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About the influence of the injection mode on tracer test results

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ABSTRACT: One of the most common techniques used to evaluate the aquifer transport properties is the well-known two-well injection-withdrawal tracer test. A radially converging flow field is created by a pumping well. A pulse of tracer-labelled water is introduced into the groundwater through the injection well. The time evolution of the tracer concentration is monitored at the pumping well. The resulting breakthrough curve can be interpreted with analytical or numerical solutions to evaluate the transport properties. Most often, the injection is supposed to be instantaneous. Such an assumption allows to interpret the breakthrough curve as the impulse response of the aquifer-piezometer system.

As mentioned by many authors, the way the injection is conducted can differ dramatically from the usual Dirac-type pulse of tracer, due to the complex interaction between the piezometer equipment and the aquifer material. This can have a critical influence on the shape of the breakthrough curve leading at the extreme to a double-peak. The interpretation of such a result disregarding the way the injection was conducted could prove erroneous.

Different tracer tests performed in the alluvial plain of the river Meuse in Belgium have shown double-peaked breakthrough curves. One of the tracer tests was selected to be replicated under different injection conditions. The breakthrough curves did not present two peaks anymore.

After some theoretical and field considerations, the tracer test results are analysed and criticised. It is shown how important it is to conduct further investigation in order to gain a better understanding of the influence of the injection mode on the breakthrough curve.

1 INTRODUCTION

One of the most common techniques used to evaluate the aquifer transport properties is the well-known two-well injection-withdrawal tracer test. A radially converging flow field is created by a pumping well. A pulse of tracer-labelled water is introduced into the groundwater through the injection well. The time evolution of the tracer concentration is monitored at the pumping well, giving the breakthrough curve, which can be used to evaluate the aquifer transport properties.

The main advantage of this technique is that, theoretically, the whole injected mass of tracer is recovered at the pumping well. This allows to interpret the results in a quantitative way by comparing the actual breakthrough curves with theoretical ones obtained with analytical or numerical solutions.

Usually, these tests are performed by injecting the tracer at a known level in a piezometer. A chase fluid accompanies and follows the injection to force the tracer to penetrate in the aquifer. A good advice is to use a volume of chase water at least equal to the volume of the piezometer, to make sure that the tracer actually reaches the aquifer. This chase fluid is often performed by imposing a water flow rate at two points surrounding the position of the tracer injection. This is done to determine the level at which the tracer is injected into the aquifer and to prevent the tracer to reach the lowest, often blind, part of the piezometer.

Two injection modes are often conducted. The most usual is an instantaneous injection. In practice, the duration of the tracer injection is very short compared to the total duration of the tracer test. The best way to do this is to use a high chase fluid of short duration. Lepiller and Mondain (1986) give a review of the notions of system theory applied to hydrogeological studies. The aquifer can be viewed as a system receiving an input (the tracer injection) and giving an output (the tracer breakthrough curve). If the injection is of the Dirac type, the output can be considered as the impulse response of the system and interpreted with such theories. Sometimes, a continuous injection is performed. It actually consists in a long time step injection, which is often very difficult to control. This injection mode is better suited when the experimenter is mainly concerned with the retardation mechanisms affecting the tracer transport. Indeed, this enhances the breakthrough curve tailing, separating it from the concentration noise of the aquifer.

It is usually difficult to get a precise idea of the actual input function of the tracer in the aquifer. The concentrations measured directly in the injection piezometer are not necessarily equal to the concentrations in the aquifer in the vicinity of the piezometer. A borehole-mixing effect is frequently observed. Moreover, the interactions between the piezometer and the aquifer are often more complex than usually supposed. Ackerer et al. (1982) present an experimental device to study that interaction. Figure 1 shows how a piezometer modifies the groundwater flow at its vicinity. The streamlines skirt round the piezometer. This confirms that the concentrations measured in the piezometer can differ from the concentrations in the aquifer at the same location, the piezometer acting more or less as a dead-water zone. To get more representative concentrations, a pumping is necessary to force an exchange of water between the piezometer and the aquifer. Locally, as the pumping can modify the flow field and the experimental conditions, it is not always a good solution.

