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# Use of radar rainfall estimates and forecasts to prevent flash flood in real time by using a road inundation warning system

Pierre Antoine Versini

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1     **Use of radar rainfall estimates and forecasts to prevent flash flood in real time by**  
2                                   **using a road inundation warning system**

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4  
5     Versini, P.-A.  
6     CRAHI-UPC, Barcelona, Spain

7  
8     **Abstract**

9  
10    Important damages occur in small headwater catchments when they are hit by severe  
11    storms with complex spatio-temporal structure, sometimes resulting in flash floods. As  
12    these catchments are mostly not covered by sensor networks, it is difficult to forecast  
13    these floods. This is particularly true for road submersions, representing major concerns  
14    for flood event managers. The use of Quantitative Precipitation Estimates and Forecasts  
15    (QPE/QPF) especially based on radar measurements could particularly be adequate to  
16    evaluate rainfall-induced risks. Although their characteristic time and space scales  
17    would make them suitable for flash flood modelling, the impact of their uncertainties  
18    remain uncertain and have to be evaluated.

19  
20    The Gard region (France) has been chosen as case study. This area is frequently affected  
21    by severe flash floods, and an application devoted to the road network has also been  
22    recently developed for the North part of this region. This warning system combines  
23    distributed hydro-meteorological modelling and susceptibility analysis to provide  
24    warnings of road inundations. The warning system has been tested on the specific storm  
25    of the 29-30 September 2007. During this event, around 200 mm dropped on the South  
26    part of the Gard and many roads were submerged. Radar-based QPE and QPF have  
27    been used to forecast the exact location of road submersions and the results have been  
28    compared to the effective road submersions actually occurred during the event as listed  
29    by the emergency services.

30  
31    Used on an area it has not been calibrated, the results confirm that the road submersion  
32    warning system represents a promising tool for anticipating and quantifying the  
33    consequences of storm events at ground. It rates the submersion risk with an acceptable  
34    level of accuracy and demonstrates also the quality of high spatial and temporal  
35    resolution radar rainfall data in real time, and the possibility to use them despite their  
36    uncertainties. However because of the quality of rainfall forecasts falls drastically with  
37    time, it is not often sufficient to provide valuable information for lead times exceeding  
38    one hour.

## 51 **1- Introduction**

52

53 Mediterranean regions are subject to violent flash floods, resulting in heavy economic  
54 damages, estimated at a billion Euros in France over the last two decades Gaume et al.,  
55 2004 and, in some cases, human casualties, as illustrated by the recent events in Nîmes  
56 (1988), Vaison-la-Romaine (1992), Tarragona (1994), Biescas (1996), Corbière (1999),  
57 Alger (2001), Gard (2002) and Var (2010). Flash floods are identified as the  
58 consequence of an intense rain event producing several hundreds of mm in few hours  
59 (Creutin and Borga, 2003; Collier, 2007; Younis et al., 2008). During this type of event,  
60 spatial and temporal variability of rainfall appears to be the main factor controlling the  
61 hydrological response (Chancibault et al., 2007; Le Lay and Saulnier, 2007) and this  
62 evolution is very difficult to predict. Flash floods typically occur in quick response  
63 watersheds for two main reasons: (i) a short concentration time due to the size generally  
64 under few hundreds km<sup>2</sup>, (ii) flood flows that are essentially composed of surface runoff  
65 water or at least fast responding runoff processes (Creutin, 2009). That makes very  
66 difficult for emergency management services to anticipate and deliver flash flood  
67 warnings in real time.

68 This is particularly true concerning the road network that could be strongly affected  
69 during flash floods. In a situation of risk, the state of the road network has appeared as a  
70 major concern within these affected regions for two main reasons. First, many flash  
71 flood victims are in fact motor vehicle passengers trapped in inundated roads (Staes et  
72 al., 1994; Bourque et al., 2007). Second, emergency services require a clear overview of  
73 possible road conditions in order to efficiently plan interventions and identify safe  
74 access or evacuation routes.

75 Based on these considerations, a Road Inundation Warning System (RIWS) for flash  
76 flood prone areas has been recently developed and tested on the North part of the Gard  
77 Region (France) frequently affected by flash floods (Versini et al., 2010a). Coupling a  
78 susceptibility analysis of river road intersections (representing one part of the  
79 vulnerability to flooding) based on geographical information (Versini et al., 2010b and  
80 a) distributed hydrological model, the RIWS has provided promising results. Tested on  
81 real cases, it was able to correctly assess the inundation risk with an acceptable level of  
82 accuracy. Nevertheless, this previous work has opened many ways of investigation  
83 before being applied in a decision support system. First, operational services interested

84 by the RIWS has advised to study its possible application on a territory where it has not  
85 been calibrated to test the transferability of the whole prototype. Secondly, as the spatio-  
86 temporal distribution of rainfall has appeared to have a major influence on the state of  
87 the road network, the hydrological model had to be adapted to take into account  
88 distributed rainfall products, especially those based on weather radar. Indeed, one  
89 important feature of road submersion is the significant number of targets (that could be  
90 located on very small watersheds) regarding the limited coverage of rain and stream  
91 gauges, making this framework close to ungauged conditions. For example, the Gard  
92 region (580 km<sup>2</sup>) is covered by 38 stream gauges for 2480 crossing structures.

93 Accurate quantitative precipitation estimates (QPE) are also crucial for operational flash  
94 flood forecasting. Ground-based operational weather radars currently appear as the only  
95 instrument able to provide valuable information with a high spatial (1 km<sup>2</sup>) and  
96 temporal (tens of minutes) resolution. The density of automated rain gauges network is  
97 generally too low and not adapted to flash flood short time and space resolutions. In this  
98 case rainfall estimation uncertainties are still a major factor limiting the accuracy of  
99 rainfall-runoff modelling (Moulin et al., 2009). Moreover, rainfall estimated using  
100 satellite remote sensing is still under development and not sufficiently advanced to be  
101 used in an operational mode. Consequently, radar QPE is accepted as one of the most  
102 reliable data that can be used for hydrological applications (Corral et al., 2000; Borga,  
103 2006; Cole and Moore, 2008).

104 This is also the case concerning quantitative precipitation forecasts (QPF). Although  
105 few works have focused on using QPF based on weather radar data, results show  
106 significant improvements in the quality of forecasted hydrographs (Corral et al., 2000;  
107 Dolciné et al., 2001; Berenguer et al., 2005; Borga, 2006; Boudevillain et al., 2006; Van  
108 Horne et al., 2006; Vivoni et al., 2006; Cole and Moore, 2008). These radar-based QPF  
109 are usually limited to forecasting time ranging from 10 to 120 minutes. Tested on rather  
110 large basins (from hundreds to thousands km<sup>2</sup>), the anticipation of flow peak could be  
111 estimated, with enough quality, with a lead-time for up to few hours. It represents a  
112 notable improvement for fast response basins such those in Mediterranean regions. It is  
113 also recognized that the nature of the event has an important effect on the quality of the  
114 forecasted flow estimates. In Collier, (2007) a review is made to study how flash floods  
115 are forecasted considering the limitations and uncertainties involved in both  
116 meteorological and hydrological models of the forecasting system. The author

117 concludes the possibility to deliver valuable information from a flash flood risk  
118 management point of view limited to a lead-time of two hours.

119 This paper deals with a practical application of this statement. The main objective of the  
120 present work is to test the use of radar-based QPE and QPF on a specific hydrological  
121 application devoted to the road network. The spatio-temporal variability information  
122 provided by the radar based precipitation estimates and forecasts will be tested using the  
123 RIWS. The warning system will be firstly transported and adapted to a new basin  
124 located in the South part of the Gard region. It will be then applied to reproduce the  
125 specific storm of 29-30 September 2007 during which 19 roads were submerged.  
126 Predicted road inundations will be compared to what actually occurred. This will allow  
127 us to assess both the transfer of the RIWS on an area where it has not been calibrated,  
128 and the use of the available QFE and QPF products for flood forecasting in a framework  
129 reproducing operational conditions.

130 This paper is organised as follows: the next section presents the scope of study in more  
131 detail, including a description of the area of study, the rainfall products, and the RIWS.  
132 Section 3 describes the methodology applied to: i) transfer and test the RIWS to the new  
133 domain, and ii) test the information provided by the QPE/QPF, and their benefits in the  
134 detection and prediction of inundated roads. The results obtained during the 29-30  
135 September 2007 storm are presented in Section 4. Finally, Section 5 will conclude on  
136 both topics presented in Section 3.

137

138

## 139 **2- Presentation of the case study**

140

### 141 2-1 The Gard region

142 The Gard region (South of France) was used to develop and test the RIWS because it is  
143 frequently affected by severe flash floods (Delrieu et al., 2005; Gaume et al., 2009).  
144 This region has a typical Mediterranean climate characterized by frequent and very  
145 heavy storm events occurring especially in autumn. The 1 in 10 year daily precipitation  
146 exceeds 100 mm on the plateaus (eastern part) and 150 mm in the mountainous western  
147 part of the area (CNRS/INPG, 1997). Single storm events can produce locally hundreds  
148 of millimetres within few hours.

149 During these storms, roads are often flooded. Significant inundation occurs at least once  
150 a year on average on the same vulnerable section of the road network. 40% of the

151 victims of floods in the Gard during the last 50 years were motorists Antoine et al.,  
152 2001. During the extreme September 2002 flood (Delrieu et al., 2005; Ruin et al.,  
153 2008), about 200 emergency vehicles were seriously damaged or destroyed by the  
154 flows. For these reasons, the monitoring of the road network during flash flood events  
155 has become a major concern for management services. The inundated road sections are  
156 now systematically inventoried during or after every major event by the local services in  
157 charge of road maintenance. It is based on these considerations that the first attempt  
158 represented by the RIWS has been conducted to forecast the possible inundated road  
159 (Versini et al., 2010a). A summary of this prototype will be described further (Section  
160 2.3).

161 This study mainly focuses on the southern part of the Gard region (Fig. 1) where both  
162 Vidourle and Vistre watersheds join the scrubland of La Camargue (swamp zone of the  
163 Rhône Delta) before entering into the Mediterranean Sea. Both watersheds are located  
164 outside the calibration area of the RIWS and differ from this one from a geographical  
165 point of view. The Vidourle basin has a drainage area of 833 km<sup>2</sup> and an altitude  
166 ranking from 3m to 770 m. This watershed is essentially covered by rural landscapes:  
167 vines and forest. The Vistre watershed (476 km<sup>2</sup>) is quite different with lower altitudes  
168 (4 m to 200 m with an average altitude of 70 m) and a more urbanized land with the  
169 presence of the city of Nîmes (150.000 inhabitants) upstream of the basin. Because of  
170 this very flat topography, river floodplains are wider and easily inundated.

