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Forsmark site investigation

Groundwater flow measurements in conjunction with the interference test with pumping in HFM14

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September 2006

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Keywords: Groundwater flow, Dilution test, Tracer test, Natural gradient, Stressed gradient, AP PF 400-06-052.

Abstract

This report describes the performance and evaluation of groundwater flow measurements in ten borehole sections in permanently installed boreholes within the Forsmark site investigation area. The objective was to determine the groundwater flow in these ten sections during both natural conditions and during pumping in HFM14.

The reason to carry out groundwater flow measurements in conjunction with the interference test was to further increase the understanding of the hydraulic connections in the area, and to investigate the possibilities to perform a large-scale, multiple hole, tracer test in the area.

The groundwater flow in the selected borehole sections was determined through tracer dilution measurements during natural conditions as well as during the pumping in borehole HFM14. Measured flow rates ranged from 0.3 to 17 ml/min during natural conditions and from 0.2 to 220 ml/min during pumped conditions.

The pumping in HFM14 caused distinct flow responses in some of the tested sections, whereas other sections hardly responded at all. The sections HFM32:3, HFM15:1 and HFM19:1 displayed the largest flow increase compared with natural conditions. In sections HFM02:2, KFM06A:5, KFM05A:4 and KFM02A:5 however, no significant flow responses were identified.

The results indicate possibilities for conducting a multiple hole tracer test using some of the tested sections. Suitable sections seem to be HFM15:1 and HFM19:1. It is somewhat uncertain whether also HFM32:3 and HFM13:1 are suitable. HFM32:3 is as far as 512 m away from the pumping hole HFM14. It might though be possible to use these two sections as well, especially if a tracer with low background concentration in the Forsmark area is used.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i tio borrhålssektioner i permanent installerade borrhål i Forsmarks platsundersökningsområde. Syftet var att bestämma grundvattenflödet i dessa tio sektioner dels under naturliga förhållanden, dels under tiden som pumpning pågick i HFM14.

Syftet med att genomföra grundvattenflödesmätningar i samband med interferenstestet var att bidra till förståelsen av de hydrauliska sambanden i området samt att utreda möjligheterna att senare genomföra ett storskaligt flerhålsspårförsök.

Grundvattenflödet mättes med utspädningsmetoden under såväl naturliga förhållanden som under pumpade förhållanden. De uppmätta grundvattenflödena låg i intervallet 0,3–17 ml/min under naturliga förhållanden och mellan 0,2 och 220 ml/min vid pumpning. Pumpningen medförde tydliga flödesresponser i några av sektionerna, medan vissa andra inte uppvisade någon signifikant respons. Speciellt mycket ökade flödet i HFM32:3, HFM15:1 och HFM19:1 jämfört med naturliga förhållanden. I borrhålssektionerna HFM02:2, KFM06A:5, KFM05A:4 och KFM02A:5 kunde däremot ingen signifikant respons identifieras.

Resultaten visar att det finns möjligheter att genomföra ett flerhålsspåförsök där några av sektionerna används. Lämpliga sektioner förefaller vara HFM15:1 och HFM19:1. Det är mer tveksamt om HFM32:3 och HFM13:1 kan användas. HFM32:3 ligger hela 512 m från pumphålet HFM14. Det skulle dock kunna vara möjligt att använda även dessa två sektioner i ett spårförsök, speciellt om ett spårämne som har låg bakgrundskoncentration i Forsmarksområdet används.

Contents

1 Introduction

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, before and in conjunction with the interference test presented in /1/, which was carried out within the Forsmark site investigation during the summer 2006. The work involved groundwater flow measurements in ten borehole sections at the Forsmark site. The measurements were made using tracer dilution technique and the measurements were conducted both during undisturbed conditions (natural gradient) and during the pumping in HFM14 (stressed gradient). The work was carried out in accordance with activity plan AP PF 400-06-052 and the field work was conducted during June and July 2006. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

Maps of the site investigation area at Forsmark including boreholes and drill sites are presented in Figures 1-1 and 1-2.

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 i samband med interferenstest med pumpning i HFM14	AP PF 400-06-052	1.0
Method description	**Number**	**Version**
System för hydrologisk och metrologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål	SKB MD 368.010	1.0

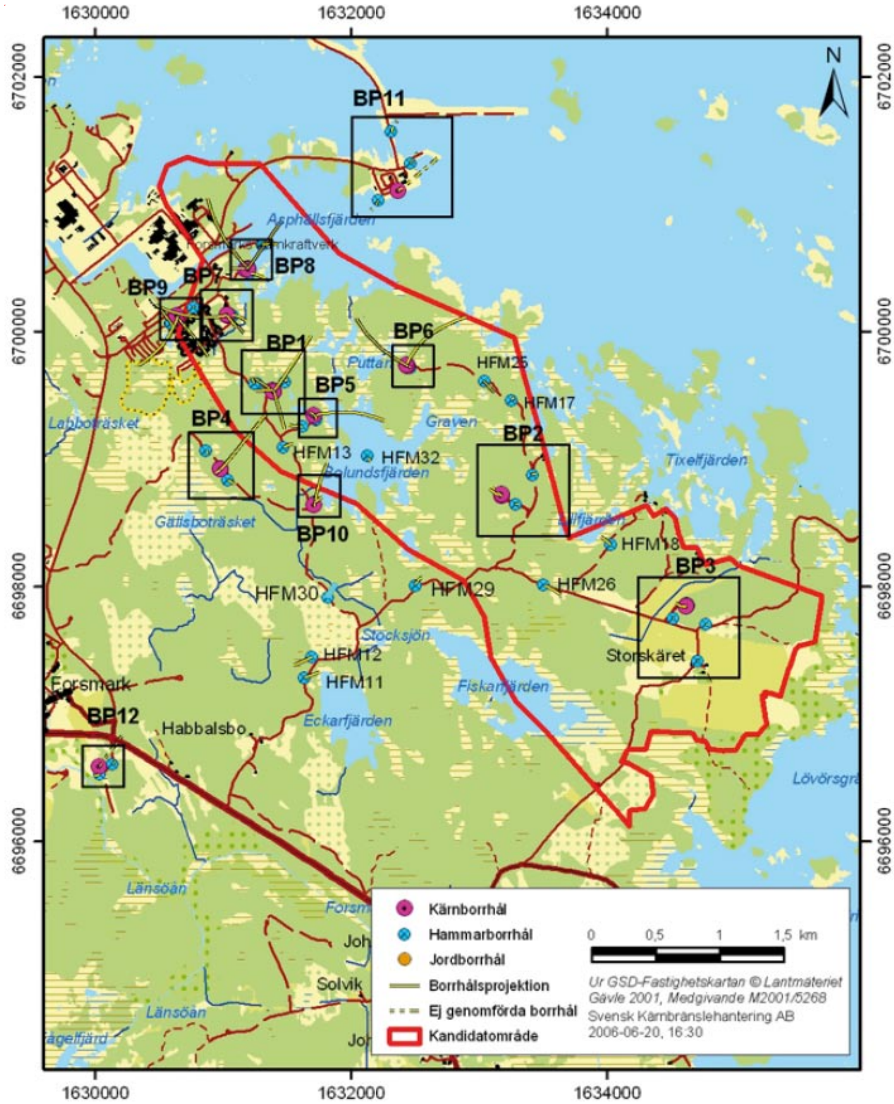

Figure 1-1. Overview of Forsmark site investigation area, showing borehole locations and drill sites.