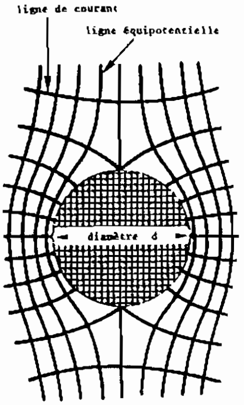

Figure 1. Modification of the groundwater flow near a piezometer (from Ackerer et al., 1982)

There are different methods to monitor the concentration evolution at the injection well. Porel (1988) measures the residual tracer concentrations at different levels in the injection piezometers with a manual multi-sampler. For saline tracers (Li$^+$,...), it is possible to use a conductivity probe to evaluate the concentration history in the piezometer. Meus (1993) used such a method to monitor the input function of Li$^+$ and KNO$_3$ for tracer tests conducted in a chalk aquifer. Derouane (1994) followed the conductivity (for saline tracers) and took manual samples in different injection piezometers during and after the injections of different tracers (Li$^+$, I$^-$, uranine, naphtionate and rhodamine WT). This allowed him to conclude that most of the tracer had left the piezometer after one day (more than 99% of the total injected mass). But he did not use the input concentration profile to simulate the tracer tests. To be really efficient, a multilevel conductivity measurement should be made, which implies the use of a very sophisticated probe.

The tracer nature is usually not taken into account. Laboratory experiments have often been conducted to study the influence of the tracer nature (Sabatini and Austin, 1991; Shiau et al., 1992), but field experiments are still missing.

The interpretation of the tracer test results is often done by taking advantage of analytical solutions (Sauty and Kinzelbach, 1987; Moench, 1995) or numerical methods (Biver and Meus, 1992). At this stage, other numerical or conceptual problems can be encountered. These are the subject of a companion paper (Dassargues et al., this issue).

2 INFLUENCE OF THE TRACER INJECTION AND CHASE FLUID

As mentioned before, impulse injections are often considered to be of the Dirac type (or square type) when interpreting the results. Moreover, the volume of water used to inject and to chase the tracer is supposed to have a negligible influence on the flow field in the vicinity of the piezometer. In practical terms, the way the injection is performed can have a dramatic influence on the shape of the breakthrough curve. Apart from the duration of the injection, the main factor influencing the result is the chase fluid that accompanies the tracer injection. Guvanasen and Guvanasen (1986) have developed an approximate semi-analytical solution for tracer injection tests in a confined aquifer with a radially converging flow field and a finite volume of tracer and chase fluid. They show how, according to the porous media properties, the way the tracer injection and the chase fluid are made can modify the shape of the breakthrough curve.

To obtain the solution, the tracer transport is conceptually divided in two parts: (1) the tracer injection and chase is considered first, (2) the effective transport of the tracer to the pumping well is calculated. During the injection, the dispersion mechanism is supposed to be negligible compared to the advection mechanism, inducing a piston-like tracer transport in all directions around the injection well. Near the injection piezometer, the combination of the groundwater velocity induced by the pumping well and the velocity due to the injection causes the initial distribution of the tracer to be non-circular and ringlike (figure 2). This initial tracer distribution is evaluated through a tracking along the pathlines. Then, the resulting tracer geometry is approximated by a series of contiguous rectangles of uniform concentration. The radial form of the advection-dispersion equation is applied to all these rectangles to calculate the resulting breakthrough curve at the pumping well.

