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Forsmark site investigation

Groundwater flow measurements and tracer tests at drill site 1

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Abstract

This report describes the performance and evaluation of measurements of groundwater flow in three borehole sections and tracer tests performed in connection with an interference test with pumping in borehole HFM01 within the Forsmark site investigation area. The interference test is reported separately /1/. The objectives were to increase the understanding of the connection between the hydraulic structures in the area and to estimate the flow- and transport properties of the water-bearing structures.

The groundwater flow in the selected borehole sections HFM02:2, HFM15:1 and KFM01A:5 was determined through dilution measurements both before and during pumping in HFM01.

All three sections showed good flow responses from the pumping why they all were used as injection sections in the tracer tests. Pumping was performed in HFM01 with a withdrawal rate of 89 l/min and samples were taken and analysed for tracer breakthrough. Tracer breakthrough could only be detected for the flow path HFM02:2→HFM01 during the three week pumping period.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av mätningar av grund-vattenflöde i tre borrhålssektioner samt spårförsök i samband med interferenstest med pumpning i borrhål HFM01 inom Forsmarks platsundersökningsområde. Resultat från interferenstestet redovisas i annan rapport /1/. Syftet var att dokumentera hur sprick-systemet hänger ihop hydrauliskt samt att få fram uppskattningar av de vattenförande strukturernas flödes- och transportegenskaper.

Grundvattenflödet i borrhålssektionerna HFM02:2, HFM15:1 och KFM01A:5 mättes med utspädningsmetoden både före och under pumpning i HFM01.

Då samtliga tre sektioner uppvisade god flödesrespons på pumpningen användes alla tre som injiceringssektioner i spårförsöket. HFM01 pumpades med ett flöde på 89 l/min och vattnet provtogs för att undersöka genombrott av spårämne. Spårämnesgenombrott kunde endast konstateras för flödesvägen HFM02:2→HFM01 under den tre veckor långa pumpperioden.

Contents

1 Introduction

This document reports the results gained from the groundwater flow measurements and tracer tests performed in connection with an interference test at drill site 1, which is one of the activities performed within the site investigation at Forsmark. The interference test is reported separately /1/. The work was carried out in accordance with activity plan AP PF 400-05-037 and the field work was performed during June and July 2005. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

A map of a selected part of the investigation area at Forsmark including the boreholes used in the tests is presented in Figure 1-1.

The original results are stored in the primary data base SICADA and are traceable by the activity plan number.

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Grundvattenflödesmätningar och spårförsök i samband med interferenstest på borrplats 1.	AP PF 400-05-037	1.0
Method documents	**Number**	**Version**
System för hydrologisk och metrologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål.	SKB MD 368.010	1.0
Metodbeskrivning för flerhålsspårförsök.	SKB MD 530.006	1.0

