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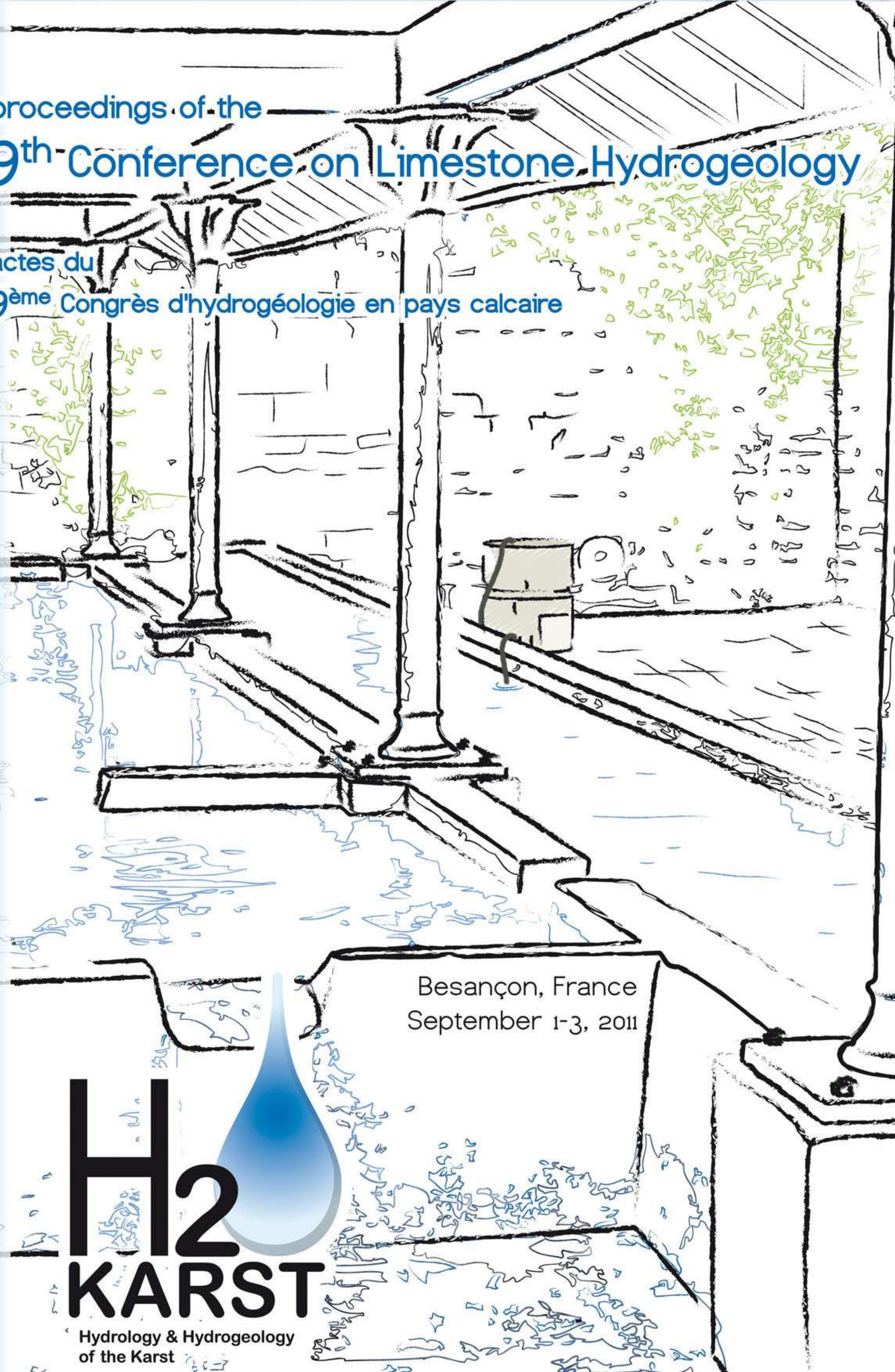

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9th conference on limestone hydrogeology

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Measured and computed solute transport behaviour in the saturated zone of a fractured and slightly karstified chalk aquifer

