P-04-65

Forsmark site investigation

Pumping tests and flow logging

Boreholes KFM06A (0–100 m) and HFM16

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April 2004

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ISSN 1651-4416
SKB P-04-65

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Keywords: Forsmark, Hydrogeology, Hydraulic tests, Pumping tests, Flow logging, Water sampling, Hydraulic parameters, Transmissivity, Flow anomaly.

Abstract

Borehole KFM06A was the sixth cored borehole drilled within the frame of the on-going site investigations in the Forsmark area. The borehole is telescopic drilled, implying that the upper part, 0–100 m, is percussion drilled with a larger diameter than the diameter of the cored part (76 mm).

In the vicinity of borehole KFM06A, borehole HFM16 was percussion drilled.

Pumping tests and flow logging were performed in the percussion drilled part, 0–100 m, of KFM06A and in HFM16. In conjunction with the borehole tests water samples were collected in both boreholes.

The main objectives of the hydraulic tests in the boreholes were firstly, to perform a hydraulic characterization of the boreholes and secondly, in particular for HFM16, to investigate the groundwater chemistry in the boreholes.

No significant hydraulic conductive sections were found during the flow logging in KFM06A (0–100 m). The total transmissivity of borehole KFM06A (0–100 m) was estimated to c. $1\cdot10^{-6}$ m^2/s.

In HFM16, four hydraulic conductive intervals were found, all of them above 70 m. Two of them (at c. 41 and 59 m) had transmissivities in the order of $1–3\cdot10^{-4}$ m^2/s. The other two (at c. 56 and 69 m) had transmissivities of $4–6\cdot10^{-5}$ m^2/s. The total transmissivity of the borehole was estimated to c. $5\cdot10^{-4}$ m^2/s.

Sammanfattning

Borrhål KFM06A var det sjätte kärnborrhålet inom ramen för de pågående platsundersökningarna i Forsmarksområdet. Borrhålet är utfört som ett s k teleskopborrhål, vilket innebär att avsnittet 0–100 m är hammarborrat med grövre dimension än det kärnborrade avsnittet som håller diametern 76 mm.

I närheten av borrhålet KFM06A, hammarborrades HFM16.

Provpumpning och flödesloggning utfördes i KFM06A (0–100 m) och HFM16. Vattenprover togs i båda borrhålen i samband med provpumpningarna.

De huvudsakliga syftena med de hydrauliska testerna i borrhålen var för det första, att utföra en hydraulisk karaktärisering av borrhålen och för det andra, speciellt för HFM16, att undersöka grundvattenkemin i borrhålen.

Inga signifikanta hydrauliskt konduktiva sektioner hittades med hjälp av flödesloggning i KFM06A (0–100 m). Den totala transmissiviteten för borrhål KFM06A (0–100 m) uppskattades till ca $1 \cdot 10^{-6}$ m^2/s.

I HFM16 hittades fyra hydrauliskt konduktiva intervall, alla på ett djup mindre än 70 m. Två av dem (vid ca 41 and 59 m) hade transmissiviteter av storleksordningen $1–3 \cdot 10^{-4}$ m^2/s. De andra två (vid ca 56 and 69 m) hade transmissiviteter mellan 4 och $6 \cdot 10^{-5}$ m^2/s. Hålets totala transmissivitet uppskattades till ca $5 \cdot 10^{-4}$ m^2/s.

Contents

1 Introduction

The on-going site investigation in the Forsmark area includes six cored boreholes, one of these, KFM06A, is located at drillsite DS6, see Figure 1-1. The borehole will be telescopic drilled, implying that the upper part, 0–100 m, is percussion drilled with a larger diameter than that of the core drilled part, which is 76 mm. The percussion borehole was drilled in two steps. The first step resulted in a borehole diameter of c. 165 mm and the second will result in a diameter of 200 mm. No large inflows were observed during drilling in KFM06A (0–100 m). The core drilling of KFM06A has not yet been performed (February 2004).

