PERFORMANCE AND INTERPRETATION OF A TRACER TEST IN THE BELGIAN COASTAL PLAIN

Alexander VANDENBOHEDE and **Luc LEBBE**

Department Geology and Soil Science, Ghent University
Krijgslaan 281 (S8), B-9000 Gent, BELGIUM

ABSTRACT

A forced gradient tracer test has been performed in a quaternary aquifer in the Belgian coastal plain. A volume of salt water was injected in the ground water reservoir and pulled towards a pumping well. The movement of the tracer was followed with a geophysical monitoring tool, the focussed electromagnetic induction log. The major advantage of this system is that continual vertical profiles can be obtained in PVC-cased wells, making detailed study of tracer breakthrough possible. Practical applicability is illustrated by the study of layered and lateral heterogeneity of the phreatic aquifer in the Belgian coastal plain near the village of Houtave.

INTRODUCTION

Solute transport is of concern in many hydrogeological problems in coastal areas, for instance in environmental topics, salinization problems of overexploited water catchments, salt water seepage in polder regions, effects of artificial recharge, etc. Therefore, tracer tests must be designed to derive solute transport parameters. Different tests are described in literature. An overview can be found in Domenico & Schwartz (1998). Relatively small-scale field tracer tests are thereby a very interesting research tool because these tests are performed under know and controlled circumstances. Geological site characterization is an important first step in tracer test interpretation. With geological site characterization, derivation of geological layering and lateral continuity of layers is understood. In this paper, the performance of a forced gradient tracer test and its qualitative interpretation is presented. An innovating geophysical borehole logging technique is thereby used to monitor tracer breakthrough. The geological site characterization and its relation with the interpretation of the test is discussed.

FORCED GRADIENT TRACER TEST

Two important choices must be made in the design of an appropriate tracer test: its configuration and the kind of tracer. For the configuration, Domenico en Schwartz (1998) makes the distinction between two types of tracer transport. In a natural gradient system, the tracer moves due to the natural occurring flow of the ground water. Otherwise, the system can be stressed by injection and/or withdrawal of water. By analogy with the term natural gradient, tests were pumping and/or injection well(s) are used are indicated here as forced gradient tracer tests. During a forced gradient tracer test, tracer movement is faster then during a natural gradient tracer test.

A forced gradient tracer test is selected for this research. Thereby, a volume of water marked with a tracer is injected in the ground water reservoir. Thereafter pumping is started at a well at some distance from the injection well. The tracer movement towards the pumping well is observed with observation wells between the injection and pumping well. This set up has several advantages. Firstly, the scale of the test is not too small, in the order of 10 meters and a few meters depth interval. It is a field test and solute transport is studied on a similar scale as actual solute transport problems. The scale of the test is, however, not too large. Therefore, the test is done under strictly know and controllable spatial boundary conditions. Due to pumping, duration of the test is relatively small, in the order of 10 to 14 days. This eliminates the difficulty to accurately model natural occurring time dependent phenomena as recharge, discharge, natural gradients, etc. Secondly, during the pumping stage of the test, not only concentration measurements can be done. Drawdown measurements can also be made and interpreted. Therefore, we prefer to refer to this aquifer test as a combined pumping and tracer test. The interpretation of both drawdown and concentration data is very profitable for the reliability with which hydraulic and solute transport parameters can be derived by application of 3D numerical modelling (Vandenbohede & Lebbe, 2002).

