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1 **Karst flash-flood forecasting in the city of Nîmes**
2 **(southern France)**

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5 **ABSTRACT**

6 In southern France, karst flash-floods may be the result of two, potentially cumulative,
7 phenomena:

- 8 - Floods from highly localized events that mostly occur during autumn and are locally
9 known as Cevenol rain events ;
10 - Floods exacerbated by recent rainfall events that contributed to saturation of the
11 aquifer before the storm event, thereby increasing runoff.

12 In any case, flash floods occurring in a karst landscape are directly linked to the structure and
13 hydraulic properties of the karst aquifer.

14 A methodology was developed for the city of Nîmes for forecasting these dangerous events,
15 based on the study and modelling of karst-aquifer response to rain events. This work was
16 composed of: (i) Definition of how the Nîmes system functions, leading to a conceptual
17 model; (ii) Modelling of this conceptual model; (iii) Definition of a tool for hazard
18 management, presented as an abacus and tested on particular strong rainfall event.

19 Keywords : Karst aquifer; Flash-flood; Modelling; Management.

20 **INTRODUCTION**

21 Due to the characteristics of groundwater flow in karst terrain, flash flooding in such a context
22 is strongly different from that in non-karst terrain, the groundwater volume being much
23 larger. Such phenomena may cause serious damage, including the loss of life. For this reason,
24 karst flash-flooding has been identified as one of the main hazards in karst terrains. It is
25 directly linked to the structure and hydraulic properties of karst aquifers. The main cause is
26 the rapid circulation of large quantities of infiltrated water through karst conduits with a
27 dynamic that is very close to that of surface-water runoff. Detailed causes of karst flash-
28 floods include (Bonacci, 2006): 1) High infiltration rate; 2) Rare or non-existent overland
29 flow and open streams; 3) Strong interaction between surface water and groundwater; 4)
30 Small storage capacity of the karst system; 5) Fast groundwater flow through karst conduits;
31 6) Strong and direct connections between surface inflow through swallow-holes and outflow

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 km².
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 α 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} ; η_1 is $1/t_{i1}$;
94 ε_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} ; η_2 is $1/t_{i2}$; ε_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 (α , η , ε) 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 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 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 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 m.d^{-1} .

118 The recession coefficient α is very low (0.006 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 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 m³/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 Salinger, 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 α 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 α 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_{rapid}
261 discharge and H_{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 α drain saturated-zone reservoir calibration value defined by a step by step trial and error
266 method is 0.005 m/15min.

267 The α 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 km²).

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 m³/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 m³/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 m³/s on 8 September 2005 and over 300 m³/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 ⁻¹)	Volume infiltrated (m ³)
Slow infiltration	225	0.004	1.95. 10 ⁶ 60 %
Quick infiltration	30	0.033	1.33. 10 ⁶ 40 %

446

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

α (m.d ⁻¹)	Dynamic volume (m ³)	Total Flow (m ³ /year)	Regulation power system
0.006	0.72.10 ⁶	17.10 ⁶	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 ³ /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