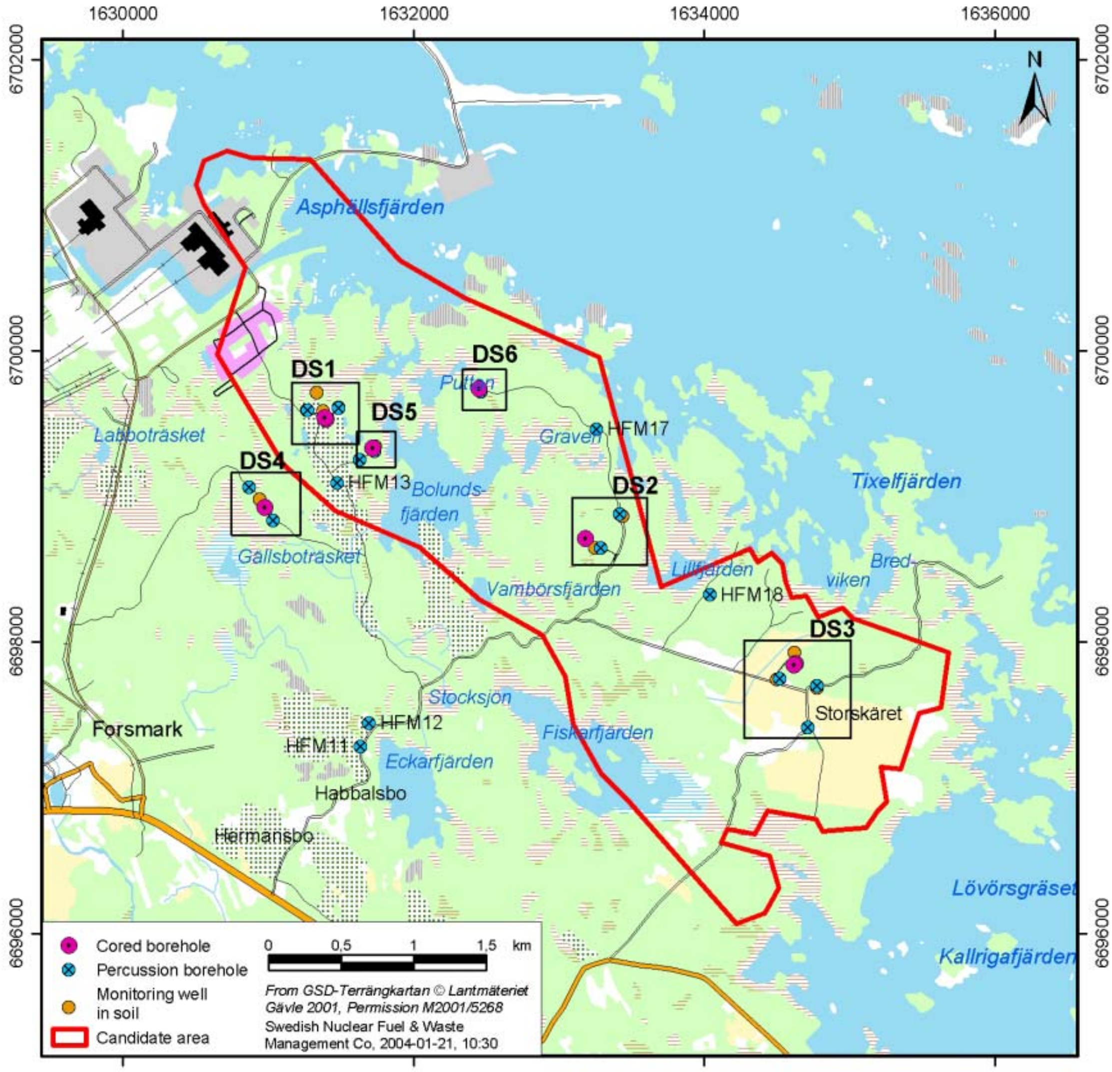


Figure 1-1. The investigation area at Forsmark including the candidate area selected for more detailed investigations. Borehole KFM06A is located at drillsite DS6.

In the vicinity of borehole KFM06A, the percussion borehole HFM16 was drilled, see Figure 1-2.

The percussion borehole HFM16 was drilled with the purpose to serve as a supply well for the flushing water needed for drilling of the cored part of borehole KFM06A. Large inflows were observed at c. 41 m, 60 m and 66 m with inflows of c. 480 L/min, 1200 L/min and 1800 L/min respectively during drilling in HFM16. A smaller inflow was observed at c. 70 m.

This report presents the results from pumping tests and flow logging in the percussion boreholes KFM06A (0–100 m) and HFM16, performed by a specially designed equipment system, the HTHB test system. Water samples were collected during pumping. The results of the chemical investigations are reported in /1/.

