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## Karst flash-flood forecasting in the city of Nîmes (southern France)

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32 through permanent or intermittent karst springs; 7) Strong and fast fluctuations of the water  
33 table in karst areas; 8) Interbasin overflow and/or redistribution of catchment areas caused by  
34 groundwater rise; 9) Limited discharge capacity of karst springs; and 10) Limited capacity of  
35 swallow-holes.

36 Studies on the Coulazou river in south of France (Bailly-Comte, 2012) show that karst  
37 watersheds can be considered as hydrological systems with low retention capacities and risk  
38 of strong amplification or generation of floods and flash floods. Rainfall characteristics and  
39 groundwater level conditions prior to the flood event are the main factors involved in karst  
40 flood generation. Considering that the flood maximum discharge is the most important  
41 parameter defining flash flood hazard, the aggravating effect due to high water table  
42 conditions prior to the rainy event may be higher than 80% with respect to expected values  
43 from surface runoff only. In the Nîmes area, the study of the double rainfall event of  
44 September 2005 has shown that the karst aquifer saturation (by the first event) induces a  
45 decrease of the retention capacity of the watershed from 85 % to 0%; corresponding to runoff  
46 coefficients of 15 and 100 % respectively for the first and the second events (Maréchal et al.  
47 2009). These results show that understanding groundwater–surface water interactions is  
48 crucial for describing the flash flood dynamics in karst terrains.

49 The important role played by groundwater requires its consideration in the design of warning  
50 systems and forecasting tools (Maréchal et al. 2008). Actually, there is no flood management  
51 strategies commonly accepted for karst basins. Only few studies exist on this topic. An  
52 example of flash flood modelling was proposed in Koiliaris River basin in Crete (Kourgialas,  
53 2012). The knowledge, in real time, of the flash flood prediction model, was used to mitigate  
54 the highest flash flood events. The difficulty in modelling such hydrosystems is mainly due to  
55 the interaction between surface- and groundwater. A modelling tool based on a reservoir  
56 approach of surface- and groundwater systems is described in this paper. It is applied to the  
57 Nîmes karst basin prone to flash-flooding, and used for designing a forecasting and flood-alert  
58 system.

## 59 **1- NÎMES KARST SYSTEM HYDROLOGY : STUDIES FOR SYSTEM** 60 **CHARACTERISATION**

### 61 **1.1. Geological and hydrological settings**

62 The Fontaine de Nîmes (FdN) spring is located in the south-eastern France, in the city of  
63 Nîmes. Most of the time, it is the only discharge point of a karst system that is famous for its  
64 rapid reaction to rainfall events. The unsaturated zone is at most 10-m thick and the saturated

65 zone is limited to a few tens of metres. A well developed karst network drains the aquifer to  
66 the FdN spring.

67 The karst basin (Fig. 1), defined by numerous tracing experiments (Fabre, 1997) and water-  
68 budget calculations (Pinault, 2001; Maréchal et al., 2005), is estimated to be about 55 km<sup>2</sup>.  
69 The area is heavily built-up in the southern part and covered by natural Mediterranean  
70 vegetation ('garrigue') in the north. The catchment area is mainly composed of limestone of  
71 Hauterivian (Cretaceous) age. The city lies at the bottom of a hill at the convergence of three  
72 intermittent streams called "cadereaux", a local term designating the small valleys around  
73 Nîmes traversed very temporarily by torrential flow during rainfall events: the Uzès stream  
74 from the east, the Alès stream from the north and the Camplanier stream from the west. These  
75 streams are monitored for their discharge by the municipal services in order to organize flood  
76 alerts and manage the emergency services during flood crises.

