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Forsmark site investigation

Pumping tests and flow logging

Boreholes HFM09 and HFM10

Jan-Erik Ludvigson, Josef Källgården, Janette Jönsson
Geosigma AB

April 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Abstract

The percussion drilled boreholes HFM09 and HFM10 are drilled at drilling site DS4 at Forsmark. The two boreholes are inclined 69° from the horisontal plane. Pumping tests were performed in these boreholes together with flow logging during February 2004.

The purpose was to investigate the hydraulic properties of the rock in the boreholes e.g. occurrence of sub-horizontal zones. Water sampling was performed to investigate the hydrochemistry of the groundwater in conjunction with the pumping tests. No other borehole tests had been carried out in the actual boreholes before this campaign.

In HFM09 two conductive sections were identified. The transmissivity of these were $4.7 \cdot 10^{-5}$ m^2/s and $3.3 \cdot 10^{-4}$ m^2/s. The total transmissivity of the borehole is about $3.7 \cdot 10^{-4}$ m^2/s. In HFM10 one conductive part was identified with a transmissivity of $3.1 \cdot 10^{-4}$ m^2/s which also is the total transmissivity of the borehole.

Sammanfattning

Hammarborrhålen HFM09 och HFM10 är borrade på borrplats 4 i Forsmark. De två borrhålen är borrade med en lutning av 69° från horisontalplanet. Pumptest och flödesloggning utfördes i båda borrhålen.

Avsikten med mätningarna var att undersöka de hydrauliska egenskaperna hos berget, t ex förekomster av sub-horisontella zoner. Vattenprover togs i båda borrhålen i samband med pumptesten. Inga andra tester hade gjorts i borrhålen innan denna mätkampanj.

I HFM09 identifierades två konduktiva partier. Transmissiviteten i dessa varierade mellan $4{,}7 \cdot 10^{-5}$ m^2/s och $3{,}3 \cdot 10^{-4}$ m^2/s. Borrhålets totala transmissivitet är ca $3{,}7 \cdot 10^{-4}$ m^2/s. I HFM10 påträffades endast ett konduktivt avsnitt med transmissivitet på $3{,}1 \cdot 10^{-4}$ m^2/s vilket också är borrhålets totala transmissiviet.

Contents

1 Introduction

Two boreholes, HFM09 and HFM10, were drilled at drilling site DS4 at Forsmark, see Figure 1-1 and Figure 1-2. HFM10 was drilled with the purpose of serving as flushing water well and HFM09 is to be used for groundwater monitoring. Pumping tests were performed in both boreholes as was water sampling in conjunction with the tests. In addition, flow meter logging was conducted in the boreholes. The pumping tests, flow logging and water sampling were performed during February 2004. No other hydraulic borehole tests had been carried out in the actual boreholes before this campaign.

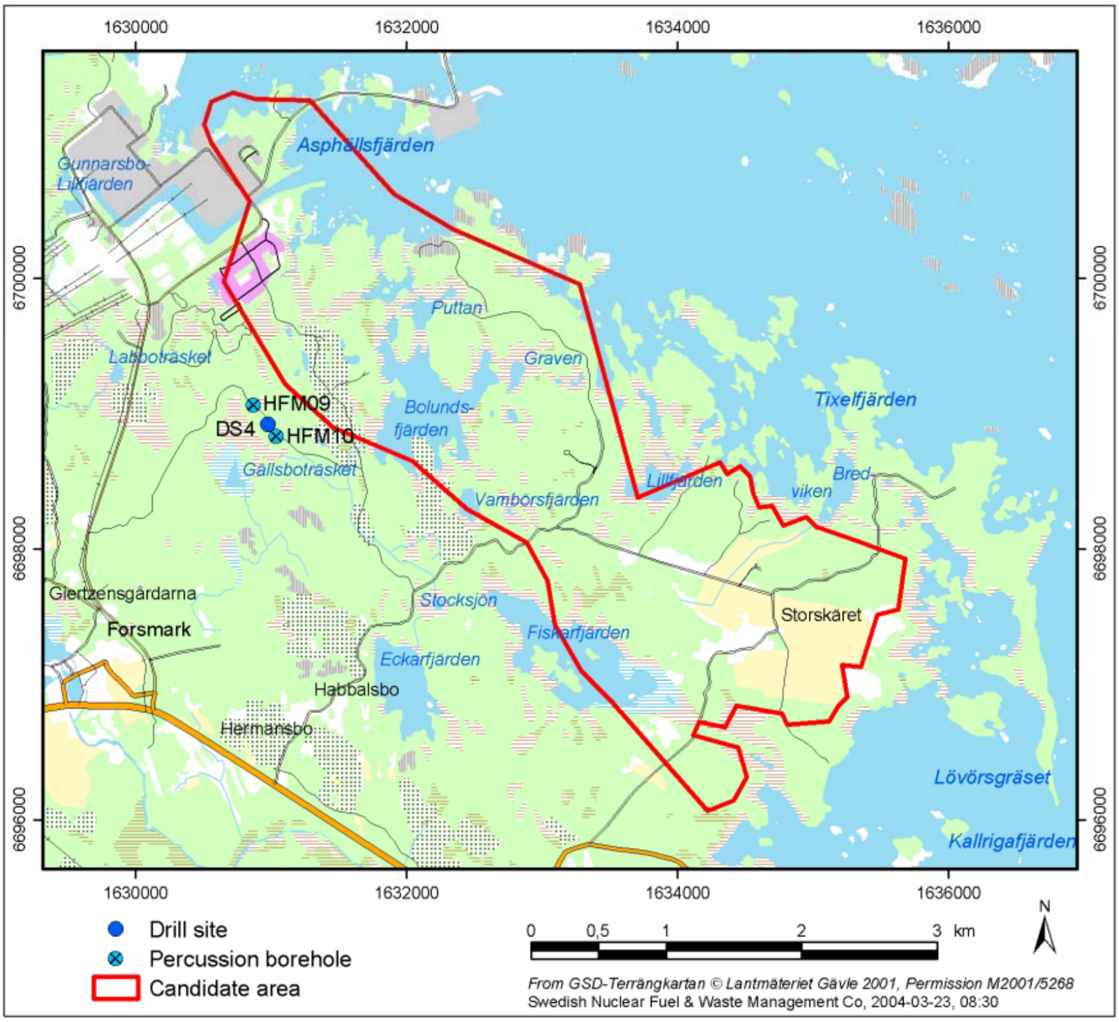


Figure 1-1. *The investigation area at Forsmark including the candidate area selected for more detailed investigations.*

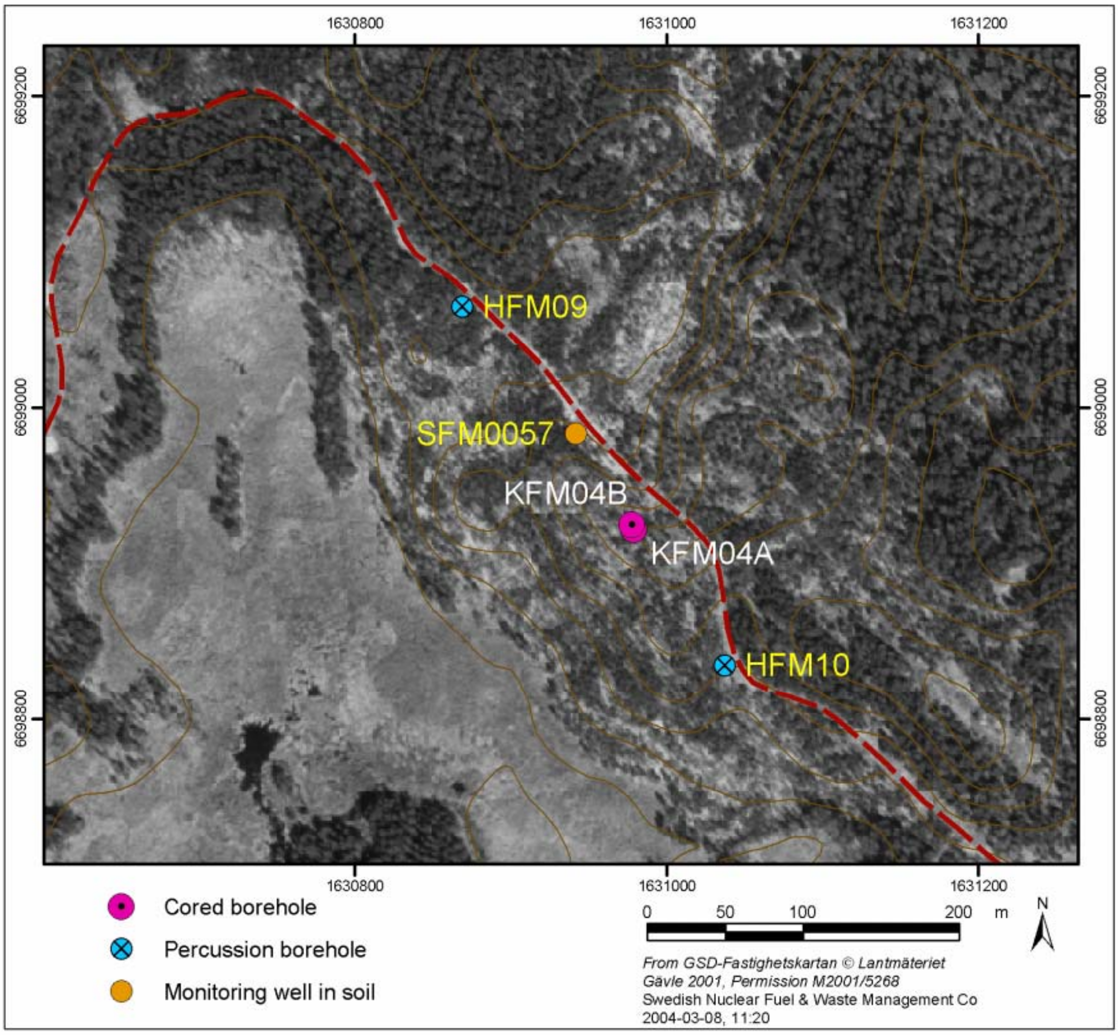


Figure 1-2. *Map showing the location of HFM09 and HFM10 at drilling site DS4 at Forsmark.*

This document reports the results gained by the *Hydraulic testing of boreholes HFM09 and HFM10*. The activity is performed within the Forsmark site investigation. The work was carried out in accordance to SKB internal controlling documents, see Table 1-1. Data and results were delivered to the SKB site characterization database SICADA with field note number: Forsmark 278.

Table 1-1. SKB Internal controlling documents for the performance of the activity.

Activity Plan	Number	Version
Hydraulic testing and water sampling in HFM09 and HFM10	AP PF 400-04-17	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för hydrauliska enhålspumptester	SKB MD 321.003	1.0
Metodbeskrivning för flödesloggning.	SKB MD 322.009	1.0
Mätsystembeskrivning för HydroTestutrustning för Hammarborrhål. HTHB	SKB MD 326.001	1.0

2 Objectives

The main objectives of the single-hole pumping tests and flow logging in HFM09 and HFM10 were to:

- Identify the position and size of inflow sections in the boreholes.
- Estimate the transmissivity of flow anomalies and of the entire boreholes.
- Study the water chemistry of the boreholes.

3 Scope

3.1 Boreholes tested

Selected technical data from the tested boreholes are displayed in Table 3-1. The reference point in the boreholes is always top of casing (ToC). The Swedish National coordinate system (RT90 2.5 gon W) is used in the x-y-direction together with RHB70 in the z-direction. The reported borehole diameter along the borehole is shown in Table 3-1. The borehole diameter (measured as the diameter of the drill bit) may change along the borehole due to wearing of the drill bit or change of drill bit.

The coordinates of the boreholes are shown in Table 3-2. Northing and Easting refer to the intersection of the boreholes with the ground surface.

Table 3-1. Selected technical data of the tested boreholes. (From SICADA).

Borehole data							
Bh 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) (°)**	**Dip-direction-top of borehole (from local N) (°)**	**Remarks**	**Drilling finished Date (YYYY-MM-DD)**
HFM09	5.150	0–17.02	0.1603	–68.899	139.359	Casing ID *	2003-06-30
		17.02–50.25	0.1409			Borehole	
HFM10	4.986	0–11.80	0.160	–68.700	92.934	Casing ID	2003-08-20
		11.80–150.0	0.1399			Borehole	

* Casing ID=inner diameter of casing

Table 3-2. Coordinates of the tested boreholes. (From SICADA).

Borehole data		
Bh ID	**Northing (m)**	**Easting (m)**
HFM09	6699065	1630869
HFM10	6698835	1631037

3.2 Tests performed

Table 3-3. Borehole tests performed.

Borehole tests				
Bh ID	**Test section (m)**	**Test type[1]**	**Test start date and time** (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
HFM09	17.02–50.25	1B	2004-02-17 14:27:14	2004-02-19 09:20:00
	17.02–49.0	6, L-Te, L-EC	2004-02-18 13:35:15	2004-02-18 15:59:46
HFM10	11.80–150.0	1B	2004-02-25 14:02:28	2004-02-26 09:41:01
		6, L-Te, L-EC	2004-02-25 16:02:27	2004-02-25 19:23:41

[1)] 1B: Pumping test-submersible pump, 2: Interference test. 3: Injection test, 6: Flow logging–Impeller. L-EC: EC-logging. L-Te: temperature logging

During the pumping tests, water samples were collected and analysed /2/. Manual observations of the groundwater level in the pumped boreholes were also made during the tests.

3.3 Equipment check

An equipment check was performed at the site prior to the tests, to establish the operating status of sensors and other equipment. In addition, calibration constants were implemented and checked.

To check the function of the pressure transducers P1 and P2 (cf Figures 4-1 and 4-2), the air pressure was recorded and found to be as expected. While lowering, recorded values from P1 were consistent with the total head of water (p/ρg). The temperature sensor displayed expected values in both air and water.

The sensor for electric conductivity showed zero in air. The impeller used in the flow logging equipment worked well as indicated by the rotation on the logger while lowering. The measuring wheel (used to check the position of the flow logging probe) and the attached sensor indicated a length that corresponded well to the pre-measured cable length.

4 Description of equipment

4.1 Overview

The equipment used in these tests is referred to as HTHB (Swedish abbreviation for Hydraulic Test System for Percussion Borehole). The HTHB unit is designed for percussion boreholes to perform pumping and injection tests in open boreholes (or above a single packer), see Figure 4-1, and in isolated sections of the boreholes (Figure 4-2) down to a total depth of 200 m. With the HTHB unit, it is also possible to perform a flow logging survey along the borehole during an open-hole pumping test (Figure 4-1). The pumping tests can be performed with either a constant hydraulic head or with a constant flow rate. For injection tests, however, the upper packer can not be installed deeper than c 80 m due to limitations in the number of pipes available.

All equipment that belongs to the HTHB is, when not in use, stored on a trailer and can be easily transported with a standard car. The equipment used in the borehole includes a submersible borehole pump with housing, expandable packers, pressure sensors and a pipe string and/or hose. During flow logging, sensors measuring temperature and electric conductivity as well as down-hole flow rate are also employed. At the top of the borehole, the total flow/injection rate is manually adjusted by a control valve and monitored by an electromagnetic flow meter. A data logger samples data at a frequency determined by the operator.

The packers are normally expanded by water (nitrogen gas is used to pressurize the water) unless the depth to the groundwater level is large. In such cases, the packers are expanded by nitrogen gas. A folding pool is used to collect and store the discharged water from the borehole for subsequent use in injection tests.

