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Origin of flash flood water of a Mediterranean river in karstic and urban environments by CTD monitoring (Las - Toulon - SE France)

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This study deals with flash flood generation in Mediterranean karstic and urban environments. Flash floods in streams are characterized by short response times to rainfall events, and high and rapid discharge variations (Nied et al. 2014, Merz and Böschl 2003, Gaume et al. 2009). They are usually generated by short, high-intensity rainfalls, mainly of convective origin that occur locally. In urban environments, impermeable areas and storm water conveyance systems significantly increase the flash floods caused by storm runoff (Miller et al. 2014). Moreover, in karstic environments, the karst groundwater baseflow supplying the stream can be highly variable. The karst groundwater discharge, mainly flowing at springs, is also disturbed by rainfall events that could quickly recharge the aquifer through permeable karst features (sinkholes, caves, shafts, karrens, open fractures...) in the catchment area and propagate through vadose and saturated zones. The resulting flood from the karst groundwater overflows into the stream. Simultaneous discharge of urban runoff origin and groundwater origin increase flash flood and hazard consequences.

When reviewing literature, one notices that the karst contribution to flash floods is not usually discussed and has a minor interest, except for a few specific papers (Maréchal et al. 2008, Fleury et al. 2013, Gutiérrez et al. 2014). The aim of this study is to use stream hydrograph separation techniques, with CTD monitoring in karstic springs, to determine the relative significance of the groundwater component and the urban runoff component in flash flood discharge. This study focuses on a Mediterranean urban and karstic catchment. We will show that:

- 1- flash floods can be of three origins: (1) karst groundwater, (2) urban runoff, (3) cumulative contribution of karst and urban waters.
- 2- flood dynamic is dependent of the water origin
- 3- short monitoring time-steps are needed for flash flood hydrograph separation, that emphasize the use of in-situ sensors
- 4- electrical conductivity (EC) can be used for hydrograph separation.

Hydrograph separation aims to divide the storm runoff hydrograph into its component sources or end-members and to calculate their relative contributions (Ogunkoya and Jenkins, 1991). Water stable isotopes (²H or ¹⁸O) have been widely used since the 1970s for hydrograph separation. This method was used to study how rainfall translated into streams, and it changed how runoff generation was conceptualized. In 2013, Klaus & McDonnell proposed a review of the isotopes hydrograph separation method, with two end-members or more, and listed more than 200 published journal articles that encompass many climatic, geological, and land use conditions. Isotopes hydrograph separation with two end-members usually shows the relative significance of pre-event water (groundwater) and event water (rainfall) in streams. Other tracers are added in multi-component mixing models. Other or additional tracers should be conservative, and many have been tested (e.g. Petelet-Giraud et Negrel 2007, Ladouche et

al. 2001, and other references in Klaus and Mc Donnell 2013): Strontium isotope, Chloride, DOC, Silica or Electric Conductivity (EC).

One limit of methods based on water stable isotopes is the monitoring time-step that requires working in two steps: in-situ sampling, and then post-event laboratory analysis. As pointed out by Liao et al. 2014, specific advantages of using in-situ time series of physical properties are their low detection cost and their continuous quality, which can be recorded over years. This becomes particularly important if high-frequency time series are required due to time-variant flow or boundary conditions, as is the case in most river systems and in flash flood studies. We propose to use EC in this study as an end-members tracer. EC is a classical physical parameter, widely used for this purpose in surface stream and groundwater flow (Liao et al. 2014, Cirpka et al. 2007, Cox et al. 2007, Meriano et al 2011, Pellerin et al. 2008). This is particularly relevant in karstic and urban environment where there is large contrast between rain runoff, which present very low EC values, and groundwater, which presents moderate to high EC values.