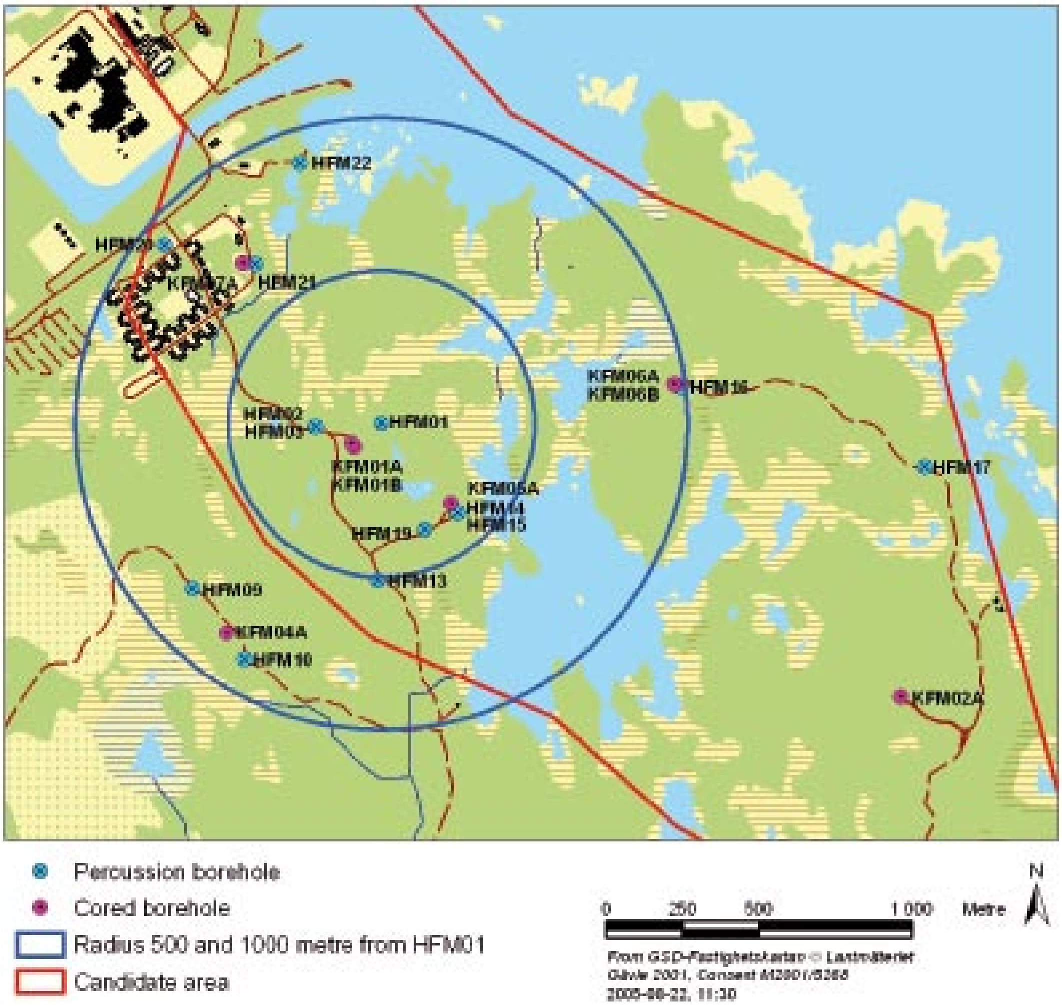

Figure 1-1. Map of a selected part of the investigation area at Forsmark. The positions of the boreholes included in the test are displayed as well as the areas corresponding to radii of 500 m and 1,000 m from HFM01, respectively.

2 Objective and scope

The objectives of the tests were to increase the understanding of the connection between the hydraulic structures in the north-western part of the investigation area at Forsmark and to estimate the flow- and transport properties of the water-bearing structures.

The groundwater flow was measured in three selected borehole sections (HFM02:2, HFM15:1 and KFM01A:5) through tracer dilution measurements both before and during pumping in HFM01. Since all three sections showed good flow responses from the pumping, they all were used as injection sections in the following tracer tests where HFM01 was used as sink. The withdrawal rate in HFM01 was 89 l/min and samples were taken and analysed for tracer breakthrough.

Table 2-1. Boreholes and sections used for groundwater flow measurements and tracer tests during the interference test in HFM01.

Borehole	Section (m)	Distance from HFM01 (m)	Comments/Type of measurements
HFM01	0–200.2	0	Sink Pressure and withdrawal rate measurements Sampling for tracer breakthrough
HFM02	38–48	222	Pressure and groundwater flow measurements Tracer injection
HFM15	85–95	325	Pressure and groundwater flow measurements Tracer injection
KFM01A	109–130	144	Pressure and groundwater flow measurements Tracer injection

3 Equipment

3.1 Description of equipment and tracers used

The boreholes involved in the tests (except HFM01) are instrumented with 2–5 inflatable packers isolating 3–6 borehole sections each. In Figure 3-1 drawings of the instrumentation in the core and percussion boreholes are presented.

All isolated borehole sections are connected to the HMS-system for pressure monitoring. In general, the sections planned to be used for tracer tests are equipped with three polyamide tubes. Two are used for injection, sampling and circulation in the borehole section and one is used for pressure monitoring.

The tracer dilution tests and the tracer tests were performed using three identical equipment set-ups, i.e. allowing all three sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-2. The basic idea is to cause an internal circulation in the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to sample the tracer concentration outside the borehole in order to monitor the dilution of the tracer with time, and thus also the tracer injection rate.

Circulation is controlled by a down-hole pump with variable speed and measured by a flow meter. Tracer injections are made with a peristaltic pump and sampling is made by continuously extracting a small volume of water from the system through another peristaltic pump (constant leak) to a fractional sampler. The equipment and test procedure is described in detail in SKB MD 368.010, SKB internal document (see Table 1-1).