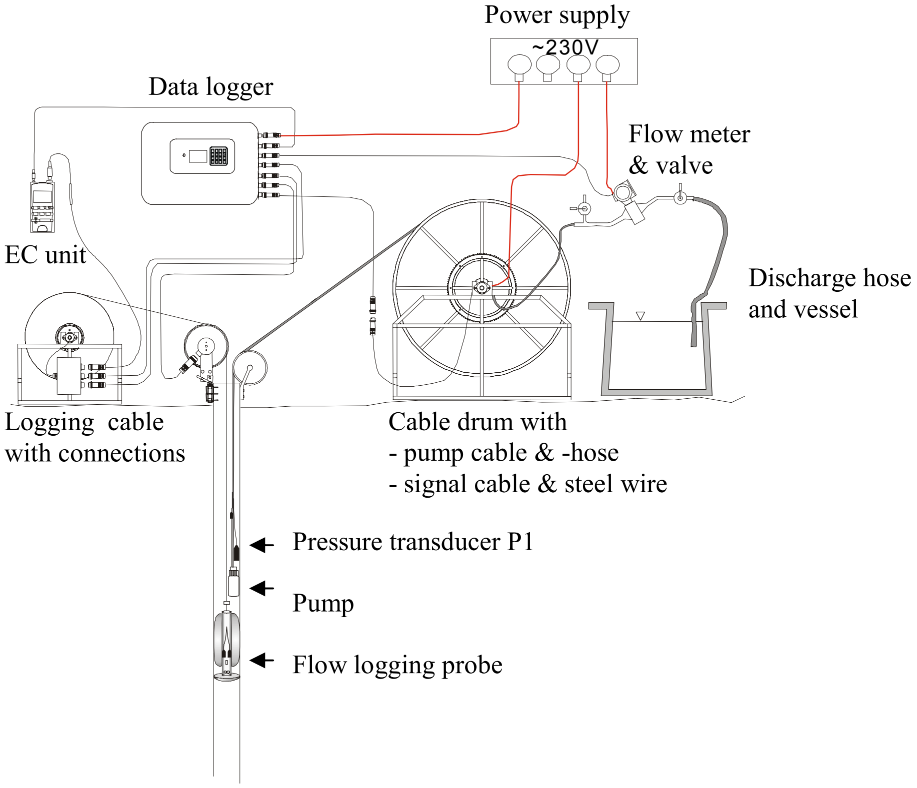


Figure 4-1. *Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB. (From the SKB internal document: SKB MD 326.001)*

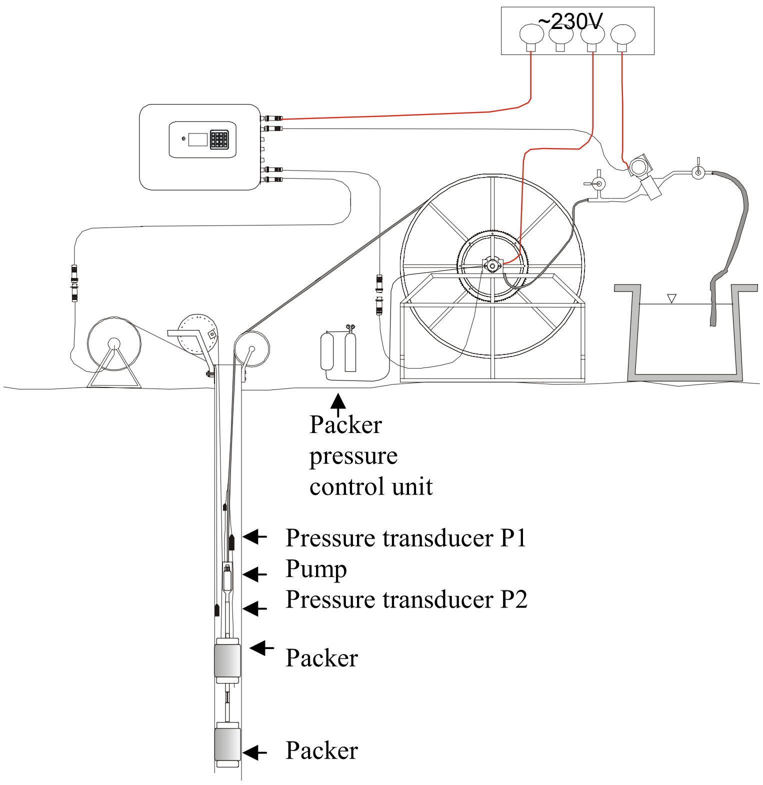


Figure 4-2. *Schematic test set-up for a pumping test in an isolated borehole section with HTHB. Additional equipment details are described in Figure 4-1. (From the SKB internal document: SKB MD 326.001)*

4.2 Measurement sensors

Technical data for the sensors and estimates of HTHB test system data for pumping tests and flow logging are given in Table 4-1.

Table 4-1. Technical data for measurement sensors and estimates of HTHB test system data (based on current laboratory and field experiences).

Technical specification Parameter		Unit	Sensor	HTHB system	Comments
Absolute pressure	Output signal	mA	4–20		
	Meas. range	kPa	0 –1500	0 –1500	
	Resolution	kPa	0.05		
	Accuracy	kPa	±1.5 *	±10	Depending on uncertainties of the sensor position
Temperature	Output signal	mA	4–20		
	Meas. range	°C	0–50	0–50	
	Resolution	°C	0.1		
	Accuracy	°C	± 0.6	±0.6	
Electric Conductivity	Output signal	V	0–2		
	Meas. range	mS/m	0–50000	0–50000	With conductivity meter
	Resolution	% o.r.**		1	
	Accuracy	% o.r.**		± 10	
Flow (Spinner)	Output signal	Pulses/s	c 0.1–c 15		
	Meas. range	L/min		2–100	115 mm borehole diameter
				3–100	140 mm borehole diameter
				4–100	165 mm borehole diameter
	Resolution***	L/min		0.2	140 mm borehole diameter and 100 s sampling time
	Accuracy***	% o.r.**		± 20	
Flow (surface)	Output signal	mA	4–20		Passive
	Meas. range	L/min	1–150	5–c 80****	Pumping tests
	Resolution	L/min	0.1	0.1	
	Accuracy	% o.r.**	± 0.5	± 0.5	

* Includes hysteresis, linearity and repeatability
** Maximum error in % of actual reading (% o.r.).
*** Applicable to boreholes with a borehole diameter of 140 mm and 100 s sampling time
**** For injection tests the minimal flow rate is 1 L/min

Errors in reported borehole data (diameter, etc) may significantly increase errors in measured data. For example, the flow logging probe is very sensitive to variations in the borehole diameter, cf Figure 4-3. Borehole deviation and uncertainties in the borehole inclination may also affect the accuracy of measured data.

The flow-logging probe is calibrated for different borehole diameters (in reality different pipe diameters), i.e. 111.3, 135.5, 140 and 160 mm. During calibration, the probe is installed in a vertically orientated pipe in which a through-flow of water is maintained by pumping. The number of spinner rotations is counted and the total discharge is measured. Calibration generally gives an excellent correlation ($R^2 > 0.99$) between total discharge and the number of spinner rotations. The calibration also clearly demonstrates how sensible the probe is to deviations in the borehole diameter, cf Figure 4-3.

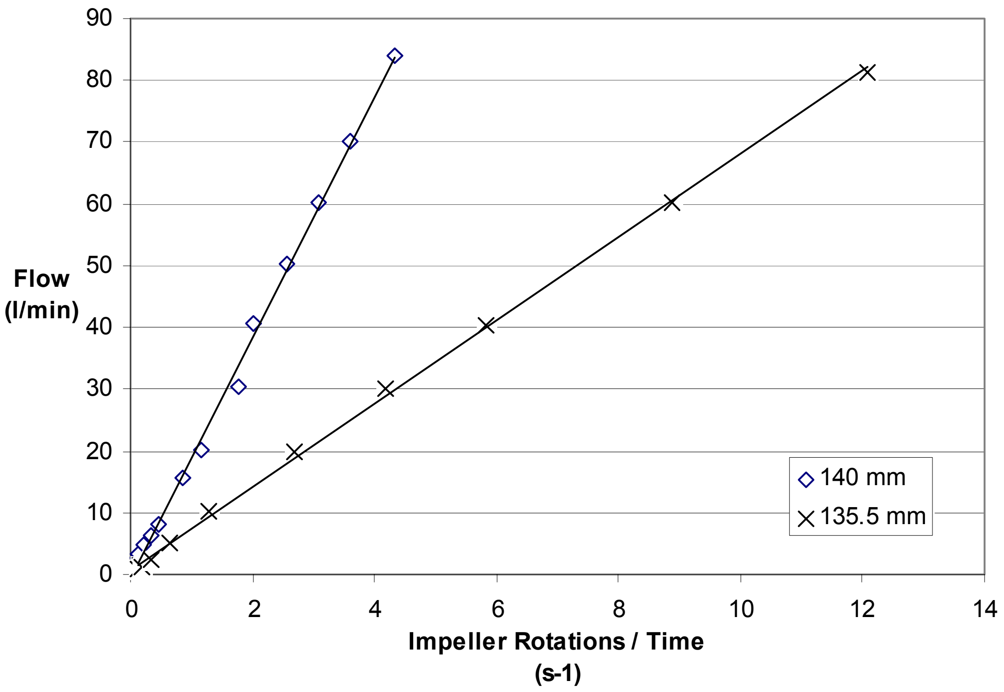


Figure 4-3. *Total flow as a function of impeller rotations for two borehole diameters (140 and 135.5 mm).*

The recorded flow at each position during flow logging was found to be rather insensitive to the measurement time (50, 100, 200 s), provided that sufficient time is allowed for the flow to stabilize. The stabilisation time may be up to 30 s at flows close to the lower measurement limit, whereas the stabilization is almost instantaneous at high flows.

Table 4-2 presents the position of sensors for each test. The following sensors are used: pressure (p), temperature (Te), electric conductivity (EC) and the (lower) level of the submersible pump (Pump). Positions are given in metre from the reference point, i.e. top of casing (ToC), lower part. The sensors measuring temperature and electric conductivity are placed in the impeller flow-logging probe, and thus the position varies (top-bottom-top of section) during a test. For specific information about the position at a certain time, the actual data files have to be examined.

Equipment affecting the wellbore storage coefficient is given in terms of diameter of the submerged item. Position is given as “in section” or “above section”. The volume of the submerged pump (~4 dm^3) is in most cases of minor importance.

In addition, the theoretical wellbore storage coefficient, C, for the actual test configurations and the geometrical data of the boreholes (Table 4-1) have been calculated, see Section 5.4.1. These values on C may be compared with the estimated values from the test interpretation described in Chapter 6.

Table 4-2. Position of sensors (from ToC) and of equipment that may affect wellbore storage for the different hydraulic tests performed.

Borehole information				Sensors		Equipment affecting wellbore storage (WBS)			
ID	**Test interval (m)**	**Test configuration**	**Test type[1]**	**Type**	**Position (m b ToC)**	**Function**	**Position relative test section [2]**	**Outer diameter (mm)**	**C (m^3/Pa) for actual test [3]**
HFM09	17.02–50.25	Open hole	1B	Pump-intake	12.4	Pump	In borehole		$2.0·10^{-6}$
						Pump hose	In borehole	33.5	(based on the casing diameter of 160 mm)
						Pump cable	In borehole	14.5	
				P (P2)	10.22	Signal cable	In borehole	8	
	17–49	Open hole	6	EC, Te, Q	17–49	Signal cable	In borehole	13.5	
						Tecalan hose	In borehole	6	
						Steel wire	In borehole	6	
HFM10	11.80–150.0	Open hole	1B	Pump-intake	7.9	Pump	In borehole		$2.0·10^{-6}$
						Pump hose	In borehole	33.5	(based on the casing diameter of 160 mm)
						Pump cable	In borehole	14.5	
				P (P2)	7.0	Signal cable	In borehole	8	
	11.8–145	Open hole	6	EC, Te, Q	11.8–145.0	Signal cable	In borehole	13.5	
						Tecalan hose	In borehole	6	
						Steel wire	In borehole	6	

1) 1B: Pumping test-submersible pump, 6: Flow logging–Impeller incl. EC-logging (EC-sec) and temperature logging (Te-sec), 3:Injection test.

2) Position of equipment that can affect wellbore storage. Position given as “In Section” or “Above Section” or “In borehole”

3) Based on the actual borehole diameter or casing diameter for open-hole tests (net values)

5 Execution

5.1 Preparations

All sensors included in the HTHB system were calibrated at the Geosigma engineering workshop in Librobäck, Uppsala. Calibration is performed on a yearly basis, or more often if needed. Last calibration of spinner and flow meter was performed in March 2003, sensor for electrical conductivity in May 2003, wheel for length measurements in June 2003 and pressure sensors together with temperature sensor in November 2003.

Before the tests, function checks and cleaning of equipment together with time synchronisation of clocks and data loggers were performed according to the Activity Plan. No errors were detected during these checks.

5.2 Procedure

5.2.1 Overview

The pumping tests were carried out as single-hole, constant flow rate tests in HFM09 and HFM10. The pumping phase was in both boreholes followed by a pressure recovery period. The intention was to obtain approximately steady-state conditions in the borehole during the flow logging.

The flow logging was performed while pumping. Discrete flow measurements were made at fixed step lengths (5 m before the first flow anomaly and 2 m after the first flow anomaly), starting from the bottom and upward along the borehole. When a detectable flow anomaly in the borehole was found, the flow probe was lowered and repeated measurements with a shorter step length (0.5 m) were made to determine the detailed position of the anomaly. The flow logging survey was terminated a short distance below the submersible pump in the borehole.

5.2.2 Details

Single-hole pumping tests

Prior to the 10 hour pumping test, short flow capacity tests were carried out in order to select an appropriate flow rate for the tests. The drilling records from HFM10 together with the BIPS-images, which showed a large crush zone at c 26-27 m below TOC, indicated high inflows in the borehole. This information together with the results from the capacity tests was considered sufficient for choosing an appropriated flow rate for the pumping tests. The pumping tests and flow meter logging were carried out after the boreholes were drilled to full depth, using the HTHB-unit. The pumped water from the boreholes was discharged on the ground sloping downhill from the borehole.

The main test in each borehole was an approximately 10 h long pumping test in the open borehole in combination with flow logging, followed by a recovery period of c 12 h. In general, the frequency of pressure measurements during the pumping tests was as presented in Table 5-1. The single-hole hydraulic tests in the boreholes were performed in the following order: HFM09, HFM10.

Table 5-1. Sampling frequency used for pressure registration during the pumping tests.

Time interval (s) from start/stop of pumping	Sampling frequency (s)
1–300	1
301–600	10
601–3600	60
>3600	600

Flow logging

Before start of the flow logging, the probe was lowered to the bottom of the borehole. While lowering (max speed= 0.5 m/s), temperature- and electric conductivity data were sampled. The probe was halted for 15 s at every 2 m to sample data with a sampling interval of 5 s.

Flow logging was performed during the long pumping test (10 h), starting from the bottom of the hole going upwards. The flow logging started when the pressure in the borehole had become approximately stable. The time needed to complete the flow logging survey depends on the length and character of the borehole. Usually 3–7 hours is required for a percussion borehole of 100–200 m length. In HFM09, the duration of the flow logging was c 2.5 h and in HFM10, c 3.5 h.

Flow logging can only be carried out up to a certain distance below the submersible pump (when logging is performed from the bottom of the borehole and upward). The remaining part of the borehole (i.e. from the pump to the casing shoe) can not be flow-logged, although high inflow zones may sometimes be located in this part. Such superficial inflows may be identified by comparing the cumulative flow at the top of the flow-logged interval (Q_T) with the discharged flow rate (Q_p) from the hole at the surface during the flow logging. If the latter flow rate is significantly higher than the cumulative flow rate, one or several inflow zones are likely to exist above the flow-logged interval. In order to check such shallow flow anomalies, short injection tests are sometimes carried out using the HTHB system in c 5 m long sections above the flow-logged interval. In boreholes HFM09 and HFM10, no additional tests were needed since the submersible pump was placed in the casing and flow logging was performed up to the casing shoe.

5.3 Data handling

Data are transformed to engineering units in the logger (Campbell CR 5000) and downloaded to a laptop using the program PC9000. All files are comma-separated (*.DAT) when copied to a computer. Data files used for transient evaluation are further converted to *.mio-files by the code Camp2mio. The operator can choose the parameters to be included in the conversion (normally pressure and discharge). Data from the flow logging are evaluated in Excel and therefore not necessarily transformed to *.mio-files. A list of the data files from the data logger is shown in Appendix 1.

Processed data files (*.mio-files) from the hydraulic tests with pressure versus time data were converted to drawdown and recovery files by the code PUMPKONV and plotted in different diagrams listed in the SKB internal document: Instruction for analysis of injection- and single-hole pumping tests (SKB MD 320.004) by the code SKBPLOT.

5.4 Analysis and interpretation

5.4.1 Single-hole pumping tests

As discussed in Section 5.2.1, the pumping tests were performed as constant flow rate tests followed by pressure recovery periods. First, a qualitative evaluation was performed of actual flow regimes (wellbore storage, pseudo-linear, pseudo-radial and pseudo-spherical flow, respectively) and possible outer boundary conditions during the tests. The qualitative evaluation was made from log-log diagrams of drawdown and/or recovery data together with the corresponding pressure derivatives versus time. In particular, pseudo-radial flow is reflected by a constant (horizontal) derivative in the diagrams. Pseudo-linear and pseudo-spherical flow is reflected by a slope of the derivative of 0.5 and –0.5, respectively, in a log-log diagram. No-flow and constant head boundaries are reflected by rapid increases and decreases of the derivative, respectively.

From the results of the qualitative evaluation, appropriate interpretation models for the tests were selected. In most cases, a certain period with pseudo-radial flow could be identified during the pumping tests. Consequently, methods for single-hole, constant-flow rate tests with radial flow in a porous medium were generally used for the evaluation of the tests. For tests indicating a fractured flow or borehole storage dominated response, corresponding type curve solutions were used.

If possible, transient analysis was applied on both the drawdown and recovery phase of the tests. The recovery data were plotted versus equivalent time. Transient analysis of drawdown and recovery data was generally made in both log-log and lin-log diagrams as described in the above mentioned Instruction and in /3/ and /4/. In addition, a preliminary steady-state analysis (e.g. Moye's formula) was used for all tests for comparison.

The transient analysis was performed using a special version of the aquifer test analysis software AQTESOLV, which enables both visual and automatic type curve matching with different analytical solutions for a variety of aquifer types and flow conditions. The evaluation is carried out as an iterative process of type curve matching and non-linear regression on the test data. For the flow period as well as the recovery period of the actual tests, a model presented by Dougherty-Babu (1984) /5/ for constant flow rate tests with radial flow, accounting for wellbore storage and skin effects, was generally used.

Estimated parameters include transmissivity, storativity and skin factor. The software also includes models for discrete fractures intersecting the borehole causing pseudo-linear flow.

The effective casing radius may also be estimated by the regression analysis. The wellbore storage coefficient can then be calculated from the actual or simulated effective casing radius, see below. The model uses the effective wellbore radius concept to account for negative skin factors. AQTESOLV also includes models for discrete fractures (horizontal and vertical, respectively) intersecting the borehole, causing pseudo-linear flow.

Rather than assuming a fixed value for the storativity of $1 \cdot 10^{-6}$ (according to the instruction in the SKB internal document: SKB MD 320.004), the storativity was assumed to a fixed value based on earlier experiences. For HFM09, the storativity has been fixed to $5 \cdot 10^{-5}$ and for HFM10 to $1 \cdot 10^{-5}$.The nomenclature used for the simulations with the AQTESOLV code is presented in the beginning of Appendix 2.

Estimates of the borehole storage coefficient, C, based on actual borehole geometrical data (net values) according to Equation (5-1), are shown in Table 4-2. The borehole storage coefficient may also be estimated from the early test response with 1:1 slope in a log-log diagram or, alternatively, from the simulated effective casing radius. These values on C may be compared with the wellbore storage coefficient based on actual borehole geometrical data (net values). The estimated values on C from the test data may differ from the net values due to uncertainties in the actual geometrical borehole data, e.g. regarding the borehole diameter or presence of fractures with significant volumes.

