



3 FRANCE: FONTAINE DE NÎMES

3.1 Overview

The Nîmes city has been forever subject to catastrophic floods events. History of the city mentions about 42 flood events from 1334 to 2005, about one flood every 16 years on average. Almost 60 % of the events happen during the three months between September and November. In the recent past, the most important one occurred on 3 October 1988 and killed 9 people among 45,000 disaster victims (Fabre, 1990). Damages were about 600×10^6 euros. The specific maximum outflow discharge (q) of the Cadereaux rivers, defined as Q/A , where A is the surface catchment area (42 km^2) and Q is maximum estimated discharge ($1600 \text{ m}^3/\text{s}$ in 1988), is equal to $38.1 \text{ m}^3/\text{s}/\text{km}^2$, the highest in a comparative study done by Stanescu and Matreata (1997) on flash floods along rivers in five European countries. These flash floods have been for a long time considered to be the result of very intensive rainfall events from Cevennes climate influence conjugated with the geomorphologic context (Ballais et al., 2005) of the city which is located at the bottom of a hill. Usually, overland flow tends to play the dominant role in flash flood formation and low infiltration capacity is the most important factor for overland flow development. However, with a very scarce and thin soil cover of high infiltration capacity, karstified limestone of Nîmes hills are in theory favourable to the infiltration of a part of rainwater, reducing the potential overland flow genesis. Therefore, soils characteristics in the watershed are such that flash flood should not happen in Nîmes city.

The Fontaine de Nîmes (FdN) spring is located in South-Eastern France, in the city of Nîmes. Most of the time, it constitutes the only discharge point of a karst system which is famous for its rapid reaction to rainfall events. The unsaturated zone is maximum ten meters thick and the saturated zone is limited to a few tens of meters. A well developed karstic network drains the aquifer to the FdN spring (*Figure 3*). Part of these drains have been mapped by speleologists during several diving explorations.

3.2 Geology

From a geological point of view, this basin consists of a succession of east-west oriented folds; the aquifer formations that are the site of underground flows are mainly the carbonate formations of the Upper Hauterivien, several hundred metres thick.

Karst has developed mainly within the limestones of the Upper Hauterivien (n3b). There are many karst phenomena on the surface: swallow holes, caves and losses attest to the intense karstification of the limestone massif. The drains of the karst network upstream of the spring, explored by speleologists, are large in diameter, allowing large flows. They are divided into two main branches:

- the western network on which the Poubelle well is located, whose large diameter suggests significant water circulation;
- the northern network on which the well of the 9 Arcades is located in the Cadereau d'Alès ("Eau Bouillie" district). With a smaller diameter, the flows seem less important.

The geological history of the Nîmes karst does not allow us to consider a very deep extension of the karstification, because it has been crossed out for a large part of its history, particularly during the Messinian crisis. A development of the karst system under the main network is limited to a few tens of meters. This karstifiable potential certainly does not exceed 100 meters.

At the outlet, the spring is located at the level of the geological contact between the limestone



massif of the Garrigues and the plio-quaternary sediments, including the Piedmont silts. This contact more or less coincides with the position of the Nîmes Fault, which, through its normal fault displacement, caused the southern compartment to drop, bringing the limestones into contact with the plio-quaternary sediments.

3.3 Geomorphology

The city is located at the bottom of the hill at the convergence of three temporary streams called “cadereaux”, which is a local term designating the small valleys around Nîmes traversed very temporarily by torrential flows during rainy events: the Uzes stream from the east, the Ales stream from the north and the Camplanier stream from the west (*Figure 3*). These streams are monitored for their discharge by the City services in order to organise the alert and manage the emergency services during flood crisis.

3.4 Climate

The climate is Mediterranean (or dry summer climate), characterized by rainy winters and dry summers, with very little precipitation (less than 40 mm) for at least three summer months. The average temperature is 13.8°C. The area receives around 740 mm annual precipitation that recharges the karst aquifer mainly by diffuse infiltration and swallow holes.

3.5 Hydrogeology

The karst basin (*Figure 3*), defined by numerous tracing experiments (Fabre, 1997) and a water budget calculation (Maréchal et al., 2005), is estimated to be on the order of 55 km². The area is quite urbanised in the southern part and covered by natural Mediterranean vegetation (Garrigues) in the north. The catchment area is mainly composed of limestone from Hauterivian, Cretaceous.

The springs of the system consist of the FdN spring, with a discharge between 0.01 and 18 m³/s, and several intermittent springs discharging only during flash floods.