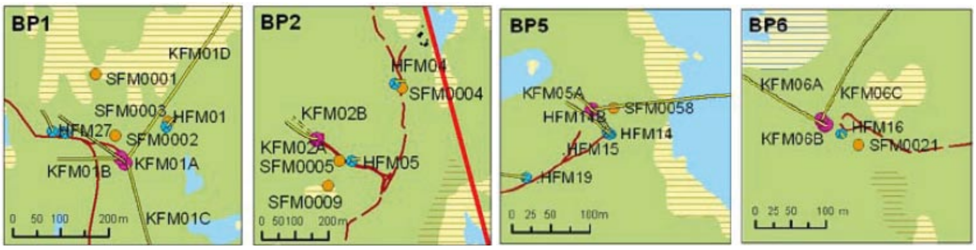

Figure 1-2. Detailed maps of drill sites 1, 2, 5 and 6, showing drill sites and borehole locations where investigations included in this report have been performed.

2 Objective and scope

The objective of this activity was to determine the groundwater flow in sections of permanently installed boreholes at Forsmark, during natural conditions and during pumping in another borehole in the area (HFM14). Ten borehole sections instrumented for this purpose (circulation sections) were to be measured, cf Table 4-1. The analysis and interpretation of the pressure responses are presented in /1/.

The groundwater flow rates in the selected borehole sections were determined through tracer dilution measurements.

The groundwater flow measurements in conjunction with the interference test were made to further increase the understanding of the hydraulic connections in the area, and to investigate the possibilities to perform a large-scale, multiple hole, tracer test.

3 Equipment

3.1 Description of equipment and tracers used

The boreholes involved in the tests are instrumented with 1–7 inflatable packers isolating 2–8 borehole sections each. In Figure 3-1 drawings of the instrumentation in 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 were performed using eight identical equipment set-ups, i.e. allowing eight sections to be measured simultaneously. As this investigation involved measurements in ten sections, two of the set-ups had to be alternately used in four of the sections. 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.

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 performed 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 are described in detail in SKB MD 368.010, SKB internal document, see Table 1-1.

The tracer used was a fluorescent dye tracer, Uranine (Sodium Fluorescein), from Merck (purum quality).

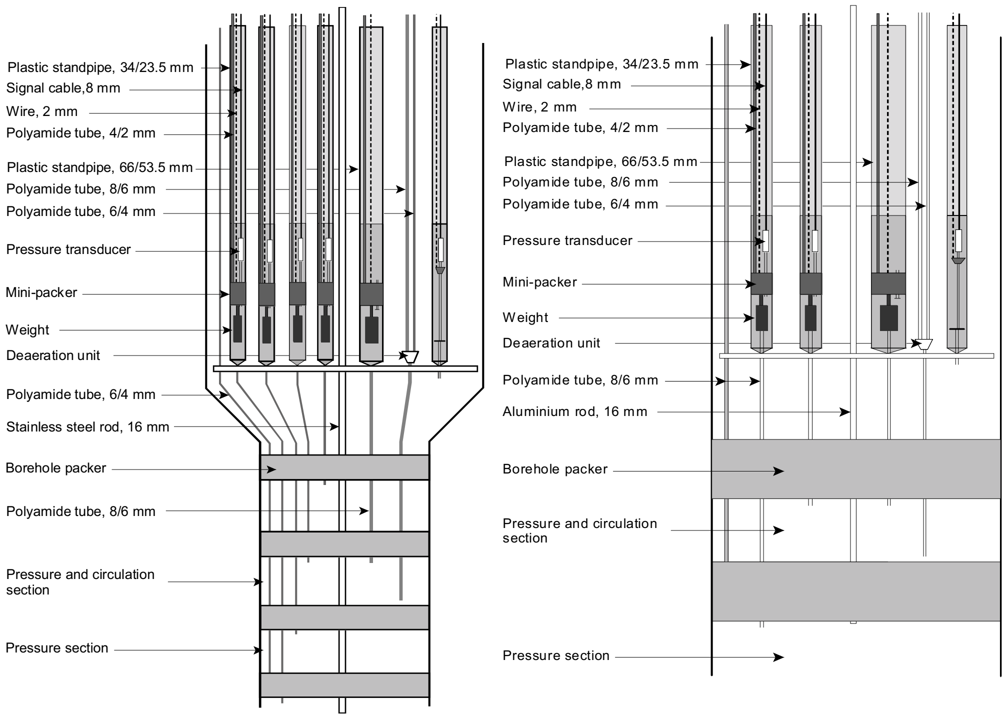

Figure 3-1. Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.

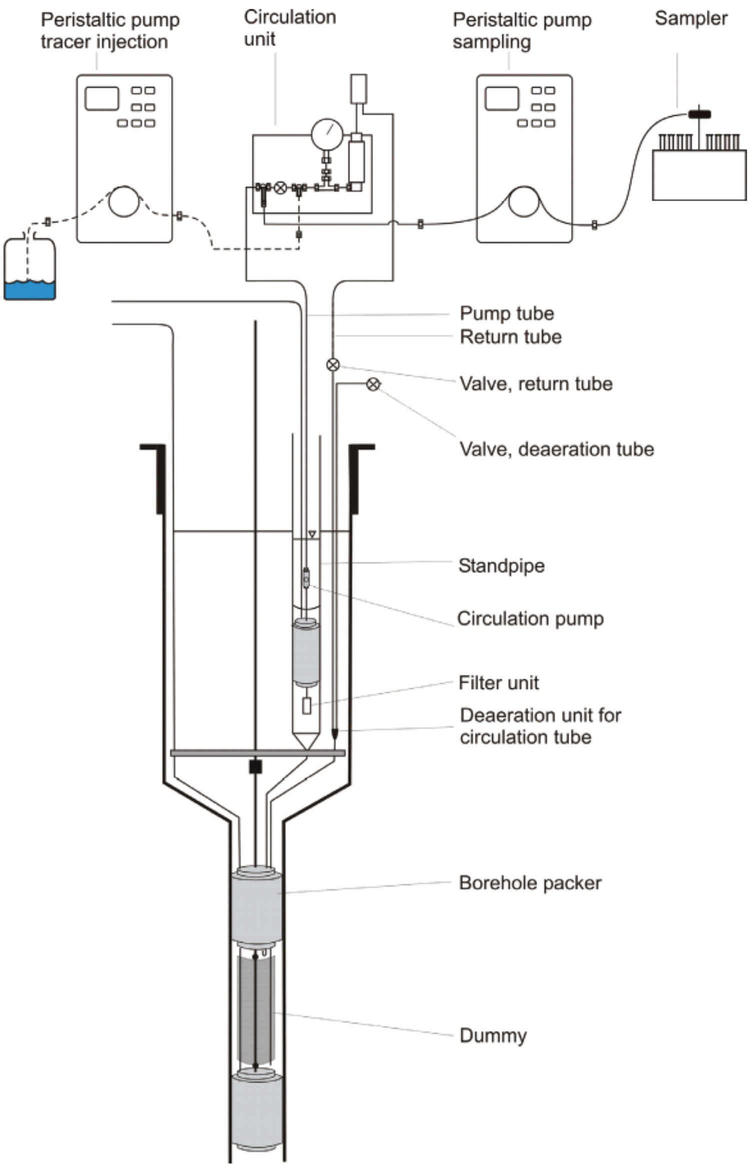

Figure 3-2. *Schematic drawing of the equipment used in tracer dilution measurements.*

4 Execution

4.1 General

In the dilution method a tracer is introduced and homogeneously distributed into a borehole test section. The tracer is subsequently diluted by the ambient groundwater, flowing through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section and the groundwater flow is calculated as a function of the decreasing tracer concentration with time, Figure 4-1.

The method description used was "System för hydrologisk och metrologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål." (SKB MD 368.010, SKB internal document), cf Table 1-1.

4.2 Preparations

The preparations included mixing of the tracer stock solution, functionality checks of the equipment and calibration of the peristaltic pumps used for sampling and tracer injections.

