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Displacement of Watershed between Two Karstic Rivers

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Abstract. Groundwater flow circulating in a karstic hydrosystem is very difficult to grasp in space and time. In cases where the karstic aquifer is located between two rivers, the watershed is not easy to identify using a single analysis of a geological map. In this study, the understanding regarding the karstic hydrosystem between the Ardèche and Cèze Rivers, in the South of France, is advanced. This study especially highlights that the watershed of a karstic hydrosystem evolves depending on the hydric condition of the karstic aquifer. The results are obtained by artificial tracing analysis through the karstic network.

1. Introduction

Karst aquifer studies arouse a great interest given the fact that they represent important freshwater resources. According to Ford and Williams [1], the karstic rocks cover 7-10 % of the Earth's surface and supply drinking water to about 25 % of the world's population. Karst systems are characterized by a highly heterogeneous structure that influences underground stream flows [2]. In order to understand the underground flows, the tracer tests between surface water loss and karst springs are appropriate to characterize the karstic hydrosystem properties [3]. For several decades, different methods have been used for investigating the karst systems: (i) Chemical tracing methods are founded on artificial tracers [4-8], or isotopic tracers [9, 10]; (ii) Biological tracing method based on groundwater invertebrate communities analysis [11, 12]. Artificial tracing studies can differentiate the classes of conduit network [13]. Sometimes, thanks to a series of tracer tests, it is possible to detail the structural model of a conduit karstic system [14]. Artificial tracing, as well as geochemical methods, allows to quantify the karstic contribution to the river [15-17]. This quantification is especially done by restitution curve analysis obtained at springs.

Documents review show that artificial tracing methods enable to find or to verify from a single or several injection points (river loss, polje, aven, abyss): (i) the divergence, convergence, storage delay of the flux; (ii) the dilution rate, velocity and distribution of the flux [18-21]. These phenomena can be explained by the flow channelling [22-25] or the interactions between the rock matrix and the fissure flows [26-29].

Especially in the case presented in this paper, the two karstic rivers under study erode the same calcareous karstic system. Currently, the catchment of each river is not defined and there is no



knowledge about the karst network contribution to the river flow. Therefore, the first aim of this study is to define the interactions between the karstic network and the two rivers. Furthermore, this case study takes into account the connectivity evolution between the karst network and the rivers according to the hydric condition of the karst aquifer. The evolution of groundwater flow directions depending on the hydric condition in the karst aquifer is an important information rarely taken into consideration when evaluating the hydrogeological basin area. In this study, the karstic contribution and the distribution in three hydric conditions are highlighted by three different artificial tracers for three different tracing.

In addition to the introduction and conclusion, this paper consists of three parts. The first one will focus on presenting the karst aquifer tracing methods. The second part will describe the study area targeted for this application, its geological structure complexity, climatic characteristics and pertinent available data. Finally, the third part will present the multitracing results.

2. Injection points and tracer selection

This work focuses on an area where there is a lack of artificial tracing. So, at the beginning of this study, the information is limited and a ground survey is necessary. The methodology includes three steps.

The first step consists of doing a water-loss survey, which includes the prospecting of the river-bed infiltration, rainwater infiltration in the karst voids and underground river or underground flow in the karst network.

The second step consists of identifying all the springs throughout the two rivers. This work is based on a geological map [30-33] and field reconnaissance. Whenever possible, the springs are equipped with fluorimeters which enable to have a continuous database of tracer concentrations and turbidity values [34]. But sometimes, the spring size or its large number does not allow installing this analysis equipment. So, in order to analyse the tracer transfer, 115 charcoal dye receptors, manufactured in our laboratory, were installed in the springs that can be traced by the water-loss targeted. The charcoal dye receptor operates like an activated carbon filter. It is a drill-tube full of active carbon retained by a thin net. Regarding its functioning, if the underground water is concentrated in tracers, the active carbon captures the tracers when the water penetrates in it. During the tracing period, the charcoal dye receptors are regularly changed to estimate the tracer transfer time from water-loss to springs. At the same time, spring waters are sampled to be analyzed by fluorescence spectrofluorometer to validate the charcoal dye receptor results and to obtain tracer concentrations.