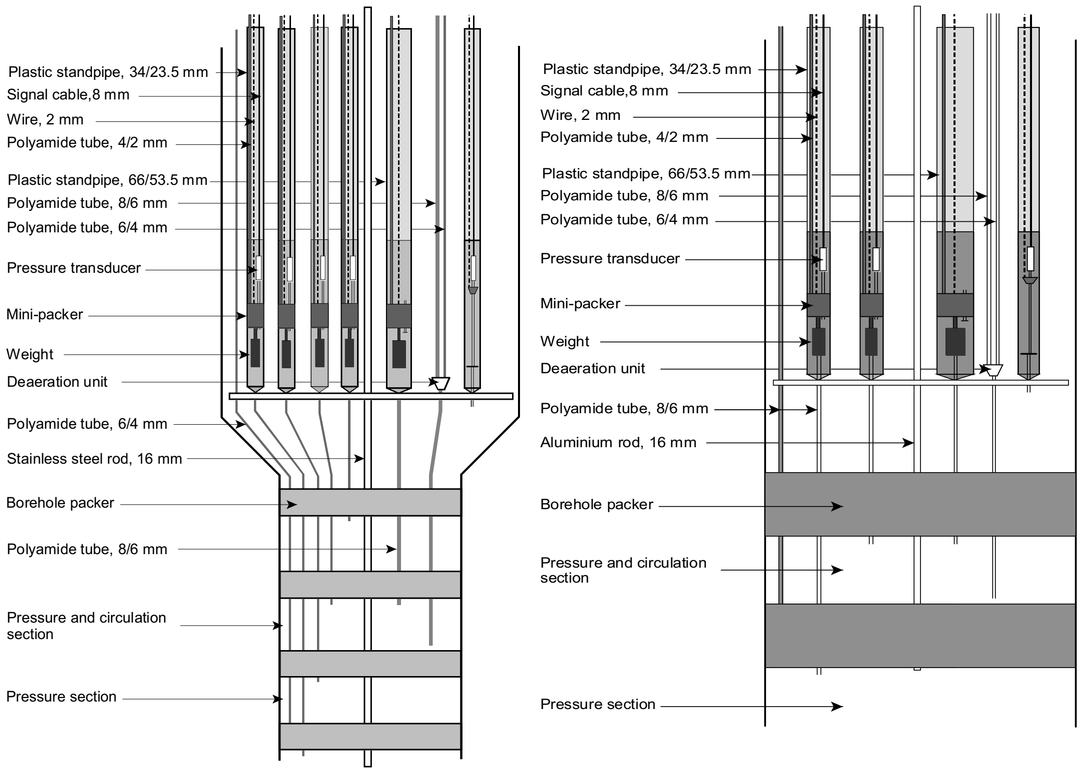

Figure 3-1. *Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.*

Samples were taken in the withdrawal borehole using two different equipments, a "constant leak" system (same as used in the injection sections described above) producing 19 ml samples integrated over time respectively an automatic programmable sampler producing discrete 500 ml samples.

The tracers used were three fluorescent dye tracers, Uranine (Sodium Fluorescein) from Merck (purum quality), Amino G Acid from Aldrich (techn. quality) and Rhodamine WT from Holiday Dyes Inc. (techn. quality).

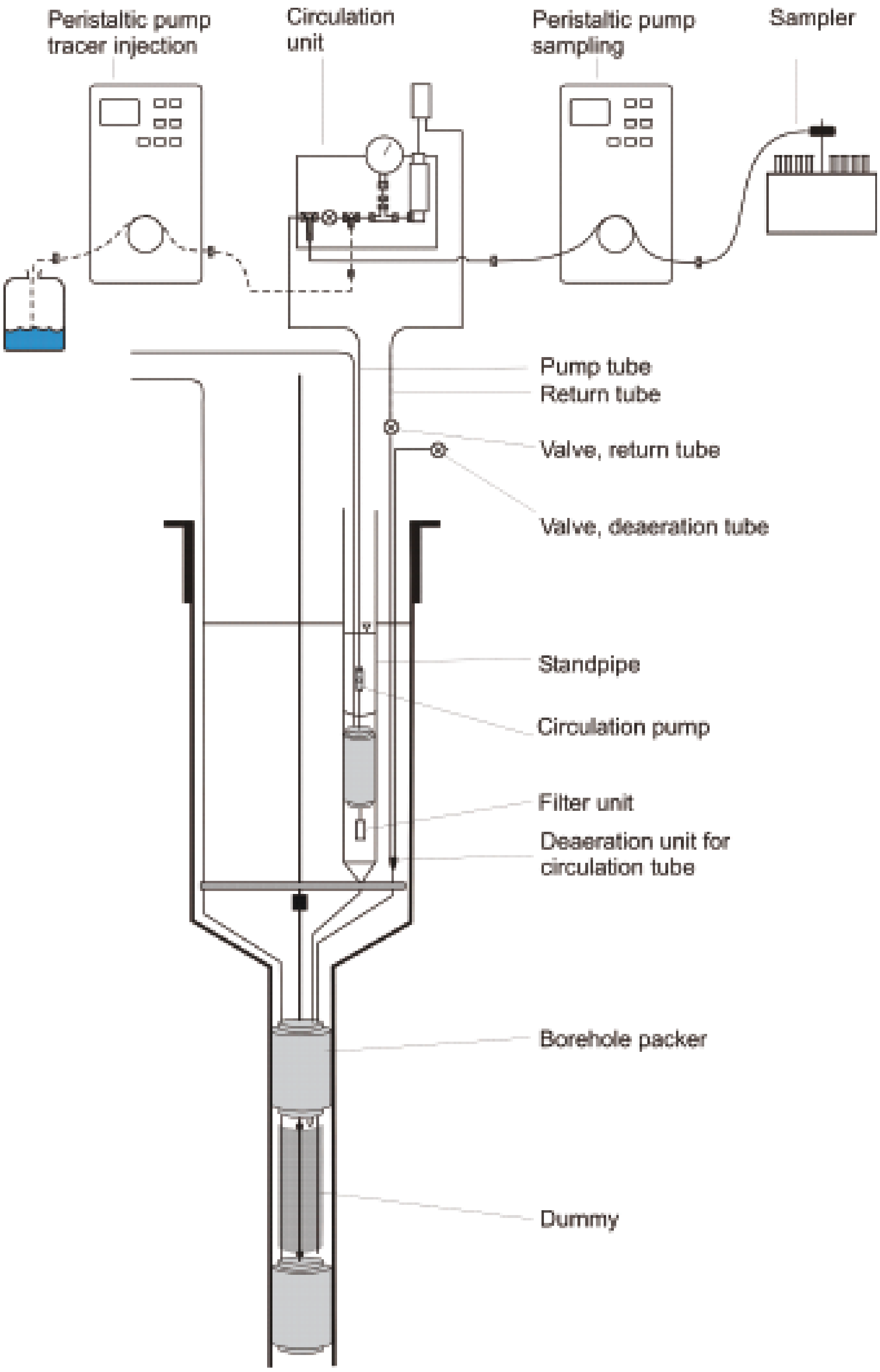

Figure 3-2. Schematic drawing of the equipment used in tracer dilution measurements.