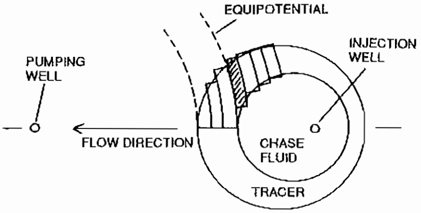

Figure 2 Initial tracer distribution in the aquifer (adapted from Guvanasen and Guvanasen, 1986)

Four non-dimensional parameters are used to determine the shape of the tracer ring at the end of the injection stage.

$$g1 = (Q_{Tr} \cdot T_{Tr} + Q_{ch} \cdot T_{ch}) / (\pi \, b\theta \, R_0{}^2)$$
$$g2 = Q_{ch} \cdot T_{ch} / (Q_{Tr} \cdot T_{Tr} + Q_{ch} \cdot T_{ch})$$
$$g3 = Q_{Tr} \cdot R_0 / Q_p \cdot r_{inj}$$
$$g4 = Q_{ch} / Q_{Tr}$$

where Q_{tr} and Q_{ch} are the tracer and chase fluid injection rates, T_{tr} and T_{ch} the time period of tracer and chase fluid injection, b is the saturated thickness of the aquifer, θ is the effective porosity of the aquifer, R_0 is the distance between the injection piezometer and the pumping well, r_{inj} is the injection piezometer radius and Q_p is the pumping rate. Parameter *g1* compares the total injection volume to the effective volume of water in the aquifer in a circle of radius R_0, *g2* compares the chase fluid volume to the total injection volume, *g3* compares the velocities due to the tracer injection to the velocities near the injection well due to the pumping Q_p, *g4* compares the chase fluid rate and the tracer injection rate. Figure 3 shows the tracer ring shape according to these different adimensional parameters. Guvanasen and Guvanasen (1986) compare on the basis of a few simple examples their results to an analytical solution considering a Dirac-type tracer injection. The differences can be dramatic, showing the important effect of the volume of injection and chase water on the shape of the breakthrough curves. At the extreme, the breakthrough curve can be double-peaked. The interpretation of such a result, disregarding the way the injection is conducted, could prove erroneous.

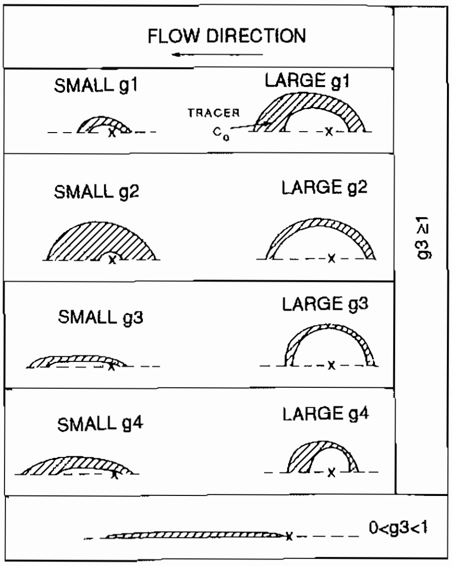

Figure 3. Effects of geometrical parameters on the tracer plume shape (adapted from Guvanasen and Guvanasen, 1986)

Different tracer tests performed in the alluvial plain of the river Meuse in Belgium have shown double-peaked breakthrough curves. One of the tracer test was replicated under different injection conditions and did not present two peaks.

3 CASE STUDIES

Both studied sites are situated in the gravel aquifer located in the alluvial plain of the river Meuse in Belgium. These sites consist in water catchment areas. Hydrogeological studies and groundwater modelling were conducted in order to define protection zones around the production wells (Derouane, 1994; Comeaga et al., 1995;). Site 1 is located at Vivegnis, near the city of Liege, on the left bank of the river Meuse. Site 2 is situated at Dinant, on the right bank of the river (figure 4).

