieval. The strength of this effect depends on the variability of rainfall at small scale. According  
352 to our tests (based on the present radar data, not shown) the resulting impact of non-linearity is  
353 negligible compared to 1 dB rounding error.

354

355 3) PROPAGATION OF THE ERRORS INTO THE SIMULATED DISCHARGE

356 #####. Fig 5 around here

357 Figure 5 displays the discharge simulated by the model at the outlets 1060 and 1074 (Fig. 1), for the  
358 2012/08/04 event. The black line is the reference simulation based on the high-resolution radar map.  
359 The dark blue line is the simulation based on the CML (1 km length and position as in Fig. 1) with perfect  
360 precision (no error on the rainfall retrieval over the link), and the other colors display the tests with  
361 precision 0.1dB (left) or 1 dB (right), and frequencies 6,12,18,24 and 30 GHz as in Fig. 4. The difference  
362 between the reference (black) and the links with no error (dark blue) reflects solely the impact of  
363 rainfall sampling. This will be discussed further in the next section. The difference between the various  
364 colors and the dark blue line is related to the signal precision and its impact on rainfall estimation over  
365 the basin. Fig. 5 confirms what was seen in Fig. 4, rain rates below a given threshold are undetected if  
366 the precision is coarse, especially for the lower frequencies. With a precision of 0.1 dB -except for the  
367 unlikely case of 1 km/6GHz link- the discharge is well reproduced; a coarse precision of 1 dB has a  
368 negative impact on the simulated discharge, especially for frequencies below 24 GHz.

369 The results are generalized in Figure 6 for all 3 events and several numerical experiments: 5  
370 frequencies; 2 precision levels and 3 link lengths (1, 5 and 10 km). The time series of the discharge  
371 simulated at outlets 1060 and 1074 for each network configuration is compared with the discharge  
372 simulated with the high-resolution radar maps. The average over the three events of the following  
373 statistics are displayed as a function of frequency/length/precision : the mean bias on the discharge,  
374 the relative error on the peak discharge and Kling–Gupta efficiency (KGE; Gupta et al. 2009).

375 Because of the high value of the coefficient  $a$  (Eq. 4; Table 1) the frequency 30 GHz is mostly immune  
376 to a lack of precision up to 1 dB, even for the shortest link length considered here, 1 km. For this  
377 frequency all 3 scores are good. For frequencies in the range 12-24 GHz which is very common in  
378 current mobile networks in urban areas, a precision better than 1 dB is needed to reproduce rainfall  
379 and discharge satisfactorily. For short links (1 km) with coarse precision (1 dB) in this range, the loss of  
380 small to medium rain rates means an underestimation of the discharge and its dynamic (also seen in

381 Figure 5), impacting all 3 scores. For lower frequencies (6 GHz) a lot of rainfall is undetected leading to  
382 a strong underestimation of the discharge, its peak and its dynamic, unless the precision is 0.1 dB or  
383 better, and the length above 5 km.

384 The horizontal lines in Figure 5 show the scores for the links with perfect precision, considering the  
385 retrieved rainfall is exactly the weighted average over the radar pixels (Eq. 5). In that case the  
386 difference with the reference simulation is due to the difference in spatial sampling. We note that this  
387 difference is higher for outlet 1060 than for outlet 1074; this is explained by the position of the links  
388 inside the basin as seen in Fig 1. The network is more homogeneous and denser for the southeastern  
389 basin (outlet 1074), though not perfect, while rainfall in the eastern part of the northern basin (outlet  
390 1060) is poorly sampled. For the latter the mean and peak discharge are underestimated. The results  
391 are also impacted by the length of the links as expected given the spatial variability of the rain field  
392 within squall lines (Fig. 2 and 3). The next section analyses further the question of the network spatial  
393 layout and its capacity to capture rainfall characteristics within the basin.

394 #####. Fig 6 around here

395

#### 396 *b. Impact of network spatial layout*

397 The network overall geometry, which includes the length, the position and the orientation of the links,  
398 determines its ability to capture and quantify rainfall variability inside the basin. As discussed with  
399 Figures 2 and 3, the convective systems that bring rainfall in West Africa exhibit high space-time  
400 variability.

401 This section investigates the impact of the network geometry on rainfall QPE (quantitative  
402 precipitation estimate) over the basin, then on the simulated discharge. This is based on several  
403 numerical experiments, either with varying length, density, and random positions and orientations of  
404 the links inside the basins or using the actual network of 75 links (Fig1).

405 1) NUMERICAL EXPERIMENT

406 The effect of the network geometry is investigated for 3 sub-basins of size 74 to 193 km<sup>2</sup> with outlets  
407 marked Ri1, Ri3 and Sa1 in Figure 1. The number of links per basin (i.e. a link which center is inside the  
408 basin)  $N$  varies from 1 to 100. For each value of  $N$ , 10 experiments with random positions and  
409 orientations of the links are generated. For each of these link positions and orientations, 3 lengths (1,  
410 5 and 10 km) are considered as in section 4. Altogether 410 synthetic network configurations are  
411 simulated for each 3 sub-basins. For each, the 3 rainfall events are sampled with the link simulator  
412 (3.c). In these experiments only the network geometry is investigated, no error is considered in the  
413 estimation of the mean rainfall intensity over each link, which is simply calculated as in Eq (5).

414 2) RAINFALL ESTIMATION AND VARIABILITY WITHIN THE BASIN

415 #####. Fig 7 around here

416 Figure 7 illustrates the spatial variability of rainfall as captured by the link network. The rainfall time  
417 series is from the 2012/08/04 event (Fig. 2 and 3). The seventy-five links positions of Figure 1 are used,  
418 but a heterogenous network of length 1 km (top) or 10 km (bottom) is simulated. At every 5 minutes  
419 time step there is a subsequent spread among the links. The spread is slightly reduced for the 10 km  
420 long links because of a spatial smoothing effect.

421 #####. Fig 8 around here

422 Figure 8 summarizes the ability of different network configurations to quantify the time evolution of  
423 the mean area rainfall, and the spatial variability inside a basin. This example is for the 2012/08/04  
424 event and the sub-basin Ri3 (Fig.1). Four configurations are considered: 1 km (left) or 10 km (right)  
425 long links; 1 (green) or 10 (red) links. For each configuration ten realizations were done, with random  
426 positioning of the links (center position and orientation). The black line is for the high-resolution radar  
427 map. The extension of the vertical green/red lines in Figure 8 illustrates the uncertainty due to the  
428 random positioning of the links to sample a highly variable rain field, consistent with Fig.7. The

429 uncertainty on the areal mean rain intensity (top plots) is very high when only one link is available per  
430 basin (green), and much reduced for ten links (red). For the same number and position of links, the  
431 estimation of the areal mean is more robust with the 10 km than with the 1 km links, as the former  
432 provide a 'natural averaging' of the rain field. Rainfall variability inside the basin is important for the  
433 hydrological response. The bottom plots of Figure 8 display the time evolution of the standard  
434 deviation (*std*) of rainfall within the sub-basin. The *std* is calculated at each five minutes time steps,  
435 among ten links (red) or among the radar pixels (black). As for the mean areal rainfall, random sampling  
436 of a variable field creates an uncertainty in the estimation, as illustrated by the red spread. Over ten  
437 realizations, the estimate of the *std* is un-biased for the 1 km long links and underestimated for the 10  
438 km long links. Figure 8 is only illustrative, the quantitative impact of the link density and size within a  
439 given basin and rainfall event varies according to the rain field structure and the basin hydrological  
440 response.