4 Execution

4.1 General

The method descriptions used were “System för hydrologisk och metrologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål.” (SKB MD 368.010, SKB internal document) and “Metodbeskrivning för flerhålsspårförsök” (SKB MD 530.006, SKB internal document), cf Table 1-1.

4.2 Execution of field work

For measurements of the groundwater flow, tracer dilution tests were performed in borehole sections HFM02:2, HFM15:1 and KFM01A:5 both before and during pumping in HFM01.

The tests were made by injecting a slug of tracer into the selected borehole sections and allowing the natural groundwater flow to dilute the tracer. All three sections were injected simultaneously. The tracer solution was continuously circulated and sampled using the equipment described above. After eight days the pumping was started in HFM01 and the dilution tests continued for another six days.

All three sections showed good flow responses from the pumping why they all were used as injection sections in the tracer tests.

In borehole HFM02 and HFM15 tracer was injected during circulation of the section volume. In borehole KFM01A tracer was injected through an “exchange” procedure, i.e. water was also withdrawn from the section during the tracer injection, the same volume as added through the injection. The tracer injections were made as decaying pulse injections, i.e. injection of a tracer pulse in a circulating system without excess pressure. A simple and reasonable assumption is that the amount of tracer that leaves the injection section (and into the transport path) is proportional to the tracer concentration in the injection section. Samples were continuously withdrawn from the injection sections to monitor the tracer injection versus time.

Pumping was performed in HFM01 with a withdrawal rate of 89 l/min and samples were taken and analysed for tracer breakthrough.

The samples were analysed for dye tracer content at the Geosigma Laboratory using a Jasco FP 777 Spectrofluorometer.

4.3 Analyses and interpretations

Tracer dilution tests

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural unlabelled groundwater, cf /2/. The so-called “dilution curves” were plotted as the natural logarithm of concentration versus time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (c/c_0) and time, t (s):

$$\ln (c/c_0) = -(Q_{bh}/V)\cdot\Delta t \qquad (4\text{-}1)$$

where Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V (m^3) is the volume of the borehole section. By plotting ln (c/c_0) versus t, and by knowing the borehole volume V, Q_{bh} may then be obtained from the straight-line slope. If c_0 is constant, it is sufficient to use ln c in the plot.

The sampling procedure with a constant flow of 6–10 ml/h also creates a dilution of tracer. The sampling flow rate is therefore subtracted from the value obtained from equation 4-1.

The flow, Q_{bh}, may be translated into a Darcy velocity by taking into account the distortion of the flow caused by the borehole and the angle between the borehole and flow direction. In practice, a 90° angle between the borehole axis and the flow direction is assumed and the relation between the flow in the rock, the Darcy velocity, v (m/s), and the measured flow through the borehole section, Q_{bh}, can be expressed as:

$$Q_{bh} = v \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha \qquad (4\text{-}2)$$

where L_{bh} is the length of the borehole section (m), r_{bh} is the borehole radius (m) and α is the factor accounting for the distortion of flow caused by the borehole.

Hydraulic gradients are roughly estimated from Darcy´s law where the gradient, I, is calculated as the function of the Darcy velocity, v, with the hydraulic conductivity, K (m/s):

$$I = \frac{v}{K} = \frac{Q_{bh} \cdot L_{bh}}{\alpha \cdot A \cdot T_{bh}} = \frac{Q_{bh} \cdot L_{bh}}{2 \cdot d_{bh} \cdot L_{bh} \cdot T_{bh}} \qquad (4\text{-}3)$$

where T_{bh} (m^2/s) is the transmissivity of the section, obtained from PSS or HTHB measurements, A the cross section area between the packers (m^2) and d_{bh}, (m) the borehole diameter.

The factor α is commonly given the value 2 in the calculations, which is the theoretical value for a homogeneous porous medium. Since the rock mostly is heterogeneous and the angles in the sections not always 90°, the calculation of the hydraulic gradient is a rough estimation.

Tracer test

Tracer mass recovery was calculated for the flow path HFM02:2→HFM01. Before the injection a sample of the stock solution was taken and the tracer concentration of the sample was measured. The injected volume together with the tracer concentration of the stock solution was used to determine the injected mass. The tracer mass recovered in the pumping borehole section was determined by integration of the breakthrough curves for mass flux (mg/h) versus time (h).

No inverse computer modelling of the breakthrough curve regarding transport parameters has been performed since only a small part of the mass from one flow path had arrived at the time the pumping was stopped. However, an example of a relatively simple model fit, based on literature data and some basic assumptions, is shown in Chapter 5.

4.4 Nonconformities

There are no nonconformities with respect to the activity plan or the method descriptions.