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Abstract

Solute transport in the saturated zone of a micro-fissured, fractured and even locally slightly karstified aquifer has been studied by multi-tracer tests in groundwater convergent flow conditions to pumping wells or towards a collecting gallery. Different behaviour has been detected that can be described by three kinds of typical breakthrough curves: (a) transport with a dominant advective component, producing narrow and symmetrical observed breakthrough curves, characteristic of solute transport in open fractures or conduits; (b) transport with significant advective and dispersive components exhibiting more spread-out breakthrough curves, with also non-symmetrical trends caused by retardation effects; (c) transport with a dominant dispersive component, showing mostly a flat breakthrough curve where dispersion and possible immobile water effects are difficult to be separated. These results were synthesized from thirty-five injections of tracers, distributed between 11 sites.

Groundwater flow and solute transport are simulated and illustrated here for one example, employing the finite element code HYDROGEOSPHERE, and using two ways for representing the fracture zones: highly contrasting hydraulic conductivity zones with a classical REV approach and discrete fractures combined with a porous medium by the use of a dual approach. Results are particularly illustrative to show that detailed parameterization and calibration of such a local situation remain difficult even on the basis of an extensive data sets from many tracer tests.

1. Introduction

For delineation of protection zones, a set of tracer tests were conducted at different locations in the Hesbaye chalk aquifer located near the city of Liège. This chalk reservoir is made of sub-horizontal layers dipping slightly towards the north (Dassargues & Monjoie, 1993) from which about 60,000 m^3/day of groundwater are abstracted from drainage galleries. A full description of the aquifer can be found in the papers about previous studies addressing mainly quantity and quality management at the regional scale (Dassargues *et al.*, 1988; Brouyère *et al.*, 2004; Goderniaux *et al.*, 2009; Orban *et al.*, 2010). 35 tracer tests distributed between 11 sites were conducted with the main objective of studying the local transport of solute contaminants. Measured breakthrough curves show different behaviour that could be linked to the coexistence of a porous matrix and fractures in the chalk aquifer. It has also been observed that some of the fractures have been enlarged by dissolution so that the aquifer is often considered as slightly karstified.

In this context, predictive capabilities related to flow and transport processes remain severely limited (Berkowitz, 2002). In fractured porous media such as chalk, it is important to distinguish the role of the porous and permeable host rock and the role of open fractures. Their combined effects can actually induce a large diversity of complex transport processes in the aquifer. Solute contaminants migrate mostly by advection and hydrodynamic dispersion. They can also be delayed or definitely trapped, resulting in a longer recorded transit time, a retardation and an attenuation which is noticeable on the measured breakthrough curves. A physical retardation, often called dual porosity effect or immobile water effect can be distinguished (Brouyère *et al.*, 2000, Brouyère, 2006).

On the basis of observed tracer tests results, three kinds of breakthrough curves are proposed in order to make a first classification. Then, using a particular case taken as a representative example, two kinds of groundwater flow and solute transport modelling are presented, proposing different ways to represent the fractures in this double permeability and double porosity medium.

2. Typical measured breakthrough curves

The tracer test campaign was preceded by a morphostructural study associated with a geophysical survey including electrical resistivity and seismic refraction measurements. Results provided information on the main expected fracturation axis.

In each of the 11 sites, multi-tracer tests have been performed in groundwater convergent flow conditions to pumping wells or towards a collection gallery (the main drainage gallery of the aquifer used for drinking water production). Results, in terms of measured breakthrough curves, can be classified in three main categories (Fig. 1).

(a) Transport with a dominant advective component, producing narrow and symmetrical observed breakthrough curves corresponding to solute transport along solutionally-enlarged fractures that connect injection and recovery locations, and showing very high velocity of tracers (between 10 and 110 mh^{-1} for distances between 5 and 130 m for any type of tracer (Fig.1a);

(b) Transport with advective and dispersive components exhibiting more spread-out breakthrough curves, with non-symmetrical trends induced by dual porosity (or immobile water) effect (Fig 1b).

