Transmissive and Capacitive Behavior of the Unsaturated Zone in Devonian Limestones, Implications for the Functioning of the Epikarstic Aquifer: An Introduction

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Abstract The hydrogeological behavior of the unsaturated zone in karst limestones is far to be completely understood. However, this part of aquifer systems is the most important for the vulnerability of drinking water resources. In Wallonia, the majority of tap water is provided by Devonian and Carboniferous limestones, which consist of highly karstified and fractured formations. The purpose of this research was to apply an experimental approach in order to assess the functioning of the unsaturated part of karst systems. We choose to follow two drip sites within the Han-sur-Lesse cave system (Rochefort, Belgium), the actual dataset covers the 2008–2013 period and the recording device is still active. We also conduct dye tracer experiment (uranin) from the surface with a fluorometer into the cave coupled with a drip collector. In this paper, we present the contextualization of the study site, the experimental methodology, and the first results.

1 Introduction

The superficial part of karst area is usually referred as the epikarstic area. This zone presents an increased degree of dissolution, weathering, and fracturation and therefore exhibits higher porosity and permeability compared with the underlying bedrock (Mangin 1975; Klimchouk 2004) (Fig. 1). Due to this, it may store a part of the infiltrated water up to a near-saturation state and, then, constituting a perched epikarstic aquifer within the unsaturated zone. Limestone and karst aquifers represent an important part of global groundwater reserves. Their vulnerability is

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Fig. 1 General overview of the unsaturated zone in karst limestones (adapted from Klimchouk 2004)

important, and therefore the protection of this resource is a major issue for the preservation of the water reserves.

The unsaturated zone (including epikarst) represents a significant transfer path for the aquifer recharge. Transmissive and storage capacity features of the unsaturated zone are poorly understood, mainly due to the lack of direct observational data and the complexity and spatial variability of these processes. One way to understand the behavior of this area, and particularly the role of the epikarst aquifer, is to interpret drip signals into the open karst of the unsaturated zone. Recent studies have already used this methodology in order to assess the various processes inside the vadose zone. Arbel et al. (2010) and Scheffer et al. (2011) used drip rate recording and tracer experiment to estimate the infiltration and recharge processes through the unsaturated zone in Israeli karstified limestones. Jex et al. (2012) provides a summary of published and unpublished sources of cave drip rate monitoring data since more than 15 years. The literature references and the study opportunities based on such data are wide; our first goal was to apply these kind of methodologies at the scale of Belgium. As the Paleozoic limestones of Wallonia are the major reserve of drinkable water in Belgium, it is essential to understand the functioning of such aquifer for the estimation of their vulnerability. In order to collect enough data to allow comparisons with historical data in various places, we chose to install drip rate recording devices in the Han-sur-Lesse cave in 2008. A tracer experiment was also carried out during March 2009.

The first part of the current project was the treatment of datasets from the two drip-sites. The breakthrough curve of the tracer experiment between the surface

and this cave has been also compiled and synthesized. This paper presents the geological and karstic context of the study site, our experimental methodologies and the complete results for the 2008–2013 period, with a short analysis.

2 Study Site

The Han-sur-Lesse cave system is located within the Calestienne in south Belgium, near the city of Rochefort (Fig. 2a). The Calestienne is a morpho-structural unit of Belgium which forms a thin band of SW-NE hills between the Fagne-Famenne plain (mean elevation of 200 m) and the Ardenne highlands (300–694 m). This unit is formed by a series of folded and fractured Upper Devonian limestones (Givetian), highly karstified. The south-Belgian Givetian rocks are mainly composed by biostromal limestones with some argillaceous limestones or nodular shales intercalations, which may locally acts as impervious layers within the karst aquifer. The flow of the Lesse River over these lithologies has favored the formation of an underground meander cutoff through the Boine massif which is now known as the Han-sur-Lesse cave system.

The Han-sur-Lesse cave system is the biggest in Belgium with a cumulated length of 13,843 m. The network is composed of an active karst with the underground Lesse river and several access to the local water table and a « fossil » part with multiple galleries within the unsaturated zone.

The first drip site is installed inside the Père Noël Cave (Fig. 2b). This cave is developed along the bedding plane in the upper part of the Givetian series in the Fromelennes Formation. This is a highly active cave in terms of percolation, which has produced one of the most concretionary cave in Belgium. The drip monitoring station is installed under a perennial stalactite flow that ranges from 15 to 70 l/day. This site was chosen by Genty and Deflandre for drip monitoring between 1991 and 1996 (Genty and Deflandre 1998).

The second drip site is in the Salle d'Armes (Fig. 2b), which is located in the Mont d'Haurs Formation within the Han-sur-Lesse cave s.s. The stalactite is a young speleothem with a drip rate ranging from 0 to 50 l/day.

