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ORIGINAL ARTICLE

Hervé Jourde
Axel Roesch
Vincent Guinot
Vincent Bailly-Comte

Dynamics and contribution of karst groundwater to surface flow during Mediterranean flood

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H. Jourde (✉) · A. Roesch
V. Guinot · V. Bailly-Comte
Hydrosciences, University of Montpellier II, 300, Avenue Emile Jeanbrau, 34095 Montpellier, France
E-mail: jourde@msem.univ-montp2.fr
E-mail: roesch@msem.univ-montp2.fr
E-mail: guinot@msem.univ-montp2.fr
E-mail: bailly@msem.univ-montp2.fr

Abstract This paper describes the role of groundwater contribution to surface flow at the Causse d'Aumelas, a karst system near Montpellier (France), which is traversed by an intermittent river, the Coulazou. A first hydrologic model integrating a digital terrain model shows the inability of a standard rainfall-runoff model to replicate recorded flood hydrographs. While the flood peaks are routed through the karstic system along the Coulazou without a phase lag, the peak magnitude is somewhat modified. These results indicate an initial karst system recharge followed by a significant contribution to surface flow. A hydrodynamic analysis of groundwater flow confirms these results: the karst system first absorbs part of the rainfall, which induces a general water table rise within the aquifer, and then contributes to surface flow in the Coulazou.

Keywords Flash flood · Karst watershed · Groundwater contribution · Hydrodynamic analysis · Flood modelling · Mediterranean · France

Introduction

The role of groundwater contribution to surface flow in karst watersheds is not well understood, although it may have a considerable impact on intense and rapid flooding in Mediterranean karst regions. This phenomenon has been studied in porous media (Freeze 1972), but has been scarcely observed in karstic heterogeneous terrains. A comparison of hydrologic and hydrogeologic processes is being carried out at the Causse d'Aumelas, a karst system near Montpellier (France), with the objective of obtaining better understanding of the dynamics and contribution of karst discharge to surface flow. The Causse d'Aumelas is crossed by the intermittent Coulazou River along which over 15 main karst features (estavelles) acting as sinkholes/springs have been recorded. The watershed is monitored with a dense monitoring network used to estimate the exchange between the Causse d'Aumelas aquifer and the surface drainage network (Fig. 1). The present study focuses on the dynamics and contribution of karst groundwater to surface flow for one particular rainfall event.

Study area and field measurements

The French karstic region called Causse d'Aumelas is a Jurassic calcareous plateau crossed by the intermittent Coulazou River (Fig. 1). This region is a binary karstic system developed within the calcareous Jurassic plateau, in contact with an Oligocene impermeable basin in the North and a Miocene impermeable basin in the South. For this study, the upstream Oligocene watershed is distinguished from the downstream Jurassic karst watershed of the Coulazou River. The upstream watershed is a synclinal mainly constituted of marly limestone covered by Oligocene detritic terrains, formed of limestone pebbles embedded in a clayey matrix. The downstream watershed corresponds to the Causse d'Aumelas karstic Jurassic plateau traversed by the Coulazou, the surface of which is about 40 km^2.

