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Forsmark site investigation

Hydraulic evaluation of pumping activities prior to hydro-geochemical sampling in borehole KFM03A – Comparison with results from difference flow logging

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Abstract

Prior to the hydro-geochemical sampling in borehole KFM03A, pumping with the Pipe String System (PSS) was performed in two borehole sections in order to clear them from flushing water and debris from the drilling operation to obtain representative water quality conditions.

Pumping was performed in the isolated borehole sections 386–391 m and 448–453 m. These sections were selected based on the results of the previous difference flow logging in the borehole. According to the flow logging, the first section contains an assumed highly conductive, narrow fracture zone at c 388 m. In the second section, a conductive fracture located at c 451 m with a moderate transmissivity was identified.

The pumping in section 386–391 m confirmed the high transmissivity of the assumed fracture zone at c 388 m. The transmissivity estimated of this fracture zone was c 2–3·10^{-4} m^2/s. The transmissivity of section 448–453 m was estimated at about 1–2·10^{-6} m^2/s.

From a short step drawdown test in section 448–453 m in conjunction with the pumping, the specific flow rate (Q/s) was c 3 times lower than that obtained from the previous difference flow logging at a similar drawdown in the borehole. At increased drawdown the specific flow decreased further, possibly due to turbulent flow in the fracture at c 451 m or other head losses. Thus, a non-linear relationship between pressure and flow rate was observed in this section. Similar conditions were also indicated during the stepwise pumping in section 386–391 m in conjunction with the difference flow logging.

No significant effects of hydraulic no-flow boundaries were detected in either of the sections during the long-term pumping activities with PSS. This fact may indicate that the assumed fractures/fracture zones at c 388 m and 451 m are extensive in the lateral direction.

No measurable pressure interference was observed in the private well at Lillfjärden during the pumping activities. This may be due to the limited drawdown achieved during the pumping in section 386–391 m in KFM03A. However, a hydraulic connection between the boreholes at a higher flow rate cannot be excluded.

The transient pressure and flow rate records in both pumped sections were strongly affected by natural pressure variations. This was particularly evident in section 386–391 m where the relative effect of these variations was considerable due to the small drawdown (c 1.5 m) applied. Correlation analyses performed indicated that the variations probably mainly are caused by variations in the sea water level in the adjacent Baltic Sea and variations in atmospheric pressure. Thus, it can be assumed that the fracture zone at c 388 m in KFM03A is hydraulically connected with the Baltic Sea. In addition, tidal effects may also have influenced the test responses.

Sammanfattning

Före den hydrokemiska provtagningen i borrhål KFM03A utfördes pumpning med rörgångssystemet (PSS) i två borrhålssektioner för att rensa dessa från spolvatten och borrkax från borrningen och för att få representativa vattenkvalitetsförhållanden.

Pumpning utfördes i de isolerade borrhålssektionerna 386–391 m och 448–453 m. Dessa sektioner valdes på basis av resultaten av den tidigare differensflödesloggningen i borr-hålet. Enligt flödesloggningen innehåller den första sektionen en högkonduktiv, smal sprickzon på ca 388 m. I den andra sektionen identifierades en konduktiv spricka på ca 451 m med måttlig transmissivitet.

Pumpningen i sektion 386–391 m bekräftade den höga transmissiviteten för den antagna sprickzonen på ca 388 m. Transmissiviteten för denna sprickzon skattades till $2–3 \cdot 10^{-4}$ m^2/s. Transmissiviteten för sektion 448–453 m skattades till $1–2 \cdot 10^{-6}$ m^2/s.

Vid en kort stegprovpumpning som gjordes i sektion 448–453 m i anslutning till renspumpningen var det specifika flödet (Q/s) ca 3 gånger lägre än det som erhölls vid den tidigare differensflödesloggningen vid liknande avsänkning i borrhålet. Vid ökad avsänkning minskade det specifika flödet ytterligare, troligen beroende på turbulent flöde i sprickan vid ca 451 m eller andra tryckförluster. Sålunda observerades ett icke-linjärt förhållande mellan tryck och flöde i denna sektion. Liknande förhållanden indikerades också under den stegvisa pumpningen i sektion 386–391 m som gjordes i samband med differensflödesloggningen.

Inga tydliga effekter av täta hydrauliska gränser upptäcktes i någon av sektionerna under långtidspumpningarna med PSS. Detta kan tyda på att de antagna sprickorna/sprickzonerna vid ca 388 m och 451 m har stor utbredning i lateral led.

Ingen mätbar tryckpåverkan från pumpningarna observerades i den privata brunnen vid Lillfjärden. Detta kan bero på den begränsade avsänkning som erhölls vid pumpningen i sektionen 386–391 m i KFM03A. En hydraulisk förbindelse mellan borrhålen vid större flöde kan dock inte uteslutas.

De transienta tryck- och flödesresponserna i de båda pumpade sektionerna var starkt påverkade av naturliga variationer i tryck, speciellt i sektion 386–391 m på grund av den lilla avsänkningen (ca 1,5 m) som skapades. Utförda korrelationsanalyser indikerade att variationerna troligen i huvudsak är orsakade av variationer i havsvattenståndet i den närbelägna Östersjön och av variationer i lufttryck. Det kan sålunda antas att den antagna sprickzonen på ca 388 m i KFM03A är hydrauliskt konnekterad till Östersjön. Dessutom kan även tidaleffekter ha påverkat testresponserna.

Contents

1 Introduction

Prior to hydro-geochemical sampling in two sections in borehole KFM03A, rinse pumping was performed with the Pipe String System (PSS) to clear the borehole sections from flushing water and debris from the drilling operation in order to obtain representative water quality conditions. The locations of borehole KFM03A and adjacent boreholes at drilling site DS3 are shown in Figure 1-1.

The rinse pumping was carried out the isolated borehole sections 386–391 m and 448–453 m, respectively. These sections were selected on the basis of the previously performed difference flow logging in the borehole /1/. In the first section an assumed, highly conductive narrow fracture zone was identified at c 388.6 m. In the second section, a conductive fracture with a moderate transmissivity located at c 451.3 m was identified.

The absolute pressure and flow rate were registered during pumping enabling evaluation of hydraulic parameters of the pumped sections. In addition, the atmospheric pressure and precipitation were measured at the site. Finally, the variations of the mean sea level in the Baltic Sea in the neighbourhood were studied. The (absolute) pressure was also monitored in a distant private well (F3:38) which possibly might intersect the same fracture zone as was pumped in KFM03A at c 388.6 m. The location of the private well (F3:38) is shown in Figure 3-1.

This document reports the results obtained by the rinse pumping and hydraulic evaluation of the responses. The rinse pumping was mainly carried out according to the Geosigma Quality Plan 03/K201 whereas the hydraulic evaluation of the tests was made in compliance with the SKB Activity Plan AP PF 400-03-70, Version 1.0 (SKB internal controlling document), referring to the Methodology Instruction for analysis of single-hole injection- and pumping tests, SKB MD 320.004, Version 1.0 (SKB internal controlling document).

Resulting data were delivered to the SKB site characterization data base SICADA under field note no Forsmark 253.

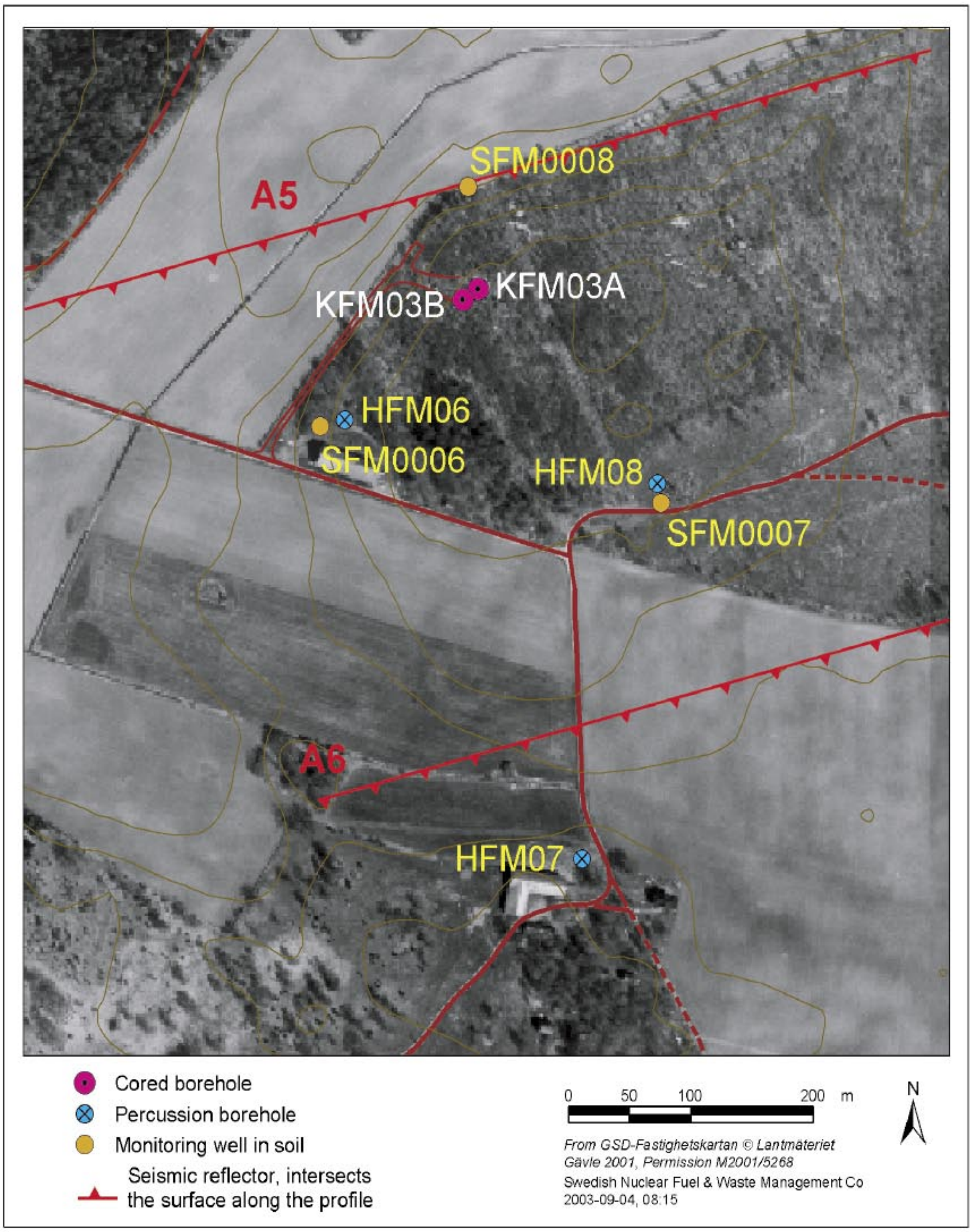


Figure 1-1. *Map showing the location of boreholes and seismic reflectors at drilling site DS3 at Forsmark. The seismic reflectors are interpreted as fracture zones, gently dipping towards SSE. Reflector A5 is assumed to intersect borehole KFM03A at c 50 m.*

2 Objective

The aim of the rinse pumping in section 386–391 m and 448–453 m in borehole KFM03A, prior to the hydro-geochemical sampling, was to clear the sections from flushing water and drilling debris from the drilling operation in order to obtain representative water quality conditions. The main purposes of the hydraulic evaluation of the responses from the rinse pumping were firstly, to estimate the transmissivity of the tested borehole sections and secondly, to deduce information on possible outer hydraulic boundaries. In addition, possible pressure interference in the private well should be analysed.

During the test campaign it was observed that the measured flow rate and absolute pressure were highly affected by presumably natural variations in e.g. atmospheric pressure, sea level and, possibly, tidal effects, particularly in section 386–391 m, in which a small drawdown (c 1.5 m) was applied. Therefore, some qualitative correlations were made to assess the impact of the natural variations of the atmospheric pressure and sea level on the flow rate and (absolute) pressure in this borehole section. Finally, an attempt was made to correct both the measured flow rate and absolute pressure regarding the variations in the atmospheric pressure.

Furthermore, during the rinse pumping in section 448–453 m, some discrepancies in calculated specific flow were observed compared to the results of the difference flow logging. Therefore, comparisons of calculated specific flows and transmissivities of the tested sections from the actual rinse pumping and difference flow logging, respectively, were made. The discrepancies of the results were discussed and documented.

3 Scope

3.1 Boreholes

Selected main technical data for the cored borehole KFM03A are shown in Table 3-1. The borehole is cased to c 12 m with a diameter of 0.2 m. The percussion-drilled borehole interval between c 12–100 m is uncased. The borehole length is c 1000 m and the borehole is almost vertical. The diameter of the core-drilled borehole interval (c 102–1001 m) is 77 mm. More detailed borehole data are available from SICADA. The reference point for all length measurements in the borehole is the centre of the top of casing (ToC). The reference coordinate system for the X-Y-coordinates is RT90 and for the elevation data RHB70. The starting point coordinates (at ToC) of the borehole are:

Northing (m): 6697852.096 RT90 2,5 gon W 0:–15

Easting (m): 1634630.733 RT90 2,5 gon W 0:–15

The private well F3:38 at Lillfjärden is c 60 m deep and documented in the inventory of wells at Forsmark prior to the site investigation /2/, see Figure 3-1. This well was used as an observation well during the rinse pumping with PSS in section 386–391 m.

Table 3-1. Selected main technical data of cored borehole KFM03A. (From SICADA).