3 Methodology

3.1 Dripping Rate Measurement

The two dripping sites where equipped with a simple self-siphoning device composed by a graduated cylinder combined with a pressure probe (Fig. 1). The cylinder volume is about 1 l (depending of the probe volume and the siphoning tube size) and is emptied by a glass tube when the water reaches a given level. The probe is a CTD-Diver (Eijkelkamp—10 m Diver) with a time-step of 5 min which

Fig. 2 Location map of Han-sur-Lesse cave system. **a** Location of the Calestienne (*gray*) in Belgium, the study site (*1*) and the city of Rochefort (*2*). **b** Geological map of the study site with the map of the caves

records the pressiometric level into the cylinder (atmospheric pressure + water pressure). As the device is filled/emptied by the dripping flow, we record a saw tooth pattern which allows calculating the dripping rate per day with a simple data treatment. The variation in atmospheric pressure is considered to be too low to influence the results of this methodology.

3.2 Infiltration Calculation

The meteorological data were given by the Royal Meteorological Institute of Belgium (RMI) for the Han-sur-Lesse station which is about 1 km from the Père Noël station and 400 m from the Salle d'Armes station. Daily estimations of temperature (°C), precipitation (mm) and atmospheric pressure are available for the 2008–2013 period, and we consider them to be reliable due to the very short distance. The infiltration water amount was estimated with the water excess (WE) based on the precipitation and the evapotranspiration given by the Thornthwaite formula (Thornthwaite 1954) as suggested by Genty and Deflandre (1998) for the same area. Due to the karst context, runoff is supposed to be negligible.

3.3 Tracer Experiment

The tracer experiment was conducted during March 2009 in the Père Noël cave area. For this particular purpose, the dripping water of the Père Noël station was diverted from the graduated cylinder into a nearby rimstone. This rimstone was

large enough to install an automatic fluorometer (GGUN-FL30 by Albillia Switzerland) in order to measure the tracer concentration with a 15 min timestep. The combination of discharge measurement and tracer concentration allows us to calculate the tracer recovery.

We use the fluorescent tracer uranin ($C_{20}H_{10}Na_2O_5$) for this experiment. It is the most used fluorescent tracer due to its very low detection limit (10^{-3} μg/l), low sorptivity, low cost, and nontoxicity at such concentration (Schudel et al. 2002). For the injection point, we choose to project the percolation site on the surface according the local dip of the limestone layers (Fig. 2). We inject 500 g of uranin with approximately 500 l water in this precise location (1 m^2). The distance between the surface and the dripping site is 70 m according to the local dip value, no other cavity is known between these two points.

4 Results and Discussion

4.1 Dripping Rate Chronicles (2008–2013)

Excepted for the beginning of 2008 and the end of 2010, the drip chronicle is generally complete for the 2008–2013 period and shows remarkable inter-annual correlations as well as very different signals between the two sites (Fig. 3). This reflects the variability of the processes and responses of the vadose zone, regarding the recharge water as well as their recurrence during several hydrological years.

4.1.1 Père Noël Site (Red Curve)

The stalactite at the Père Noël station is perennial with drip rate between 15 and 70 l/day. It shows four different stages during the year:

- *Phase 1*: During the periods without infiltration (summer and autumn), a long and slow decreasing is observed until a minimal value around 15–20 l/day. This is interpreted as the epikarst drainage and suggests that the epikarst storage provides most of the discharge of unsaturated percolations during low water level periods.
- *Phase 2*: After the decrease phase, a quick and sharp increase of the discharge is observed, despite the recovery of the infiltration since several days or weeks. This highlights the storage capacity of the epikarst and the fact that a certain infiltration threshold is needed prior to feed the stalactite drip. This has been already observed by many studies in other karst systems (Arbel et al. 2008, 2010; Scheffer et al. 2011).
- *Phase 3*: The drip discharge is highly variable, and correlated to the recharge rate. This could indicate that the storage capacity of the epikarst is reached. This phase lasts for 4–5 months.

Fig. 3 Drip rate results for 2008–2013 at the two recording stations within the Han-sur-Lesse caves

- *Phase 4*: A slow, but significant increasing of the stalactite discharge until a punctual maximal discharge value, without any infiltration input. This value is higher than the maximal discharge observed at the beginning of the winter. Furthermore, this maximum discharge is the same in 2008, 2009, 2010, 2011 and 2012 (67.7 l/day, with an accuracy of 0.97 l/day).

The three first annual phases at the Père Noël station were already observed by Genty and Deflandre (1998). The fourth phase was not observed, and cannot be explained at this point of our study.