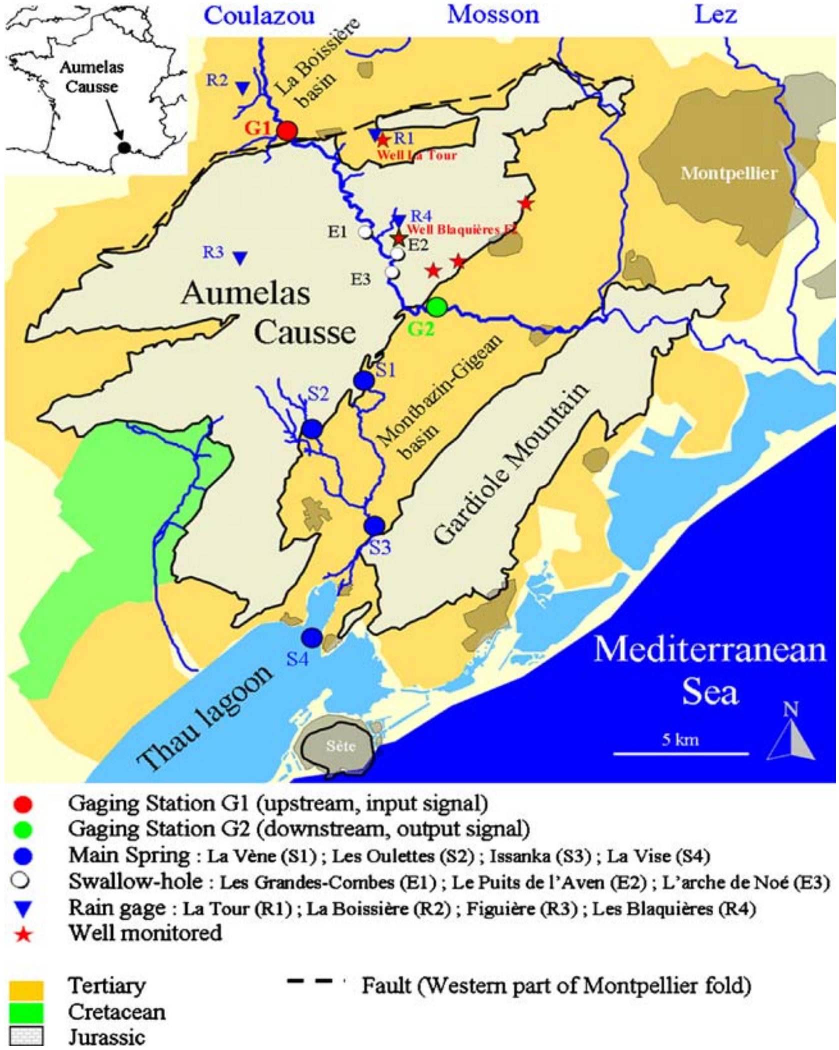

Fig. 1 Monitoring network of the watershed karst system

During the periods of high water table level, many sinkhole/springs (estavelles) in the Coulazou valley contribute to superficial flows. Under normal conditions, the underground flow is directed towards four main karstic outlets: S1 (intermittent spring La Vène), S2 (intermittent spring Les Oulettes), S3 (permanent spring Issanka) and S4 (submarine spring La Vise). For this karst system, an upper compartment associated with a surface drainage network with S1, S2, and the Coulazou River as main outlets can be distinguished from a lower compartment connected to a deep drainage network, the main outlets of which are S3 and S4. Pressure and temperature data in the upper compartment of the karst system are available at four wells and two sinkholes/springs (Fig. 1) from April 2004 onwards with a 10 min time step. Measurements are recorded every 5 min at four rain gauges distributed over the area and two gauging stations at the entrance and the outlet of the Coulazou karst watershed.

Hydrodynamic analysis

Figure 2 shows the water table variations (m above mean sea level) in the two swallow holes located within the Coulazou riverbed and the river level water stage at the upstream (G1, Coulamont) and downstream (G2, Coulaval) gauging stations. During surface flooding, the water table rises in both monitored sinkholes/springs (E1, E2).

The rise takes place a little earlier in the downstream sinkhole/spring (E2, Aven) than in the upstream sinkhole/spring (E1, Grandes Combes).

The water table elevation exhibits a plateau at E1 and E2 during 20 and 42 h, respectively. This plateaus indicate that karst overflow occurs with groundwater contribution towards the Coulazou River. Furthermore, a second peak is observed at the downstream gauging station with higher amplitude than at the upstream gauging