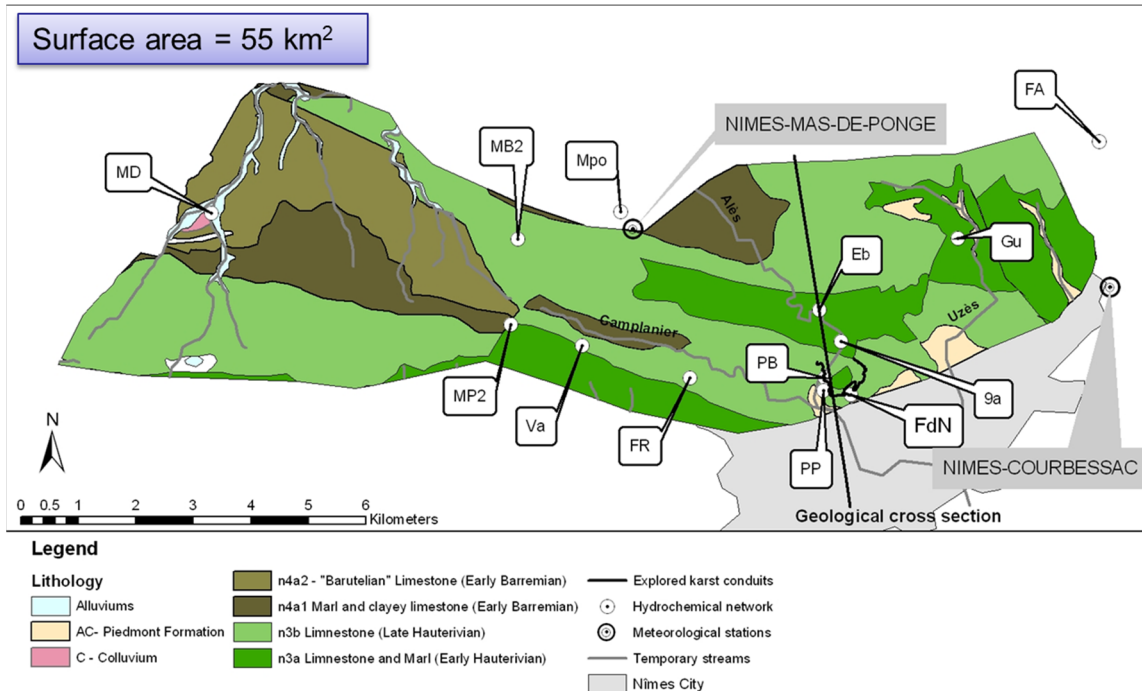


Figure 3: Hydrogeological basin of Fontaine de Nîmes karst system (location of the main spring (FdN) and other springs or wells monitored for hydrochemistry analysis)

The groundwater table has been monitored during an inundation event thanks to a network of water level recorders located in observation wells. The evolution of water levels shows that the fissured system (out of karst conduits – in wells) has been saturated on 6th and 7th September a few hours after the first event: rate of groundwater rising ranges between 0.2 and 0.5 m/h. The small fissures are quickly filled by groundwater. During the second event, the infiltrated water could not be stored in the karst and therefore contributed to the surface runoff. Local flooding effects are also observed where geomorphology is favourable, in local depressions for example. The fast saturation of the fissured karst is due to its small storage capacity partly explained by the little thickness (1 – 10 meters) of the unsaturated zone as shown by small water table depths in wells before the event.

This saturation of the fissured karst system induces many intermittent springs located in the whole karst basin. It appears that these springs were discharging and the fissured karst was saturated while the water level in the conduits network was much deeper (Poubelle well in Figure 6). This means that, in this case, the fissures are not saturated by water from the karst conduits as observed in other cases by hydraulic inversion (Marina Bay, Bonacci et al., 2006) but by water infiltrating directly on its shallow part characterized by extreme fracturing, the epikarst. Geochemical information makes it possible to consolidate these interpretations.