171

## 172 2-2 Meteorological and Hydrological data:

173 Known as an area very sensitive to flash flood, the Gard region is covered by a dense  
174 network of rain gauges and two weather radars (Nîmes and Bollène). Rain gauge and  
175 discharge data used in this study were collected and analysed in the framework of the  
176 Cevennes-Vivarais hydro-meteorological observatory (OHM-CV,  
177 [www.lthe.hmg.inpg.fr/OHM-CV](http://www.lthe.hmg.inpg.fr/OHM-CV)). This observatory is a research initiative aiming at  
178 monitoring and understanding intense Mediterranean storms and flash floods (Delrieu,  
179 2004). On the other hand, two different services are in charge of hydro-meteorological  
180 warning and are authorized to deliver QPE and QPF for flood management in real-time:  
181 (i) the service of flood prevention (SPC for “Service de Prévention des crues” in  
182 French) is the local service in charge of flooding prevention specially devoted to the

183 Gard region, and (ii) the national meteorological agency, Meteo France (MF hereafter),  
184 that delivers radar-based rainfall maps for the whole country. Processing of this  
185 different data is briefly described below.

#### 186 *2.2.1 Cevennes-Vivarais hydro-meteorological observatory data*

187 Seventeen automatic hourly rain gauges are located within or close to the Vidourle and  
188 Vistre watersheds. They have been set up for flood forecasting purposes. While the  
189 density of about two gauges per 100 km<sup>2</sup> is quite good, it could not enable accurate  
190 estimations of rainfall intensities by spatial interpolation at time and space scales suited  
191 to flash flood dynamics: sub-hourly time step and kilometric scale (Moulin et al., 2009).  
192 OHM-CV uses an ordinary kriging technique (Journel and Huijbregts, 1978), using a  
193 spherical variogram model, to interpolate the rain gauge measurements and map rainfall  
194 rates at a 15-minutes time step and 1 km<sup>2</sup> grid covering the area of study Lebel et al.,  
195 1987. As rain gauge data are only available at hourly time step, constant rainfall  
196 intensities were assumed for the entire hours.

197 The Vidourle catchment is well instrumented with numerous hourly stream gauges.  
198 Three dams (Ceyrac, Conqueyrac, and La Rouvière) are located in the upstream part  
199 and four gauge stations (Quissac, Vic-Le-Fesq, Sommières, Marsillargues) on the  
200 principal stream in the Vidourle valley (see Figure 1). On the other hand, the Vistre  
201 catchment is poorly instrumented with only one station located at the watershed outlet  
202 (Le Cailar).

203

#### 204 *2.2.2 Gard region data*

205 Complex SPC inundation forecasting system Bressand, 2002 is able to deliver valuable  
206 spatial rainfall intensity at the 1km<sup>2</sup> scale every 5 minutes. Although this system has  
207 been created by the private company REAH®, some basic elements can be explained on  
208 the processes involved to correct and generate radar images Ayrat, 2005. The Gard  
209 region is divided into 5 windows corresponding approximately to the five main basins  
210 of the region (Vistre, Vidourle, upstream Hérault, Gardon and upstream Cèze, Gardon  
211 and downstream Cèze). In each window, the radar maps are specifically adjusted with  
212 the rain gauge measurements using a calibration factor (FC). This coefficient is  
213 calculated every 5 minutes using the three last measurements (Eq. 1). It usually varies  
214 between 0.5 and 3.

215

$$FC = \frac{\sum_{i=1}^n P_i}{\sum_{i=1}^n R_i} \quad (1)$$

216 Where  $P_i$  is the rain gauge measurement,  $R_i$  is the radar measurement at the rain gauge  
 217 location,  $n$  is the total number of rain gauges used to adjust radar data.

218 Precipitation forecasts are also calculated for different lead times varying between 5  
 219 minutes to one hour. In this case, FC used to adjust radar-based rainfall is fixed. This  
 220 represents one of the weaknesses of the system. Consider the radar/rain gauge relation is  
 221 constant during the storm can lead to misestimate –often underestimate- rainfall  
 222 forecast.

223

### 224 2.2.3 Meteo France data

225 Meteo France produces QPE and QPF every 5 minutes over the whole country at the 1  
 226 km<sup>2</sup> scale based on an aggregation of radar data. After a processing chain that corrects  
 227 ground clutter, partial beam blocking, VPR effects, and advection, the radar image is  
 228 corrected using the rain gauges data (Tabary, 2007; Tabary et al., 2007). The principle  
 229 to fit radar data to rain gauge values is also based on the use of a calibration factor. Two  
 230 differences with the FC calculated for SPC data can be noted. First, this one takes into  
 231 account previous rain gauge and radar measurements over a longer period. In order to  
 232 give more importance to the newest values, they are multiplied by weights increasing  
 233 with time. Second, a “memory” coefficient is added to constrain FC to converge to a  
 234 monthly calibration factor  $FC_{month}$  when there is little rain between two events.

235

$$FC = \frac{\sum_{i=H-M}^H \omega_i \cdot P_i + C_{rec}}{\sum_{i=H-M}^H \omega_i \cdot R_i + \frac{C_{rec}}{FC_{month}}} \quad (2)$$

236 Where  $M$  is the period on which the factor is calculated,  $H$  is the lead time,  $P_i$  is the rain  
 237 gauge measurement at time  $H$ ,  $R_i$  is the radar measurement at the rain gauge location at  
 238 time  $H$ ,  $\omega_i$  is the weight to filter oldest values at time  $H$ ,  $C_{rec}$  is the memory coefficient,  
 239  $FC_{month}$  is the monthly coefficient.



240 QPF are produced for different lead times ranging from 5 to 70 minutes. The method  
241 used (Juvanon du Vachat et al., 1995a; Juvanon du Vachat et al., 1995b) derives the  
242 motion field between consecutive radar scans from the distance of the mass centers of  
243 two corresponding radar echoes. The centers are assumed to be representative for  
244 individual convective cells. This motion field is then extrapolated and applied to  
245 produce future rainfall field.

## 246 247 2-3 The Road Inundation Warning System

248 The RIWS for flash flood prone area has been developed within the FLOODsite<sup>1</sup> project  
249 funded by the European Sixth Framework Program. It focuses on intersections between  
250 road and river networks that can be flooded during a flash flood event, and it has been  
251 calibrated and tested on the North part of the Gard region (called “calibration area” in  
252 the rest of the paper). Both components of the RIWS (susceptibility analysis and  
253 hydrological model) are briefly presented below. For a detailed presentation, please  
254 refer to Versini et al., 2010a; Versini et al., 2010b).

### 255 *2.3.1 Susceptibility rating method*

256 An inventory of past road inundations was carried out by the public agency in charge of  
257 the road management on the North part of the Gard region, outside the studied area  
258 (Lignon, 2004). As comprehensive as possible, its objective was to collect the location  
259 of the most frequent road submersions. Based on the employees’ experience and  
260 memory, it contains the exact location of 167 road sections flooded (and noted) during  
261 the last 40 years on the main road network. From this inventory, four categories of  
262 susceptibility to flooding (high, medium, low, and safe) were defined. Geographical  
263 characteristics (local altitude and slope, upstream watershed area) of crossing structure  
264 have been highlighted to explain this susceptibility to flooding and allocate every road  
265 intersection in a category. Using historical road inundations and their estimated  
266 frequency of flooding, a statistical distribution of return period of flooding was  
267 calculated for each susceptibility category.

### 268 269 *2.3.2 Hydrological model*

270 The CINECAR hydrological model (Gaume et al., 2004) has been selected to simulate  
271 distributed discharges. Developed specifically to model flash floods, it represents the

---

<sup>1</sup> <http://www.floodsite.net/>

272 entire watershed as a network of river reaches having a simple rectangular cross-section,  
273 connected to two rectangular slopes (characterized by areas of few km<sup>2</sup>). The US Soil  
274 Conservation Service (SCS) Curve Number (CN) model is used to calculate the  
275 evolution of the runoff coefficient on each slope during the storm event, and the  
276 kinematic wave model is used to route the flows on the slopes and through the network  
277 of river reaches. The CINECAR model has been calibrated and validated based on the  
278 discharge time series available on 12 watersheds over the period 2000-2005. Because of  
279 the lack of available radar data, OHM-CV kriged data was used for these procedures.  
280 The performance of the model was evaluated on several rainfall events with a total  
281 rainfall exceeding 100mm available on this period. Acceptable results were obtained  
282 (average Nash criterion value of 0.3) that looked comparable to those obtained in  
283 similar studies (Borga, 2008). Based on this study, it has been considered the  
284 CINECAR model depends on only two parameters: widths of the rectangular sections  
285 representing the rivers that can be fixed *a priori* and adjusted during the storm  
286 depending on the flood magnitude, and the CN that can be also determined *a priori*  
287 from an expert judgment.

288

### 289 2.3.3 Risk levels

290 Finally, every road intersection is characterized by a susceptibility category and is  
291 connected to a river reach where the discharge is simulated. These discharges are  
292 compared at each time step with the theoretical return period thresholds for two, ten,  
293 and fifty years:  $Q_2$ ,  $Q_{10}$  and  $Q_{50}$ . These theoretical return periods are approximated using  
294 a regional discharge quantile estimation method, the Crupedix method Cemagref, 1980,  
295 adjusted for France. Inundation risk levels are defined based on the susceptibility  
296 category and the discharge magnitude, or only on the discharge magnitude if  
297 susceptibility analysis is not used (see Table 1). Three levels of risk are assigned: high  
298 submersion risk (HSR), significant risk (SR), and moderate risk (MR). A warning is  
299 issued when one of the thresholds is exceeded.

300

## 301 **3- Application of the RIWS and protocol assessment**

### 302 3-1 The case of the 29-30 September 2007

303 The rainfall event happened during the night between the 29 and 30 September 2007  
304 and was one of the most important that occurred in the Vistre and Vidourle watersheds

305 over the last years. A stationary storm with a “V” shape moved from the west to the east  
306 and intensive precipitations fell on the central part of the watersheds between 22:00 and  
307 00:00. Between 80 and 120 mm were measured on both watersheds and locally more  
308 than 200 mm. At 2:30 the Vidourle river overflowed in Sommières. Rainfall forecasts  
309 preventing this event and issued by the French meteorological agency Meteo France  
310 were quite accurate. At the beginning of the storm (20:00), they issued a moderate  
311 warning reporting “heavy rainfall storm” during the night. An average rainfall of 50 mm  
312 was forecasted on the region around Nîmes and locally more than 150 mm. Road  
313 management and rescue services were advised of possible troubles during the night.

314 Finally, important damages occurred during this event. Some houses and garages were  
315 submerged, and the road network was particularly affected. Nineteen roads were closed  
316 during the night by the regional services and reopened one after the other the next day.  
317 It made rescue operations difficult and has represented a major threat to lives. The fire  
318 brigade and the regional service of rescue recognized about fifty interventions due to the  
319 inundations. Despite the advice he has been given, a motorist crossed the Vidourle and  
320 was swept away by the important flow.

321

### 322 3-2 Methodology

323 The objective is to assess the use of the quantitative precipitation estimates and  
324 forecasts by the RIWS. First, a direct analysis of the QPE/QPF will be conducted to  
325 evaluate the quality of the RIWS input. Then, the RIWS has to be transferred and  
326 applied on the South part of the Gard region where it has not been calibrated. That  
327 means both susceptibility analysis and hydrological model will be assessed on a new  
328 landscape with another road network configuration. Their results will be compared to  
329 those obtained on the calibration area. Finally, RIWS will be applied on the 29-30  
330 September 2007 storm and its results will be analysed comparing the warnings it  
331 delivers to the actually inundated roads. The three steps, direct QPE/QPF analysis, the  
332 RIWS transfer and the RIWS assessments with QPE and QPF are described thereafter.