For pumping tests in open boreholes (and in the interval above single packers) the wellbore storage coefficient may be calculated as:

$$C = \frac{\pi \cdot {r_{we}}^{2}}{\rho \cdot g} \qquad (5\text{-}1)$$

where

r_{we} = borehole radius where the changes of the groundwater level occur (either r_w or r_c) or simulated effective casing radius
r_w = nominal borehole radius (m)
r_c = inner radius of the borehole casing (m)
ρ = density of water (kg/m^3)
g = acceleration of gravity (m/s^2)

5.4.2 Flow logging

The measured parameters during flow logging (flow, temperature and electric conductivity of the borehole fluid) were first plotted versus borehole length. From these plots, flow anomalies were identified along the borehole, in this case defined as borehole intervals above which changes of flow higher than c 1 L/min, occur. The magnitude of the inflow at the flow anomaly is determined by the actual change in flow rate over the interval. In some cases, the flow changes are accompanied by corresponding changes in temperature and/or electric conductivity of the fluid. If the actual borehole diameter differs from the one assumed by the calibration of the flow probe, corrections of the borehole flow rate may be necessary, cf Figure 4-3.

The transmissivity (T) of the entire borehole is calculated from the analysis of the pumping test during the flow logging. The cumulative transmissivity at the top of the flow-logged interval (T_{FT}=ΣT_i) was then calculated according to the Methodology description for Impeller flow logging (assuming zero natural flow in the borehole):

$$T_{FT} = \Sigma T_i = T \cdot Q_T / Q_p \qquad (5\text{-}2)$$

If $Q_T < Q_p$, one or several flow anomalies may be located above the flow-logged interval. In such cases the transmissivity of these anomalies may be estimated from Equation (5-3).

The transmissivity of individual flow anomalies (T_i) was calculated from the measured inflow (dQ_i) at the anomaly and the calculated transmissivity of the entire borehole (T) according to /1/:

$$T_i = T \cdot dQ_i / Q_p \qquad (5\text{-}3)$$

For comparison, estimation of the transmissivities of the identified flow anomalies were also made from the specific flows, simply by dividing the measured inflow (dQ_i) at the anomaly by the drawdown (s_{FL}) in the hole during the flow logging (assuming negligible head losses). The sum of the specific flows may then be compared with the total transmissivity (and specific flow) of the borehole.

The cumulative transmissivity T_F (L) along the borehole length (L) as determined from the flow logging may be calculated as:

$$T_F (L) = T \cdot Q(L) / Q_p \qquad (5\text{-}4)$$

where Q(L)=cumulative flow at borehole length L.

The lower limit of transmissivity (T_{min}) in flow logging may be estimated similar to Equation (5-3):

$$T_{min} = T \cdot Q_{min} / Q_p \qquad (5\text{-}5)$$

In a borehole with a diameter of 140 mm, Q_{min}=3 L/min, see Table 4-1, whereas Q_p is the actual flow rate during flow logging.

Similarly, the lower measurement limit of transmissivity of a flow anomaly can be estimated from Equation (5-3) using dQ_i (min) = 1 L/min ($1.7 \cdot 10^{-5}$ m^3/s). This value is considered to be the minimal change in borehole flow rate that may be used to identify a flow anomaly. The upper measurement limit of transmissivity of a flow anomaly is estimated from Equation (5-3) with Q_{max} = 100 L/min.

5.5 Nonconformities

The test program in the boreholes was performed mainly according to the Activity Plan. However, some modifications regarding the recommended test times in the SKB internal document: Methodology Description for single-hole pumping tests (SKB MD 321.003, Version 1.0) were made.

The recommended test time (24 h+24 h for drawdown/recovery) for the longer tests during flow logging was decreased to c10 h +12 h for practical reasons (mainly to avoid uncontrolled pumping over night and to eliminate the risk of freezing, theft/sabotage etc). Experience from similar tests also indicates that c 10 h of pumping and 12 h of recovery in general is sufficient for estimation of hydraulic properties of the borehole regarding, e.g. wellbore storage effects and other disturbing factors.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the pumping tests and flow logging are in accordance with the SKB internal documents: Instruction for analysis of single-hole injection- and pumping tests (SKB MD 320.004), and Methodology description for flow logging (SKB MD 322.009), cf Section 3.2. Additional symbols used are explained in the text. The nomenclature for the analyses using the AQTESOLV code is presented in Appendix 2.

6.2 Water sampling

The water samples collected during the pumping tests in the boreholes and submitted for analysis are listed in Table 6-1. The analyses are presented in /2/.

Table 6-1. Data of water samples collected during the pumping tests in the boreholes and submitted for analysis.

Bh ID	Date and time of sample	Pumped section (m)	Pumped volume (m^3)	Sample type	Sample ID no	Remarks
HFM09	2004-02-18 12:40	17.0–50.25	10.3	WC080	8333	Open-hole test
“	2004-02-18 15:45	“	20.5	WC080	8334	Open-hole test
“	2004-02-18 19:40	“	30.8	WC080	8335	Open-hole test
HFM10	2004-02-25 11:11	12.0–150.0	4.2	WC080	8336	Open-hole test
“	2004-02-25 15:07	“	15.9	WC080	8337	Open-hole test
“	2004-02-25 19:26	“	28.9	WC080	8338	Open-hole test

6.3 Single-hole pumping tests

Below, the results of the pumping tests are presented test by test. The barometric pressure, sea level, temperature and precipitation were monitored at the site during the testing periods. No corrections of measured data, e.g. for changes of the barometric pressure or tidal fluctuations, have been made prior to analysis of the data. For the single-hole tests, such corrections are generally not needed considering the rather short test time and relatively large drawdown applied in the boreholes. However, for longer tests with a smaller drawdown applied, such corrections may be necessary.

Drilling records were checked in order to identify possible effects on the hydraulic test data from drilling or other activities in nearby boreholes during the test periods. These records showed that some drilling and/or pumping activities were in progress at drilling site DS5 (KFM05A), during the actual test periods, cf Table 6-2.

Table 6-2. Activities in nearby boreholes during the hydraulic test periods in HFM09–10. (From SICADA)

Hydraulic tests Pumping Bh ID	Hydraulic test period (drd+rec)	Reported drilling activity in borehole interval	Time period
HFM09	2004-02-17 14:27-2004-02-19 09:20	KFM05A: Drilling	20040216 22:00 to 20040219 12:00
		HFM13: Pumping	20040216 22:00 to 20040219 12:00
HFM10	2004-02-25 14:02-2004-02-26 09:41	KFM05A: Drilling	20040223 11:00 to 20040226 09:00
		HFM13: Pumping	20040224 11:00 to 20040226 09:00

6.3.1 Borehole HFM09

General test data for the open-hole pumping test in borehole HFM09 in conjunction with flow logging are presented in Table 6-3.

Table 6-3. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFM09 in conjunction with flow logging.

General test data				
Borehole	HFM09			
Test type[1]	Constant Rate withdrawal and recovery test			
Test section (open borehole/packed-off section)	Open borehole			
Test No	1			
Field crew	J. Jönsson, P. Askling (GEOSIGMA AB)			
Test equipment system	HTHB1			
General comment	Single hole test			
	Nomen-clature	Unit	Value	
Borehole length	L	m	50.25	
Casing length	L_c	m	17.02	
Test section – secup	Secup	m	17.02	
Test section – seclow	Seclow	m	50.25	
Test section length	L_w	m	33.23	
Test section diameter	$2 \cdot r_w$	mm	top 140.9 bottom 140.9	
Test start (start of pressure registration)		yymmdd hh:mm:ss	040217 14:27	
Packer expanded		yymmdd hh:mm:ss		
Start of flow period		yymmdd hh:mm:ss	040218 10:11:01	
Stop of flow period		yymmdd hh:mm:ss	040218 20:12:58	
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	040219 09:20:00	
Total flow time	t_p	min	601.95	
Total recovery time	t_F	min	787.03	

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW Level (masl)** [3]
Absolute pressure in borehole before start of flow period	p_i	kPa	171.81	3.05
Absolute pressure in test section before stop of flow period	p_p	kPa	145.42	0.24
Absolute pressure in test section at stop of recovery period	p_F	kPa	169.85	2.74
Pressure change by the end of flow period	dp_p	kPa	26.39 [2]	

Manual groundwater level measurements			**GW level**	
Date YYYY-MM-DD	**Time tt:mm.ss**	**Time (min)**	**(m bToC)**	**(m a s l)**
2004-02-17	10:59	–1392	2.22	3.08
2004-02-17	13:30	–1241	2.23	3.07
2004-02-17	16:59	–1032	2.25	3.05
2004-02-18	09:46	–85	2.25	3.05
2004-02-18	11:50	99	4.61	0.85
2004-02-18	13:24	193	4.81	0.66
2004-02-18	19:43	573	5.25	0.25
2004-02-18	20:08	597	5.26	0.24
2004-02-19	09:15	1324	2.59	2.73
2004-02-19	10:33	1462	2.58	2.74

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$9.46 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$9.46 \cdot 10^{-4}$
Total volume discharged during flow period	V_p	m^3	34.3

1: Constant Head injection and recovery or Constant Rate withdrawal and recovery
2: Calculated from pressure data.
3: From manual groundwater level measurements.

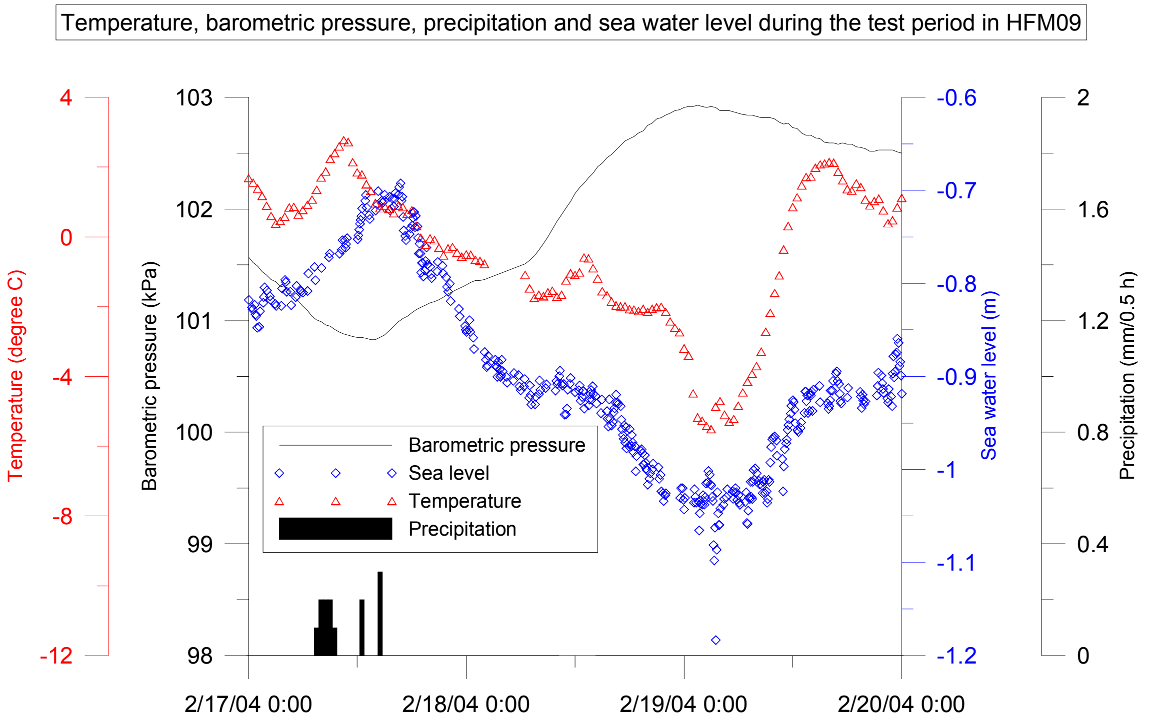


Figure 6-1. *Barometric pressure, sea level, precipitation and temperature during the test period in HFM09.*

Comments on the test

The pumping test was performed as a constant flow rate test with the intention to achieve (approximately) steady-state conditions during the flow logging. No drilling records were available, but an examination of the BIPS-images showed crush zones at 22–23 m and 26–27 m.

The barometric pressure, together with the precipitation, sea level and temperature during the test period in HFM09 are displayed in Figure 6-1. The barometric pressure increased whereas the sea level as well as the temperature decreased during the test period.

Table 6-4. Comparison between estimated specific capacity from the capacity test and pumping test, respectively, in borehole HFM09.

Test	Duration (min)	Flow rate (L/min)	Drawdown s_w (m)	Specific capacity Q/s_w (m^2/s)
Capacity test	35	39.7	2.08	$3.18 \cdot 10^{-4}$
Pumping test	602	56.77	2.69	$3.52 \cdot 10^{-4}$

Table 6-4 indicates a good agreement between the capacity test and the pumping test, which indicates that the hydraulic borehole conditions were not altered between the tests.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2:1–5 in Appendix 2. The initial phase of both the flow- and recovery periods indicate wellbore storage effects from the pressure versus time diagrams in Figures A2:2 and A2:4, respectively. After initial wellbore storage effects, the drawdown derivate indicates a transition period to apparent pseudo-radial flow from c 40 min to c 100 min. The response during the recovery period is consistent with the drawdown response. After initial wellbore storage effects, pseudo-radial flow occurred from c 40 min cf Figure A2:4. At the end of both the flow period and the recovery phase a second pseudo-radial flow regime is indicated. The type curve has been fitted to the early flow regime in both flow and recovery phase.

Interpreted parameters

The transient interpretation of the flow and recovery periods of the test is presented in lin-log and log-log diagrams in Figures A2:2–3 and 4-5, respectively in Appendix 2. Quantitative analysis was made from both the flow and recovery periods according to the methods described in Section 5.4.1. The results are listed in the Test Summary Sheets and in Table 6-13, 6-14 and 6-15 in Section 6.5. The judged best estimate of transmissivity is from the early pseudo-radial flow regime during the flow period.

6.3.2 Borehole HFM10

General test data for the open-hole pumping test in borehole HFM10 in conjunction with flow logging are presented in Table 6-5.

Table 6-5. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFM10 in conjunction with flow logging.

General test data			
Borehole	HFM10		
Test type[1]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section)	Open borehole		
Test No	1		
Field crew	T. Svensson, P. Askling (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comment	Single hole test		
	Nomenclature	**Unit**	**Value**
Borehole length	L	m	150.0
Casing length	L_c	m	11.8
Test section – secup	Secup	m	11.8
Test section – seclow	Seclow	m	150.0
Test section length	L_w	m	138.2
Test section diameter	$2 \cdot r_w$	mm	top 139.9 bottom 139.3
Test start (start of pressure registration)		yymmdd hh:mm:ss	040224 14:02
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	040225 09:48:02
Stop of flow period		yymmdd hh:mm:ss	040225 19:50:02
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	040226 09:41:01
Total flow time	t_p	min	602
Total recovery time	t_F	min	831

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)** [3]
Absolute pressure in borehole before start of flow period	p_i	kPa	137.04	2.61
Absolute pressure in test section before stop of flow period	p_p	kPa	107.76	–0.42
Absolute pressure in test section at stop of recovery period	p_F	kPa	135.19	2.37
Pressure change by the end of flow period	dp_p	kPa	29.28 [2]	

Manual groundwater level measurements **Date YYYY-MM-DD**	**Time tt:mm.ss**	**Time (min)**	**GW level (m bToC)**	**(m a s l)**
2004-02-24	13:20	–1228	1.92	3.19
2004-02-25	09:39	–9	2.55	2.61
"	10:14	26	4.79	0.51
"	10:30	42	4.91	0.40
"	10:49	61	5.02	0.30
"	12:01	133	5.25	0.08
"	13:34	286	5.43	–0.08
"	15:04	316	5.57	–0.21
"	19:47	599	5.79	–0.42
2004-02-26	09:38	1430	2.80	2.37

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$8.32 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$8.33 \cdot 10^{-4}$
Total volume discharged during flow period	V_p	m^3	30.1

1) Constant Head injection and recovery or Constant Rate withdrawal and recovery
2) Calculated from pressure data
3) Calculated from manual groundwater level measurements.

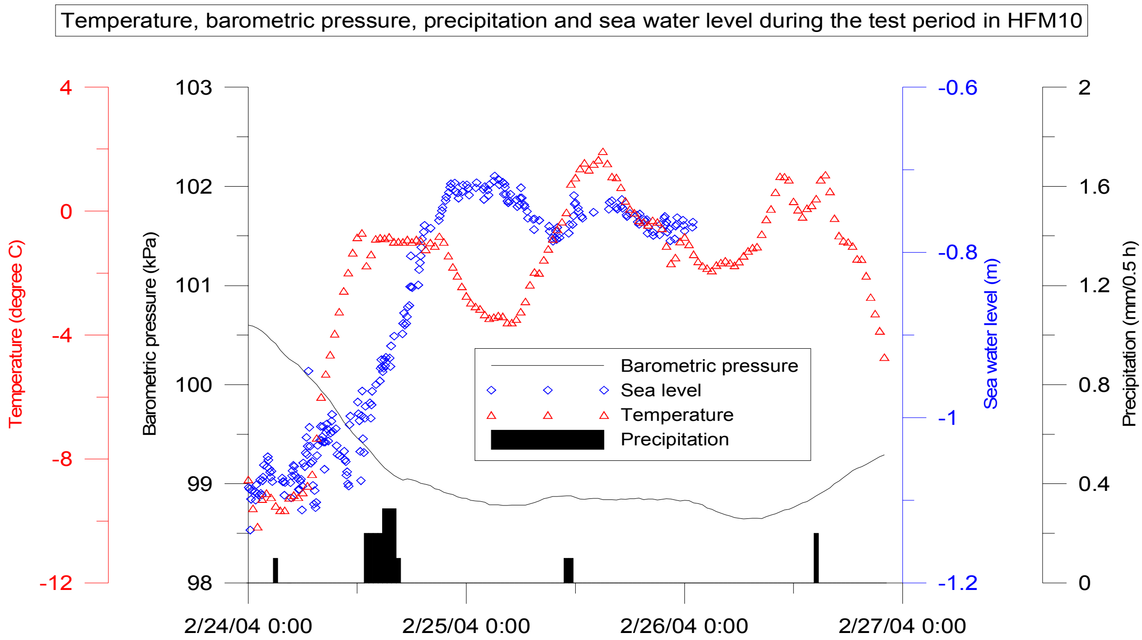


Figure 6-2. *Barometric pressure, sea level, precipitation and temperature during the test period in HFM10.*

Comments on the test

The pumping test was performed as a constant flow rate test with the intention to achieve (approximately) steady-state conditions. A capacity test before the pumping test was performed. Drilling records indicated high inflows at 114 m, 116 m and at 128 m.