The third and last step is the tracer choice. This is an important step in the tracing study because the chemical properties define the dilution, adsorption and degradation problems of the tracer. So, in this case the selected tracers should be compatible with multitracing, and with fluorimeter equipment, they must be captured by activated carbon and should have low detection limit, low adsorption, toxicity, ecotoxicity and have a good chemical stability. To answer all these criteria, the selected tracers are fluorescein, rhodamine B and eosin described in Table 1 [35-39].

Table 1. Properties of selected fluorescent dyes.

Name	Fluorescein	Rhodamine B	Eosin
Chemical formula	C ₂₀ H ₁₂ Na ₂ O ₅	C ₂₈ H ₃₁ ClN ₂ O ₃	C ₂₀ H ₈ Br ₄ O ₅
Excitation/Emission spectra (nm)	492/513	555/582	515/535
Detection limit (µg.L⁻¹)	0.002	0.006	0.01
Adsorption	Very low	Strong	Low
Activated carbon capture	Yes	Yes	Yes

In order to understand the karst system functioning, the tracers are injected in three water losses appropriate to tracing, during different weather conditions. The first tracing was carried out when the karst aquifer was considered in mean water level. The second tracer was injected before summer

period to check how the karst systems performed in low water level. Finally, the third and last tracing was made during flood period. This procedure is important because the karst network of the study area is arranged in several levels, so there is a probability that the underground flow directions, and therefore the watershed, are conditioned by the hydric states of the karst.

3. Karstic study area

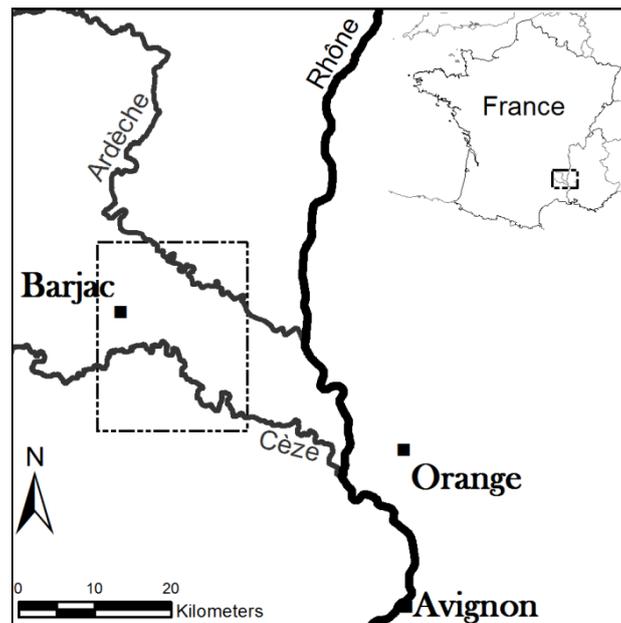


Figure 1. Location map of the study area

Located in a large karstic area in the South of France, between the Ardèche and the Cèze Rivers, both tributaries of the Rhône River (Figure 1.), the study area is the subject of a multidisciplinary study which aims to characterize the exchanges between aquifer and river [40]. This study area is an attempt to meet a territorial policy, in order to obtain a sustainable management of streams and aquifers. In this location, the Mediterranean climate induces a period of drought in summer and high-flood in autumn. The karstic area is incised by two different rivers, the Ardèche and the Cèze. The Ardèche River is longer than the Cèze, and the Ardèche's measured mean flow is about $65 \text{ m}^3/\text{s}$ while that of the Cèze mean flow is about $22 \text{ m}^3/\text{s}$. Moreover, sometimes during drought period the Cèze River may dry up, highlighting river water infiltrations. The Southern part of the study area is geologically and hydrogeologically well studied, including borehole investigations, karstic network investigations and especially previous groundwater tracing [41, 42]. Geological studies suggest that there is proof of the interactions between rivers and rocks in the Lower Cretaceous, Barremian and Lower Aptian (so called Urgonian) which is a highly karstified calcareous geological unit. Whether on the Ardèche right bank or the Cèze left bank, some springs may dry up during drought period. Therefore, the water flux directions can be reversed. In drought period the river can supply the Karst aquifer, consequently the karstic underground water flux directions change.