## 77 1.2. Recession analysis

78 The recession shape of a hydrograph is influenced by the size of the karst aquifer, but it is  
79 also a function of hydrodynamic characteristics, such as the infiltration rate into the vadose or  
80 unsaturated zone and the flow-rate of water in the saturated zone. In general, it is considered  
81 that the recession curve is influenced by two components: **quickflow** through the network of  
82 channels, and **baseflow** through the porous matrix and its small cracks and stratification  
83 joints. Analysis of FdN flow during the very long dry period of 2005 (Fig. 3) has shown that  
84 three components (one baseflow + two quickflow components) are necessary to explain the  
85 flow recession. According to the Mangin (1975) expressions, the discharge at time t can be  
86 expressed via the formula:

$$87 \quad Q(t) = q_0^b e^{-\alpha t} + q_0^{*1} \frac{1 - \eta_1 t}{1 + \varepsilon_1 t} + q_0^{*2} \frac{1 - \eta_2 t}{1 + \varepsilon_2 t} \quad \text{Eq. 1}$$

88 where the first term of the sum is the baseflow at time t ( $q_0^b$  is the baseflow extrapolated from  
89  $t_i$  at the start of recession and  $\alpha$  is the baseflow coefficient) expressed by Maillet's formula  
90 (1905). This component corresponds to the drying-up of the saturated zone.

91 The second term of the equation is an empirical function describing the first component of  
92 quickflow at time t ( $q_0^{*1}$  is the difference between the total discharge  $Q_0$  at the spring at time  
93  $t=0$  and the sum of baseflow component  $q_0^b$  and second quickflow component  $q_0^{*2}$ ;  $\eta_1$  is  $1/t_{i1}$ ;  
94  $\varepsilon_1$  characterizes the importance of the concavity of quickflow in terms of  $t^{-1}$ ). This function is  
95 defined between  $t = 0$  and  $t_{i1}$ , which is the duration of first quickflow. This component  
96 corresponds to the influence of rapid infiltration into the epikarst.

97 The third term is an empirical function describing the second component of quickflow at time  
98  $t$  ( $q_0^{*2}$  is the difference between total discharge  $Q_0$  at the spring at time  $t = 0$  and the sum of  
99 baseflow component  $q_0^b$  and first quickflow component  $q_0^{*1}$ ;  $\eta_2$  is  $1/t_{i2}$ ;  $\varepsilon_2$  characterizes the  
100 importance of the concavity of the quickflow in terms of  $t^{-1}$ ). This function is defined between  
101  $t=0$  and  $t_{i2}$ , which is the duration of second quickflow. This component corresponds to the  
102 influence of slow infiltration into the epikarst.

103 The various coefficients of Eq. 1 ( $\alpha$ ,  $\eta$ ,  $\varepsilon$ ) are defined using a modified version of the classical  
104 Mangin method (see figure 2 - Mangin conceptual model) which is a graphical method based  
105 on the fitting of the recession flow curve. Result is presented on Fig. 3. This method permits  
106 the identification of three components of discharge which are presented on Fig. 3. Associated  
107 volumes can be calculated, including their durations which are directly read on the graph.

108 The duration of rapid infiltration is quite short (30 days) and the infiltration velocity is rather  
109 high ( $0.033 \text{ m.d}^{-1}$ ). This indicates that part of the infiltrated rainfall rapidly enters the  
110 saturated zone of the system through a fissure network connected to the infiltration zone  
111 (epikarst). This component represents 40% ( $1.33 \text{ million m}^3$ ) of the total infiltrated volume.  
112 Rapid infiltration contributes to much (80%,  $1.2 \text{ m}^3/\text{s}$ ) of the total spring flow ( $1.45 \text{ m}^3/\text{s}$ )  
113 three days after the recession start.

114 Another part of the efficient rain infiltrates through a fracture network that is not well  
115 connected to the saturated zone. The volume of slow infiltration is  $1.95 \text{ million m}^3$ , about  
116 60% of total infiltration. Duration of slow infiltration is about 225 days. Infiltration velocity  
117 of this slow component is very low at  $0.004 \text{ m.d}^{-1}$ .