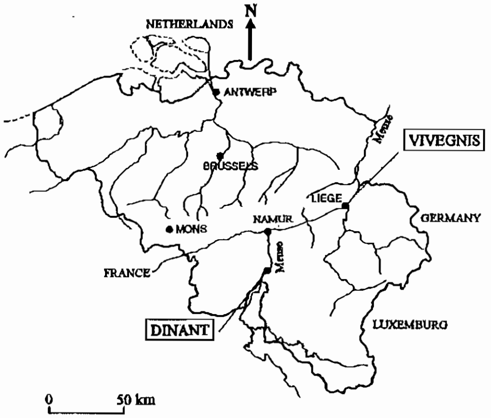

Figure 4. Situation map

Site 1

The geology of this site is composed of an upper carboniferous bed-rock consisting in shales and sandstones. This constitutes the impervious basis of the aquifer. Loose materials deposited by the river Meuse on that substratum are composed of gravel bodies imbedded in old channels filled with sandy to silty or clayey sediments. At the studied site, the vertical succession shows, from bottom to top, aquifer well-sorted gravels, sandy to clayey gravels and surface deposits. The total thickness of the main gravel layer is about 7 meters. There are four pumping wells extracting about 8000 m^3/d. For the needs of the study, ten piezometers have been drilled, completing the set of boreholes already existing in the area. The aquifer is unconfined on nearly the whole of the studied area.

Seven tracer tests have been performed on that site, with saline tracers (Li^+, I^-) and fluorescent tracers (uranine, naphtionate and rhodamine WT). One of these tests, performed with Li^+, presented a double-peaked breakthrough curve (figure 5). This test was the replication, with a higher chase fluid, of a previous one conducted with I^-. This first injection was not performed under 'good' experimental conditions: due to a density effect the tracer remained in the blind deepest part of the injection piezometer. A breakthrough curve could be identified at the pumping well only when a further bottom chase fluid was performed in the piezometer, four days after the injection of I^-.

If one compares the two results, the first arrivals are almost the same. The peak of Li^+ arrives later than the peak of I^- but this difference can be attributed to different injection conditions. Since the experimental conditions are not perfectly controlled, the comparison between the two tracer tests can only be made on a qualitative level. As two peaks are not identifiable on the iodide breakthrough curve, the hypothesis of a transport of the tracer along two different paths can be rejected and the influence of the injection mode has to be considered.

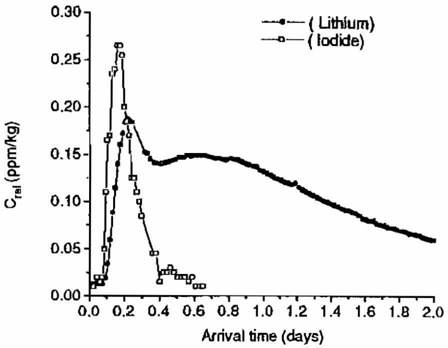

Figure 5. Tracer breakthrough curves at Vivegnis

Site 2

The geology of site 2 is composed of a devonian and carboniferous bed-rock made of sandstones, limestones and shales. The bed-rock cannot be considered as the impervious basis of the aquifer. The different studies conducted on the site have set into evidence a incoming water flux from the bed-rock to the gravel aquifer. The loose materials have the same structure and succession as in Vivegnis. Due to the presence of sandy to clayey gravel over the well-sorted gravel, the aquifer can be considered as semi-confined. There are two pumping wells (P1 and P2) extracting a mean water flux of 1500 m^3/d from the gravel aquifer. For the purpose of the study, seven piezometers have been drilled in the gravel aquifer and in the bed-rock.

In a first phase, three tracer tests were performed. The injections were made at piezometers situated in the vicinity (20 to 30 meters) of the pumping well P1. These tests are summarised in table 1 (together with the tests conducted at Vivegnis). The breakthrough curves (normalised according to the injected mass of tracer) are shown in figure 6.

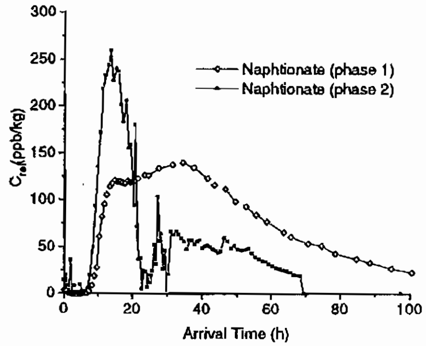

Figure 6a.