441

### 442 3) SIMULATED DISCHARGE

443 #####. Fig 9 around here

444 Figure 9 illustrates the uncertainty in the simulated discharge due to the imperfect sampling of rainfall  
445 variability inside the basin. The simulated discharge is analyzed at Ri3; the tested network  
446 configurations are the same as for Figure 8a/c: ten realizations (various colors) of a network with ten  
447 links of length 1 km. The spread within the ten realizations is larger for the simulated discharge (Fig. 9)  
448 than for the mean rainfall (Fig 8a). For several random positions of the links the peak discharge is  
449 overestimated by a factor close to two; while for one of the simulations (set 1), the peak is  
450 underestimated by a factor 3 and not in phase. The enhanced sensitivity of the discharge simulation  
451 to the position of the links is explained by the impact of rainfall variability within the basin on the  
452 hydrological response. The reproduction of discharge sensitivity to the rainfall pattern is model-

453 dependent. The sensitivity is enhanced by the non-linearity of the model equations (SCS formula) and  
454 well perceived with a high-resolution distributed model like ATHYS.

455

456 #####. Fig 10 around here

457 Figure 10 synthesizes the results for all the experiments with the randomly positioned network ( 3 link  
458 lengths x 10 realizations x 3 events X 3 sub-basins; Fig 10a, b) and with the actual network of 75 links  
459 (Fig 10c); for the latter, tests were made keeping all links, or only links up to 5 km length, or only links  
460 longer than 5 km. In order to summarize the total length of links inside the basin for each  
461 configuration a link density [ $\text{km}/\text{km}^2$ ] equal to the sum of the link lengths divided by the sub-basin  
462 area, is introduced. The KGE of the simulated discharge compared to the reference simulation is  
463 plotted against the link density. The numerical experiments with different link lengths are plotted in  
464 color (1 km, blue; 5 km green; 10 km, red). Figures 10a and b, based on the randomly distributed  
465 network, show that the quality of the hydrological simulations increases sharply with the density of  
466 information provided by the links. From about  $0.5 \text{ km}/\text{km}^2$  (i.e. for instance, ten 5 km links in a basin  
467 of  $100 \text{ km}^2$ ) all simulations have a positive KGE. The increase in the simulation quality is sharper and  
468 the KGE for a given density higher for short links, as the rain field structure is better sampled with  
469 several small links than a single long one. For instance, the mean KGE is above 0.5 for a density  
470 equivalent to ten 1 km link per  $100 \text{ km}^2$  (density, 0.1), but five 5 km or two 10 km length  $100 \text{ km}^2$   
471 (density 0.25) are needed for the same scores. Fig. 10c provides a similar analysis for the real network  
472 configuration of 75 links seen in Fig. 1, with their lengths ranging from 0.3 to 26 km. As for the top  
473 figures the rainfall at each link is the weighted average (Eq. 5), no estimation error is considered. In  
474 order to compare the relative impacts of the shortest and longest links, the results are also presented,  
475 when only the 18 links longer than 5 km or on the contrary the 57 links shorter than 5 km, are kept.  
476 For link linear density below  $0.5 \text{ (km}/\text{km}^2)$  the spread for a given basin and network configuration  
477 (same shape and color) illustrates the variability of the rainfall structure among the 3 rain events. For

478 a given linear density (in km/km<sup>2</sup>), event and basin there is no significant difference between the tests  
479 where we kept only the smallest (below 5km) or on the contrary the longest (above 5km) links. It is  
480 noteworthy that because of the Thiessen interpolation method, a link which is partially or entirely  
481 outside a sub-basin may or not contribute to the rain estimation for this basin and a given  
482 configuration, depending on the other links available. The differences between events and the impact  
483 of the configuration is marked for outlet Ri3 which is mostly rural and poorly sampled by the real  
484 network.

485 Figure 10 is illustrative. More case studies would be needed to account for the complexity of the  
486 problem and all the parameters to be considered like the orientation of the links compared to the  
487 anisotropy of the rain field, the spatial decorrelation of the rain field, the size and shape of the basin  
488 etc. Figure 10 and the other figures in this section tend to show that a dense (in km/km<sup>2</sup>) network of  
489 short links, if they are evenly spread inside the basin (not clustered), is more suited for hydrology than  
490 the same linear density of longer links, because it samples better rainfall variability inside the basin. As  
491 noted in section 3c the rain information is spatialized in ATHYS by considering each rainfall estimate as  
492 a punctual value at the center of the link and using Thiessen interpolation. Other interpolation  
493 methods (Zinevich et al. 2008, 2009) could be used to exploit the spatial information provided by the  
494 links and account for their length and orientation. This a field of research on its own. Capturing the  
495 spatial variability of rainfall is however only one aspect of the problem.

496 *c. Discharge spatial distribution*

497 **#####. Fig 11 and Fig 12**

498 Figures 11 and 12 illustrate the spatial variability of rainfall and of the simulated discharge quality.  
499 Figure 11 show the rainfall accumulation for the 2012/08/04 event as seen by the high-resolution radar  
500 map. A strong gradient is seen from North to South, and in several locations inside the city the rainfall  
501 accumulation is high, with the maximum value over the domain at 70 mm and a minimum at 7 mm.  
502 This is consistent with the strong variability observed at 5 minutes time steps in Figures 2 and 3. As

503 discussed previously, the CML network captures only partially this intense rainfall variability. Figure 12  
504 analyses the ability of the model, forced by the CML network to represent the spatial variability of the  
505 discharge. The experiment is with the original network as seen in Figure 1, with all links operating at  
506 13 GHz. The top left map is for precision 1 dB and the top right precision 0.1 dB. The values of the KGE  
507 of the simulated discharge compared to the reference (simulation with high resolution radar map) are  
508 mapped in different points within the basin. The simulation for a 0.1 dB precision is improved, but the  
509 simulation with 1dB is already satisfactory, with the KGE for most points within the basin above 0.4.  
510 To put the performance of the CML based simulations in perspective compared to other types of  
511 rainfall measurement, the bottom figures display the results for two extra experiments: for Fig 12c the  
512 sampling of a satellite rainfall product was emulated by averaging the high resolution radar rain maps  
513 over the whole domain (about 1000 km<sup>2</sup>) – no error on the satellite estimation is considered which is  
514 a strong idealization; for Figure 12d the rainfall series used to force the hydrological model comes from  
515 the central pixel (white star) emulating what a single rain gauge situated in the city center would see.  
516 In most of the basin the simulations based on the CML sampling represent much better the discharge  
517 and its variability than the simulations based on a single source of information (spatial average or single  
518 gauge). This good results in the urban part of the basin are consistent with previous findings. Fencl et  
519 al. (2013, 2015) also found that the density of the network at urban scale is beneficial to reproduce  
520 the hydrological dynamics. They also notice that the links, especially when short, may introduce bias  
521 in the rainfall and recommend using both gauge and link information (Fencl et al. 2017; Smiatek et al.  
522 2017). Similar conclusions were drawn by Pastorek et al. (2019) and Stransky et al. (2018). Only at the  
523 very East end of the basin, where only two long links are available, the simulation based on the central  
524 pixel or the average perform slightly better than the CML. The benefit of the CML sampling for  
525 distributed hydrological modeling, even when a coarse precision is considered in the raw signal, is  
526 clearly striking in Fig. 12. The results are very similar for the 2 other rainfall events. Table 2 summarizes  
527 the results of these experiments for the three events. The statistical scores for the discharge at two  
528 main basins outlets (1060 and 1074) are reported. The error on the mean and on the maximum



529 discharge are much lower for the links, even with coarse precision, than for the single pixel or spatial  
530 mean forcing. The benefit of the CML ability to capture rainfall is also marked on the KGE, confirming  
531 the importance of the spatial information on rainfall to reproduce the discharge dynamics. For both  
532 sub-basins the linear link density (defined in 5b) is above 0.4 km/km<sup>2</sup> and KGE above 0.7, even with  
533 coarse precision. The results are even better for outlet 1074, with KGE above 0.9 whatever the  
534 precision, because the network covers this basin more homogeneously.