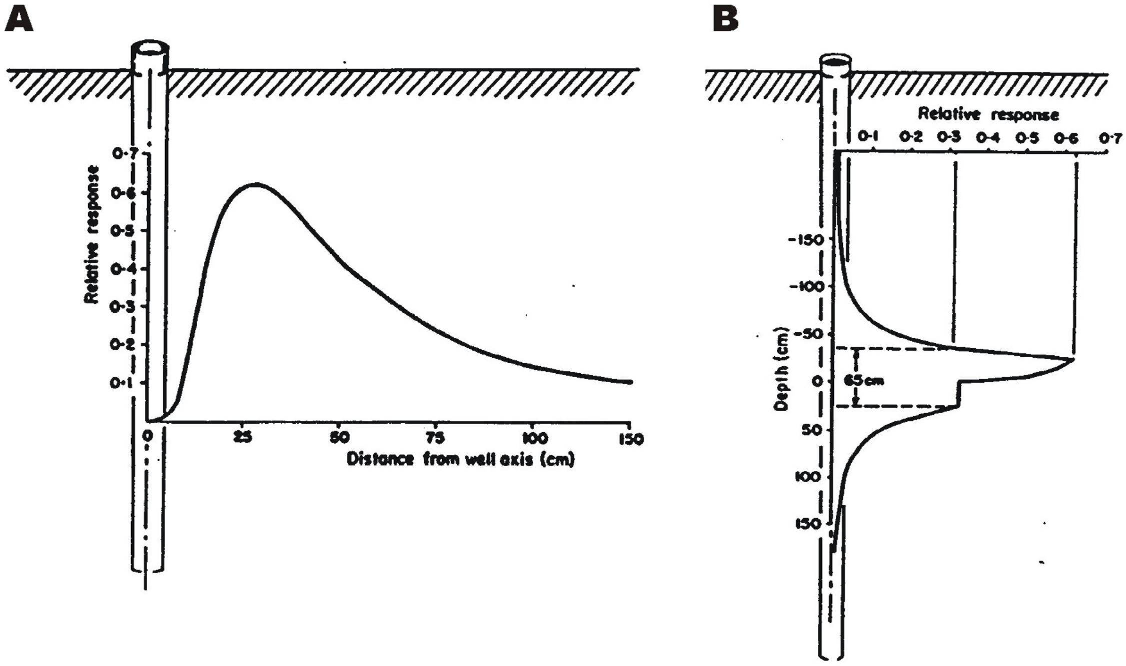

***Figure 1** Relative response with radial distance from borehole axis (A) and with vertical distance above and below the centre (B) of the EM39 logger*

Here, the tracer test is performed using one injection and one withdrawal well along with several observations wells. The forced gradient tracer test starts with the injection of a pulse of water marked with a high NaCl-content. After the injection, pumping is started in another well. The injected tracer plume moves to the pumping well and this is monitored in observation wells between the injection and pumping well. The observations are performed with a focussed electromagnetic induction tool (EM39, Geonics©). The EM39 is specially designed for use in wells encased with electrical non-conductive materials. This is a major advantage in comparison with older electrical methods (long normal and short normal), which could only be performed in open boreholes or in fully screened wells, which however induce hydraulic short-circuits. EM39 employs a small internal transmitter coil energised with an audio-frequency current to induce eddy currents in the soil surrounding the well. These eddy currents generate an alternating secondary magnetic field, which can be observed by small receiver coils located at some distance from the transmitter. The small secondary magnetic field will be linearly proportional to the electrical conductivity of the surrounding material and the device can be calibrated to read the terrain conductivity directly (McNeill,1986). The distance between transmitter and receiver coil is 50 cm. With this relatively short intercoil spacing, a centrally located focussing coil must be incorporated to reduce the response from conductive borehole fluid to negligible proportions. This arrangement of coils provides relatively large lateral range and a high degree of vertical resolution, which makes it very suitable for hydrogeological research. EM39 measures the electrical conductivity of the surrounding soil within a distance range from 20 to 100 cm from the well axis while being insensitive to conductivity of the borehole fluid and disturbed material situated near the well axis. The vertical resolution is a few tenths of meters. The relative response with radial distance form the borehole axis and with vertical distance above and below the measurement centre is shown in figure 1 (McNeill et al. 1990). This means that detailed vertical profiles can be made in observation wells during the tracer test. Numerous horizons of tracer breakthrough can be observed. This is a great asset compared with the collection of water samples in wells with relatively long filter screens. As will be shown in the next section, it is also very easy and straightforward to calculate from EM39 conductivities, the total dissolved solids (TDS) of the pore water in the sediments.

In their paper, Gelhar et al. (1992) classify tracer tests in three reliability classes with respect to the derivation of dispersivity. A forced gradient tracer test has a strictly known tracer input and a converging radial flow and is a variant of a two-well pulse test with a conservative tracer. The scale of the tests makes further that the boundary conditions are well known. With an appropriate interpretation, this test can be considered as reliable for future derivation of solute transport parameters.

