Nordic Hydrology, 24, 1993, 263-274

Tracer Test in Fractured Chalk
1. Experimental Design and Results

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A two-well tracer test was conducted in eastern Denmark, in which a short duration pulse of lithium chloride was injected into a recharge well and made to flow through a fractured chalk aquifer to a discharge well. The wells were 25 m apart, and the concentration of lithium arriving at the discharge well was monitored at five vertical intervals in the well for a 21-day period. The observed breakthrough curves show a sharp breakthrough front, with an arrival time that is consistent with advective transport through the fractures in the chalk. The breakthrough curves also exhibit a long tail in the falling limb, suggesting the influence of a secondary transport mechanism of diffusion into the porous matrix.

Introduction

Groundwater represents an extremely important resource in Denmark. It provides over 99% of the country's drinking water supply, in addition to satisfying a large percentage of rural water needs. Due to the continued generation of industrial, municipal, and agricultural wastes and their subsequent subsurface or surface disposal however, an increasing amount of the country's groundwater resources have been threatened by contamination. If groundwater is to continue to play an important role in the development of Denmark's water resource potential, the fate of contaminants in groundwater must be better understood.

In eastern Denmark the water supply is often provided from water stored in fractured chalk aquifers. To better understand transport processes in a fractured porous medium, a field tracer test was conducted in a fractured chalk aquifer near the town of Karlstrup representing an aquifer typical of the eastern part of Denmark.

A tracer test is a field method for obtaining data to describe advection and dispersion in an aquifer. There are basically three main classes of tests: 1) single-well test, 2) two-well test, and 3) natural gradient test. Gelhar *et al.* (1985) and Gelhar *et al.* (1992) have discussed the various methods and also compiled the results of tracer studies from 59 field sites. The transport parameters varied from site to site depending on the geological environment and the scale of the experiment. However, the reliability of many of the experiments was reported to be questionable due to *e.g.* an ill-defined input function, inaccurate monitoring or inappropriate models used for interpreting the results. An important issue in relation to tracer experiments is the dimensionality of the study. Field observations of contaminant transport have generally shown that the vertical mixing of the contaminant as it travels through an aquifer is often very small and therefore the plume is constrained to relatively narrow vertical intervals. This has been documented in studies of glaciofluvial environments (Sudicky *et al.* 1983; Freyberg 1986; LeBlanc *et al.* 1991, Jensen *et al.* 1993), but there are reasons to believe that the vertical dimension may be equally important for contaminant transport in other aquifer systems such as fractured chalk. Many of the previous tracer studies have involved depth-averaged (vertically mixed) monitoring, which hence may lead to misinterpretation of the transport and dispersion characteristics.

A number of tracer experiments have been carried out in sandy aquifers primarily as two-well (*e.g.* Pickens and Grisak 1981: Molz *et al.* 1986) or natural gradient experiments (*e.g.* Freyberg 1986; LeBlanc *et al.* 1991, Jensen *et al.* 1993). Only a few experiments have been reported for fractured aquifer material (Grove and Beetem 1971; Kreft *et al.* 1974; Claasen and Cordes 1975; Ivanovitch and Smith 1978; Novakowski *et al.* 1985), which have all been carried out as either two-well or radially converging experiments.

The recent natural gradient experiments have been monitored and interpreted in three dimensions while most of the reported single- and two-well experiments have been monitored and analyzed in two dimensions (depth-averaged concentrations). One of the exceptions is a study by Molz *et al.* (1986), where a three-dimensional numerical model was applied. The data from the tracer experiments in fractured media have generally been interpreted using simple analytical solutions.

The present paper describes the results of a field tracer test which was conducted as two-well experiment, in which a short duration pulse of lithium was introduced over a vertical interval in a recharge well and measured over several vertical intervals in a nearby pumping well, without recirculation of the pumped water. The experimental design is described and the results presented as observed concentrations of lithium from the discharge well in the form of breakthrough curves. In an accompanying paper the experimental results are interpreted using a numerical model (Brettmann *et al.* 1993).