535 **### Table 2 around here ###**

536

## 537 **6. Conclusion**

538 This work investigates the potential benefits of CMLs rainfall estimation for urban hydrology in West  
539 Africa. One expected benefit of CMLs for hydrological application is the density of the network,  
540 especially in urban, thus populated, areas; on the other hand, as for any indirect measurement, rainfall  
541 estimation from CMLs is subject to uncertainties. A pending question for the development of CMLs  
542 based hydrological applications is: what is the final balance between the benefits and drawbacks of  
543 CMLs rain measurements, and how basin dependent and network dependent are they.

544 A simulation setup based on high resolution radar rain maps and a distributed hydrological model was  
545 used for a case study over the city of Ouagadougou. The radar is a research radar that operated in  
546 Burkina Faso as part of a satellite validation program in 2012 and 2013. The distributed model (ATHYS)  
547 was developed and calibrated for Ouagadougou area in the framework of an urban flood prediction  
548 project. Here the radar rain maps were used as a reference rainfall, as forcing to the hydrological model  
549 and for generating synthetic CML measurements which can in turn be used as model input. This setup  
550 was used to analyze the ability of the microwave link network to i) quantify rainfall over the urban  
551 basins, ii) to capture rainfall space and time variability. In this work we primarily focused on two  
552 characteristics of the CMLs network that influence rainfall estimates: i) the accuracy of the raw

553 information (digitizing step) provided by the operator and ii) the network configuration that includes  
554 the position and orientation, length and operating frequency of the links.

555 For the majority of numerical experiments, the discharge simulated with the synthetic links data as  
556 entry is close to the reference based on the high-resolution radar map. The performance is reduced  
557 when the raw data from the operator is provided with a coarse precision (1dB), especially if the  
558 frequency is low (below 10 GHz) and for short links, because the lower rain rates are undetected. The  
559 trend in mobile communication networks is for the operating frequencies to increase in order to match  
560 the operational needs (need for increase bandwidth in particular), this will help the detection of rainfall  
561 from CMLs. Higher operating frequencies are also expected in the perspective of the next generation  
562 networks (5G). As the networks modernize the built in monitoring software are also improved and  
563 accessing to the data with a good sampling rate (15 minutes or less) and fine precision (0.1 dB)  
564 becomes common (personal communications from Orange and Nokia engineers). The number of links  
565 inside the basin is important. To quantify this effect, numerical experiments with an increasing number  
566 of links randomly distributed within the sub-basins were performed. The performance in terms of  
567 discharge dynamics (KGE criteria), mean bias and error on the maximum discharge increases quickly  
568 with the network density -expressed in total length of link in km per km<sup>2</sup> of basin- and especially with  
569 the number of short (1 km) links. For the present simulations satisfactory results (KGE close to or above  
570 0.5) are obtained from a density of 0.1 km/km<sup>2</sup> for 1 km long links (i.e. 10 links inside a 100 km<sup>2</sup> basin)  
571 and 0.3 km/km<sup>2</sup> (3 links of size 10 km for 100 km<sup>2</sup>). When the positions of a real network are used,  
572 with a total of seventy-five links of various lengths for the Ouagadougou area (1000 km<sup>2</sup>) the  
573 simulations with the CML sampling are very close to the reference (KGE above 0.5) for most of the  
574 basin. The CML sampling, even when a coarse precision is considered, outperforms the simulation  
575 based on idealized satellite pixel or a single gauge situated in the city center.

576 These good results are partly explained by the nature of rainfall systems in the study region. Rainfall  
577 in West Africa (and in most of the Tropics) is provided by deep convection, where most of the rain

578 accumulation is associated with intense rain rates. These intense rain rates create a strong micro-wave  
579 attenuation which is well detected by the CML network, whatever the length and frequency. The  
580 present work and previous studies show indeed that the relative error on rainfall estimation from CML  
581 decreases with rainfall intensity (Leijnse et al. 2008a,b). The spatial organization and dynamics of the  
582 convective cells influence the space-time structure of the rain fields. The relevant observational scales  
583 to capture these structures are kilometric and sub-hourly, which is compatible with the current CML  
584 networks in populated areas.

585 This positive outcome encourages to continue promoting CMLs as a source of information on rainfall  
586 quantities and space-time distribution in urban basins, especially in tropical regions where weather  
587 radar is not yet routinely available.

588 The presented simulation setup could be used for further sensitivity studies and for accounting for  
589 other sources of uncertainties that were not explicitly considered here (wet antenna; error in the  
590 baseline determination; uncertainty in the attenuation-rain rate relationship etc.). Here only the errors  
591 brought in by the difference in the rain forcing were considered, by comparing the output to a  
592 reference simulation based on a high-resolution radar map and a given setup of the hydrological  
593 model. The radar data is used as a realistic proxy of rain fields for simulations purposes. In reality radar  
594 estimation of rainfall is subject to many uncertainties, described at length in the literature (Berne and  
595 Krajewski 2013; Cecinati et al. 2017). The hydrological brings in its own uncertainties in the discharge  
596 prediction system (Beven and Binley 1992; Ajami et al. 2007). They come from the simplistic  
597 representation of hydrological processes, the equifinality problem in the optimization of parameters  
598 and other factors such as the interpolation of the rain information inside the model. These were  
599 beyond the scope of this paper but are being investigated.

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613 and Orange.

## 614 **Data Availability Statement**

615 The data used for this study is openly available – A specific repository will be created when  
616 the paper is accepted.

617 ATHYS code is freely available here: <http://www.athys-soft.org>.

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859 [2016-540](https://doi.org/10.5194/hess-2016-540).

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867 **Tables**

868

Frequency (GHz)		6	12	18	24	30
(a ; b)		(0.00145 ; 1.29)	(0.0268 ; 1.17)	(0.0818 ; 1.06)	(0.143 ; 1.03)	(0.226 ; 0.997)
Rainfall	1dB/1km	157	22.1	10.6	6.57	4.447
equivalent	0.1dB/1km	26.4	3.08	1.21	0.705	0.442
PIA/L	1dB/10km	4.46	0.430	0.137	<i>0.0756</i>	<i>0.0439</i>
(mm/h)	0.1dB/10km					

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871 Table 1:

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873 Minimum detectable rainfall ( $\text{mm}\cdot\text{h}^{-1}$ ) as a function of frequency, signal precision and link  
874 length.

875 The second row reports the values of the prefactor ( $a$ ) and exponent ( $b$ ) of the attenuation-  
876 rainfall or k-R relationship (see text) for the indicated frequencies. The three last rows illustrate  
877 the equivalent in rain rate [ $\text{mm}/\text{h}$ ], of an increment in the measured attenuation (0.1 or 1 dB)  
878 for the indicated link length (1 km, 10 km) and frequency. The *italic* highlights  
879 frequency/length combinations which are not likely on operational networks (short link and low  
880 frequency ; long link at high frequency).