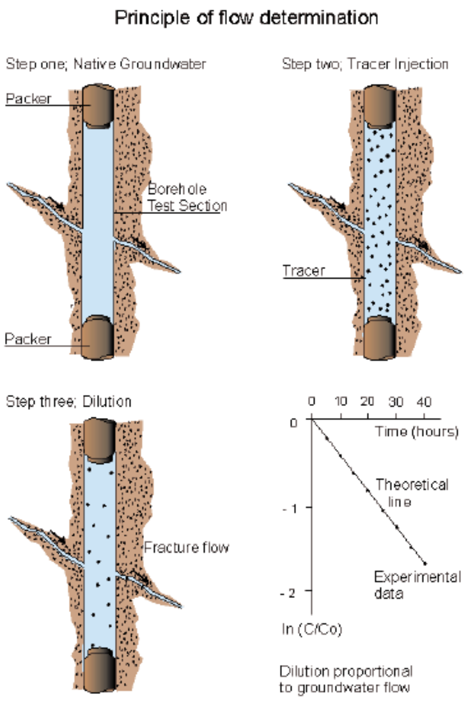

Figure 4-1. General principles of dilution and flow determination.

4.3 Execution of field work

The test campaign involved 10 different borehole sections listed in Table 4-1. The duration of each test during the period with natural gradient varied from 75 to 165 hours, and the corresponding time during the period with stressed gradient were from 68 to 170 hours.

The pumping in HFM14 started at 10:06 on July 4 and the flow rate was kept at c 350 l/h after an initial period of regulation to obtain a suitable flow rate. The pumping is further described in detail in a separate report regarding the interference test /1/.

The tests were made by injecting a slug of tracer (Uranine, 500 mg/l) in the selected borehole sections and allowing the natural groundwater flow to dilute the tracer. The tracer was injected during a time period equivalent to the time it takes to circulate one section volume. The injection/circulation flow ratio was set to 1/1,000, implying that the start concentration in the borehole section would be about 0.5 mg/l. The tracer solution was continuously circulated and sampled using the equipment described in Section 3.1.

In some of the borehole sections two or more tracer injections had to be made in order to obtain a concentration of tracer above the measurement limit for the analysis. Also, in some of the borehole sections the dilution was fast, and in order to be able to measure the dilution during a sufficient time period the initial tracer concentration had to be increased in these sections. This was made by increasing the injection/circulation ratio and in one case also by increasing the duration of the tracer injection period. The details of the tracer injections in the different borehole sections are presented in Table 4-2.

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

Table 4-1. Borehole sections used for groundwater flow measurements in conjunction with interference test, summer 2006.

Borehole: section	Depth (m)	Transmissivity (m^2/s)	Geologic character***	Distance from pumping hole HFM14 (m)	Test period (yymmdd)
KFM02A:3	490–518	2.1 E–6*	Zone A2	1,620	060630–060707
KFM02A:5	411–442	2.5 E–6*	Zone A2	1,600	060627–060630 060707–060711
KFM05A:4	254–272	1.4 E–8*	Single fracture	240	060627–060710
KFM06A:3	738–748	1.2 E–7*	Single flow anomaly, Zone NE061	940	060630–060707
KFM06A:5	341–362	3.5 E–6*	2 flowing fractures, Zone NE060	790	060626–060630 060707–060711
HFM02:2	38–48	5.9 E–4**	Zone	536	060629–060710
HFM13:1	159–173	2.9 E–4**	Zone A2	297	060628–060711
HFM15:1	85–95	1.0 E–4**	Zone	72	060627–060710
HFM19:1	168–182	2.7 E–4**	Zone A2	247	060628–060710
HFM32:3	26–31	2.3 E–4**	Zone	512	060626–060707

* From PSS measurements, transient evaluation, /2, 3/ and /4/.
** From HTHB measurements, transient evaluation, /5, 6, 7/ and /8/.
*** Deformation zones according to Forsmark 2.1 site descriptive model /9/.

Table 4-2. Tracer injections made in the borehole sections used for groundwater flow measurements in conjunction with interference test, summer 2006.

Borehole: section	Injection no	Injection/ circulation ratio	No of section volumes circulated during tracer injection
KFM02A:3	1	1/1,000	1
KFM02A:5	1	1/1,000	1
KFM05A:4	1	1/1,000	1
KFM06A:3	1	1/1,000	1
KFM06A:5	1	1/1,000	1
HFM02:2	1	1/75	1
	2	1/92	1
	3	1/46	1
	4	1/44	2
HFM13:1	1	1/1,000	1
	2	1/1,000	1
	3	1/500	1
HFM15:1	1	1/1,000	1
HFM19:1	1	1/1,000	1
	2	1/1,000	1
	3	1/110	1
HFM32:3	1	1/1,000	1

4.4 Analyses and interpretations

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural unlabelled groundwater, cf /10/. 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 5–7 ml/h also creates a dilution of tracer. The sampling flow rate is therefore subtracted from the value obtained from equation 4-1.

4.5 Nonconformities

There are no nonconformities with respect to the activity plan (AP PF 400-06-052) or the method description.

5 Results

5.1 Groundwater flow measurements

A summary of the results obtained is presented in Table 5-1 including measured groundwater flow rates, together with transmissivities and volumes for the sections.

In Figure 5-1 an example of a typical tracer dilution curve is shown, in this case borehole section HFM32:3. The flow rate is calculated from the slope of the straight-line fit. Tracer dilution graphs for each borehole section are presented in Appendix 1. In Appendix 2 the groundwater level during the entire test period is shown for the selected boreholes, see also Table 4-1 for actual measurement period for each section.

In general, the equipment worked well during the field campaign. However, some minor malfunctions caused a period of missing data for the sections HFM13:1 and HFM32:3 (see Figure A1-2 and A1-5). This has not affected the possibility to evaluate the data.

The results show that the groundwater flow during natural conditions varies from 0.3 to 17 ml/min and during pumped conditions from 0.2 to 220 ml/min. There are sections displaying both higher and lower flow rates after the pumping starts (Table 5-1).

The groundwater levels in the measured sections (and many others) showed that there were no major hydraulic disturbances during the measurement period. The pump in HFM14 was tested the day before the pumping started (2006-07-03), and this is visible as a pressure decrease in some sections (see Appendix 2). However, this has not caused any disturbance on the groundwater flow measurements.

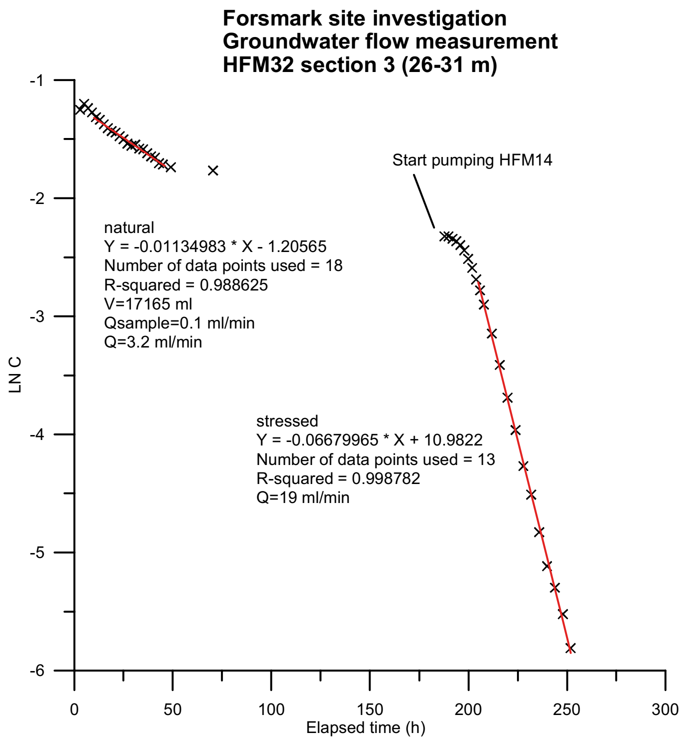

Figure 5-1. *Example of a tracer dilution graph (Logarithm of concentration versus time) for borehole HFM32 Chapter 3, including straight-line fits during both natural and pumped conditions.*

Table 5-1. Results from groundwater flow measurements in conjunction with hydraulic interference test, summer 2006.