PERFORMANCE OF THE TEST

The test was performed on a site in the Belgian coastal plain near the polder village of Houtave. A lithological cross-section is presented in figure 2. From bottom to top, the ground water reservoir consists of sandy clay (semi-permeable), silty sand to sand (permeable) and peat and clay layers (semi-permeable). The basis of the ground water reservoir consists of clay, which can be considered as impermeable in this study. The used well configuration is also indicated in figure 2. A volume of 0.5 m³ of salt water with total dissolved solid (TDS) of 19000 mg/l is injected in PP5, which is placed in the top of the permeable layer. PP5 has a screen length of 1 m. This layer is initially filled with brackish water (TDS of 2500 mg/l) in the upper part. Deeper in the ground water reservoir salinity increases. During the test, water is pumped continuously with a discharge rate of 31 m³/d at a distance of 7.3 meter of the injection well. Between injection (PP5) and pumping well (PP), two observation wells (PP4 and PP5) are placed to monitor the displacement of the tracer.

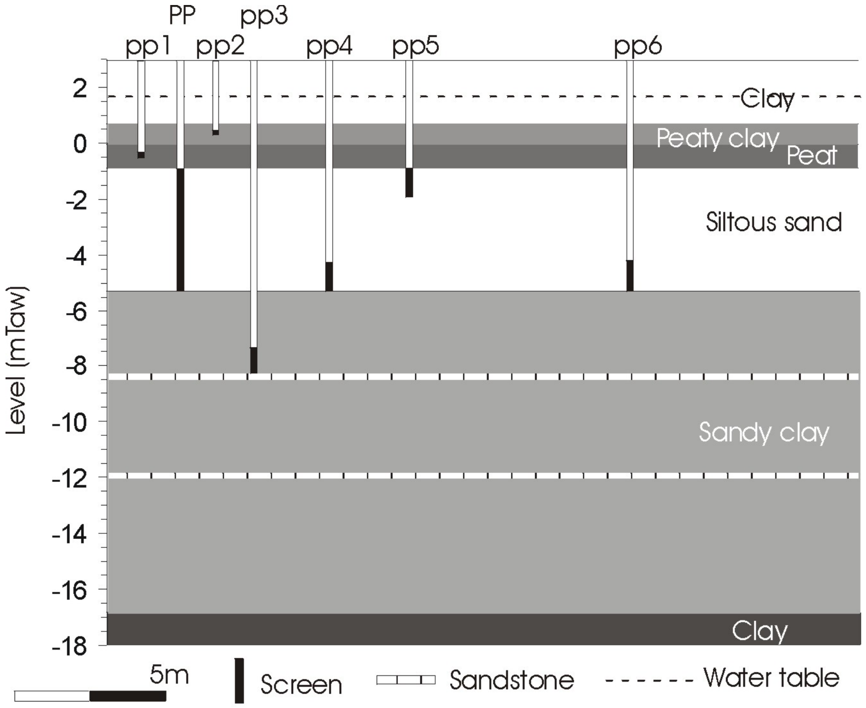

Figure 2 *Schematic cross-section through the study area with indication of well placements.*

GEOLOGICAL SITE CHARACTERIZATION

Geological site characterization consists of the identification of the geological layering and lateral continuity. This is a very important first step in tracer test interpretation. With the EM39 tool, vertical logs can be made of tracer breakthrough. It may therefore be interesting to compare these logs with the logs that describe the geological layering and continuity of these layers. The advantage is in both ways. With knowledge of heterogeneity of the ground water reservoir, one can better understand tracer breakthrough curves. With detailed vertical observations of tracer breakthrough, heterogeneity can be better understood.

For the geological site characterization, natural gamma logs and electrical conductivity logs are used. The first log measures the natural gamma of the sediments. This is mainly due to the occurrence of K^{40} in clay minerals. Sediments with a high clay content, will consequently have a large signal. Sphere of influence is the sphere from which 90% of the measured gamma rays are coming. The radius of this sphere is between 15 to 30 cm depending on the density of the sediments, well casing and borehole or well fluids. To measure the natural gamma of a layer without influence of surrounding layers, the layer must be minimum as thick as the diameter of the sphere of influence. Otherwise a combination of signals from more than one layer is measured. Natural gamma is logged in all wells shown in figure 2 and the results of these measurements are presented in figure 3. All measurements are performed in PVC-cased wells. The top clay and peaty clay layer are easily recognisable by their high counts per second (cps). The peat layer coincides with a layer of low cps. The clay content of the peat layer is very low, hence the low counts per second. This zone thickens towards the pumping well. The permeable sand layer has an intermediate cps. Vertical as well as lateral heterogeneity is visible. The base of this layer (between –5 and –6 m TAW, the Belgian ordnance datum TAW refers to mean low water level, about 2,3 m below mean sea level) has for instance lower clay content. Note that between the level –3 and –5 m TAW, there is a zone with a lower clay content, which evolves into more clayey sediments between PP4 and PP3. Also in the upper part of the permeable layer, lateral heterogeneity can be observed. Towards the pumping well, clay content diminishes. The lowest part of the logs shows the glauconite bearing sandy clay to clayey sand. This unit is however only logged in one well, PP3 and no information of lateral heterogeneity is available.