The barometric pressure, together with the precipitation, sea level and temperature during the test period in HFM10 are displayed in Figure 6-2. Some precipitation was received during the later half of the test period. The barometric pressure as well as the sea level were fairly stable throughout the injection period. Towards the end of the recovery period the barometric pressure decreased about 1 kPa.

Table 6-6. Comparison between estimated specific capacity from the capacity test and pumping test, respectively, in borehole HFM10.

Test	Duration (min)	Flow rate (L/min)	Drawdown s_w (m)	Specific capacity Q/s_w (m^2/s)
Capacity test	80.9	59.9	3.39	$2.94 \cdot 10^{-4}$
Pumping test	602	49.95	2.98	$2.79 \cdot 10^{-4}$

Table 6-6 indicates a good agreement between the capacity test and pumping test, which indicates that the hydraulic borehole conditions were not altered between the tests.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2:6–10 in Appendix 2. The initial phases of both the flow- and recovery period indicate well bore storage from the pressure versus time diagrams in Figures A2:7 and A2:9, respectively. After initial well-bore storage effects, the drawdown derivate indicates a transition period to apparent pseudo-radial flow from about 10 to 70 min. The response during the recovery phase is basically consistent with the drawdown response. After initial wellbore storage effects, pseudo-radial flow occurred from c 10 min, cf Figure A2:9. At the end of both the flow period and the recovery phase a second pseudo-radial flow regime is indicated. The type curve has been fitted to the early flow regime in both flow and recovery phase.

Interpreted parameters

The transient interpretation of the recovery period of the test is illustrated in lin-log and log-log diagrams in Figures A2:9–10 according to the methods described in Section 5.4.1. The results are shown in the Test Summary Sheets and in Table 6-13, 6-14 and 6-15 in Section 6.5. The judged best estimate of transmissivity is from the early pseudo-radial flow regime during the flow period.

6.4 Flow logging

6.4.1 Borehole HFM09

General test data for the flow logging in borehole HFM09 are presented in Table 6-7.

Table 6-7. General test data, pressure, groundwater level and flow data for the flow logging in borehole HFM09.

General test data				
Borehole	HFM09			
Test type(s)[1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	GEOSIGMA AB			
Test equipment system	HTHB1			
General comments	Single pumping borehole			
	Nomenclature	**Unit**	**Value**	
Borehole length		m	50.25	
Pump position (lower level)		m	13	
Flow logged section – Secup		m	17.02	
Flow logged section – Seclow		m	49.0	
Test section diameter	2·rw	mm	top 140.9	
			bottom 140.9	
Start of flow period		yymmdd hh:mm	040218 10:11	
Start of flow logging		yymmdd hh:mm	040218 13:35	
Stop of flow logging		yymmdd hh:mm	040218 15:59	
Stop of flow period		yymmdd hh:mm	040218 20:12	
Pressure data	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)** [2]
Absolute pressure in borehole before start of flow period	p_i	kPa	171.81	3.05
Absolute pressure in test section before stop of flow period	p_p	kPa	145.42	0.24
Absolute pressure in test section at stop of recovery period	p_F	kPa	169.85	2.74
Absolute pressure in borehole before start of flow period	p_i	kPa	171.81	3.05
Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)** [2]
Groundwater level in borehole, at undisturbed conditions, open hole	h_i	m	2.25	3.05
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m	5.26	0.24
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	3.01 [2]	
Flow data	**Nomen-clature**	**Unit**	**Flow rate**	
Pumping rate at surface	Q_p	m^3/s	$9.46 \cdot 10^{-4}$	
Corrected cumulative flow rate at Secup at pumping rate Q_p	Q_T	m^3/s	$9.58 \cdot 10^{-4}$	
Measurement limit for borehole flow rate during flow logging	Q_{Measl}	m^3/s	$5 \cdot 10^{-5}$	
Minimal change of borehole flow rate to detect flow anomaly	dQ_{anom}	m^3/s	$1.7 \cdot 10^{-5}$	

1) 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging
2) Calculated from manual groundwater measurements.

Comments on the test

The flow logging was made from the bottom of the borehole and upwards. The first detectable flow anomaly was encountered at 46.5 m from top of casing. The step length between flow measurements was 0.5 m in the borehole interval 17–29 m due to continuous change in flow.

The measured electric conductivity has been corrected for temperature. Flow logging was performed up to the casing since the pump was placed within the casing. The calibration constants used in HFM09 were based on a borehole diameter of 140 mm.

Logging results

The nomenclature used for the flow logging is in accordance with the methodology description for flow logging. The measured cumulative borehole flow rate at the top of the flow-logged interval (Q_T) was equal to the total flow rate pumped from the borehole at the surface (Q_p).

The measured flow distribution along the borehole together with the temperature-compensated electric conductivity (EC) and temperature (Te) of the borehole fluid are presented in Figure 6-3.

The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Equation (5-2) and the transmissivity of individual flow anomalies (T_i) from Equation (5-3). An estimation of the transmissivity of the interpreted flow anomaly was also made by the specific flow (dQ_i/s_{FL}). The transmissivity of the entire borehole is derived from the transient evaluation of the early pseudo-radial flow regime indicated during the flow period of the pumping test.

The results of the flow logging in borehole HFM09 are presented in Table 6-8 below. Two flow anomalies were identified in the borehole. The measured inflow (dQ_i) at the respective identified flow anomaly is presented. The largest inflow is from the interval 22–29 m.

Table 6-8. Results of the flow logging in borehole HFM09. Q_T=cumulative flow at the top of the logged interval. Q_p=pumped flow rate from borehole, s_{FL}=drawdown during flow logging. T=transmissivity from the pumping test.

HFM09 Flow anom.		Q_T=9.58·10^{-4} (m^3/s)	Q_p=9.46·10^{-4} (m^3/s)	T=3.72·10^{-4} (m^2/s)	s_{FL}=2.69 m
Interval (m) (from ToC)	**B.h. length (m)**	**dQ_i (m^3/s)**	**T_i (m^2/s)**	**dQ_i/s_{FL} (m^2/s)**	**Supporting information**
22–29	7	8.28·10^{-4}	3.26·10^{-4}	3.08·10^{-4}	EC, T
46.5–49	2.5	1.19·10^{-4}	4.67·10^{-5}	4.41·10^{-5}	EC, T
Total		**Σ=9.47·10^{-4}**	**Σ=3.72·10^{-4}**	**Σ=3.52·10^{-4}**	
Difference		Q_p–Q_T=0.000012			

Summary of results

Table 6-9 presents an overview of the results from the pumping test. The results in Table 6-9 are consistent and show that the entire transmissivity of the borehole is located within the flow-logged interval.

Table 6-9. Compilation of results from the different hydraulic tests performed in borehole HFM09.

Test type	Interval (m)	Specific flow Q/s (m^2/s)	T (m^2/s)
Flow logging	17–49	3.52·10^{-4}	3.72·10^{-4}
Pumping test	17–50.25	3.52·10^{-4}	3.72·10^{-4}

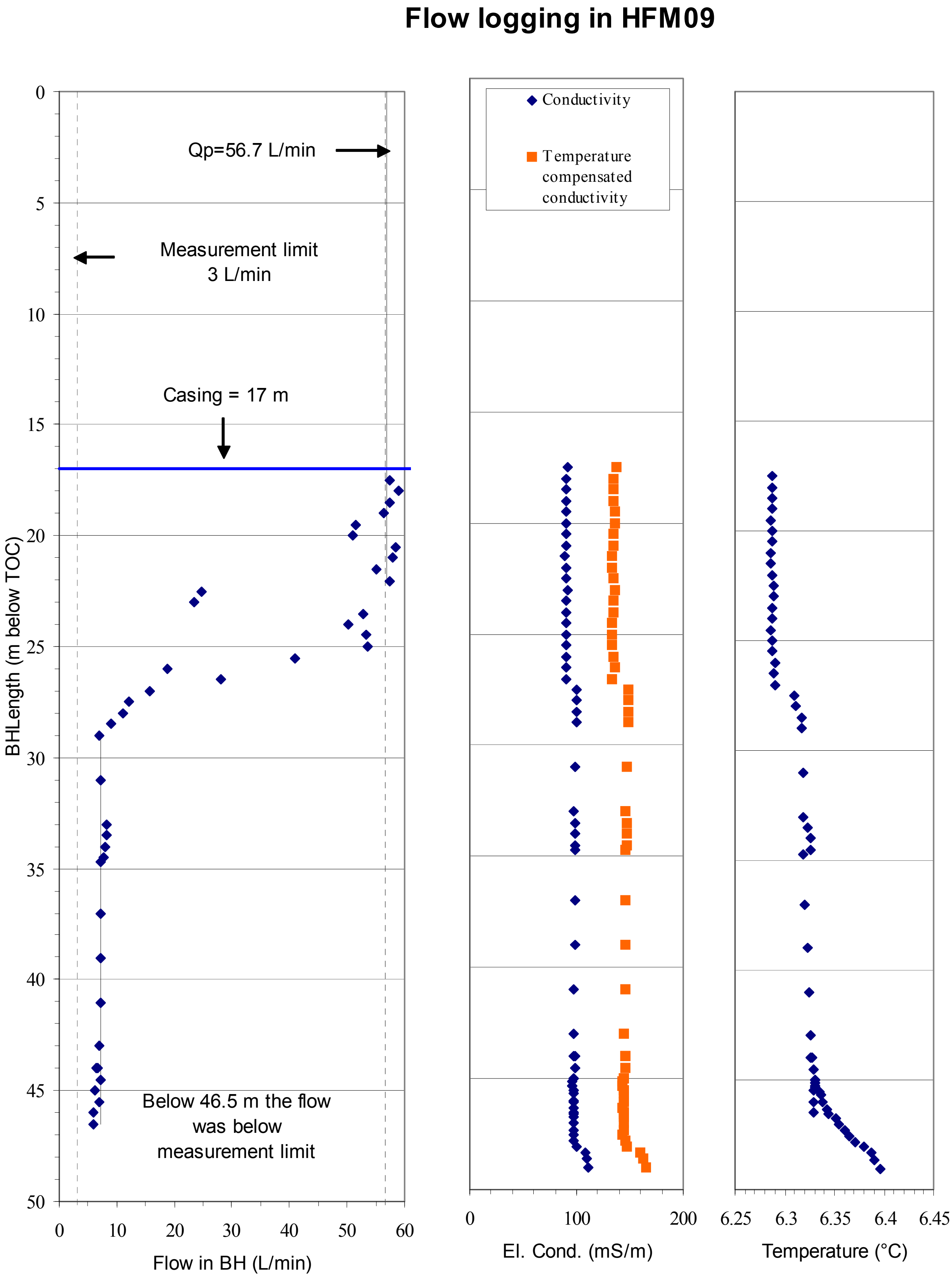


***Figure 6-3.** Measured inflow distribution together with the electric conductivity and temperature distribution of the borehole fluid along borehole HMF09 during flow logging.*

Figure 6-4 displays the cumulative transmissivity T_F (L) versus the borehole length (L) from the flow logging calculated from Equation (5-4). Since the width of the flow anomalies in the borehole is not known in detail, the change in transmissivity at the anomalies is represented by a sloping line across the anomaly. The estimated lower limit of T and the total transmissivity of the borehole are also shown in the figure, cf Section 5.4.2.

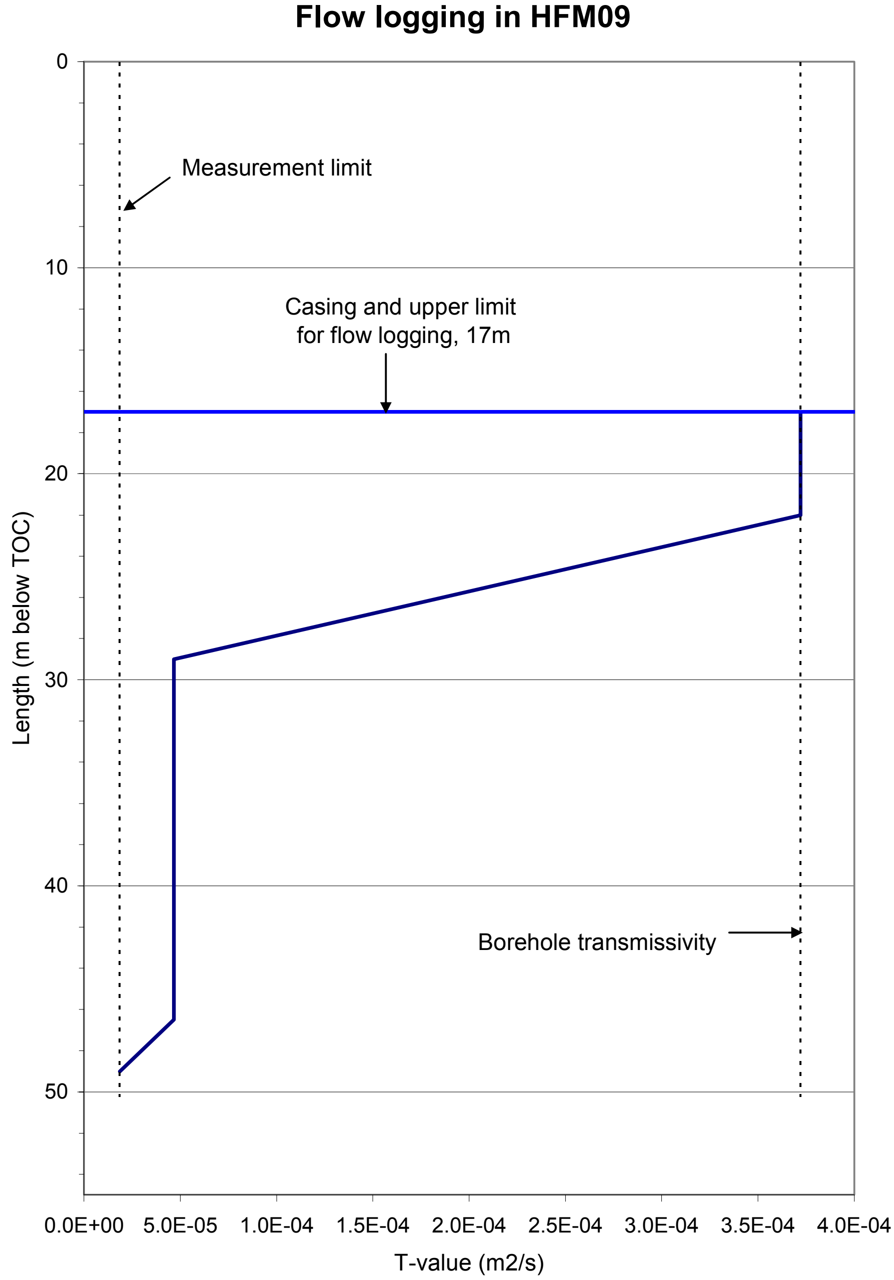


Figure 6-4. *Calculated cumulative transmissivity along the flow-logged interval of borehole HFM09. Below c 46.5 m, the borehole transmissivity is below the measurement limit. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.4.2 Borehole HFM10

General test data for the flow logging in borehole HFM10 are presented in Table 6-10.

Table 6-10. General test data, pressure, groundwater level and flow data for the flow logging in borehole HFM10.

General test data				
Borehole	HFM10			
Test type(s)[1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	T. Svensson, P. Askling (GEOSIGMA AB)			
Test equipment system	HTHB1			
General comments	Single pumping borehole			
	Nomenclature	Unit	Value	
Borehole length		m	150.0	
Pump position (lower level)		m	8.5	
Flow logged section – Secup		m	11.80	
Flow logged section – Seclow		m	145.0	
Test section diameter	2·rw	mm	top 139.9	
			bottom 139.3	
Start of flow period		yymmdd hh:mm	040225 09:48	
Start of flow logging		yymmdd hh:mm	040225 16:02	
Stop of flow logging		yymmdd hh:mm	040225 19:23	
Stop of flow period		yymmdd hh:mm	040225 19:50	
Pressure data	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)[2]**
Absolute pressure in borehole before start of flow period	pi	kPa	137.04	2.61
Absolute pressure in test section before stop of flow period	pp	kPa	107.76	–0.42
Absolute pressure in test section at stop of recovery period	pF	kPa	135.19	2.37
Absolute pressure in borehole before start of flow period	pi	kPa	29.28	3.03
Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)[2]**
Groundwater level in borehole, at undisturbed conditions, open hole	h_i	m	2.55	2.61
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m	5.79	–0.42
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	2.80[2]	2.37
Flow data	**Nomen-clature**	**Unit**	**Flow rate**	
Pumping rate at surface	Q_p	m^3/s	$8.32 \cdot 10^{-4}$	
Corrected cumulative flow rate at Secup at pumping rate Q_p	Q_T	m^3/s	$8.22 \cdot 10^{-4}$	
Measurement limit for borehole flow rate during flow logging	Q_{Measl}	m^3/s	$5 \cdot 10^{-5}$	
Minimal change of borehole flow rate to detect flow anomaly	dQ_{anom}	m^3/s	$1.7 \cdot 10^{-3}$	

1) 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging
2) Calculated from manual groundwater level measurements.

