# Spatial and Temporal Hydrodynamic Variations of Flow in the Karst Vadose Zone (Rustrel, France) in Function of Depth and Fracturing Density

**A. Barbel-Perineau, C. Emblanch and C. Danquigny**

**Abstract** The hydrodynamical response at 45 flow points in the gallery of the Low Noise Underground Laboratory—carbonate aquifer (Rustrel, southern France) was monitored in order to determine the relationship between the hydrodynamical functioning of each flow component—slow, intermediate and quick, the depth and the fracturing density. Analysis of the relationship between the distribution of each flow component in function of depth and fracturing density in the karst vadose zone revealed the importance of (1) the variation of flow activation conditions with the depth, (2) the evolution of the flow component distribution with the depth and the fracturing density, and (3) the variability of the vadose zone role in supplying baseflow discharge, in function of carbonate thickness and fracturing state of the study area.

## 1 Introduction

The study of the flows in the vadose zone of a karst system needs some access to this part of the aquifer. Such kind of flow has been directly monitored since 2004 in the Laboratoire Souterrain à Bas Bruit (LSBB) located in Rustrel (South-East of France), an underground laboratory dug across the vadose zone of the Fontaine-de-Vaucluse karst aquifer.

This artificial gallery (3,800 m length) intersects arbitrarily fault networks from 30 to 500 m depth in carbonated rocks. Spatial and temporal hydrodynamical variations of 3 perennial and 42 temporary flows have been monitored throughout the gallery (Fig. 1), under variable and contrasting climatic conditions from 2004 to 2012 (Barbel-Perineau 2013). Within this period, all of the flow points have

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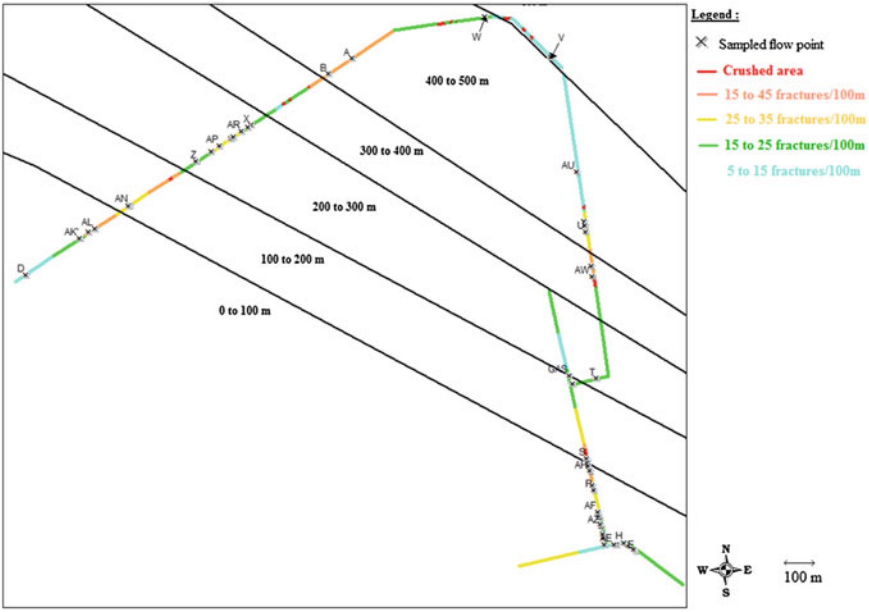


**Fig. 1** Flow points location within the gallery and fracturing density (after Thiebaud (2003) modified)

been observed and measured at least once only during the 2008–2009 hydrological cycle. Thus in this study, only the 2008–2009 hydrological cycle is considered.

In previous studies (Perineau et al. 2010; Barbel-Perineau 2013; Perineau-Barbel et al. 2013), results highlight (1) an hydrodynamical flow classification in three components that have been characterized: a slow component, with permanent flows, regardless of the hydrological conditions (amount of rainfall); an intermediate component, with temporary flows, but these flows have some temporal flow continuity when they are active (few days to several months), and are assumed to obey a non linear hysteretic function; a quick component, with temporary flows too, but these flows have no temporal flow continuity (1 day to several days), they run only during important groundwater recharge and when the discharges of the permanent flows (slow component) are about or even reach their upper discharge levels. These three previous flow components are not specific to the study area because it has been shown (Barbel-Perineau 2013) that they match with the three flow components deduced from the numerical model of Tritz et al. (2011) in the vadose zone.