118 The recession coefficient  $\alpha$  is very low ( $0.006 \text{ m.d}^{-1}$ ), indicating that the saturated zone is  
119 drying up slowly as the karst network is not well connected to the saturated zone. The  
120 dynamic volume is low ( $0.72 \text{ million m}^3$ ) compared to the total flow through the system of  
121  $17 \text{ million m}^3/\text{year}$ . Therefore, the regulation power of the system is very low (0.04), and the  
122 karst system cannot store a large amount of water in its saturated zone.

123 Those karst parameters defined from 2005 recession flow are summarised in Tables 1 and 2.

124 Examination of the sorted-discharge-rates diagram of the FdN spring over a long period  
125 (1998-2005: Maréchal et al., 2008, 2009) shows that during high flood periods ( $Q > 13$  to  
126  $15 \text{ m}^3 \text{ s}^{-1}$ ) the hydraulic properties of the hydrosystem change: the discharge rate at the main  
127 spring increases less rapidly. This is typical of a participation of other, intermittent, overflow  
128 springs to the total discharge of the system; therefore, the discharge at the main spring

129 increases less because water flows elsewhere. The presence of less permeable Quaternary  
130 deposits filling the valley downstream is responsible for this type of hydrogeological  
131 behaviour.

### 132 **1.3. Conceptual model of flow**

133 During low-flow conditions (Fig. 4a), the water table in the matrix is close to the level of the  
134 karst conduit network. Discharge at the outlet is very low. During flood conditions (Fig. 4b),  
135 the vadose zone is quickly saturated as it is very thin (only a few tens of metres). Water  
136 infiltrating in swallow holes flows rapidly through the karst conduits and contributes to  
137 drastically increasing the spring discharge. However, as the karst conduits are too small for  
138 the total amount of water, backflooding in sinkholes connected to the main karst conduits  
139 leads to intermittently flowing springs. Similarly, the saturated epikarst gives rise to further  
140 intermittent springs.

141 The specific characteristics of the Nîmes karst that favour flash floods are: (i) High infiltration  
142 rates due to scarce and highly permeable soils; (ii) Rapid infiltration of storm flow entering  
143 the aquifer through sinkhole drains, (iii) Rapid circulation in the well-developed karst  
144 conduits; (iv) Backflooding and sinkhole flooding close to the spring due to conduit  
145 constriction; and (v) A small storage capacity of the fissured karst system, generating runoff  
146 of the excess water that cannot infiltrate .

## 147 **2- MODELLING THE CONCEPTUAL MODEL: DRAIN WATER-LEVELS AND**

### 148 **FONTAINE DE NÎMES DISCHARGE**

#### 149 **2.1. Karst-system functioning and impact on floods**

150 The major role of karst groundwater in flood genesis means that this component must be  
151 taken into account in the ‘ESPADA’ warning system of Nîmes Municipality, which up to now  
152 was based essentially on the monitoring of surface floods, using limnimeters and video  
153 cameras, and of rainfall using rain gauges and radar (Delrieu et al., 1988, 2004). In fact, the  
154 karst water-table requires regular monitoring as an indicator of aquifer saturation during flood  
155 crises.

156 In the case of Nîmes, studies show that when the karst aquifer reaches a saturation level  
157 “*threshold*”, recharge to the aquifer becomes limited and overflow can occur from temporary  
158 springs. This excess runoff component, here called “*karst component*”, is due to a decrease in  
159 infiltration capacity and overflow from temporary springs. This karst component induces a

160 non linearity in the system, with a sudden rise in discharge once the saturation threshold is  
161 reached.

162 This condition appears when discharge at FdN spring exceeds 13 to 15 m<sup>3</sup>/s, corresponding to  
163 a water level of 53 masl (metres above sea level) at FdN. The option that was adopted is to  
164 model the karst-conduit water level. The modelling findings should permit forecasting when  
165 the threshold is reached and the resulting occurrence of the karst component that induces  
166 floods.