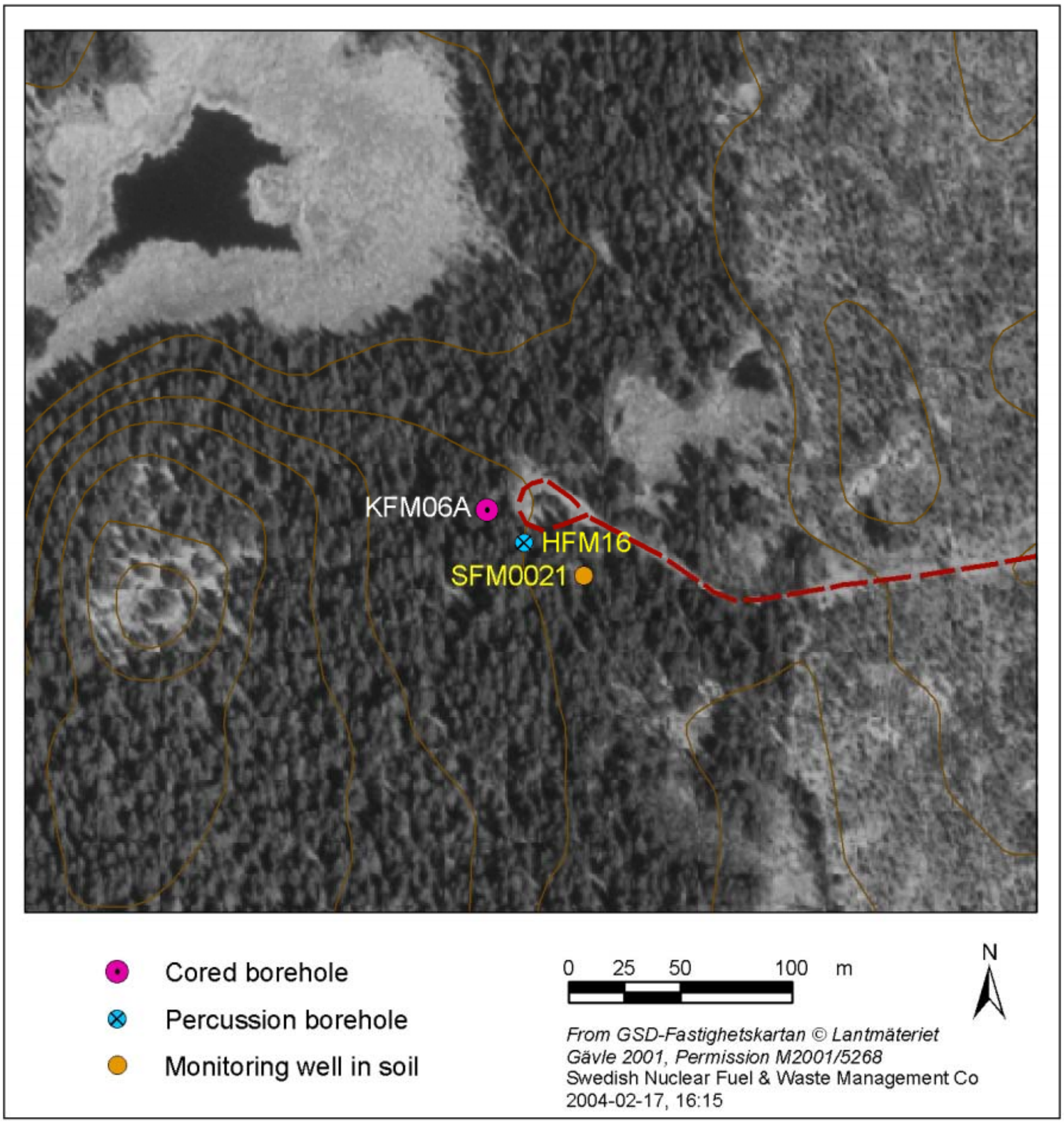


Figure 1-2. *Map showing the location of boreholes at drill site DS6 at Forsmark.*

This document reports the results gained by the *Hydraulic testing of the boreholes KFM06A and HFM 16.* The activity is performed within the Forsmak 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 238.

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

Activity Plan	**Number**	**Version**
Hydraulic testing of the boreholes KFM06A and HFM 16	AP PF 400-03-101	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
Metodbeskrivning för provtagning i hammarborrhål efter borrning.	SKB MD 423.002	1.0
Mätsystembeskrivning för HydroTestutrustning för Hammarborrhål- HTHB.	SKB MD 326.001-015	1.0

2 Objectives

Pumping tests, flow logging and groundwater sampling were performed in the percussion boreholes KFM06A (0–100 m) and HFM16. The objectives of the pumping test in the interval 0–100 m in KFM06A (more exactly 12.3–100.3 m) were to characterize the hydraulic properties of the rock penetrated by the borehole, before installation of a borehole casing, and furthermore, to investigate the hydrogeochemical character of the borehole water.

The main objectives of the hydraulic tests in the percussion borehole HFM16 were firstly, to perform a hydraulic characterisation of the borehole and secondly, to investigate the water chemistry, partly for a general hydrogeochemical characterization, and partly for a judgement of its potential to serve as a supply well for flushing water during the core drilling of KFM06A.