Other new features provided by these data are many sharp decreases of the drip rate (5–10 l in few days). These anomalies are highly correlated to major or prolonged infiltration events. The best example of this phenomenon is observed between January and July 2009, with seven decreasing events. An explanation could be a bypass phenomenon when the infiltration rate is too high and overflows the usual infiltration path, leading to a decrease of the drip rate. This seems to be the best explanation as no peak flow related to the infiltration peak is observed at the stalactite, even after a few days.

On the contrary, during periods with little or without infiltration, the drip rate increases frequently with a linear trend. This is related to the Phase 4 of the hydrological cycle which takes place during the longest period without infiltration water.

4.1.2 Salle d'Armes Site (Blue Curve)

The drip rate chronicle at the Salle d'Armes station is much simpler compared to the previous one. The discharge is in a range between 0 and 50 l/day and shows a seasonal variation in three stages: (i) due to the infiltration lack, a long and slow decease during summer and fall: depending on the year, the stalactite may dry up during a certain period; (ii) the sharp increase when the epikarst storage is filled by the recovery of the infiltration in winter; and (iii) a high discharge stage with quick reactions to the recharge variations.

4.2 Tracer Experiment

The uranin was injected above the *Père Noël* cave the 27th of March at 14:00 and the first appearance of the tracer into the dripping water was observed the 28th at approximately 5:30 (Fig. 4). The maximum water transit speed through the limestone massif (70 m thick) is approximately 4.5 m/h. This first result is quite surprising, while there is no evidence (at the surface and in the cave) for a dissolution enlarged flow path, where quick flow is possible. The maximum tracer concentration (72.2 ppb) is observed 3.5 days after the release, which means a modal velocity of 0.83 m/h. The total breakthrough lasted for more than 150 days, with a return to the background noise after 200 days. The tracer mass recovery is 0.013 %.

During this tracer test, the electrical conductivity of the water shows two significant decreases, corresponding to two periods of negative drip rate anomalies (during high infiltration periods). This means that the drip water is influenced by low-conductive precipitation water. Otherwise, when the discharge is increasing (corresponding to low or absent infiltration periods), the electrical conductivity is also increasing. This particular feature of the drip rate and E.C record reflects an epikarst water drainage caused by lack of infiltration water. We note that even if precipitation water influences the E.C., the water temperature is very stable and does not show any meteoric influence.

4.3 Discussion

The Han-sur-Lesse cave provides a relevant study site for unsaturated zone investigation in Devonian limestones of Belgium.

The drip rate chronicle is very satisfying and shows only few periods of technical issues leading to a lack of discharge data. The particular behavior of the Père Noël stalactite drip has not been explained yet. It is evident that these unknown features of stalactite drip are very interesting, as they reflect particularities of the epikarst functioning. The comparison with the Salle d'Armes drip will be an interesting reference, because they show different behaviors for the same drip rate range and for the same surface infiltration conditions.

The tracer experiment exhibits the duality of the epikarst behavior. On one hand, it shows a very fast percolation within the unsaturated zone. The BTC reflects a high permeable pathway, with no significant dilution along the way as shown by the shape of the curve and the high maximal concentration. On the other hand, the tracer release lasted for more than 150 days with only 0.013 % recovery. The long-term storage capacity of the epikarst is evident, regarding the two last characteristics. Furthermore, no significant clue of the water flush (500 l) was recorded in the drip chronicle after the injection. This indicates that the tracer probably spreads widely around the injection point, and this may be an explanation for a very low tracer recovery, but a high maximum concentration. A quick visual

Fig. 4 Breakthrough curve at the Père Noël station during the tracer experiment in March 2009

inspection of the surrounding percolation points was made during the uranin breakthrough (the tracer was visually detectable in the cave) but no other tracer seepage was detected.

5 Conclusions and Research Prospect

The very simple recording methodology for drip rate allowed us to collect 6 years of data for two stalactite sites. The device shows is ability to record precise and reliable data, whereas very little maintenance is required. The different stations are still operational and will record more data during the next few years. The available discharge data highlights recurring processes inside the vadose zone, as well as strong seasonal difference between the two locations. These records offer a promising base to identify the behavior of the epikarst regarding the karst aquifer recharge in the belgian Devonian limestones. A better understanding of these processes will lead to an improved management of drinkable water reserves in Wallonia.

Tracer results confirm the fast vertical drainage inside the unsaturated zone but reflect a potentially large dispersion (low tracer recovery) and a long (>150 days) storage of the tracer.

The following steps of the project are: (i) looking over the existing literature, to drive our analysis perspectives; (ii) building a conceptual model of the unsaturated zone in limestones, regarding discharge and tracer experiment data; (iii) integrating

a numerical model able to predict discharge variation cycles with the infiltration data, in order to test the conceptual sketch; and (iv) attempting to validate our models with future data from drip stations, and new tracer experiments.

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