## 167 **2.2. Different types of models**

168 Conceptual or reservoir models are developed using the results of a hydrogeological study  
169 that determines the general aquifer structure and the overall functioning of the system. They  
170 consist of simple transfer equations linking connected reservoirs. The reservoirs fill and  
171 empty, transforming rainfall into flow rates. The structure of these models is generally based  
172 on a production function and a transfer function. Reservoir models remember the previous  
173 hydraulic head in each reservoir and simulate the main steps of the flow dynamics. This type  
174 of model is commonly used in hydrology for flow-rate or groundwater-level simulations using  
175 rainfall data (rainfall-discharge or rainfall/groundwater-discharge models), and includes  
176 TOPMODEL (Beven and Kirkby, 1979), HBV (Bergström and Forman, 1973), IHACRES  
177 (Jakeman et al., 1990), and GR4J (Perrin et al., 2003).

178 The simulations of the major drain water level and spring discharges have been done using  
179 reservoirs models. A reservoir model describes a hydrological system using reservoirs in  
180 cascades representing sub-systems which interact together through simple physical laws. This  
181 type of model simulates the relationship between rainfall (as an input) and discharge or water  
182 level (as an output).

183 This method, already applied to many karst systems, is well suited for deciphering their  
184 overall behaviour (Larocque et al., 1998; Labat et al., 2002; Denic-Jukic and Jukic, 2003;  
185 Rimmer and Salingar, 2006; Dörfliger et al., 2009; Fleury et al., 2009).

186 In our study, Vensim® software was used for developing a 15-minutes time-scale model that  
187 reproduces the Mazauric-drain water level and spring discharge. This time scale is  
188 deliberately short and was chosen to be consistent with the Nîmes flood-alert system. The  
189 model is characterized by two reservoirs, one representing soil, the other the saturated karst  
190 zone.

## 191 **2.3. Data**

192 The Nîmes region is characterized by high storm variability that causes strong spatial  
193 differences in rainfall data. For that reason, rainfall was estimated using two different  
194 methods. For medium- and low rainfall events, a weighting technique based on Thiessen  
195 polygon (stations weighted according to their relative areas defined using a polygonal  
196 analysis) of three rainfall stations was used, which are Anduze, Uzès and Bonfa (Fig 1). The  
197 inherent uncertainty of this method is estimated at 20 to 30% due to high space and time  
198 variability of rainfall on the catchment of the karst spring (Météofrance, pers. Comm). For  
199 major discharge events, however, rainfall is distributed over the entire watershed covered by  
200 nine rainfall stations again using the Thiessen polygon method. For recent events, radar  
201 images are used as well. The latter method is more accurate and uncertainty is reduced to  
202 about 10%.

203 Five major events have been identified since 1988, and all were associated to an important  
204 discharge in the cadereaux. These events are the October 1988, May 1998, September 2002,  
205 September 2005, September 2010 ones. Cumulative rainfall for these events is given in  
206 Table 3. Note that the September 2005 event was characterized by a double rainfall event on 6  
207 and 8 September, with at least 200 mm precipitation each time. In November 2004, another  
208 significant storm occurred, but discharge in the Alès cadereau was minor ( $<20 \text{ m}^3/\text{s}$ )  
209 compared to other important events. We will demonstrate hereafter why this event is still  
210 important for calibration purposes.

211 Drain water-level measurements started at FdN spring in October 1998 and are ongoing. The  
212 probe was deficient in September 2002, for which reason the September 2005 event is the  
213 only important one with groundwater data. A flow meter was operational from October 2004  
214 until April 2005. The discharge data permit defining the rating curve at the spring. For the  
215 water-level data, the threshold of 53 masl (meters above sea level) was reached three times: in  
216 November 2004 (53.1 masl), on 6 September 2005 (53 masl) and 8 September 2005  
217 (53.5 masl). Water level was close to the threshold on September 2010 (52.9 masl). The  
218 November 2004 and September 2010 events were very interesting because the drain water-  
219 level reached the threshold or was close but cadereau maximum discharge was not very high.  
220 For this reason, November 2004 and September 2010 events constitute reference events for  
221 the karst-component contribution assesment.