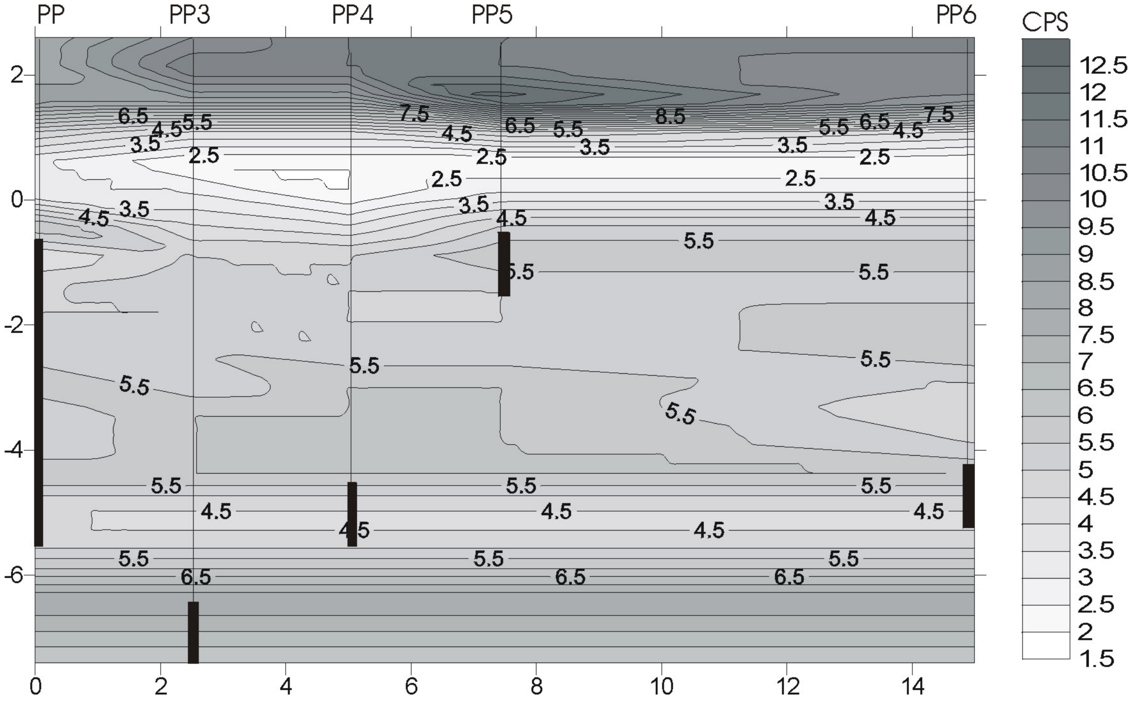

Figure 3 *Cross-section through the test site showing the natural gamma ray measurements (counts per second)*

Figure 4 shows the EM39 log in observation well PP3. A layer with high electrical conductivity is observed between 1 and 0 m TAW. This coincides with the peaty clay layer and the base of the top clay layer. Electrical conductivity diminishes upwards because of the decrease of the water content in the unsaturated zone. Peat has also a low electrical conductivity. The bulk electrical sediment conductivity is not only influenced by the matrix conductivity but also by the conductivity of its pore water. Therefore, it can be seen that below the peat layer electrical conductivity increases with depth. Here, the salt content of the pore water increases with depth. So, the transition zone between fresh and salt water is observed. The electrical conductivity σ_b (mS/m) measured with the EM39 can be related to the TDS of the pore water (mg/l):

$$TDS = 10 * F * \sigma_b$$

where F is the formation factor. F is the ratio of the conductivity of the pore water and the bulk conductivity of the sediments. With the above equation, it is very straightforward to recalculate the EM39 conductivities to TDS values. This is then the mean TDS value, which is present in the observation torus according to the relative responses shown in figure 1. Formation factor of the Houtave test site is 3.8. Measurements in the different wells show approximately the same profiles. Therefore, only the data from the deepest well are represented. In the particular case of a coastal aquifer, the EM39 is well suited to study the distribution of fresh and salt water. Together with the natural gamma log and drilling descriptions, it provides us a clear insight into the aquifer and water quality composition.