Comments on the test

The flow logging was made from the bottom of the hole and upwards. The first detectable flow anomaly was at 117.5 m (lower limit). The largest step length between flow measurements was 2 m. At each flow anomaly the step length was decreased to 0.5 m. Flow logging was performed up to the casing, since the pump was placed within the casing. The calibration constants used in HFM10 were based on a borehole diameter of 140 mm.

Logging results

The nomenclature used for the flow logging is in accordance with the methodology description for flow logging. The measured cumulative borehole flow rate at the top of the flow logged interval (Q_T) was equal to the total flow rate pumped from the borehole (Q_p) at the surface.

The measured flow distribution along the borehole during flow logging as well as the measured and temperature-corrected electric conductivity (EC) and temperature (Te) distribution of the borehole fluid are presented in Figure 6-5.

The results of the flow logging in borehole HFM10 are presented in Table 6-11 below. Only one flow anomaly was identified in the borehole. The measured inflow (dQ_i) at the identified flow anomaly is presented.

The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Equation (5-2) and the estimated transmissivity of individual flow anomalies (T_i) from Equation (5-3). An estimation of the transmissivity of the interpreted flow anomaly was also made by the specific flow (dQ_i/s_{FL}). The transmissivity of the entire borehole was calculated from the transient interpretation of the pumping test during flow logging.

Table 6-11. Results of the flow logging in borehole HFM10. Q_T=cumulative flow at the top of the logged interval. Q_p=pumped flow rate from borehole, s_{FL}= drawdown during flow logging. T=transmissivity from the pumping test.

HFM10 **Flow anomalies**		Q_T=8.22·10^{-4} (m^3/s)	Q_p=8.32·10^{-4} (m^3/s)	T=3.11·10^{-4} (m^2/s)	s_{FL}=2.98 m
Interval (m bToC)	**B.h. length (m)**	dQ_i (m^3/s)	**T_i (m^2/s)**	**dQ_i /s_{FL} (m^2/s)**	**Supporting information**
114.5–121	6.5	8.33·10^{-4}	3.11·10^{-4}	2.74·10^{-4}	EC & T
Total		Σ=8.33·10^{-4}	**Σ=3.11·10^{-4}**	**Σ=2.74·10^{-4}**	
Difference		Q_p–Q_T=0.00001			

Summary of results

Table 6-12 shows an overview of the results from the tests performed in the borehole. The results in Table 6-12 are consistent and demonstrate that the entire transmissivity is located within the flow-logged interval.

Table 6-12. Compilation of results from the pumping test and corrected results from the flow logging in borehole HFM10.

Test type	Interval (m)	Specific flow Q/s (m^2/s)	T (m^2/s)
Flow logging	11.8–145	$2.74 \cdot 10^{-4}$	$3.11 \cdot 10^{-4}$
Pumping test	11.8–150.0	$2.74 \cdot 10^{-4}$	$3.11 \cdot 10^{-4}$

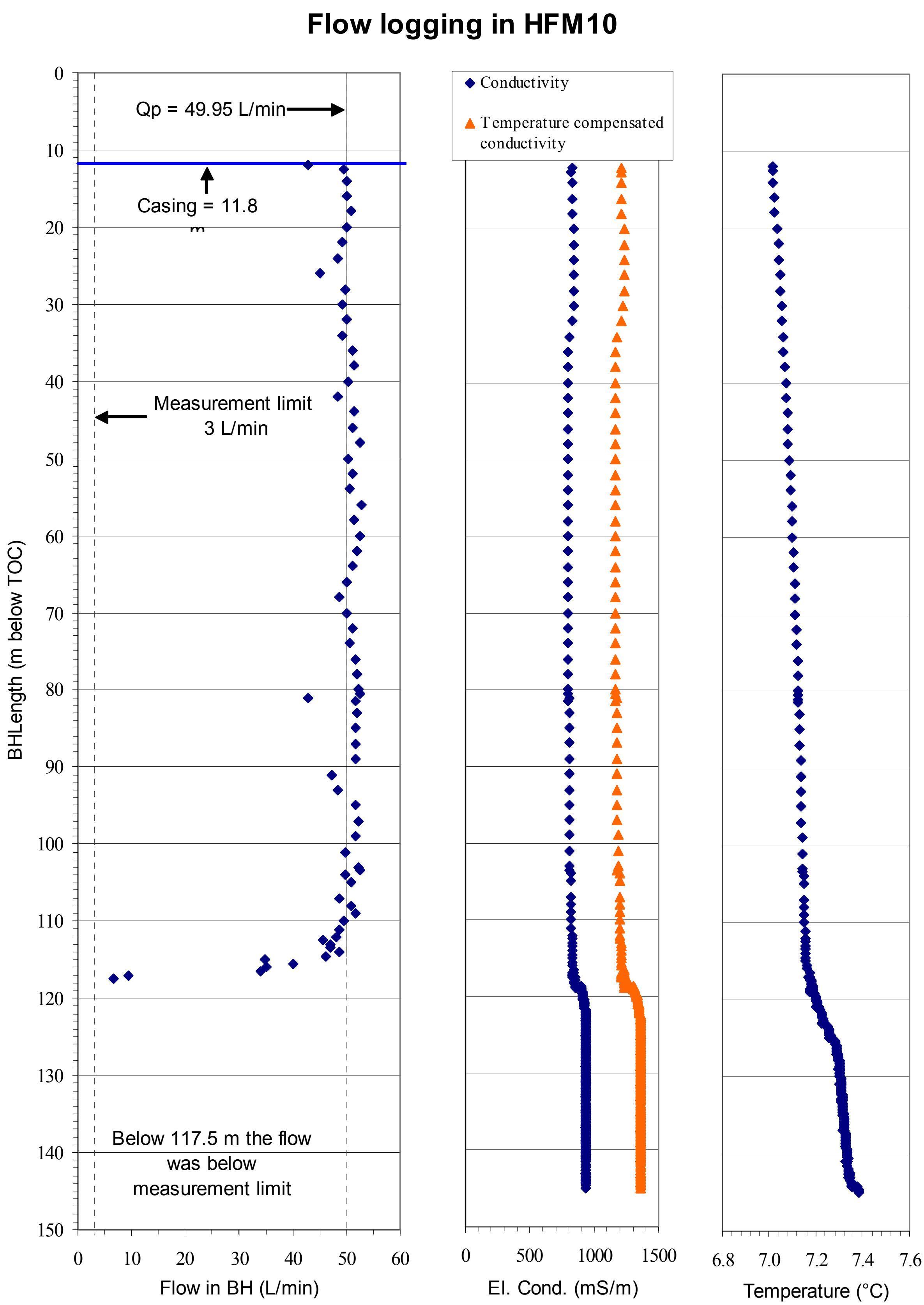


__Figure 6-5.__ Measured inflow distribution together with the electric conductivity and temperature distribution of the borehole fluid along borehole HMF10 during flow logging.

Figure 6-6 reveals the calculated cumulative transmissivity T_F (L) versus the borehole length (L) from the flow logging using Equation (5-4). Since the detailed positions of the flow anomalies in the borehole are not known, the change in transmissivity at the anomalies is represented by a sloping line across the anomaly. The estimated lower limit of T and the total T of the borehole are also shown in the figure, cf Section 5.4.2.

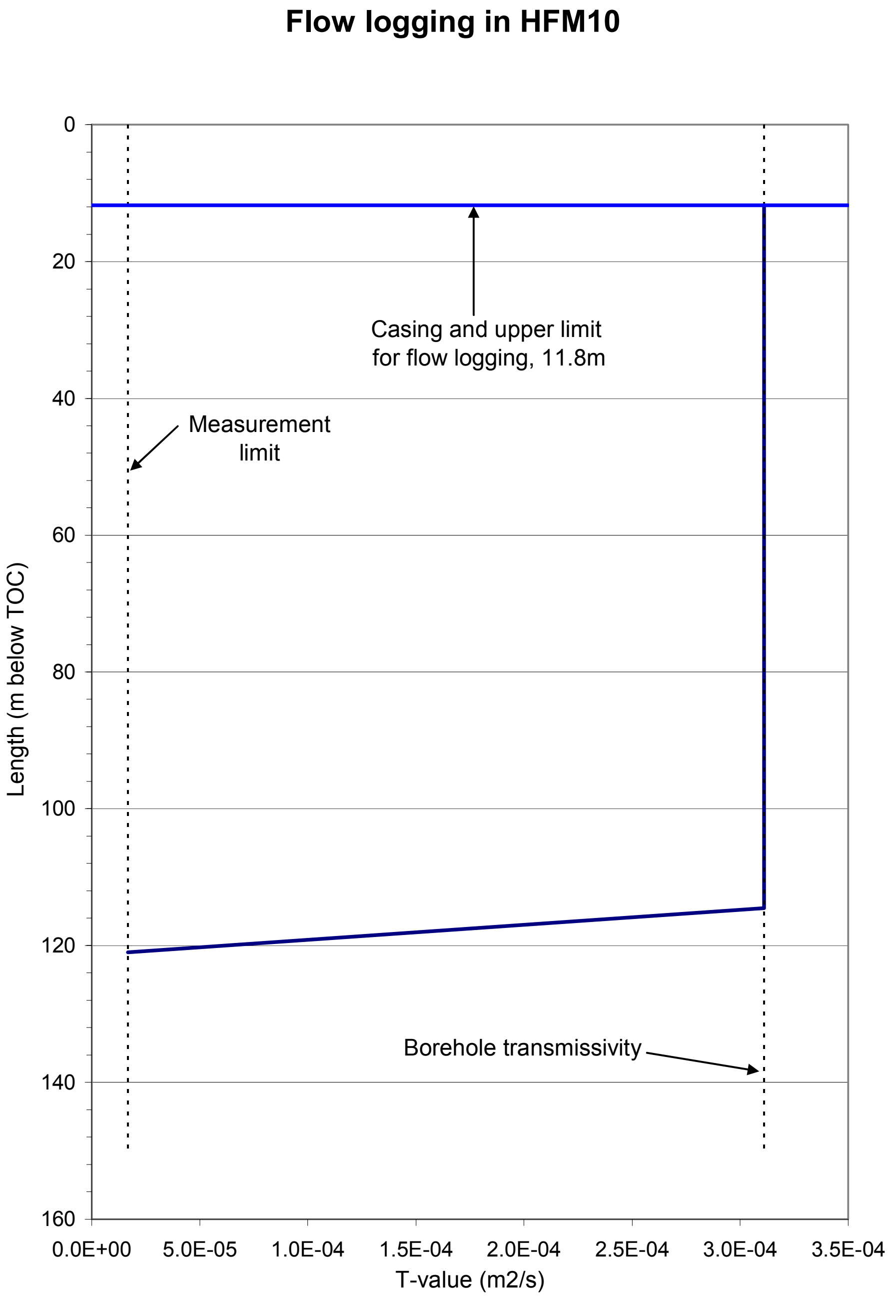


Figure 6-6. *Calculated, cumulative transmissivity along the flow-logged interval of borehole HFM10. The single flow anomaly in Figure 6-6 is interpreted as the borehole transmissivity. Below c 121 m the transmissivity is below the measurement limit. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.5 Summary of the hydraulic tests

A compilation of measured test data from the hydraulic tests carried out during the test campaign is presented in Table 6-13. In Tables 6-14 and 6-15, calculated hydraulic parameters of the formation and borehole, respectively, are shown. The results of the flow logging are given in Section 6.4.

The lower measurement limit for the HTHB system, presented in the tables below, is expressed in terms of specific flow (Q/s). For pumping tests, the lower limit is based on the smallest flow rate, for which the system is designed (5 L/min) and an estimated maximal allowed drawdown (c 50 m) in a percussion borehole, cf Table 4-1. These values correspond to a practical lower measurement limit of Q/s–L=$2\cdot10^{-6}$ m^2/s of the pumping tests.

Similarly, the practical upper measurement limit of the HTHB system is estimated from the maximal flow rate (c 80 L/min) and a minimal drawdown of c 0.5 m, which is considered significant in relation to background fluctuations of the pressure before and during the test. These values correspond to an estimated practical upper measurement limit of Q/s–U=$2\cdot10^{-3}$ m^2/s for both pumping tests and injection tests.

In Table 6-14 to 6-15, the parameter explanations are according to the Instruction for analysis of injection tests and single-hole pumping tests. The parameters are also explained in the text above, except the following:

T_M = steady-state transmissivity calculated from Moye's formula
T_T = representative transmissivity from the pumping test
T_i = estimated transmissivity of flow anomaly from flow logging
ζ = skin factor

Table 6-13. Summary of test data from the pumping tests performed in boreholes at drilling site DS4 in the Forsmark area.

Borehole ID	Section (m)	Test type[1)]	p_i (kPa)	p_p (kPa)	p_F (kPa)	Q_p (m^3/s)	Q_m (m^3/s)	V_p (m^3)
HFM09	17–50.25	1B	171.8	145.4	169.8	$9.46\cdot10^{-4}$	$9.46\cdot10^{-4}$	34.3
HFM10	11.8–150.0	1B	137.0	107.8	135.2	$8.32\cdot10^{-4}$	$8.33\cdot10^{-4}$	30.1

1) 1B: Pumping test-submersible pump, 6: Flow logging–Impeller. L-EC: EC-logging, L-Te: temperature logging, 3: Injection test.

Table 6-14. Summary of calculated hydraulic parameters of the formation from the hydraulic tests performed in boreholes HFM09–10 in the Forsmark area.

Borehole ID	Section (m)	Flow Anomaly interval (m)	Test type	Q/s (m^2/s)	T_M (m^2/s)	T_T (m^2/s)	T_i (m^2/s)	S (–)
HFM09	17–50.25		1B	$3.52 \cdot 10^{-4}$	$3.64 \cdot 10^{-4}$	$3.72 \cdot 10^{-4}$		$5.0 \cdot 10^{-5}$
HFM09	17–49	22–29	6	$3.08 \cdot 10^{-4}$			$3.26 \cdot 10^{-4}$	
HFM09		46.5–49	6	$4.41 \cdot 10^{-5}$			$4.67 \cdot 10^{-5}$	
HFM10	11.8–150		1B	$2.79 \cdot 10^{-4}$	$3.20 \cdot 10^{-4}$	$3.11 \cdot 10^{-4}$		$1.0 \cdot 10^{-5}$
HFM10		114.5–121	6	$2.79 \cdot 10^{-4}$			$3.11 \cdot 10^{-4}$	

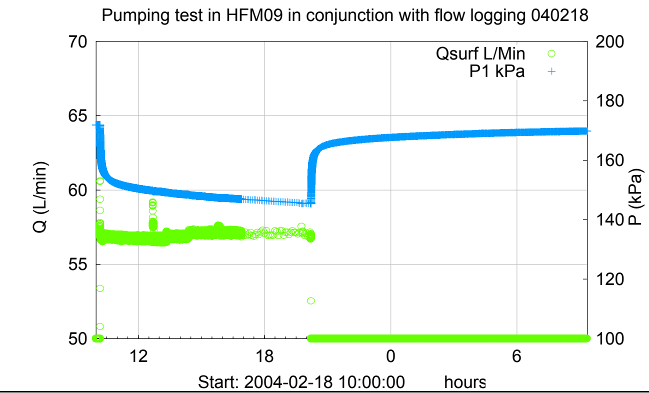
[1)] 1B: Pumping test-submersible pump, 6: Flow logging–Impeller. L-EC: EC-logging, L-Te: temperature logging.

Table 6-15. Summary of calculated hydraulic parameters from hydraulic tests performed in boreholes within drilling site DS4 in the Forsmark area.

