Borehole dilution experiment in a Karoo aquifer in Bloemfontein

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Abstract

This paper shows that a borehole dilution experiment using common salt is a useful technique for better understanding of some hydrogeological features of a fractured aquifer. A series of such tracer experiments was performed in the campus site aquifer, a hydrological experimental site of the Institute for Groundwater Studies at the University of the Orange Free State in Bloemfontein. It is demonstrated that the model for use in homogeneous aquifers may be adapted in fractured aquifers. Results have revealed valuable information on hydraulic parameters of the fracture system at different scales. Profiles of electrical conductivities monitored in several boreholes can be used to locate horizontal fracture zones in the aquifer. These results may provide an important guide to formulate realistic conceptual models for borehole protection zoning. The experiment can also serve as a reference to future experiments of this kind in Karoo aquifers which cover some 50% of the subcontinent of Southern Africa.

Introduction

Tracer experiments have been extensively utilised in hydrogeological studies overseas. According to available information (Peck et al., 1988; Davis et al., 1980), a tracer experiment can be conducted either under a natural gradient or under an induced gradient and its result is scale-related.

In South Africa, Bredenkamp et al. (1995) touched on some dye tracer experiments under the induced gradient conducted mainly in Karoo aquifers of Beaufort West in 1977. To date, very few tracer experiments have been performed locally. One of the reasons would be that flow regimes in our aquifers are often complicated by unpredictable fracture systems.

Generally speaking, tracer tests are more established for primary aquifers. For instance, tracer tests using common salt are often performed in porous media. Even so its applications are not very popular on the ground that the tracer does not flow far along the natural flow paths due to its denser solution and tends to sink to the bottom of the aquifer. This problem may be overcome if a fast-flow fracture zone could be separated from the matrix. To do so, straddle packers may be used to separate a fracture zone from the matrix in a borehole. We selected a Karoo aquifer at the campus site of the University of the Orange Free State (UOFS) for a series of borehole dilution experiments. The experiment, part of a project entitled "Utilization of tracer experiments for the development of rural water supply management strategies for secondary aquifers" sponsored by the Water Research Commission, is aimed at establishing appropriate methodology for tracer application in secondary aquifers.

Experiment

The selected aquifer is a hydrogeological experimental site for the Institute of Groundwater Studies at the UOFS in Bloemfontein (Fig. 1). The site consists of the Beaufort Group of Karoo sedimentary rocks. The ground surface is fairly flat with a slight dip toward the North-East direction. The depth to piezometric surface is about 11 m. In this campus aquifer, a horizontal fracture zone has been identified occurring at depths of 21 to 25 m below ground surface. The fracture zone was selected for this experiment.

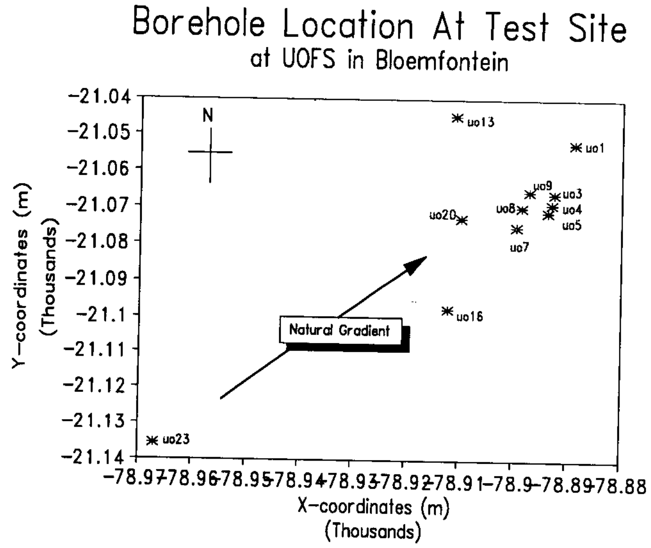

Figure 1
Borehole location map

The in-hole common salt dilution test using electrical conductivity (EC) as tracer indicator was conducted in a borehole termed UO20 on the campus site at the UOFS on 13 February 1996. According to measurements in borehole UO20 and borehole UO1, natural gradient was determined at 0.6% along UO20 to UO1.