Borehole KFM03A							
ID	**Elevation of top of casing (ToC) (m.a.s.l.)**	**Borehole interval from ToC (m)**	**Casing/ Bh-diam. (m)**	**Inclination-top of bh (from horizontal plane) (º)**	**Dip-direction-top of bore-hole (from local N) (º)**	**Remarks**	**Drilling finished Date (YYYY-MM-DD)**
KFM03A	8.285	0.0–11.96	0.200	–85.747	271.523	Casing ID	
″		11.96–100.29*	0.196			Open hole**	
″		102.05–1001.19***	0.077			Open hole***	2003-06-23

* percussion borehole

** the interval 97.20–101.85 m is cased with successively decreasing casing diameters

*** cored borehole interval

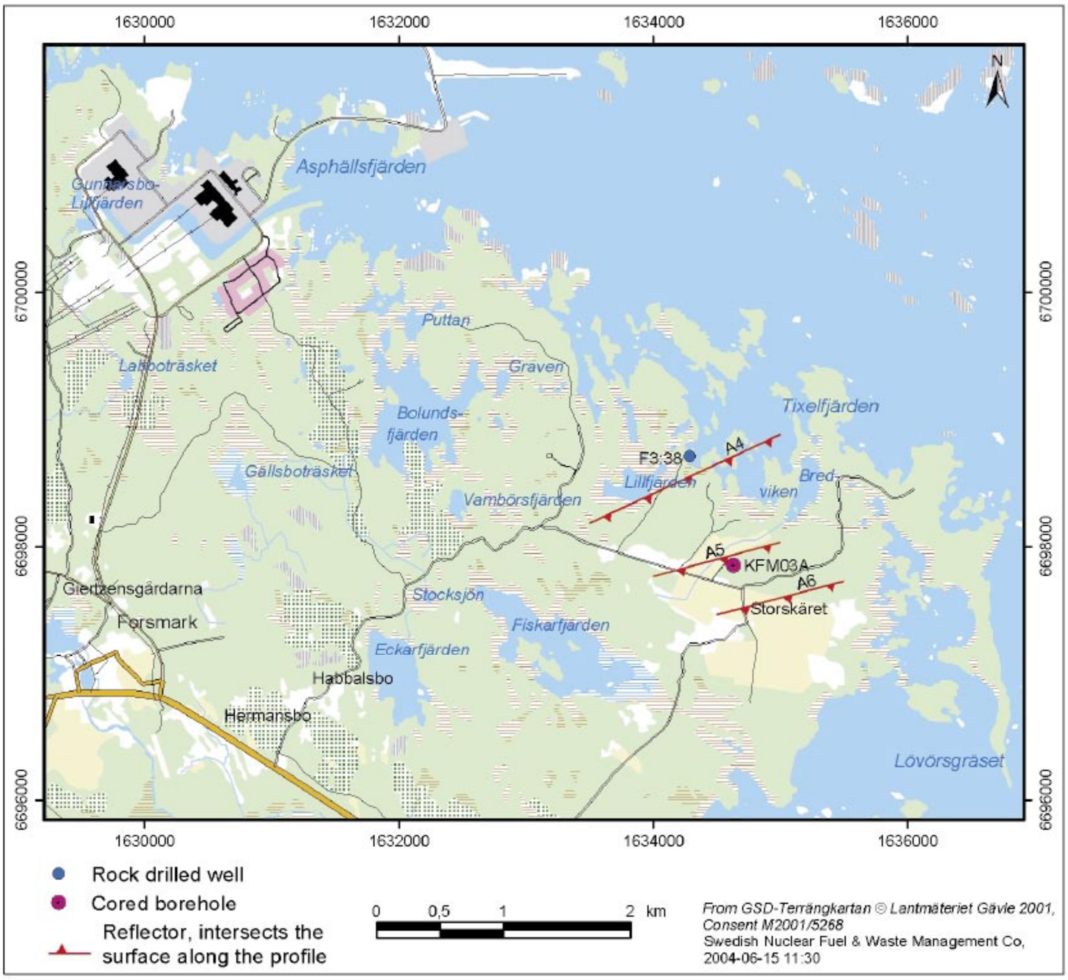


Figure 3-1. Map showing the location of the private well F3:38 in relation to borehole KFM03A and the interpreted seismic reflectors in the area. Reflector A4 may possibly be intersected by borehole KFM03A at c 389 m.

3.2 Tests performed

The rinse pumping in KFM03A was performed under a constant drawdown in the isolated borehole sections 386–391 m and 448–453 m, respectively. The duration of the pumping in the former section was c 4 weeks and c 2.5 weeks in the latter section. Interruptions occurred during pumping in both sections due to power failures, cf the overview linear graph in the Test Summary Sheets. Pertinent data of the rinse pumping are shown in Table 3-2. The start and stop times in Table 3-2 for each test refer to the total test duration, including interruptions and recovery periods.

Table 3-2. Total duration (including recovery) of the rinse pumping prior to hydro-geochemical sampling in the selected two sections in borehole KFM03A.

PumpingBh ID	Pumped section (open hole) (m)	Test type[1]	Test no	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
KFM03A	386.0–391.0	1B	1	2003-09-11 15:00	2003-10-08 13:30
KFM03A	448.0–453.0	1B	1	2003-10-09 14:41	2003-10-27 09:59

1)

1B: Pumping test with submersible pump with subsequent recovery

4 Equipment

4.1 Description of equipment

The rinse pumping in the selected two sections prior to the hydro-geochemical sampling in borehole KFM03A was performed with the SKB Pipe String System (PSS).

4.2 Sensors

Technical specifications for the individual measurement sensors included in the PSS are shown in Table 4-1. For the flow sensors also an estimation of the measurement uncertainty of the entire system, including loggers etc, has been done. For pumping tests, the flow rate range is c1–30 L/min depending on the actual drawdown and depth to the test section.

The sensor positions are fixed relative the top of the test section, given a specific length of the test section. In Table 4-2, some data for the test sections and the position of sensors are given.

Table 4-1. Technical data of sensors together with estimated data on accuracy of the PSS system (only for flow sensors).

Technical specification					
Parameter		**Unit**	**Sensor**	**PSS system**	**Comments**
Absolute pressure	Output signal	mA	4–20		
	Meas. range	MPa	0–13.5		
	Resolution	kPa	< 1.0		
	Accuracy[1)]	% F.S	0.1		
Temperature	Output signal	mA	4–20		
	Meas. range	°C	0–32		
	Resolution	°C	< 0.01		
	Accuracy	°C	±0.1		
Flow Qbig	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67\cdot10^{-5}$–$1.67\cdot10^{-3}$		
	Resolution	m^3/s	$6.7\cdot10^{-8}$		
	Accuracy[2)]	% O.R	0.15–3	0.2–1	The specific accuracy is depending on actual flow
Flow Qsmall	Output signal	mA	4–20		
	Meas. range	m^3/s	$1.67\cdot10^{-8}$–$1.67\cdot10^{-5}$		
	Resolution	m^3/s	$6.7\cdot10^{-10}$		
	Accuracy[2)]	% O.R	0.4–10	0.4–20	The specific accuracy is depending on actual flow

[1)] 0.1% of Full Scale. Includes hysteresis, linearity and repeatability

[2)] Maximum error in % of actual reading (% o.r.). The higher numbers correspond to the lower flow

Table 4-2. Data for the test sections together with position of borehole sensors. The same test configuration was used for both tests.

Geometrical data of test section	
Length of test section L (m)	5
Equipment displacement volume in test section [1)]	4
Total volume of test section [2)]	23
Sensor position (m from secup) [3)]	
Pa, pressure above test section	1.85
P, pressure in test section	–4.4
Pb, pressure below test section	–7.05
Tsec, temperature in test section	–3.75

[1)] Displacement volume (in litre) in test section due to pipe string, signal cable and packer ends.

[2)] Total volume (in litre) of test section ($V=\pi*d^2/4*L$).

[3)] Position of sensor relative top of test section. A negative value indicates a position below top of the test section (secup).

5 Execution

5.1 Preparations

5.1.1 Calibration

All sensors included in PSS were calibrated at Geosigma's engineering service station in Uppsala prior to the pumping activities. Results from calibration, e.g. calibration constants, of all sensors are kept in a document folder in PSS.

5.1.2 Functional inspections

Functioning checks of equipment were made during the establishment of PSS at test site. Simple function checks of down-hole sensors at change of test section and further checks while lowering the pipe string along the borehole were made as well.

5.2 Test performance

The rinse pumping in the two selected sections in borehole KFM03A was mainly performed according to the Geosigma Quality Plan 03/K201 whereas the hydraulic evaluation of the tests was carried out in compliance with Activity Plan AP PF 400-03-70. The capacity test in section 386–391 m prior to the pumping showed that the maximal flow capacity of the actual pump was c 30 L/min at a drawdown of c 1.5 m.

During the pumping in section 386–391 m, the pressure was also monitored at the private well F 3:38 at Lillfjärden, see Figure 3-1, to identify any pressure interferences. There are some indications from reflection seismic that the private well possibly might intersect the same reflector (A4) as is intersected by borehole KFM03A at c 388.6 m. This reflector may represent a major fracture zone.

In section 448–453 m, the flow rate was only c 2 L/min at a drawdown of c 30 m. This was significantly lower than predicted from the results of the difference flow logging, see Section 6.5.2. In order to check any uncertainties in the length recording to the actual fracture, the packer system was moved a distance of 2 m upwards and downwards, respectively, but the flow rate remained relatively unchanged at the same drawdown applied. To investigate the dependence of the magnitude of drawdown on the flow rate in this section, a step drawdown test was carried out after the recovery phase, see Section 6.5.2.

During the tests in both sections, the atmospheric pressure and precipitation were measured at the site. In addition, sea level data in the Baltic Sea during the test in section 386–391 m were acquired.

5.2.1 Test principle

The rinse pumping was performed at a constant drawdown in the pumped borehole sections. The flow period was followed by a pressure recovery period.

5.2.2 Test procedure

Section 386–391 m

In section 386–391 m, the rinse pumping was performed at a relatively constant drawdown of c 15 kPa (1.5 m) during c 4 weeks, see Figure A2:1 in Appendix 2. An interruption occurred during 030923 – 030924 due to a power failure, dividing the flow period into two phases. The flow rate decreased from c 30 L/min to c 19 L/min during the first flow phase. By the end of the second flow phase the flow rate decreased to c 28.5 L/min, cf Figure 6-2. The pumped flow was discharged at the ground surface sloping downhill from the borehole.

Section 448–453 m

In section 448–453 m, pumping was performed at a constant drawdown at c 300 kPa (30 m) during c 2.5 weeks, see Figure A2:6 in Appendix 2. An interruption occurred 031022 due to a power failure, again dividing the flow period into two phases. The flow rate was c 2 L/min by the end of the first phase and c 2.4 L/min by the end of the second phase. The pumped flow was discharged at the ground surface sloping downhill from the borehole.

5.3 Data handling

With the PSS system primary data are handled with the software Orchestrator (Version 2.3.8). During a test, data are continuously logged in *.odl-files. After the test is finished, a report file (*.ht2) with space separated data is generated. The *.ht2-file (mio-format) contains logged parameters as well as test specific information such as calibration constants and background data. The parameters are presented in percentage of sensor measurement range and not in engineering units. This is the raw data file.

The *.ht2-files are automatically named with borehole id, top of test section and data and time of test start (as for example __KFM01A_0105.45_200305261130.ht2). The name differs slightly from the convention stated in SKB MD 320.004.

By the software IPPLOT (Version 2.0), the *.ht2-files are converted to parameter files, suitable for plotting by the code SKB-plot.

5.4 Analyses and interpretation

The hydraulic evaluation of the rinse pumping activities is described in the Activity Plan AP PF 400-03-70 and in SKB MD 320.004.

Firstly, a qualitative evaluation was performed to identify the actual flow regimes during the flow- and recovery periods (e.g. wellbore storage, pseudo-radial flow etc) and possible outer hydraulic boundary conditions. For both tests, the analysis was mainly made from the responses during the long flow period (first phase) together with the corresponding derivatives versus time in log-log diagrams.

The pressure recovery was plotted versus equivalent time dt_e after stop of pumping. However, due to the long duration of the flow period and the short recovery period, there is little difference between the actual and equivalent recovery time in this case, see e.g. Figure A2:4-5 in Appendix 2.

The quantitative, transient interpretation of hydraulic parameters from the pumping borehole (e.g. transmissivity and skin factor) is in general based on the identified pseudo-radial flow regimes according to methods described in /3/, /4/ and in SKB MD 320.004 for tests in an equivalent porous medium.

The responses from the flow- and recovery period were analysed with methods for constant drawdown- and constant flow rate tests, respectively. In addition, a steady-state analysis (Moye's formula) was also made from the flow period.

5.5 Nonconformities

During the course of the work, a number of extra tasks were included in this study. The following items were added to the tasks described in the Activity Plan AP PF 400-03-70:

- Comparison and documentation of discrepancies between the results of the rinse pumping and difference flow logging /1/, respectively in the two tested sections.
- Correlation of atmospheric pressure variations with measured absolute pressure and flow rate in the tested sections together with attempts to correct the measured data for the atmospheric pressure variations.
- Correlation of the sea level variations in the Baltic Sea with measured absolute pressure and flow rate in the tested sections.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the pumping test are according to SKB MD 320.004. Additional symbols used are explained in the text.

6.2 Rinse pumping with PSS

As described in Section 5.2, the rinse pumping with PSS in selected borehole sections in KFM03A prior to hydro-geochemical sampling was basically performed as constant drawdown tests. However, due to the long duration of the tests, natural cyclic pressure variations due to changes in the atmospheric pressure, tidal effects and variations of the Baltic Sea level affected the test data. In particular, both pressure and flow rate in section 386–391 m, where a rather low drawdown was maintained, was strongly affected by natural pressure variations.

The absolute pressure, i.e. the sum of the groundwater and atmospheric pressure, was measured in the test sections. If the barometric efficiency (the relative influence of the atmospheric pressure in the test section) is considerable (near 100%) the atmospheric pressure should be subtracted from the absolute pressure data. To investigate this effect, the latter correction was made when analysing the pressure recovery data, see below.

Furthermore, flow rate will also fluctuate as a result of a varying absolute pressure when using an automatic regulation system to maintain a constant pressure in the test section. An attempt was made to correct flow data for variations in the atmospheric pressure (see Section 6.2.2).

Since no estimates on storativity from observation boreholes were available, the storativity (S^*) was assumed at $1 \cdot 10^{-6}$ by the calculation of the skin factor according to SKB MD 320.004. A summary of the results of the rinse pumping activities with PSS is presented in Section 6.4. Test diagrams are shown in Appendix 2.

6.2.1 Section 386–391 m

General test data from the entire period of the rinse pumping with PSS in borehole section 386–391 m in KFM03A are presented in Table 6-1 below.

Table 6-1. General test data from the rinse pumping in borehole section 386–391 m in KFM03A.

Pumping borehole	KFM03A		
Test type	Constant drawdown- and recovery test		
Test section (open borehole/packed-off section):	Packed-off section		
Test No	1		
Field crew	J. Källgården, T. Svensson, J. Olausson, GEOSIGMA		
Test equipment system	PSS3		
General comment	Single-hole test with pressure registration in private well		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	1001.19
Casing length	L_c	m	11.96 (ID 0.200 m)
Test section- secup	Secup	m	386.0
Test section- seclow	Seclow	m	391.0
Test section length	L_w	m	5.0
Test section diameter	$2 \cdot r_w$	mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20030911 15:00
Packer expanded		yymmdd hh:mm:ss	20030911 15:05:35
Start of flow period		yymmdd hh:mm:ss	20030911 16:04:00
Stop of flow period		yymmdd hh:mm:ss	20031007 08:46:04
Test stop (stop of pressure registration)		yymmdd hh:mm	20031008 13:29:58
Total flow time	t_p	min	35597
Total recovery time	t_F	min	1466

Groundwater pressure data

Groundwater pressure data in pumping section 386–391 m in borehole KFM03A	Nomen-clature	Unit	Value
Absolute pressure in borehole section before start of flow period	p_i	kPa	3946.72
Absolute pressure in borehole section before stop of flow period	p_p	kPa	3931.09
Absolute pressure in borehole section at stop of recovery period	p_F	kPa	3947.28
Maximal pressure change in borehole section during flow period	dp_p	kPa	15.63

Flow data

Flow rate data in pumping section 386–391 m in borehole KFM03A	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$4.76 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$4.42 \cdot 10^{-4}$
Total volume discharged during flow period	V_p	m^3	944.5

Interpreted flow regimes

Selected test diagrams according to SKB MD 320.004 are presented in Appendix 2. The main analysis was made from the first phase of the flow period, before the interruption, and from the short recovery period. The analyses were made on uncorrected, measured data. An attempt to make corrections for the natural variations of the atmospheric pressure was also made, see Section 6.2.2.