Borehole: section	Borehole length (m)	Transmissivity (m^2/s)	Volume (l)	Measured flow (ml/min) Natural gradient	Measured flow (ml/min) Stressed gradient	Significant response from pumping (Yes/No)
KFM02A:3	490–518	2.1 E–6*	44.63	1.3	0.7	Yes
KFM02A:5	411–442	2.5 E–6*	41.57	0.3	0.3	No
KFM05A:4	254–272	1.4 E–8*	27.18	1.0	0.7	No
KFM06A:3	738–748	1.2 E–7*	50.48	0.7	0.2	Yes
KFM06A:5	341–362	3.5 E–6*	33.62	0.3	0.3	No
HFM02:2	38–48	5.9 E–4**	23.08	17	17	No
HFM13:1	159–173	2.9 E–4**	31.13	6.5	11	Yes
HFM15:1	85–95	1.0 E–4**	29.80	1.2	64	Yes
HFM19:1	168–182	2.7 E–4**	36.51	5.1	220	Yes
HFM32:3	26–31	2.3 E–4**	15.38	3.2	19	Yes

* From PSS measurements, transient evaluation, /2, 3/ and /4/.
** From HTHB measurements, transient evaluation, /5, 6, 7/ and /8/.

Some sections showed pressure responses although no significant flow responses could be measured (KFM02A:5, KFM06A:5 and HFM02:2). Also, some sections displaying significant flow responses show no or very small pressure responses (HFM32:3, KFM06A:3).

All borehole sections except HFM32:3 were previously measured with the same technique during a campaign in November and December 2005 /11/, see Table 5-2 for comparison.

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 400-06-052).

Table 5-2. Results from groundwater flow measurements in June–July 2006 compared with results from measurements in Nov–Dec 2005 (natural gradient).

Borehole: section	Borehole length (m)	Transmissivity (m^2/s)	Volume (l)	Measured flow (ml/min) Natural gradient Nov–Dec 2005 /11/	Measured flow (ml/min) Natural gradient June–July 2006
KFM02A:3	490–518	2.1 E–6*	44.63	1.4	1.3
KFM02A:5	411–442	2.5 E–6*	41.57	0.6	0.3
KFM05A:4	254–272	1.4 E–8*	27.18	0.3	1.0
KFM06A:3	738–748	1.2 E–7*	50.48	0.3	0.7
KFM06A:5	341–362	3.5 E–6*	33.62	0.3	0.3
HFM02:2	38–48	5.9 E–4**	23.08	30	17
HFM13:1	159–173	2.9 E–4**	31.13	18	6.5
HFM15:1	85–95	1.0 E–4**	29.80	0.6	1.2
HFM19:1	168–182	2.7 E–4**	36.51	7.8	5.1
HFM32:3	26–31	2.3 E–4**	15.38	–***	3.2

* From PSS measurements, transient evaluation, /2, 3/ and /4/.
** From HTHB measurements, transient evaluation, /5, 6, 7/ and /8/.
*** Not measured.

5.2 Prerequisites for a multiple hole tracer test

To perform a tracer test the flow rate through the injection section has to be large enough (otherwise the transport time becomes too long). Also, there has to be a clear response from the pumping, indicating that the water is moving towards the pumping well. These two conditions leave 4 possible sections for further investigation; HFM13:1, HFM15:1, HFM19:1 and HFM32:3.

To be able to detect the breakthrough of the tracer in the pumping well the tracer concentration must be significantly higher than the background concentration of tracer in the area. The background concentration of Uranine in the Forsmark area is c 1–10 ppb.

Comparing the flow rate in the pumping well with the groundwater flow in the injection sections during pumping gives an indication of how large the dilution of tracer is, assuming that all water flowing through the injection section reaches the pumping hole. In reality this is not true, since it is likely that there are other sinks as well. Dispersion has also to be considered and the dispersion depends on the distance between the wells and the properties of the bedrock.

A rough estimation of which tracer concentration that can be expected in the pumping well is presented in Table 5-3. The calculation is made with the following assumptions:

- All water flowing through the injection well reaches the pumping well, i.e. there are no other sinks.
- The dispersion dilutes the tracer by a factor 10.
- The distance between the pumping well and the injection section is not considered.
- The initial concentration of tracer in the injection section is 10,000 ppm.
- The withdrawal rate in the pumping well is 350 L/min.

The calculation example indicates that HFM15:1 and HFM19:1 are suitable for a tracer test. It is more uncertain whether HFM32:3 and HFM13:1 can be used. The expected concentration of tracer in HFM13:1 and HFM32:3 is certainly above the assumed background (10 ppb), but the calculations are very rough and assume ideal conditions. For instance it is not likely that 100% of the water flowing through the section reaches the pumping well. Hence, to be sure to be able to detect the tracer in the pumping well, it is desirable that the expected concentration calculated by this very rough estimation is well above the background concentration (1–10 ppb).

This calculation also assumes equally large dispersion independent of the distance to the pumping well. Since the distance (512 m) to HFM32:3 is rather long, it is likely that the dispersion (and hence the dilution of tracer) is larger along that flow path than for the other three borehole sections.

Table 5-3. Roughly expected (under the assumptions presented above) concentration of tracer in pumping well HFM14 for sections with sufficient high flow rates and significant responses from the pumping.

Borehole: section	Borehole length (m)	Distance from HFM14 (m)	Section volume (l)	Measured flow stressed gradient (ml/min)	Dilution factor including dispersion (–)	Expected concentration in pumping well HFM14 (ppb)
HFM13:1	159–173	297	31.13	11	3.14E–05	31
HFM15:1	85–95	72	29.80	64	1.83E–04	183
HFM19:1	168–182	247	36.51	220	6.29E–04	629
HFM32:3	26–31	512	15.38	19	5.43E–05	54

The sections HFM15:1 and HFM19:1 seem to be suitable for a tracer test. It is also possible that HFM13:1 can be used. The long distance between the pumping well HFM14 and HFM32:3 implies that this is not a suitable section to include in the tracer test although it responds clearly to the pumping. If a tracer with lower background concentration (< 1 ppb) than Uranine is used, all the four sections HFM15:1, HFM19:1, HFM13:1 and HFM32:3 may be possible as injection sections in a tracer test.