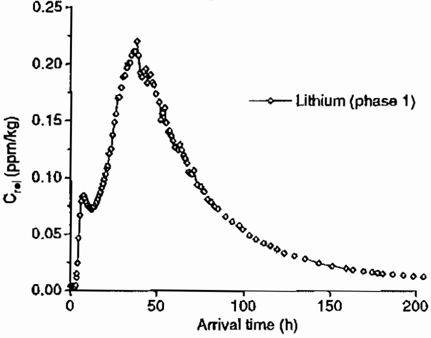

Figure 6b.

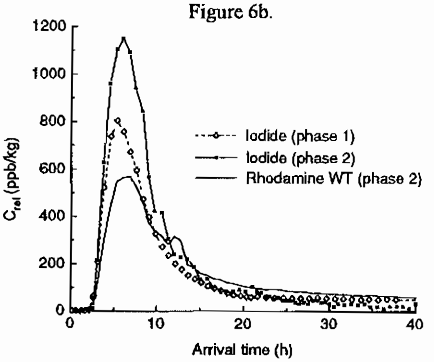

Figure 6c.

Figure 6. Tracer breakthrough curves at Dinant

Naphtionate and lithium present a double-peaked breakthrough curve (figure 6a and 6b, phase 1). Iodide presents a unimodal breakthrough curve with a very long and flat tailing (figure 6c, phase 1). First, the double-peaked tracer tests were interpreted as the result of a tracer transport along two different paths. These could be two gravel layers with different permeabilities or a gravel layer and a preferential fissured path in the bed-rock. One year after, the naphtionate and iodide tracer tests were performed under similar experimental conditions. Rhodamine WT was added to I^- to check the influence of the tracer nature. The extracted flow rate at P1 was nearly unchanged. The main difference was in the injection mode. The chase fluid (which was suspected to be the main cause of the double-peaked results) was dramatically diminished. The breakthrough curves observed during the second phase are superimposed to the corresponding curves during the first phase in figure 6a and 6c. When the chase fluid is lower, both peaks are enhanced. Furthermore, there is no more double peak visible on the naphtionate breakthrough curve. The iodide breakthrough curve shows a rapidly decreasing tailing. This was not the case during the first phase where the longer tailing was due to a higher dispersion of the tracer in the aquifer during the high chase fluid.

So, the first interpretation considering the double-peaked shape of the breakthrough curve has to be rejected. The influence of the chase fluid seems to provide a better explanation. If one considers only the tracer transfer aspects, the influence seems to be minimal since the first arrival and modal times are nearly the same. But if one is concerned with the retardation effects, one has to be very careful about the way the injection is conducted.

Figure 6a also shows the influence of the tracer nature on the result. Rhodamine WT was injected with I^-. The breakthrough curve clearly shows that the peak of rhodamine WT appears later than the peak of I^-. This is probably due to a greater sorption of rhodamine WT on shales. This is a lesser problem than the previous one mentioned since it is easily possible to conduct an experiment (even in laboratory) to demonstrate the sorption of rhodamine WT.

4 INTERPRETATION OF THE RESULTS

Table 2 shows the four adimensional parameters defined by Guvanasen and Guvanasen (1986), calculated for both tracer tests. In fact, we are not exactly working on the assumptions of their paper since the aquifer should be confined. We can suppose that we are not far from that hypothesis since the gravels are overlaid by sandy to silty gravels which make them semi-confined. The transport parameter values are those obtained through the simulations of the tracer tests with finite elements (Derouane, 1994) and finite differences (Rentier, 1996).