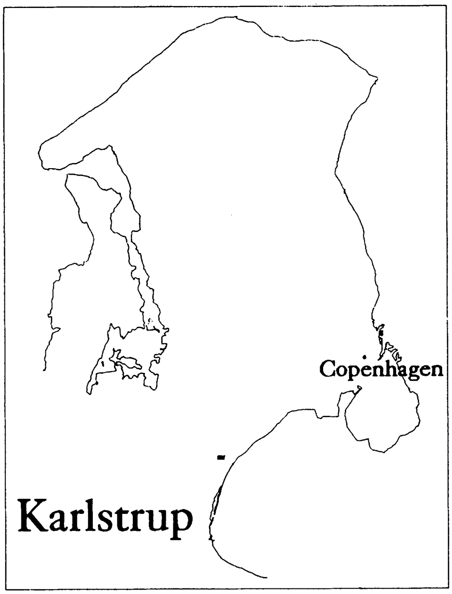

Fig. 1. Location map of Karlstrup field site.

Field Site Description

The field site is located approximately 35 km south of Copenhagen in Karlstrup, Fig. 1. The entire region is underlain by a sequence of Cretaceous and Early Tertiary chalks several hundreds metres thick which serves as the regional aquifer. Rock fragments collected during drilling and observations at a nearby quarry provided detailed information of the upper 25 m. The chalk is coarse, consisting of Bryozoic fragments of sand size held in a finer carbonate mud with variable cementation characteristics. Chert layers are found throughout the penetrated sequence. Some layers are up to 25 cm thick and show no signs of fractures for many metres in the exposure, while others are more or less connected nodules forming a layer. In the quarry exposures the layers follow and emphasize the elongated domed structure of the former Bryozoan reefs or banks.

At the field site a thin layer of till clay with embedded minor sand lenses covers the chalk over most of the studied area, increasing from less than 1 m in the northern part to 5 m in the southern part of the area. The till was deposited during the last glaciation period. The ice movements during that period generated an upper section of the chalk of about 10 m with numerous, closely spaced fractures of random orientation. The lower section of the aquifer is geologically similar to the upper section, but contains a much lower density of fractures.

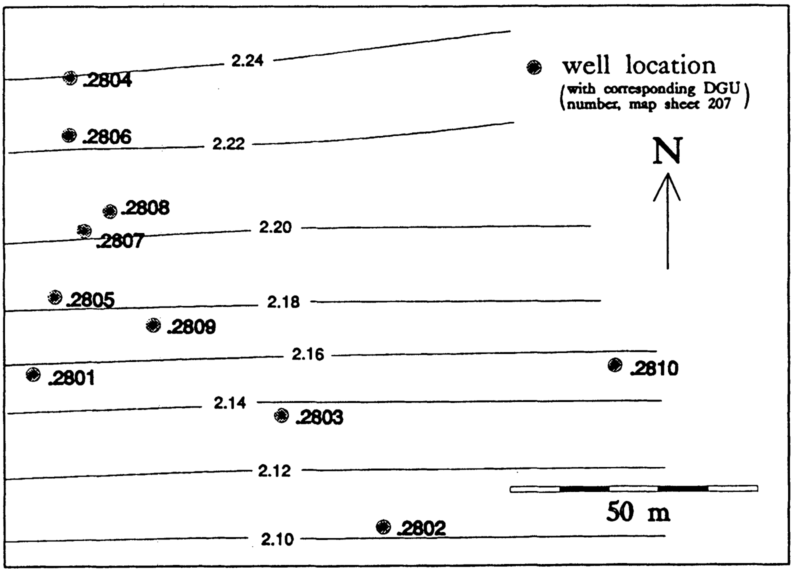

Fig. 2. Plan view of well locations and the observed hydraulic head levels (m) prior to the second tracer test.

The test site is an area approximately 80 m by 120 m, and contains 10 wells which penetrate the aquifer to an elevation of approximately -20 m (all elevations are relative to mean sea level, MSL). The elevation of the soil surface is approximately 7 m. Fig. 2 shows the location of the wells and the observed head levels in the aquifer prior to the tracer test.

The wells were drilled using the ODEX down-the-hole-hammer technique and left as open holes. Due to the dense fracturing of the chalk, blocks fell into the borehole and consequently reopening was required, which was done by rotating a casing to the bottom while clearing the inside with a bailer. Before the casing was removed, a 120 mm diameter drain pipe was installed in the well.