333

#### 334 *3.2.1 Direct analysis of precipitation*

335 Both QPE and QPF produced by both services (MF and SPC) will be compared and  
336 evaluated. Particular attention will be given to the spatio-temporal variability of the  
337 rainfall distribution. Both hyetograms and rainfall accumulation maps will be analysed

338 at the watershed scale for the Vistre and the Vidourle basins. These data will be  
339 compared to kriging interpolation-based, used as reference. It is assumed that kriged  
340 data correctly represent the temporal variability of the precipitation at such large spatial  
341 and temporal scale. The local heterogeneities of rainfall that are not captured by the rain  
342 gauge network should have a relative low impact on the mean estimated rainfall.  
343 Moreover, kriged data were processed after the storms and do not include any errors  
344 associated with real time data (as QPE and QPF can do). In order to study the different  
345 QPE at a smaller scale more representative of small ungauged watersheds, comparison  
346 between radar-based kriged data and QPE accumulations will be also drawn at the cell  
347 scale (1km<sup>2</sup>).

348

### 349 3.2.2 Road Inundation Warning System transfer

350 First, the susceptibility rating method is applied. Based on geographical information  
351 (local slope and altitude, watershed area), the river road intersections of the Vistre and  
352 Vidourle watersheds will be spread in the four categories of susceptibility (high,  
353 medium, low and safe). The verification will consist in analysing the susceptibility  
354 category of the road sections effectively submerged during the 29-30 September 2007  
355 storm. Locally, where intersections are subjected to the same rainfall hazard, the most  
356 susceptible intersections should be flooded in priority. As the susceptibility rating  
357 method has been calibrated on a region quiet different from the studied watersheds, its  
358 extrapolation could be inappropriate without any adjustments.

359 The transfer of the hydrological model has also to be assessed. Once the watersheds  
360 have been desegregated as a network of river reaches connected to sub-basins, the  
361 parameters have to be evaluated *a priori*. The widths of the river reaches have been  
362 fixed to those representing a moderate discharge at the beginning of the event, and can  
363 be modified during the storm according to the discharge magnitude. The key parameter  
364 is the CN because it represents the evolution of the runoff coefficient value during the  
365 storm taking into account the initial condition. Based on the work realized in Versini et  
366 al., 2010a), an *a priori* range of CN will be used. The simulated discharges will be  
367 compared to the observations available for the stream gauges of the Vistre and Vidourle  
368 watersheds. In order to test the viability of this calibration *a priori*, simulated discharges  
369 at the gauge stations will be also calculated using a value especially calibrated for this

370 event (CNcal). The simulation achieved with CNcal will represent the best performance  
 371 we can expect from the hydrological model at the gauged basin scale. Every simulation  
 372 will be evaluated using the Nash efficiency (Nash, 1969):

$$373 \quad \text{Nash} = 1 - \frac{\sum_{i=1}^n (Q_{\text{obs}_i} - Q_{\text{sim}_i})^2}{\sum_{i=1}^n (Q_{\text{obs}_i} - \overline{Q_{\text{obs}}})^2} \quad (3)$$

374 Where  $Q_{\text{sim}_i}$  represent the simulated discharges,  $Q_{\text{obs}_i}$  the observed discharges,  $\overline{Q_{\text{obs}}}$   
 375 the average observed discharge during the storm, and  $n$  the number of time steps.

376

### 377 3.2.3 RIWS assessment using radar-based QPE and QPF

378 The skill of the RIWS is assessed using a classical contingency statistical analysis. An  
 379 efficient RIWS should be able to identify a large proportion of the actually observed  
 380 inundations and limit the number of “false alarms” - predicted inundations that are not  
 381 observed. Four criteria are therefore used to assess the performance of the proposed  
 382 RIWS using the available information on the actually observed inundations:

383 - Probability of Detection (POD) calculated as the ratio between the number of  
 384 inundated sections where a warning has been issued (Correct Warnings) and the  
 385 total number of inundated road sections:

$$386 \quad \text{POD} = \frac{\# \text{Correct Warnings}}{\# \text{Inundated roads}} \quad (4)$$

387 - False alarm ratio (FAR) calculated as the ratio between the number of non-  
 388 inundated sections where a warning has been issued (false warnings) and the  
 389 total number of warnings delivered by the RIWS:

$$390 \quad \text{FAR} = \frac{\# \text{False alarms}}{\# \text{Warnings}} \quad (5)$$

391 - Correct negative (COR) represents the ratio between the number of non-  
 392 inundated sections where a no warning has been issued (Safe) and the total  
 393 number of misses:

394 
$$\text{COR} = \frac{\# \text{ Safe}}{\# \text{ Safe} + \# \text{ Misses}} \quad (6)$$

395 These very intuitive skill scores are computed using rainfall estimates for both services  
 396 in a framework reproducing operational conditions. Four lead times (15, 30, 45, and 60  
 397 minutes) are used to test the accuracy of this data and its possible degradation over time.

398 In addition, the false positive rate (FPR), which is the ratio between false alarms and the  
 399 number of effective non-inundated road sections (Non inundated roads), is computed.  
 400 Coupled with the maximum value of POD over the event, it is used to plot ROC  
 401 (Receiver Operating Characteristic) curves and evaluate the sensibility of the two-class  
 402 prediction problem (flooded – not flooded). It will be particularly useful to compare the  
 403 results with those obtained on the calibration area, using or not the susceptibility  
 404 analysis:

405 
$$\text{FPR} = \frac{\# \text{ False alarms}}{\# \text{ Non inundated roads}} \quad (7)$$

406  
 407 **4- Results**  
 408

409 4-1 Radar-based QPE and QPF direct analysis

410 Rainfall accumulations during the entire storm have been computed in a window  
 411 including both Vistre and Vidourle watersheds for every type of data (OHM-CV  
 412 kriging, QPE and QPF from MF and SPC). They are presented in Figure 2. Scatter plots  
 413 comparing radar-based QPE with kriged data are illustrated on Figure 3. Hyetograms  
 414 representing mean areal intensity (with 15 minutes time step) at the watershed scale for  
 415 both Vidourle and Vistre watersheds are also presented for every rainfall data in Figure  
 416 4.

417

418 *4.1.1 Quantitative Precipitation Estimates*

419 First, the spatial distribution of rainfall is studied. Despite the location of the storm core  
 420 is the same for the three estimations, a marked difference in rainfall amount can be  
 421 noted. The maximum accumulation exceeds 250 mm for the SPC estimates whereas it  
 422 only exceeds 150 mm for MF data, respectively 200 mm for the kriging. This is also  
 423 corroborated by Vic-Le-Fesq rain gauge data located where the most intense

424 precipitation occurred. A total amount of 175 mm was locally measured whereas 215  
425 mm were estimated by SPC QPE, respectively 130 mm for MF QPE. It is also  
426 confirmed by scatter plots on Figure 3. At the 1km<sup>2</sup> scale, MF QPE have a tendency to  
427 underestimate the most intense precipitation. On the other hand, SPC QPE overestimate  
428 some of the highest accumulations measured on the Vidourle watershed, but the highest  
429 differences with kriging are located on the cells where the precipitation is interpolated.  
430 The numerous underestimations for the lowest values correspond to the Vistre  
431 watershed. As it has been shown above, SPC data is calibrated for two different  
432 geographical windows on the Vidourle and Vistre watersheds. This is strongly visible  
433 on the accumulation map with local intensities higher than 250 mm measured on the  
434 Vidourle window neighbouring a value three times lesser on the Vistre window. A short  
435 band is shared by both windows where both estimated rainfall can be compared. A  
436 significant difference around 35% is noted. It can be assumed that the FCs used during  
437 the storm tend to overestimate rainfall on the Vidourle window and/or to underestimate  
438 on the Vistre one.

439 Second, temporal distribution of rainfall is analysed on both watersheds. Looking at the  
440 hyetograms (Fig. 4), precipitation estimates appear to be very different from a data to  
441 another on the Vidourle basin. For example, at 22:00 the kriging interpolation-based  
442 displays a maximum intensity of 15 mm/h. It is well reproduced by the SPC estimates  
443 (17 mm/h), but widely underestimated by MF ones (10 mm/h). On the other hand, the  
444 Vistre case shows a coherent rain amount between both services and the kriged data.  
445 The maximum intensity of 38 mm/h arises between 23:00 and 00:00 on the three  
446 observed hyetograms. The large overestimation highlighted on SPC rainfall  
447 accumulation map is only slightly reflected on both hyetograms because the highest  
448 precipitations fell outside the studied watersheds.

449  
450

#### 451 4.1.2 Quantitative Precipitation Forecasts

452 QPF provided by MF and SPC are very heterogeneous depending on the studied  
453 watershed, but they all have a strong tendency to underestimate the storm intensity for  
454 the largest lead times. On the Vistre watershed, where rainfall was the highest, SPC  
455 forecasts can lose up to 30% of the maximum intensity while MF more than 60% (see  
456 Fig. 4). This time, SPC QPF show a coherent merging between both zones because the

457 same FC equal to 1 is used (Fig. 2). Nevertheless, despite the storm stationarity is well  
458 represented, they have a tendency to underestimate precipitation with time, especially  
459 for the highest intensities. It should be interesting to obtain additional information on  
460 the SPC QPF production to interpret them more thoroughly.

461 MF QPF appear to be more uncertain. Accumulation maps (Fig. 2) show a tendency to  
462 transfer the convective system to the east part of the Vistre watershed. This situation  
463 corresponds to the typical case of a regenerative system over several hours, whom the  
464 system velocity is different from the cells velocities composing the system. During a  
465 certain time, the system velocity is almost equal to zero and the storm is nearly  
466 stationary while the cells -with a lifetime shorter- are moving eastward. The method  
467 used to extrapolate motion field in operational mode capture the movement of small  
468 scale structures, typically the scale of the convective cells. In most cases this diagnosis  
469 is appropriate. Here, the displacement obtained suggests a movement towards the east,  
470 which evacuates the system too quickly and does not restore the stationarity of the  
471 regenerative system. As the forecasted system is moved to the east, it always crosses the  
472 Vistre watershed and few affect the predictions on this basin. A slight overestimation is  
473 noted for the 30 minutes forecast. Conversely, the forecasts on the Vidourle watershed  
474 are highly affected by this error. The precipitation peak that occurred at 22:00 is  
475 strongly underestimated and almost absent in the one hour forecast.

476

477 4-2 Road Inundation Warning System transfer

478 *4-2-1 Susceptibility analysis*

479 The road susceptibility rating method has been applied on both Vidourle and Vistre  
480 watersheds. 468 river road intersections were identified using existing river and road  
481 network GIS layers. These road intersections have been classified into the 4 categories  
482 defined above. The high susceptible category contains 12% of the river crossings;  
483 respectively 20%, 50% and 18% for the medium, low and safe categories. Susceptibility  
484 repartition of Vistre and Vidourle intersections is very similar to those obtained on the  
485 North part of the Gard where the method was calibrated (see Table 2). Although the  
486 density of linear road is quite the same ( $1511\text{km}/\text{km}^2$  in the calibration area vs  
487  $1433\text{km}/\text{km}^2$  on the study area), the density of river intersections is different:  $0.87$   
488  $\text{intersections}/\text{km}^2$  vs  $0.44\text{intersections}/\text{km}^2$ . The river network is less dense on the South  
489 part of the region and the number of intersections with the road network is also lower.