5 Results

The results obtained within this activity are

- ground water flow, Darcy velocity and hydraulic gradient in HFM02:2, HFM15:1 and KFM01A:5 during unpumped (natural) conditions,
- ground water flow, Darcy velocity and hydraulic gradient in HFM02:2, HFM15:1 and KFM01A:5 during pumping in HFM01 (stressed conditions),
- tracer breakthrough data in HFM01 from tracer injections in HFM02:2, HFM15:1 and KFM01A:5.

Figure 5-1 shows the groundwater level in the three selected sections HFM02:2, HFM15:1 and KFM01A:5 during the entire test period. Diagrams of the groundwater level in all sections in boreholes HFM02, HMF15 and KFM01A during the tests are presented in Appendix 1. Flow rate and pressure versus time in the pumping borehole HFM01 during the test are also shown in Appendix 1.

The original results are stored in the primary data base SICADA. These data are available for further interpretation and are traceable by the activity plan number (AP PF 400-05-037).

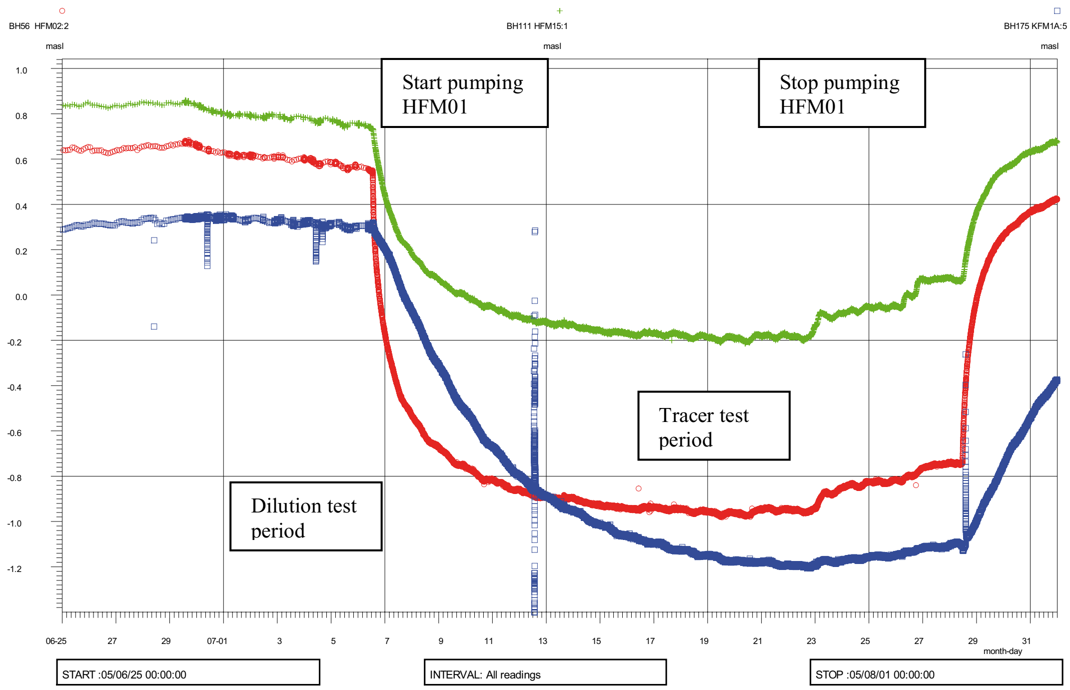

Figure 5-1. *Groundwater level (m.a.s.l.) in HFM02:2 (red), HFM15:1 (green) and KFM01A:5 (blue), 2005-06-25–2005-07-31.*

5.1 Ground water flow measurements

The results from the groundwater flow measurements are presented in Table 5-1 (natural, i.e. undisturbed conditions) and Table 5-2 (stressed conditions during pumping in HFM01). The tables contain measured groundwater flow rates, Darcy velocities and hydraulic gradients together with transmissivities and volumes used.

All three sections showed good flow responses from the pumping why they all were decided to be used as injection sections in the subsequent tracer tests.

A comparison of the groundwater flow rates determined prior to and during pumping shows a clear increase of the flow rate in HFM15 and KFM01A. However, in HFM02, the opposite situation yields. This indicates that flow direction is reversed or partly reversed due to pumping. Thus, the natural flow is most probably directed westwards compared to eastwards during pumping.

Table 5-1. Results from tracer dilution tests, natural conditions.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Volume (l)	Qnatural (ml/h)	Darcy velocity (m/s)	Hydraulic gradient
HFM02:2	38–48	5.9 E–4*	23.08	3,870	3.93E–07	0.0067
HFM15:1	85–95	1.0 E–4*	29.80	46	4.60E–09	0.0005
KFM01A:5	109–130	1.0 E–7**	18.12	7	6.07E–10	0.1274

* From HTHB measurements, transient evaluation /3/ and /4/.
** From PSS measurements, transient evaluation /5/.