The experimental procedure was:

- to establish the background chemistry of the groundwater, measuring EC in boreholes of interest (average of 85 mS/m at a temperature of 18.5°C in this case);
- to prepare salt solution with EC of 1 130 mS/m by dissolving 70 g NaCl in 10 *ℓ* of tap water of 20 mS/m EC;
- to seal off 1 m fracture zone with centre at depth of around 21 m in borehole UO20 using straddle packers with screen diameter of 160 mm (Fig. 2);

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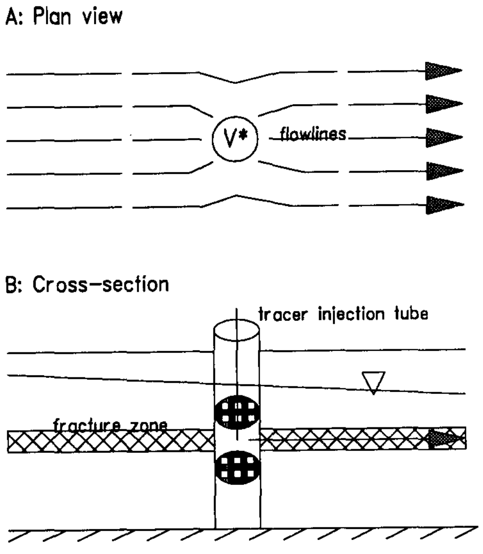

Figure 2
Sketch of borehole dilution experiment

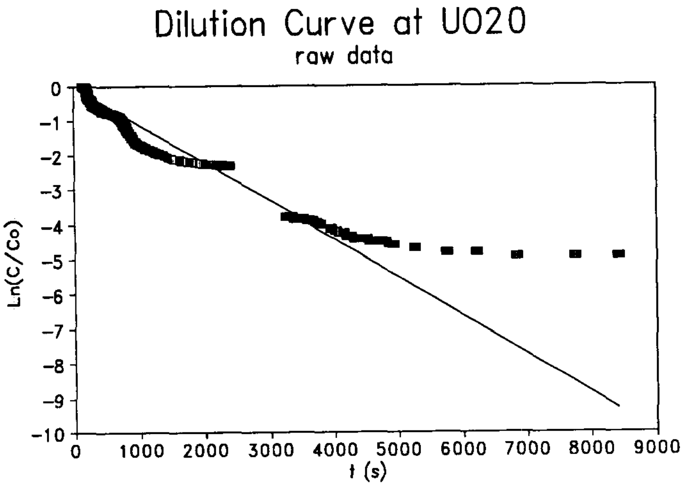

Figure 3
Dilution curve

- to inject the solution into the chamber sealed off; and
- finally to monitor EC recession against time using an EC probe.

Locating the horizontal fracture zone for the injection position was done using double packer tests metre by metre from aquifer top to bottom.

The dilution experiment in borehole UO20 was completed within 5 h and an almost complete recession curve was obtained. Observations were made at a depth of 21 m in borehole UO9 some 15 m downstream from injection borehole UO20.

On 21 and 29 February 1996, injections of two salt pulses with the same EC were again introduced into UO20. In order to assess EC spread in the vicinity, measurements at fracture depths in several boreholes downstream were made but EC response with time was not properly recorded. Accurate EC profile measurements were, however, carried out on 29 February and 1 March 1996.

Interpretation theory

The dilution test is a simple tracer experiment with the purpose of determining flow velocity and hydraulic conductivity (Fig. 2). The interpretation model of Drost et al. (1968) was used employing a mass balance which leads to the following equations for an advective transport model:

$$dC = -\{(AV^*C)/W\}dt \quad (1)$$

$$\mathrm{Ln}(C/C_o) = -AV^*t/W \quad (2)$$

$$V = V^*/(n\alpha) \quad (3)$$

where V* is flow velocity inside the hole (Darcy's velocity equals V*/α); V is pore water velocity; W is volume of dilution chamber isolated by two packers; A is vertical cross-sectional area through the centre of the isolated chamber; C is concentration of injected tracer at time t; C_o is initial concentration of the tracer; n is effective porosity of aquifer; α is a parameter (distortion factor).