#### 222 2.4. Model structure

223 The *soil reservoir* was modelled for calculating infiltration; it feeds the *saturated zone (drain*  
224 *and matrix)* reservoirs. The infiltration was calculated from rainfall as inflow and actual

225 evapotranspiration, AET, as outflow. Infiltration occurs when the soil reservoir is full, when it  
226 cannot store any more water.

227 The soil reservoir is characterized by a water height,  $H_{soil}$ , that fluctuates according to the  
228 input and output of the reservoir. At time  $t$ , this depth is equal to that of the preceding time  
229 step to which is added the depth of the rainfall and from which one subtracts the discharge  
230 from AET and the infiltration, according to the following volume conservation equation  
231 (Fig. 5):

$$232 \quad (H_{soil})_{t1} = (H_{soil})_{t0} + \text{Rainfall} - \text{AET} - \text{Infiltration} \quad \text{Eq. 2}$$

233 All variables are water heights in mm.

234 After a long drought period, it is observed that the first 50 mm of rainfall do not produce any  
235 rise at the spring, but more rain produces an increase in the groundwater level at the spring.  
236 This means that the first 50 mm contribute to filling the shallow level in our model soil  
237 reservoir, and extra rainfall contributes to infiltration.

238 AET discharge obeys Maillet's law, which describes reservoir outflow through a porous  
239 outlet (Maillet, 1905). Under these conditions, a variation in the amount of discharge  
240 corresponding to a variation in water height of the reservoir is written as:

$$241 \quad (H_{out})_t = (H_{out})_0 \cdot e^{-\alpha t} \quad \text{Eq. 3}$$

242 where  $(H_{out})_t$  is the discharged water height at time  $t$  (m/time unit),  $(H_{out})_0$  is the discharged  
243 water height at  $t = 0$  (m/time unit), and  $\alpha$  is the recession coefficient of the reservoir (1/time  
244 unit), the time unit being 15 minutes.

245 The water height leaving the reservoir each time is determined using the following equation:

$$246 \quad \int_t^{t+1} H_{out} = \alpha * H_{reservoir} (t) \quad \text{Eq. 4}$$

247 where  $H_{out}$  is the water height leaving the reservoir (m/time unit), and  $H_{reservoir}$  is the water  
248 height in the reservoir (m).

249 In this case, the  $\alpha$  soil reservoir coefficient defined by a manual "trial and error" calibration  
250 is 0.0003 m/15min. This value permits a good reconstruction of infiltration happening after  
251 different drought periods. After 50 days without rain, the soil reservoir is almost empty (less  
252 than 10 mm left).

253 The saturated zone is represented by two routing reservoirs, matrix and drain, that are both  
254 characterized by a water height,  $H$  drain/matrix, that fluctuates according to the input and

255 output of the reservoir. At time  $t$ , this depth is equal to that of the preceding time step, to  
256 which is added the infiltration water height and from which one subtracts the discharge of the  
257 system, according to the following equation:

$$258 \quad (H_{\text{drain}})_{t1} = (H_{\text{drain}})_{t0} + \text{infiltration} - H_{\text{rapid discharge}} \quad \text{Eq. 5a}$$

$$259 \quad (H_{\text{matrix}})_{t1} = (H_{\text{matrix}})_{t0} + \text{infiltration} - H_{\text{slow discharge}} \quad \text{Eq. 5b}$$

260 where  $H_{\text{drain/matrix}}$  is the water height in the saturated reservoir (drain and matrix).  $H_{\text{rapid}}$   
261 discharge and  $H_{\text{slow}}$  discharge are the water leaving the karst system at each time step,  
262 feeding the Fontaines de Nîmes spring.  $H_{\text{out drain}}$  represents rapid discharge and  $H_{\text{out matrix}}$   
263 represents slow discharge. All the variables are water heights in m.

264 Discharge from the drain saturated-zone reservoir as soil reservoir obeys Maillet's law.

265 The  $\alpha$  drain saturated-zone reservoir calibration value defined by a step by step trial and error  
266 method is 0.005 m/15min.

267 The  $\alpha$  matrix saturated-zone reservoir reproduces the recession; its value, defined by results  
268 from flow-recession-curve analysis, is 0.006 m/day, or 0.0006 m/15min.