Borehole ID	Section (m)	Test type	ζ (–)
HFM09	17–50.25	1B	–3.78
HFM10	11.8–150.0	1B	–3.58

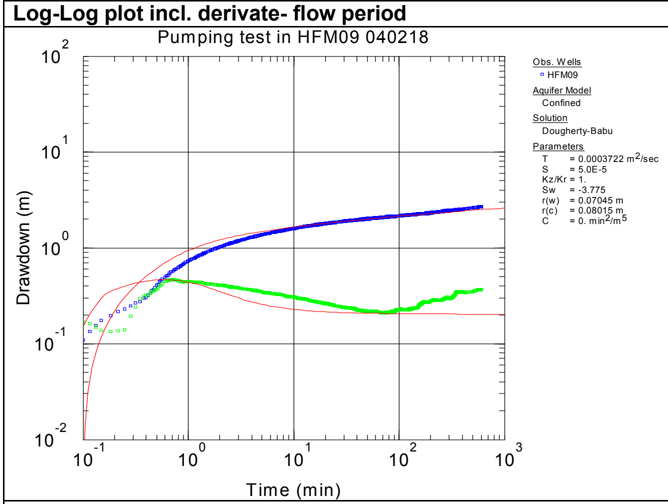
Test Summary Sheet			
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM09	Test start:	2004-02-17 14:27
Test section (m):	17.0–50.25	Responsible for test performance:	GEOSIGMA AB J. Jönsson, P. Askling
Section diameter, $2 \cdot r_w$ (m):	Top 140.9 Bottom 140.9	Responsible for test evaluation:	GEOSIGMA AB J-E. Ludvigson

Linear plot Q and p

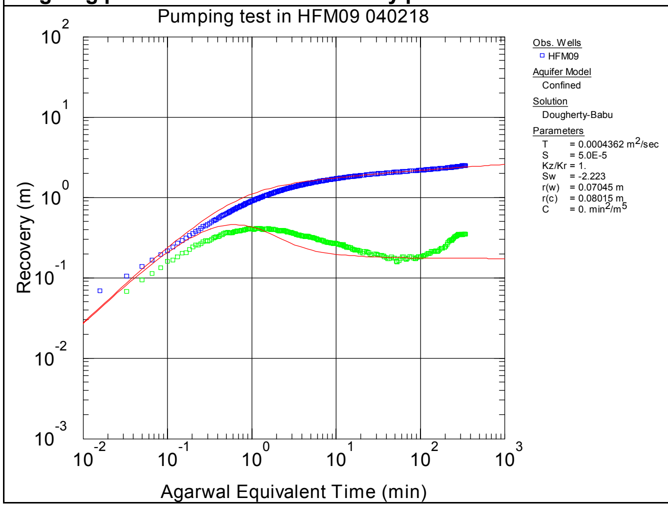


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	171.8		
p_i (kPa)	171.8		
p_p(kPa)	145.4	p_F (kPa)	169.8
Q_p (m^3/s)	$9.46 \cdot 10^{-4}$		
tp (min)	601.95	t_F (min)	787.03
S*	$5 \cdot 10^{-5}$	S*	$5 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.5	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$3.52 \cdot 10^{-4}$		
T_{Moye}(m^2/s)	$3.64 \cdot 10^{-4}$		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	40	dt_{e1} (min)	40
t_2 (min)	100	dt_{e2} (min)	100
T_w (m^2/s)	$3.72 \cdot 10^{-4}$	T_w (m^2/s)	$4.36 \cdot 10^{-4}$
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 (–)	–3.78	ξ (–)	–2.22
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters.

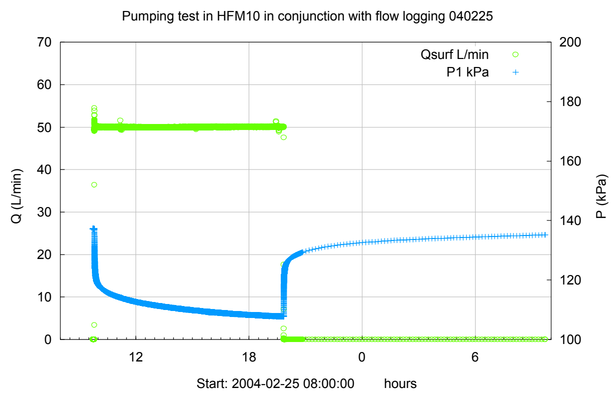
Flow regime:	PRF	C (m^3/Pa)	
t_1 (min)	40	C_D (–)	
t_2 (min)	100	ξ (–)	–3.78
T_T (m^2/s)	$3.72 \cdot 10^{-4}$		
S (–)			
K_s (m/s)			
S_s (1/m)			

Comments: Initial wellbore storage transiting to pseudo-radial flow during both the flow- and recovery period after c 40 min for the flow and c 40 min for the recovery phase. By the end of both the flow and the recovery phase is a second pseudo-radial flow regime indicated.

Test Summary Sheet

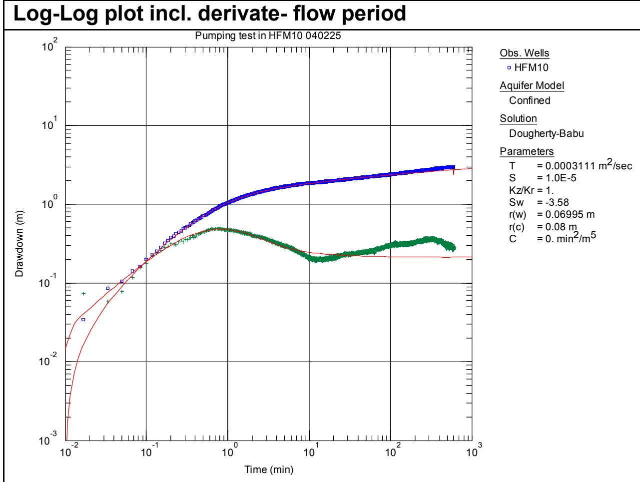
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM10	Test start:	2004-02-24 14:02:28
Test section (m):	11.8–150.0	Responsible for test performance:	GEOSIGMA AB J. Jönsson, P. Askling
Section diameter, $2 \cdot r_w$ (m):	top 0.1399 bottom 0.1393	Responsible for test evaluation:	GEOSIGMA AB J-E. Ludvigson

Linear plot Q and p

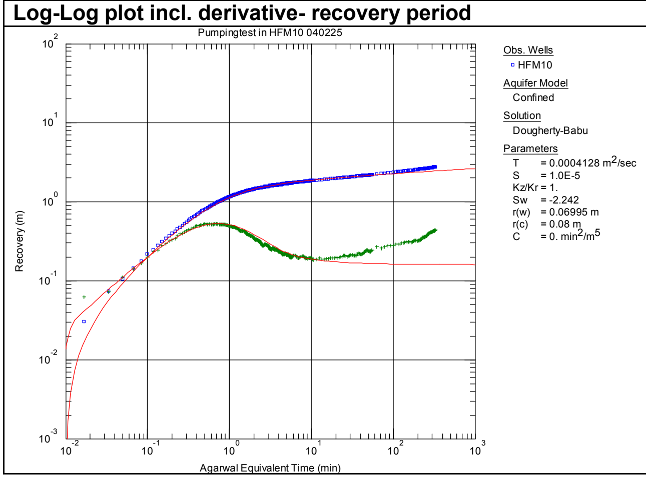


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	137.04		
p_i (kPa)	137.04		
p_p(kPa)	107.76	p_F (kPa)	135.19
Q_p (m^3/s)	$8.32 \cdot 10^{-4}$		
tp (min)	602	t_F (s)	830.98
S*	$1 \cdot 10^{-5}$	S*	$1 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.3	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$2.79 \cdot 10^{-4}$		
T_{Moye}(m^2/s)	$3.20 \cdot 10^{-4}$		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	10	dt_{e1} (min)	5
t_2 (min)	70	dt_{e2} (min)	50
T_w (m^2/s)	$3.11 \cdot 10^{-4}$	T_w (m^2/s)	$4.13 \cdot 10^{-4}$
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 (–)	–3.58	ξ (–)	–2.24
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters.

Flow regime:	PRF	C (m^3/Pa)	
t_1 (min)	10	C_D (–)	
t_2 (min)	70	ξ (–)	3.58
T_T (m^2/s)	$3.11 \cdot 10^{-4}$		
S (–)			
K_s (m/s)			
S_s (1/m)			

Comments: A short period of wellbore storage during both flow phase and recovery phase. Transition to pseudo-radial flow after c 10 min for the flow and after c 5 min for the recovery period. By the end of the flow and the recovery period is a second pseudo-radial flow regime indicated.

7 References

/1/ **Claesson L-Å, Nilsson G, 2004.** Forsmark site investigation. Drilling of a flushing water well, HFM10, a groundwater monitoring well in solid bedrock, HFM09, and a groundwater monitoring well in soil, SFM0057, at drilling site DS4. SKB P-04-76, Svensk kärnbränslehantering AB. P-report in progress.

/2/ **Nilsson D, 2004.** Sampling and analyses of groundwater in percussion drilled boreholes. Results from the percussion-drilled boreholes HFM09 to HFM19 and the percussion drilled parts of KFM05A and KFM06A. SKB P-04-XX. Svensk kärnbränslehantering AB. P-report in progress.

/3/ **Morosini, M, Almén K-E, Follin S, Hansson K, Ludvigson J-E and Rhén I, 2001.** Metoder och utrustningar för hydrauliska enhålstester. Metod och programaspekter för geovetenskapliga platsundersökningar. Tekniskt Dokument TD-01-63, Svensk Kärnbränslehantering AB.

/4/ **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.

/5/ **Dougherty, D E and D K Babu, 1984.** Flow to a partially penetrating well in a double-porosity reservoir, Water Resour. Res., 20 (8), 1116–1122.

Appendix 1

List of data files

Files are named"*bhnamn_secup_yymmdd_XX*", where *yymmdd* is the date of test start, *secup* is top of section and XX is the original file name from the HTHB data logger. If necessary, a letter is added (a, b, c,) after "*secup*" to separate identical names. XX can be one of five alternatives: *Ref_Da* containing constants of calibration and background data, *FlowLo* containing data from pumping test in combination with flow logging. *Spinne* contains data from spinner measurements; *Inject* contains data from injection test and *Pumpin* from pumping tests (no combined flow logging).

Bh ID	**Test section (m)**	**Test type**[1]	**Test no**	**Test start Date, time** YYYY-MM-DD tt:mm:ss	Test stop Date, time YYYY-MM-DD tt:mm:ss	**Datafile, start Date, time** YYYY-MM-DD tt:mm:ss	Data file, stop Date, time YYYY-MM-DD tt:mm:ss	**Data files of raw and primary data**	**Content (parameters)**[2]	**Comments**
HFM09	0-50.25	1B	1	2004-02-17 14:27:14	2004-02-19 09:20:00	2004-02-17 14:27:14	2004-04-19 09:20:00	HFM09_17.0_040218_FlowLo00.DAT	P, Q, T, EC	
		1B	1			2004-02-17 13:28:09	2004-02-19 09:20:00	HFM09_17.0a_040218_Ref_Da00.DAT		
HFM09	17.0-49.0	6 L-EC L-T	1	2004-02-18 13:35:15	2004-02-18 15:59:45	2004-02-18 13:35:15	2004-02-18 15:59:45	HFM09_17.0_040218_Spinne00.DAT	P, Q, T, EC, SP	
		6 L-EC L-T	1			2004-02-17 13:28:09	2004-02-19 09:20:00	HFM09_17.0b_040218_Ref_Da00.DAT		
HFM10	0-150.5	1B	1	2004-02-25 09:43:11	2004-02-26 09:41:01	2004-02-24 14:02:28	2004-02-26 09:41:01	HFM10_12.0_040225_FlowLo00.DAT	P, Q, T, EC	
		1B				2004-02-24 13.40:18	2004-02-26 09:41:04	HFM10_12.0a_040225_Ref_Da00.DAT		
HFM10	11.8-145.0	6 L-EC L-T		2004-02-25 16:02:27	2004-02-25 19:23:40	2004-02-25 16:02:27	2004-02-25 19:23:40	HFM10_12.0_040225_Spinne00.DAT	(P,Q,T,Sp, EC)	
		6 L-EC L-T				2004-02-24 13:40:18	2004-02-25 19:47:35	HFM10_12.0b_040225_Ref_Da00.DAT		

1: 1A: Pumping test-wire-line equipment, 1B: Pumping test-submersible pump, 1C: Pumping test-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, Logging-EC: L-EC, Logging temperature: L-T, Logging single point resistance: L-SPR
2: P =Pressure, Q =Flow, Te =Temperature, EC =El. conductivity. SPR =Single Point Resistance, C =Calibration file, R =Reference file, Sp= Spinner rotations

Appendix 2

Test diagrams

Diagrams are presented for the following tests:

1. Pumping test in HFM09 17.0-50.25 m

2. Pumping test in HFM10 11.8-150.0 m

Nomenclature for Aqtesolv:

T=transmissivity (m^2/s)

S=storativity (-)

K_Z/K_r= ratio of hydraulic conductivities in the vertical and radial direction (set to 1)

S_W=skin factor

r(w)=borehole radius (m)

r(c)= effective casing radius (m)

C= well loss constant (set to 0)

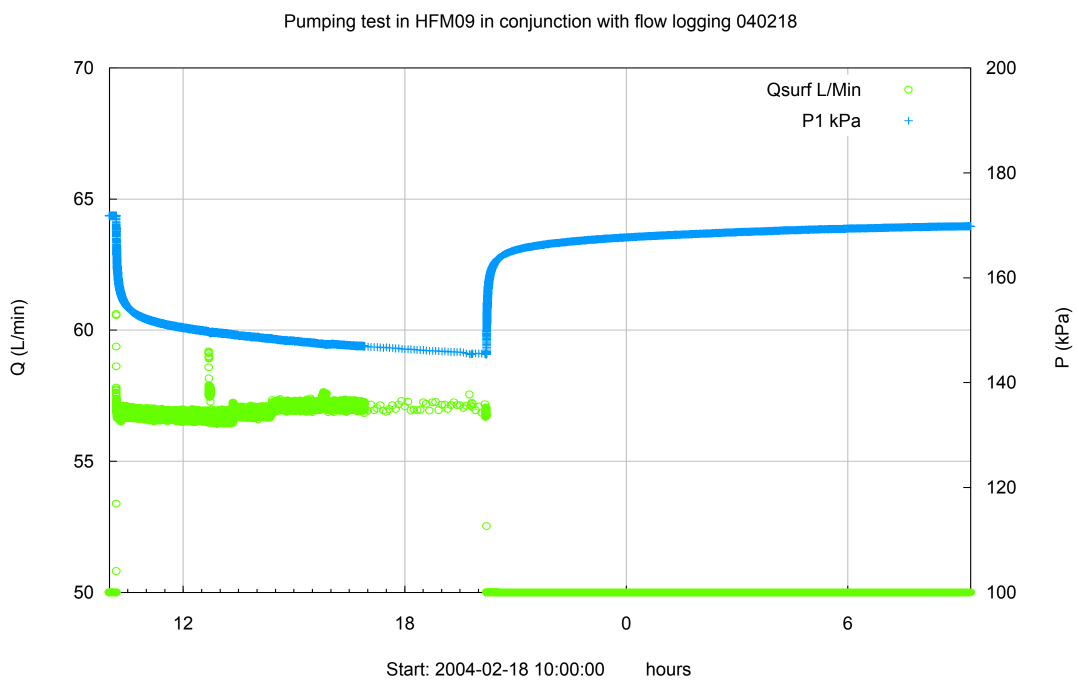


***Figure A2:1**. Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM09 in conjunction with flow logging.*

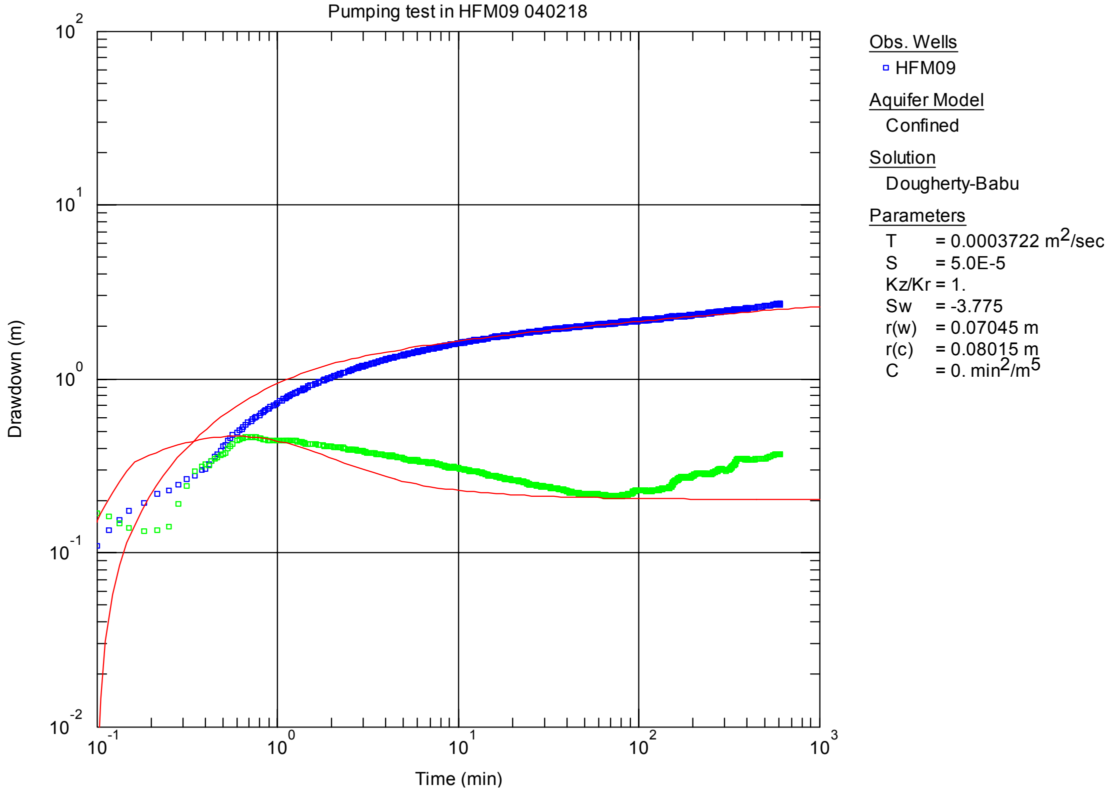


Figure A2:2. *Log-log plot of drawdown (blue) and drawdown derivative (green) versus time together with simulated curves (red) during the pumping test in HFM09.*