6 References

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Tracer dilution graphs

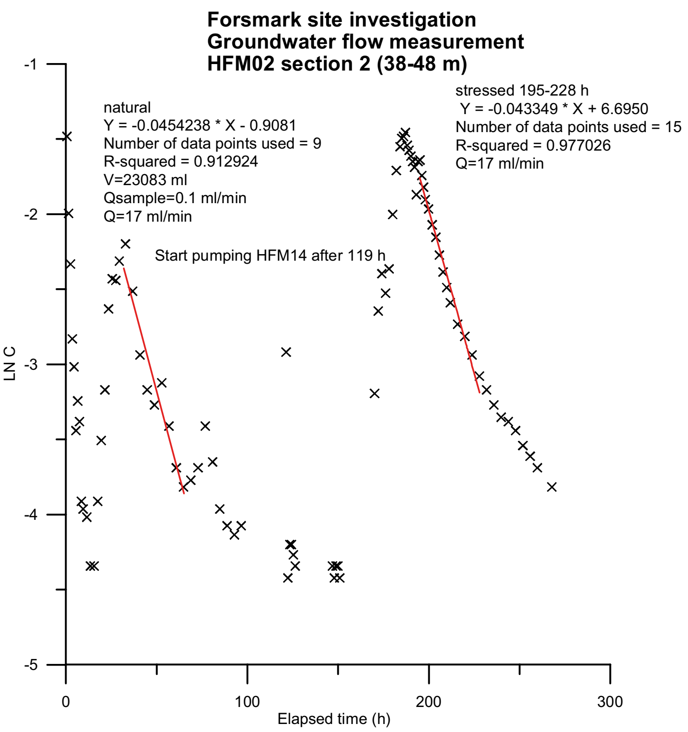

Figure A1-1. *Tracer dilution graph for section HFM02:2.*

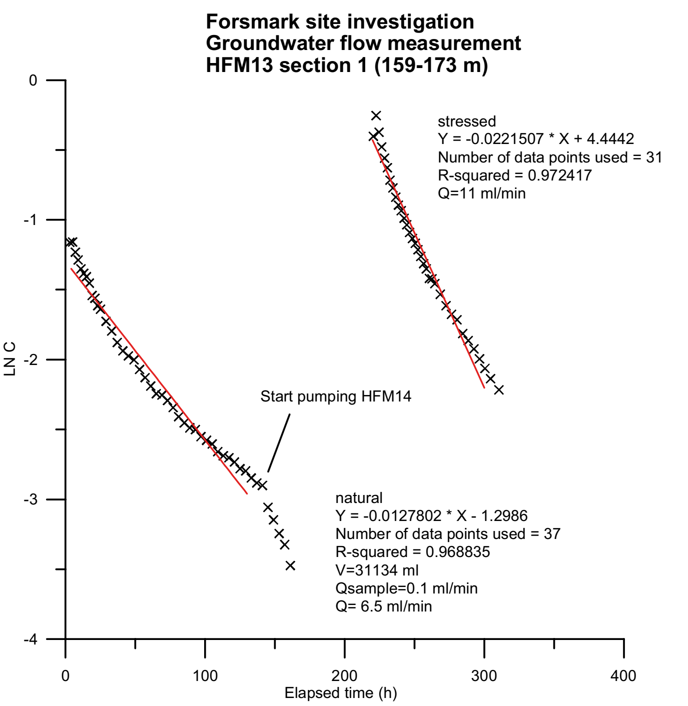

Figure A1-2. *Tracer dilution graph for section HFM13:1.*

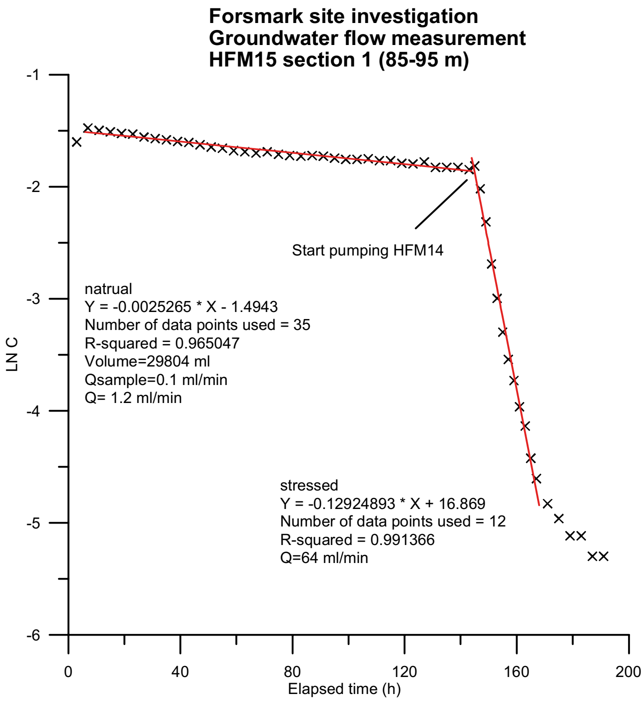

Figure A1-3. *Tracer dilution graph for section HFM15:1.*

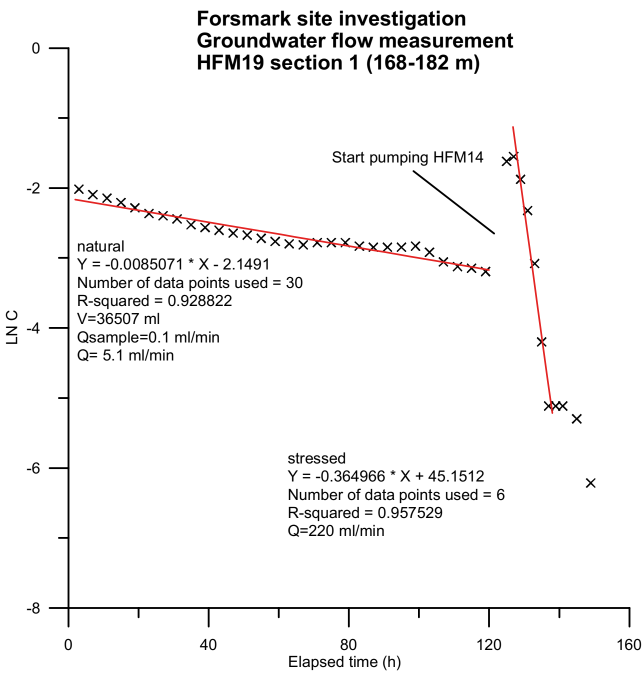

Figure A1-4. *Tracer dilution graph for section HFM19:1.*

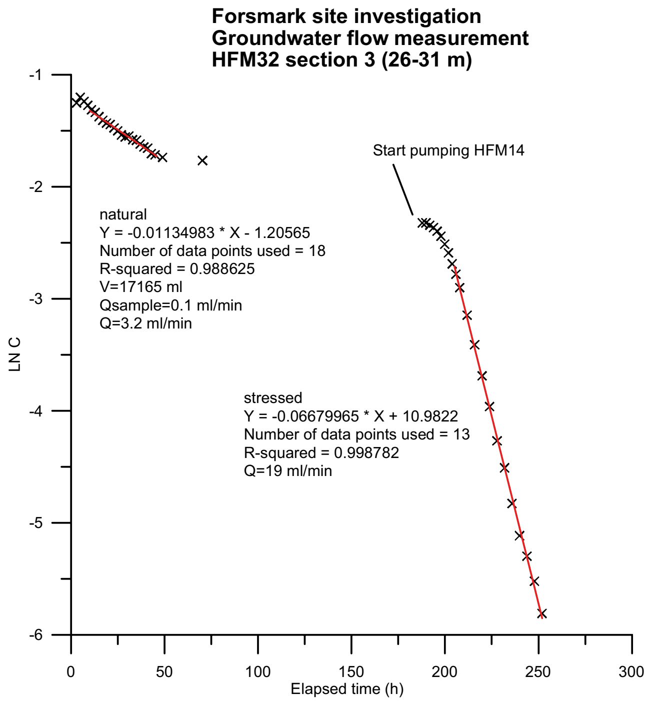

Figure A1-5. *Tracer dilution graph for section HFM32:3.*