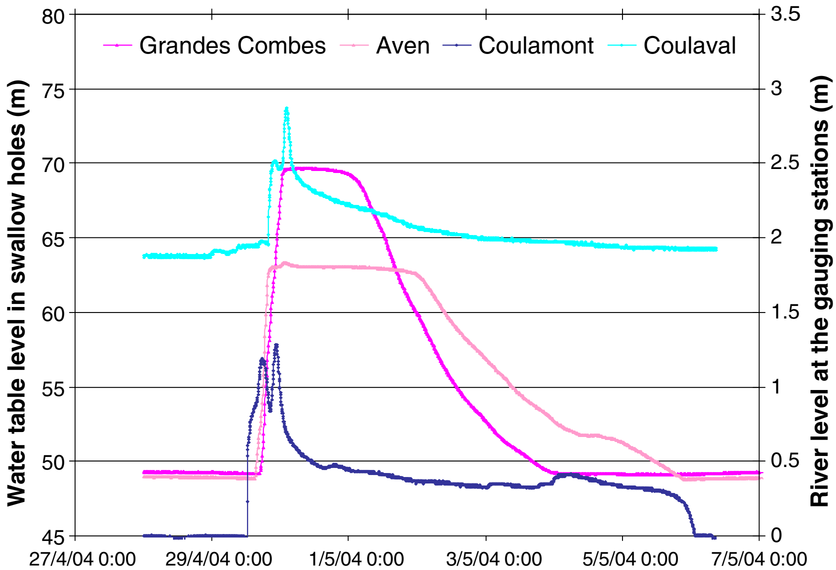

Fig. 2 Water table and river level variation

station when overflows occur on both sinkhole/springs. This behaviour is in agreement with the observed general increase in the water table level propagating from downstream of the aquifer to upstream before groundwater contributes to surface flow of the Coulazou.

Figure 3 shows the water table variation (m above mean sea level) in the downstream swallow hole (E2, Aven) located in the Coulazou riverbed and in two monitored wells (Blaquières F2, Forage La Tour). When overflow occurs at E2, it affects the water table variations in the conduit and thus in Blaquières F2 well. From aerial photographs, well Blaquières F2 and sinkhole/spring E2 can be observed to be on a main fault. It can explain their apparent hydraulic connectivity illustrated by their common hydrodynamic behaviour. This may indicate that both holes are connected to a high conductivity conduit linked to the main drainage network of the aquifer, since water table rises and decreases rapidly with amplitude of 18 m. The well La Tour is in the northern part of the karstic watershed, very close to its boundary with the upstream Oligocene watershed. It shows very rapid water table rises with a high amplitude (30 m), synchronized with the previous ones. However, the dynamics of the water table decrease is slightly different, which may be related to a compartment of the karstic aquifer with a lower porosity or lower conductivity conduit. The hydrodynamic behaviour observed on these three monitored stations during water table rise confirms that the karst system first absorbs part of the rainy event, which induces a general water table rise within the aquifer, thus contributing significantly to surface flow in the Coulazou.

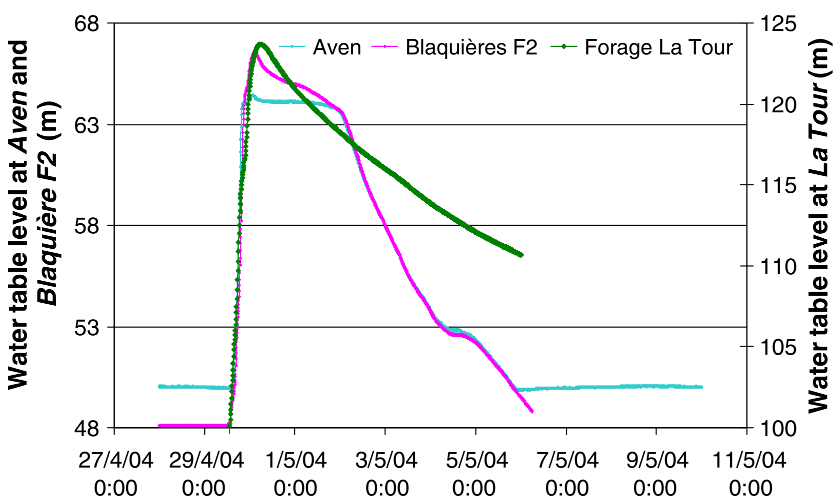

Fig. 3 Water table variation

Hydrologic modelling

Before the studied flood event, this intermittent river was dry and flowed only from 28 April to 5 May 2004. To assess the fraction of the rain contributing to surface runoff, the flood hydrograph was integrated between these two dates, at the upstream (non karstic watershed) and downstream (karstic watershed) gauging stations.