490 This is due to the geographical characteristics of the region: flatter and more urbanised  
491 and domesticated.

492 Concerning the twenty-three river road intersections responsible for the 19 flooded  
493 roads during the 29-30 September 2007 storm, five of them are located upstream very  
494 small watersheds ( $<1 \text{ km}^2$ ), and seven are located upstream small watersheds ( $<10 \text{ km}^2$ ).  
495 For these watersheds, the concentration time is very short, lesser than 15 minutes for the  
496 smallest ones, making difficult interventions between rainfall and its possible  
497 consequences. Among the 468 river crossings identified in the study area, the twenty-  
498 three inundated crossing structures are characterized by rather high levels of  
499 susceptibility (see Table 2). Eight of them (35%) are included in the high susceptibility  
500 category and seven (30%) in the medium one. Seven (30%) are in the low category and  
501 one (5%) in the safe category. As they are characterized by a distribution of level of  
502 susceptibility focused on the highest values, submerged crossing structures seem to be  
503 related with the susceptibility categories defined in the calibration area (yet  
504 geographically and topographically different). Considering this only event and the small  
505 size of classes, it is not possible to be more conclusive.

#### 506 *4-2-2 Hydrological model*

507 Out of the eight stream gauges located on both Vistre and Vidourle watersheds, only  
508 four have registered a peak of discharge during the studied storm. All gauges of the  
509 upstream part of the Vidourle catchment did not receive sufficient water to measure  
510 such an increase. This is particularly true for the three dams for which the output  
511 discharge remained constant during the entire storm. Finally, discharge peaks were  
512 registered only at Vic-Le-Fesq ( $505 \text{ km}^2$ ), Sommières ( $620 \text{ km}^2$ ), Marsillargues ( $798$   
513  $\text{ km}^2$ ) and Le Cailar ( $440 \text{ km}^2$ ); respectively  $25.8 \text{ m}^3/\text{s}$  ( $0.051 \text{ m}^3/\text{s}/\text{km}^2$ ),  $232.5 \text{ m}^3/\text{s}$   
514 ( $0.375 \text{ m}^3/\text{s}/\text{km}^2$ ),  $235.0 \text{ m}^3/\text{s}$  ( $0.294 \text{ m}^3/\text{s}/\text{km}^2$ ), and  $58 \text{ m}^3/\text{s}$  ( $0.132 \text{ m}^3/\text{s}/\text{km}^2$ ). As the  
515 discharge peak measured at Vic-Le-Fesq is very low –a specific discharge bellow 0.1 is  
516 hardly represented by the hydrological model- only the three remaining gauges have  
517 been kept to assess the model simulations.

518 First, these observations have been compared to the discharges obtained by the CNs  
519 selected *a priori* and used in an operational mode. In the calibration process, Versini et  
520 al., 2010a) have proposed a range of two CN values related to the date and the  
521 antecedent rainfall amount. The beginning of the autumn season combining with a total

522 amount of antecedent precipitation lesser than 100 mm carries to use both 40 and 50 CN  
523 values. Second, a calibrated CN (CN<sub>cal</sub>) has been estimated in a dichotomous way,  
524 calibrating a first CN for all the sub-basins located upstream Sommières, a second CN  
525 for the sub-basins between Sommières and Marsillargues, and a third one for the Vistre  
526 sub-basins. The objective of this calibration is to assess the hydrological model's ability  
527 to reproduce correctly the studied storm and to have an idea on the spatial distribution  
528 of the CN. These simulations have been carried out using OHM-CV kriged data, and  
529 both SPC and MF estimates. The different hydrographs and the Nash efficiencies  
530 evaluating the simulation performance are presented in Figure 5 and Table 3.

531 The simulations obtained with the CNs selected *a priori* appear to be acceptable and  
532 similar to those obtained on the calibration area (see Versini et al., 2010a). They are  
533 particularly reliable on Sommières watershed where the peak of the hydrograph is well  
534 represented (Figure 5-a). As for Le Cailar basin, discharges calculated with CN<sub>cal</sub> are  
535 almost all enclosed between both discharges calculated with the *a priori* CNs,  
536 suggesting the hydrological model is well calibrated on these parts of the study area.  
537 Note that the shape of Le Cailar hydrograph is not well reproduced due to the complex  
538 structure of the basin through highly urbanized and irrigated. Conversely, at  
539 Marsillargues (Figure 5-b), the CN<sub>cal</sub> values are systematically outside the range  
540 defined by both *a priori* CNs. The CN=50 tends to underestimate the discharge for the  
541 MF estimates whereas the CN=40 tends to overestimate the discharge using SPC data.  
542 Simulated discharges obtained with the calibrated values show the simulations could  
543 seriously be improved.

544 It is clear the results depend on the type of precipitation data used. The previously  
545 presented differences in rainfall estimates represent a factor explaining the results of  
546 hydrological modelling simulations. The calibrated CN<sub>cal</sub> corrects the difference  
547 between both radar-based QPE (MF and SPC) and illustrates QPE are far from perfect.  
548 An underestimation of rainfall is offset by a larger CN, and reciprocally. Although  
549 rainfall amount based on kriging seems to be well represented at the watershed scale  
550 (Fig. 4), the corresponding simulations appear to be the worst (lowest Nash efficiency).  
551 In these cases, the simulated hydrographs are late in comparison with the observed ones,  
552 and this problem of synchronization drastically affects the Nash efficiency computation  
553 (Table 3). This can be explained by the low spatio-temporal resolution of this data, but  
554 also by the rainfall-runoff model structure and calibration. The river widths that conduct

555 the transfer have been fixed and may be not adequate in this case. SPC and MF  
556 estimates delivered in real time seem to better simulate the discharge. Once the bias is  
557 corrected (compensated by the value of CN), the radar leads to a well representation of  
558 the flood dynamics.

559 Further conclusions cannot be issued about the quality of the different QPEs because of  
560 the simplicity of the hydrological model. As CINECAR only represents surface runoff,  
561 it does not take into account sub-surface processes for instance. This component can be  
562 significant for large basin as illustrated by the shape of the observed hydrographs. Its  
563 simplification may overestimate direct runoff; that will conduct to overestimate  
564 discharge on small basins where this process is prominent.

565 Nevertheless, the objective of this calibration procedure was to assess the hydrological  
566 model's ability to reproduce the observed discharge and to define optimised CN for  
567 each QPE. These CNcal values will be applied on the sub-basins located upstream the  
568 stream gauges. They represent the best performance we can expect from the model at  
569 the gauged basin scale. On the other sub-basins of the studied area (downstream  
570 Marsillargues and Le Cailar basins), where no stream gauge is located, CNcal has been  
571 extrapolated from the values previously calibrated on the Vistre watershed. CNcal  
572 calculated with the Le Cailar stream gauge have been implemented on these sub-basins  
573 for two reasons: (i) proximity because almost all these sub-basins are located in the  
574 Vistre watershed, (ii) geographical similarity because they are characterized by the same  
575 CN value estimated by the USDA method (USDA, 1985) using land occupation and soil  
576 infiltration capacities, It is finally assumed the hydrological model with its restrictions  
577 can be applied on the entire study area.

578

579

580

581

582 4-3 RIWS assessment using radar-based QPE and QPF

583 The RIWS has been applied in a framework reproducing operational conditions during  
584 the night of the 29 and 30 September 2007. For each time step  $t_i$ , warnings have been  
585 computed using radar estimates available on real time (for both SPC and MF services)  
586 from the beginning of the storm until time step  $t_i$ , but also kriged data. To prevent from  
587 the floodings that can occur in the near future, rainfall forecasts associated with both

588 radar-based QPE have been used for the four following lead times: 15, 30, 45, and 60  
589 minutes. To assess the pertinence of using radar-based QPE and QPF, the RIWS has  
590 been employed by testing different options: i) the susceptibility analysis has been turned  
591 on and off, ii) the hydrological model has been used with *a priori* values of CN=40 and  
592 CN=50, and also with the calibrated values (CNcal) defined in Section 4.2.2. The results  
593 have been evaluated using the different skill scores and compared with those obtained in  
594 the calibration area. They are summarized in Table 4 and the most significant are  
595 represented on Figures 6.

#### 596 4.3.1 On the use of radar-based QPE

597 The results obtained with kriged data are very often worse than those obtained with  
598 radar-based QPE (see Table 4). Almost no inundated roads (POD=14%) are detected by  
599 the RIWS with CN equal to 40. The use of the calibrated CNcal can get the best  
600 discharge simulations at the location of the stream gauge, but fails in reproducing the  
601 exceedance warning thresholds, especially for the intersections not located on a major  
602 stream (where most of the inundations occurred). Moreover, COR scores are always  
603 worse than those computed with radar-based QPE. Looking at the results in details,  
604 these bad scores are due to a higher number of misses and a lower number of correct  
605 warnings. The number of false alarms –similar to that obtained for radar-based QPE -  
606 indicates that an underestimation of the precipitation is not solely responsible for the  
607 non-detection of the inundations; otherwise, the total number of false alarms should be  
608 lower. At small scale, the kriging-based interpolation of rain gauge measurements is not  
609 able to represent the spatio-temporal variability of rainfall, which is essential in this  
610 study. Moreover, it can be seen that the evolution of the different skill scores suffers a  
611 delay of at least one hour compared to those computed from the others QPE (see Figure  
612 6). This is due to the under-estimation of the first rainfall peaks (see Figure 4), and the  
613 uniform distribution of the hourly data on the four 15 minutes time steps because the  
614 most intense rainfall occurred at the beginning of an hour (18:00).

615 Using SPC QPE, around 80% of the flooded roads are detected with the CNcal – for  
616 which the simulated discharges were the best – (see Figure 6). The scores obtained for  
617 CN=50 are very similar to those calculated with CNcal and decrease when CN=40 is  
618 used (POD drops to 60%). As most of the floodings were located downstream the  
619 gauged basins, the detection is clearly influenced by the choice made to extrapolate the

620 CN values. The use of the CN adjusted on Le Cailar basin (the high value of 46) leads  
621 to simulate significant discharges, high enough to exceed the warning thresholds.

622 In this best case, the remaining 20% missed floodings are located on the Vistre  
623 watershed. This should not be related to a possible under-estimated precipitation on the  
624 Vistre window because the RIWS applied with MF or kriged data is also not able to  
625 detect these floodings (Figure 6). As the hydrological model seems to be able to  
626 reproduce correctly observed discharge at the Vistre gauge station, it has to be assumed  
627 that the use of an average *CN*, distributed on the entire Vistre watershed, is not adapted.  
628 The model should be influenced by the heterogeneous precipitation distribution on this  
629 watershed whose downstream part was particularly affected by the most intense rainfall.  
630 A better description of the spatial distribution of *CN* is probably required.