269 When the threshold in karst is reached (53 m asl in FdN), the karst component occurs and  
270 there will not be as much water from infiltration filling in the karst reservoir. Good results for  
271 modelling water levels are obtained with a diversion coefficient of 70% of infiltration as  
272 overflow. These modelling results show that when the karst aquifer is full, only a minor part  
273 of rainfall infiltrates through the soils while a major part is flowing to the surface stream  
274 network.

275 Studies of recession curves analysis part 1.2. (Figure 3 and Table 1) show that fast infiltration  
276 represents 40% and the slow component 60%. Therefore, to reproduce spring discharge,  
277 drain- and matrix-reservoir contributions are respectively 40% and 60% of the recharge area  
278 (55 km<sup>2</sup>).

279 In order to reproduce the water levels measured in the drain at the karst outlet, water levels in  
280 the *Drain Saturated-Zone* reservoir were multiplied by a newly fitted parameter. Level 0 in  
281 the Saturated-Zone reservoir corresponds to the low-water level value of 51.1 m commonly  
282 observed, except in September 2005 after a 9-month drought when the groundwater level fell  
283 to 50.8 m.

284 Results of the FdN drain water level and discharge obtained with the model are given in  
285 Figures 6 and 7.

286 The model was developed and tested for the October 2004 to March 2006 period, when two  
287 significant events were recorded: November 2004 and September 2005. November 2004 was  
288 defined as the reference event for karst contribution and September 2005 as the strongest  
289 event of the last 20 years with more than 400 mm of rainfall within three days. Both events  
290 are well simulated for drain water level and spring discharge.

291 The model has been validated on September 2010 event. This event is not of major  
292 magnitude; nevertheless it represents, as the event of November 2004, a transitional event; it  
293 is also the rainiest event (180 mm of rainfall) in 24 hours since September 2005. The rainfall  
294 occurs after the summer, during dry conditions. The first 50 mm allow to saturate the soil  
295 reservoir, afterwards the karst recharge occurs. Water level simulation presented in Fig. 8  
296 shows that the maximum water level simulated is well represented, which validates the  
297 approach.

298 The model was then applied to the main flood events, i.e. October 1988, May 1998,  
299 September 2002 and September 2010 (Fig 9). October 1988 and September 2002 caused  
300 significant flow in the Alès cadereau ( $>40 \text{ m}^3/\text{s}$ ), and were associated with the occurrence of a  
301 karst component, meaning that the karst threshold had been reached. May 1998 and  
302 September 2010 were transitional events, as November 2004, water level was closely below  
303 the threshold and the maximum discharge in cadereau was not very high ( $<20 \text{ m}^3/\text{s}$ ).

304 For most of the main events, water-level data were not available, but the high discharge rates  
305 measured in the cadereau streams show that the karst component occurred. The simulations of  
306 these events (Table 4) agree with this observation: the threshold of 53 m was systematically  
307 reached for major events.

### 308 **3- TOOLBOX FOR FLOOD MANAGEMENT: CONSTRUCTION OF AN ABACUS**

309 The model was then used for preparing a user-friendly tool for flood management. A  
310 “*Rainfall vs. Drain water-level*” abacus (Fig. 9), developed with modelling results, allows  
311 predicting water level in the Mazauric drain from rainfall forecasts.

312 Three alarm levels corresponding to three thresholds were defined together with the municipal  
313 “Alarm Management” technical service, on the basis of the impact of past flood events. *Below*  
314 *a water level of 52 meter above sea level (m asl) at FdN spring*, the karst aquifer is below  
315 saturation and no specific action is required. From 52 to 53 masl, karst saturation is  
316 significant, as such levels are getting close to full saturation and the occurrence of a karst  
317 component. Discharge in the cadereaux is not important at these levels, but vigilance is  
318 advised. November 2004 and September 2010 were at that threshold, discharge during these