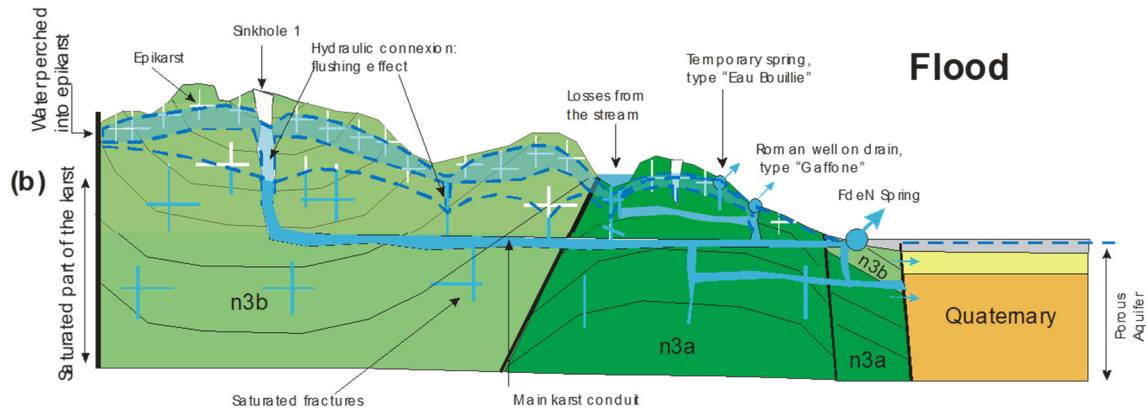


Figure 4: schematic hydrogeological cross-section of Fontaine de Nîmes karst aquifer during high flow conditions

3.6 Hydrodynamic characteristics

Examination of the sorted discharge rates diagram of the FdN spring on a long period (1998-2005) shows that during high flood periods ($Q > 13 \text{ m}^3/\text{s}$), the slope of straight line α_3 is superior to α_2 (Figure 5). When discharge exceeds $13 \text{ m}^3/\text{s}$, hydraulic properties of the hydrosystem change (slope break): the discharge rate at the main spring increases less quickly. This is typical of the participation of intermittent overflow springs to the total discharge of the system: therefore, the discharge at the main spring increases less because water is flowing elsewhere.

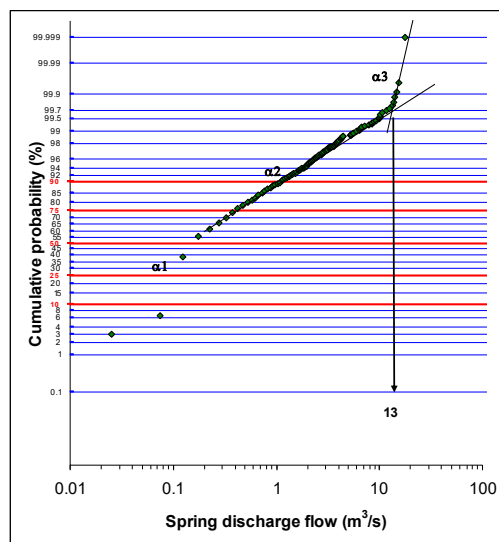


Figure 5: Sorted discharge rates of FdN spring during 1998-2005 period ($0.05 \text{ m}^3/\text{s}$ class)

Some of these intermittent springs are very close to the known conduits network with which they are directly connected. An example (Figure 6) is a Roman well and a sinkhole which flood with significant discharge rates (as an example, $1.4 \text{ m}^3 \text{ s}^{-1}$ on 7th September and $2.2 \text{ m}^3/\text{s}$ on 9th September; Jouanen, Personal Communication). This flooding should be due to backup of excess flow behind a constriction in the major conduit leading to the spring: this phenomenon

is known in karst hydrology as backflooding (Lowe and Waltham, 2002). Indicators of flow inversion (diving rope displacement) have been observed by speleologist divers in the conduit after large floods (Jouanen, Personal Communication). This backflooding induces sinkhole flooding and large intermittent springs upstream of the city, which contribute to the flood.

