Localisation of a Reactive Transport Zone in a Saturated Karstic Conduit Deduced from Natural and Artificial Tracer Tests

Stéphane Binet, Ali Joodi, Emmanuelle Joigneaux, Patrick Albéric, Alexis Gutierrez

LOCALISATION OF A REACTIVE TRANSPORT ZONE IN A SATURATED KARSTIC CONDUIT DEDUICED FROM NATURAL AND ARTIFICIAL TRACER TESTS

Binet S.[1], Joodi A.[1] , Joigneaux E.[1, 2], Albéric P.[1] , A. Gutierrez [2]

[1] Institut des Sciences de la Terre d'Orléans - UMR 6113 Université d'Orléans, CNRS/INSU, Université François Rabelais - Tours Campus Géosciences 1A, rue de la Férollerie, 45071 Orléans cedex 2 France.

[2] Bureau des Ressources Géologique et Minières 3 avenue Claude-Guillemin 45060 Orléans Cedex 2 - France

ABSTRACT: For groundwater resources managers, flow modeling is a useful tool to investigate sustainable scenarios of water use. However, in karstic aquifers, the quality of scenarios is limited by the difficulties of locating and describing the position, geometry and possible time evolution of conduits. The location of conduits in the karstic aquifer of the « Val d'Orléans » (France) were defined using 200 boreholes, surface collapses and 24 artificial tracer tests, which facilitated the development of a simplified conceptual model of flow in the saturated conduits and the surrounding rocks. 68 logs present voids > 50 cm and locate a highly porous zone around 80 m.a.s.l. with voids that average 3.5 meter in diameter. In this saturated conduit, 1D quantitative interpretation of artificial tracer tests validate the proposed conceptual model of a saturated conduit under pressure, with an efficient section about 10m² an input flow about 3,1 m^3/s with 2,9 m^3/s flowing from the conduit toward the surrounding rock before arriving at the Loiret Spring. The conceptual model of flow and the previous water chemical analysis show that the transported elements in the groundwater react and dissolve carbonate rocks, mainly inside the conduit, and that this may increase the diameter of the conduit zone by an estimated 40 cm in 100 years.

INTRODUCTION

For groundwater resource managers, groundwater flow modeling is an essential tool for investigating proposed sustainable scenarios of water uses. Applied to karstic aquifers, the modeler is confronted by the duality of flows, with the major role of the permeable conduits as the water transfer compartment and the important role of the surrounding rock as the water storage compartment (Kiraly et al., 1995). This duality is enhanced by the existence of shear stress in water (Joodi *et al*. 2009) and by turbulent flows (Cheng and Chen, 2004) that may take place in the conduits. Thus in most karstic groundwater flow models, accuracy is limited by the difficulties of describing the location and the geometry of the conduits. Furthermore, long term accuracy of models is limited by rock dissolution, that creates porosity change and may modify the conduit / rock relationship.

The paper uses a well known conduit flow system (The Val d'Orleans karst system), through 200 boreholes and 28 artificial tracer tests, to deduce a conceptual model of conduits in this karstic system. An average diameter approximation method is proposed for describing the conduit, with the aim of inferring their exact geometry. The conceptual model is validated using a 1D artificial tracer test model. In this chemically active karst system, the proposed conceptual model uses the chemical reactions identified by Albéric and Lepiller (1998) to estimate a change rate of the conduit diameter.

HYDROGEOLOGICAL SETTING

The Val d'Orléans is considered as a major depression in the bed of the Loire river, 37 km long and from 4 to 7 km wide (Fig. 1). The karst aquifer is hosted within an Oligocene carbonate lacustrine deposit called the limestone of Beauce. The Loire River feeds more than 80% of the water hosted in the carbonated karstic aquifer (from 15 to 100 m^3/s). The water runs from Jargeau through the under pressure karst networks toward several springs of the Loiret River: the Bouillon, Béchets, Bellevue, and the Pie springs (Fig. 1) (Zunino 1979; Chéry 1983; Lepiller 2006). The Loiret springs are considered as the main emergence of the water lost close to Jargeau in the Loire River (from 0.1 to 5 m^3/s). In this area the conduits have been explored by a speleologist diver and the total flow rate in this section of the conduit is about 2 to 10 m^3/s (personal communication from Mr Boismoreau). In Albéric and Lepiller (1998), the existence of calcite dissolution was demonstrated in this system by the oxidation of riverine organic matter. The magnitude of the reaction is controlled by dissolved O_2, nitrate for organic matter oxidation and by the release of Ca^{2+} for calcite dissolution (Fig.1). Numerous surface collapses were observed around Orléans.