As shown in table 2, parameters g2 and g4 are nearly the same for the two phases conducted on site 2. The corresponding parameters g1 and g3 are shorter in phase 2 than in phase 1 (approximately 1/3 and 1/2). Remembering that g1 is a measure of the total chase volume and g3 a comparison between the

Table 1. Tracer tests results

Site	Qp (m^3/h)	Tracer	d (m)	I.M.(kg)	Vtr (l)	Ttr (min.)	Vch (l)	Tch(min.)	Vmax (m/h)	Vmod (m/h)	R (%)
Vivegnis	120	iodide	26.85	2	---	---	---	---	~16.11	6.78	14.8
		lithium	26.85	3.48	70	5	2100	120	11.93	5.1	88
Anseremme *phase 1*	57.9	lithium	18.63	3.25	170	13	1145	30	6.1	2.07/0.48	87
		iodide	19.78	7.65	288	6	2016	72	9.13	3.65	61
		naphtionate	31.12	5	272	5	1720	45	5.31	2.09/0.93	49
phase 2	53.6	iodide	19.78	1.53	75	3	241	17	7.657	3.25	52
		naphtionate	31.12	0.5	77	3	234	12	4.5	2.28	24

Qp : pumping rate
d: distance between pumping well and piezometer
I.M. : injected mass
R : Recovery factor
Vtr : tracer injection volume
Ttr : tracer injection duration
Vch : chase volume
Tch : chase duration

Table 2. Geometrical parameters for the different tracer test according to Guvanasen and Guvanasen (1986)

Site	Qp (m^3/h)	Tracer	d (m)	r_{inj} (m)	b(m)	θ (%)	g1	g2	g3	g4
Vivegnis	120	iodide	26.85	---	---	---	---	---	---	---
		lithium	26.85	0.08	7.0	5.8	0.00236	0.968	2.352	1.250
Anseremme *phase 1*	57.9	lithium	18.63	0.058	6.0	9.0	0.00200	0.871	4.390	2.920
		iodide	19.78	0.058	6.0	6.5	0.00480	0.875	17.110	0.583
		naphtionate	31.12	0.058	6.0	9.0	0.00120	0.863	30.510	0.703
phase 2	53.6	iodide	19.78	0.058	6.0	6.5	0.00066	0.763	9.630	0.567
		naphtionate	31.12	0.058	6.0	9.0	0.00019	0.750	17.880	0.760

r_{inj} : injection piezometer radius
b: aquifer thickness
θ : effective porosity
g1-g4 : geometrical parameters defined by Guvanasen and Guvanasen (1986)

velocities due to the pumping in the vicinity of the piezometer and the velocity due to the injection, it is easy to understand the reasons why the tracer tests have been disturbed by the injection mode. In the first phase, the chase fluid volume was too big, which modified the velocity field near the injection piezometer, inducing a ring-like shape of tracer. The double peak is due to that shape. The first peak is the result of the part of the ring which was 'pushed' in the direction of the pumping well by the chase fluid, the second peak is the result of the part of the ring which was 'pushed' upstream with regard to the main flow direction and was, therefore, delayed. Even the tracer test performed with I^- was disturbed by the injection. The results of the first phase show a lower peak intensity and a very long and flat tailing, which is probably the consequence of a high artificial dispersion of the tracer in the medium due to the chase fluid.

5 CONCLUSIONS

According to the presented results, it is obvious that tracer test experimenters should be very careful with the way they conduct the injections, particularly when the tracer test distances are short (10 to 30m). Of course it is interesting to chase the injected tracers with a volume of water added after the injection, but this chase should not be too strong to avoid a high deformation of the initial tracer cloud in the aquifer. If the tracing distances are longer (50 to 100 meters), the influence of the injection is probably mitigated by the hydrodynamic dispersion in the media.

As far as we know, the case studies presented here are the first mentioned in the literature. But this is perhaps because other tracer tests have not been interpreted with the knowledge of the possible occurrence of such problems.

In the future, two kinds of experiments should be undertaken. It would be interesting to model such results with numerical methods and to check if it is actually possible to reproduce the influence of the chase. To do so, the difficulty is that one is faced with numerical problems: oscillations, dispersion and mass conservation. Representing the injection remains tremendously difficult. In the field, it should be very interesting to conduct a research on a simple experimental site composed of one or two injection piezometers (aligned if possible) and a pumping well. Various injection modes should be checked to gain a better understanding of what actually occurs and different tracers should be used to compare their respective response.

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