The volume of water that flowed at the upstream gauging station corresponds to 9% of the net cumulated rainfall over the upstream watershed. The difference between the volume of water that flowed at the downstream and at the upstream gauging station corresponds to 36% of the net cumulated rainfall over the downstream karstic watershed. The 36% net rainfall for the downstream watershed also integrates the groundwater contribution to surface flow since it is calculated from the downstream Coulazou River hydrograph. The 9% net rainfall for the upstream watershed is in agreement with the land use. Indeed, it mainly comprises vineyards on marly and clayey ploughed terrains that may retain most of the water. These net rainfall volumes were used in the hydrologic model for the upstream and downstream watershed, respectively. The flood event was modelled with the Mike SHE and Mike 11 software (Graham and Refsgaard 2001).

Hydrologic data

A digital terrain model (DTM) with a cell size of 50 m (Fig. 4) was used to define the topography of the site and the Coulazou River watershed, which fits correctly with the watershed determined from the topographic maps. The spatial variability of the rainfall was inferred from measurements while considering also the topography of the whole watershed and the rain gauges monitoring stations elevations. This distribution was felt to be more adequate than a Thiessen Polygon-based method because of the topography (Fig. 4: watershed DTM) and the geological properties of the watershed. Four sub-watershed were distinguished: the upstream watershed of La Boissière, the western karst watershed of Mas de Figuière (mean elevation 250 m), the southern karst watershed of Les Garrigues (mean elevation 150 m), and the intermediate karst watershed of Mas de La Tour (mean elevation 100 m).

Hydrodynamic data

The flood wave propagation in the Coulazou was modelled using the diffusive wave approximation. The longitudinal profile of the river was measured and var-

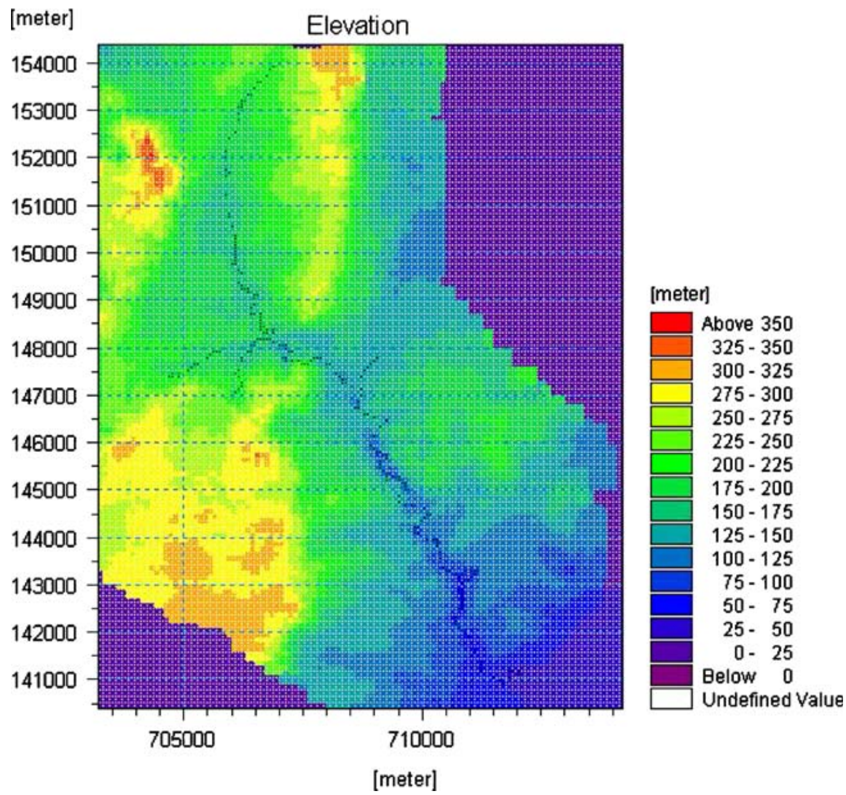

Fig. 4 Watershed digital terrain model

ious significant (widening, narrowing) cross sections determined.