Their work had been based on flow distortion caused by a typical borehole structure constructed in a homogeneous aquifer in the presence of a screen and sand or gravel pack. The parameter α was assumed to range from 0.5 to 4 and to be related to the change in hydraulic conductivities in the vicinity of the borehole and its geometry. The α range is too wide to be interpreted and also generally too complicated to be determined. Thus the validation of application of the above interpretation model in a hard-rock aquifer would totally depend on accurate determination of the distortion factor α. For adaptation of the model in such a hard-rock aquifer as the campus site, α may range from 1 to 2 with average of 1.5 because:

- The dilution is being confined to the fracture zone isolated by straddle packers eliminating the difference of velocities inside and outside the borehole. This means that V* can be regarded as the Darcy's velocity within the fracture zone.
- For borehole UO20 in hard rock without sand or gravel pack present, α = 2, which can analytically be derived from Drost et al. (1968) and Strack (1988).
- Validation of the interpretation will be evaluated and verified by numerical simulations.

Results

Figure 3 shows the recession curve of the dilution experiment conducted in borehole UO20 on 13 February 1996. Injection was introduced within 12 min, whence EC started decaying. The whole experiment was completed within 5 h resulting in the almost complete recession curve. The dilution curve as seen in Fig. 3 can be divided into two portions: initially an almost straight line and a latter part obviously deviating from the straight line.

Estimation of hydraulic conductivity (K)

The initial part of the dilution curve in Fig. 3 is fitted with a straight line according to Eqs. (2) and (3). As a result, Darcy's velocity interpreted is 6.00 m/d, and with a natural gradient measured at 0.006 at the time, the K value calculated is 1 000 m/d. Hence this clearly implies that the hydraulic conductivity of the fracture zone could be as high as 1 000 m/d.

The K value of the horizontal fracture zone was investigated by the double packer tests with a vertical testing interval of 2 m (Botha et al., 1994). According to data from three boreholes (UO4, UO9 and UP16) in the vicinity of UO20, the average K value was 22.64 m/d. Obviously this K value is much smaller than

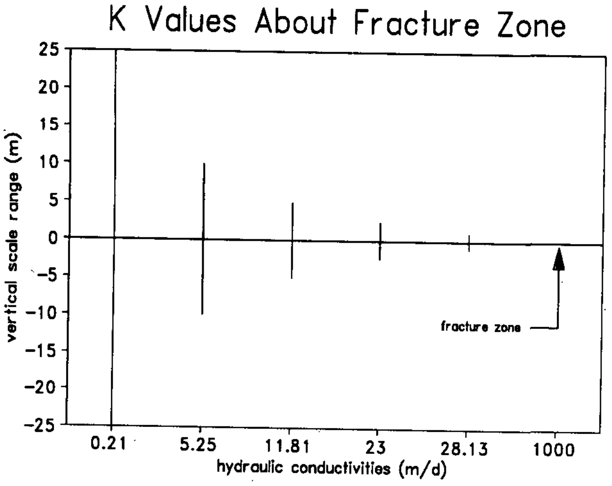

Figure 4
Horizontal K vs. vertical scales

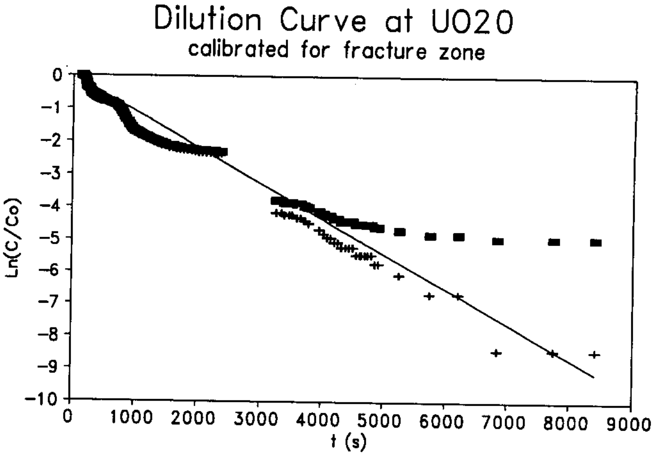

Figure 5
Fracture aperture estimated

that of 1 000 m/d obtained at UO20 using the dilution test, compared to an average K value of 10 m/d for Karoo aquifers obtained from various pumping tests performed in the past (Botha et al., 1994, Kirchner et al., 1991). The K value obtained appears to be too high. The discrepancy could result from the different scales. The high K may be masked by the larger scales which pumping tests represent.