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	Bias abs (%)		Err max abs (%)		KGE	
	1060	1074	1060	1074	1060	1074
Radar						
mean	37.6	47.6	60.1	50.8	0.19	0.60
One pixel	26.7	75.4	55.0	83.6	0.24	0.71
Perfect	8.80	7.07	17.1	7.27	0.77	0.90
0.1 dB	8.83	6.23	17.9	7.04	0.76	0.91
1 dB	12.0	4.43	23.8	8.68	0.71	0.91

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889 Table 2 :

890 Statistics on the simulated discharge for different rainfall sampling experiments compared to  
891 the reference simulation (based on the high-resolution rain map). The following statistics are  
892 reported for the two main outlets (1060 and 1074, see text) : the absolute error on the event  
893 mean discharge (in %) ; the absolute error on the event maximum discharge (in %) ; the KGE.  
894 For each statistics the mean over the 3 events is reported. The scores are reported for the  
895 following rainfall forcing as described in section 5c: spatial mean of radar rainfall ; rainfall at  
896 central pixel ; rainfall from the 75 links at 13 Ghz network (Fig. 1) with perfect precision,  
897 precision 0.1 dB or precision 1 dB.

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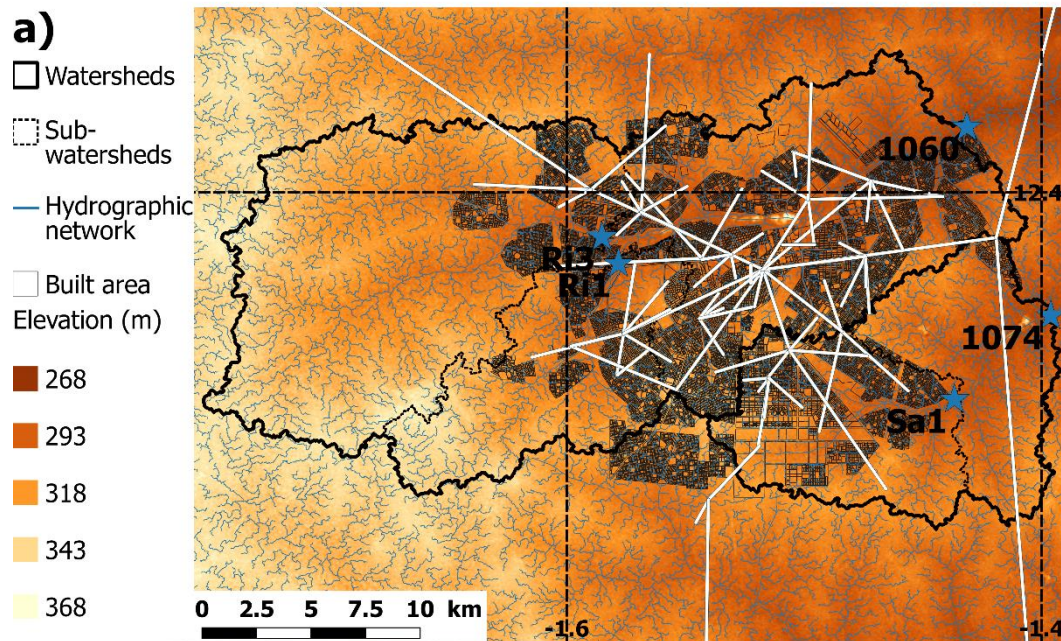
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## 902 Figures

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906 Figure 1 : The study area in Ouagadougou. The gray shading is the urbanized (built) area ; the  
907 blue lines represent the hydrographic network and the black lines the contours of the studied  
908 basins and sub-basins ; the blue stars are the outlets where the simulated discharge is analyzed  
909 for the various numerical experiments detailed in the text. The white lines are the positions of  
910 the 75 microwave-links (13 GHz) available for one of the operational mobile networks.

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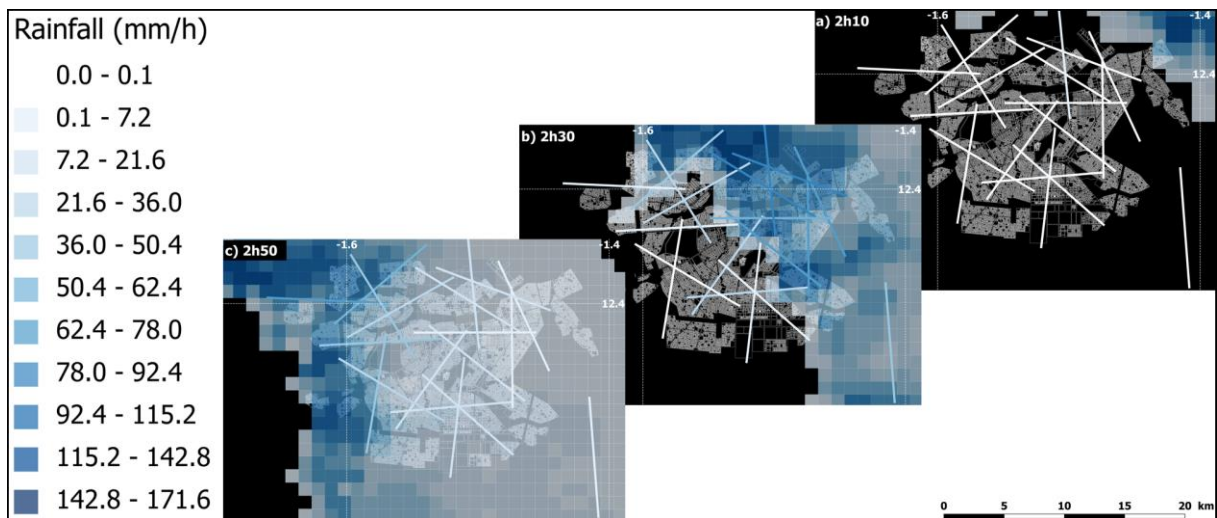
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920 Fig 2 :

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922 Figure 2 : Evolution of rain intensity maps over the area on the 2012/08/04 event as seen by the  
923 radar and the simulated links. The three images show the radar rain maps crossing the study  
924 domain at three moments in time a) 02:10 UTC. b) 02:30 UTC and c) 02:50 UTC; the color  
925 shading over the 1kmx1km pixels show the rainfall intensity as indicated by the legend. The  
926 nineteen straight lines superimposed on each image represent the simulated microwave links  
927 and their color indicates the mean rainfall over the link, as calculated by the link simulator (see  
928 text and Eq 5.).