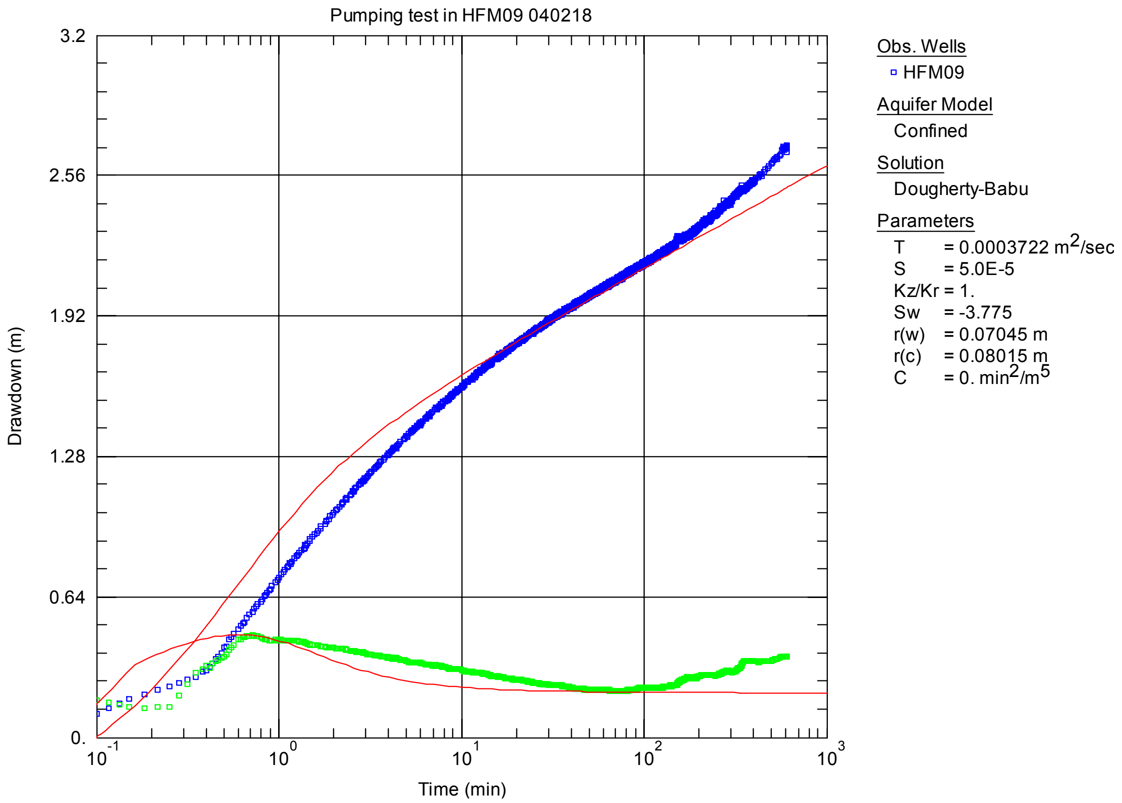


Figure A2:3*. Lin-log plot of drawdown (blue) and drawdown derivative (green) versus time together with simulated curves (red) during the pumping test in HFM09.*

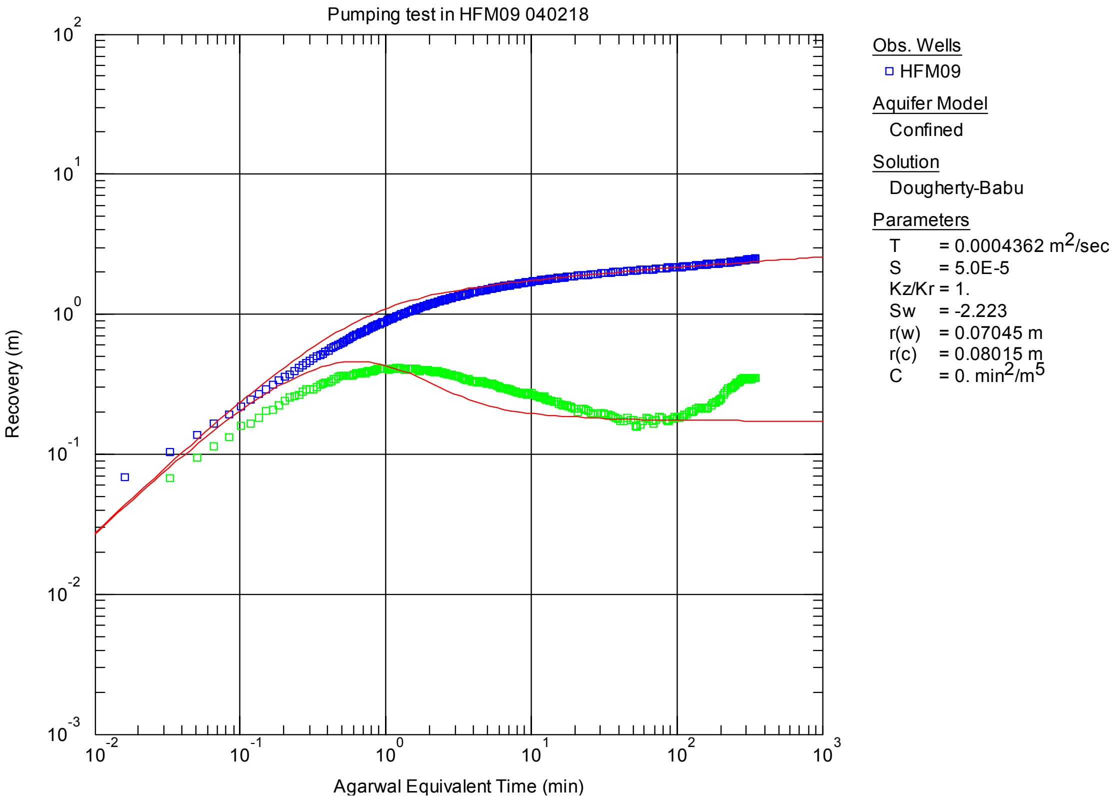


***Figure A2:4**. Log-log plot of pressure recovery (blue) and derivative (green) versus equivalent time together with simulated curves (red) during the pumping test in HFM09.*

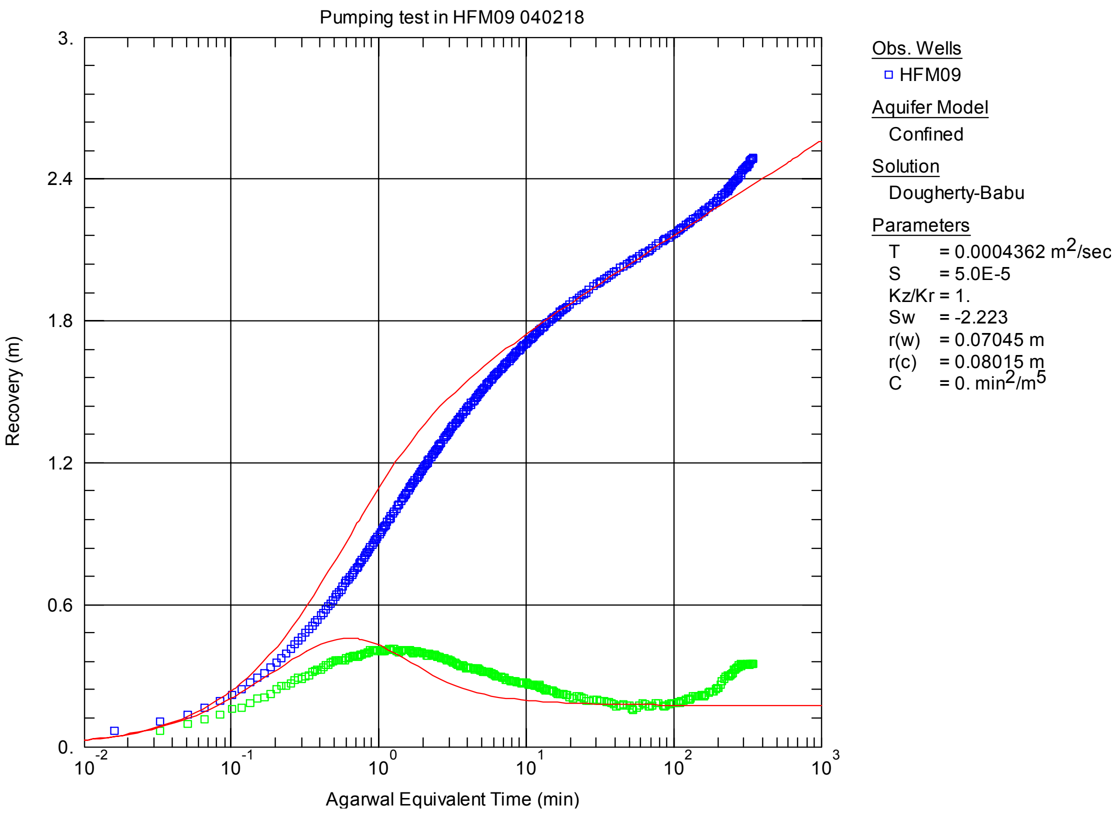


***Figure A2:5.** Lin-log plot of pressure recovery (blue) and derivative (green) versus equivalent time together with simulated curves (red) during the pumping test in HFM09.*

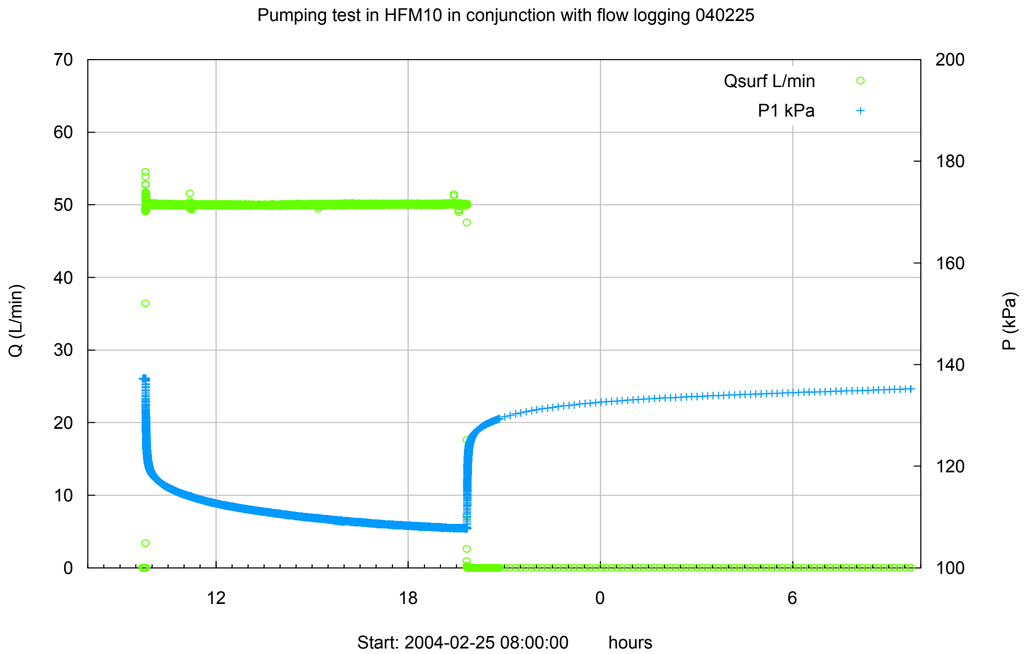


Figure A2:6. *Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM10 in conjunction with flow logging.*

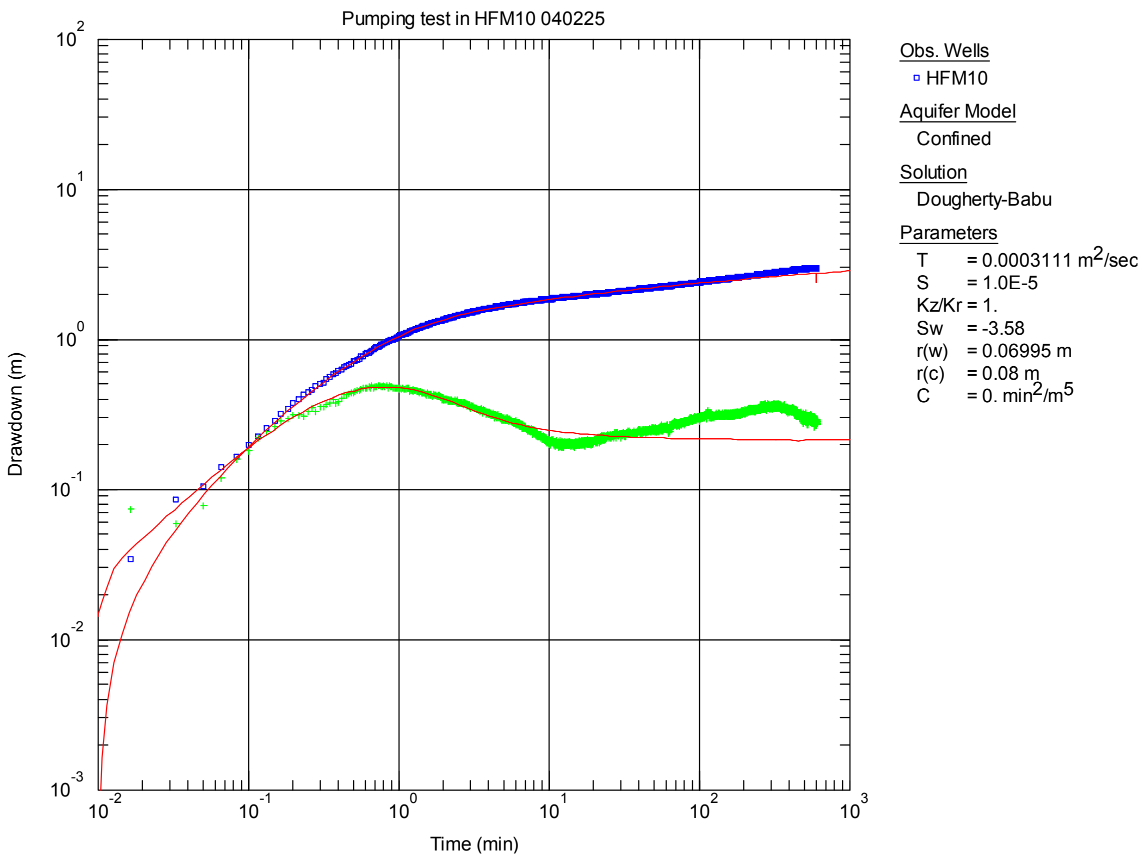


Figure A2:7*. Log-log plot of drawdown (blue) and drawdown derivative (green) versus time during the pumping test in HFM10.*

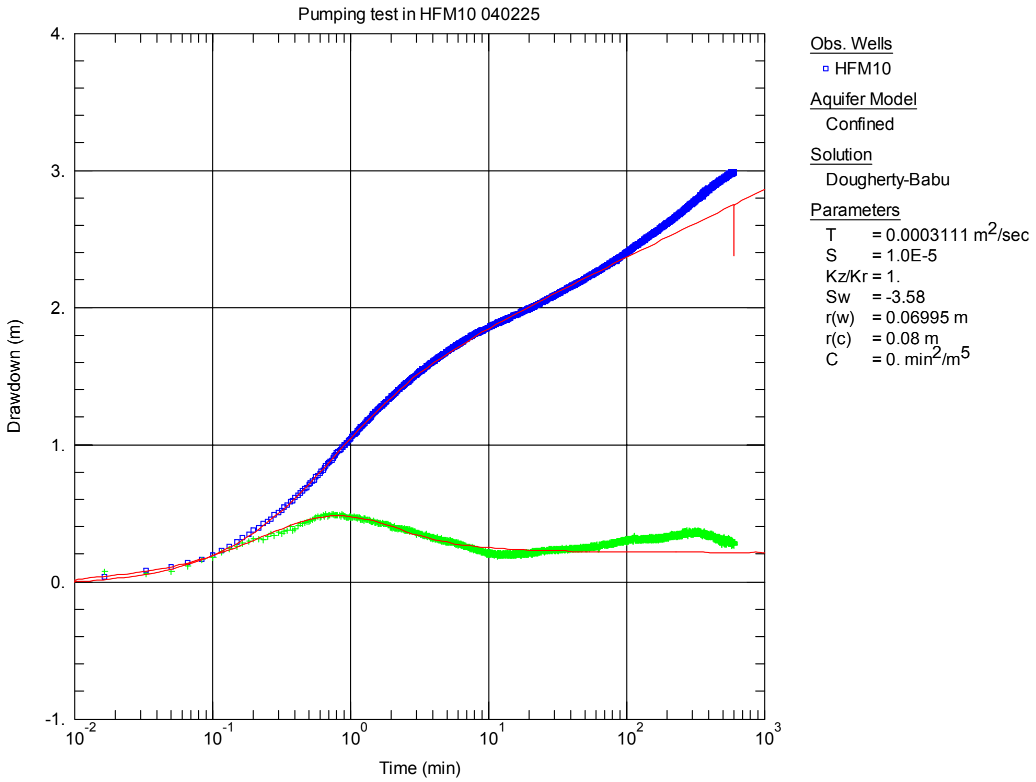


Figure A2:8. *Lin-log plot of drawdown (blue) and drawdown derivative (green) versus time during the pumping test in HFM10.*