METHODS

The location of the conduits is deduced from two databases (borehole logs and surface collapses realized by BRGM, the French geological survey (http://infoterre.brgm.fr/ and http://www.bdcavite.net/). In the Val d'Orléans aquifer, 200 borehole logs were analyzed to extract information about underground karstic voids. The location (X,Y) of voids encountered are presented in Figure 1. Results are presented using the frequency curves in percent (Figure 2). To refine to location of conduits, the 147 collapses observed in the surface (cavity database) were considered to be activated by the presence of an underground active conduit (triangle in Fig.1). 24 artificial tracer tests (Lepiller, 2006, Joodi *et al.* 2009) demonstrate that observed voids are a part of the karstic conduit (dashed lines in Fig.1). To validate the average geometrical data deduced from the boreholes, an artifical tracer test was carried out on October 24th 2009 during a low water period. 1Kg of uranine was injected in the Loire River under the Jargeau Bridge. Recovery was recorded at the Bouillon Spring (Fig.3)

A 1D model is applied to the tracer test results. If we consider the conduits as an equivalent conduit with a section A (m²) and a porosity n_f (%), a 1D solution of the advection / dispersion / reaction equation can be applied for a Dirac injection type.

$$c(x,t) = \frac{\Delta M}{2\ A\ n_f \sqrt{\pi\ D_L\ t}} \exp\left[-\frac{(x-ut)^2}{4\ D_L\ t}\right] \exp(-\lambda t)$$ Equation 1 (Sauty *et al*., 1992)

where the concentration c(x,t) is described by the injected mass ΔM (Kg), an average flow velocity u (m/s) and the longitudinal diffusion coefficient D_L (m). Usually, λ (s^{-1}) is a decay constant. Calculation is resolved with a new software program, TRAC (download possible from the BRGM web site www.brgm.fr/trac)

If the flow velocity (u) in the conduit and the leak flow rate (Qm) from the conduit to the hosting rock are constant with x and t, we can use an analogy where the decay phenomenon λ (s^{-1}) becomes a leakage constant describing the amount of tracer flowing toward the hosted rock. Qm can be calculated with λ (s^{-1}). Qm = λ Qf dt and Qo = Qm + Qf

Water chemistry has been compiled from previous studies (Chéry 1983; Alberic and Lepiller 1998,) (Figure 1). Following Albéric and Lepiller (1998), calcium, is used to estimate the amount of dissolved calcite between two points.

RESULTS

Conduit location and geometry

On the 220 boreholes logs, 68 logs present voids > 50 cm. These are interpreted as karstic features and are presented in the Fig.1. The whole data set enables a 100 meters wide zone to be drawn where there is a high probability of finding a conduit (Fig.1). This zone includes voids, collapses and the probable path between the tracer injections areas and the recovery points. These zones have two preferential flow directions: NE/SW and E/W in the system

Figure 2 shows that average elevation of the voids are around 80 meters above sea level, or about 10 to 20 meter below the ground surface. In this zone, voids have an average diameter of 3.5 meter diameter. An effective cross-section of about 10 m² is estimated, assuming a circular shape. The conduit is located in a zone around 70 - 80 meter a.s.l. (10 meter thick). This zone is considered as the zone with a high probability to find a conduit in.

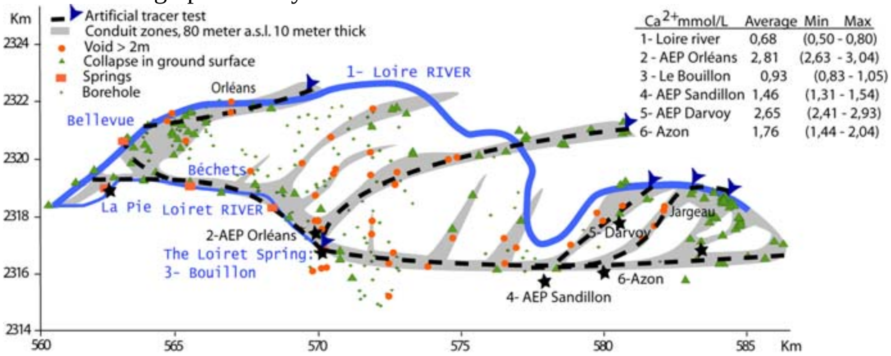

Figure 1: Map of the Val d'Orléans Aquifer with in grey the zone with a 3 to 40 % probability of finding a conduit. This conduit zone was interpreted from observed voids in the boreholes (circles), collapses on the surface (triangles) and tracer tests (dashed lines). The calcium concentrations in water are presented in the table for 6 boreholes in and around the conduit (average data from 1970 to 2009)

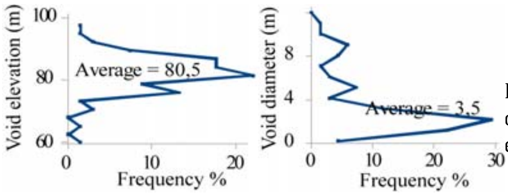

Figure 2: Frequency distribution of voids observed in the boreholes related to a/ the elevation, b/ their diameters.