Hydraulic Investigations

Methods

The hydraulic parameters of the aquifer were determined based on the results of two traditional pumping tests, in addition to a series of separation injection tests (SIT's) (Nilsson and Jakobsen 1990) which were performed in each well in order to determine the vertical profile of horizontal hydraulic conductivity. During the SIT, fresh water and salt water were injected into the well bore simultaneously by two tubes located at the top and the bottom of the borehole, respectively (Fig. 3). A

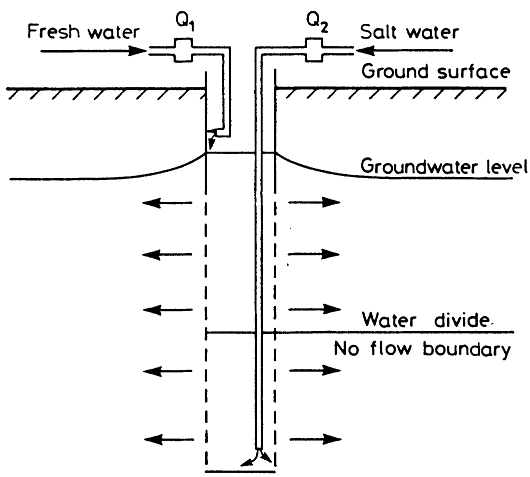

Fig. 3. Schematic illustration of the separation injection test. (From Nilsson and Jakobsen, 1990).

no-flow interface between the fresh water and the salt water was established in the borehole, the location of which was dependent on the ratio between the pumping rates and the hydraulic conductivity above and below the interface. The position of the interface was measured using a conductivity cell. By conducting the test multiple times while changing the ratio of the injection rates of salt and fresh water in steps of 10 %, the local horizontal hydraulic conductivity profile was determined for each flow partial on the basis of the change in hydraulic head after 10 minutes of injection and the injection rate using the relation derived by Theis *et al.* (1963) relating transmissivity to specific capacity.

The measurements of the hydraulic parameters of the dual-porosity aquifer as a whole were supplemented by measurement of matrix porosity and hydraulic conductivity on plugs from some of the larger chalk blocks which were recovered during drilling.

Results

The hydraulic head distribution prior to the tracer test is shown in Fig. 2. Groundwater flow occurs under unconfined conditions over most of the study site, with an average water table elevation between 2 and 3 m. Confined conditions exist over the southern one-third of the site where the water table extends into the overlying moraine layer, which acts as a confining layer. Under natural flow conditions, a slight hydraulic gradient (0.001) exists towards the south. Vertical head gradients within the aquifer appear to be small. Groundwater recharge is due to water infiltrating directly to the aquifer or through the overlying moraine.