3 Scope

3.1 Boreholes tested

Selected technical data of the boreholes tested are shown in Table 3-1. The reference point in the boreholes is always top of casing (ToC). The Swedish National coordinate system (RT90 2.5 g W) is used in the x-y-direction together with RHB70 in the z-direction. The reported borehole diameter along the hole is shown in Table 3-1. The borehole diameter (measured as the diameter of the drill bit) usually decreases c. 1–2 mm/100 m along the borehole in the type of rock prevailing at Forsmark due to successively increased wear of the 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) (º)**	**Dip-direction-top of borehole (from local N) (º)**	**Remarks**	**Drilling finished Date (YYYY-MM-DD)**
KFM06A ”	4.098	0.00–12.3** 12.3–100.3**	0.182** 0.164**	–60.252	300.916	Casing ID* borehole	
HFM16 ”	3.210	0.00–12.02 12.02–82.00	0.160 0.140	–84.218	327.957	Casing ID* borehole	
”		82.00–132.50	0.139			borehole	2003-11-11

* Casing ID=inner diameter of casing
** Preliminary data, not in SICADA

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

Borehole data		
Bh ID	**Northing (m)**	**Easting (m)**
KFM06A	6699732.879	1632442.506
HFM16	6699721.098	1632466.182

3.2 Tests performed

The tests performed in the boreholes are listed in Table 3-3 according to Activity Plan AP PF 400-03-101 (SKB internal controlling document). Pumping tests and impeller flow meter logging were carried out with the HTHB (Hydro Testutrustning i Hammar-Borrhål) unit. The test performed are described in the corresponding methodology descriptions (SKB internal document), for single-hole pumping tests (SKB MD 321.003: Metodbeskrivning för hydrauliska enhålspumptester) and flow logging (SKB MD 322.009: Metodbeskrivning för flödesloggning). None of the boreholes were tested previously. In conjunction with the flow logging, temperature- and electric conductivity logging of the borehole water was also performed.

During the pumping tests, water samples were collected and submitted for analysis, see Section 6.2. Of primary interest was to decide if the borehole water in HFM16 was of sufficient quality to be used as flushing water for drilling of the cored borehole KFM06A.

Manual observations of the groundwater level in the pumped boreholes were also made during the tests as a back-up for the automatic registrations.

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)**
KFM06A	12.3–100.3	1B	2003-12-08 09:10	2003-12-09 08:55
”	34.5–66	6, L-Te, L-EC	2003-12-08 15:21	2003-12-08 18:26
HFM16	12.02–132.50	1B	2003-12-02 08:56	2003-12-03 00:12
”	12–126	6, L-Te, L-EC	2003-12-02 13:43	2003-12-02 17:38

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

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 sensors P1 and P2 (cf. Figures 4-1 and 4-2), the pressure in air was recorded and found to be as expected. Submerged in water while lowering, P1 coincided well to the total head of water (p/ρg). The temperature sensor showed expected values in both air and water.

The sensor for electric conductivity showed a zero value 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 sensor attached to it indicated a length that corresponded well to the pre-measured cable length.

4 Description

4.1 Overview

The equipment used in these tests is referred to as HTHB (Swedish abbreviation for Hydraulic Test System for Percussion Boreholes), which is described in SKB MD 326.001-15, Version 1.0 (Mätsystembeskrivning för HTHB-utrustning. Handhavandedel. SKB internal document)

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 c. 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 constant hydraulic head or, alternatively, with constant flow rate. For injection tests, the deepest position of the packer is limited to c. 80 m.