4. Climatic conditions, monitoring and return of tracing

Among the three tracings presented in this part, two of them are made directly in the endokarst and the third one in the subsurface water-loss in the Paleogene geological units. The injection points are shown in Figure 2 and Table 2.

The first tracing was carried out on 03/29/2014 in the endokarst, in the “Grotte Flandin” cave of 120 m deep (123 m NGF (general leveling of France)). A total of 10 kg of Fluorescein was injected in about 0.1 L/s estimated flow water-loss (e.g. 2 to 5 L/s during flood period). The hydrologic condition at the tracer injection time was high-water following a dried-up period. The three months previous to the tracing, there were 469 mm of rainfall. A trace of Fluorescein was detected at Gournier (04/24/2014) and Dragonnière (04/11/2014) springs. However, the tracer was clearly detected at the Castors (02/07/2015, 03/28/2015 and 04/28/2015) spring. Nevertheless, one of these results obtained by charcoal dye receptors was not validated by spectrofluorometer analysis, this is the charcoal dye receptor of 02/07/2015 (Table 2). Later, two other points were impacted by Fluorescein: (i) Monteil spring (11/21/2014, 11/26/2014, 12/05/2014 and 12/11/2014), and (ii) borehole “Pavillon” (02/18/2015) (Figure 2 and Table 2).

The second tracer was injected on 05/06/2014 in the Roméjac River, which is a tributary of the Cèze River. During that time, this tributary was dry because of the water-loss in the bedrock. All along of the injection river section, around 100 m, the flow decreased from 40 L/s to zero. Upstream of the section, 3 kg of Eosin were injected. The three months previous to the tracing there were 99 mm of rainfall. The tracer was detected by charcoal dye receptors and spectrofluorometer analysis on the left bank of the Cèze River. The concentration of Eosin detected in Monteil spring (06/10/2014, 06/16/2014 and 09/18/2014) was higher than that at Baumes spring (06/16/2014 and 09/02/2014) (Table 2). The third and last tracing was carried out in the endokarst at “Aven d’Orgnac” sinkhole, 150 m deep (155 m NGF). The injection of 10 kg of Rhodamine B was made on 11/14/2014 in a groundwater-loss. Then, about 70 m³ of water were injected in this water-loss to produce a flush effect. Given the fact that it was a flood period (570 mm of rainfall during the previous four months), Rhodamine B clearly appeared one week later at the Gournier spring only (11/20/2014, 11/24/2014 and 12/01/2014) (Table 2).