(c) Transport with a dominant long term dispersive component, showing a flat breakthrough curve where dispersion and possible immobile water effects are difficult to separate. At very short times, an advective peak can be sometimes detected (Fig. 1c) showing that this breakthrough curve is the result of combined effects of the porous and permeable chalk and of the open fractures.

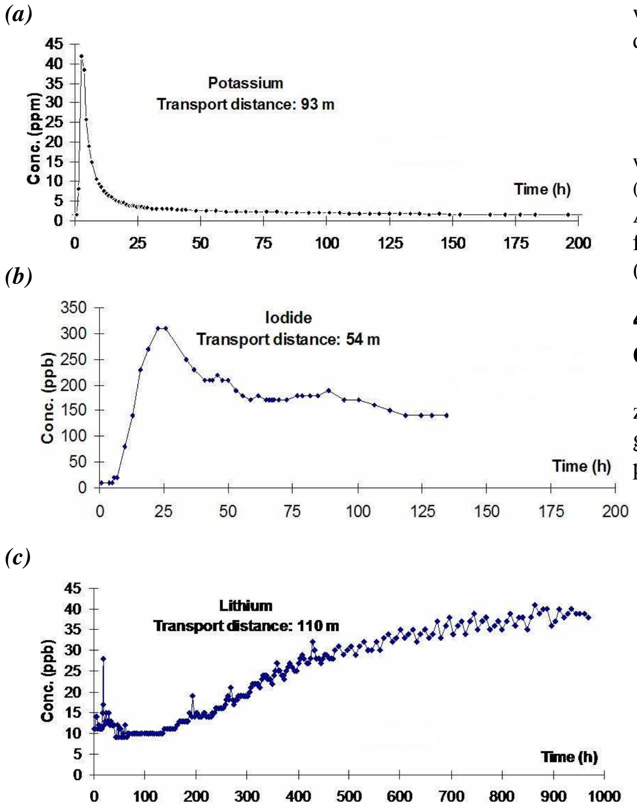

Fig. 1: Examples of measured breakthrough curves showing three kinds of solute transport behaviour: (a) advective dominant transport in open fractures or conduits; (b) advective-dispersive transport with a strong immobile water effect; (c) transport with a dominant dispersive component at long term, with a first advective arrival at very short arrival times.

3. Conceptual choices for groundwater flow and solute transport simulation

There exists a large scientific literature about groundwater flow and solute transport in a porous and fractured medium. Among many others, THERRIEN & SUDICKY (1996), BOUR & DAVY (1998), BERKOWITZ (2002) provided excellent papers describing different conceptual approaches to simulate the combined processes associated with the role of the porous and permeable host rock and the role of open fractures. On the other hand, dual porosity (i.e. porosity of the host rock matrix and fissure porosity) models allow the contaminant retardation due to the immobile water effect to be taken into account (GALLO *et al.*, 1996; BROUYÈRE *et al.*, 2000; BROUYÈRE, 2006). This immobile water effect accounts for a diffusion process between the nearly immobile water in the pores of the matrix and the fast-moving water in the open fractures or micro-fractures.

If the chosen scale of interest is local, another alternative consists of explicitly describing the fractured zones within the spatial discretization of the model. Using the capabilities of the HYDROGEOSPHERE code (THERRIEN *et al.*, 2010; THERRIEN & SUDICKY, 1996; SUDICKY & MCLAREN, 1992), two possibilities are here tested for modelling an example chosen from the results of the studied chalk aquifer: (1) the fracture zones are distinguished in the model by elongated zones of higher hydraulic conductivity and very low effective porosity (model 1); (2) the fractures zones are represented in the model by discrete open fractures (model 2) as developed by SUDICKY & MCLAREN (1992) and THERRIEN & SUDICKY (1996) where the hydraulic conductivity is computed from a law depending on the aperture as described by BEAR (1972):

$$K_{fracture} = \frac{\rho g a^2}{12\mu} \qquad \textbf{(1)}$$

where a is the aperture of the fracture and μ the dynamic viscosity (which varies with the solute concentration).