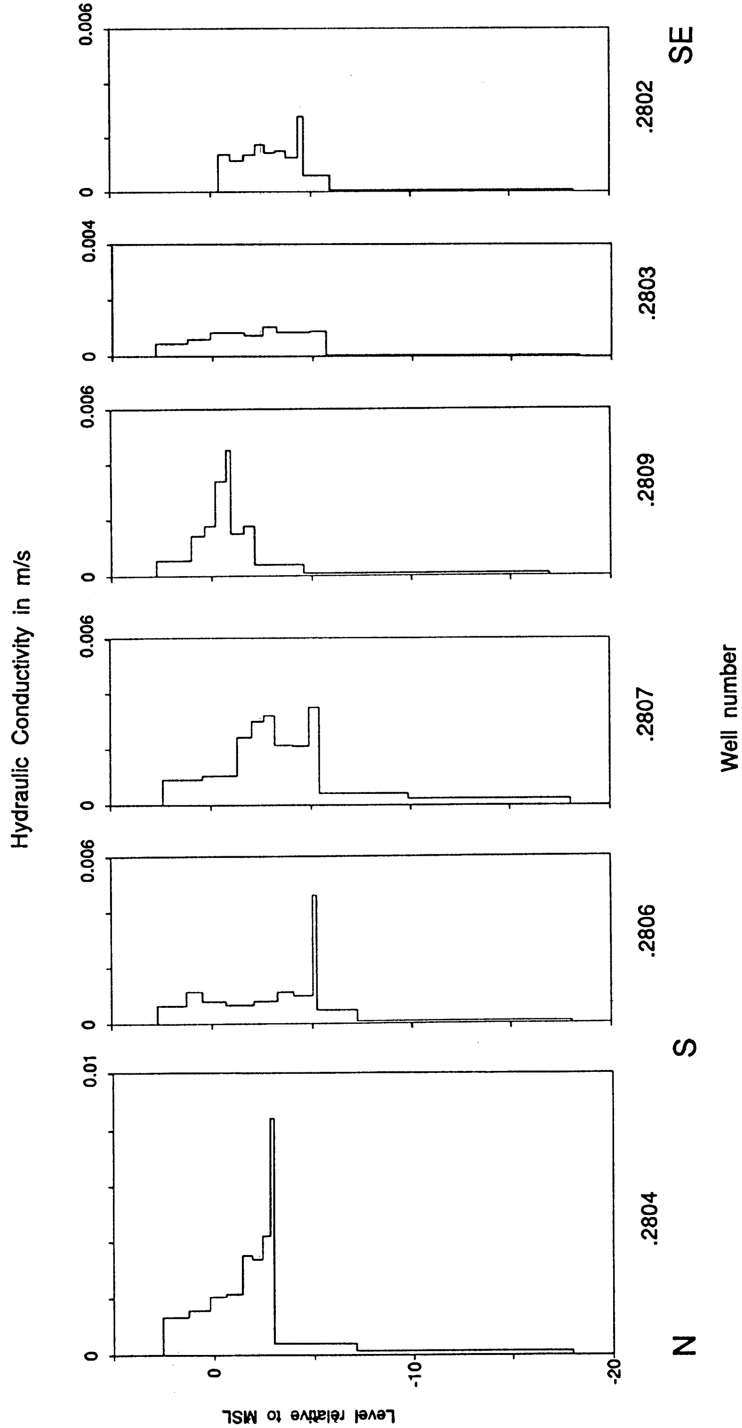

Fig. 4. Distributions of hydraulic conductivity in selected wells.

Analysis of the data from pumping tests conducted in wells 2801 and 2807, respectively shows that the regional transmissivity of the aquifer is around 0.01 m^2/s and that the confined aquifer storativity is in the order of 0.001-0.005 while the unconfined aquifer storativity is approximately 0.015. This value is expected to represent the fracture porosity because the pumping tests were carried for a relatively short period (less than 30 minutes) during which only the fractures are expected to dewater.

Fig. 4 shows hydraulic conductivity profiles derived from the SIT's in six wells located in a cross-section along a NW-SE line. Each step on the graphs represents a 10 % flow partial indicating the value of the hydraulic conductivity and the interval over which it applies. As shown by the profiles the hydraulic conductivity is not uniformly distributed over depth with the highest values found in the upper 10 m of the aquifer corresponding to the region of highest fracture density. These findings are consistent with the observations in the quarry. The horizontal hydraulic conductivity in this section of the aquifer is most typically in the order of 1.0×10^{-3} m/s. According to the SIT's, approximately 90 % of the flow occurs in this section of the aquifer. The lower section is hydraulically tighter due to less extensive fracturing and has a horizontal hydraulic conductivity of approximately 5×10^{-5} m/s. Some wells show peaks of very narrow, high conductivity zones. This is consistent with the observations in the quarry exposures, where certain levels showed wide fractures extending for up to 5-10 m particularly in the top of the thick chert layers. The peaks cannot be correlated from well to well which probably means that the lateral extension of these dominating fractures is smaller than 10 m.

The measurements on the plugs showed a rather high matrix porosity in the order of 20-35 % and a very low hydraulic conductivity in the order 10^{-7}-10^{-8} m/s.

Tracer Experiment

Methods

The tracer test was made as a two-well test with an upstream well used for a pulse injection and a downstream well used for pumping. Using the partials determined by the separation injection tests as discharge partials, a separation of the flow both during injection and during pumping was possible. The tracer was injected through a tube ending in the middle of the interval where the tracer was meant to enter. The rate corresponded to the recharge partial of that interval. At the same time freshwater was injected above and below through separate tubes at rates corresponding to the recharge partials of the intervals above and below the interval where the tracer was injected.