Validation using a quantitative tracer test interpretation

Using equation 1 and the average previous values ($A* n_f$ = 10 m²) it is possible to predict the recovery curve at the Loiret Springs (x=13km). During low water period, the flow rate in this zone (Loiret springs + underground conduit) is estimated around 0,4 m^3/s (with a 10m² of efficient flow section an average flow velocity about 3,6 cm/s). The only unknown parameters are the diffusion coefficient and the leakage constant. Best fit give D = 55m and λ = 1,25 $10^{-5}s^{-1}$ and is presented Fig.3. The model results reproduce the average residence time and the recovery rate and validate the possibility of using the geometrical observations realized in boreholes to describe the conduits at the aquifer scale. The shape of the curve cannot be fitted with this 1D model. A significant physical mechanism taking place in the conduit may be neglected, such as shear stress in water created by tortuosity of the conduit zone as described by Joodi *et al.* 2009 or by turbulent flows (Cheng and Chen, 2004).

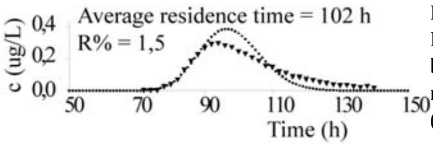

Figure 3 :Artificial tracer test recovery curve at the Loiret spring realized in October 2009 (triangle) and best fit from 1D solution with x=13km; D= 55 m; A n_f=10m²; ΔM=1kg; u =3;6 cm/s; λ= 1;25 10^{-5} s^{-1} (square). .

Water Chemistry around the conduit zone

Water chemistry analyses since 1970 for 6 points located within or outside the conduit zone (Fig.1) show that the calcium concentration increases between the Loire river and the Bouillon Spring (in average for more than 100 analysis) by about 0,5 mmol/L. The water from the Bouillon is characteristic of the conduit flows. All the boreholes around the conduit zone show higher calcium concentration (2 mmol/L) (Chéry 1983, Alberic and Lepiller, 1998).

DISCUSSION

A conduit generally under pressure.

The geological data, the voids characterization and the tracer tests model from the boreholes enables a conceptual model of flows in these conduit zones to be proposed (Fig.4) Overall, the conduits are under pressure and feels the surrounding rock. The conduit zone is 20 meters under the ground surface in the limestone of Beauce. The input flow rate (Qo) for the 2009 low water period can be estimated around 3,4 m^3/s for this conduit with 3 m^3/s flowing from the conduit toward the surrounding rock, before arriving at the Loiret spring. 0.4 m^3/s flow through the conduit zone located around the Loiret springs.

Calcite dissolution in the conduit and porosity change.

According to this conceptual model, to Lepiller (2006) and to Joodi *et al.* (2009), most of the time the drain is under pressure and feeds the surrounding rock. Thus dissolution takes place mainly inside the conduit. Calcium concentration increases with the distance from the conduit zone. This may explain the 147 ground surface collapse observed in this area. Using the 0,25 mmol/L of calcium observed between Loire River and Loiret Spring (Fig. 1) and taking calcite density about 2.7, a conduit about 13 km long, a 10 m² effective flow section, the diameter of the conduit may increase about 40 cm in 100 years. Dissolution seems to be a significant process to understand flow rate change from the last 100 years. The magnitude order estimated here needs to be deepens, if we want improving the long term groundwater management.

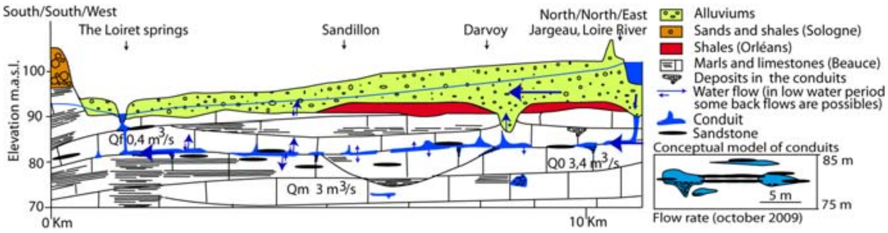

Figure 4: Cross-section of the Val d'Orléans

CONCLUSION

The conduits in the karstic aquifer of the « Val d'Orléans » (France) were located in a 100 meter wide highly porous zone around 80 m.a.s.l. with an average diameter of 3.5 meters. 1D quantitative interpretation of artificial tracer tests validate the proposed geometrical model of the conduit, with 3 m^3/s flowing from the conduit toward the surrounding rock. The conduit flows are under pressure and water chemistry analysis shows that the transported elements in the groundwater react and dissolve carbonate rocks, mainly inside the conduit, where conduit diameter can increase about 40 cm/100 years. This opens questions about the porosity changes and long-term stability of the water flow rate in the Loiret River.

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