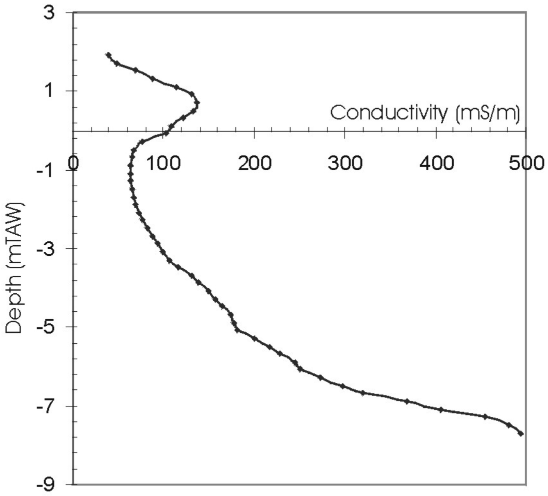

Figure 4 *EM39 measurement in PP3*

RESULTS OF THE TRACER TEST

After the injection of the tracer, pumping has continued for a period of 12 days. During this period the observation wells were logged daily to twice a day with the EM39 tool. Measurements in PP4 and PP3 are shown respectively in figure 5 and figure 6. After 118.6 h conductivity between the level –1 and –2.5 rose in PP4, indicating the first tracer entree in the distal part from the EM39 observation torus with regard to the pumping well. The observations done at 143.9 and 160.8 hours show a distinctive interval around –2 m TAW where the conductivity is lower then above and below it. This is a small layer where hydraulic conductivity is somewhat lower than average. Maximum tracer breakthrough occurred after approximately 184.8 hours. Afterwards electrical conductivity is decreasing. Note that in the all but last measurement, after 260.8 hours, still a higher conductivity is measured around –2 m TAW whereas above and beneath this level, the conductivity is back to normal. This is the already mentioned horizon of smaller hydraulic conductivity in which tracer movement is a little slower. Around –1.2 m TAW, conductivity rises from about 208 h. The conductivity stays around 100 mS/m until the last measurements. Apparently, some volume of tracer moves very slowly in the transition zone between the peat and underlying sand layer. In PP3, electrical conductivity starts to rise between –1.5 to –2.5 m TAW after 184.8 hours. Maximum conductivity values are measured after about 250 hours. In comparison with PP4, the maximum conductivity is less and tracer breakthrough in general is less explicit in PP3. This is due to both to dispersion and advection. Due the larger travel times, the tracer plume is more dispersed in PP3 then in PP4. Dispersion is the product of dispersivity and velocity. Hence larger velocities towards the pumping well enhance the dispersion.