In the discharge well six pumps were installed, the upper five positioned in the middle of the five 20 % flow partials and the sixth pump at the top of the lower

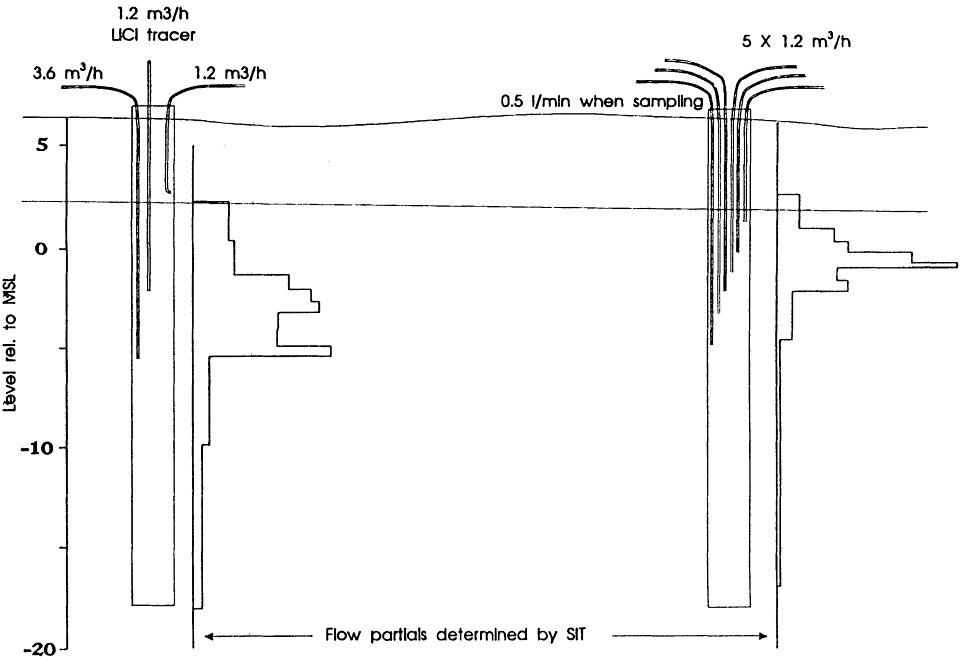

Fig. 5. Experimental design of the two-well tracer test.

10 % partial. The five upper pumps were pumped at equal rates while the sixth was pumped during sampling at a rate of 1 % of the total rate. The pump arrangement consisted of four submersible pumps (one 2″ and three 4″ pumps) and two surface - installed suction pumps connected to 1″ tubing to fit the arrangement into the 120 mm pipe installed in the well. The experimental setup is shown schematically in Fig. 5. The figure shows that in the discharge well the level of the water table was slightly lower (0.75 m) than the upper boundary of the flow partial determined by the SIT implying that the position of the water table during the SIT was higher than at the start of the tracer test. This difference presumably displaces the position of the intervals, and furthermore the water table was lowered approximately 0.25 m during the tracer test, resulting in a total difference of approximately 1.0 m. To compensate for this the pumps were placed 0.2, 0.4, 0.6, 0.8, and 1,0 metre, respectively, lower than the positions predicted by the SIT.

Tracer Application

Lithium was chosen as a tracer because it enabled easy field analysis on an inexpensive portable flame photometer (Jenway FP7). Field analysis made it possible to adjust sampling intervals according to the rate of change in concentration. The concentration of lithium arriving at the discharge well was monitored in the discharge water of the five pumps placed at various vertical locations in the well. The tracer test was carried out using well 2807 for injection and well 2809 for discharge (henceforth referred to as well 7 and 9, respectively).

After well 9 was pumped for approximately 7 hours, the tracer injection began at well 7, which was located 25 m from well 9 (see Fig. 2). The injection began with fresh water being pumped into the well from two tubes that were positioned at the top and the bottom of the well bore, respectively. Fresh water was pumped into the upper interval at 1.2 m^3/h and into the bottom interval at 3.6 m^3/h. After 10 minutes of fresh water injection, the injection of a lithium chloride solution started from a tank containing 944 mg/l of lithium. The lithium solution was injected into the well at a rate of 1.2 m^3/h from a tube located in the well at −2 m. The lithium solution was pumped into the well for 49.5 minutes for a total mass of 935 grams. After the lithium had been injected, fresh water continued to be injected above and below the tracer interval for another 30 minutes in order to flush any remaining lithium from the well bore.

The injection of fresh water above and below the interval of tracer injection was also intended to isolate the lithium to a relatively narrow interval in the well bore, since no packers were present in the well. The lithium concentration in the injection well during and after the injection was derived from an electric conductivity log using a conductivity meter (WTW LF191). These measurements indicate that a certain amount of mixing occurred in the well bore nevertheless, such that lithium was injected into the formation over the vertical extent of the well at varying concentrations. The spreading of the tracer was primarily in the downwards direction suggesting that the density contrasts between the injected fluid and the native groundwater (density contrast approximately 0.6 %) may have had an effect; yet, some vertical flow may have been induced in the borehole during injection which also may have contributed to the mixing.