319 events being about 10 and 20 m<sup>3</sup>/s in the Ales Cadereau. *At 53 masl the threshold level is*  
320 *crossed*, and a karst component with significant discharge occurs in the cadereaux. This level  
321 is linked to an “**orange alert**”, which concerns levels between 53 and 53.5 masl and covers  
322 most of the significant events observed (September 2002, 6 September 2005) with flow in  
323 Ales cadereau of up to 30 m<sup>3</sup>/s. *The last threshold is at 53.5 masl.* Once this level is reached,  
324 the high discharge can cause important damage and the “**red alert**” is triggered. This situation  
325 corresponds to the 8 September 2005 and October 1988 events. Discharge in Alès cadereau  
326 was evaluated at 80 m<sup>3</sup>/s on 8 September 2005 and over 300 m<sup>3</sup>/s in October 1988.

327 The amounts of rainfall corresponding to these events are as follows: (a) The first 50 mm of  
328 rainfall do not have any impact on karst level as the precipitation remains in the top soil; (b)  
329 An additional 150 mm of rainfall induces filling of the karst; (c) After a precipitation of  
330 200 mm (50 mm stored in soil and 150 mm in karst aquifer), the karst is close to overflow and  
331 the threshold of 53 masl is reached in the FdN drain.

332 When there is a significant interruption in rainfall the karst starts to dry up, which should be  
333 taken into account as well. Three drying-up equations were empirically defined using drain  
334 water-level data:

335 Water level >52 masl: drying up of 3 cm/h

336 52 masl > Water level > 51,5 masl: drying up of 2 cm/h

337 Water level < 51.5 masl: drying up of 1 cm/h

338 Concerning the uncertainties on water levels, tests were done using the model with rainfall  
339 variations of +/- 10%, which showed that drain water-level variations were about 20 cm due  
340 to rainfall uncertainties.

341 The use of the Rainfall vs. Drain water-level abacus is illustrated with the September 2005  
342 event that can be divided into five sub-events (Table 5). During the preceding month of  
343 August 2005 there was no rainfall and the soil contained no water. We thus were at point A at  
344 the start of the event (Fig. 10). The five sub-events were:

345 1- From 6 September 15:30 hrs to 7 September 02:30 hrs: 225 mm of continuous rainfall.  
346 Point B was reached with a level on the abacus of 53.2 m (from point A with 0 soil-water  
347 content to B where the karst was filling).

348 2- No rain fell from 7 September 02:30 hrs to 8 September 07:00 hrs. The associated drying  
349 up was 86 cm (drying up of 3 cm/h). Point C with 52.3 masl was reached.

350 3- On 8 September from 07:00 hrs to 17:00 hrs 135 mm of rainfall. Point D was reached at  
351 53.5 masl.

352 4- On 8 September no rain fell from 17:00 hrs to 20:30 hrs; after 3.5 hours of drying up at  
353 3 cm/h, a water level of 53.3 masl was reached at point E.

354 5- On 8 September, from 20:30 hrs to 23:45 hrs, 65 mm of rainfall caused a water-level rise to  
355 53.6 masl.

356 Comparison of the observed water levels and those obtained from the abacus show that the  
357 latter results are close to the observed data. Error is about 20 cm. This means that the tool as  
358 developed seems to be of good quality.

## 359 **Conclusions**

360 The methodology of karst flash-flood forecasting developed for the city of Nîmes was based  
361 on definition of the functioning of the Nîmes system. During flood conditions the karst  
362 aquifer becomes quickly saturated, discharge at the spring increases and, due to the small  
363 storage capacity, the excess infiltration causes excess runoff. This runoff reaches the surface  
364 stream ('cadereau') that starts flowing and then flooding.

365 Our study, based on measurements of discharge in the cadereaux and from the karst spring, as  
366 well as of karst water-levels, has allowed developing a conceptual model of karst-aquifer  
367 functioning, representing drain water-levels and discharge from the Fontaine de Nîmes spring.  
368 Testing the model with different rainfall scenarios has led to the construction of a "Rainfall  
369 vs. Drain water-level" abacus, a toolbox for flood management, incorporating existing flood-  
370 alarm levels. The abacus permits predicting water levels in the drains according to rainfall  
371 events and their associated risk. Tests using known main rainfall events have shown this  
372 abacus to be robust, and it is now operational within the Nîmes flood-crisis management  
373 service.