The present case study is a 8km-long Mediterranean stream in Southern France, called the “Las river”, which flows through the city of Toulon. This stream drains a karst groundwater catchment around 50 km², and an urban catchment of a few km². The Las river is supplied by two main karst springs: the Saint Antoine spring (0.02 to 4 m³/s) and the Dardennes springs (0.05 to more than 30 m³/s), and also by surface runoff during rainy periods (Figure 1). The Dardennes springs are beneath an artificial lake used as a reservoir for drinking water. Three monitoring stations were equipped with CTD sensors (CTD, C: Electric Conductivity, T: Temperature, D: Depth) with a 15 minute-time-step: the Lagoubran station in the Las river at the downstream point of the studied area, the Saint Antoine spring and the Ragas, an overflow spring 500 meters upstream the Dardennes lake. Discharges are calculated from water heights. We perform a two-component hydrograph separation at the Las Lagoubran station in order to simulate the runoff discharge and the karst groundwater discharge, with electric conductivity (EC) as the end-members tracer. The Saint Antoine discharge as part of the total Las discharge is not simulated but included as a known value in the hydrograph separation. We compare the simulated discharges with hydrometric measurements at the Dardennes station and validate the method based on EC approach during a range of hydrologic and climatic conditions. EC end-members values are tested for fixed values as commonly proposed in the hydrograph separation method (Klaus & McDonnell 2013) and for time-dependent values (Pilgrin 1979) at a karst representative station (CTD at the Ragas monitoring station). However, in this work we do not simulate the flood wave propagation in the stream channel, and the assumption of steady transfer in the 8 km long channel is supported by field data that shows a rapid propagation from the upstream point (Dardennes, figure 1) to the downstream station (Lagoubran) in less than 2 hours.

36 months (2012 to 2015) of data are available, with a few periods lacking data due to sensor failure. The Las discharge at the Lagoubran station varied from a few tens of liters per seconds during low flow (end of summer and autumn) to 40 m³/s during high floods with flash flood behavior. During this period of measurements, the applied hydrograph separation method shows that high discharge can be correlated to two distinctive flood generation processes. For instance, on one hand the local 19/09/2014 rainfall event generated a flash flood with a peak flow of 36 m³/s in less than 30 minutes and a decrease to 1m³/s in 2h15min after the peak, without any contribution of the karst groundwater. This flood was related exclusively to urban runoff. On the other hand, the 27/11/2014 flood had also a maximum discharge close to 40 m³/s, but with 100% of contribution from the karst groundwater. The flood remained above 30 m³/s during 12 hours, without significant rainfall during this period.

This high discharge event was also monitored at the Ragas overflow spring as the highest level recorded since 2012.

These two exceptional flash floods, among many others, show that in order to understand the development of floods in urban and karstic environments, we must separate both the karstic contribution and the urban runoff from the total stream discharge. It is possible to measure the water height in the karst to predict what the karstic contribution would be to the stream discharge. The karst contribution does not present the same behavior as urban runoff. Even though the karst reacts very quickly, it slows down flash floods caused by very intense Mediterranean rainfalls. The example of Toulon shows that the risk would strongly increase in the case of a disadvantageous situation where a karstic flash flood and a urban runoff-generated flash flood would occur at the same time. This case study is also very interesting as Toulon was identified as a Territory exposed to an important Flood Risk (in french “*TRI : Territoire à Risque Important d’Inondation*”). This work suggests to local manager to install a network of CTD monitoring in streams and karstic springs in order to evaluate the origin of flash flood water and its propagation. The hydrograph separation based on the EC tracer is a first step for the rainfall-discharge modeling for risk assessment. The modeling of the total discharge of the Las river could be improved by using two independent forecasting rainfall-discharge numerical models, one for each source of discharge and hydrological process (urban runoff and karst groundwater).

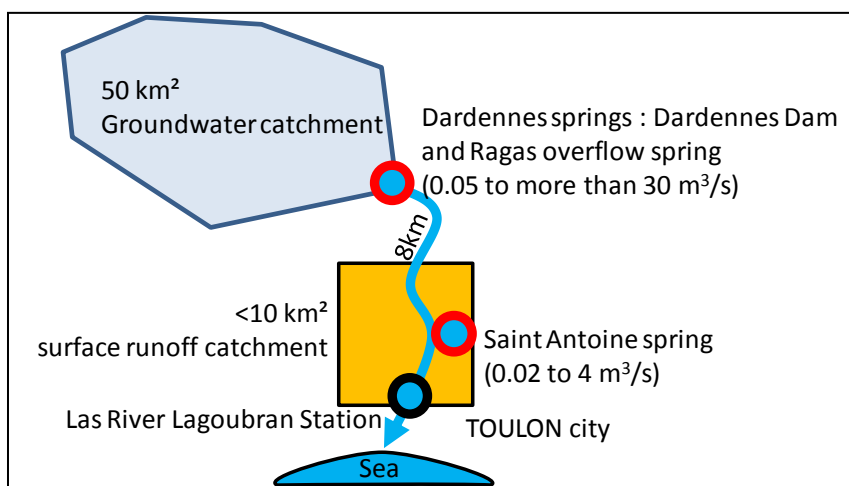


Figure 1: Schematic view of the main features of the studied area

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