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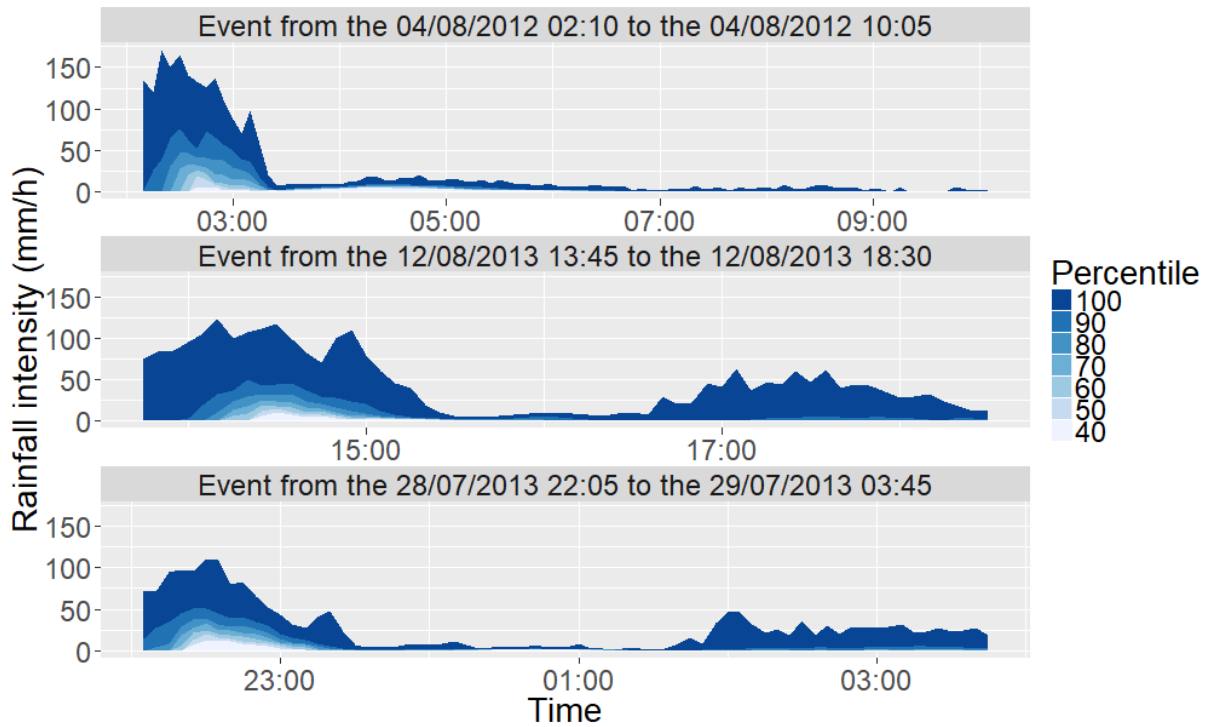
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940 Figure 3: Time evolution of radar rainfall over the studied area (from Fig. 1) for the three

941 indicated rainfall events. For each five minutes time step the distribution of the rainfall rates

942 among the 1060 radar pixels is illustrated by the percentiles.

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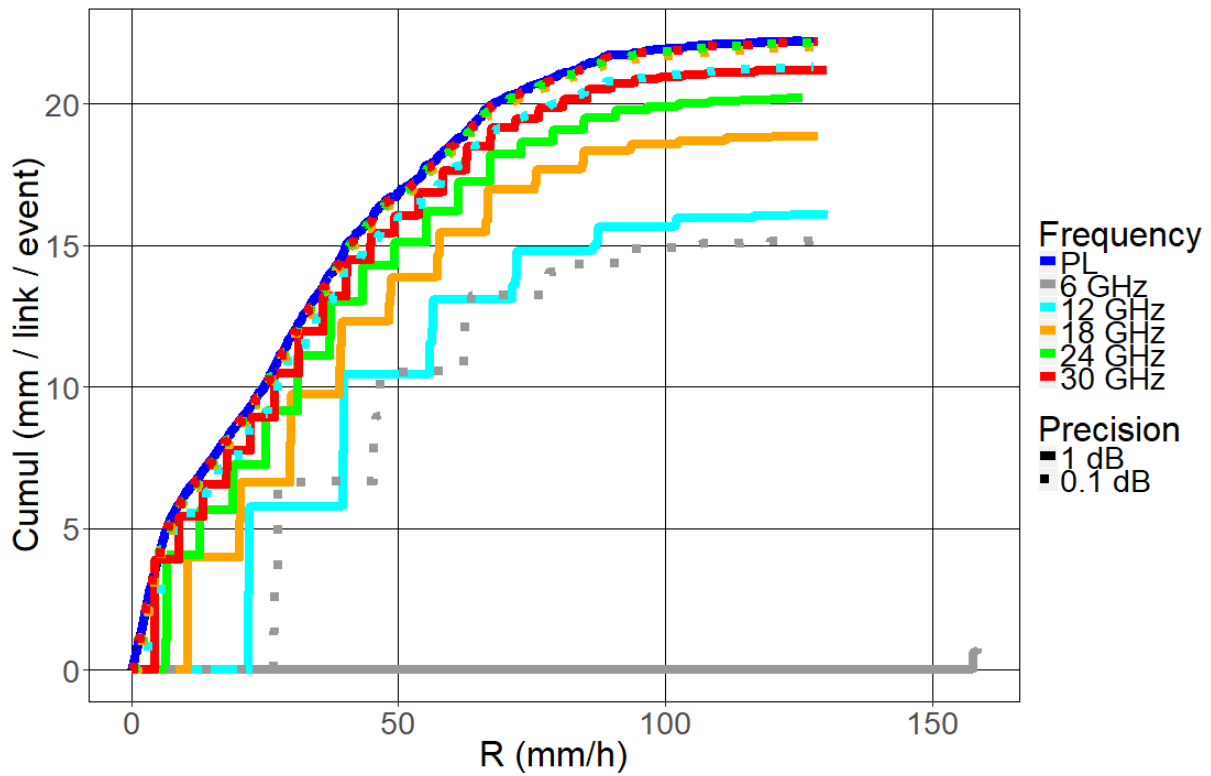
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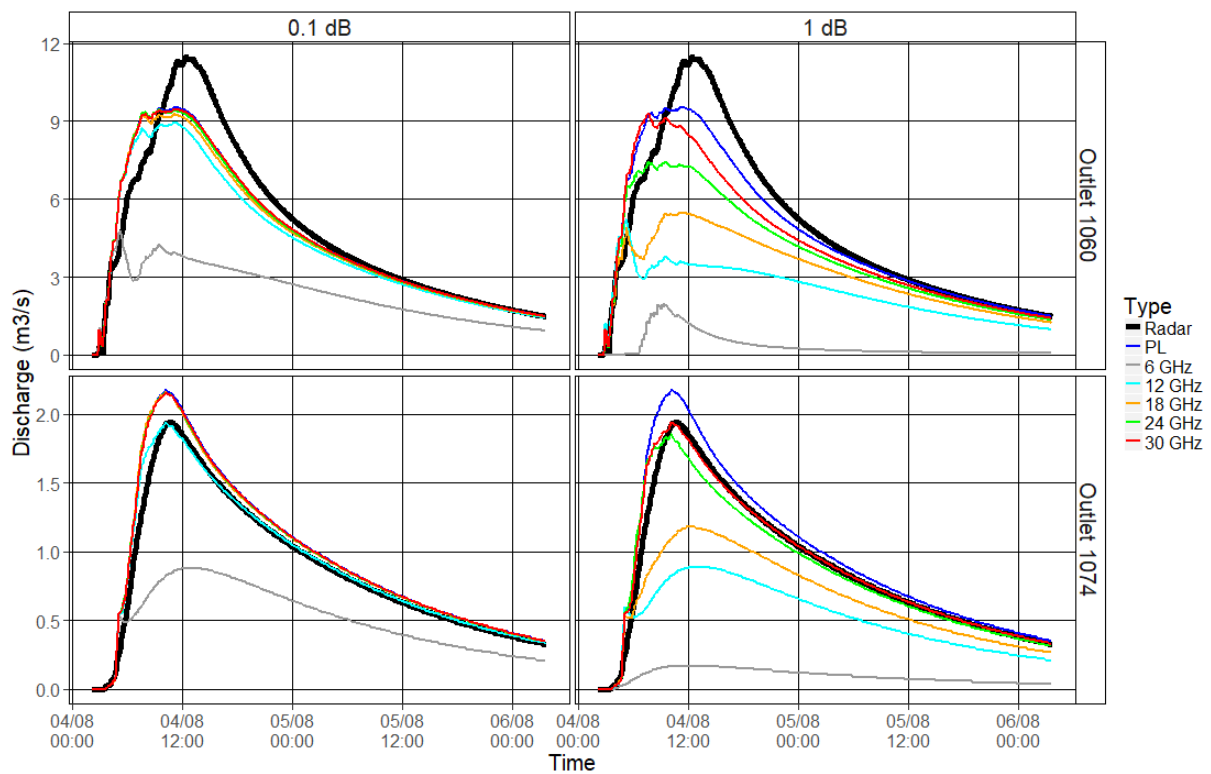