Figures A2:2–3 show that although large variations of the flow rate, a rather well-defined pseudo-radial flow period occurred during intermediate to late times of the first phase of the flow period at constant pressure. By the end of the flow period, effects of a constant head boundary are indicated. No evidences of hydraulic no-flow boundaries were seen during the long flow period.

During the initial phase of the recovery period, a fractured response with a slope of 1:2 was indicated transiting to pseudo-radial flow by the end of the recovery period, cf Figure A2:4. As discussed above, (natural) pressure variations disturbed both the flow rate during the flow period and the pressure during the recovery period.

Interpreted parameters

The transient analyses of the flow- and recovery periods according to the methods described in Section 5.4, based on the identified periods with pseudo-radial flow, are presented in the Test Summary Sheets. The representative values are presented in Table 6-4. The analyses were made on measured, uncorrected data.

6.2.2 Influence of atmospheric pressure and sea water level on the measured flow rate and pressure in section 386–391 m

As mentioned above, natural fluctuations probably distorted test data (pumping flow rate and absolute pressure) during the test in section 386–391 m. These fluctuations may be connected to variations in atmospheric pressure, sea water level or tidal effects. The relative importance of such an influence will increase when the applied drawdown in the test section is small.

Since the automatic regulation of the flow rate to keep a constant drawdown in the test section is based on the measured absolute pressure, variations in the flow rate cannot be avoided, due to natural fluctuations in the absolute pressure. Thus, if the latter fluctuations mainly depend on variations in atmospheric pressure, it might be possible to correct the flow rate for the effect of these variations. This procedure, attempted in this study, would then possibly result in a smoothing of the flow rate data before the transient analysis of the flow period. Assuming that the resulting effect on flow rate is linear, the following correction for atmospheric pressure was applied:

$Q_{corr} = Q \cdot [dp_i / (dp_i + dp_{atm})]$

Q = measured pumping flow rate at a certain time

Q_{corr} = corrected pumping flow rate Q

dp_i = initial drawdown in the test section

dp_{atm} = $p_{atm} - p_{atm,i}$

p_{atm} = atmospheric pressure at a certain time

$p_{atm,\,i}$ = initial atmospheric pressure

The results of this correction of the pumping flow rate are visualized in Figure 6-1 together with the atmospheric pressure during the first phase of the flow period in section 386–391 m.

Even if a certain influence of the atmospheric pressure on the measured pumping flow rate cannot be excluded, this effect does not seem to explain the dominating fluctuations in the flow rate in Figure 6-1. Thus, no significant improvement (smoothing) of the flow rate data was achieved by this correction and the correction was not considered as relevant in this case. An attempt was also made to correct the pressure recovery data for the natural variations in the atmospheric pressure. However, subtraction of the atmospheric pressure from the measured absolute pressure data did not either significantly improve the quality of the pressure recovery data.

No further attempts to correct the measured flow rate and pressure data for natural variations in the atmospheric pressure were made. Thus, the uncorrected flow rate and absolute pressure, respectively, were used in the transient hydraulic analysis although the actual data from this section seem to be strongly disturbed by these effects.

However, when comparing the measured flow rate with the variations of the sea level in the Baltic, a good correlation can be seen (Figure 6-2). The flow rate during both flow periods of the pumping is shown together with the atmospheric pressure and Baltic Sea water level. Even though there is a certain time lag in the flow rate response, it is obvious that there is a correlation between the flow rate and the water level in the Baltic Sea. Also the atmospheric pressure seems to have an influence on the flow rate. Atmospheric pressure has an opposite effect to sea water level, since low atmospheric pressure normally correspond to high sea water levels and vice versa. No attempts were though made to correct the flow rate and pressure for the variations in the sea water level. Such corrections are beyond the scope of this study and require long measurement series of both absolute pressure and sea water level, as eg. in the groundwater head monitoring program.

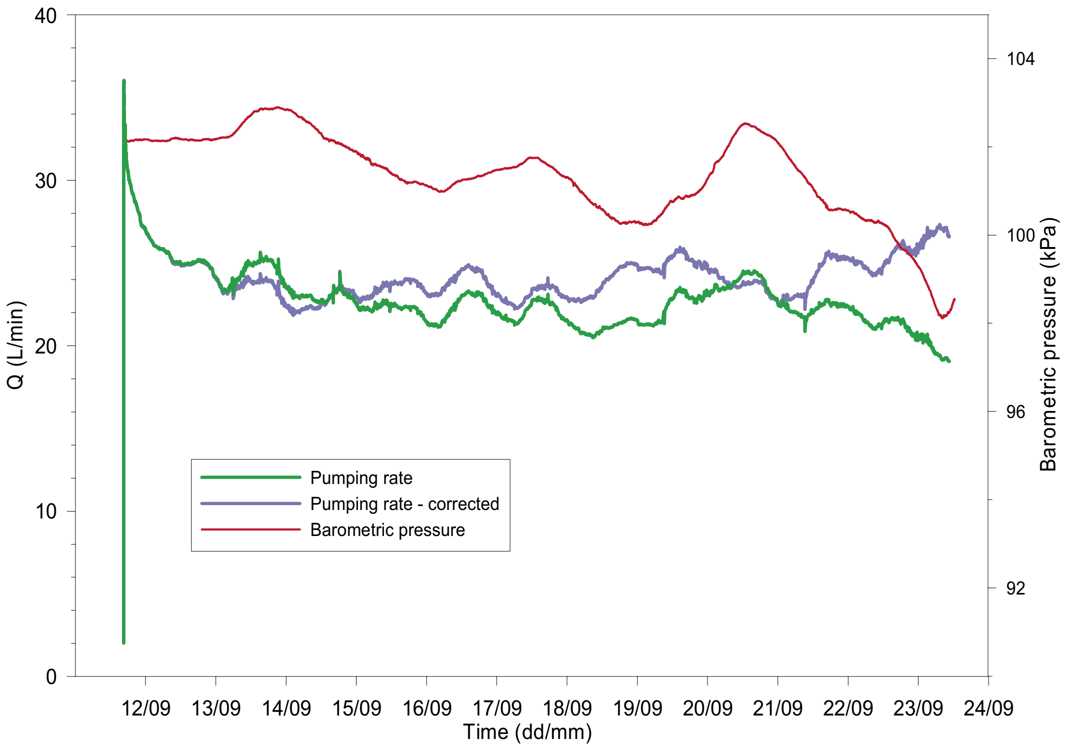


***Figure 6-1.** Measured (green) and corrected (blue) pumping flow rates together with the atmospheric pressure during the first phase of the flow period in section 386–391 m in borehole KFM03A.*

In Figure 6-3, a part of the diagram in Figure 6-2 (detail A) is selected and zoomed-in to further illustrate the effect of sea water level and atmospheric pressure. Since there is a time lag between the sea water level and flow rate four hours have been added to the actual times of the sea water level data in Figure 6-2. The four hours is a rough, first approximation of the time lag. The generally good correlation between sea water level and pumping flow rate in Figure 6-3 is disturbed by the relatively large fluctuation in atmospheric pressure between September 26 and 28. The same pattern can be seen during other periods with large fluctuations in atmospheric pressure, indicating that the flow rate is depending on both sea water level and atmospheric pressure.

As the effect on pumping flow rate is secondary, depending on the PSS system trying to maintain a constant pressure in the test section, it would have been preferable to study the effect of the variations in atmospheric pressure and sea water level directly on an undisturbed pressure registration period. Unfortunately, the recovery period during this test was too short to allow for such a study.

Nevertheless, the results though indicate that the potential fracture zone intersecting the pumped section at c 388 m (possibly the seismic reflector A4) has a good hydraulic communication with the Baltic Sea.

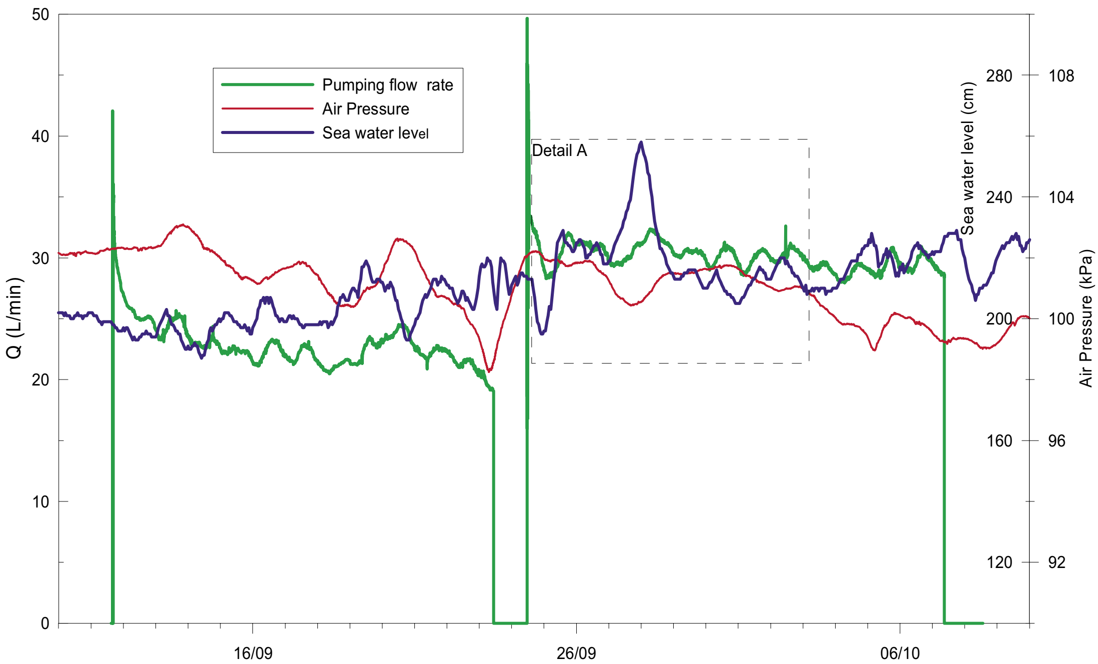


__Figure 6-2.__ Correlation between measured pumping flow rate (green), atmospheric pressure (red) and water level in the Baltic Sea (blue) during the entire flow period in section 386–391 m in borehole KFM03A.

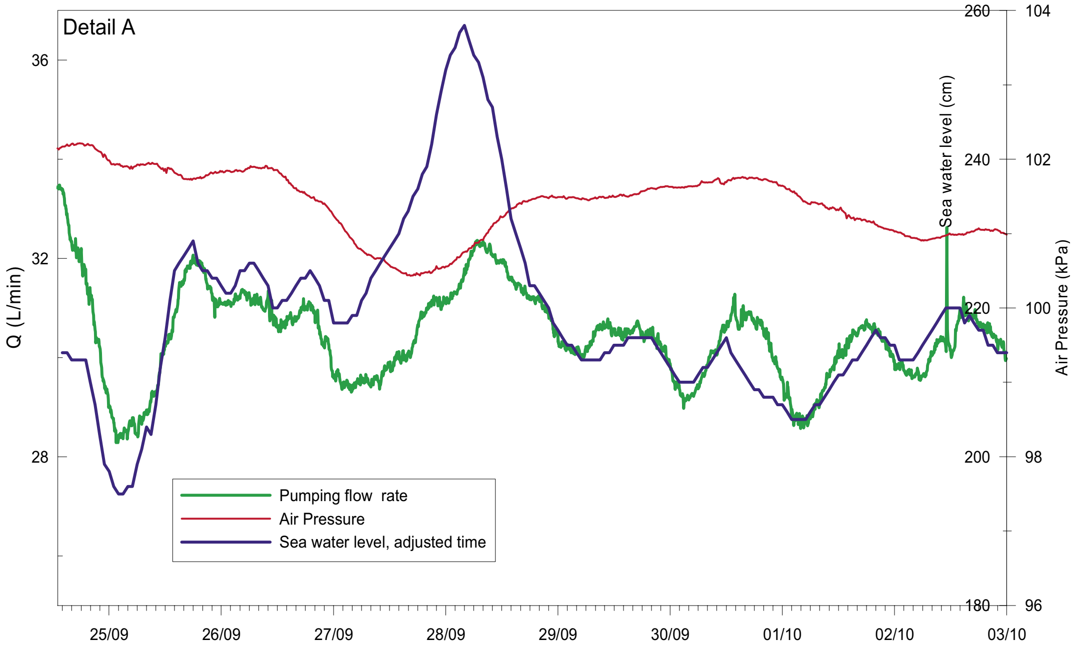


***Figure 6-3.** Correlation between measured pumping flow rate (green), atmospheric pressure (red) and sea water level (blue) in the Baltic Sea (detail from Figure 6-2). Four hours have been added to the actual times for the sea water level data.*

6.2.3 Section 448–453 m

General test data from the entire period of the rinse pumping in borehole section 448–453 m in KFM03A are presented in Table 6-2.

Table 6-2. General test data from the rinse pumping in borehole section 448–453 m in KFM03A.

Pumping borehole	KFM03A		
Test type	Constant drawdown and recovery test		
Test section (open borehole/packed-off section):	Packed-off section		
Test No	1		
Field crew	J. Levén, T. Svensson, GEOSIGMA		
Test equipment system	PSS3		
General comment	Single-hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	1001.19
Casing length	L_c	m	11.96 (ID 0.200 m)
Test section- secup	Secup	m	448.0
Test section- seclow	Seclow	m	453.0
Test section length	L_w	m	5.0
Test section diameter	$2 \cdot r_w$	mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20031009 14:41
Packer expanded		yymmdd hh:mm:ss	20031009 14:42:43
Start of flow period		yymmdd hh:mm:ss	20031009 14:53:51
Stop of flow period		yymmdd hh:mm:ss	20031024 11:28:12
Test stop (stop of pressure registration)		yymmdd hh:mm	20031027 09:59
Total flow time	t_p	min	20363
Total recovery time	t_F	min	4288

Groundwater pressure data

Groundwater pressure data in pumping section 448–453 m in borehole KFM03A	Nomen-clature	Unit	Value
Absolute pressure in borehole section before start of flow period	p_i	kPa	4566.79
Absolute pressure in borehole section before stop of flow period	p_p	kPa	4268.25
Absolute pressure in borehole section at stop of recovery period	p_F	kPa	4569.55
Maximal pressure change in borehole section during flow period	dp_p	kPa	298.54

Flow data

Flow data in pumping section 448–453 m in borehole KFM03A	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$4.01 \cdot 10^{-5}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$3.47 \cdot 10^{-5}$
Total volume discharged during flow period	V_p	m^3	42.4

Interpreted flow regimes

Selected test diagrams according to SKB MD 320.004 are presented in Figures 2:6–10 in Appendix 2. The qualitative analyses were made on uncorrected, measured data from the first and second phase of the flow period and from the short recovery period.