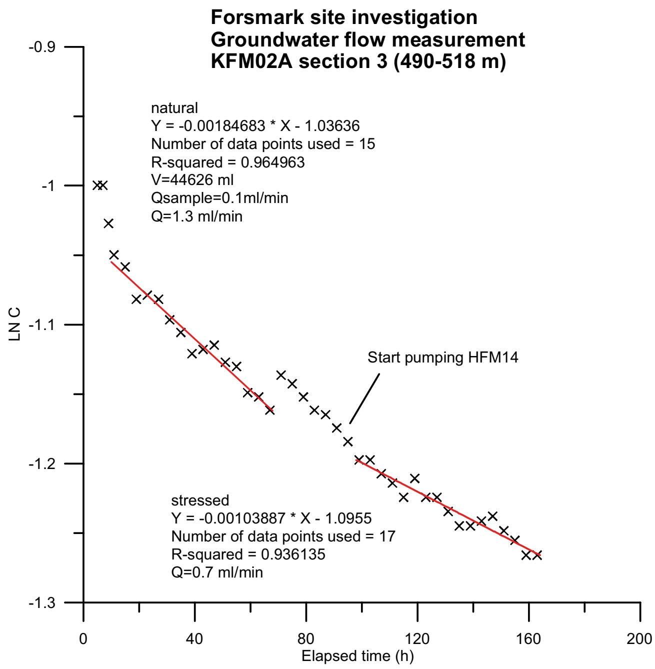

Figure A1-6. *Tracer dilution graph for section KFM02A:3.*

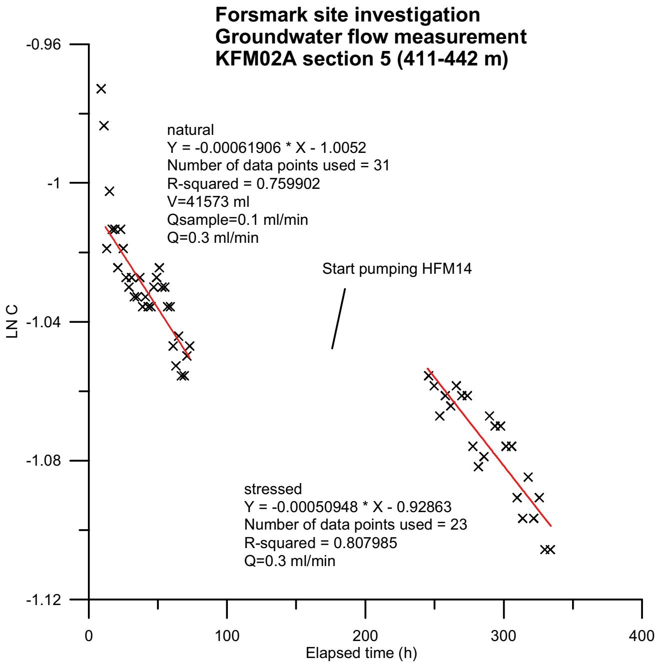

Figure A1-7. *Tracer dilution graph for section KFM02A:5.*

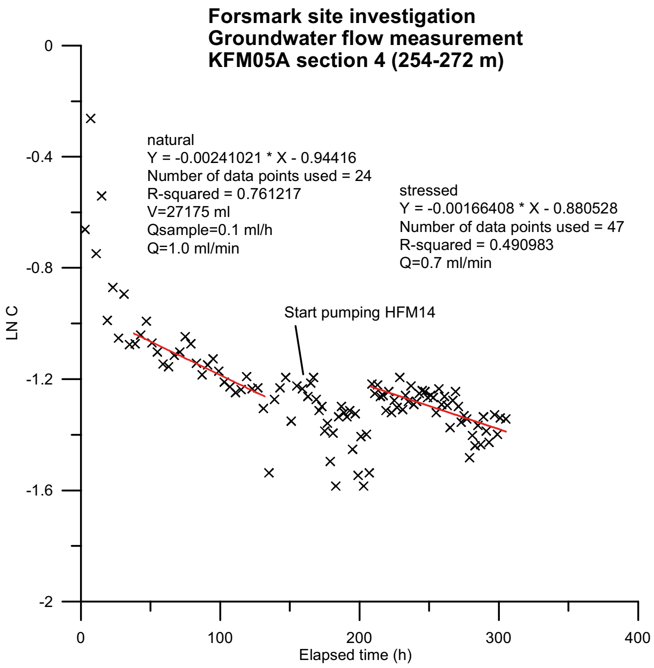

Figure A1-8. *Tracer dilution graph for section KFM05A:4.*

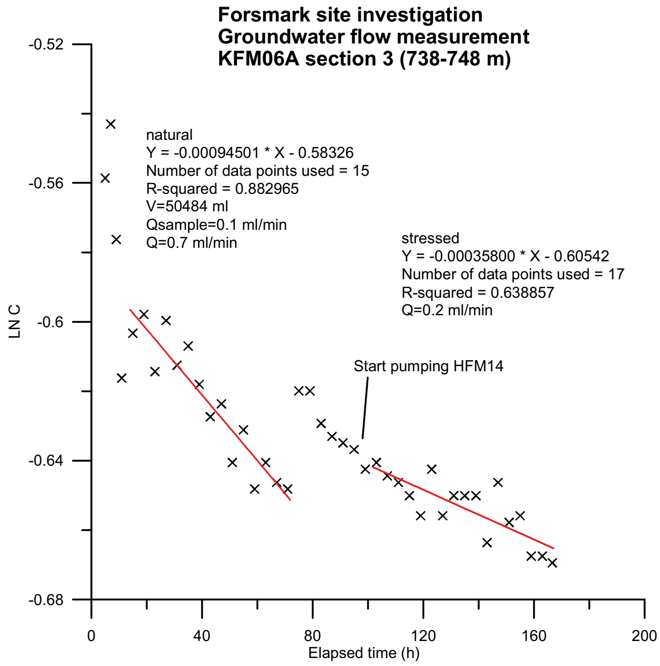

Figure A1-9. *Tracer dilution graph for section KFM06A:3.*

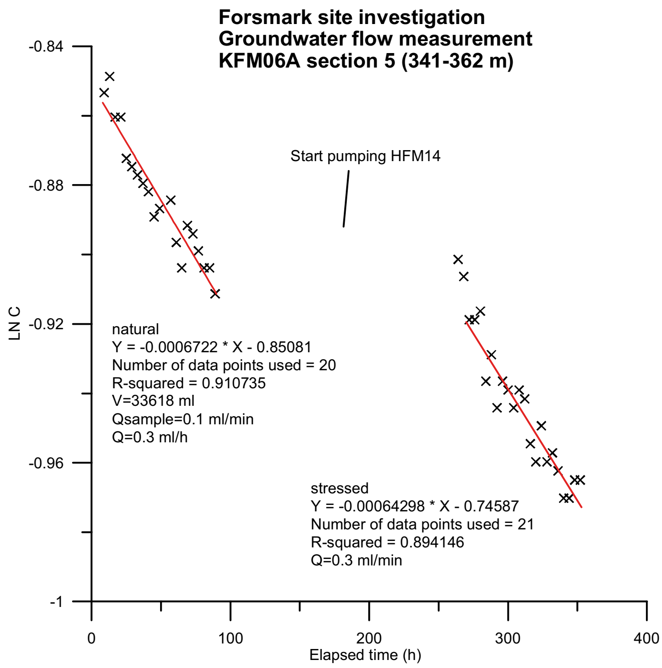

Figure A1-10. *Tracer dilution graph for section KFM06A:5.*

Appendix 2

Groundwater levels (m.a.s.l.)

2006-06-24–2006-07-13.