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Figure 4: Cumulated rainfall distribution per rain rate classes as a function of link frequency and attenuation precision – here for links of length 1 km. The Y axis is the mean amount of rainfall per link and event (see text) and the X axis the intensity classes. The dark blue line is for a link with perfect precision; for the others the color indicates the frequency (GHz), the plain lines are for precision 1dB and the dash line for precision 0.1 dB.



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968 Figure 5: Effect of raw signal precision for different frequencies on the simulated discharge for  
 969 the 2020/08/04 event (top row in Fig. 3). The top figures are for outlet 1060 and the bottom  
 970 figures for outlet 1074. The left column is for precision 0.1 dB and the right column for 1 dB.  
 971 As for Figure 4 the length is 1 km for all links and their frequency is indicated by the color. The  
 972 dark blue line is for links with perfect precision and the black line is for the reference simulation  
 973 based on the high-resolution radar map.

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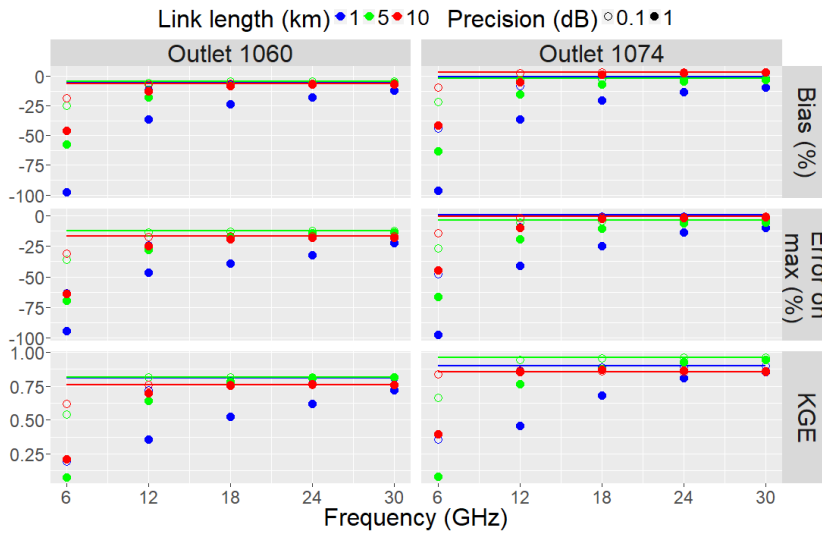
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983 Figure 6: Effect of signal precision, link length and frequency on the simulated discharge. The  
984 simulated discharge when the model is forced by microwave links (with positions as in Fig. 1)  
985 is compared with the reference simulation based on the radar maps. Three criteria are presented:  
986 the mean bias on the event's discharge, the error on the maximum discharge and the KGE. For  
987 each criteria the average value for the 3 events is plotted. The left column is for outlet 1060 and  
988 the right column for outlet 1074. The results are shown as a function frequency (X axis) ; link  
989 length (blue for 1 km, green for 5, and red for 10 km) ; signal precision (hollow circles for 0.1  
990 dB and plain dots for 1 dB). The results for the links with perfect precision are shown by the  
991 horizontal lines.

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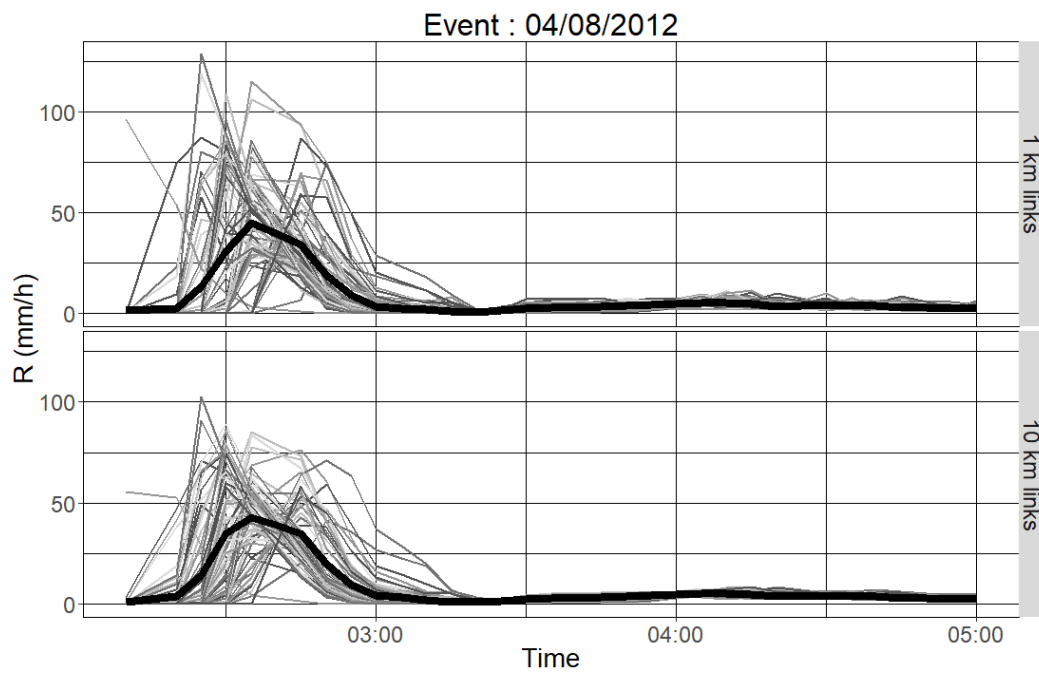
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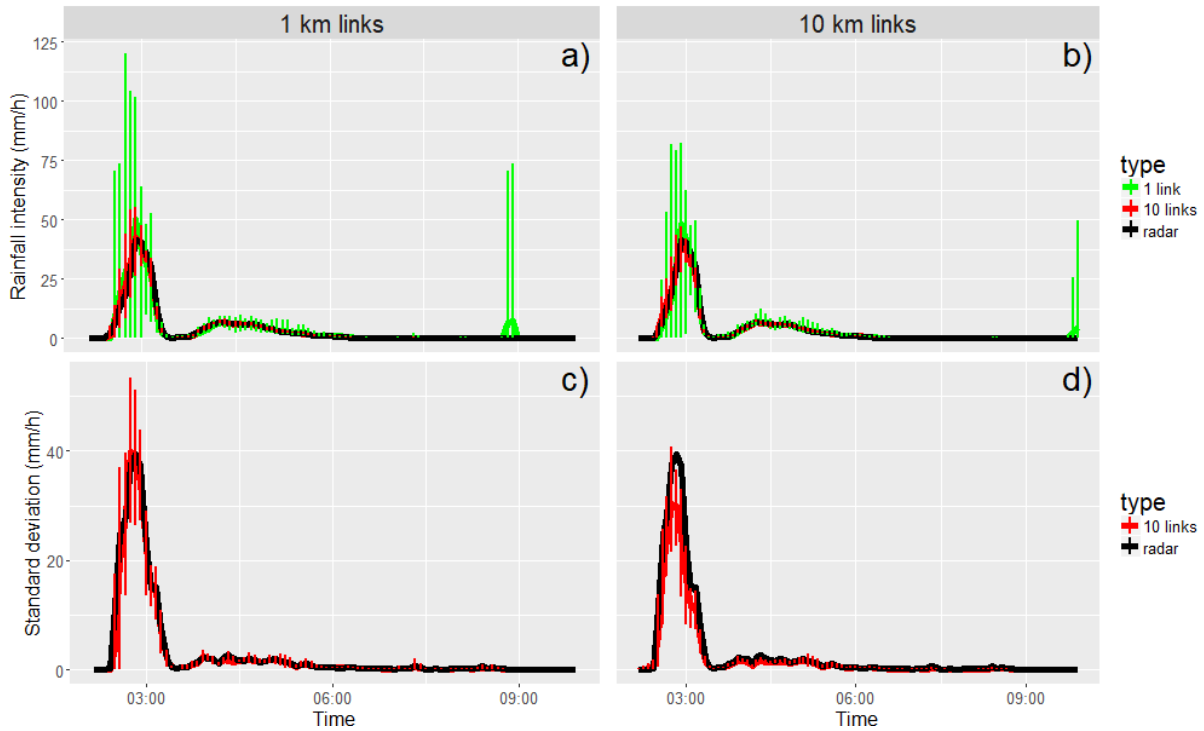
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1004 Fig 7: Illustration of the spread within the rainfall time series among all 75 links (center position  
1005 and orientation as in Fig. 1) for links of length 1 km (top) or 10 km (bottom) for the 2012/08/04  
1006 event. The average rainfall over all links by 5 minutes time steps is the thick black line.