The qualitative analysis shows that a pseudo-steady state flow developed rapidly during both the flow period (Figure A2:7–8) and the recovery period. The flow rate decreased slightly in a few small steps during the flow period, see e.g. Figure A2:8. The pressure recovery in the test section was almost instantaneous, cf Figure A2:9–10. No evidences of hydraulic no-flow boundaries were seen during the long flow period.

Interpreted parameters

Only a steady-state analysis of the flow period was made for this test. The results are presented in Table 6-4.

6.3 Pressure in the private well at Lillfjärden

The absolute pressure was registered in the private well F3:38 at Lillfjärden, see Figure 3-1, during the rinse pumping in section 386–391 m performed 030911–031007. In this case, the atmospheric pressure was subtracted from the absolute pressure since the registrations were made in an open well located in the upper part of the bedrock, i.e. the well is directly exposed to the atmospheric pressure. Figure 6-4 shows the gauge pressure in the well (absolute pressure minus atmospheric pressure) and the flow rate from the pumped section in KFM03A together with the sea water level and average daily precipitation at Forsmark. The scatter in the gauge pressure in the well is caused by small temporary water abstractions from the well. The general pressure trend in the well is clear despite the scatter.

Figure 6-4 firstly shows clearly that the private well is unaffected by the rinse pumping in section 386–391 m in KFM03A. No quantitative evaluation of hydraulic parameters could thus be made from the well. Secondly, the variations in gauge pressure in the private well and the fluctuations in the measured pumping flow rate from section 386–391 (see Figure 6-2) are clearly correlated with the variations of the mean sea level.

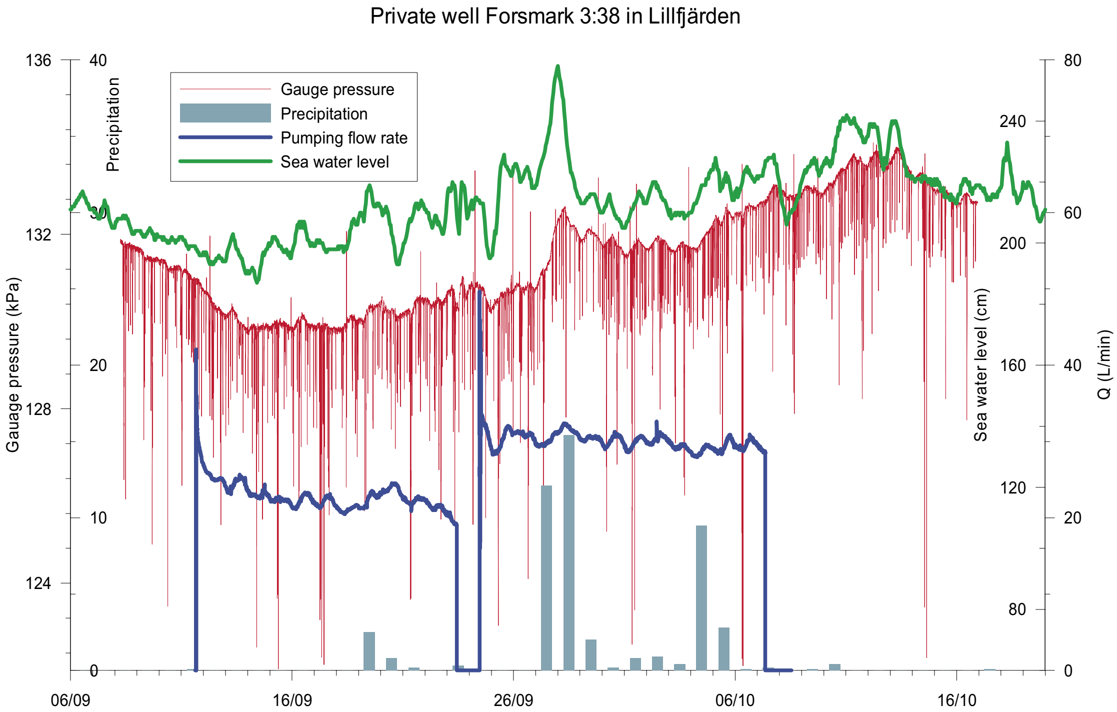


Figure 6-4. Gauge pressure in the private well F3:38 at Lillfjärden (red) and pumping flow rate (blue) from section 386–391 m in KFM03A together with mean Baltic Sea level (green) and precipitation (grey) at Forsmark.

6.4 Summary of test data and results from the PSS tests

Pertinent test data from the rinse pumping activities with PSS prior to the hydrogeo- chemical sampling in borehole KFM03A are summarized in Table 6-3. The calculated hydraulic parameters are presented in Table 6-4 and in the Test Summary Sheets below. The calculated hydraulic parameters are likely to represent conductive fractures at c 388.6 m and 451.3 m as identified from the previous difference flow logging in KFM03A. In Table 6-4 also the estimated measurement limits of specific flow are shown. In this case, the lower measurement limit is based on the minimal flow rate for the actual pump (c 1 L/min) and a recommended drawdown of c 30 m. Similarly, the upper limit is based on the maximal flow rate (c 30 L/min) and a practical minimal drawdown, e.g. due to natural fluctuations, of c 0.5 m.

Test data diagrams from the tests are shown in Appendix 2. The parameter files of the results from the rinse pumping activities to be stored in the SICADA data base are presented in Appendix 3.

Table 6-3. Summary of test data from the rinse pumping with PSS prior to hydrogeo-chemical sampling in borehole KFM03A. (Explanations to nomenclature are found in Table 6-2.)

Borehole ID	Interval (m)	Test type[1)]	p_i (m a s l)	p_p (m a s l)	P_F (m a s l)	Q_p (m^3/s)	V_p (m^3)	Q_m (m^3/s)
KFM03A	386.0–391.0	1B	3946.72	3931.09	3947.28	$4.76 \cdot 10^{-4}$	944.5	$4.42 \cdot 10^{-4}$
KFM03A	448.0–453.0	1B	4566.23	4268.25	4569.55	$4.01 \cdot 10^{-5}$	42.4	$3.47 \cdot 10^{-5}$

[1)] 1B: Pumping test-submersible pump followed by a recovery test

Table 6-4. Summary of calculated hydraulic parameters from the rinse pumping with PSS prior to hydro-chemical sampling in borehole KFM03A.

Borehole ID	Interval (m)	Q/s (m^2/s)	T_M (m^2/s)	T (m^2/s)	S* (–)	ζ (–)	Q/s-measl-L (m^2/s)	Q/s-measl-U (m^2/s)
KFM03A	386.0–391.0	$2.97\cdot10^{-4}$	$2.44\cdot10^{-4}$	$3.06\cdot10^{-4}$	$1\cdot10^{-6}$	–5.52	$5\cdot10^{-7}$	$1\cdot10^{-3}$
KFM03A	448.0–453.0	$1.31\cdot10^{-6}$	$1.08\cdot10^{-6}$	–	–	–	$5\cdot10^{-7}$	$1\cdot10^{-3}$

Q/s = specific flow

T_M = steady-state transmissivity from Moye's formula

T = calculated transmissivity from transient evaluation of the test

S^* = assumed value on the storativity

ζ = skin factor

Q/s-measl-L = lower measurement limit

Q/s-measl-U = upper measurement limit

6.5 Comparison with results from difference flow logging

In this section the results of the rinse pumping with PSS are compared with the results of the previously performed difference flow logging in the two sections in KFM03A, presented in /1/. Several flow measurements at different drawdowns were made at the conductive fracture zone at c 388.6 m in conjunction with the difference flow logging due to the high transmissivity of the fracture zone. A short summary of the results of the flow measurements during the flow logging in this fracture zone is given below.

6.5.1 Section 386–391 m

Due to a high inflow (above the measurement limit of the DIFF probe) no results were achieved from the interpreted fracture zone at c 388.6 m during the ordinary difference flow logging. Therefore, stepwise flow measurements were made at very small (constant) drawdowns in the borehole after the ordinary difference flow logging campaign, see Figure A2:11 in Appendix 2 in this report. The flow measurements were made using the standard DIFF probe in a 1 m long test section (388.14–389.14 m) across the fracture zone.

The duration of each step varied between c 0.5–1 hour. The flow rate Q was almost constant during each step (except the first). During the first step, which was performed at natural conditions, the flow rate decreased initially due to not fully recovered water table in the borehole from the pumping during the ordinary difference flow logging. However, the water table stabilized by the end of the first step. The results of the stepwise flow measurements in the fracture zone at c 388 m are shown in Table 6-5.

In Table 6-5, the drawdown s_w in the borehole and the corresponding flow rates Q together with the specific flow Q/s_w at each step are shown. The natural flow by the end of the first step was subtracted from the measured flows during steps 2–4 when calculating the corrected specific flow (Q/s_w–corr). The results in Table 6-5 indicate a decreasing trend of specific flow at increasing drawdown in the borehole, probably due to some type of head losses.

Table 6-5. Selected results of the stepwise flow measurements at the fracture zone at c 388.6 m in conjunction with difference flow logging in KFM03A.

Step #	s_w (m)	Q (L/min)	Q/s_w (m^2/s)	Q/s_{w}_corr (m^2/s)
1	0	0.172*	–	–
2	0.045	0.693	$2.57 \cdot 10^{-4}$	$1.93 \cdot 10^{-4}$
3	0.108	1.385	$2.14 \cdot 10^{-4}$	$1.87 \cdot 10^{-4}$
4	0.244	2.494	$1.70 \cdot 10^{-4}$	$1.59 \cdot 10^{-4}$

* at natural conditions

Table 6-6. Selected results from the rinse pumping activities with PSS in section 386–391 m in KFM03A.

Phase of flow period	Duration (days)	Q_p (L/min)	s_w (m)	Q_p/s_w (m^2/s)
First	11.9	19.2	1.425	$2.25 \cdot 10^{-4}$
Second	12.9	28.5	1.593	$2.97 \cdot 10^{-4}$

The final flow rate Q_p, drawdown s_w and specific capacity Q_p/s_w from the flow period of the rinse pumping with PSS in section 386–391 m in KFM03A are shown in Table 6-6. As discussed in Section 5.2.2, the flow period was divided into two phases due to a pump failure. During the second phase of the flow period, the specific flow was slightly higher than during the first phase. The reasons to this fact are not clear. It might possibly be an effect of the rinsing capability of the pumping.

The comparison between the results from the stepwise flow measurements in conjunction with the difference flow logging and the rinse pumping activities with PSS is not straightforward in this borehole section, mainly due to the significantly different magnitude of drawdown applied by the two types of investigations. Nevertheless, the estimated specific flow at the lowest drawdown (step 2) at the stepwise pumping in conjunction with difference flow logging in Table 6-5 is in good agreement with the calculated specific flow from the first phase of the flow period during the rinse pumping with PSS in Table 6-6.

6.5.2 Section 448–453 m

The estimated transmissivity of this section from the difference flow logging indicated that a higher flow rate could be pumped from the section compared to the actual flow rate by PSS during the rinse pumping. The latter pumping was carried out at a much higher drawdown than was used during the difference flow logging, cf Table 6-7. Therefore, a test with four pressure drawdown steps was carried out with PSS after the recovery period from the rinse pumping in this section. The main aim of this test was to study the flow rate behaviour at different drawdown conditions to get indications of possible head losses (e.g. turbulence) at increasing drawdown. Another aim of the test was to obtain a relevant basis for comparison of the estimated transmissivity from the rinse pumping and the difference flow logging with the same drawdown applied (c 6.3 m). During each step, the pressure was kept constant. The duration of each step was c 15 min. The flow rate during each step was almost constant, see Figure A2:12 in Appendix 2.

The results from the difference flow logging (PFL-DIFF), rinse pumping with PSS (PSS-Pumping) and the step drawdown test with PSS (PSS-Step test) are shown in Table 6-7. The first and second phases of the PSS-pumping refer to the periods before and after the power failures, cf Section 5.2.2. The transmissivity of the fracture calculated from difference flow logging (T_D) and from Moye's formula from the rinse pumping (T_M) are also shown in Table 6-7.

Table 6-7 firstly demonstrates that the specific flow (Q/s_w) during the step drawdown test decreases with increasing drawdown in the tested section due to head losses, possibly turbulent flow in the fracture. Thus, it may not always be possible to "scale up" the flow rate proportionally from estimated specific flows at a lower drawdown. This phenomenon is discussed to some extent in Sections 5.3–4 in /5/.

Secondly, Table 6-7 shows that the estimated specific flow from the difference flow logging ($6.48 \cdot 10^{-6}$) is c 2.8 times higher than that from the step drawdown test with PSS at similar drawdown ($2.33 \cdot 10^{-6}$). The reason to this deviation in results at similar drawdown is not clear. Although rather high, the deviation might be within the uncertainty interval of the two methods. At larger drawdown, the difference between the two methods is higher (a factor of c 6 at step #4). This fact probably depends on head losses (e.g. turbulence) in the fracture at increased drawdown.

Table 6-7. Results from difference flow logging (PFL-DIFF), rinse pumping (PSS-Pumping) and step drawdown test with PSS (PSS-Step test) in borehole section 448–453 m in KFM03A.

Method	Phase/ Step #	Drawdown s_w (m)	Flow rate Q_p (L/min)	Q_p/s_w (m^2/s)	T_D (m^2/s)	T_M (m^2/s)
PFL-DIFF		6.2	2.4	$6.48 \cdot 10^{-6}$	$6.65 \cdot 10^{-6}$ *	
PSS-Pumping	1st phase	30.9	2.0	$1.09 \cdot 10^{-6}$		$9.00 \cdot 10^{-7}$ **
PSS-Pumping	2nd phase	30.7	2.4	$1.31 \cdot 10^{-6}$		$1.08 \cdot 10^{-6}$ **
PSS-Step test	1	6.3	0.882	$2.33 \cdot 10^{-6}$		
PSS-Step test	2	12.1	1.27	$1.75 \cdot 10^{-6}$		
PSS-Step test	3	24.1	1.78	$1.23 \cdot 10^{-6}$		
PSS-Step test	4	35.2	2.96	$1.02 \cdot 10^{-6}$		

* calculated from the difference flow logging /1/

** calculated according to Moye's formula

6.6 Conclusions

The long-term rinse pumping with PSS in section 386–391 m in KFM03A confirmed the high transmissivity of the fracture zone at c 388.6 m, identified from the previous difference flow logging. The estimated transmissivity of this fracture zone is $2–3 \cdot 10^{-4}$ m^2/s from both the stepwise flow measurements in conjunction with difference flow logging and the rinse pumping with PSS.