A coupling between the porous medium and the discrete fracture network model is organised by use of dual nodes (GERKE & VAN GENUCHTEN, 1993; THERRIEN *et al.*, 2010).

4. Example of groundwater flow and contaminant simulation

The case study site is described in Fig.2 with the fracture zones as detected by geophysical survey, the collecting gallery, the pumping well PW1 and the injection piezometers Pz2, Pz3, Pz4 and Pz5.

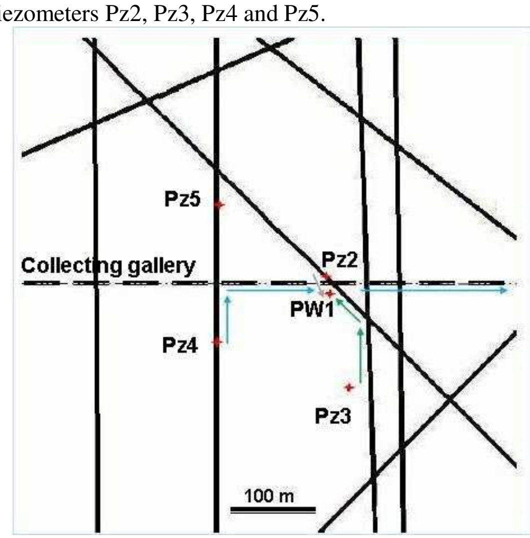

Fig. 2: Local area in the chalk aquifer with the main detected fractured zones (dark thick lines), the collecting gallery (dashed line), pumping well (PW1) and piezometers (Pz2, Pz3, Pz4 and Pz5).

Multi-tracer tests were performed from Pz4, Pz2 and Pz3 and the corresponding breakthrough curves were obtained describing respectively solute transport between Pz4 and the collecting gallery, Pz2 and the pumping well PW1, and between Pz3 and PW1. Simulation results for this last tracer test with its typical measured breakthrough curve of Li^+ (Fig.1c) are shown here using both numerical techniques describes here above.

Model 1, with fractured zones modelled using high values of hydraulic conductivities in elongated parts of the grid, is satisfactorily calibrated in steady state flow and transient transport conditions to obtain the results as shown in Fig. 3 (piezometric map) and in Fig. 4 (tracer concentration map at a time of 505 hours after tracer injection).

Table 1 shows the calibrated values taken for the porous matrix and for the fractured zones A and B. Fig. 5 shows the obtained fitting of the computed breakthrough curve on the measured one. Despite a general satisfactory agreement, it can notably be observed that the early advective peak of Li^+ is not reproduced by the model. The recovery rate of tracer is very low but similar values are found for measured (1.7 %) and computed (1.6 %) values.

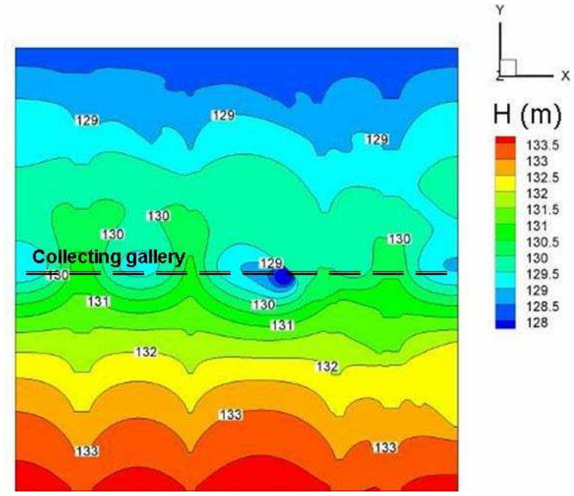

Fig. 3: Computed steady state piezometric map with the combined influences of the pumping well and collecting gallery (model 1).