The discharge well was pumped at a steady rate throughout the 21-day duration of the test, and water samples were taken from the outflow of the five pumps and analyzed for lithium every 30 minutes for the first 12 hours and then at progressively longer intervals as the rate of change in concentration became smaller.

Results of the Tracer Experiment

To describe the transport of lithium between the recharge well and the discharge well, lithium concentrations were monitored in the pumped water from the five flow partials identified by the SIT tests. Breakthrough curves were obtained by plotting the observed lithium concentrations *vs.* time for these intervals (Fig. 6). Examination of the breakthrough curves shows that the highest peak concentrations of lithium observed were in the interval from 0 to −2 m, corresponding to the interval where most of the lithium mass was injected in well 7. Lower peak concentrations of lithium were observed above and below this interval, especially just

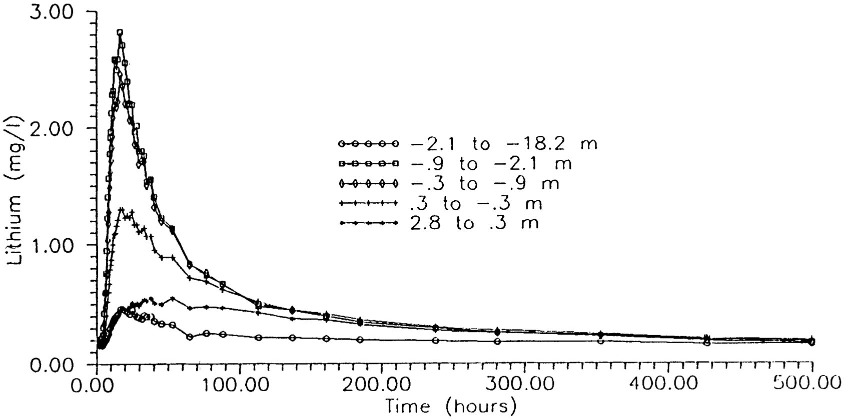

Fig. 6. Observed breakthrough curves of lithium from five vertical intervals in the discharge well.

below the moraine layer and also in the deepest intervals of the aquifer where relatively low concentrations of lithium were found in the recharge well. The breakthrough curves are quite asymmetrical, as they exhibit a sharp breakthrough front followed by a long tail which gradually approaches the background lithium concentration of 0.16 mg/l. The presence of this tail suggests that lithium transport was affected by some process(es) in addition to advection and dispersion in the fractures.

It is also interesting to note that the arrival times of the peak lithium concentrations in the discharge well were approximately the same for all of the intervals (about 17 hours after lithium injection began), with the exception of the uppermost interval in which the arrival time of the peak was about 24 hours. For lithium transport in the deepest interval this is somewhat surprising, because the hydraulic conductivity in the lower level of the aquifer is at least one order of magnitude smaller than it is in the upper aquifer. One possibility is that the relatively lower fracture porosity in the lower interval somewhat compensates for the low value of hydraulic conductivity, resulting in groundwater velocities that are the same order of magnitude as those found in the upper aquifer. Another possible, and perhaps plausible way to describe this observation is to assume that the lithium detected in the bottom interval of the discharge well was actually transported through the higher conductivity layers of the upper aquifer. Upon reaching the discharge well, this lithium could have mixed into the lowest interval of the well and therefore discharged through the lowermost pump in the well. This seems quite possible considering that no packers were present in the discharge well to restrict mixing in the borehole and the lowermost pump was located approximately one to two metres below the interval where the highest concentrations of lithium were measured.

Mass recovery was determined by integration of the breakthrough curves from the individual vertical intervals multiplied by the flow rates. After 10 days of pumpage approximately 60 % of the mass was recovered and after another 10 days 70 % was recovered. Complete mass recovery would only be attained after pumping over very long time due to the slow process of back diffusion from matrix to fractures. These results are comparable to the mass recovery obtained in a similar study by Novakowski *et al.* (1985).

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First received: 17 February, 1993
Revised version received: 24 May, 1993
Accepted: 27 May, 1993

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