631 Using SPC QPE, the numbers of false alarms is very high. Indeed, they represent  
632 between 90% and 100% of the warnings delivered at the beginning of the storm, then  
633 they drop to 85% during the night. Although this ratio may seem important, the number  
634 of COR is high (close to 99%). That means despite a significant number of false alarms,  
635 the RIWS is able to rate the safe roads at the watershed scale. In order to have an  
636 overview on the whole road network, the warnings issued by the RIWS during all the  
637 storm are represented on Figure 7. 149 of the 468 existing intersections are identified as  
638 inundated sections at some point in the night (but not simultaneously). Among them, 13  
639 correspond to effective submersions which 12 are characterized by high and significant  
640 risk. All the warnings are concentrated in areas particularly risky. That means the RIWS  
641 can capture the spatial repartition of floodings when accurate QPE are used.

642 Finally, the results obtained with MF QPE are less satisfactory than those obtained with  
643 SPC QPE. With a maximum of 50% for POD, the RIWS detections appear not to be  
644 satisfactory. The use of  $CN=40$  does not permit the RIWS to deliver warnings during  
645 the night. The simulated discharges are probably too low. As rainfall estimates from MF  
646 are lower than those produced by SPC, *CN* has to be higher to simulate discharges  
647 susceptible to exceed the different thresholds. Setting the *CN* equal to 50, it is not yet  
648 sufficient and the results obtained with kriged data are still better. Only the optimised  
649 *CN*<sub>cal</sub> –higher than 50- gives acceptable skill scores (Fig. 6). The detected inundated  
650 roads are those located around Sommières where the estimates were the most intensive.  
651 The other inundations located a little South of Sommières and detected by the RIWS  
652 using SPC data are not identified here. As seen in Figure 2, SPC estimates tend to

653 extend the intense rainfall core to the North part of the region – as it can be confirmed  
654 by kriged data, and this is not reproduced by MF data.

655 Using the three best cases (calibrated CN for MF, SPC and kriging data), the warning  
656 thresholds have been reduced in order to detect all the floodings (POD=100%). It has to  
657 be noticed that a reduction of 90% of the threshold was necessary to detect every  
658 flooded roads, because one of the floodings was located in an area little affected by the  
659 intense precipitation (see Section 4.3.3). The evolution of POD and FAR skill scores are  
660 represented on Figure 8. One more time, it seems that detections using radar-based QPE  
661 are more efficient than those using kriging data. For a same value of POD, FAR score is  
662 always slightly lower for both MF and SPC data. Moreover, only kriging-based QPE  
663 has issued 100% of false alarms, while the other QPE always issue effective warnings.  
664 It could confirm that radar-based QPE better represent the spatio-temporal structure of  
665 precipitation.

#### 666 *4.3.2 On the improvement brought by QPF*

667 The use of QPF seems to be interesting in road submersion forecasting. All the results  
668 offer a significant anticipation (between 15 to 45 minutes), at least during the crucial  
669 steps of the event when POD highly increases, between 22:00 and 00:00. This  
670 anticipation is extended to the previous time steps depending on the accuracy of the  
671 QPE-based detection. Indeed, the contribution of forecasts looks being correlated with  
672 the quality of the detection noticed using QPE. A better anticipation resulting from the  
673 RIWS occurs when using SPC QPF, and among them, those obtained with the  
674 calibrated CN (see Figure 6). When small values of CN (40) are used, SPC QPF data  
675 provide less significant information. MF QPF appears to be useful only between 22:30  
676 and 23:30, when they allow preventing from inundations with a lead-time of 30  
677 minutes. During this short period, COR and FAR are better. Despite the propagation of  
678 the convective system to the east, the use of MF QPF appears to improve the skill  
679 scores, especially when the most intense precipitation occurred.

680 Regarding the best case (calibrated CN for SPC data), radar-based QPF can help to  
681 detect in advance the floodings during the entire storm. Skill scores obtained with  
682 QPF15 are very similar to those obtained with QPE but with an anticipation of 15  
683 minutes, meaning the quality of the rainfall forecast is quite good. The use of QPF30,  
684 QPF45 and QPF60 allow to detect the submersions with an advance comprised between

685 15 and 45 minutes, reflecting the quality of forecasts deteriorates with lead time.  
686 Regarding the response time of the concerned small watersheds (around 30 minutes),  
687 this anticipation of 45 minutes appears to be very important. In this case, the  
688 anticipation offered by simulations based on QPE is too limited to prevent from the  
689 submersion. Note the inundations detected during this anticipation time follow strictly  
690 the order of the inundations detected with the only QPE and that really occurred:  
691 starting from the submersions located on the west part on the study area until the  
692 inundations that occurred downstream the Vidourle watershed.

693

#### 694 *4.3.3 On the RIWS transfer and the use of the susceptibility analysis*

695 Overall, the results provided for this particular storm are quite similar to those obtained  
696 for the three storms studied during the calibration step (see Versini et al., 2010a) that are  
697 summarized in Table 4 and Figure 9. On the calibration area, the good results obtained  
698 in terms of flooding detection were due to the use of the susceptibility analysis. It  
699 allowed to focus in priority the RIWS on the most vulnerable road sections without  
700 having detailed rainfall estimate. The POD score was generally higher than 85% with a  
701 COR score very close to 100%. Nevertheless, the number of false alarms was yet  
702 significant with more than 60% of the warnings issued. Without the susceptibility  
703 analysis, the accuracy of the RIWS dropped significantly with POD around to 70% and  
704 higher FAR score, reaching 100% during the event. When comparing the results  
705 obtained on calibration and current areas in ROC space, it appears that the use of  
706 susceptibility analysis in calibration area allowed to improve the number of detections  
707 while decreasing the number of false alarms. It is not the case on the Vistre/Vidourle  
708 area, where the use of the susceptibility analysis seems to not be so significant and only  
709 leads to decrease the total number of issued warnings (both correct warning and false  
710 alarms scores are lower). Although they are not represented here, the skill scores have  
711 almost the same distribution if the susceptibility analysis is used or not to characterize  
712 the road intersections (see Table 4). The good scores provided by the best case  
713 (calibrated CN for SPC data) may result from the use of spatially distributed QPE. Here,  
714 the RIWS is focus in priority on the locations where the precipitation was the most  
715 intense. Two points can be noted to explain the limit of the susceptibility analysis  
716 transfer.

717 When the susceptibility analysis is used, intersections characterized by a high  
718 susceptibility can be hit by a warning without the two years return period being  
719 exceeded. Most of the intersections characterized by the highest level of susceptibility  
720 are located downstream of the Vistre and Vidourle watersheds, where subcatchments  
721 are, in general, bigger and flatter. Fortunately, this part of the territory was affected by  
722 intense rainfall, and many warnings were also reported, reaching 100% of false alarms  
723 at the beginning of the event. If the storm had been further north, the results would have  
724 probably been different. Second, the flooded road classified in the safe category is not  
725 identified as potentially inundated section when the susceptibility analysis is used. It is  
726 located downstream a very small catchment of 0.95 km<sup>2</sup> in the upper North part of the  
727 Vidourle watershed. Here, rainfall was heavy but not sufficient to exceed the fifty years  
728 return period discharge threshold required to deliver a warning. Indeed, the simulated  
729 discharge is characterized by a two years return period. We can hypothesize that local  
730 structural problem (under-dimensioning, jam, falling tree...) could have been  
731 responsible for the flooding.

732

733

## 734 **5- Conclusion**

735

736 The Road Inundation Warning System developed for flash flood prone areas, and  
737 recently calibrated on the North part of the Gard region, has been applied on the South  
738 part of the Gard. Working in a framework simulating operational conditions, the RIWS  
739 has been tested to predict the inundated roads during the 29-30 September 2007 event.  
740 These results obtained for this specific storm event are very similar to those obtained in  
741 the calibration area (Versini et al., 2010b). They are promising and encourage the use of  
742 radar based spatial rainfall data. This convective storm with important spatial variability  
743 is particularly interesting to legitimate the use of the weather radar. The prototype is  
744 able to rate the inundation risk with an acceptable level of accuracy: despite many false  
745 alerts, it has a relatively high probability of detection (proportion of actually flooded  
746 points affected by a significant risk level around 80% in the best case), and a good  
747 detection of non-flooded roads (correct negative higher than 98%). From these results,  
748 some conclusions can be made on the transfer of the RIWS on a region it has not been  
749 calibrated, and on the use of radar-based QPE and QPF delivered by both services in  
750 charge of hydro-meteorological risk management.



751 The use of weather radar QPE, *a priori* more representative of the spatio-temporal  
752 variability of rainfall than kriged rainfall fields based on rain gauge measurements,  
753 seem to provide better results when they are not too biased. By using a simple rainfall-  
754 runoff model, simulated discharges at the stream gauges have been improved by taking  
755 into account the spatio-temporal distribution of rainfall as depicted from radar data.  
756 Conversely, simulations using rough spatio-temporal resolution of kriged data are less  
757 satisfactory. This tends to confirm the spatial variability represents a major source of  
758 temporal variability in hydrological simulation (Obled et al., 1994; Sempere-Torres et  
759 al., 1999). Second, the use of radar-based QPE has improved the detection of road  
760 inundations. Skill scores are almost always better than those obtained with kriged data.  
761 As expected, radar-based QPE allow to better represent the structure of rainfall on small  
762 watersheds. When only kriged data are used, most of the non-detected inundations are  
763 located downstream small watersheds with an area smaller than 10 km<sup>2</sup>. It has been  
764 noted that both services (SPC and MF) do not provide radar-based QPE with the same  
765 accuracy for this particular case of the 29-30 September 2007 storm. While SPC QPE  
766 show a trend to overestimate rainfall on the Vidourle watershed, both services seem to  
767 describe correctly rainfall on the Vistre watershed. This conclusion is specific of this  
768 particular case study and should be different for another storm.

769 Adding radar-based QPF in real time can also improve the detection of inundations,  
770 especially for the cases where radar-based QPE already produced good results. In the  
771 best cases, the use of QPF can anticipate the inundations with up to 45 minutes ahead.  
772 This can represent valuable information from a practical point of view. Knowing that a  
773 severe storm will occur (a warning has been issued few hours before the beginning of  
774 intense rainfall) the road management and rescue services are prepared to intervene. If  
775 they receive the information where the roads could be flooded 30 or 45 minutes before  
776 it happen, they will have the opportunity to communicate and optimize the deployment  
777 of its teams. For now, the RIWS prototype should therefore not be considered as a  
778 decision support system but rather as a useful source of information - possibly  
779 completed by field observations - that can help the emergency services during a flood  
780 event to improve their decision.

781 The RIWS has shown a significant sensibility to precipitation input and rainfall-runoff  
782 model calibration. Using accurate radar-based QPE, the RIWS could be used to assess  
783 the results of the selected hydrological model and/or the definition of discharge

784 thresholds on ungauged basins. The results have demonstrated that the detection of  
785 flooding is very sensitive to the CN values (skill scores are usually better when CN is  
786 higher). The value of CN implemented on the ungauged area can also be discussed.  
787 Moreover, despite the difference between both SPC and MF estimates, almost all the  
788 inundated roads located on small streams of the Vistre watershed are missed, because  
789 the simulated discharges did not exceed any warning thresholds. One explanation could  
790 be that the average CN calibrated to simulate discharge on the main stream of the Vistre  
791 basin is not sufficient to reproduce correctly the discharges (underestimated) on small  
792 internal watersheds. The method proposed by Versini et al., 2010a) and calibrated on  
793 the North rural part of the Gard region to estimate *a priori* a range of two CN values  
794 may be unadapted here. CN values could probably be modified to take into account  
795 better the specificity of the land cover (very urbanized with the presence of the city of  
796 Nîmes) and the initial soil moisture. Another alternative is that theoretical return period  
797 thresholds, adjusted from a large-scale study, are here overestimated. Despite the  
798 intense rainfall and an acceptable simulation at Le Cailar, too few two years return  
799 period threshold are exceeded. As illustrated in the study, one way to estimate new  
800 discharge thresholds could be to adjust them in order to enable the RIWS to issue  
801 warnings for the submerged roads that occurred in this watershed. In general, the  
802 adjustment of new CN and threshold values will need additional events causing  
803 floodings in this area. Particular attention should be made on the real cause of the  
804 submersions in order to not to force the detection of a flooded road due to local  
805 structural problem.