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

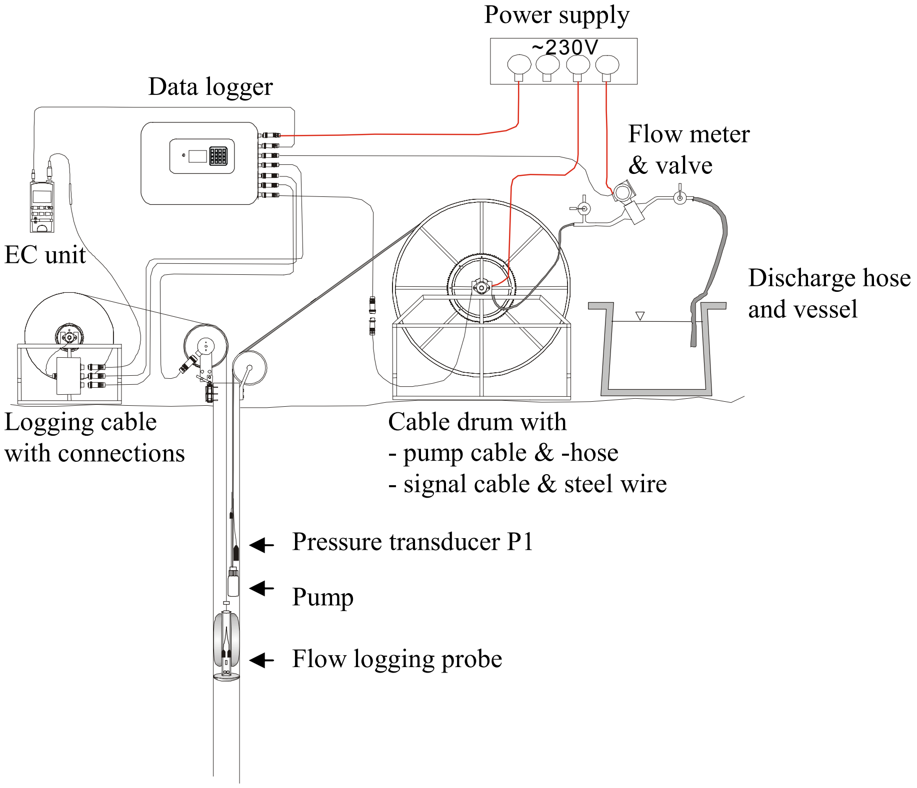


Figure 4-1. *Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB.*

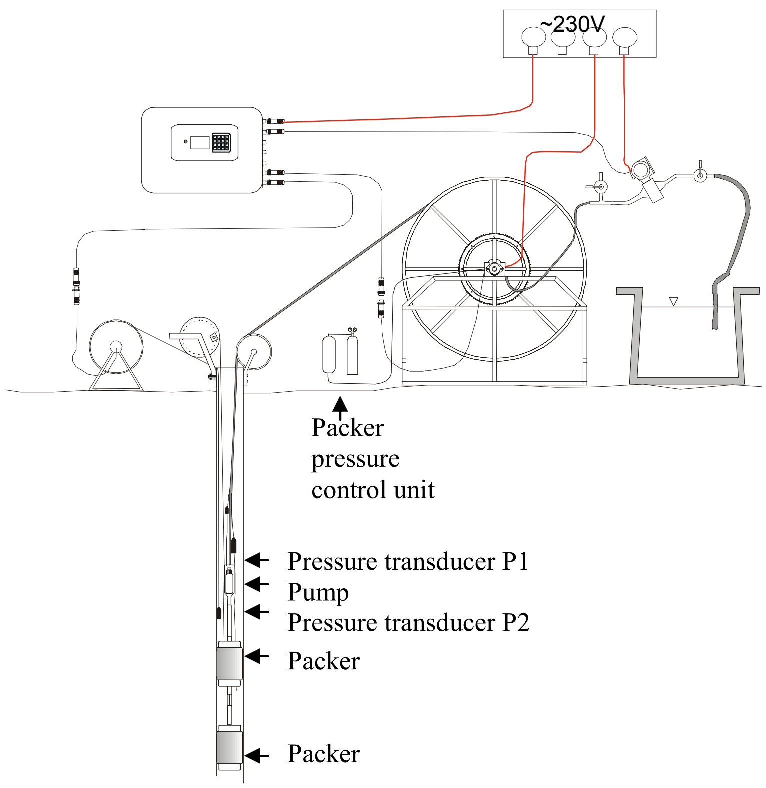


Figure 4-2. *Schematic test set-up for a pumping test in an isolated borehole section with HTHB.*

4.2 Measurement sensors

Technical data of the sensors used together with estimated data specifications of the HTHB test system for pumping tests and flow logging are given in Table 4-1.

Errors in reported borehole data (diameter etc) may significantly increase the error in measured data. For example, the flow logging probe is very sensitive to variations in the borehole diameter, c.f. 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 (e.g. different pipe diameters), i.e. 111.3, 135.5, 140 and 160 mm. During calibration the probe is installed in a vertically orientated pipe and a water flow is pumped through. Spinner rotations and the total discharge are measured. Calibration gives excellent correlation ($R^2 > 0.99$) between total discharge and the number of spinner rotations. The calibration also clearly shows how sensible the probe is to deviations in the borehole diameter, c.f. Figure 4-3.

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 stabilisation time is allowed to a change in flow. The stabilisation time may be up to 30 s at flows close to the lower measurement limit whereas this time is almost instantaneous at high flows.

Table 4-1. Technical data of measurement sensors used together with estimated data specifications of the HTHB test system for pumping tests and flow logging (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	0–500	0–500	
	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–		
	Meas. range	L/min	c. 15	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
	Accuracy***	% o.r.**		± 20	100 s sampling time
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 repeatibility
** 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