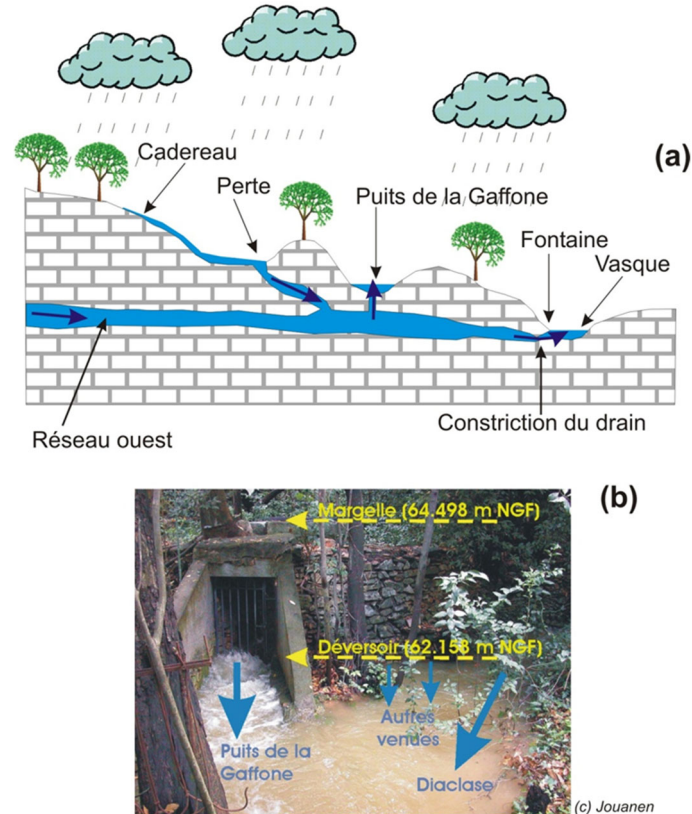


Figure 6: Inverse flow recorded in a Roman well and a sinkhole during 9th September event, due to backflooding (© G. Jouanen, Association Fontaine de Nîmes)

With a catchment area of 55 km² and a maximum estimated discharge of 30 m³/s in 1988, the specific maximum outflow discharge q_M is equal to 0.55 m³/s/km², one of the highest compared to other karst springs studied by Bonacci (2001) in Croatia, France, USA and Yugoslavia. The limited discharge capacity of FdN spring is coherent with a previous analysis (Bonacci, 2001) which considers that karst springs with $q_M < 1$ can be classified as those with limited discharge capacity.

3.7 Data available for the project

This is a SNO Karst observatory: http://www.sokarst.org/index.asp?menu=cinq_obs
Hydrodynamic and physico-chemical measurements recorded at the spring, in surface water (cadereaux, which are dry streams used to channel rainwater), in boreholes or in cavities, augmented by geochemical campaigns have made it possible to describe the mechanisms responsible for the genesis or attenuation of flash flooding in the Mediterranean karst environment (Maréchal et al. 2008; Maréchal et al. 2009). Numerical modeling has improved flood forecasting (Fleury et al. 2013). Complementary tracing tests have also been conducted (Maréchal et al. 2010). The network of hydrodynamic monitoring rests on the following data:



- Discharge (8 hydrometric stations on the 5 cadereaux and 1 station at the Fontaine de Nîmes)
- Piezometry (8 piezometric stations)
- Pluviometry (9 rain gauge stations)
- Hydrochemistry (spatial campaigns on the drainage basin)

Since 2012, the measuring system has been enhanced by a fluorimeter that continuously (every 15 minutes) measures variations in natural fluorescence associated with the transport of dissolved natural organic and particulate matter. This continuous monitoring is supplemented by spatial campaigns making it possible to quantify Total Organic Carbon and to define the spectral signature (3D excitation/emission matrix) of fluorescent compounds.

The objective of this work is to:

- Describe the dynamics of organic contaminant transfer in a karst system, using the strong anthropic signal on this system,
- Define new indicators of rapid infiltration in a karst environment to describe better the qualitative state of the water and spring pollution vulnerability.
- Determine the relationship (non-linearity, seasonal effects, etc.) between natural fluorescence and the water's organic content.

1. FdN spring			
Data type	Time step	Monitoring period	Time period
Discharge	15 minutes	22 years	1998-2020
Electrical conductivity	15 minutes	22 years	1998-2020
Temperature	15 minutes	22 years	1998-2020
Major anions/cations	Monthly	3 years	2004-2007
Turbidity, fluorescence	15 minutes	3 years	2019-2022

*unreliable data



3.8 Summary

Pilot name	Fontaine de Nîmes Spring		
Country	France	EU-region	Mediterranean
Area (km ²)	55	Lithology	Limestone
Short description: Fontaine de Nîmes spring is the main outlet of a Mediterranean karst system (55 km ²) close to the coast. Located North of Nîmes city, its fast reaction to rainfall induces floods. A part of the catchment being occupied by thousands of inhabitants, the monitoring of fluorescence and TOC has been used in order to trace quick flow components during rainfall.			
Monitored objects	Spring (one), wells (two)		
Monitored data	Discharge, temperature, EC, chemistry, isotopes, fluorescence		
Contact person	Vincent Bailly-Comte (v.bailly-comte@brgm.fr)		



3.9 References

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