806 Finally, the susceptibility analysis that has been previously developed on the North part  
807 of the Gard region has appeared to not be very satisfactory, for this particular event, on  
808 the South part, flatter and more urbanized. Despite inundated roads are classified in the  
809 highest susceptibility categories, numerous false alarms have been issued at the  
810 beginning of the event by the RIWS. This is due to the location of intense precipitation  
811 where intersections characterized by the highest level of susceptibility are concentrated.  
812 In the downstream part, too many intersections are comprised in this category, meaning  
813 discharges characterized by return periods shorter or equal to two years are sufficient to  
814 flood roads. Of course it is not true, but as a consequence too many road sections are  
815 identified as flooded. On the other hand, the presence of a submerged road in the safe  
816 category illustrates the method could not be adapted to this part of the Gard region.

817 Additional future events and submerged roads should be also necessary to grow the size  
818 of the different susceptibility categories and be more conclusive. This method could be  
819 modified in function of the specific configuration of the environment, but also be  
820 completed by post-field investigations (Gaume and Borga, 2008). The characterization  
821 of susceptibility, as discharge thresholds definition, could be improved with time and  
822 accumulation of damage data.

823 Nowadays, the RIWS seems to have potentials for capturing timing, magnitude, and  
824 spatial repartition of the flooding risk. Using accurate QPE and QPF, it gives indications  
825 about the areas where the roads are flooded, but inside these areas, a lot of false alarms  
826 are issued. That is why the susceptibility analysis represents a key part of the RIWS and  
827 should be improved. A good susceptibility analysis will allow to focus on the most  
828 vulnerable road sections and capture effectively the magnitude of the risk. Since no  
829 information is available on the time of inundation, we cannot conclude on the ability to  
830 capture the timing for now. The complementarity between the timing, the spatial  
831 repartition and the magnitude of the warning will make the RIWS reliable to define safe  
832 itineraries and/or prepare interventions from an operational point of view.

833

834

### 835 **Acknowledgment**

836

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843 Central des Ponts et Chaussées for sharing Prediflood project data  
844 (<http://heberge.lcpc.fr/prediflood/>).

845

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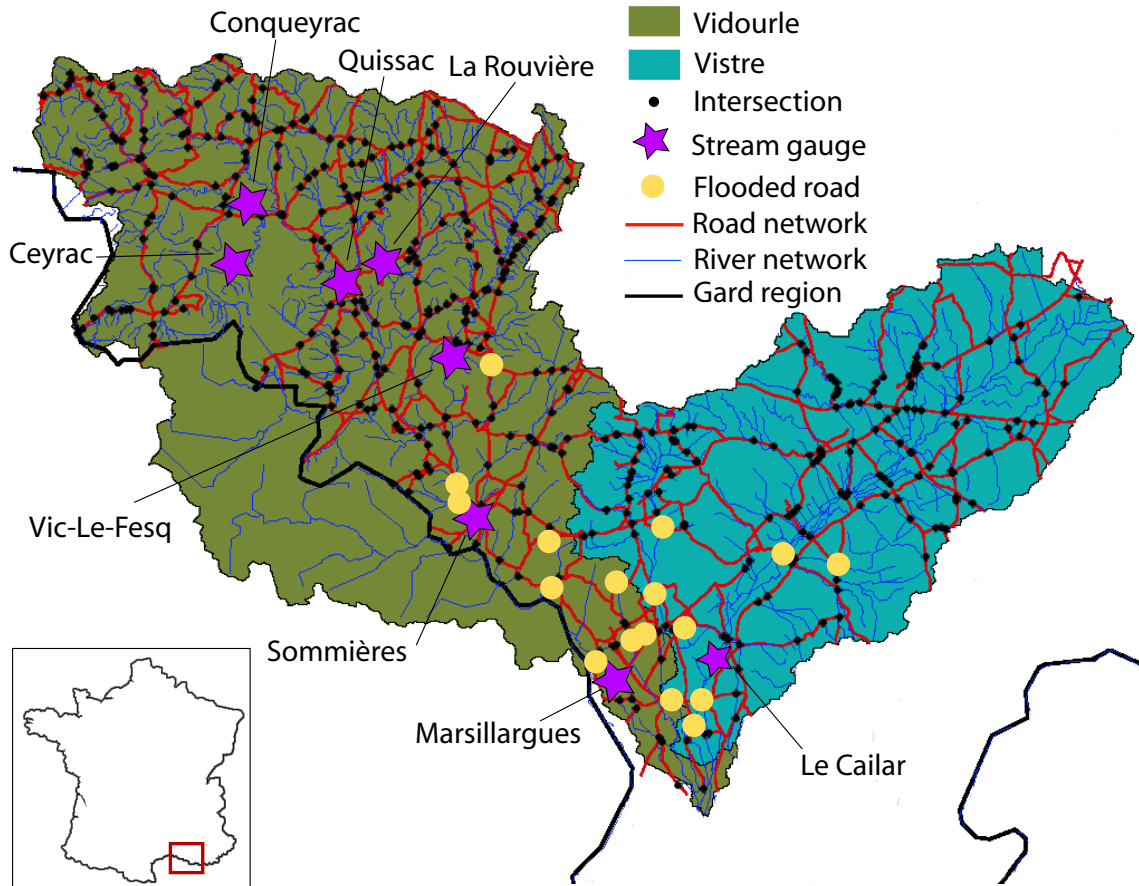
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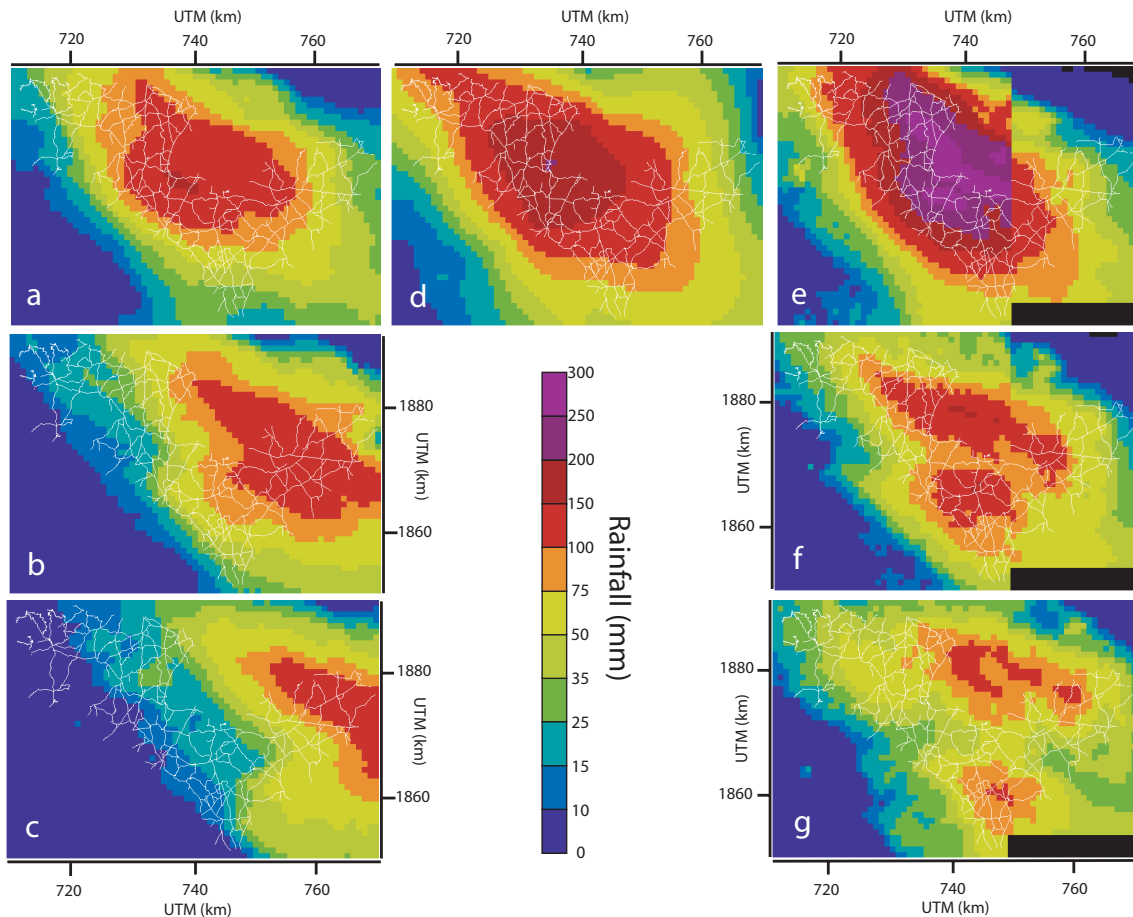
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975 **Figure captions**