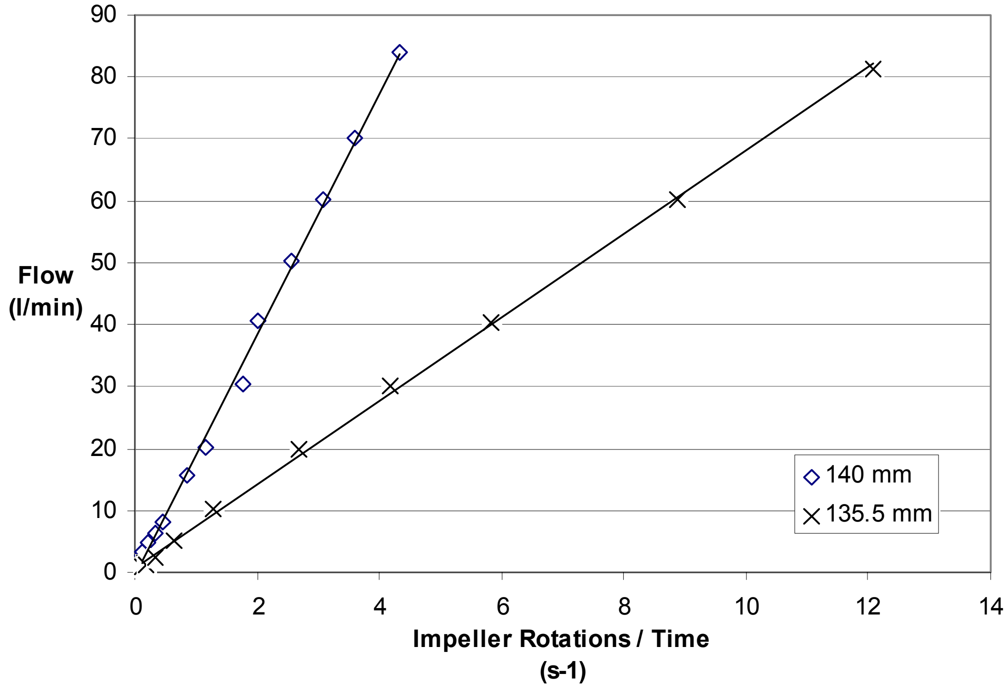


Figure 4-3. *Illustration of total flow as a function of impeller rotations for two borehole diameters (140 and 135.5 mm).*

Table 4-2 shows the position of sensors for each test. The following type of sensors is used: pressure (p), temperature (Te), electric conductivity (EC) together with the (lower) level of the submersible pump (Pump). Positions are given in meter 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 the position is thus varying (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 consulted.

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 well-bore storage coefficient C for the actual test configurations and the geometrical data of the boreholes (Table 3-1) has been calculated, see Section 5.4.1. These values on C may be compared with the estimated ones from the test interpretations 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[2] relative test section**	**Outer diameter (mm)**	**C (m^3/Pa) for actual test[3)]**
KFM06A (0–100)	12.3–100.3	Open hole	1B	Pump-intake	30.5	Pump	In borehole		$2.2 \cdot 10^{-6}$ (based on the bore hole diameter of 164 mm)
						Pump hose	In borehole	33.5	
						Pump cable	In borehole	14.5	
						Tecalan hose	In borehole	8	
			1B	P (P1)	27.22	Signal cable	In borehole	6	
			6	EC, Te, Q	34.5–66	Signal cable	In borehole	6	
HFM16	12.02–132.50	Open hole	1B	Pump-intake	8.0	Pump	In borehole		$2.0 \cdot 10^{-6}$ (based on the casing diameter of 160 mm)
						Pump hose	In borehole	33.5	
						Pump cable	In borehole	14.5	
						Tecalan hose	In borehole	8	
			1B	P (P1)	4.72	Signal cable	In borehole	6	
			6	EC, Te, Q	12–126	Signal cable	In borehole	6	

1) 1B: Pumping test-submersible pump, 6: Flow logging–Impeller incl. EC-logging (EC-sec) and temperature logging (Te-sec)
2) Position of equipment that can affect wellbore storage. Position given as "In Section" or "Above Section" or "In borehole"
3) Based on the casing diameter or the actual borehole diameter for open-hole tests (net values)

5 Execution

The pumping tests and flow logging were performed according to Activity Plan AP PF 400-03-101 (SKB internal controlling document) in accordance with the methodology descriptions for single-hole pumping tests (SKB internal documents), SKB MD 321.003, Version 1.0 (Metodbeskrivning för hydrauliska enhålspumptester), and flow logging, SKB MD 322.009, Version 1.0 (Metodbeskrivning för flödesloggning).

5.1 Preparations

All sensors included in the HTHB system are calibrated at GEOSIGMAs engineering workshop in Librobäck, Uppsala. Calibration is performed on a yearly basis, or more often if needed. The last calibrations before the tests were done at different occasions during 2003. Calibration protocol was submitted in the delivery of raw data after the test campaign.

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 sensor P1 (cf. Figures 4-1), the pressure in air was recorded and found to be as expected. Submerged in water while lowering, P1 coincided well to the total head of water (p/ρg). The temperature sensor showed expected values in both air and water.

The sensor for electric conductivity showed a zero value 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 sensor attached to it indicated a length that corresponded well to the pre-measured cable length.

5.2 Procedure

5.2.1 Overview

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

The flow logging was performed while pumping. Discrete flow measurements were made at fixed step lengths (2 m), 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 at a short distance below the submersible pump in the borehole.

5.2.2 Details

Single-hole pumping tests

Short flow capacity tests were carried out to choose an appropriate flow rate for the pumping tests. All 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 pumping borehole.