The effect of differences in scale can be demonstrated by compiling K values against a range of vertical scales progressively away from the fracture zone. In Fig. 4, positive and negative values of vertical axis indicate vertical scale limits above and below the fracture, respectively. For instance, a scale from -25 m (below the fracture) to 25 m (above it) has a hydraulic conductivity of 0.21 m/d. This would be the result of a normal pumping test over the whole thickness of an aquifer in the Karoo. All data used in Fig. 4 are from Botha et al. (1994) and from the present study in the campus aquifer. As can be seen, Fig. 4 clearly indicates that K values about the fracture may drastically increase if vertical scales about the fracture decrease.

It must be pointed out that the K value estimated for the fracture zone is that in flow direction along the natural gradient. To obtain K values in other directions, borehole dilution tests under induced gradient have to be conducted.

Verification of K Value

According to Eqs. (2) and (3), the dilution data are supposed to display a straight line in Fig. 3. Obviously this is not the case. For the purpose of verifying the K value obtained using Eqs. (2) and (3), the deviation from the straight line has to be accounted for.

Assume the presence of a fracture zone in the borehole, which would cause differential flow and consequently induce addition of tracer in the stagnant part of the dilution chamber to the fracture zone of fast flow where the EC probe is installed. Concentration measured at time t (C_T) consists of two components: one due to dilution in the fracture and the other due to addition from the surrounding areas. Eqs. (2) and (3) are valid for use in homogeneous aquifers. To account for a case where a horizontal fracture zone is present in the dilution chamber, Eqs. (2) and (3) may be modified and written as follows:

$$\mathrm{Ln}(C/C_o) = -V^*t/r_o \qquad (4)$$
$$C = C_T - \lambda C_o e^{-1/t} \qquad (5)$$

where V* is equal to Darcy's velocity assuming that α may approach 1 for a horizontal fracture zone with a high K value; r_o is a borehole radius; C_T is concentration measured at time t minus the background concentration; C_o is initial concentration of the injected tracer; λ is a calibration constant which may vary from borehole to borehole.

The same data as in Fig. 3 are calibrated based on Eq. (5). As can be seen in Fig. 5, the calibrated data fitted a straight line as expressed in Eq. (4). The fitted hydraulic conductivity for the horizontal fracture zone is 1 250 m/d which is almost identical to that obtained previously. Based on Cubic Law, an equivalent fracture aperture of 0.16 mm is calculated. However, the aperture of 0.16 mm could not be verified in this study but provides quantitative information concerning the size of the fracture in Karoo aquifers. The dilution test can therefore be used to directly estimate the fracture aperture.

Estimation of effective porosity

A peak arrival time of 4.02 h at borehole UO9, situated 14.66 m downstream from injection hole UO20, was derived from the breakthrough curve recorded. Actual pore water velocity along the horizontal fracture zone from UO20 to UO9 was 87.69 m/d. An effective porosity of the fracture zone involved was estimated by comparison of the actual velocity with the Darcy's velocity of 6.00 m/d calculated from the dilution test in UO20. This yielded 6.84% for the horizontal fracture zone.

Fracture identification using EC profiles

Fast-flow fracture zones tend to dilute salt concentration while slow matrix flow below a fracture would permit a build-up of salt concentration. In a fractured aquifer, occurrence of fractures in a borehole would be reflected in EC profiles due to the differential flow. Figure 6 depicts an EC profile with a profile of horizontal hydraulic conductivities in borehole UO9 and a horizontal fracture zone at depths of 21-23 m is confirmed. In a single borehole like UO9, EC above the fracture zone is diluted due to fracture flow while EC below the fracture obviously builds up due to slow flow through the matrix (Fig. 6).