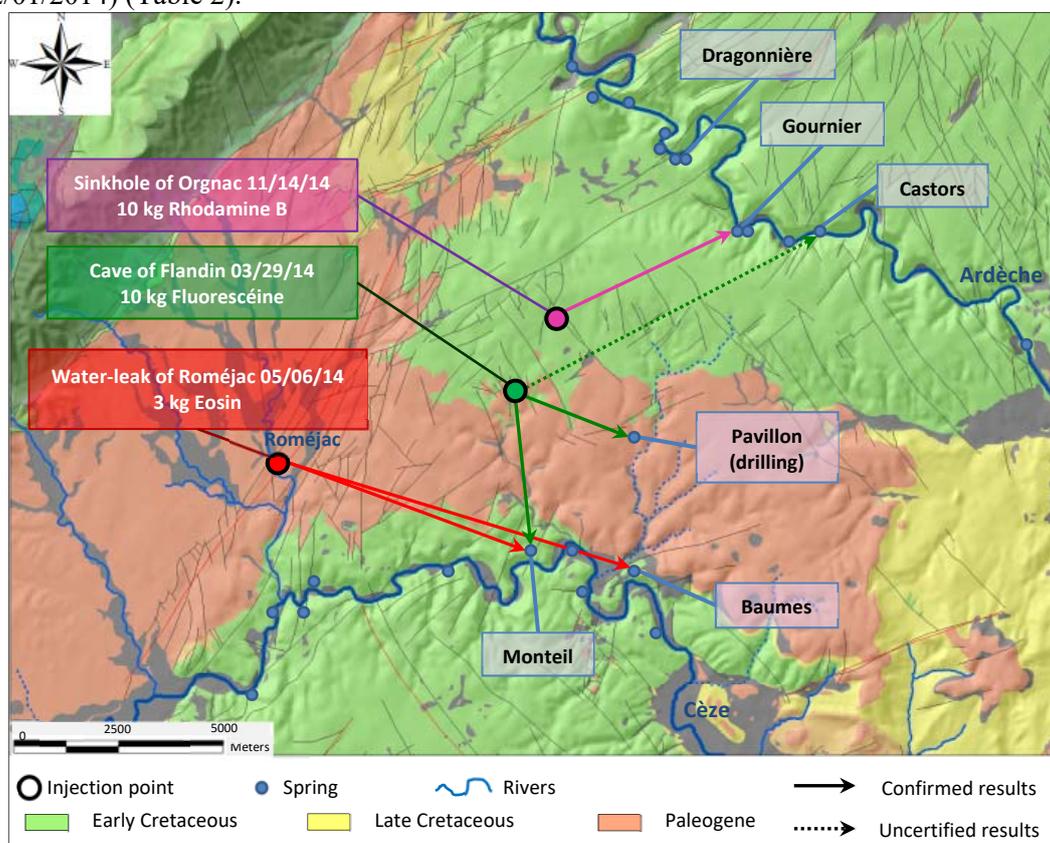


Figure 2. Geological map showing the tracer injection points and results.

Table 2. Tracing results by all analyses.

River	Observation point	Analysis equipment	Sample	04/11/2014	04/24/2014	06/10/2014	06/16/2014	09/02/2014	09/18/2014	11/20/2014	11/21/2014	11/26/2014	12/05/2014	12/11/2014	02/07/2015	02/18/2015	03/28/2015	04/28/2015	
				CEZE	Monteil spring	Colorimeter	C.d.r.			P	P					P	P	P	P
Fluorometer	C.d.r.										P	P	P	P					
Spectro-fluorometer	C.d.r.			P		P			P		P	P	P	P					
	Baumes spring	Colorimeter	C.d.r.				P	P											
Fluorometer		C.d.r.								N	N	N	N						
Spectro-fluorometer		C.d.r.					P	T			N	N	N	N					
	Gournier spring	Colorimeter	C.d.r.		P														
Fluorometer		C.d.r.										P	P						
Spectro-fluorometer		C.d.r.		N								P	P						
	Dragonnière spring	Colorimeter	C.d.r.		N														
Fluorometer		C.d.r.		N											N	N			
Spectro-fluorometer		C.d.r.		T											N	N			
	Castors spring	Colorimeter	C.d.r.		N														
Fluorometer		C.d.r.													P		P	P	
Spectro-fluorometer		C.d.r.													N		P	P	
	Pavillon drilling	Colorimeter	C.d.r.																
Fluorometer		C.d.r.																	
Spectro-fluorometer		C.d.r.													N		P		
	Pavillon drilling	Colorimeter	C.d.r.																
Fluorometer		C.d.r.																	
Spectro-fluorometer		C.d.r.													N				
	Pavillon drilling	Colorimeter	C.d.r.																
Fluorometer		C.d.r.																	
Spectro-fluorometer		C.d.r.																	

Legend: C.d.r. = Charcoal dye receptor
 N Negative sample Fluorescein Eosin Rhodamine B P Positive sample T Trace concentration

5. Interpretation and conclusion on the tracing results

These three tracings allow to approximately locating the watershed between Ardèche and Cèze Rivers. The tracings, especially the Flandin cave, allow delimiting the main diffiulties for different karst hydric conditions (Figure 3).