The main test in each borehole was a c. 10 h long pumping test in the open hole in combination with flow logging, followed by a recovery period of c. 12 h. In borehole HFM16 the duration of the recovery period was decreased to 5 h due to a failure of electrical power to the data logger. In general, the sampling frequency of pressure during the pumping tests was according to Table 5-1. The hydraulic tests in HFM16 were performed before the tests in KFM06A (0–100 m).

The test program performed in the boreholes was mainly according to the Activity Plan. Compared to the methodology description for single-hole pumping tests, one deviations was made regarding the recommended test times:

- the recommended test time (24h+24h for drawdown/recovery) for the longer tests during flow logging was decreased to c.10 h +12 h due to 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 to estimate the hydraulic properties of the borehole regarding, e.g. wellbore storage effects and other disturbing factors.

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 along the borehole (max. speed= 0.5 m/s), temperature- and electric conductivity data were sampled. In general, the probe was halted at every ten meters to sample data.

Flow logging was performed during the long pumping test (10 h), starting from the bottom of the hole going upward. The logging started when the pressure in the borehole was approximately stable. The time needed to complete the flow logging survey depends on the length and character of the borehole. In general, between 3–7 hours is normal for a percussion borehole of 100–200 m length.

Flow logging can only be carried out up to a certain distance below the submersible pump (when logging from the bottom of the hole upward). The remaining part of the borehole (i.e. from the pump to the casing) 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 superficial flow anomalies, short injection tests are sometimes carried out by the HTHB system in c. 5 m long sections above the flow logged interval.

5.3 Data handling

Data are downloaded from the logger (Campell CR 5000) to a laptop with the program PC9000 and are, already in the logger, transformed to engineering units. 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 and plotted in different diagrams listed in the Instruction for analysis of injection- and single-hole pumping tests (SKB MD 320.004, SKB internal document) by the software AQTESOLV and the codes PUMPKONV together with SKB-plot.

5.4 Analyses and interpretation

5.4.1 Single-hole pumping tests

Firstly, a qualitative evaluation of actual flow regimes (wellbore storage, pseudo-linear, pseudo-radial and pseudo-spherical flow, respectively) and possible outer boundary conditions during the tests was performed. The qualitative evaluation was made from analyses of 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 a rapid increase and decrease of the derivative, respectively.

By the analysis of the data, different values were applied on the filter coefficient (step length) by the calculation of the pressure derivative to achieve maximal smoothing of the derivative without altering the original shape of the data.

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 by the evaluation of the tests. For tests indicating a fractured- or borehole storage dominated response, corresponding type curve solutions were used by the routine analyses.

If possible, transient analysis was made both on 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 both in log-log and lin-log diagrams as described in the above Instruction and in /2/ and /3/. In addition, a preliminary steady-state analysis (e.g. Moye's formula) was made 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 performed 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) /4/ for constant flow rate tests with radial flow, accounting for wellbore storage and skin effects, was generally used for estimating transmissivity, storativity and skin factor for actual values on the borehole- and casing radius. The software also includes models for discrete fractures (horizontal and vertical, respectively) intersecting the borehole causing pseudo-linear flow.

For tests showing a pseudo-linear (fractured) response in the beginning of the test period, a model for a horizontal fracture intersecting the borehole /5/ was also used in addition to the standard model by Dougherty and Babu. The analysis by the fracture model is however considered as more uncertain and merely used for comparison.

The effective casing radius may also be estimated by the regression analysis. The wellbore storage coefficient can 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.

Rather than assuming a fixed value of the storativity of $1 \cdot 10^{-6}$ by the analysis according to the instruction SKB MD 320.004 (SKB internal document) a higher storativity value was occasionally assumed, e.g. $5 \cdot 10^{-5}$. This is considered as justified in this case since the tests were performed in the upper part of the bedrock in which part a higher storativity sometimes may be relevant.

Estimations of the borehole storage coefficient C, based on actual borehole geometrical data (net values) according to Eqn. (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 deviations of the actual geometrical borehole data from the anticipated, e.g. borehole diameter, or presence of fractures with significant volumes.

For pumping tests in an open borehole (and in the interval above a single packer) the wellbore storage coefficient may be calculated as:

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

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 the flow logging (flow, temperature and electric conductivity of the borehole fluid) are firstly plotted versus borehole length. From these plots, flow anomalies were identified along the borehole, i.e. borehole intervals over which changes of flow higher than c. 1 L/min, in this case, 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.

The transmissivity (T) of the entire borehole was calculated from the analysis of the pumping test during the flow logging. The cumulative transmissivity at the top of the flow-logged interval ($T_{FT}=\Sigma T_i$) was then calculated according to the SKB internal document Methodology description for Impeller flow logging, SKB MD 322.009 (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 (order of magnitude) of the transmissivity of these anomalies may be estimated from Eqn. (5-3).