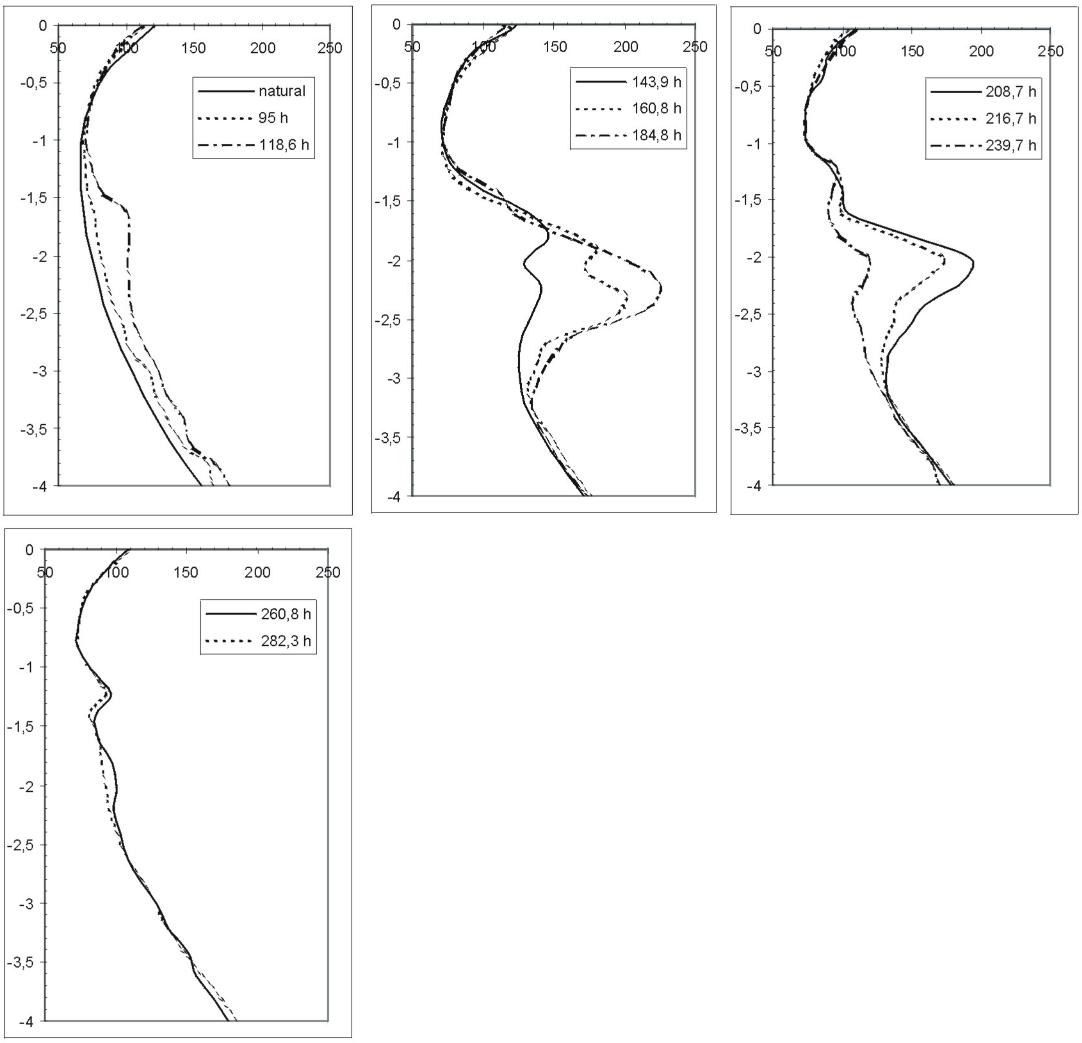

__Figure 5__ EM39 observations during the tracer test in PP4

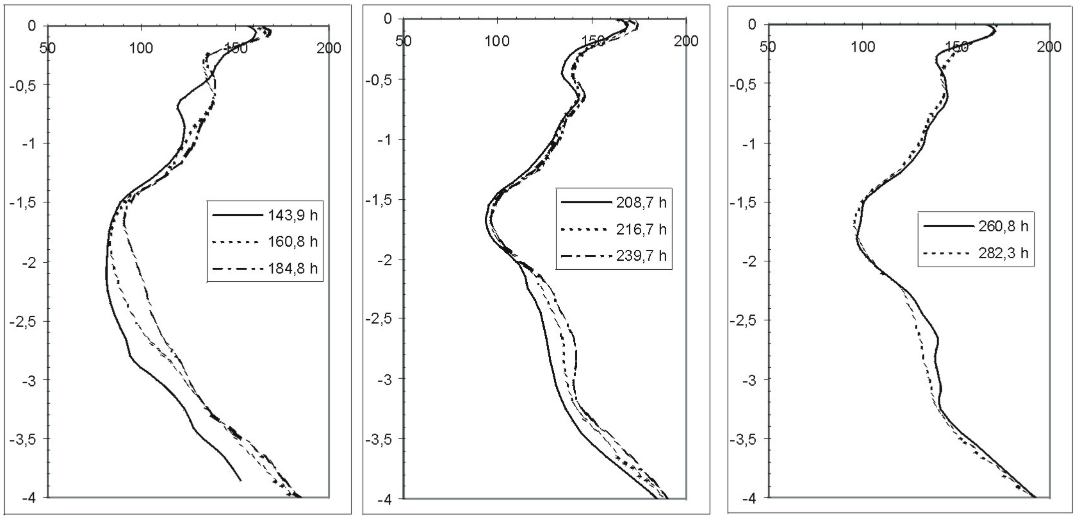

__Figure 6__ EM39 observations during the tracer test in PP3

This distance dependency (and also the time dependencies) makes that advection also accounts for the dispersion of the tracer plume. The side of the plume facing towards the pumping well moves faster then the side facing away from the pumping well. Therefore, the tracer plume is thorn apart by advection. This can be seen as an advective dispersion term. Finally, a small sagging of the plume can be observed. Maximum conductivity during tracer breakthrough is found at –2.3 m TAW in PP4 whereas this is on –2.6 m TAW in PP3.

Besides the tracer movement, the conductivity measurements show also the upconing or rise of the fresh-salt water transition zone. Only PP3, which is the observation well closed to the pumping well, provides observations under the level of the pumping well and is therefore best placed to measure the upconing. In PP4, measurements can only be done above the level of the pumping well base and PP5 is too far away from the pumping well. Figure 7 shows the evolution of TDS in time in PP3 for the depth interval below the tracer plume. Most of the upconing happens in the first six to seven days. Thereafter, the transition zone does not move much further upwards. Below the level –7 m TAW, upconing becomes very small due to the low vertical velocities. The maximum vertical upward movement is of the 9000 mg/l concentration contour lines located initially 0.5 m beneath the bottom of the pumping well. In the upper part of the pumped layer, movement of concentration contour lines is small due to the dominant horizontal velocity towards the pumping well.

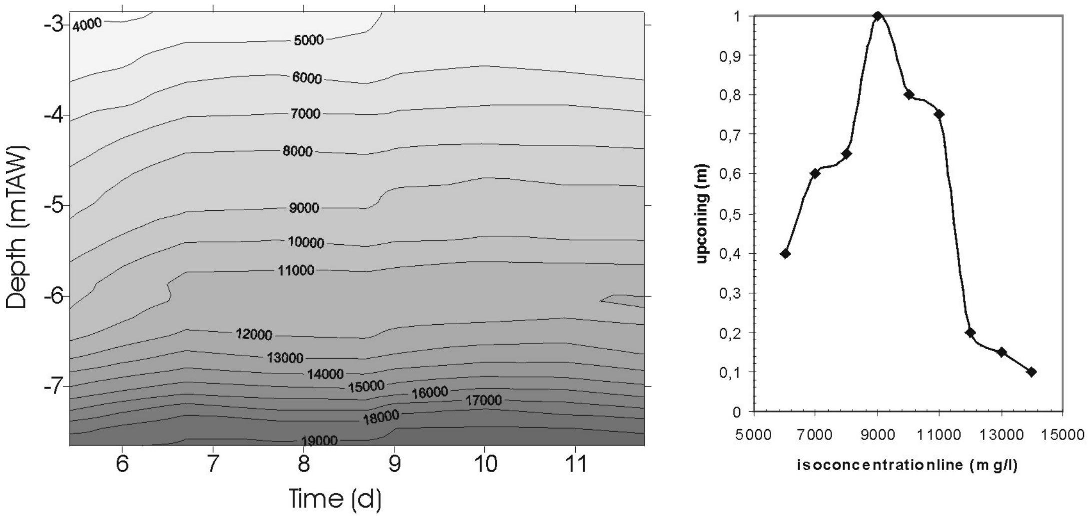