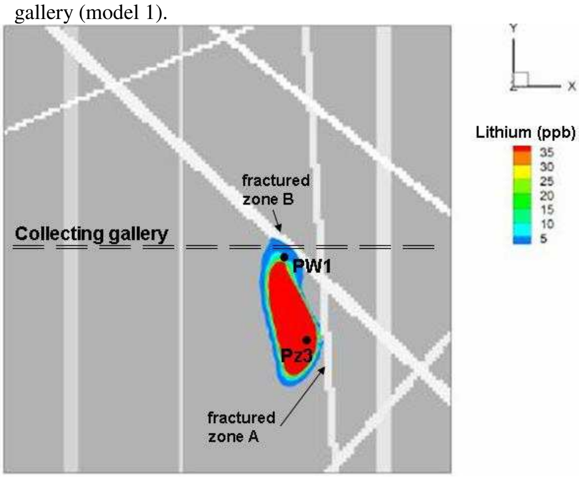

Fig. 4: Computed plume of Li^+ 505 hours after injection in Pz3 (model 1).

	K (m/s)	n_e (-)	a_L (m)	a_T (m)
Chalk matrix	1.10^{-6}	0.0068	20	32
Fractured zone A	2.10^{-3}	0.0068	20	32
Fractured zone B	3.10^{-4}	0.0010	30	7

Table 1: Values for hydraulic conductivity, effective porosity, longitudinal and transverse dispersivities in the different zones of model 1.

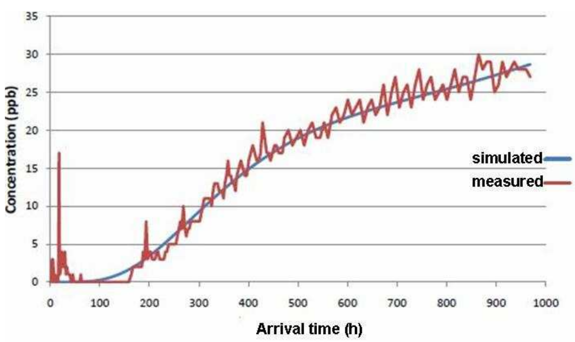

Fig. 5: Computed vs measured breakthrough curves of Li^+ in the pumping well PW1 (model 1).

Model 2 – with fractured zones represented by discrete fractures, is also calibrated in steady state flow (Fig. 6). The best obtained solute transport simulations for calculating the Li^+ plume after 35 hours and 505 hours are given in Figs. 7 and 8. Contrary to model 1, model 2 simulates an early peak (even if not yet perfectly simulated here) in the breakthrough curve as shown in Fig.9. In this case, the main flow parameter to be fitted in the fractured zones is the aperture (*a*) of the supposed uniform open fractures. Table 2 shows the corresponding parameters for model 2.

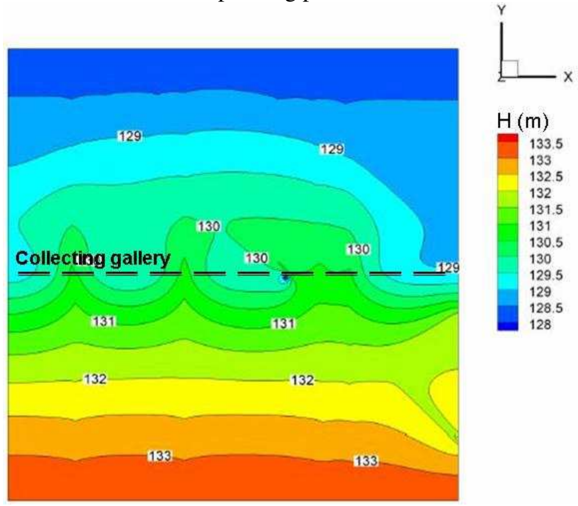

Fig. 6: Computed steady state piezometric map with the combined influences of the pumping well and collecting gallery (model 2).

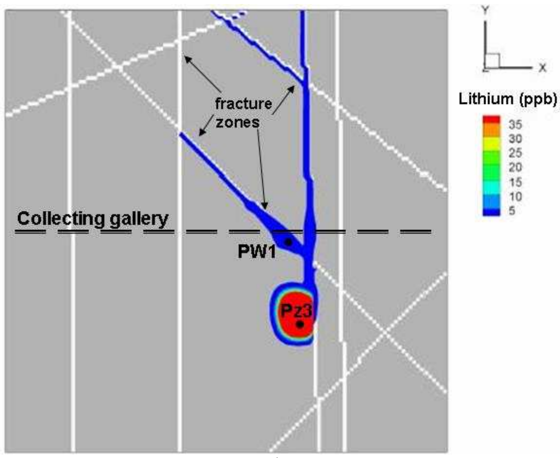

Fig. 7: Computed plume of Li^+ 35 hours after injection in Pz3 (model 2).