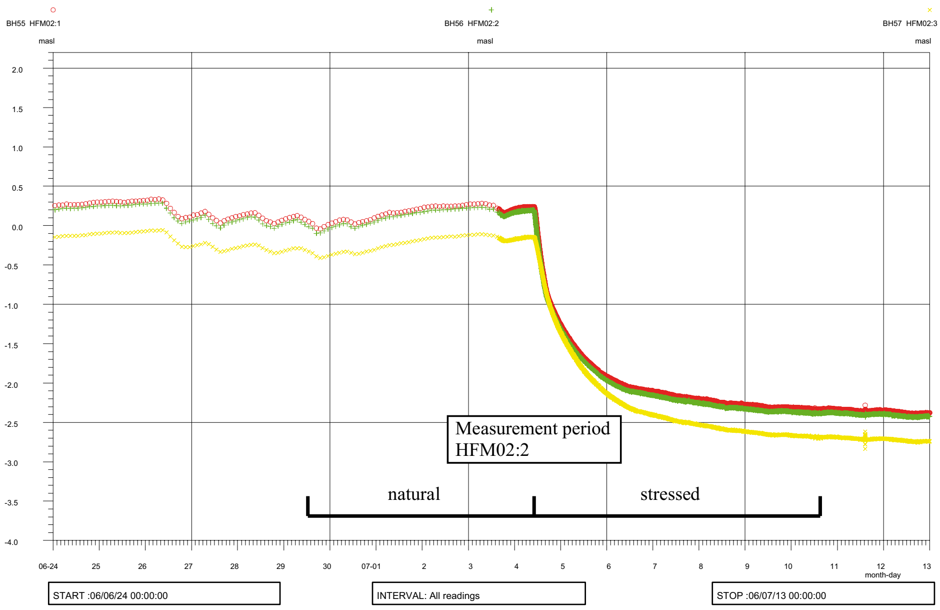

Figure A2-1. *Groundwater levels in borehole HFM02. Measured section: HFM02:2 (green).*

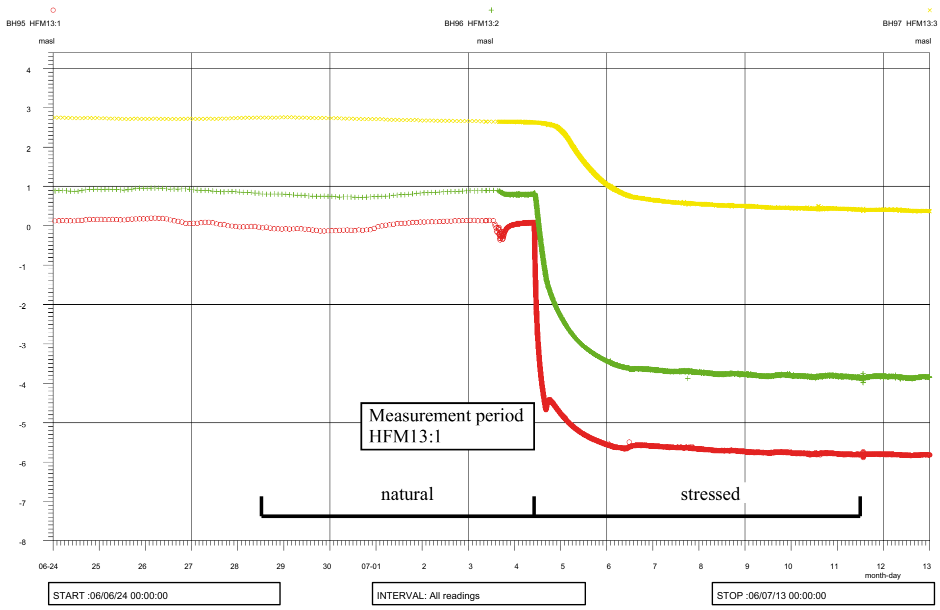

Figure A2-2. *Groundwater levels in borehole HFM13. Measured section: HFM13:1 (red).*