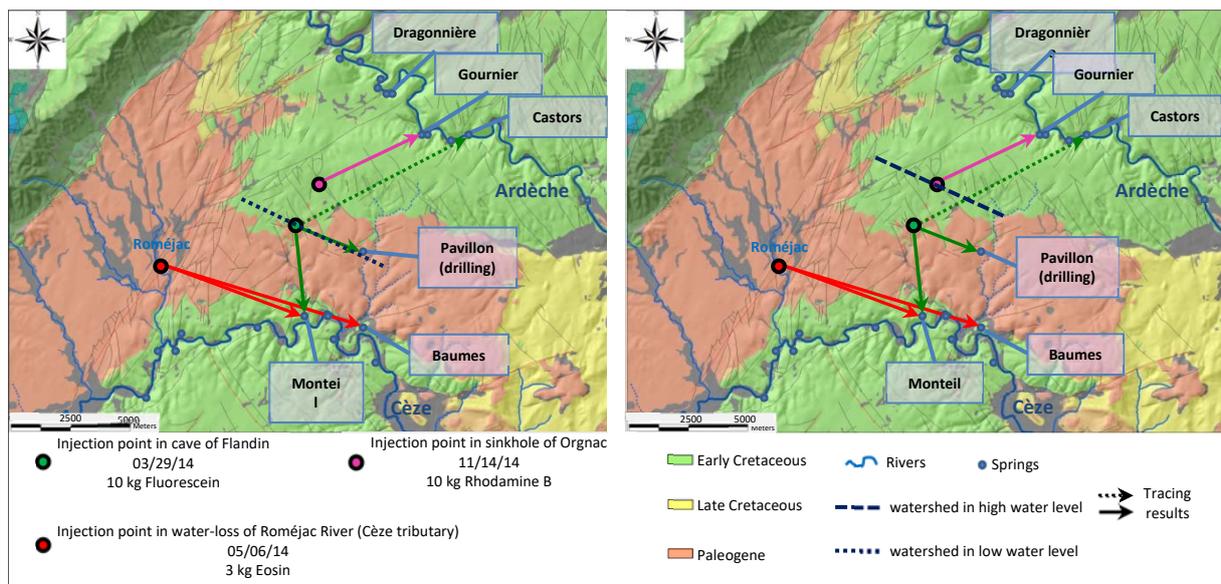


Figure 3. The variation in the watershed limit depending on the hydric condition of karst

Indeed, during low-water periods, groundwater tends to supply two springs of the right bank of the Ardèche River. The underground flow follows a North-East direction from Flandin cave to Castors

spring. The Gournier spring result is not considered because the presence of Fluorescein in the charcoal dye receptor is not confirmed by spectrofluorometer analysis. In high-water, Gournier spring is supplied by water coming from the Orgnac sinkhole. That means there is a karstic network shared by these two water-losses. Moreover, the Flandin cave water-loss also supplies the Monteil spring on the Cèze left-bank during high-water period only.

So, there is an underground flow diffluence depending on the hydric condition of the karstic hydrosystem. This phenomenon highlights that the watershed boundary moves according to the hydric condition. The watershed boundary is close to the Cèze River in low-water period and in high-water the boundary moves between the Orgnac sinkhole and the Flandin cave (Figure 3).

In this karst system throughout the Cèze and the Ardèche Rivers, there are a lot of springs (Figure 3). Despite their abundance, few of them can be equipped because of the tough accessibility and/or the submersion risk. Consequently, it is difficult to setup continuous recording equipment (fluorometer, automatic sampler) in each spring. An alternative is to install charcoal dye receptors and make manual water-sampling. However, there is an uncertainty on the charcoal dye receptors results because active carbon can absorb a fluorescent element which is naturally present in the organic matter. So, these results should be validated by spectrofluorometer analysis whenever it is possible. It is important to compare the results obtained by these two different analysis methods, to distinguish the accumulation in the charcoal dye receptors of the tracer which naturally occurs in organic matter from the artificial tracer. If low tracer concentrations (traces) in the charcoal dye receptors are not confirmed by water-samples of spectrofluorometer analysis, these results must be treated cautiously.