Model calibration

During model calibration, the hydrologic response was obviously controlled by the spatial distribution of surface runoff, but also by sub-surface detention storage (mm). Therefore, various sub-regions corresponding to different land use and geological properties were determined. A high surface roughness, with a Strickler coefficient equal to 25 $m^{1/3}/s$ was selected for the detritic Oligocene part of the upstream watershed, cultivated with vineyards. For the remainder of this upstream watershed (pastoral activity), a lower surface roughness (higher surface runoff), with a Strickler coefficient equal to 35 $m^{1/3}/s$ was used.

For the downstream karst watershed, a high surface roughness value with a Strickler coefficient equal to 22 $m^{1/3}/s$ was selected. Finally, a high roughness value with a Strickler coefficient equal to 7 $m^{1/3}/s$ was chosen for the Coulazou riverbed. The river bed is constituted of blocks of various sizes and both the main channel and the floodplain are highly vegetated.

The best fit between the simulated and observed hydrographs was obtained using net rainfall coefficients of 13% and 32% over the upstream and downstream watersheds, respectively (Fig. 5). They were also assigned a sub-surface detention storage of 5 and 10 mm, respectively.

Figure 6 shows the measured and simulated flood hydrographs at the upstream gauging station. On the measured hydrograph, two peaks were observed on 29/04/2004 at 6.00 p.m. and 11.00 p.m., with estimated discharges of 3 and 4 m^3/s, respectively. On the simulated hydrograph, two peaks on 29/04/2004 at 6.20 p.m. and 11.00 p.m. were evident with values of 3.55 and 3.52 m^3/s, respectively. Accordingly, the fit is good, although the two peaks are more noticeable on the measured hydrograph.

Figure 7 shows the measured and simulated flood hydrographs at the downstream gauging station. On the measured hydrograph, two peaks are observed at 10.00 p.m. on 29/04/2004 and at 2.30 a.m. on 30/04/2004. Estimated discharges are 10.3 and 23 m^3/s, respectively. On the simulated hydrograph, only one peak is evident for this period, 30/04/2004 at 0.49 a.m., with a discharge