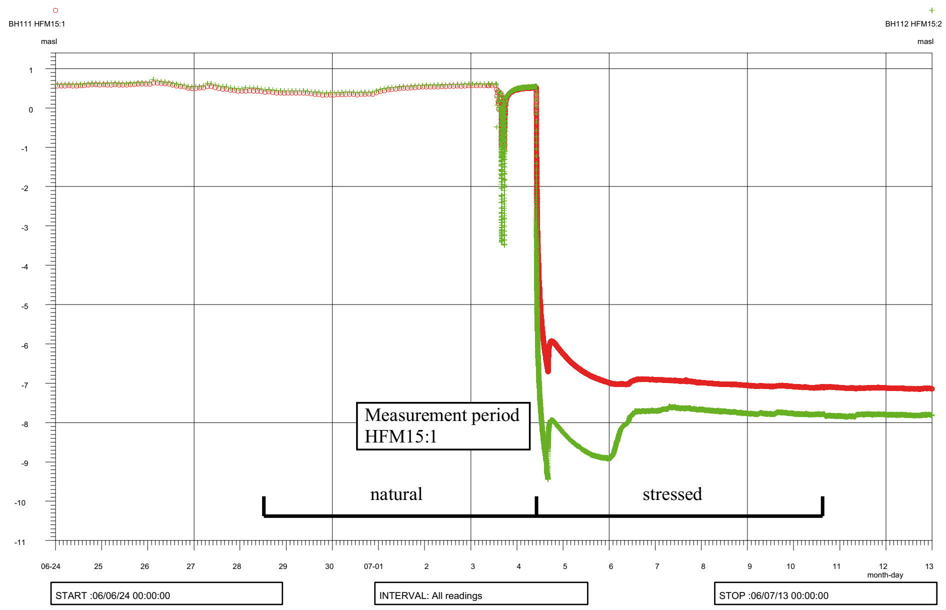

***Figure A2-3.** Groundwater levels in borehole HFM15. Measured section: HFM15:1 (red).*

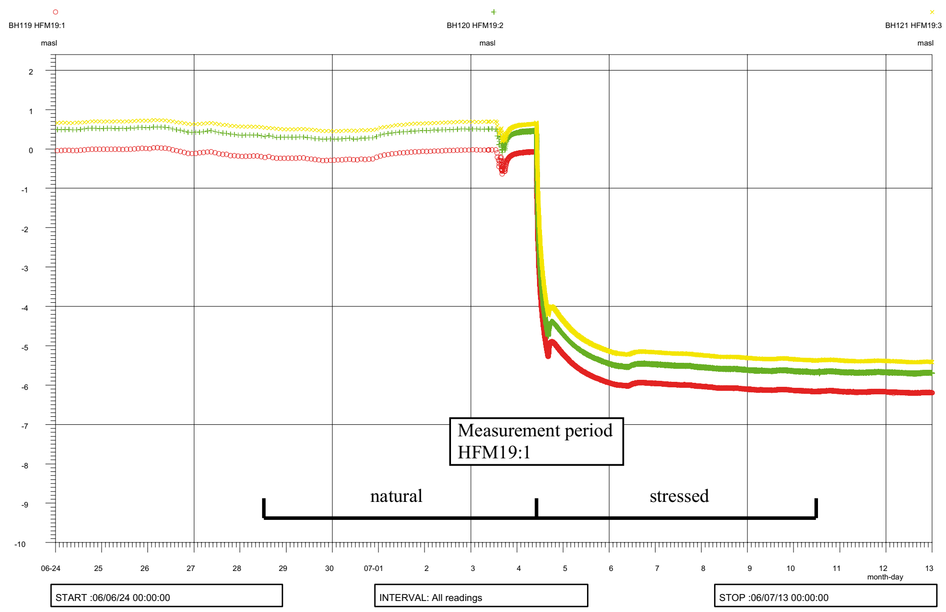

***Figure A2-4.** Groundwater levels in borehole HFM19. Measured section: HFM19:1 (red).*

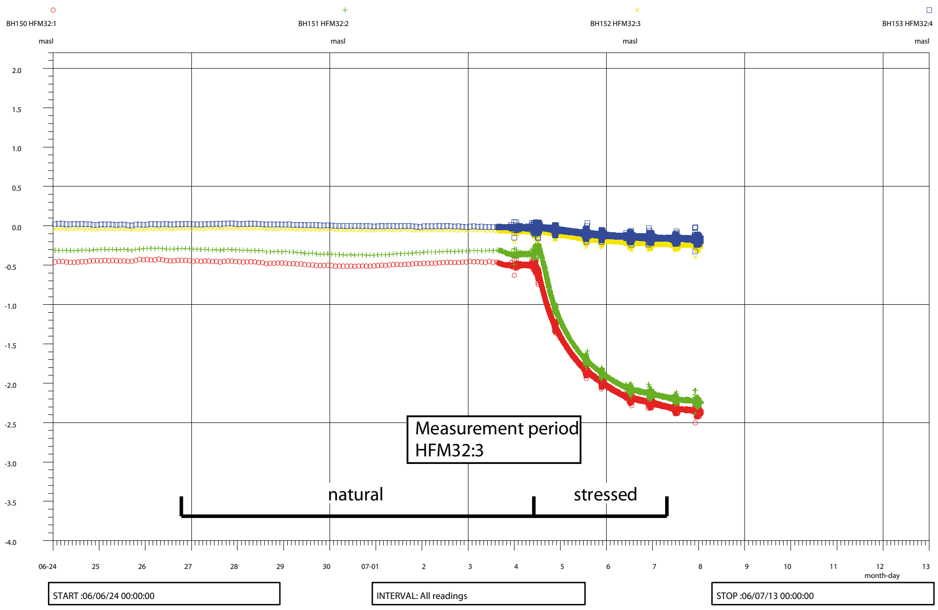

***Figure A2-5.** Groundwater levels in borehole HFM32. Measured section: HFM32:3 (yellow).*

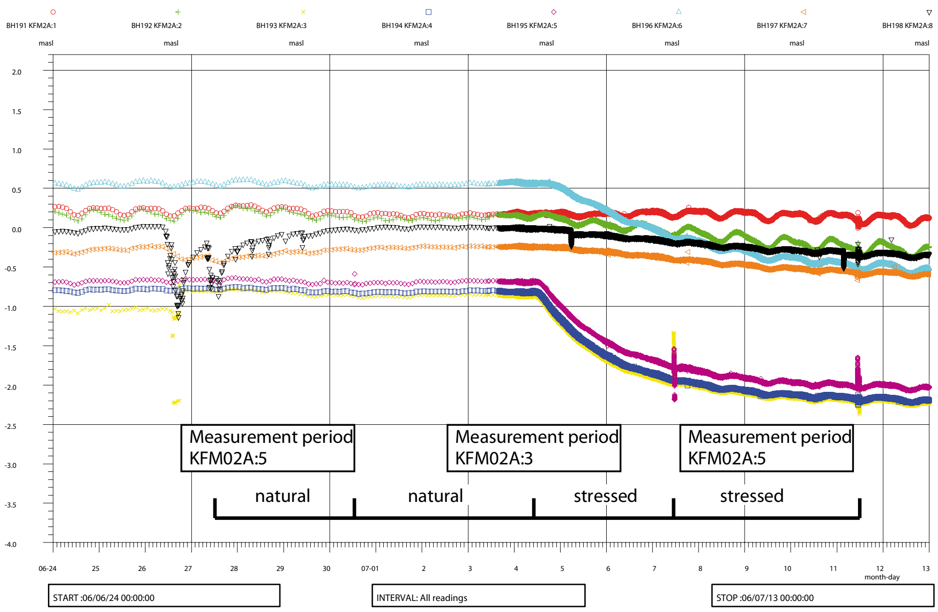

***Figure A2-6.** Groundwater levels in borehole KFM02A. Measured sections: KFM02A:3 (yellow) and KFM02A:5 (dark red).*

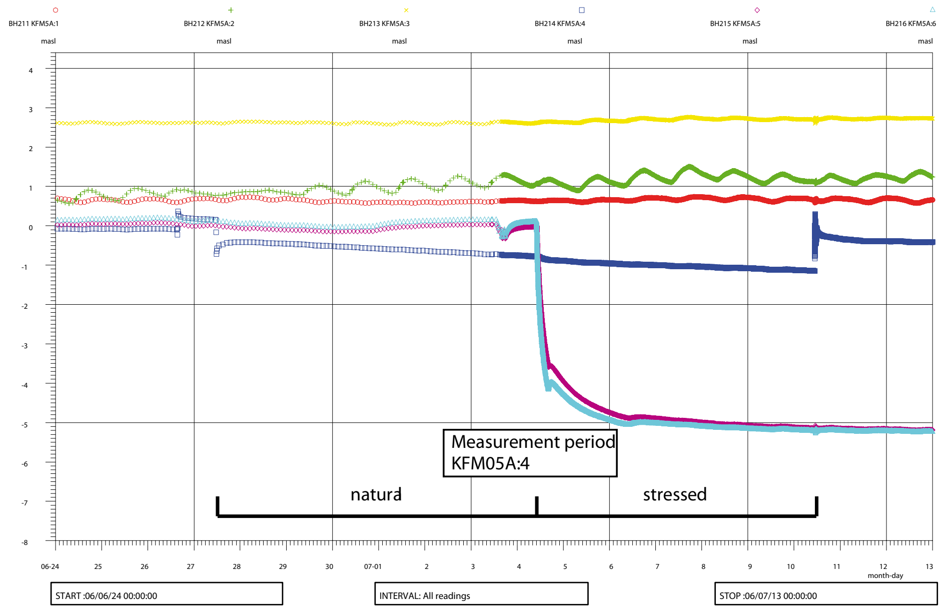

Figure A2-7. *Groundwater levels in borehole KFM05A. Measured section: KFM05A:4 (dark blue).*

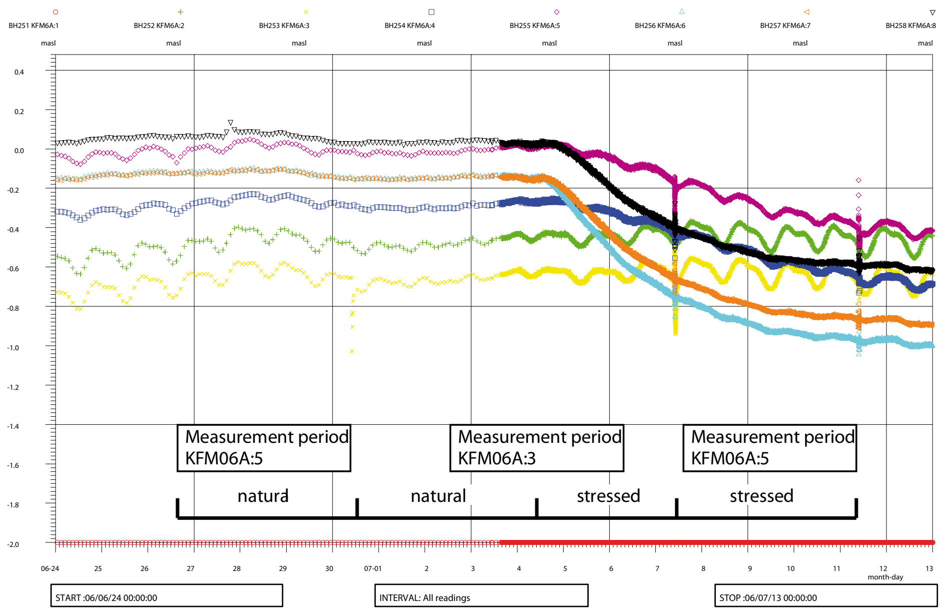

Figure A2-8. *Groundwater levels in borehole KFM06A. Measured sections: KFM06A:3 (yellow) and KFM06A:5 (dark red).*