Results also demonstrate flow organization depending on depth and fracturing density; indeed the number of flow points decreases with depth. Moreover, results show that flows become permanent in depth and flows are concentrated in well-fractured and karstified areas, in which flow continuity is ensured (Perineau et al. 2010). It is now necessary to cross these previous results in order to study organization of these flow components in function of depth and geological layout of the vadose zone. Limestone is relatively homogeneous in this geological set, so the geological layout will be studied through fracturing density in the vadose zone.

Using the LSBB hydrodynamical data set, the objective of this paper is to study the relationship between the flow organization and the hydrodynamical functioning of each flow component with depth and fracturing density: which is the most important flow component in function of depth and fracturing density?

## 2 Data and Methods

The LSBB (http://www.lsbb.eu) is an underground gallery dug for a military purpose and converted into a research laboratory. It is hosted in the vadose zone limestone (Lower Cretaceous) of the Fontaine-de-Vaucluse Mounts, in Rustrel (France). The gallery is 3.8 km long. The rock's cover over the gallery varies from 0 to 519 m due to the topography. As the gallery comes across the karst medium, it intersects also with some flow paths through the vadose zone.

In this underground area, flows are accessible in many natural cavities (speleology) and in galleries of the LSBB which provide a readily access to them.

Between 2004 and 2008, drought period, (Barbel-Perineau 2013; Perineau-Barbel et al. 2013), only three permanents and two temporary flow points are observed and measured (Garry et al. 2008) at different depths. The rest of temporary flow points (40) was observed for the first time in winter 2008 during a heavy rainy period.

All the flow points (permanent and temporary) are located throughout the gallery (Fig. 1). This study is based on hydrodynamical flow measurements in a gallery. Its originality consists of: (i) the number of observation points (45) and (ii) flows that intersect randomly throughout a gallery and not caves, as it is often the case (e.g. Baldini et al. 2006; Fairchild et al. 2006).

To measure discharge rates of each flow point, the wall of the gallery is drilled to reach the rock and flows; then water inflows are concentrated in a spillway with a funnel. Discharge is weekly manually measured at the outlet of the funnel.

Discharge rates are weekly manually measured for many technical reasons: (i) for temporary flow points, it is difficult to set up and look after of around fifty pressure captors (dust, scaling and calibration problems), (ii) the three permanent flow points are equipped with pressure captor but scaling problems complicate the conversion of the water head in discharge with a calibrating curve.

Geological and geotechnical surveys made during the gallery drilling (CEBTP 1968) provide a characterization of lithology, faults, joints, cracks, karstification, and seepages. Moreover, the fracturing frequency (Fig. 1) was calculated by Thiebaud (2003) and the depth of each flow point was also calculated.

To have enough hydrodynamical data in the whole vadose zone, the gallery is divided into five depth classes of 100 m thick (Table 1). Thus for each depth class, the gallery length is large enough to be considered as representative (Table 1).

**Table 1** Total linear length of gallery (m) per each depth class

| | Total linear length of gallery per each depth class (m) | % |
|---|---|---|
| 0–100 m | 713 | 22 |
| 100–200 m | 496 | 15 |
| 200–300 m | 492 | 15 |
| 300–400 m | 441 | 13 |
| >400 m | 1,138 | 35 |
| Total | 3,280 | 100 |

# 3 Results and Discussions

## *3.1 Flow Components Distribution in Function of the Depth*

Table 2 indicates the flow point's distribution for each flow component in function of depth (five depth classes of 100 m thick) in the vadose zone. Values with a star depict two flow points with peculiar hydrodynamical characteristics:

- Regarding the slow component, the flow point between 0 and 100 m depth (D) is located near the epikarst (30 m depth); however, this flow point shows identical hydrodynamical and hydrochemical characteristics studied in details by Carrière (2014).
- Regarding the intermediate component, (i) the temporary flow point (C), situated between 200 and 300 m depth, is located at boundaries of two flow components, slow and intermediate, because when it is running during wet periods, it is almost permanent (up to 1 year) (ii) the flow point (W) located in depth (>400 m) is a temporary flow point, but when this flow point is running, its hydrodynamical and hydrochemical characteristics are strongly identically to hydrodynamical characteristics of slow component (Barbel-Perineau 2013). Thus, this temporary flow point is also located at boundaries of the two flow's components, slow and intermediate.
- Except the particular case of the D point, the slow component only circulates in depth. Even if this flow point is characterized as a slow component, its peculiar hydrodynamical features are linked to its epikarst position, or a lack of observation linked to a non-representativeness of the LSBB. However, outside the epikarst, it seems logical to find the slow flow component in depth.
- However, the quick component exists throughout the vadose zone, only during strong recharge periods (with large amount of rainfall and strong intensity) and only when the two other flow components are active (Barbel-Perineau 2013). So its hydrodynamical characteristics involve an hydrodynamical flow's behavior within the vadose zone less structured than the slow component. Note that in this study the quick component does not include direct runoffs from surface karst landing to the saturated zone (no doline, even… in the study area).

**Table 2** Flow components distribution in function of depth (number of flow points in each depth class)

| | 0–100 m | 100–200 m | 200–300 m | 300–400 m | >400 m |
|---|---|---|---|---|---|
| Quick component | 13 | 7 | 5 | 4 | 1 |
| Intermediate component | 6 | 4 | 1* | – | 1* |
| Slow component | 1* | – | – | – | 2 |
| Total | 20 | 11 | 6 | 4 | 4 |

Values with a star are specific values which are explain in the text

- Finally, the intermediate component shows a different distribution in the vadose zone, this flow component prevails in the firth 200 m depth, and then this component seems to disappear, or rather to become more hydrodynamically organized, i.e., to become permanent flows, typical of the slow component.

### *3.2 Flow Components Distribution in Function of Depth and Fracturing Density*

Tables 3, 4 and 5 summarize, for each flow component, the ratio between the number of flow point and 100 m of gallery length, in each depth class and fracturing class, during the 2008–2009 hydrological cycle (within this period all of the flow points have been observed and measured at least once).

The fracturing density is also divided into five classes, from slightly fractured area (5–15 fractures/100 m) to crushed area. The comparison of Tables 3, 4, and 5 indicates that the intermediate component (Table 4) tends to preferentially gather in well-fractured, karstified areas, from the surface (to 200 m depth), on contrary to the two other flow's components. Regarding the peculiar temporary flow point W (see above), theoretically located in the 15–25 fracturing class, in depth (>400 m), more precisely this flow point is located in the gallery within a local small-scale crushed area (in the work of Thiebaud (2003), small-scale crushed areas have been indexed as single fractures). So to have an accurate table, the corresponding value ("0.09*") is written in corresponding cells "crushed areas" versus ">400 m."

The quick component (Table 3) circulates in the whole vadose zone, whatever the depth or fracturing density may be, because important hydraulic connectivity and strong pressure are both necessary to observe this flow's component running in the vadose zone (Barbel-Perineau 2013). Flows corresponding to the quick component circulate throughout well-developed drain paths which can get through the whole vadose zone. Nevertheless, as the slow component flows corresponding to the quick component tend to concentrate in depth in well-fractured areas, in which karstification process is well-developed.

Finally, the slow component (Table 5) is characterized almost exclusively by flow circulations in depth, in preferential flow paths, well fractured (except the flow point D as explained above).

**Table 3** Quick component distribution in function of depth and fracturing density

| | 0–100 m | 100–200 m | 200–300 m | 300–400 m | >400 m |
|---|---|---|---|---|---|
| 5–15 fractures/100 m | 0.14 | ** | 0.00 | 0.00 | 0.09 |
| 15–25 fractures/100 m | 0.98 | 0.20 | 0.41 | 0.00 | 0.00 |
| 25–35 fractures/100 m | 0.56 | 0.81 | 0.61 | 0.45 | 0.00 |
| 35–45 fractures/100 m | 0.14 | 0.40 | ** | 0.23 | 0.00 |
| Crushed areas | 0.00 | 0.00 | 0.00 | 0.23 | 0.00 |

The two stars mean that the fracturing class is not represented in the depth class and zero corresponds to the lack of flow in depth classes