The fracture zone at c 388.6 m has a transmissivity above the measurement limit for quantitative evaluation from standard difference flow logging /5/. However, as was made in KFM03A, repeated flow measurements in a short section across the fracture zone may be performed with the DIFF probe in conjunction with standard difference flow logging. Such measurements were made at certain flow steps with a very low drawdown in the borehole. The results of these flow measurements at the fracture zone at c 388.6 m were consistent with the results of the rinse pumping with PSS.

The specific flow (and transmissivity) of section 448–453 m in KFM03A was estimated at $1–2 \cdot 10^{-6}$ m^2/s from the rinse pumping with PSS, including a step drawdown test, to be compared with an estimated transmissivity of c $7 \cdot 10^{-6}$ m^2/s from the difference flow logging in this section. During both the flow- and recovery period of the rinse pumping, nearly steady-state conditions developed at rather short times with stable flow rate and pressure.

Thus, the specific flow rate in section 448–453 m was c 3 times lower with PSS than was obtained from the difference flow logging at similar drawdown. At higher drawdown the specific flow decreased further, possibly due to turbulent flow in the fracture at c 451.3 m or other head losses. Thus, a non-linear relationship between pressure and flow rate was observed in this section. Similar conditions were also indicated during the stepwise flow measurements in section 386–391 m with the DIFF probe.

By the end of the flow period in borehole section 386–391 m, effects of a constant-head boundary are indicated. In borehole section 448–453 m, a pseudo-steady-state flow was rapidly achieved during both the flow- and recovery period. No effects of hydraulic no-flow boundaries were detected during the long-term rinse pumping with PSS in the two borehole sections. This fact may indicate that the assumed fracture zones at c 388.6 m and 451.3 m are extensive in the lateral direction.

Both the pressure and flow rate transient histories from the two test sections were affected by variations in section pressure during the pumping with PSS, particularly in section 386–391 m due to the relatively low drawdown (c 1.5 m) applied. The variations are probably mainly caused by natural variations of the sea water level in the adjacent Baltic Sea and in atmospheric pressure. This indicates that the assumed fracture zone at c 388 m in KFM03A is hydraulically connected to the Baltic Sea. In addition, variations in tidal effects may also have influenced the test responses.

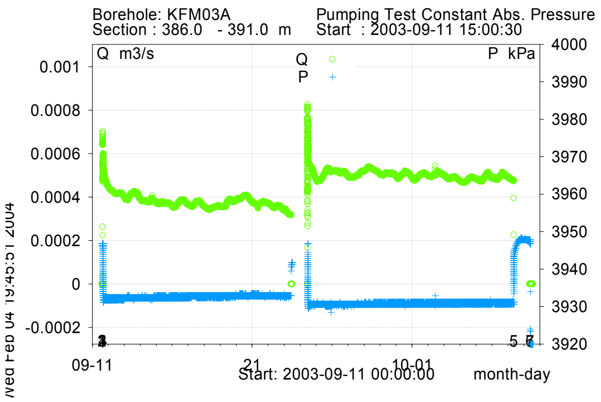
To investigate the influence of external variables (sea water level, atmospheric pressure, tidal variations etc) on the measured parameters in the tested sections in borehole KFM03A, it would have been expedient to analyse natural pressure measurements, undisturbed from human activities, in the sections. If this is of further interest, one of the sections, or both, should be isolated for long-term groundwater pressure monitoring when a multi-packer system is installed in the borehole.

No measurable pressure interference between the private well at Lillfjärden and section 386–391 m in KFM03A was observed during the rinse pumping with PSS. However, a measurable response at a higher pumping rate cannot be excluded. As for the flow rate and absolute pressure in section 386–391 m, the gauge pressure in the private well is clearly correlated to the Baltic Sea level.

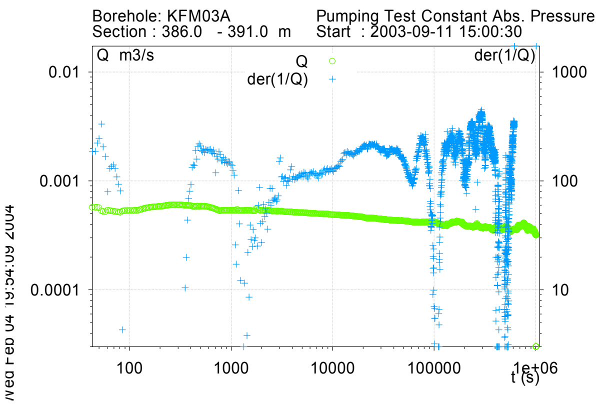
Test Summary Sheet – Pumping borehole KFM03A

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	KFM03A	Test start:	2003-09-11 15:00
Test section (m):	386.0-391.0	Responsible for test performance:	GEOSIGMA AB J Källgården, T Svensson, J Olausson
Section diameter, $2 \cdot r_w$ (m):	0.077	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

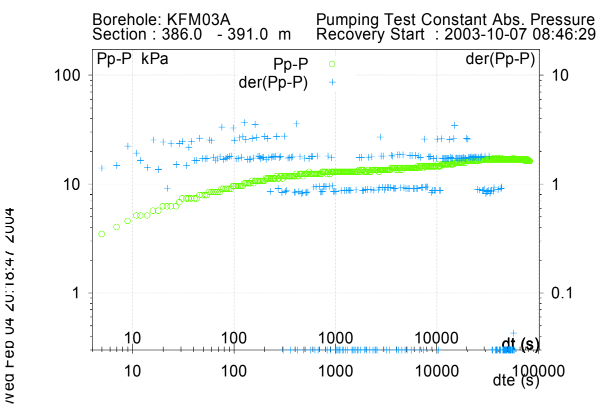
Lin-Lin plot – Entire test period



Log-Log plot incl. derivative- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)	3946.72		
p_i (kPa)	3946.72		
p_p (kPa)	3931.09	p_F (m.a.s.l.)	3947.28
Q_p (m^3/s)	$4.76 \cdot 10^{-4}$		
tp (min)	35597	t_F (min)	1466
S^*	$1 \cdot 10^{-6}$	S^*	$1 \cdot 10^{-6}$
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	$2.97 \cdot 10^{-4}$		
T_M (m^2/s)	$2.44 \cdot 10^{-4}$		
Flow regime:	PRF	Flow regime:	PRF?
t_1 (min)	150	t_1 (min)	0.03
t_2 (min)	15000	t_2 (min)	5
T_w (m^2/s)	$3.06 \cdot 10^{-4}$	T_w (m^2/s)	$2.15 \cdot 10^{-4}$
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	-	C (m^3/Pa)	-
C_D (-)	-	C_D (-)	-
ξ (-)	-5.52	ξ (-)	-6.1
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

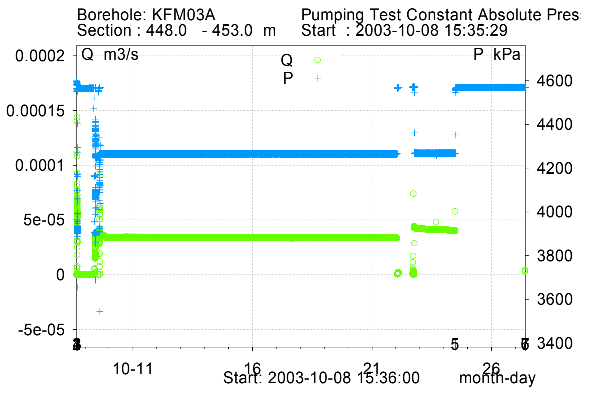
Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	10000	C_D (-)	-
t_2 (min)	1000000	ξ (-)	-5.52
T_T (m^2/s)	$3.06 \cdot 10^{-4}$		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Pseudo-radial flow developed after c. 10000 s (150 min) during the flow period. By the end of the flow period effects of a constant head boundary are indicated. Cyclic trends, probably caused by natural variations of the atmospheric pressure and sea water level, affected both the pressure and flow rate during the entire test sequence.

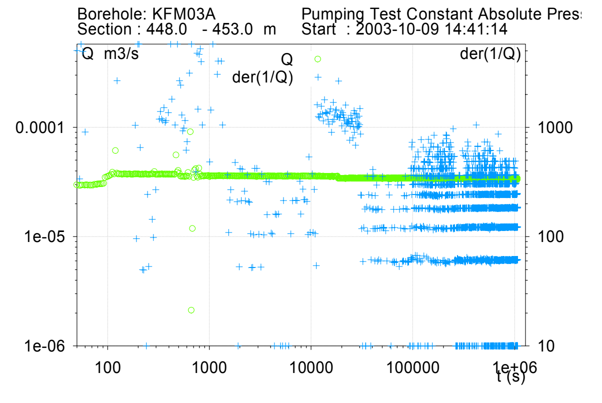
Test Summary Sheet – Pumping borehole KFM03A

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	KFM03A	Test start:	2003-10-09 14:41
Test section (m):	448.0-453.0	Responsible for test performance:	GEOSIGMA AB J Levén, T Svensson
Section diameter, $2 \cdot r_w$ (m):	0.077	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

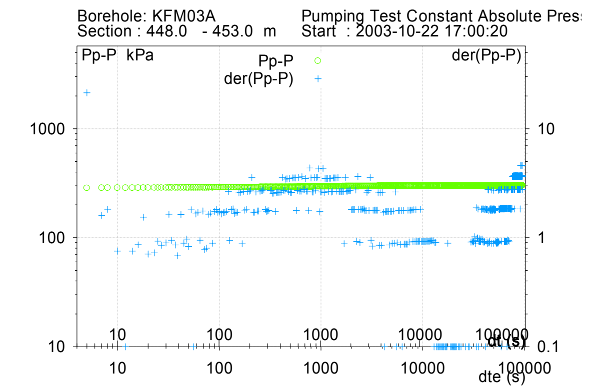
Lin-Lin plot – Entire test period



Log-Log plot incl. derivative- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)	4566.79		
p_i (kPa)	4566.23		
p_p (kPa)	4268.25	p_F (kPa)	4569.55
Q_p (m^3/s)	$4.01 \cdot 10^{-5}$		
tp (min)	20363	t_F (min)	4288
S^*	$1 \cdot 10^{-6}$	S^*	$1 \cdot 10^{-6}$
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	$1.31 \cdot 10^{-6}$		
T_M (m^2/s)	$1.08 \cdot 10^{-6}$		
Flow regime:	PSS	Flow regime:	PSS
t_1 (min)	-	t_1 (min)	-
t_2 (min)	-	t_2 (min)	-
T_w (m^2/s)	-	T_w (m^2/s)	-
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	-	C (m^3/Pa)	-
C_D (-)	-	C_D (-)	-
ξ (-)	-	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

Flow regime:	PSS	C (m^3/Pa)	-
t_1 (min)	-	C_D (-)	-
t_2 (min)	-	ξ (-)	-
T_T (m^2/s)	-		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: During both the flow and recovery period almost pseudo-steady-state flow conditions occurred rapidly, persisting to the end of the periods.

7 References

/1/ **Rouhiainen P, Pöllänen J, 2003.** Forsmark Site Investigation – Difference Flow measurements in borehole KFM03A. Report P-03-xx, Svensk Kärnbränslehantering AB.

/2/ **Ludvigson J-E, 2002.** Brunnsinventering i Forsmark (In Swedish). Rapport R-02-17, Svensk Kärnbränslehantering AB.

/3/ **Almén K-E, Andersson J-E, Carlsson L, Hansson K, Larsson N-Å, 1986.** Hydraulic testing in crystalline rock. A comparative study of single-hole test methods. Technical Report 86-27, Svensk Kärnbränslehantering AB.

/4/ **Morosini M, Almén, K-E, Follin S, Hansson K, Ludvigson J-E, Rhén I, 2001.** Metoder och utrustningar för hydrauliska enhålstester – Metod och programaspekter för geovetenskapliga platsundersökningar. (In Swedish). Rapport TD-01-63, Svensk Kärnbränslehantering AB.

/5/ **Ludvigson J-E, Hansson K, Rouhiainen P, 2003.** Methodology study of Posiva difference flow meter in borehole KLX02 at Laxemar. Report R-01-52, Svensk Kärnbränslehantering AB.

Appendix 1

Test data files

Bh ID	Test section (m)	Test type[1]	Test start Date, time YYYY-MM-DD tt:mm	Test stop Date, time YYYY-MM-DD tt:mm	Datafile, start Date, time YYYY-MM-DD tt:mm:ss	Datafile, stop Date, time YYYY-MM-DD tt:mm:ss	Data files of raw and primary data	Selected Parameters measured	Comments
KFM03A	386-391	1B	2003-09-11 15:00	2003-09-23 12:25	2003-09-11 15:00	2003-09-23 12:25	__KFM03A_0386.00_200309111500.ht2	Q, P, Te	
KFM03A	386-391	1B	2003-09-24 11:08	2003-10-08 13:32	2003-09-24 11:08	2003-10-08 13:32	__KFM03A_0386.00_200309241108.ht2	Q, P, Te	
KFM03A	386-391	1B	2003-09-11 15:00	2003-10-08 13:29	2003-09-11 15:00	2003-10-08 13:29	__KFM03A_0386.00_030911-031008.ht2	Q, P, Te	
KFM03A	448-453	1B	2003-10-09 14:41	2003-10-22 02:59	2003-10-09 14:41	2003-10-22 02:59	__KFM03A_0448.00_200310091441.ht2	Q, P, Te	
KFM03A	448-453	1B	2003-10-22 17:00	2003-10-27 09:59	2003-10-22 17:00	2003-10-27 09:59	__KFM03A_0448.00_200310221700.ht2	Q, P, Te	
KFM03A	448-453	1B	2003-10-27- 11:07	2003-10-27 12:19	2003-10-27- 11:07	2003-10-27 12:19	__KFM03A_0448.00_200310271107.ht2	Q, P, Te	
KFM03A	448-453	1B	2003-10-08 15:35	2003-10-27 09:59	2003-10-08 15:35	2003-10-27 09:59	__KFM03A_0448.00_031008-031027.ht2	Q, P, Te	