***Figure 7** Upconing in PP3 The right figure shows the total rise (upconing) of concentration contour lines, the left figure shows the upconing in function of time.*

With the EM39 probe, a measurement has been done every 20 cm. This means that tracer breakthrough curves can be studied on different levels in the observation wells. This is presented here by the relative times of maximum breakthrough. For each level in which the tracer moves, the time of maximum concentration T_i is determined and the mean time T is calculated. Figure 8 shows the ratio T/T_i for the different levels in PP4 and PP3. If T/T_i is larger than 1, the time of tracer breakthrough is smaller than average and the horizontal conductivity is larger than average. If T/T_i is less than 1, the time of tracer breakthrough is earlier than average and the horizontal conductivity is smaller than average. Therefore, with such velocity profiles layered heterogeneity can be studied and individual layers can be identified within an apparent homogeneous unit. If these layers are lateral homogeneous, then the same velocity profiles should be derived in different observation wells. This is the case below the level of –2.3 m TAW. At –2.7 m TAW a horizon with a slightly smaller conductivity can be seen. Above –2.3 m TAW, the velocity profiles in PP3 and PP4 are not completely the same. This is due to lateral heterogeneity. In PP4, a zone with smaller conductivity is observed around –2.1 m TAW. This coincide with a less sandy sediments. Above this level, a layer with higher hydraulic conductivity exists. This is found slightly higher in PP3. In general, from this velocity profiles, it can be learned that just below the peat layer, a lateral heterogeneous layer exist. This layer is probably a heterogeneous transition zone between the permeable sand layer and the less permeable peat layer. Below this zone, the vertical heterogeneity is far more important then the lateral heterogeneity.

