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

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ABSTRACT

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

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

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

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

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

INTRODUCTION

Due to the characteristics of groundwater flow in karst terrain, flash flooding in such a context is strongly different from that in non-karst terrain, the groundwater volume being much larger. Such phenomena may cause serious damage, including the loss of life. For this reason, karst flash-flooding has been identified as one of the main hazards in karst terrains. It is directly linked to the structure and hydraulic properties of karst aquifers. The main cause is the rapid circulation of large quantities of infiltrated water through karst conduits with a dynamic that is very close to that of surface-water runoff. Detailed causes of karst flash-floods include (Bonacci, 2006): 1) High infiltration rate; 2) Rare or non-existent overland flow and open streams; 3) Strong interaction between surface water and groundwater; 4) Small storage capacity of the karst system; 5) Fast groundwater flow through karst conduits; 6) Strong and direct connections between surface inflow through swallow-holes and outflow through permanent or intermittent karst springs; 7) Strong and fast fluctuations of the water table in karst areas; 8) Interbasin overflow and/or redistribution of catchment areas caused by groundwater rise; 9) Limited discharge capacity of karst springs; and 10) Limited capacity of swallow-holes.

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

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

1- Nîmes karst system hydrology : studies for system characterisation

1.1. Geological and hydrological settings

The Fontaine de Nîmes (FdN) spring is located in the south-eastern France, in the city of Nîmes. Most of the time, it is the only discharge point of a karst system that is famous for its rapid reaction to rainfall events. The unsaturated zone is at most 10-m thick and the saturated zone is limited to a few tens of metres. A well developed karst network drains the aquifer to the FdN spring.

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

1.2. Recession analysis

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

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

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

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

The third term is an empirical function describing the second component of quickflow at time t (q_o*^2 is the difference between total discharge Q_0 at the spring at time t = 0 and the sum of baseflow component q_0^b and first quickflow component q_o*^1; η_2 is $1/t_{i2}$; ε_2 characterizes the importance of the concavity of the quickflow in terms of t^{-1}). This function is defined between t=0 and t_{i2}, which is the duration of second quickflow. This component corresponds to the influence of slow infiltration into the epikarst.

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

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

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

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

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

Examination of the sorted-discharge-rates diagram of the FdN spring over a long period (1998-2005: Maréchal et al., 2008, 2009) shows that during high flood periods (Q >13 to 15 $m^3\ s^{-1}$) the hydraulic properties of the hydrosystem change: the discharge rate at the main spring increases less rapidly. This is typical of a participation of other, intermittent, overflow springs to the total discharge of the system; therefore, the discharge at the main spring increases less because water flows elsewhere. The presence of less permeable Quaternary deposits filling the valley downstream is responsible for this type of hydrogeological behaviour.

1.3. Conceptual model of flow

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

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

2- MODELLING THE CONCEPTUAL MODEL: DRAIN WATER-LEVELS AND FONTAINE DE NÎMES DISCHARGE

2.1. Karst-system functioning and impact on floods

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

In the case of Nîmes, studies show that when the karst aquifer reaches a saturation level "*threshold*", recharge to the aquifer becomes limited and overflow can occur from temporary springs. This excess runoff component, here called "*karst component*", is due to a decrease in infiltration capacity and overflow from temporary springs. This karst component induces a non linearity in the system, with a sudden rise in discharge once the saturation threshold is reached.

This condition appears when discharge at FdN spring exceeds 13 to 15 m3/s, corresponding to a water level of 53 masl (metres above sea level) at FdN. The option that was adopted is to model the karst-conduit water level. The modelling findings should permit forecasting when the threshold is reached and the resulting occurrence of the karst component that induces floods.

2.2. Different types of models

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

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

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

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

2.3. Data

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

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

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

2.4. **Model structure**

The *soil reservoir* was modelled for calculating infiltration; it feeds the *saturated zone (drain and matrix)* reservoirs. The infiltration was calculated from rainfall as inflow and actual evapotranspiration, AET, as outflow. Infiltration occurs when the soil reservoir is full, when it cannot store any more water.

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

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

All variables are water heights in mm.

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

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

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

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

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

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

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

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

The saturated zone is represented by two routing reservoirs, matrix and drain, that are both characterized by a water height, H drain/matrix, that fluctuates according to the input and output of the reservoir. At time t, this depth is equal to that of the preceding time step, to which is added the infiltration water height and from which one subtracts the discharge of the system, according to the following equation:

(Hdrain)t1 = (Hdrain)t0 + infiltration – Hrapid discharge Eq. 5a

(Hmatrix)t1 = (Hmatrix)t0 + infiltration – Hslow discharge Eq. 5b

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

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

The α drain saturated-zone reservoir calibration value defined by a step by step trial and error method is 0.005 m/15min.

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

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

Studies of recession curves analysis part 1.2. (Figure 3 and Table 1) show that fast infiltration represents 40% and the slow component 60%. Therefore, to reproduce spring discharge, drain- and matrix-reservoir contributions are respectively 40% and 60% of the recharge area (55 km²).

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

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

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

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

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

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

3- TOOLBOX FOR FLOOD MANAGEMENT: CONSTRUCTION OF AN ABACUS

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

Three alarm levels corresponding to three thresholds were defined together with the municipal "Alarm Management" technical service, on the basis of the impact of past flood events. *Below a water level of 52 meter above sea level (m asl) at FdN spring*, the karst aquifer is below saturation and no specific action is required. From 52 to 53 masl, karst saturation is significant, as such levels are getting close to full saturation and the occurrence of a karst component. Discharge in the cadereaux is not important at these levels, but vigilance is advised. November 2004 and September 2010 were at that threshold, discharge during these events being about 10 an 20 m^3/s in the Ales Cadereau. *At 53 masl the threshold level is crossed*, and a karst component with significant discharge occurs in the cadereaux. This level is linked to an “**orange alert**”, which concerns levels between 53 and 53.5 masl and covers most of the significant events observed (September 2002, 6 September 2005) with flow in Ales cadereau of up to 30 m^3/s. *The last threshold is at 53.5 masl*. Once this level is reached, the high discharge can cause important damage and the “**red alert**” is triggered. This situation corresponds to the 8 September 2005 and October 1988 events. Discharge in Alès cadereau was evaluated at 80 m^3/s on 8 September 2005 and over 300 m^3/s in October 1988.

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

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

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

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

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

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

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

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

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

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

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

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

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

Conclusions

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

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

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

Acknowledgements

This study was financed by the city of Nîmes. Part of the methodology for the developed toolbox was funded by a SCHAPI contribution. Finally, the authors would like to thank Egis Eau for providing data on the cadereaux.

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

	Duration (days)	Velocy ($m.d^{-1}$)	Volume infiltrated (m^3)
Slow infiltration	225	0.004	$1.95.\ 10^6$ 60 %
Quick infiltration	30	0.033	$1.33.\ 10^6$ 40 %

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

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

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

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