1: 1B: Pumping test-submersible pump

Test data diagrams

The following diagrams are presented for each test:

a) Overview of entire test sequence- lin-lin diagram

b) Flow period – log-log and lin-log diagram

c) Recovery period – log-log and lin-log diagram

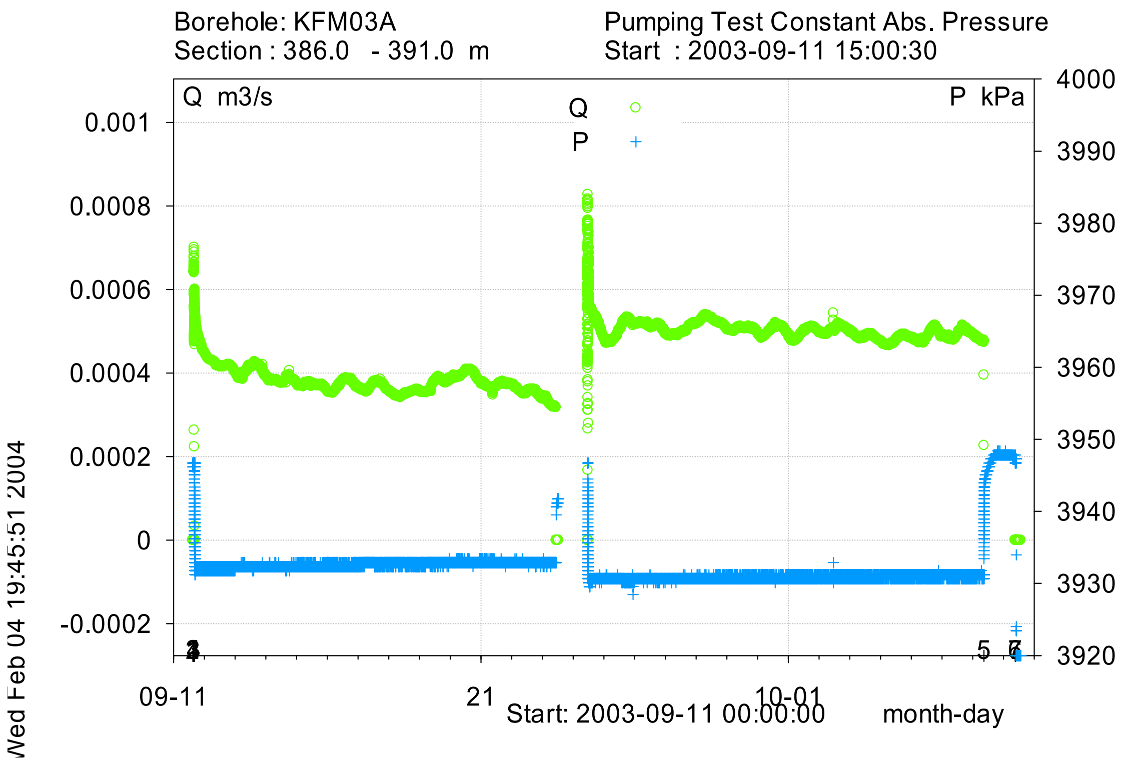


Figure A2:1. *Linear plot of absolute pressure (p) and flow rate (Q) versus absolute time during the pumping test in section 386-391 m in borehole KFM03A.*

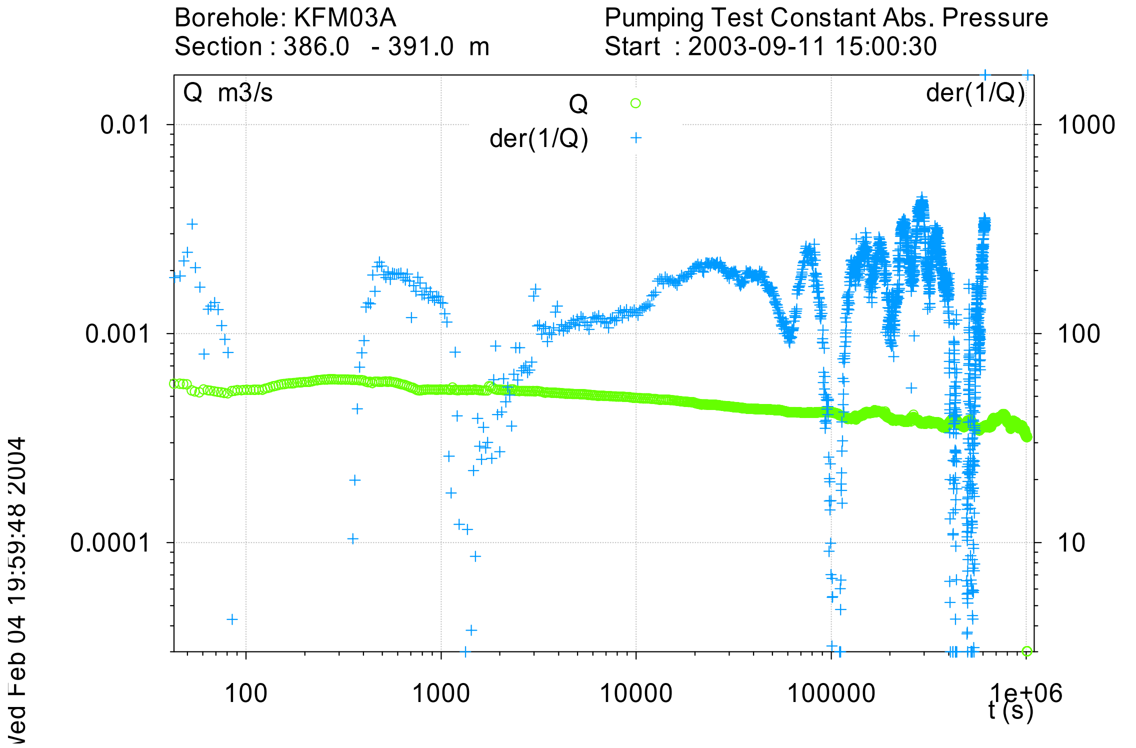


Figure A2:2. *Log-log plot of flow rate (Q) and derivative, d(1/Q)/d(ln t), versus time (t) during the pumping test in section 386-391 m in borehole KFM03A.*

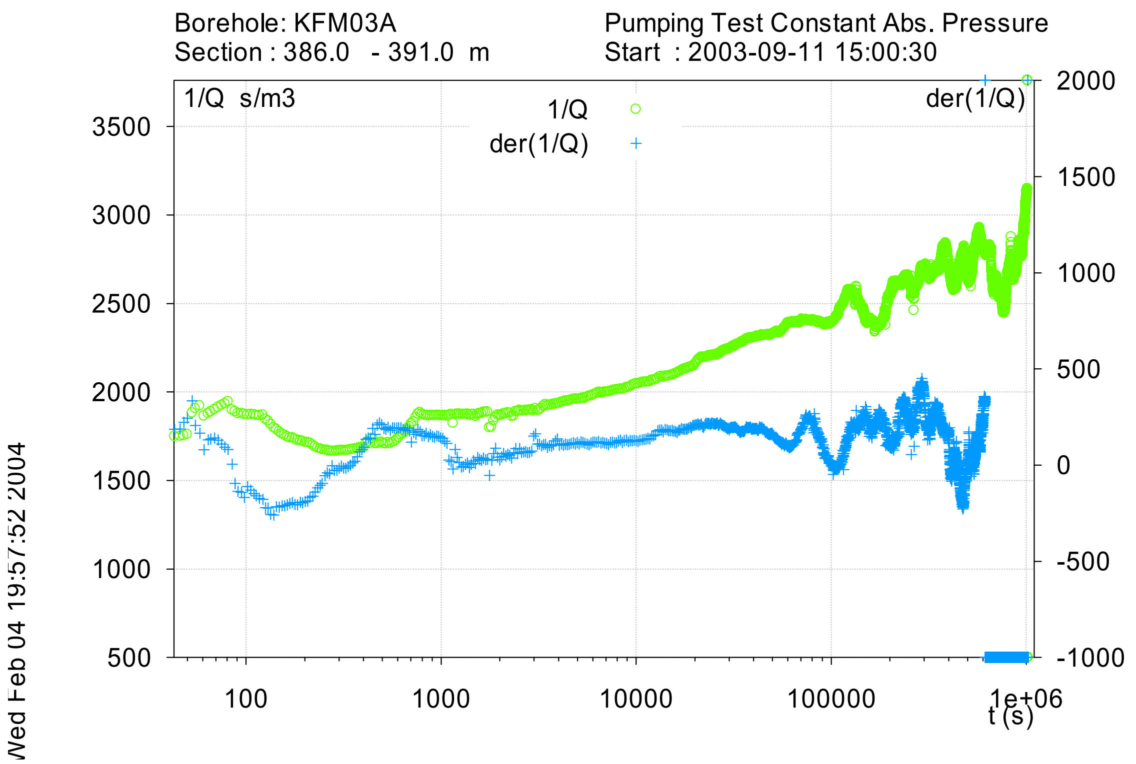


Figure A2:3*. Lin-log plot of reciprocal flow rate (1/Q) and derivative, d(1/Q)/d(ln t), versus time (t) during the pumping test in section 386-391 m in borehole KFM03A .*

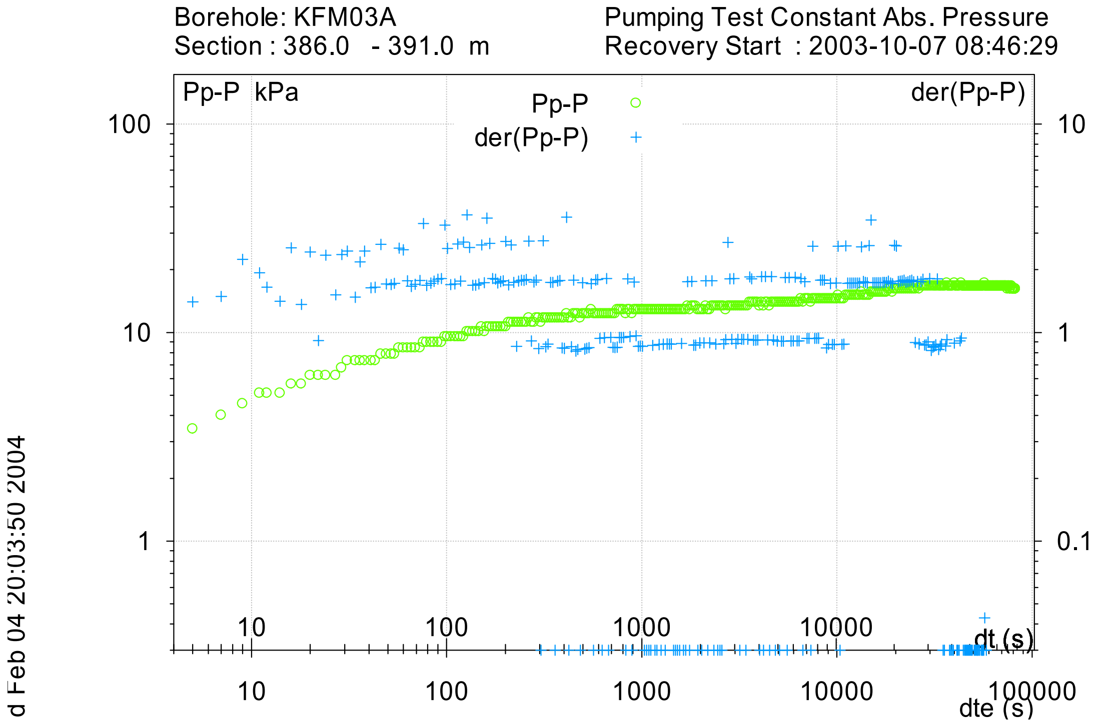


Figure A2:4. *Log-log plot of pressure recovery (p-p$_p$) and - derivative d(p-p$_p$)/d(ln dte) versus equivalent time (dt$_e$) during the pumping test in section 386-391 m in borehole KFM03A.*

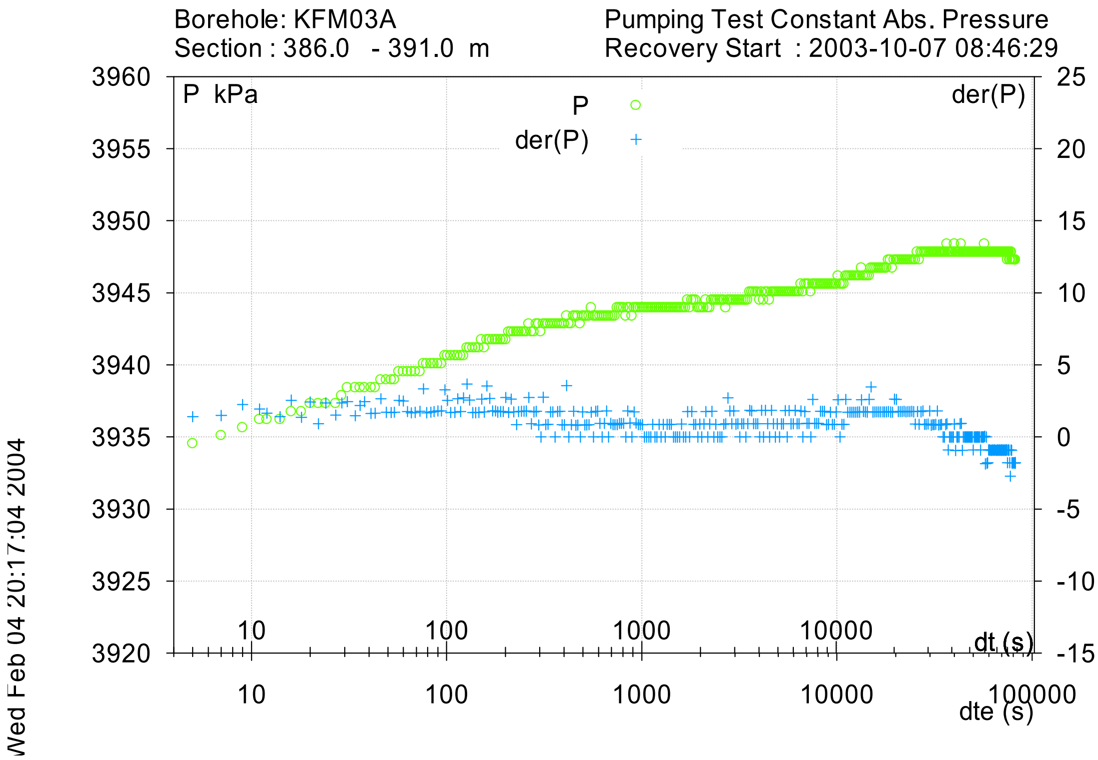


Figure A2:5. *Lin-log plot of pressure recovery (p) and - derivative d(p)/d(ln dte) versus equivalent time (dt$_e$) during the pumping test in section 386-391 m in borehole KFM03A.*