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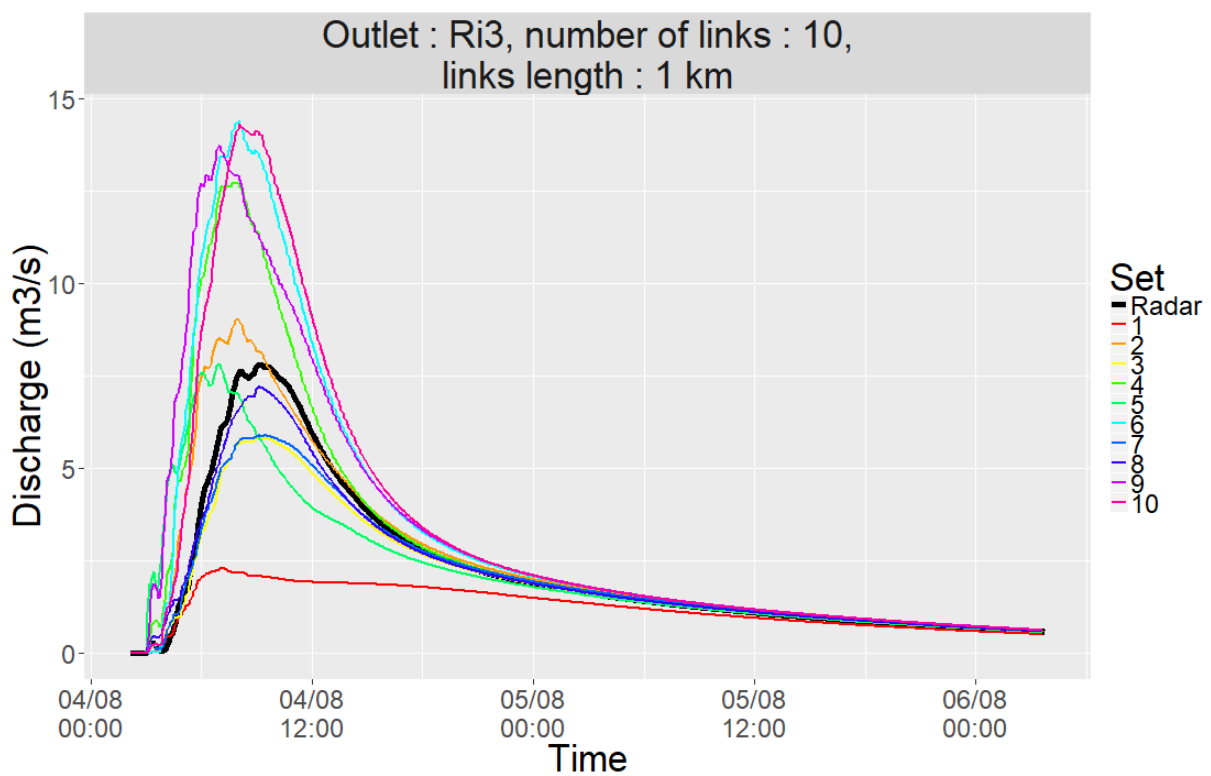
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1014 Figure 8: Rainfall variability between realizations and among simulated links, illustrated for  
1015 2012/08/04 event over the sub-basin Ri3. The top plots show the time evolution of the sub-  
1016 basin average rain rate for links of size 1 km (a) or 10 km (b), in green for a network of one link  
1017 and in red for a network of ten links. The links are assumed to have perfect precision. The  
1018 vertical lines illustrate the spread (from minimum to maximum) among ten realizations of  
1019 network simulations. The black line shows the sub-basin mean rainfall calculated from the  
1020 reference radar rain field. The bottom figures show the time evolution of the standard deviation  
1021 of rain rate inside the basin as captured by 10 links (red) of length 1 km (c) or 10 km(d) and by  
1022 the radar (black). The vertical red lines illustrate the spread in the standard deviation (from  
1023 minimum to maximum) among the ten realizations.