Table 1 indicates the vertical depths of horizontal fracture zones in nearby boreholes determined by using EC profiles before

TABLE 1
FRACTURE ZONES DETECTED BY EC PROFILES (1 m INTERVAL)

Boreholes	UO2&3	UO4	UO5	UO6	UO7	UO8	UO9	UO20
Fracture depths (m)	no major fractures	23.5 m, 24.5 m	22.5 m, 23.5 m	22.5 m, 23.5 m	21.5 m, 22.5 m, 23.5 m	21.5 m, 22.5 m, 23.5 m	21.5 m, 22.5 m	21.5 m, 22.5 m

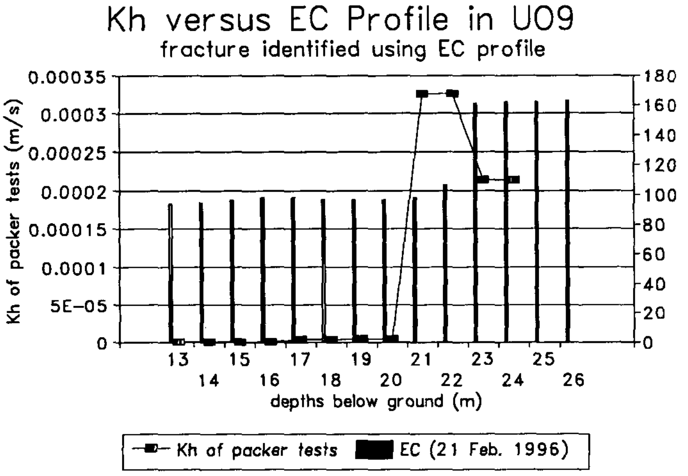

Figure 6 Comparison between Kh and EC profiles

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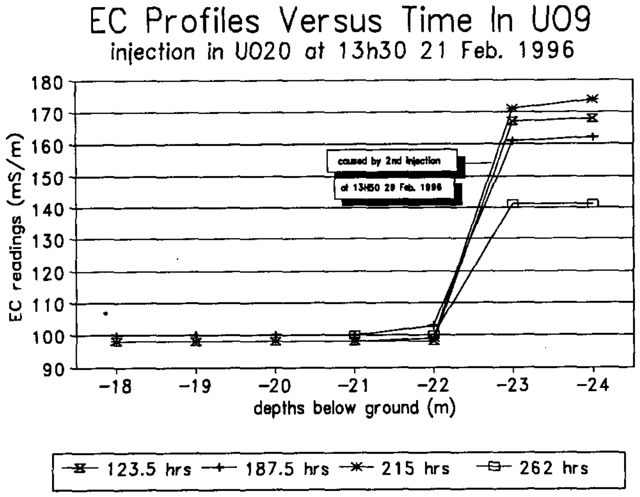

Figure 7
EC profiles in UO9

and after tracer injections. The result is in good agreement with borehole core information as well as pumping test results.

It is worth noticing that the second injection in UO20 on 29 February 1996 can only be detected from EC readings below the fracture rather than from measurements above it (Fig. 7). This again proves that because of the quick fracture flow any build-up would quickly dissipate. Therefore the bottom portion of the profile vs. time will produce more reliable information on arrival times of individual pulses.

Discussion

Most assumptions used for the above interpretation presume that the tracer is an ideal one and that the flow within the fracture zone is a predominantly piston flow. Otherwise the interpretation would be complicated by the dispersion process.

Although it is assumed that in-hole velocity is equal to the Darcy's velocity in the case of a fracture zone, the difference between the two velocities may still exist in the fracture zone scenario. Drost et al. (1968) presented formulas for the calculation of the distortion factor α which is related to hydraulic conductivities around a borehole and its geometry as well. It seems that the size of a borehole or screen diameter may be also related to the distortion of the velocity field. This hydraulic behaviour is similar to that of a tiny circular pond which would collect water from an upstream aquifer and recharge it into a downstream formation. As the gradient inside the hole, like the tiny pond, is zero, horizontal hydraulic conductivity must be assumed to be infinite in order to maintain a non-zero horizontal velocity V* which transports the injected tracer along the flow path. The 2-D numerical simulation of flow distortion was performed using ModIME (Zhang et al., 1995) to analyse the relationship between borehole flow velocity V* and Darcy's velocity V^*/α in an aquifer. Under steady-state, flow through a borehole (AV*) must equal flow from its upstream catchment ($A_m V^*/\alpha$) where A_m stands for the maximum cross-sectional area of the borehole's upstream catchment and the same holds for the downstream situation. Thus the distortion factor α may be approximately defined as a ratio (r) of borehole maximum catchment width (W_m) to borehole diameter ($2r_o$). Alternatively, the following relation between α and r may be established, assuming that catchment widths increase linearly from borehole ($2r_o$) to the maximum width (W_m):