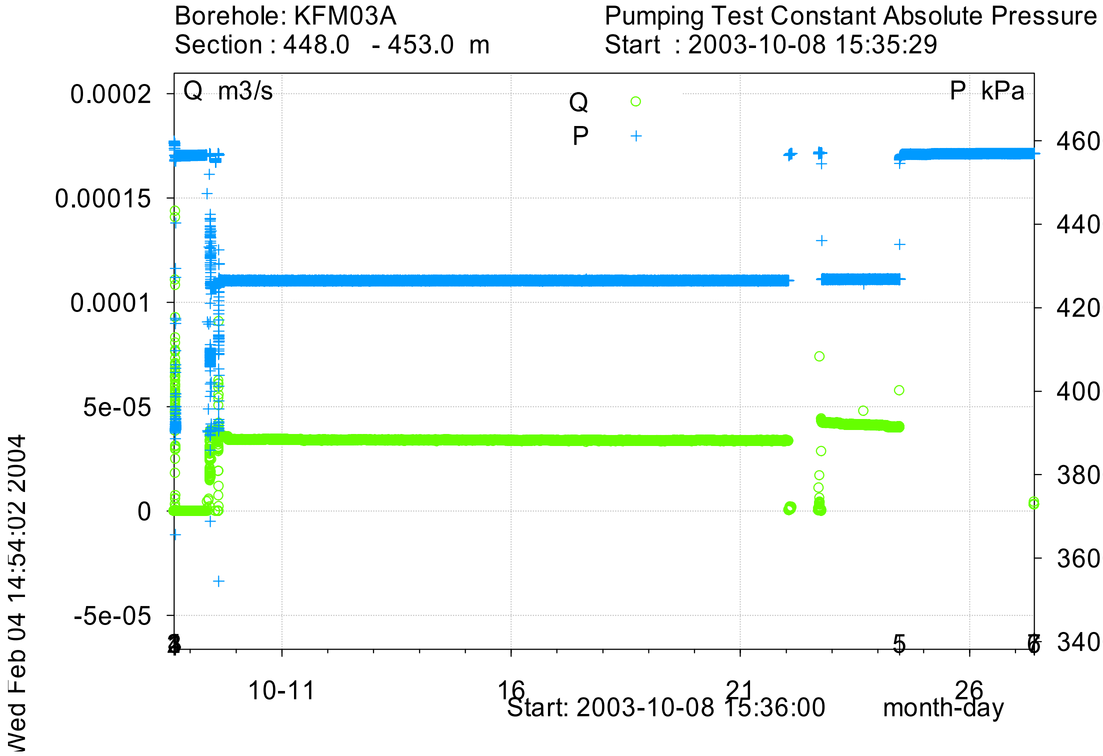


Figure A2:6. *Linear plot of absolute pressure (p) and flow rate (Q) versus absolute time during the pumping test in section 448-453 m in borehole KFM03A.*

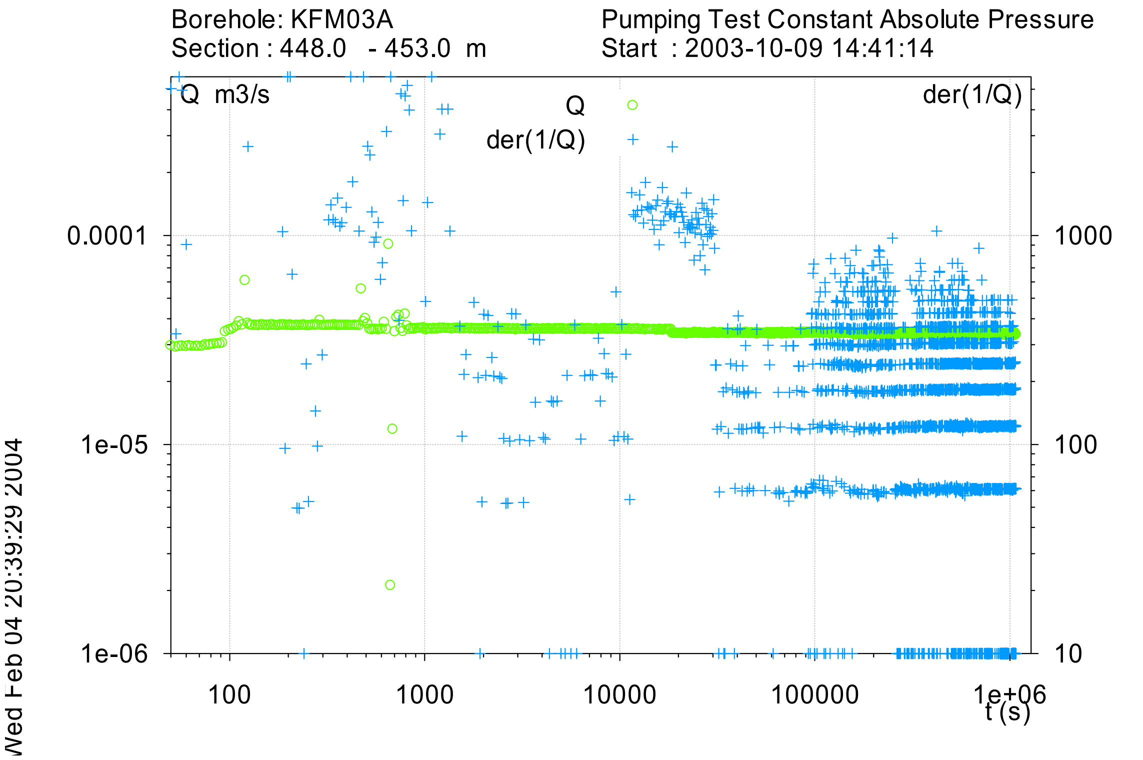


Figure A2:7. *Log-log plot of flow rate (Q) and derivative, d(1/Q)/d(ln t), versus time (t) during the pumping test in section 448-453 m in borehole KFM03A.*

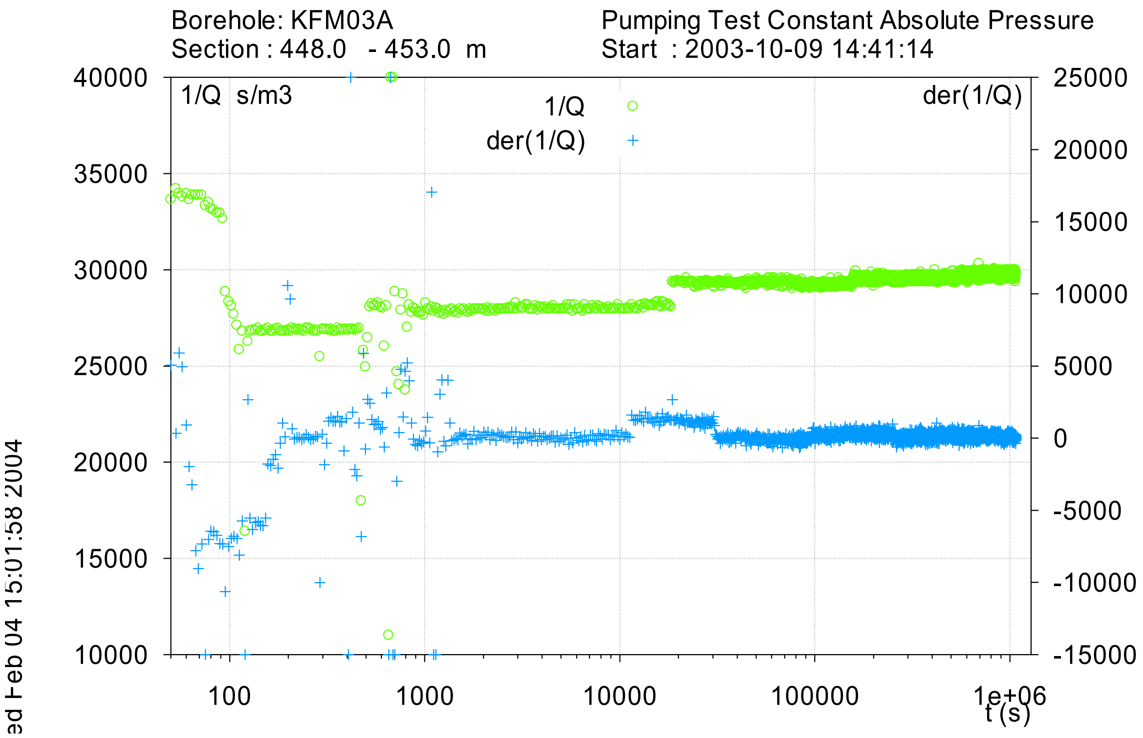


Figure A2:8. *Lin-log plot of reciprocal flow rate (1/Q) and derivative, d(1/Q)/d(ln t), versus time (t) during the pumping test in section 448-453 m in borehole KFM03A .*

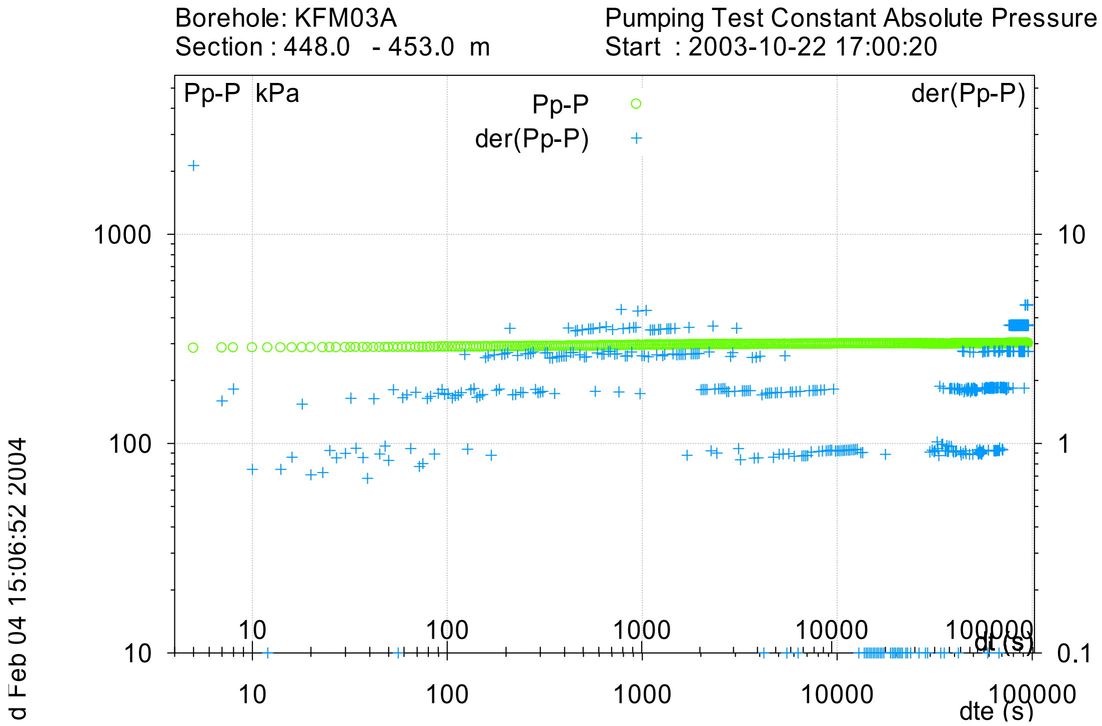


Figure A2:9. *Log-log plot of pressure recovery (p-p_p) and - derivative d(p-p_p)/d(ln dte) versus equivalent time (dt_e) during the pumping test in section 448-453 m in borehole KFM03A.*

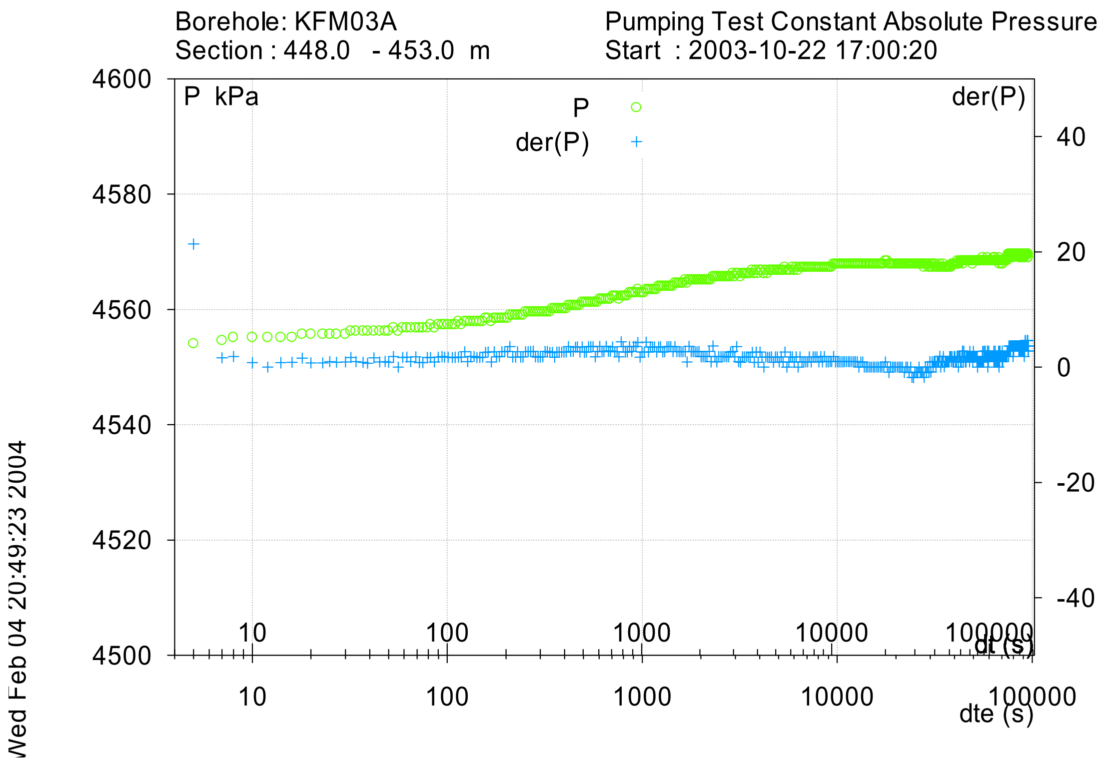


Figure A2:10. *Lin-log plot of pressure recovery (p) and - derivative d(p)/d(ln dte) versus equivalent time (dt_e) during the pumping test in section 448-453 m in borehole KFM03A.*