374 This approach is being now adapted to other karst systems for the French national forecasting  
375 flood event office (SCHAPI). Several basins are under study in order to adapt the whole  
376 method including the definition of the abacus to various types of karst systems. The tool  
377 under test by the Flood Forecasting Service (SPC) has given satisfactory results especially  
378 regarding the decreasing rate of "false" alerts.

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444

445 Table 1. Parameters of karst infiltration calculated from 2005 recession flow.

|                    | Duration (days) | Velocity (m.d <sup>-1</sup> ) | Volume infiltrated (m <sup>3</sup> ) |
|--------------------|-----------------|-------------------------------|--------------------------------------|
| Slow infiltration  | 225             | 0.004                         | 1.95. 10 <sup>6</sup><br>60 %        |
| Quick infiltration | 30              | 0.033                         | 1.33. 10 <sup>6</sup><br>40 %        |

446

447 Table 2. Karst parameters deduced from 2005 recession flow.

| $\alpha$ (m.d <sup>-1</sup> ) | Dynamic volume (m <sup>3</sup> ) | Total Flow (m <sup>3</sup> /year) | Regulation power system |
|-------------------------------|----------------------------------|-----------------------------------|-------------------------|
| 0.006                         | 0.72.10 <sup>6</sup>             | 17.10 <sup>6</sup>                | 0.04                    |

448

449 Table 3. Characteristics of major rainfall events

| Date               | Cumulative rainfall (mm) | Soil recharge | Rainfall duration (h) | Peak discharge in Alès cadereau (m <sup>3</sup> /s) |
|--------------------|--------------------------|---------------|-----------------------|---|
| 3 October 1988     | 360                      | Yes           | 8                     | < 300   |
| 27-28 May 1998     | 180                      | No            | 30                    | ~20   |
| 8-9 September 2002 | 190                      | Yes           | 26                    | ~40   |
| November 2004      | 90                       | Yes           | 9                     | ~20   |
| 6 September 2005   | 225                      | No            | 15                    | ~30   |
| 8 September 2005   | 200                      | Yes           | 18                    | ~80   |
| 7-8 September 2010 | 180                      | No            | 24                    | ~12   |

450

451 Table 4. Results of drain water levels simulated for the main events

| Date           | Maximum $h_{drain}$ simulated (masl) (threshold: 53 m) | Maximum $h_{drain}$ measured (masl) |
|----------------|--|-------------------------------------|
| 3 October 1988 | 54.2   | -                                   |

|                    |      |      |
|--------------------|------|------|
| 27-28 May 1998     | 52.8 | -    |
| 8-9 September 2002 | 53.2 | -    |
| November 2004      | 52.8 | 53.1 |
| 6 September 2005   | 53.1 | 53   |
| 8 September 2005   | 53.6 | 53.5 |
| 7-8 September 2010 | 53   | 52.9 |

452

453

Table 5. Five periods of September 2005 event

| Start       | End         | Rainfall (mm) | Drying up (cm) | Water level (m) from abacus | Water level observed (m) | Point |
|-------------|-------------|---------------|----------------|-----------------------------|--------------------------|-------|
| 06/09 15:30 | 07/09 02:30 | 225           |                | 53.2                        | 53                       | B     |
| 07/09 02:30 | 08/09 07:00 | 0             | 86             | 52.3                        | 52.3                     | C     |
| 08/09 07:00 | 08/09 17:00 | 135           |                | 53.5                        | 53.4                     | D     |
| 08/09 17:00 | 08/09 20:30 | 0             | 10             | 53.4                        | 53.4                     | E     |
| 08/09 20:30 | 08/09 23:45 | 65            |                | 53.6                        | 53.5                     | F     |

454