**Table 4** Intermediate component distribution in function of depth and fracturing density

| | 0–100 m | 100–200 m | 200–300 m | 300–400 m | >400 m |
|---|---|---|---|---|---|
| 5–15 fractures/100 m | 0.28 | ** | 0.00 | 0.00 | 0.00 |
| 15–25 fractures/100 m | 0.56 | 0.40 | 0.00 | 0.00 | ** |
| 25–35 fractures/100 m | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 35–45 fractures/100 m | 0.14 | 0.60 | ** | 0.00 | 0.00 |
| Crushed areas | 0.00 | 0.00 | 0.20 | 0.00 | 0.09* |

The two stars mean that the fracturing class is not represented in the depth class and a zero corresponds to the lack of flow in depth classes

**Table 5** Slow component distribution in function of depth and fracturing density

| | 0–100 m | 100–200 m | 200–300 m | 300–400 m | >400 m |
|---|---|---|---|---|---|
| 5–15 fractures/100 m | 0.14 | ** | 0 | 0 | 0.00 |
| 15–25 fractures/100 m | 0.00 | 0 | 0 | 0 | 0.00 |
| 25–35 fractures/100 m | 0.00 | 0 | 0 | 0 | 0.00 |
| 35–45 fractures/100 m | 0.00 | 0 | ** | 0 | 0.18 |
| Crushed areas | 0.00 | 0 | 0 | 0 | 0.00 |

The two stars mean that the fracturing class is not represented in the depth class and a zero corresponds to the lack of flow in depth classes

Each flow component is organized in function of the state of the media, the quick component is a temporary component because flow through drains involve low water storage to supply flows of this component. The functioning of the intermediate component in function of depth and fracturing density tends to show a water supply, a support to the slow component. Intermediate flows could be actually considered as next slow flows, but not enough structured to drain a necessary volume of water storage to supply base flow.

Finally, the role of the vadose zone varies with the rock thickness, (i) the existence and/or the distribution of the three flow's components at the bottom of the vadose zone can be a function of both the karstification state and the vadose zone thickness of studied areas, (ii) permanent baseflow (slow component) within the vadose zone is linked to the thickness of considered vadose zone, which may be several hundred meters. For a long time, vadose zone is supposed to achieve a major role of storage and baseflow discharge supply (e.g., Emblanch et al. 2003; Perrin 2003; White 2006; Mudarra and Andreo 2011). Recently, this hypothesis has been indirectly demonstrated (e.g. Padilla et al. 1994; Charlier et al. 2012) and directly (e.g. Perrin 2003; Garry et al. 2008; Pronk et al. 2009; Barbel-Perineau 2013), with measurements within the vadose zone.

This study puts the role of the vadose zone into perspective. Indeed inside karstic aquifers with an important thickness of vadose zone, the vadose zone has a major hydrodynamic role, even during prolonged low-flow periods. Conversely inside karstic aquifers with a little thick vadose zone, its hydrodynamical role is less important. Thus, in future coming modeling studies of karst aquifers, it would be wise to adjust assigned coefficients of each karstic sub-system, especially the vadose zone, in function of several parameters, as thickness, karstification state, fracturing state, instead of set them arbitrarily (as e.g. Bezes 1976; Fleury et al. 2007).

## 4 Conclusion

Finally, this study highlights the distribution of flow components within the vadose zone in relation with the depth and the fracturing density: (1) the slow component is characterized almost exclusively by flow circulations in depth, in preferential flow paths, well-fractured areas. (2) The quick component circulates in the whole vadose zone, whatever the depth and the fracturing density may be, because an important hydraulic connectivity and strong pressure are both necessary to observe it. Flows corresponding to the quick component circulate throughout well-developed drain paths, which can get through the whole vadose zone, (3) tends to preferentially gather in well-fractured, karstified areas, from the surface (to 200 m depth), the intermediate component shows a particular distribution in the vadose zone, this flow component prevails in the firth 200 m depth, and then seems to disappear, or rather to become more hydrodynamically organized, i.e., to become permanent flows, typical of the slow component.

Thus, this study allows deducing the importance of (1) the variation of flow activation conditions with the depth and (2) the evolution of the flow component distribution with the depth and fracturing density, (3) the variability of the vadose zone role in supplying baseflow discharge, in function of carbonate thickness and fracturing state of the study area.

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