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Figure 9

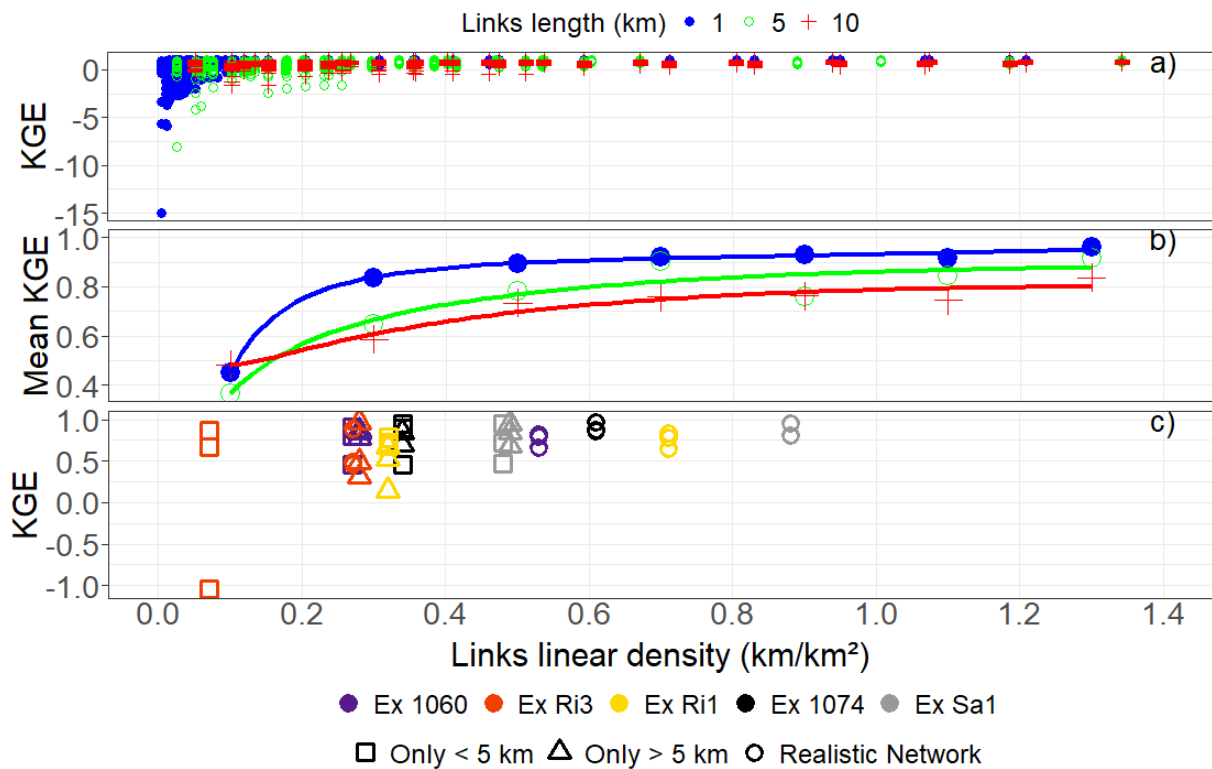


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Figure 9: Simulated discharge over the Ri3 sub-basin outlet for the 2012 August 04 rainfall event, here for a simulated network of 10 links of length 1 km. The outputs for 10 realizations are displayed with different colors together with the reference simulation (black) using the radar map.

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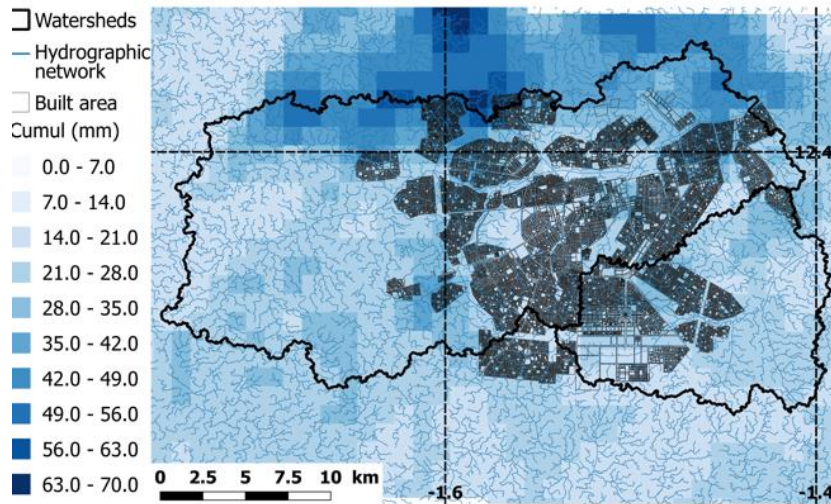
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1045 Figure 10 : Summary of the effect of rainfall sampling by the link network considering all  
1046 numerical experiments : a) and b) experiments with the randomly generated network, 3 link  
1047 lengths (blue dots, 1km; green circles, 5 km; red crosses, 10 km) x 10 realizations x 3 events X  
1048 3 sub-basins. a) KGE for the simulated discharge compared to the reference (radar based) is  
1049 shown as a point for each experiment. The X axis expresses the density of information as the  
1050 cumulated length of all links inside the sub-basin (in km) per sub-basin area (in km<sup>2</sup>). b) mean  
1051 KGE per link density (average by bins of 0.2km/km<sup>2</sup> width). The fit on b) is only there for  
1052 readability. c) KGE of the simulated discharge in the indicated outlets compared to the  
1053 reference, for the simulations based on the actual network configuration (Fig 1), keeping the

1054 whole network (circles), keeping only links of length 5 km and below (triangles) , and keeping  
1055 only links longer than 5 km .  
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1058 Figure 11 : rainfall accumulation map over the area for the 2012/08/04 event, as measured by  
 1059 the radar.

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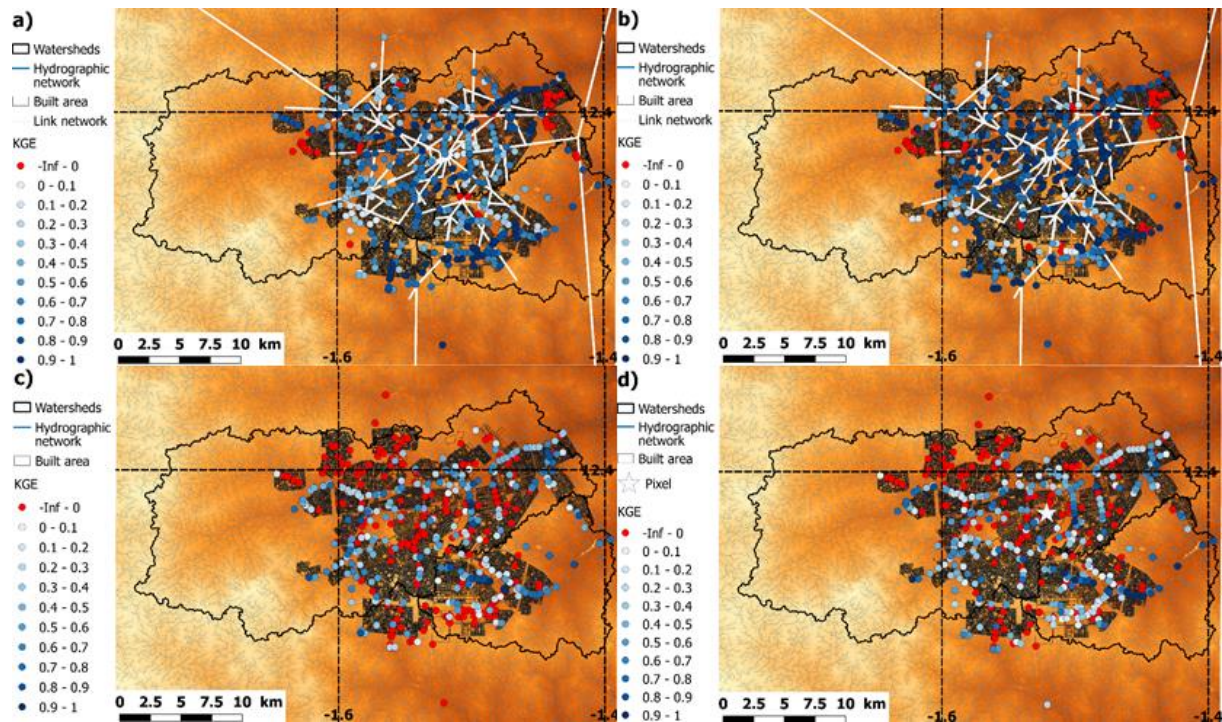
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1071 Figure 12 : Spatial distribution of KGE for the simulations with various rain forcing

1072 compared to the reference simulation based on the high resolution radar rain map, for the

1073 2012/08/04 event : a) rain forcing based on the network seen in Fig. 1 with frequency 13

1074 GHz and precision 1 dB b) same as a with precision 0.1 dB. c) rain forcing based on the area

1075 average rainfall from the radar and d) rain forcing from the central pixel (shown by a

1076 star).

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