Table 5-2. Results from tracer dilution tests, stressed conditions with pumping in HFM01.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Volume (l)	Qstressed (ml/h)	Darcy velocity (m/s)	Hydraulic gradient
HFM02:2	38–48	5.9 E–4*	23.08	350	3.55E–08	0.0006
HFM15:1	85–95	1.0 E–4*	29.80	122	1.22E–08	0.0012
KFM01A:5	109–130	1.0 E–7**	18.12	30	2.60E–09	0.5461

* From HTHB measurements, transient evaluation /3/ and /4/.
** From PSS measurements, transient evaluation /5/.

5.2 Tracer tests

Tracer injections were performed in borehole sections HFM02:2, HFM15:1 and KFM01A:5. Tracer injection data are presented in Table 5-3 together with the distance and head difference between the respective injection section and pumping borehole HFM01.

HFM01 was pumped with a withdrawal rate of 89 l/min and the water was continuously sampled for tracer breakthrough.

Tracer breakthrough in HFM01 was detected from the injection of Amino G acid in HFM02:2, see Figure 5-2. No tracer breakthrough could be noticed from the injections in HFM15:1 (Rhodamine WT) and KFM01A:5 (Uranine).

Tracer mass recovery for Amino G acid was 3.4% when sampling was stopped 380 hours after the injection.

Since only the first rising part of the breakthrough curve was measured, it is very difficult to fit a theoretical model to the data in an unambiguous way. However, by using field scale data from tests in similar scales and rock types, e.g. tests performed in fracture zones at Finnsjön, located about 20 km from Forsmark, it is possible to at least give an example of one possible solution for the transport between HFM02 and HFM01.

Earlier performed tracer tests in fracture zones in Swedish crystalline bedrock, e.g. /6/, /7/ and /8/, have given dispersivities in the order of 1–10% of the travel distance. In Figure 5-3 an example of a breakthrough curve using a theoretical model with a classical one-dimensional advection-dispersion equation /9/ is shown. The model is fitted to the data by eye using a dispersivity (longitudinal) of 20 m (i.e. 9% of the travel distance 222 m). The theoretical curve also assumes 100% tracer recovery and homogeneous flow conditions.

Based on this example, a mean travel time of around 500–1,000 hours would be the result. Using this mean travel time and the earlier determined value of the transmissivity in the fracture zone of T=1 E–4 m^2/s /1/, a rough estimate of the flow porosity can be made as described e.g. in /6/. The approximate value of flow porosity determined, 0.1, is high for fractured rock but may very well reflect the very porous structure of the zone indicated from the drilling and mapping of the zone. A similar tracer test performed at Finnsjön /6/ in a fracture zone having the same transmissivity (T=1 E–4 m^2/s) over a 440 m distance yielded a flow porosity of about 0.01, i.e. 10 times lower.

Table 5-3. Tracer injection data (measured values).

Borehole sec	Section interval (m)	Volume (l)	Distance from HFM01 (m)	Head difference (m)	Tracer	Max inj. conc. (mg/l)	Inj. mass (g)
HFM02:2	38–48	23.08	222	24.2	Amino-G acid	340	135
HFM15:1	85–95	29.80	325	25.0	RhodamineWT	4,150	180
KFM01A:5	109–130	18.12	144	24.0	Uranine	3,200	91

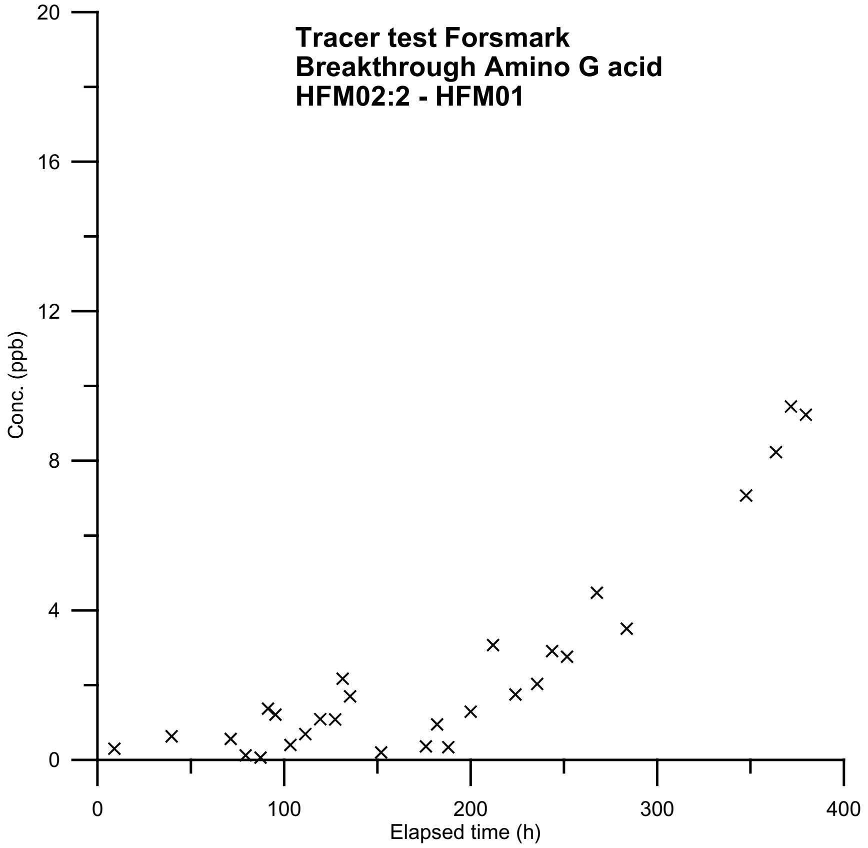

Figure 5-2. *Tracer breakthrough in HFM01 from injection in HFM02:2 (Amino G acid).*