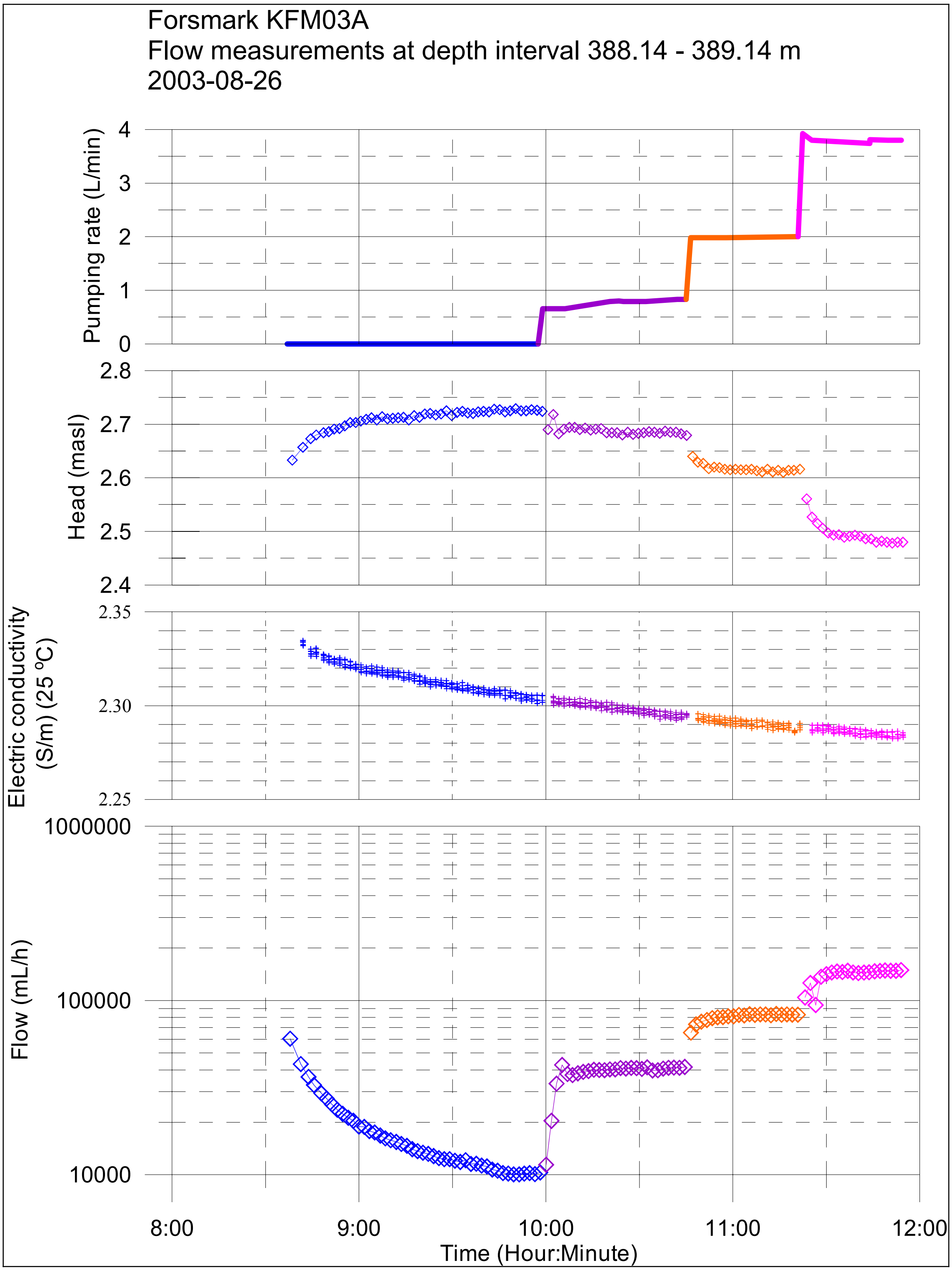


Figure A2:11. *Lin-lin plot of measured flow rate from fracture and EC-fracture together with freshwater head and pumping rate versus time during the step flow test in section 388.14-389.14 m during difference flow logging in borehole KFM03A. From /1/.*

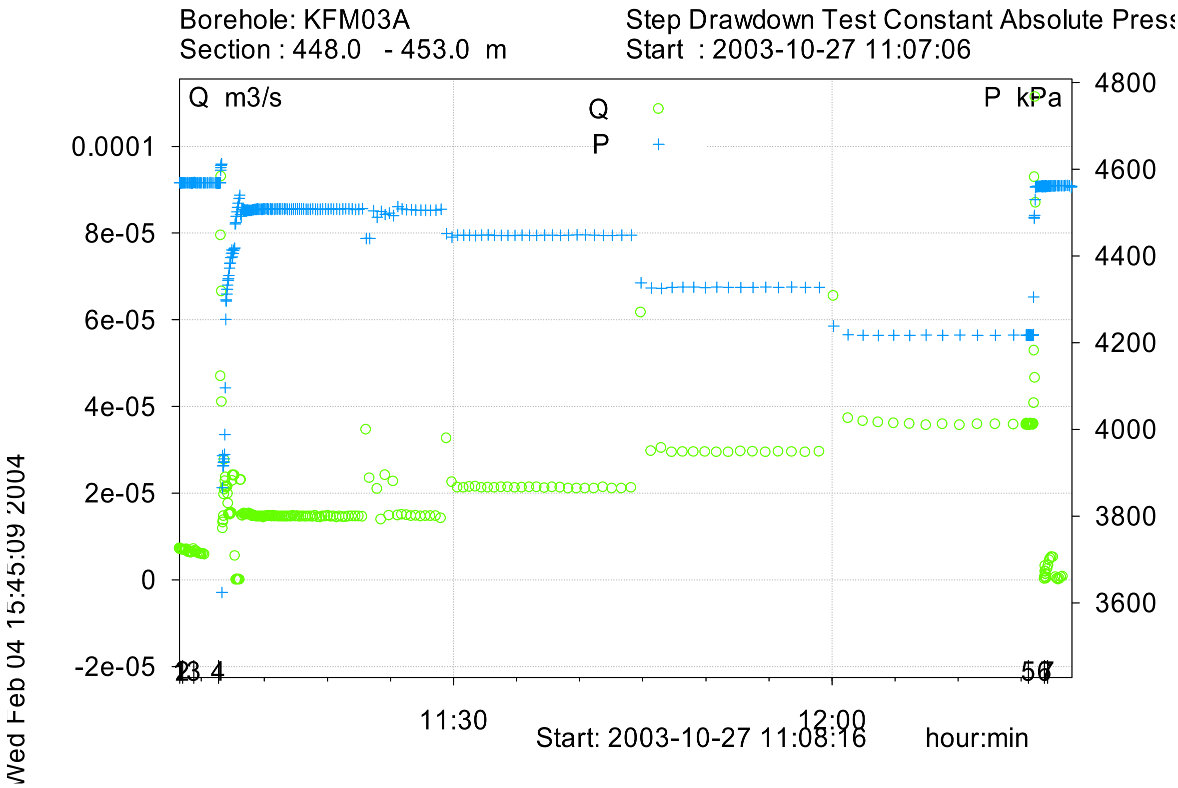


Figure A2:12. *Lin-lin plot of absolute pressure (p) and flow rate (Q) versus absolute time during the step drawdown test in section 448-453 m in borehole KFM03A.*

Appendix 3

Parameter file to SICADA

Parameter file to SICADA of results from single-hole pumping tests with PSS in borehole KFM03A prior to hydro-geochemical sampling.

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_d; General information

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	Date and time for test, start YYYYMMDD hh:mm	Date and time for test, stop YYYYMMDD hh:mm	Date and time of flow/ injection, start YYYYMMDD hh:mm:ss	Date and time of flow/ injection, stop YYYYMMDD hh:mm:ss	Q_p (m**3/s)	Value type-Q_p (-1,0,1)	Q-measl-L (m**3)/s	Q-measl-U (m**3)/s
KFM03A	386.00	391.00	1B	1	2003-09-11 15:00	2003-10-08 13:30	2003-09-11 16:04:00	2003-10-07 08:46:04	4.76E-04	0	1.7E-05	5.0E-04
KFM03A	448.00	453.00	1B	1	2003-10-09 14:41	2003-10-27 09:59	2003-10-09 14:53:51	2003-10-24 11:28:12	4.01E-05	0	1.7E-05	5.0E-04

cont.

V_p (m**3)	Q_m (m**3/s)	tp (s)	t_F (s)	h_i (m a sl)	h_p (m a sl)	h_F (m a sl)	p_i (kPa)	p_p (kPa)	p_F (kPa)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	TDS_{wm} (mg/ L)	Reference	Comments (-)
944.5	4.42E-04	2135820	87960				3946.72	3931.09	3947.28						
42.4	3.47E-05	1221780	257280				4566.79	4268.25	4569.55						

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_ed1; Basic evaluation

Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YYYYMMDD hh:mm	Q/s (m^2/s)	Value type-Q/s (-1, 0, 1)	T_Q (m^2/s)	T_M (m^2/s)	b (m)	B (m)	TB (1D) (m^3/s)	TB-measl-L (1D) (m^3/s)	TB-measl-U (1D) (m^3/s)	SB (1D) (m)	SB* (1D) (m)	L_f (1D) (m)	T_T (2D) (m^2/s)	Value type-T_T (-1, 0, 1)
KFM03A	386.00	391.00	2003-09-11 15:00	2.97E-04	0		2.44E-04	5								3.06E-04	0
KFM03A	448.00	453.00	2003-10-09 14:41	1.31E-06	0		1.08E-06	5									0

cont.

Q/s-measl-L (m^2/s)	Q/s-measl-U (m^2/s)	S (2D) (-)	S* (2D) (-)	K′/b′ (2D) (1/s)	K_S (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	L_p (m)	C (m**3/Pa)	C_D (-)	ξ (2D) (-)	ω (-)	λ (-)	t_1 (s)	t_2 (s)	Comments (-)
5.00E-07	1.00E-03		1.00E-06										-5.52			10000	2135820	
5.00E-07	1.00E-03		1.00E-06															

Header	Unit	Explanation
Borehole		ID for borehole
Borehole secup	m	Length coordinate along the borehole for the upper limit of the test section
Borehole seclow	m	Length coordinate along the borehole for the lower limit of the test section
Test type (1- 7)	(-)	1A: Pumping test - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumpingtest-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-sequential, 5B: Difference flow logging-PFL-DIFF-overlapping, 6:Flow logging_Impeller,7:Grain size analysis
Date for test start		Date for the start of the pumping or injection test (YYYYMMDD hh:mm)
Start flow / injection		Date and time for the start of the pumping or injection period (YYMMDD hh:mm:ss)
Start flow / injection		Date and time for the end of the pumping or injection period (YYMMDD hh:mm:ss)
Q_m	m^3/s	Arithmetric mean flow rate of the pumping/injection period.
Q_p	m^3/s	Flow rate at the end of the pumping/injection period.
Value type	-	Code for Q_p-value; -1 means Q_p<lower measurement limit, 0 means measured value, 1 means Q_p> upper measurement value of flowrate
Q-measl_L	m^3/s	Estimated lower measurement limit for flow rate
Q-measl_U	m^3/s	Estimated upper measurement limit for flow rate
V_p	m^3	Total volume pumped (positive) or injected (negative) water during the flow period.
t_p	s	Time for the flowing phase of the test
t_F	s	Time for the recovery phase of the test
h_i	m	Initial formation hydraulic head. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_p	m	Final hydraulic head at the end of the pumping/injection period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_F	m	Final hydraulic head at the end of the recovery period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
p_i	kPa	Initial formation pressure.
p_p	kPa	Final pressure at the end of the pumping/injection period.
p_F	kPa	Final pressure at the end of the recovery period.
Te_w	gr C	Fluid temperature in the test section representative for the evaluated parameters
EC_w	mS/m	Electrical conductivity of the fluid in the test section representative for the evaluated parameters
TDS_w	mg/L	Total salinity of the fluid in formation at test section based on EC.
TDS_{wn}	mg/L	Total salinity of the fluid in formation at test section based on water sampling and chemical analysis.
Sec.type,	(-)	Test section (pumping or injection) is labeled 1 and all observation sections are labeled 2
Q/s	m2/s	Specific capacity, based on Qp and s=abs(pi-pp). Only given for test section (label 1) in interference test.
T_Q	m2/s	Steady-state transmissivity based on specific capacity and a function for T=f(Q/s). The function used should be referred in "Comments"
T_M	m2/s	Steady-state transmissivity based on Moye (1967)
b	m	Interpreted formation thickness representative for evaluated T ot TB.
B	m	Interpreted witdth of a formation with evaluated TB
TB	m3/s	1D model for evaluation of formation properties. T=transmissivity, B=width of formation
TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or less than TB-measlim

Header	Unit	Explanation
TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or greater than TB-measlim
SB	m	1D model for evaluation of formation properties. S= Storativity, B=width of formation
SB*	m	1D model for evaluation of formation properties. Assumed SB. S= Storativity, B=width of formation
L_f	m	1D model for evaluation of Leakage factor
T_T	m2/s	2D model for transient evaluation of formation properties. T=transmissivity
T-measl-L	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or less than T-measlim
T-measl-U	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or grater than T-measlim
S	(-)	2D model for evaluation of formation properties. S= Storativity
S*	(-)	2D model for evaluation of formation properties. Assumed S. S= Storativity
K´/b´	(1/s)	2D model for evaluation of leakage coefficient. K´= hydraulic conductivity in direction of leaking flow for the aquitard, b´= Saturated thickness of aquitard (leaking formation)
K_S	m/s	3D model for evaluation of formation properties. K=Hydraulic conductivity
K_S-measl-L	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or less than KS-measlim
K_S-measl-U	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or greater than KS-measlim
S_S	1/m	3D model for evaluation of formation properties. Ss=Specific Storage
S_S*	1/m	3D model for evaluation of formation properties. Assumed Ss. Ss=Specific Storage
L_p	m	Hydraulic point of appication, based on hydraulic conductivity distribution (if available) or the midpoint of the borehole test section
C	(m3/Pa)	Wellbore storage coefficient
C_D	(-)	Dimensionless wellbore storage coefficient
ξ	(-)	Skin factor
ω	(-)	Storativity ratio
λ	(-)	Interporosity flow coefficient
dt_1	s	Estimated start time after pump/injection start OR recovery start, for the period used for the evaluated parameter
dt_2	s	Estimated stop time after pump/injection start OR recovery start, for the period used for the evaluated parameter
	m	Length coordinate along the borehole for the upper limit of the observation section
	m	Length coordinate along the borehole for the lower limit of the observation section
p_{ai}	kPa	Initial formation pressure of the observation section, which is located above the test section in the borehole
p_{ap}	kPa	Final pressure at the end of the pumping/injection period in the observation section, which is located above the test section in the borehole
p_{aF}	kPa	Final pressure at the end of the recovery period in the observation section, which is located above the test section in the borehole
p_{bi}	kPa	Initial formation pressure of the observation section, which is located below the test section in the borehole
p_{bp}	kPa	Final pressure at the end of the pumping/injection period in the observation section, which is located below the test section in the borehole
p_{bF}	kPa	Final pressure at the end of the recovery period in the observation section, which is located below the test section in the borehole
References		SKB report No for reports describing data and evaluation
Index w		Active borehole or borehole section