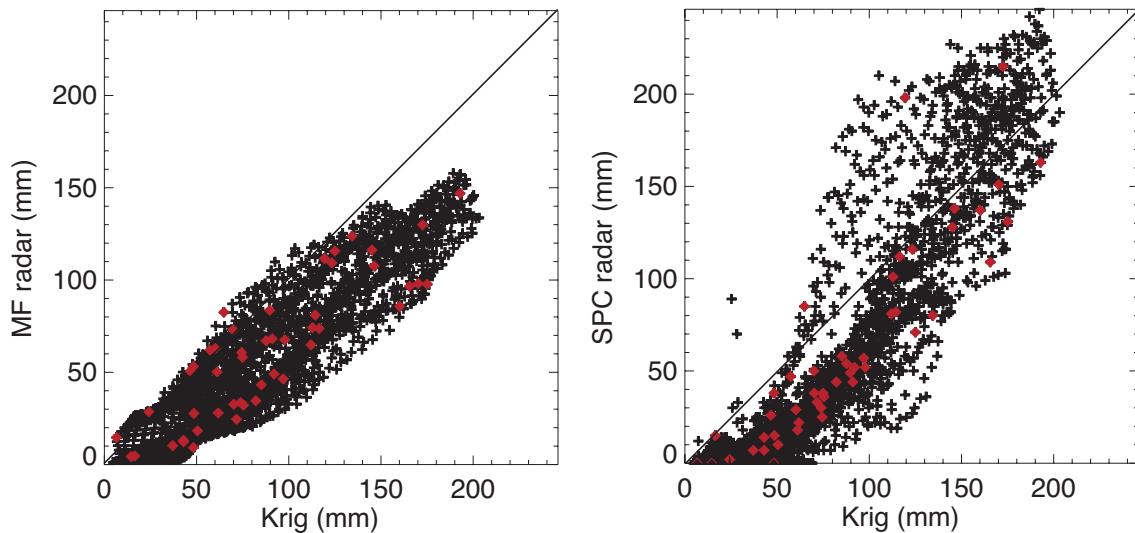


976  
977 Figure 1. The Vidourle and Vistre watersheds  
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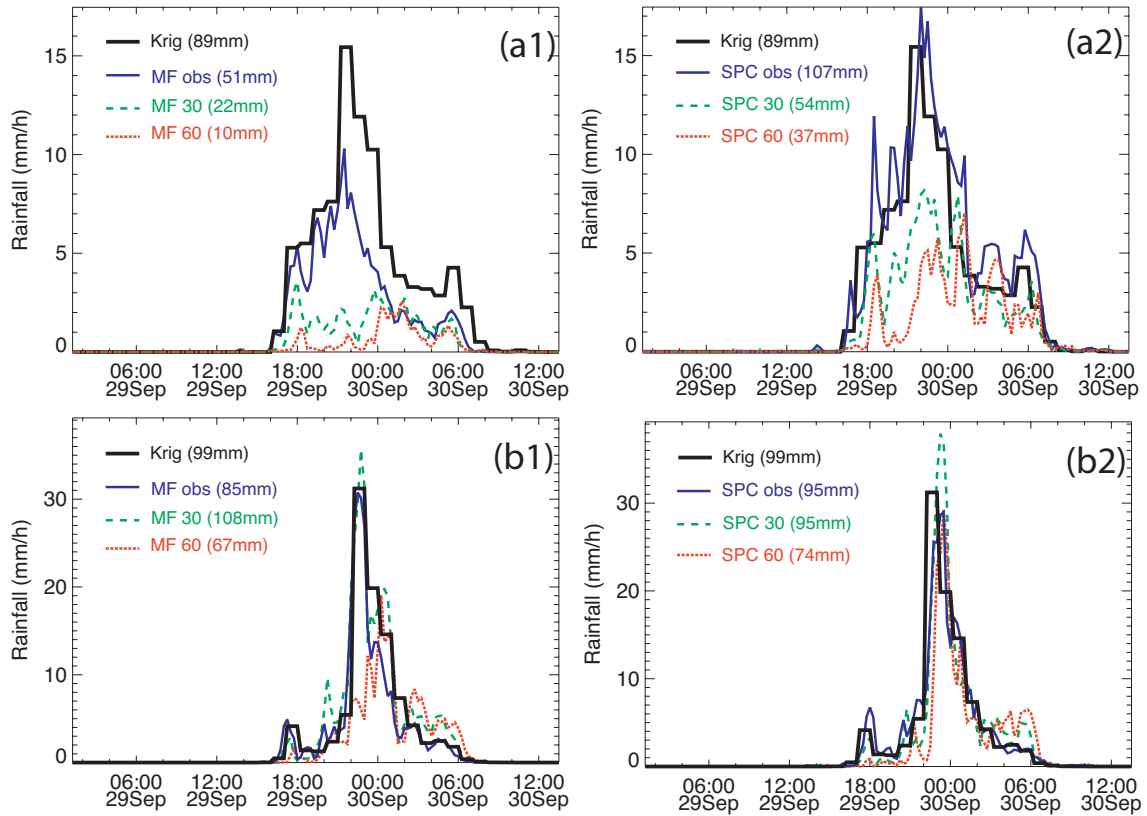
Figure 2. Rainfall accumulation: (a) MF QPE, (b) MF QPF30, (c) MF QPF60, (d) Kriging, (e) SPC QPE, (f) SPC QPF30, (g) SPC QPF60



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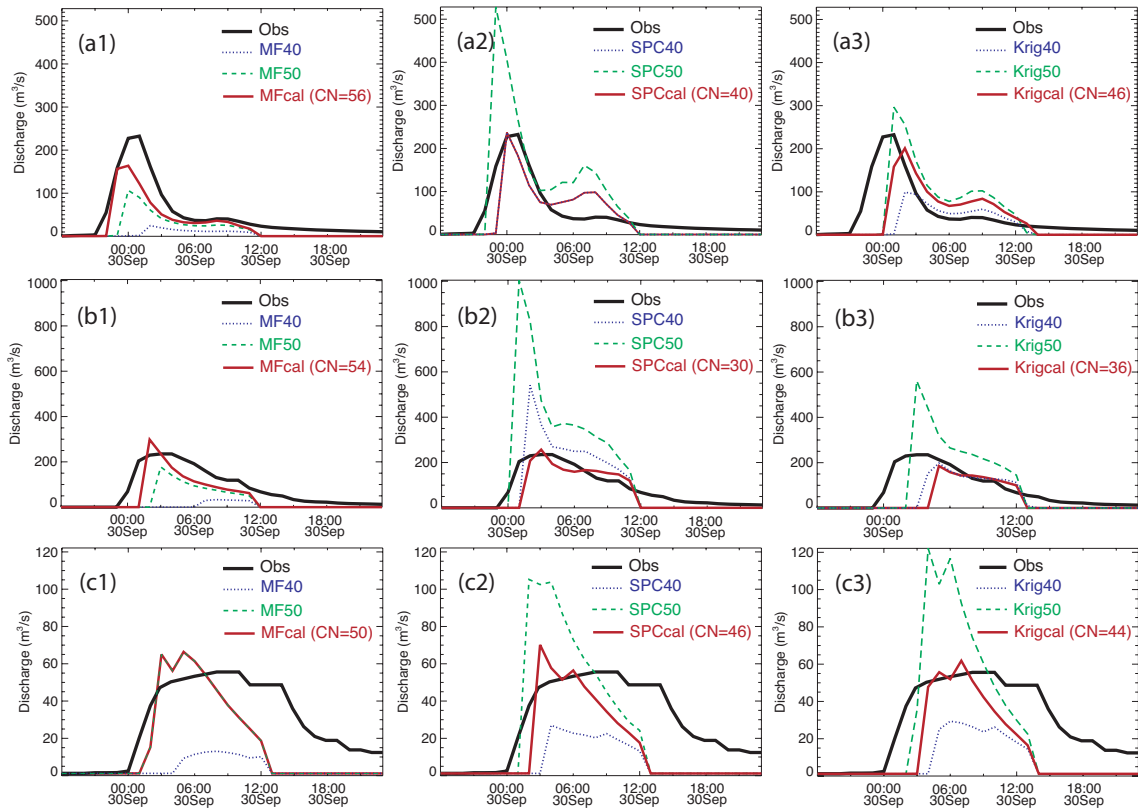
Figure 3. Scatter plots of precipitation accumulation at  $1 \text{ km}^2$ , (a) comparison between kriged data and SPC QPE, (b) comparison between kriged data and MF QPE. The red diamonds correspond to the rain gauge cells where the measure was made.





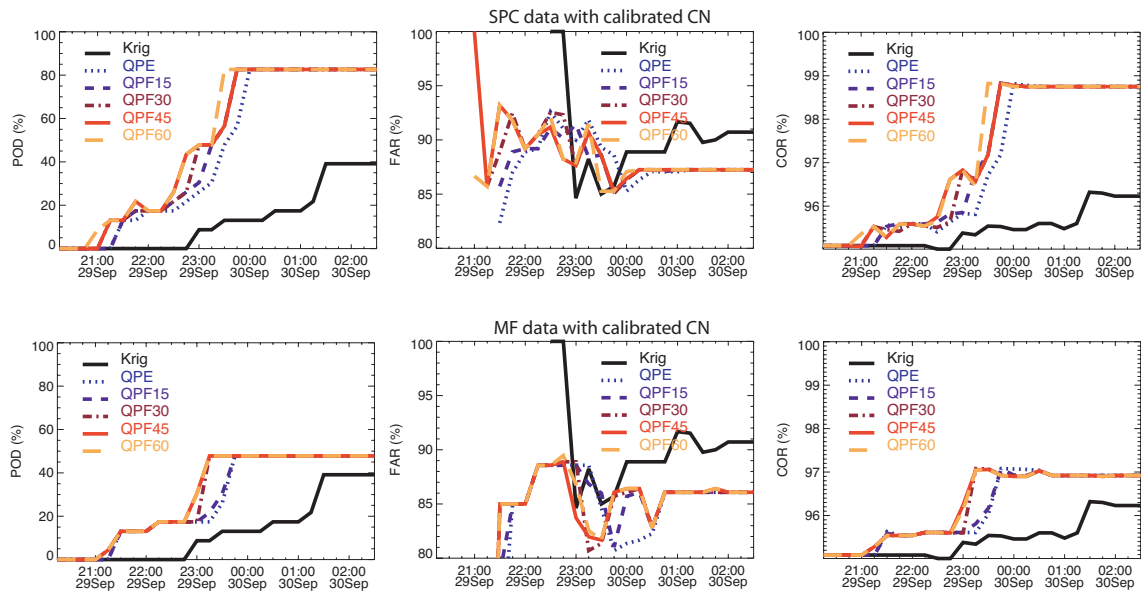
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Figure 4. Rainfall hyetogram and total amount of precipitation on the Vidourle watershed (a) and on the Vistre watershed (b), for MF data (1) and SPC data (2). Precipitation estimate is represented by full line, 30 minutes forecast data by spaced dotted line, 60 minutes forecast data by small dotted line, and reference kriging data by large full line.



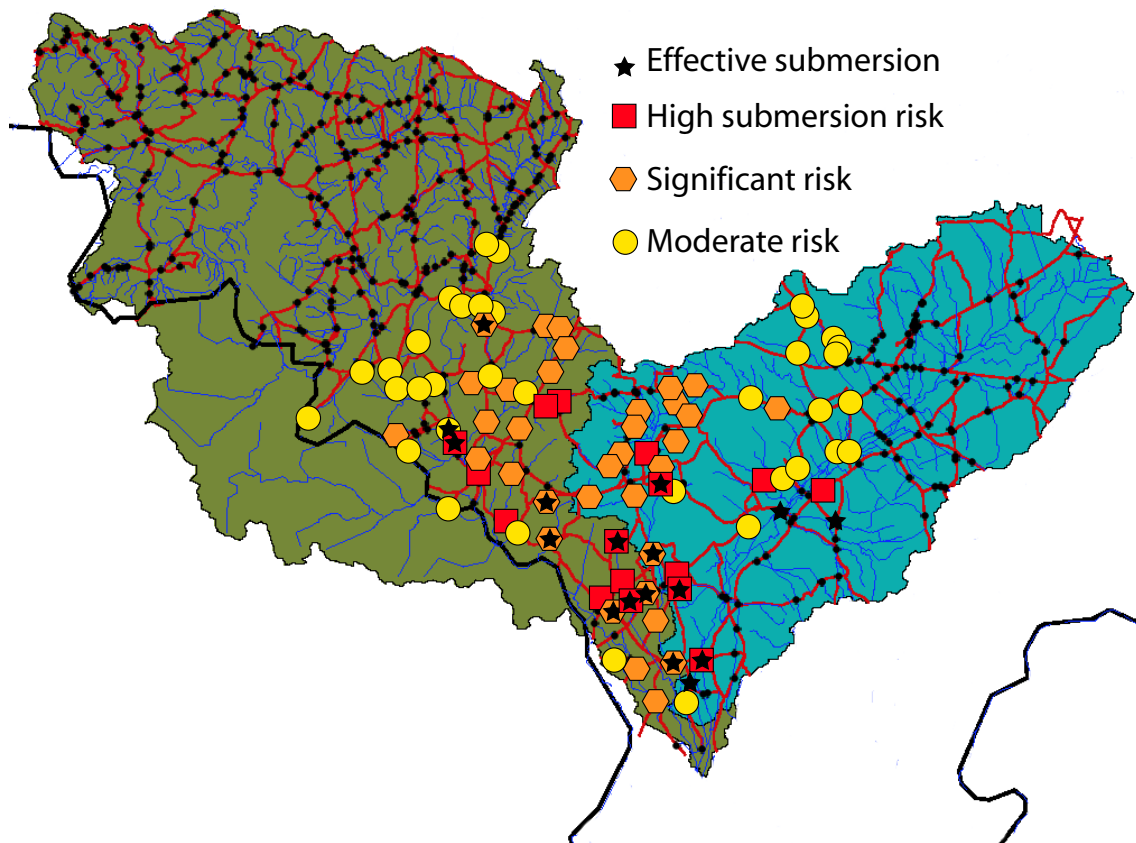
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Figure 5. Discharge simulations on Sommières watershed (a), on Marsillargues watershed (b), and on Le Cailar watershed (c), using MF data (1), SPC data (2), and kriging data (3). Observations are represented by full large black line, simulations based on *a priori* CN (40 and 50) by small and spaced dotted line, and calibrated CN (the value of CNcal is written in parentheses) by full red line.