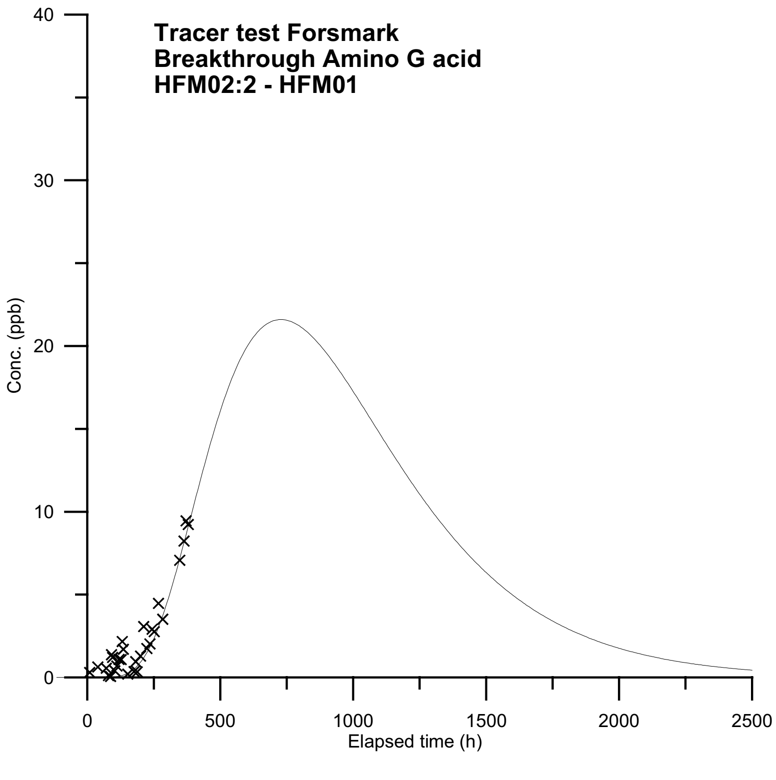

Figure 5-3*. Example of a theoretical model fit to experimental data for the tracer breakthrough in HFM01 from injection in HFM02:2.*

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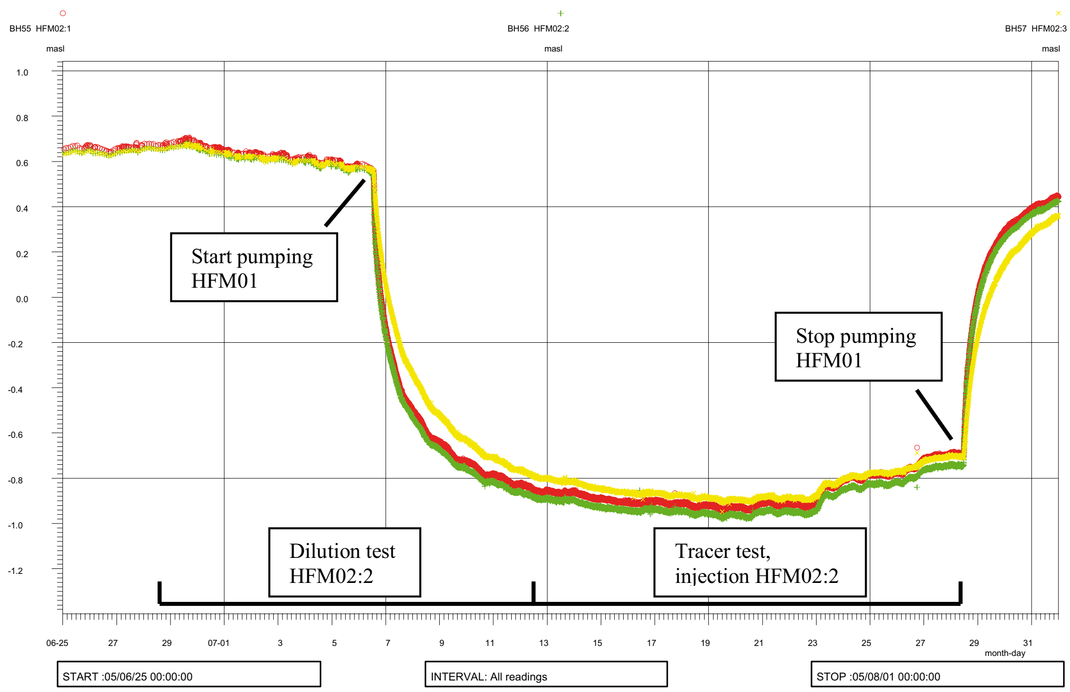
Groundwater level (m.a.s.l.) in HFM02, HFM15 and KFM01A