$$\alpha = r \ln(r)/(1-(1/r)) \qquad (6)$$

The catchment width (W_m) can be numerically found to determine r in Eq. (6). In the present study, the catchment width was evaluated using pathline analysis. It was found that the parameter α varies between 1 and 2 for diameter ranges from 50 mm to 200 mm, compatible with an α value of 2 calculated for the same conditions from the formula proposed by Drost et al. (1968). According to Eq. (6), α will have a limit of 1 when r approaches 1, which means that the flow distortion caused by a borehole would disappear if the borehole is unable to induce a catchment of its own ($r = 1$). Hydrogeologically speaking, the condition ($r = 1$) may be met when a borehole is situated in a highly permeable zone like a horizontal fracture zone.

The above evaluation of the distortion factor α implies that the Darcy's velocity can vary from 12.00 m/d to 6.00 m/d and the hydraulic conductivities from 2 000 to 1 000 m/d with α increasing from 1 to 2. Such high K values have to be explained by the fracture zone scenario.

A diffusion experiment of UO20 water using a dialysis tube was also carried out in the laboratory to assess a diffusion process. It was found that the diffusion coefficient of the EC tracer was 1.2 ~3.5 $\times 10^{-7}$ m^2/s. In real aquifer situations, this may still be reduced by a factor of 0.5 ~ 0.01 (Freeze and Cherry, 1979). The diffusion component was very insignificant, especially in a fracture-flow system. This is consistent with a statement that the influence of molecular diffusion can be disregarded if Darcy's velocity in the aquifer is greater than 0.3 m/d (Drost et al., 1968). Other velocity components still not accounted for include the velocities caused by density convection, vertical current in the well screen, etc.

It should be pointed out that the in-hole tracer mixing is a prerequisite for a borehole dilution experiment because Eq. (2) assumes uniform mixing in the dilution chamber (Novakowski, 1996). Although no mechanical mixer was installed in the chamber, injection of a large volume of tracer solution would provide fairly good mixing. However, the problem of in-hole mixing must be solved to improve accuracy of the results.

The breakthrough curve of borehole UO9 was not fully used for interpretation. There are two reasons for that. The first is that the observation points after peak arrival time were not sufficient enough to establish a reliable tailing of the curve. The second is that the monitoring depth was 21 m just above the main fracture which is located at depth of 22.5 m as was revealed by the EC profile (Fig. 6). Thus the peak arrival time, as well as effective porosity, so estimated may not be very reliable. However, the approach used is relevant to this kind of preliminary investigation.

Of significance is that the K value on the fracture scale cannot be determined by the conventional pumping test. As a result, characteristics of such a fracture system may not be readily recognised. A further study of 3-D pathline analysis of the campus site system is being carried out by using ModIME (Zhang et al., 1995). Although beyond the scope of this paper, the numerical modelling exercise has demonstrated that the impact of highly permeable fractures on wellfield protection is very significant.

Finally, there are some limitations for application of EC experiments in Karoo aquifers. Firstly, the scale of the experiment must be small so that the induced EC change is detectable, otherwise it could be masked by higher EC values in different hydrogeochemical facies. Secondly, the experiment is unsuitable for areas where background EC is already very high, e.g. in the dry area of the South-Western part of the Karoo.

Conclusion

In an attempt to obtain hydraulic parameters for the protection of borehole water quality in Karoo aquifers, a series of borehole dilution experiments using common salt as tracer was conducted at the campus site of the University of the Orange Free State in Bloemfontein. The experimental result is interpreted for the scenario of the fractured aquifer. The study has revealed valuable information on the fractured Karoo system:

- Dilution tests with one observation hole can be used to estimate horizontal hydraulic conductivity of a fracture zone as well as its effective porosity on the scale of the campus site aquifer. It is demonstrated that the borehole dilution may also be adapted to estimate the equivalent fracture aperture.
- EC profiles can be utilised to detect actual locations of fractures occurring in boreholes. This would be one of the most economical techniques for obtaining information on the depth of pump installation in rural water supply situations.
- The result may still be improved, provided that the mixer is devised and installed during an experiment.

The role of highly conductive fracture zones in flow regimes should be investigated. This would add new information on transport features and thus provide a better understanding of borehole protection measures in secondary aquifers.

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