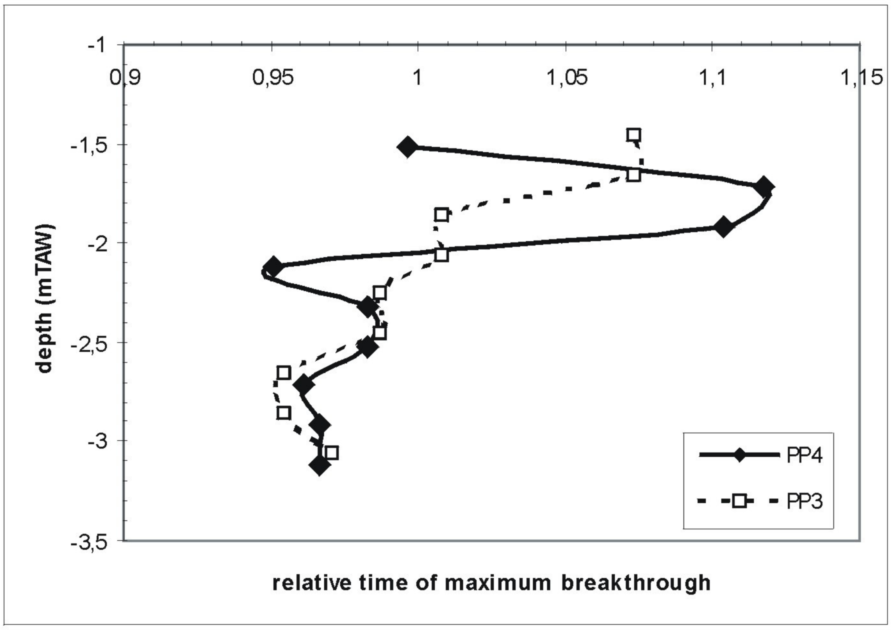

Figure 8 *Relative time of maximum tracer breakthrough (dimensionless) in function of depth for PP4 and PP3*

CONCLUSIONS

A forced gradient tracer test is presented in which the monitoring of tracer movement is done by a new geophysical method, the focussed electromagnetic induction measurements in observation wells. It has the major advantage that tracer movement can be studied with continues vertical logs in observation wells. A test has been done in the Belgian coastal plain to show its practical validity. Qualitative interpretation shows that with the continual vertical measurements, vertical and lateral heterogeneity in the ground water reservoir can be studied. This is done with the interpretation of the tracer breakthrough on small depth intervals (20 cm). The qualitative interpretation is a first important step towards numerical analyses of the test with a 3D density dependent numerical model.

REFERENCES

Domenico, P.A. & Schwartz, F.W. (1998). Physical and chemical hydrogeology. Second Edition, John Wiley & Sons, Inc. New York. 506 p.

Gelhar, L.W., Welty, C. & Rehfeldt, K.R. (1992). A critical review of data on field-scale dispersion in aquifers. Water Resources Research, 28(7), 1955-1974

McNeill, J.D. (1986). Geonics EM39 Borehole conductivity meter – Theory of operation. Technical Note TN-20, Geonics Limited.

McNeill, J.D., Bosnar, M. & Snelgrove, F.B. (1990). Resolution of an electromagnetic borehole conductivity logger for geotechnical and ground water applications. Technical Note TN-25, Geonics Limited.

Vandenbohede, A & Lebbe, L (2002). Simultaneous interpretation of drawdown and concentration data during tracer tests: sensitivity analyses. *Proc. ModelCARE2002, Prague, 17-20 June 2002, Acta Universitatis Carolinae* (accepted for publication).