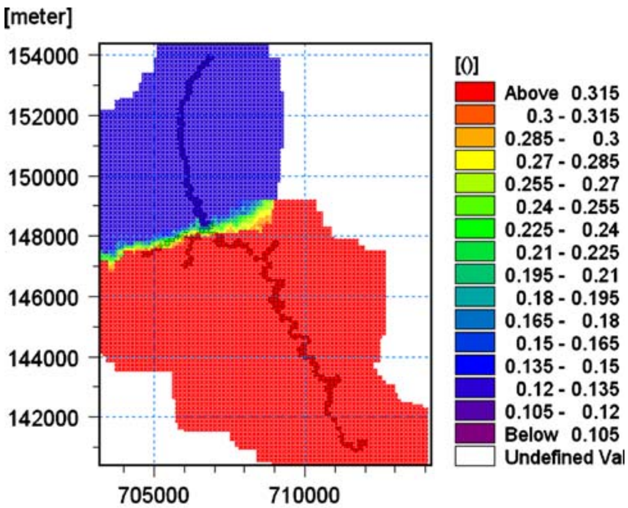

Fig. 5 Net rainfall spatial distribution

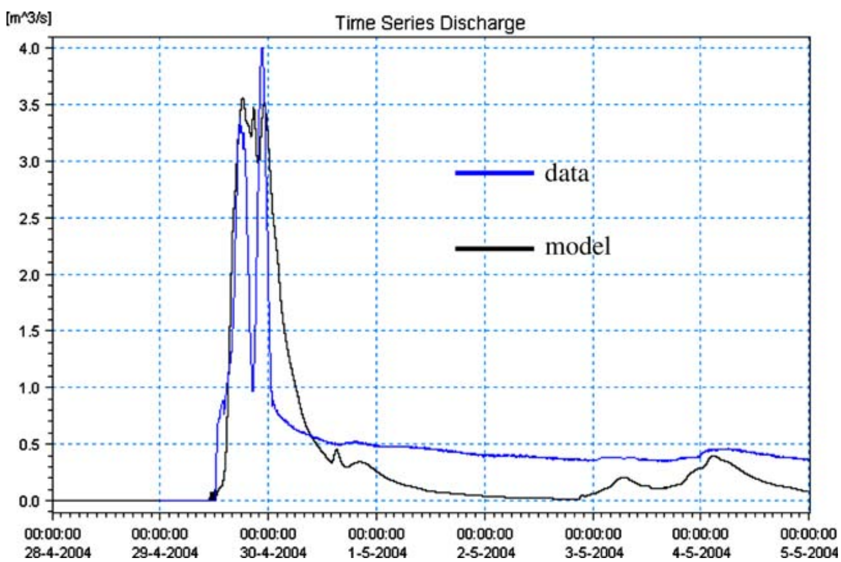

Fig. 6 Estimated and simulated flood hydrographs at the upstream gauging station

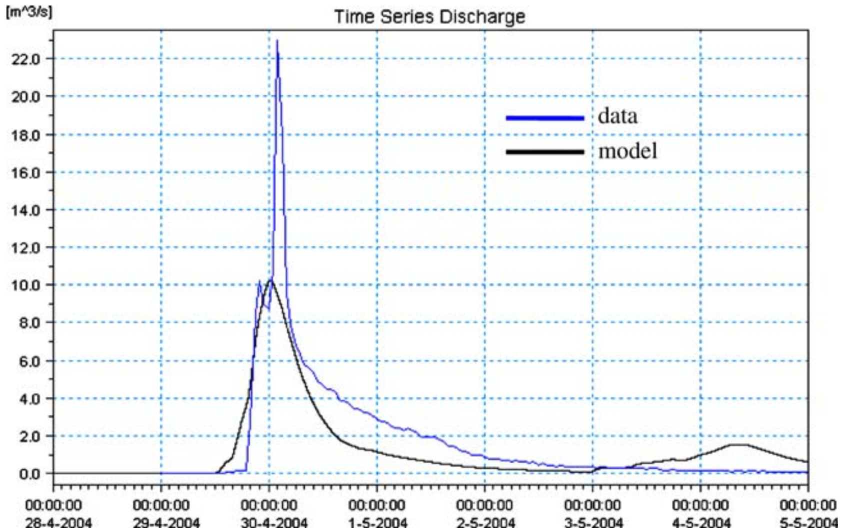

Fig. 7 Estimated and simulated flood hydrographs at the downstream gauging station

of 10.24 m^3/s. The first maximum discharge is thus correctly simulated (same order of magnitude), but the second maximum flow rate does not appear on the simulation. Therefore, either the model calibration is incorrect, or the surface runoff hydrologic model cannot simulate the second peak because there is an additional contribution to surface flow.

Given the good fit on the upstream gauging station and the previous hydrodynamic analysis, this discrepancy for the second peak of the hydrograph is probably related to a delayed contribution of karst groundwater to surface flow. The difference between simulated and measured volumes appears to be about 410,000 m^3, which may correspond to groundwater contribution. This volume constitutes 36% of the whole surface water volume at the downstream gauging station, which means that for this particular rainy event, karst groundwater contribution constituted over one-third of the total flood volume of the Coulazou. To characterize the dynamics of karst groundwater contribution to the surface drainage network, it would be interesting to model this flood event with a fully coupled surface–subsurface hydrologic model (e.g. Panday and Huyakorn 2004). However, it implies building a hydrogeologic model at the aquifer scale that includes geometric and tectonic information (Jourde et al. 2002), which is difficult in such a heterogeneous media as the Causse d'Aumelas karst watershed.

Conclusion

This study illustrated for one particular rainy event karst groundwater contribution to surface flow during a Mediterranean flood, both with hydrodynamic analysis and hydrologic modelling. The inability of a standard rainfall-runoff model to replicate recorded flood hydrographs in a karst watershed was confirmed. However, the hydrologic model allowed the karst groundwater contribution to surface flow to be quantified. It was also shown that the karst flow represents more than one-third of the cumulated flow at the outlet of the karst watershed. Hopefully, other flood events will be recorded and examined if this explanation can be generalized. It will then be possible to build a coupled surface–subsurface hydrologic model for the Causse d'Aumelas karst watershed.

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