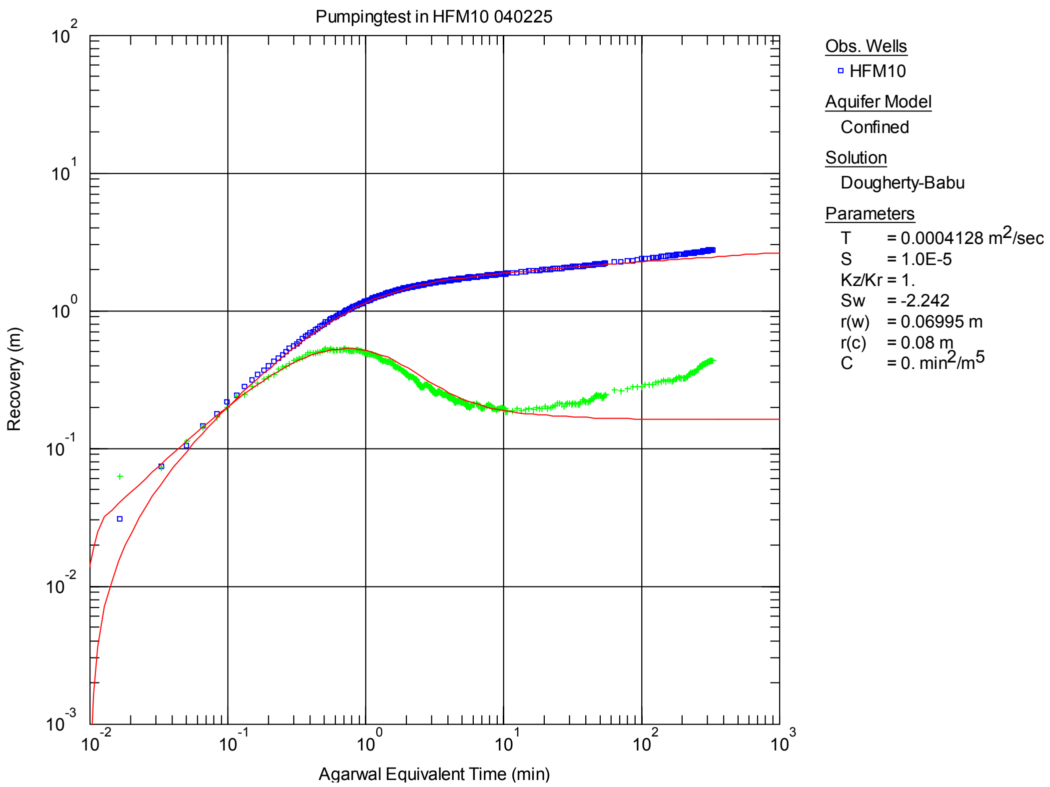


Figure A2:9. *Log-log plot of pressure recovery (blue) and derivative (green) versus equivalent time together with simulated curves (red) during the pumping test in HFM10.*

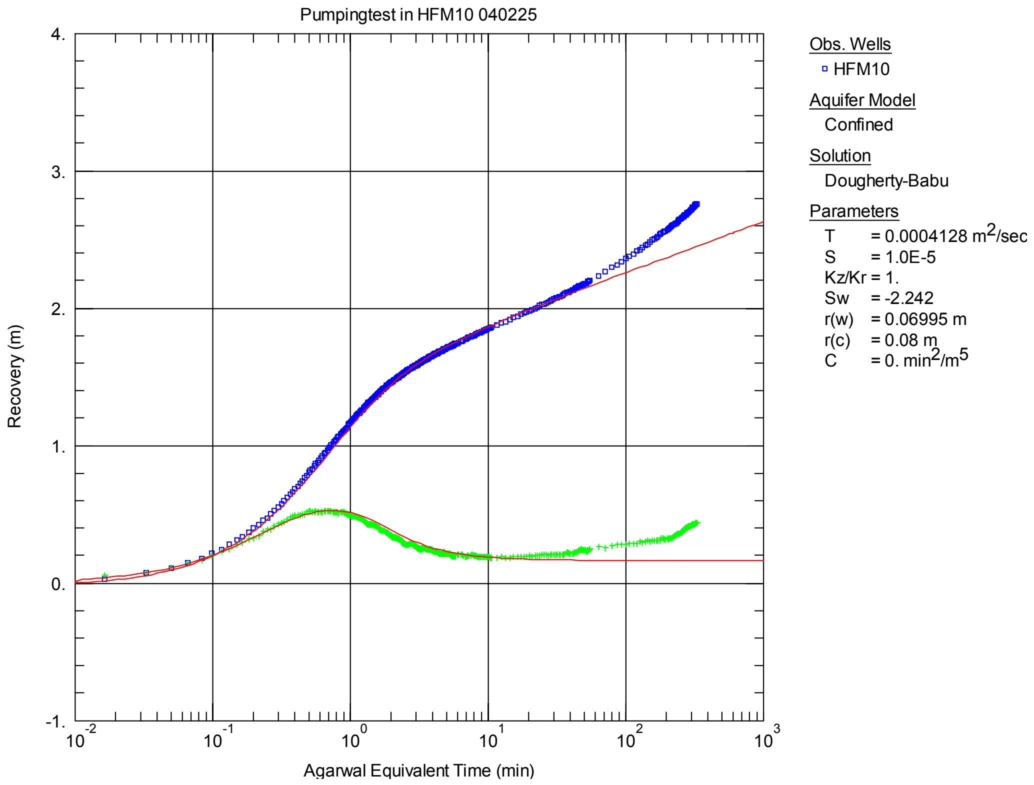


Figure A2:10. *Lin-log plot of pressure recovery (blue) and derivative (green) versus equivalent time together with simulated curves (red) during the pumping test in HFM10.*

Appendix 3

Result tables to Sicada

The following Result Tables are presented:

1. Result Tables for Single-hole pumping and injection tests

2. Result Tables for flow meter logging

A. Result Table for Single-hole tests in boreholes HFM09-10 at Forsmark for submission to Sicada

plu_s_hole_test_d

Borehole	Date and time for test, start	Date and time for test, stop	Borehole secup	Borehole seclow	Section no	Test type	Formation type	Date and time for flow period, start	Date and time for flow period, stop	Q_m	Qp
idcode	YYYYMMDD hh:mm:ss	YYYYMMDD hh:mm:ss	(m)	(m)		(1-6)	(-)	YYYYMMDD hh:mm:ss	YYYYMMDD hh:mm:ss	(m^3/s)	(m^3/s)
HFM09	20040217 14:27:14	20040219 09:20:00	17,00	50,25		1B	1	20040218 10:11:01	20040218 20:12:58	9,46E-04	9,46E-04
HFM10	20040224 14:02:28	20040226 09:41:01	11,80	150,00		1B	1	20040225 09:48:02	20040225 19:50:02	8,33E-04	8,32E-04

cont.

Value type	Q-measl-L	Q-measl-U	V_p	tp	t_F	h_i	h_p	h_F	p_i	p_p	p_F	Te_w	EC_w	TDS_w	TDS_{wm}	Reference	Comments	L_p
(-1, 0 or 1)	(m^3/s)	(m^3/s)	(m^3)	(s)	(s)	(m a sl)	(m a sl)	(m a sl)	(kPa)	(kPa)	(kPa)	(^{o}C)	(mS/m)	(mg/ L)	(mg/ L)		(-)	
0	8.3E-05	1.3E-03	34.3	36117	47221.98	3.05	0.24	2.73	171.8	145.4	169.9					P-04		
0	8.3E-05	1.3E-03	30.1	36120	49858.98	2.61	-0.42	2.37	137.0	107.8	135.2					P-04		

plu_s_hole_test_ed1

Borehole	Date and time for test, start	Date and time for test, stop	Borehole secup	Borehole seclow	Section no	L_p	Section length	Q/s	Value type	T_Q	Value type	bc	T_M	bc	Value type
	YYYYMMDD hh:mm:ss	YYYYMMDD hh:mm:ss	(m)	(m)			(m)	(m^2/s)	(-1, 0 or 1)	(m^2/ s)	(-1, 0 or 1)	(1, 0)	(m^2/ s)	(1, 0)	(-1, 0 or 1)
HFM09	20040217 14:27:14	20040219 09:20:00	17.00	50.25				3.52E-04	0				3.64E-04	0	0
HFM10	20040224 14:02:28	20040226 09:41:01	11.80	150.00				2.79E-04	0				3.20E-04	0	0

cont.

K_M	b	B	TB (1D)	TB-measl-L (1D)	TB-measl-U (1D)	SB (1D)	SB* (1D)	L_f (1D)	T_T (2D)	Value type	bc	Q/s-measl-L	Q/s-measl-U	S (2D)	S* (2D)
(m^2/s)	(m)	(m)	(m^3/ s)	(m^3/ s)	(m^3/ s)	(m)	(m)	(m)	(m^2/ s)	(-1, 0 or 1)	(1, 0)	(m^2/ s)	(m^2/ s)	(-)	(-)
	33.23								3.72E-04	0	1	2.0E-06	2.0E-03		5.00E-05
	138.2								3.11E-04	0	1	2.0E-06	2.0E-03		1.00E-05

cont.

K'/b' (2D) (1/s)	K_S (3D) (m/s)	Value type (-1, 0 or 1)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	C m^3/Pa	C_D (-)	ξ (2D) (-)	ω (-)	λ (-)	t_1 (s)	t_2 (s)	T_{ILR} (m^2/ s)
									-3.78			40	100	
									-3.58			10	70	

cont.

S_{ILR} (-)	Value type (-1, 0 or 1)	bc (1, 0)	$C_{,ILR}$ (m**3/Pa)	$C_{D,ILR}$ (-)	ξ_{ILR} (-)	ω_{ILR} (-)	λ_{ILR} (-)	T_{GRF} (m^2/ s)	Value type (-1, 0 or 1)	bc (1, 0)	S_{GRF} (-)	D_{GRF} (-)	Comments

Header	Unit	Explanation
Borehole		ID for borehole
Date for test start		Date for the start of the pumping or injection test (YYYYMMDD hh:mm)
Date for test stop		Date for the stop of the pumping or injection test (YYYYMMDD hh:mm)
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 - wire line eq., 1B:Pumping test-submersible pump, 1C: Pumping test-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
Formation type	-	1= rock
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	Arithmetic 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 flow rate
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.
L_p	m	Hydraulic point of application, based on hydraulic conductivity distribution (if available) or the midpoint of the borehole test section
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 Q_p and s=abs (p_i-p_p). Only given for test section (label 1) in interference test.
T_Q	m2/s	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	Transmissivity based on Moye (1967)
bc	-	Best choice code. 1 means Tmoye is best choice of T, 0 means Tmoye is not best choice
b	m	Interpreted formation thickness representative for evaluated T or TB.
B	m	Interpreted width 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
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 evaluation of formation properties. T=transmissivity
bc	-	Best choice code. 1 means T_T is best choice of T, 0 means T_T is not best choice
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
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

B. Result Table for Flow logging in boreholes HFM09-10 at Forsmark for submission to Sicada

FLOWLOGG-IMPELLER TESTS-plu_impeller_basic

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	Date and time of test start YYYYMMDD hh:mm	Date and time of test stop YYYYMMDD hh:mm	Date and time of flowl., start YYYYMMDD hh:mm	Date and time of flowl., stop YYYYMMDD hh:mm
HFM09	17.00	50.25	6	1	20040217 14:27	20040219 09:20	2004-02-18 13:35	2004-02-18 15:59
HFM10	11.8	150	6	1	20040224 14:02	20040226 09:41:01	2004-02-25 16:02	2004-02-25 19:23

cont.

Q-measl-L (m^3/s)	Q-measl-U (m^3/s)	Q_p (m^3/s)	tp (s)	t_{FL} (s)	h_0 (m a s l)	h_p (m a s l)	s_{FL} (m)	Reference (-)	Comments (-)
5.0E-05	1.7E-03	9.46E-04	36117	8086	3.05	0.24	2.69		
5.0E-05	1.7E-03	8.32E-04	36120	49859	2.61	-0.42	2.98		

FLOW LOGG-IMPELLER TESTS-plu_impell-main_res

Borehole	Borehole secup (m)	Borehole seclow (m)	L Corrected (m)	Te_{w0} (°C)	EC_{w0} (mS/m)	TDS_{w0} (mg/ L)	Q_0 (m^3/s)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	Q_{1T} (m^3/s)	Q_T (m^3/s)
HFM09	17.00	50.25									9.46E-04	9.46E-04
HFM10	11.8	150									8.32E-04	8.32E-04

cont.

Q_{Tcorr}	T Entire hole (m^2/ s)	T_{FT} (m^2/ s)	T_F-measl-L (m^2/ s)	T_F-measl-U (m^2/ s)	Reference (-)	Comments (-)
-	3.72E-04	3.72E-04	2.0E-06	2.0E-03		
-	3.11E-04	3.11E-04	2.0E-06	2.0E-03		

FLOWLOGG-IMPELLER TESTS plu_impeller_anomaly

Borehole	Borehole secup (m)	Borehole seclow (m)	Upper limit L (m)	Lower limit L (m)	Te_w ($^o C$)	EC_w (mS/m)	TDS_w (mg/ L)	$deltaQ_i$ (m^3/s)	$deltaQ_{icorr}$ (m^3/s)	$deltaQ_i/s_{FL}$ (m^2/s)
HFM09	17.00	50.25	22	29				8.28E-04	8.28E-04	3.08E-04
			46.5	49				1.19E-04	1.19E-04	4.42E-05
HFM10	11.8	150	114.5	121				8.33E-04	8.33E-04	2.79E-04

cont.

b_i (m)	T_i (m^2/ s)	T_i-measl-L (m^2/ s)	T_i-measl-U (m^2/ s)	Reference (-)	Comments (-)
7	3.26E-04	6.6E-06	3.7E-04	P-04	
2.5	4.67E-05	6.6E-06	3.7E-04	P-04	
6.5	3.11E-04	6.2E-06	3.1E-04	P-04	

Header	Unit	Description
Date/time test start	date	Date for the stop of the test (YYYY-MM-DD hh:mm)
Date/time test stop	date	Date for the stop of the test (YYYY-MM-DD hh:mm)
Borehole	idcode	Object or borehole identification code
Borehole secup	m	Length coordinate along the borehole for the upper limit of the logged section (Based on corrected length L)
Borehole seclow	m	Length coordinates along the borehole for the lower limit of the logged section. (Based on corrected length L)
date and time, start	date_s	Date and time of flow logging start (YYYY-MM-DD hh:mm:ss)
date and time, stop	date_s	Date and time of flow logging stop (YYYY-MM-DD hh:mm:ss)
Test type (1-7)		1A: Pumping test - wire line eq., 1B:Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-comb.Sequentia, 5B: Difference flow logging-PFL-DIFF-Overlapping, 6: Flow logging-Impeller 7: Grain size analysis
Formation type		1: Rock, 2: Soil (superficial deposits)
Q-measl-L	m^3/s	Estimated lower measurement limit for borehole flow rate in flow logging probe
Q-measl-U	m^3/s	Estimated upper measurement limit for borehole flow rate in flow logging probe
Q_p	m^3/s	Flow rate at surface during flow logging
t_p	s	Time for the flowing phase of the test
t_{FL}	s	Duration of the flow logging survey
s_{FL}	m	Average drawdown of the water level in open borehole during flow logging
h_0	masl	Initial hydraulic head. Measured as water level in open borehole with reference level in the local coordinates system with z=0 m.
h_p	masl	Stabilized hydraulic head during first pumping period. Measured as water level in open borehole with reference level in the local coordinates system with z=0 m.
L , Corrected	m	Corrected length to point considered representative for measured value
Q	m**3/s	Cumulative flow rate: Q1-Qo. Position for measurement is related to L (corrected length)
Q_0	m^3/s	Natural (undisturbed) measured cumulative flow rate. Position for measurement is related to L (corrected length)
Q_1	m^3/s	Cumulative flow rate during pumping. Position for measurement is related to L (corrected length)
Q_{1T}	m^3/s	Cumulative flow rate:Q_1 at the top of measured interval
Q_T	m^3/s	Cumulative flow rate: Q at the top of measured interval
Q_{Tcorr}	m^3/s	Cumulative flow rate: QT at the top of measured interval, based on corrected borehole diameter
T(Entire hole)	m**2/s	Evaluated transmissivity for the entire hole section that is considered representative for the flow logging (also reported in data file for single-hole interpretation)
T_F	m**2	Cumulative transmissivity based on impeller measurement. 2D model for evaluation of formation properties of the test section. T_F = Óti = T*(Q_T/Q_p)
T_{FT}	m**2	Cumulative transmissivity of the entire measured interval, based on impeller measurement
T_F-measl-L	m**2/s	Estimated lower measurement limit for evaluated T_F. If estimated T_F equals T-measlim in the table, the actual T_F is considered to be equal or less than T_F - measlim
T_F-measl-U	m**2/s	Estimated upper measurement limit for evaluated T_F. If estimated T_F equals T-measlim in the table, the actual T_F is considered to be equal or greater than T_F - measlim
Te_{w0}	gr C	Natural (undisturbed) fluid temperature in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected length)
EC_{w0}	mS/m	Natural (undisturbed) electrical conductivity of the fluid in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected length)
TDS_{w0}	mg/L	Natural (undisturbed) total salinity of the fluid in the test section representative for the evaluated parameters based on EC. Position for measurement is related to L (corrected length)
Upper limit	m	Corrected length coordinate along the borehole for the upper limit of the flow anomaly
Lower limit	m	Corrected length coordinate along the borehole for the lower limit of the flow anomaly
Te_w	centigrade	Natural (undisturbed) fluid temperature in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected length)
EC_w	mS/m	Natural (undisturbed) electrical conductivity of the fluid in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected

		length)
TDS_w	mg/L	Natural (undisturbed) total salinity of the fluid in the test section representative for the evaluated parameters based on EC. Position for measurement is related to L (corrected length)
$deltaQ_i$	m**3/s	deltaQi : Flow rate of interpreted flow anomaly i
$deltaQ_{icorr}$	m**3/s	deltaQicorr: Flow rate of interpreted flow anomaly calculated with corrected borehole diameter.
$deltaQ_i/S_{FL}$	m**2/s	deltaQi/s_{FL}: Specific capacity of interpreted flow anomaly
b_i	m	Interpreted formation thickness representative for evaluated Ti of anomaly i.
T_i	m**2/s	Evaluated transmissivity of flow anomaly i considered representative for the flow logging
T_i-measlim-L	m**2/s	Estimated lower measurement limit for evaluated $T_{i.}$ If estimated T_i equals T-measlim in the table actual T_i is considered to be equal or less than T_i-measlim
T_i-measlim-L	m**2/s	Estimated upper measurement limit for evaluated $T_{i.}$ If estimated T_i equals T_i-measlim in the table actual T_i is considered to be equal or greater than T_i-measlim
Reference		SKB number for reports describing data and results
Comments		Short comment on evaluated parameters