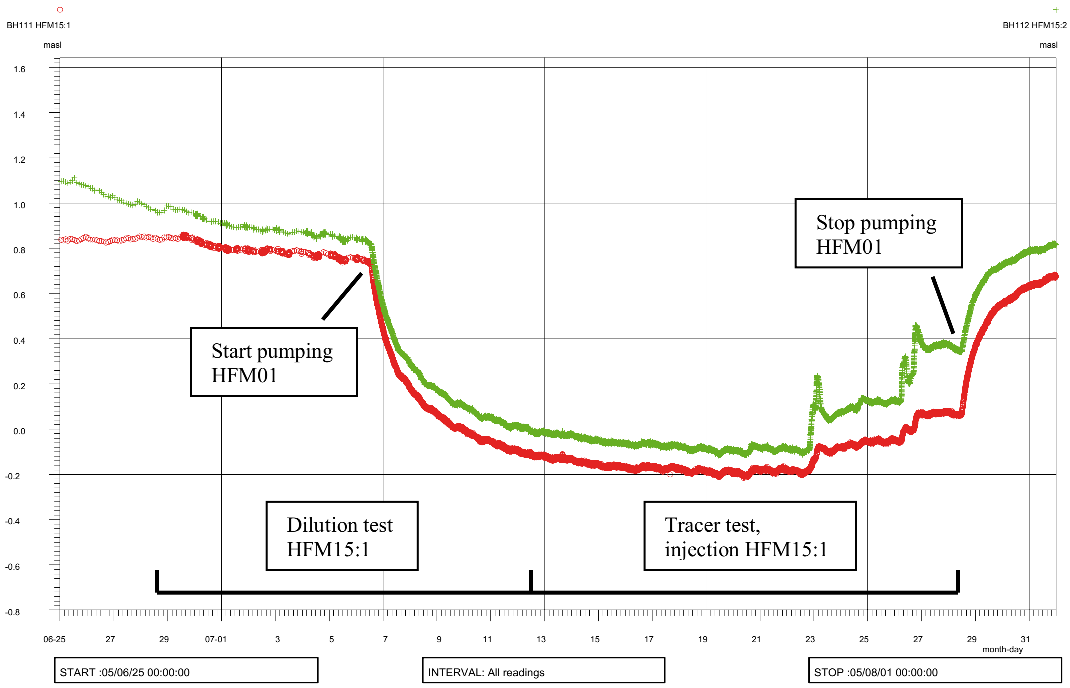
2005-06-25–2005-07-31

HFM02



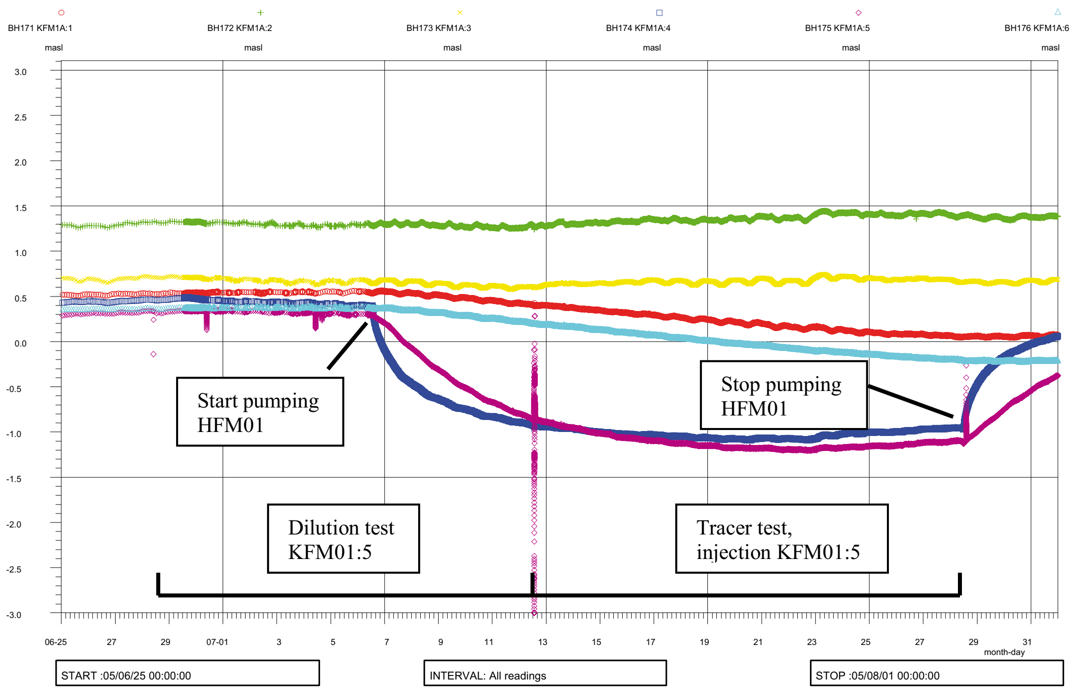
Measured section: HFM02:2 (green)

HFM15



Measured section: HFM15:1 (red)

KFM01A



Measured section: KFM01:5 (dark red)

Flow rate and pressure versus time in the pumping borehole HFM01 during the test

HFM01