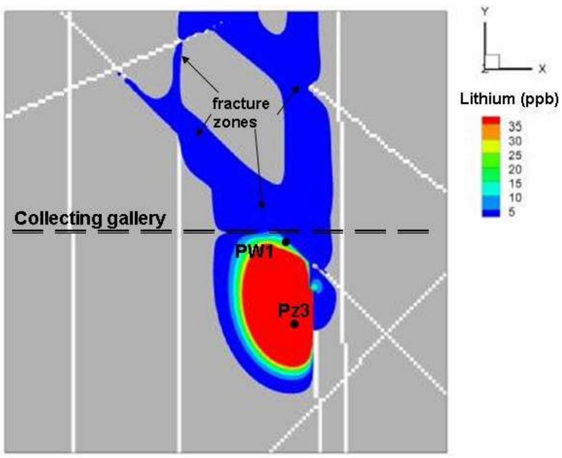

Figure 8: Computed plume of Li^+ 505 hours after injection in Pz3 (model 2).

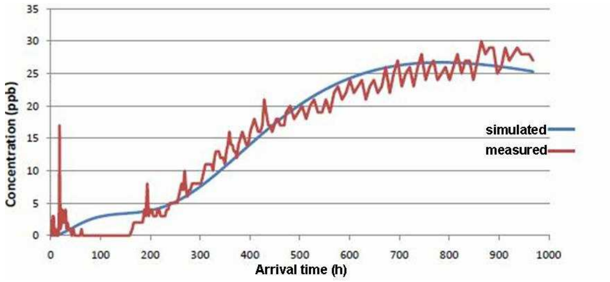

Fig. 9: Computed vs measured breakthrough curves of Li^+ in the pumping well PW1 (model 2).

	K (m/s)	n_e (-)	a_L (m)	a_T (m)
Chalk	5.10^{-6} m/s	0.01	45	30
Fractures	a = 0.008 m		1	0.1

Table 2: Values for parameters of model 2.

It can be observed that using model 2 allows using already more realistic values for the solute transport effective porosity n_e in the chalk. A value around 0.01, as previously measured by BIVER & DASSARGUES (1993), is not unusual when considering that the only mobile water is located in micro-fissures in the chalk matrix (i.e. even if small finite elements are used in the model, their size is still too large for representing accurately the micro-fissuration in the chalk matrix).

Clearly one must distinguish this solute transport effective porosity from the specific yield resulting from drainage processes of a porous medium. Measured values of specific yield from pumping tests in this water table chalk aquifer can range between 0.05 and 0.15 (DASSARGUES & MONJOIE, 1993).

The simulated plumes as shown in Fig.4 (model 1) and Fig.7 (model 2) are quite different. The last one demonstrates the ability of model 2 for simulating rapid advective component in the fracture network.

5. Conclusions

Flow and solute transport in a porous and fractured aquifer are never straightforward to measure, to interpret and to simulate for groundwater protection calculations. On the basis of many tracer tests, three main categories of breakthrough curves are distinguished and then simulation results are produced for representing solute transport in a case where the tracer plume is obviously influenced by both the micro-fissured porous medium and the main fractures.

Promising results are found using a discrete approach for representing the fractures. In this last case, an aperture of the order of the millimetre is enough for creating clearly a fast advective peak combined with a long highly dispersive component due to the chalk matrix. Even if the breakthrough curves are not yet perfectly calibrated, there is hope for better results and comparison with other techniques. The discrete fracture approach save the modeller from introducing unrealistically low values for the effective porosity in the fracture zones as it is the case in the classical REV-based method where the fractured zones are simply represented by elongated REV.

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