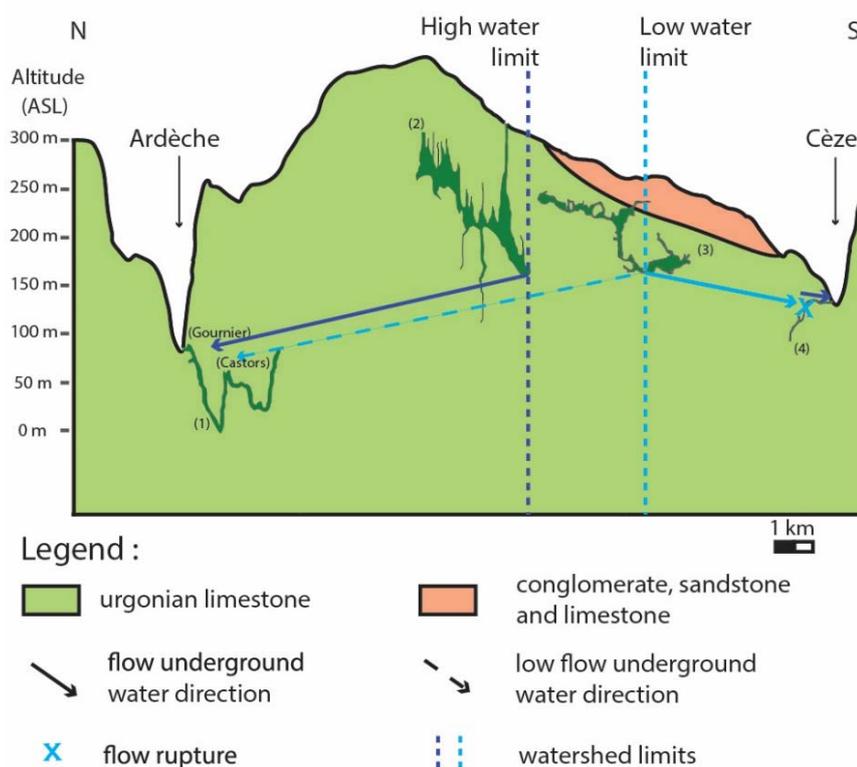


Figure 4. Schematic illustration of underground water flow in low or high water context. (1) Dragonnière spring; (2) Orgnac sinkhole; (3) Flandin cave; (4) Monteil spring. The topographies of caves are taken from works of [43; 44; 45]. NGF is the reference levelling of France, which is equivalent to ASL (above mean sea level)

The Figure 4 shows the underground water disfluency in low water and high water contexts. In the future, it is necessary to have a better understanding of the location of the watershed limit between the Orgnac sinkhole and the Flandin cave during high-water. Moreover, during the low-water hydric condition, it is necessary to validate the flow direction and the watershed limit.

In the Orgnac sinkhole, a new low-water tracing will allow comparing high-water and low-water underground flow direction.

As for the Flandin cave, the tracing should be remade in low-water condition to confirm the traces detected in the Gournier spring and the continuous small groundwater flow from Flandin cave to Castors spring. Another tracing in high-water condition allows to better understand the karst network. For the moment, a small underground flow from the Flandin cave to the Ardèche River is supposed, but the assumption is that the main underground flow goes in the direction of the Cèze River. Perhaps in low-water hydric condition this flow could be broken in a natural siphon. This assumption could explain why the tracer run off at the Monteil spring after a heavy precipitation, 8 months after the injection.

From a karstic network geomorphology point of view (Figure 4), the tracing results call to mind the groundwater flow evolution since the end of the early Cretaceous period. This period is the beginning of a long karstification process in the calcareous formations of this study area. In the case of the Orgnac sinkhole, this karstic network seems to develop towards the Cèze River. This assumption is also proposed and argued by the EDYTEM¹ laboratory [43]. At the present time, as it is shown by the Orgnac sinkhole tracing, the sinkhole water-losses flow in the Ardèche River direction by the Castors spring. This phenomenon corresponds to an evolution of groundwater flows caused by a modification of limit conditions in accordance with geological time. The groundwater flows from Orgnac sinkhole to Castors spring with a hydraulic gradient $i=0.0209$ from the injection point in the Orgnac sinkhole to the Castors spring, and $i=0.0118$ from the injection point to the Monteil spring. Given that the erosion of the Ardèche riverbed is higher than that of the Cèze River, the altimetry data between the Ardèche and the Cèze Rivers, at the same latitude, show a positive difference in height, about 30 meters, for the Ardèche River. The Flandin cave tracing results show this particularity of groundwater flows evolution. However, when the water-table is higher, other karstic networks of the Flandin cave drain an important groundwater amount into the Cèze River supplying the Monteil spring. According to these assumptions, it is possible that the Ardèche calcareous catchment basin increases at the expense of the Cèze catchment. Consequently, the geomorphology of significant penetrable karst network is surely a good physical record of the last groundwater flow directions, but not a good indicator of the actual groundwater flow directions.

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¹ Environnements Dynamiques Territoires Montagnes (EDYTEM): French laboratory in environment

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