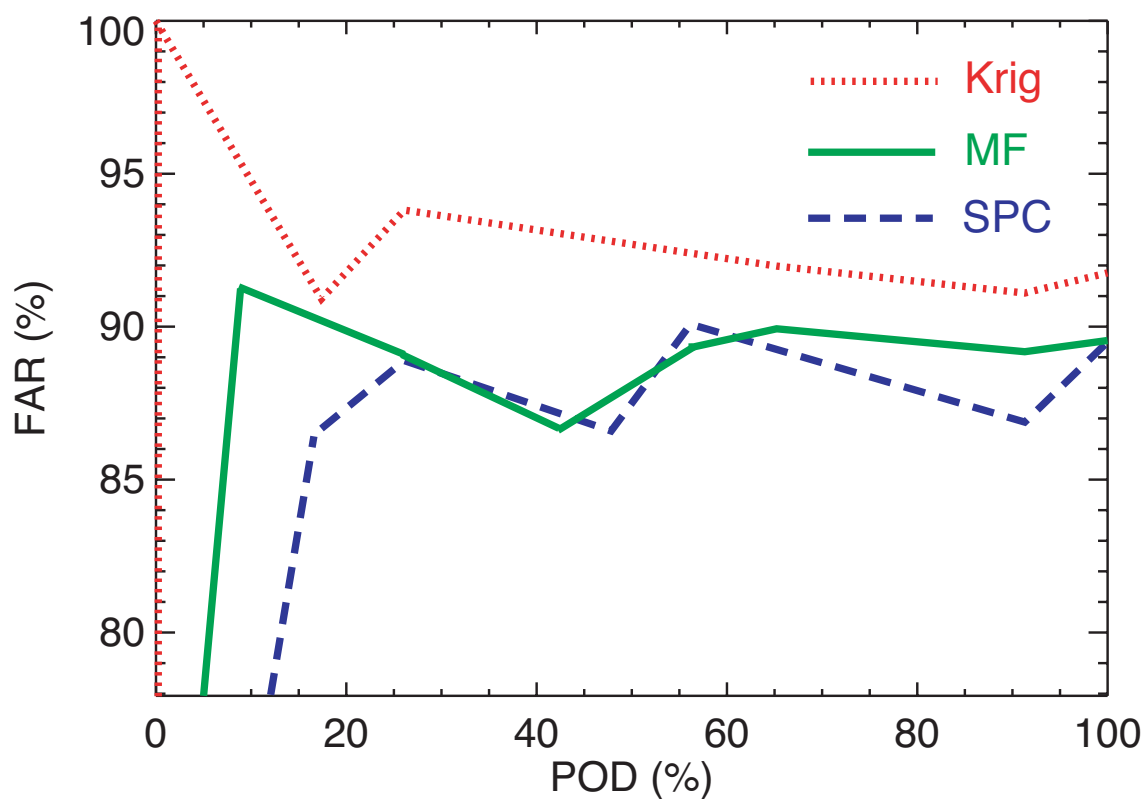
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Figure 6. Skill scores for SPC data (top) and MF data (bottom) with calibrated CN. *QPE* represents the skill score calculated with the only estimations, *QPF15* those with the 15 minutes forecast added, respectively *QPF30*, *QPF45*, *QPF60* with the 30, 45, and 60 minutes forecasts added. Finally, *Krig* represents the skill score computed using kriged data



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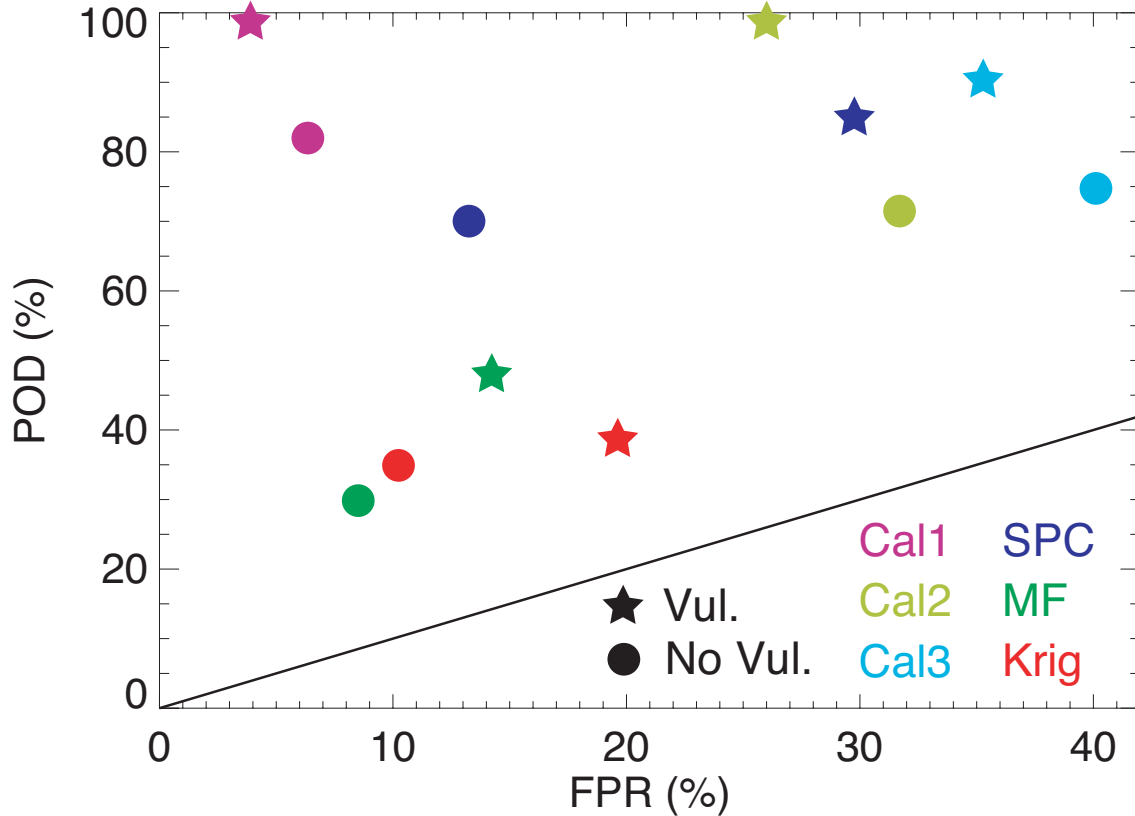
Figure 7. Warnings issued by the RIWS during all the event using SPC QPE, CNcal and the susceptibility analysis



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Figure 8. Evolution of FAR and POD skill scores reducing the warning threshold for kriging, MF and SPC QPE using the calibrated CN.

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Figure 9. Inundation forecasts represented in the ROC space. The results obtained for the 3 calibration events (Cal1, Cal2 and Cal3) are compared to those computed with SPC, MF, and Krig QPEs. POD and FPR values are calculated using the total number of correct warnings and false alarms issued during the event.

**Table captions**

	$Q_2/2 < Q_{sim} < Q_2$	$Q_2 < Q_{sim} < Q_{10}$	$Q_{10} < Q_{sim} < Q_{50}$	$Q_{sim} > Q_{50}$
Susceptibility High	SR	HSR	HSR	HSR
Susceptibility Medium	MR	SR	SR	HSR
Susceptibility Low	No risk	MR	MR	SR
Safe	No risk	No risk	No risk	MR
No susceptibility analysis	No risk	MR	SR	HSR

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Table 1. Risk levels based on exceeded discharge thresholds – with susceptibility category or without

Category of susceptibility	Calibration area	Study area	Submerged intersections
High	8%	12%	35%
Medium	22%	20%	30%
Low	54%	50%	30%
Safe	16%	18%	5%

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Table 2. Repartition of the road sections between the four susceptibility categories using the road susceptibility rating method applied on the previous calibration area, on the Vistre and Vidourle area and on the 29-30 September 2007 storm flooded road

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	SPC40	SPC50	SPCcal	MF40	MF50	MFcal	Krig40	Krig50	Krigcal
Sommières	0.81	-0.65	0.81	-0.18	0.44	0.73	0.00	-0.13	0.28
Marsillargues	0.19	-4.05	0.70	-0.32	0.40	0.67	0.18	-0.19	0.35
Le Cailar	0.03	-0.06	0.39	-0.26	0.43	0.43	0.10	-0.24	0.37

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1036 Table 3. Nash efficiency for discharge estimation using CN=40, CN=50 and CNcal for  
 1037 the following watersheds: Sommières (a), Marsillargues (b), and Le Cailar (c)

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	SPC			MF			Krig			<i>Cal</i>
	40	50	Cal.	40	50	Cal.	40	50	Cal.	
POD	60.2/56.5	82.6/78.3	82.6/69.6	0/0	34.8/17.4	47.8/30.4	14.0/0	58.3/50.1	39.1/34.8	<b>76.0/96.0</b>
COR	97.8/97.6	98.8/98.6	98.8/98.2	95.2/95.4	96.5/95.7	97.1/96.2	95.5/0	97.3/97.1	96.3/96.3	<b>96.3/98.2</b>
FAR	90.2/75.5	87.3/84.8	87.2/78.4	0/0	86.7/90.0	86.1/85.4	86/100	87.3/89.5	93.7/87.7	<b>63.0/73.0</b>

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1040 Table 4. Summary of the RIWS maximum skill scores for the different types of QPE  
 1041 (SPC, MF and kriged data) and different CN values. The left value is computed without  
 1042 considering the susceptibility analysis, the right one considering the susceptibility. The  
 1043 last column contains the average results obtained in the calibration area for 5 events.  
 1044