The transmissivity of an individual flow anomaly (T_i) was calculated from the measured inflow (dQ_i) at the anomaly and the calculated transmissivity of the entire borehole (T) according to /2/:

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

For comparison, estimations 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 Eqn. (5-3):

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

In a 140 mm borehole, 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 for a certain flow logging can be estimated from Eqn. (5-3) using dQ_i (min) = 1 L/min ($1.7 \cdot 10^{-5}$ m^3/s) which is considered as the minimal change in borehole flow rate to identify a flow anomaly. The upper measurement limit of transmissivity of a flow anomaly corresponds to the actual transmissivity of the borehole.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the pumping tests and flow logging are according to the instruction for analysis of single-hole injection- and pumping tests, SKB MD 320.004, Version 1.0 (Metodinstruktion för analys av injektions- och enhålspumptester, SKB internal document) and the methodology description for impeller flow logging, SKB MD 322.009, Version 1.0. Metodbeskrivning för flödesloggning, SKB internal document), cf Section 3.2. Additional symbols used are explained in the text. The nomenclature for the analyses by the AQTESOLV code is presented in Appendix 2.

6.2 Water sampling

Water samples were collected during the pumping tests in the boreholes at drillsite DS6 at Forsmark (Figure 1-2) and submitted for analysis, see Table 6-1.

Table 6-1. Data of water samples taken 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
KFM06A (0–100 m)	2003-12-08 17:07	12.0–100.3	1.7	WC080	8186	Open-hole test
“	2003-12-08 18:53	“	2.0	WC080	8187	Open-hole test
HFM16	2003-12-02 10:38	12.02–132.5	6.2	WC080	8162	Open-hole test
“	2003-12-02 15:26	”	25	WC080	8163	Open-hole test
“	2003-12-02 18:41	“	38	WC080	8164	Open-hole test

6.3 Single-hole pumping tests

Below, the results of the pumping tests are presented test by test. The barometric pressure and precipitation was 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 before the analysis of the data. For the actual single-hole tests such corrections are generally not needed considering the rather short test time and relatively high drawdown applied in the boreholes. However, for longer tests with a small drawdown applied such corrections may be necessary.

Drilling were in progress at HFM17, approximately 1 km from drillsite DS6, see Figure 1-1, during testing in HFM16 and KFM06A (0–100 m). However, no obvious signs were detected that showed interference between the drilling in HFM17 and HFM16 or KFM06A (0–100 m).

6.3.1 Borehole KFM06A (0–100 m)

General test data for the open-hole pumping test in the upper, percussion-drilled interval of borehole KFM06A are presented in Table 6-2. Flow logging was performed during this test. The variations in barometric pressure, sea level, precipitation and temperature during the test period in KFM06A are shown in Figure 6-1.

Table 6-2. General test data for the open-hole pumping test in the upper, percussion-drilled interval of borehole KFM06A in conjunction with flow logging.

General test data			
Borehole	KFM06A (0–100 m)		
Test type1[1)]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comment	Single hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	100.3
Casing length	Lc	m	12.3
Test section- secup	Secup	m	12.3
Test section- seclow	Seclow	m	100.3
Test section length	L_w	m	88.0
Test section diameter	$2 \cdot r_w$	mm	164
Test start (start of pressure registration)		yymmdd hh:mm	031208 09:10
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	031208 09:19:42
Stop of flow period		yymmdd hh:mm:ss	031208 19:21:04
Test stop (stop of pressure registration)		yymmdd hh:mm	031209 08:54:50
Total flow time	t_p	min	601.37
Total recovery time	t_F	min	813.77

[1)]: Constant Head injection and recovery or Constant Rate withdrawal and recovery

Pressure and groundwater level data

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW level (m a s l)***
Absolute pressure in borehole before start of flow period	p_i	kPa	299.48	1.01
Absolute pressure in test section before stop of flow period	p_p	kPa	108.55	–18.74
Absolute pressure in test section at stop of recovery period	p_F	kPa	294.67	0.37
Maximal pressure change during flow period	dp_p	kPa	190.93	

* Calculated from the groundwater level measurements

Manual groundwater level measurements in KFM06A (0–100 m)			GW level	
Date YYYY-MM-DD	Time tt:mm.ss	Time (min)	(m b. ToC)	(m a s l)
2003-12-04	13:58		3.79	0.81
2003-12-05	12:45		3.92	0.69
2003-12-05	14:16		3.01	1.48
2003-12-05	14:32		3.28	1.25
2003-12-08	09:00		3.88	0.73
2003-12-08	09:16	–4	3.56	1.01
2003-12-08	12:59	219	18.29	–11.78
2003-12-08	19:19	599	26.30	–18.74
2003-12-09	08:49	1409	4.29	0.37

Flow data

Flow data	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$4.92 \cdot 10^{-5}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$5.71 \cdot 10^{-5}$
Total volume discharged during flow period	V_p	m^3	2.06

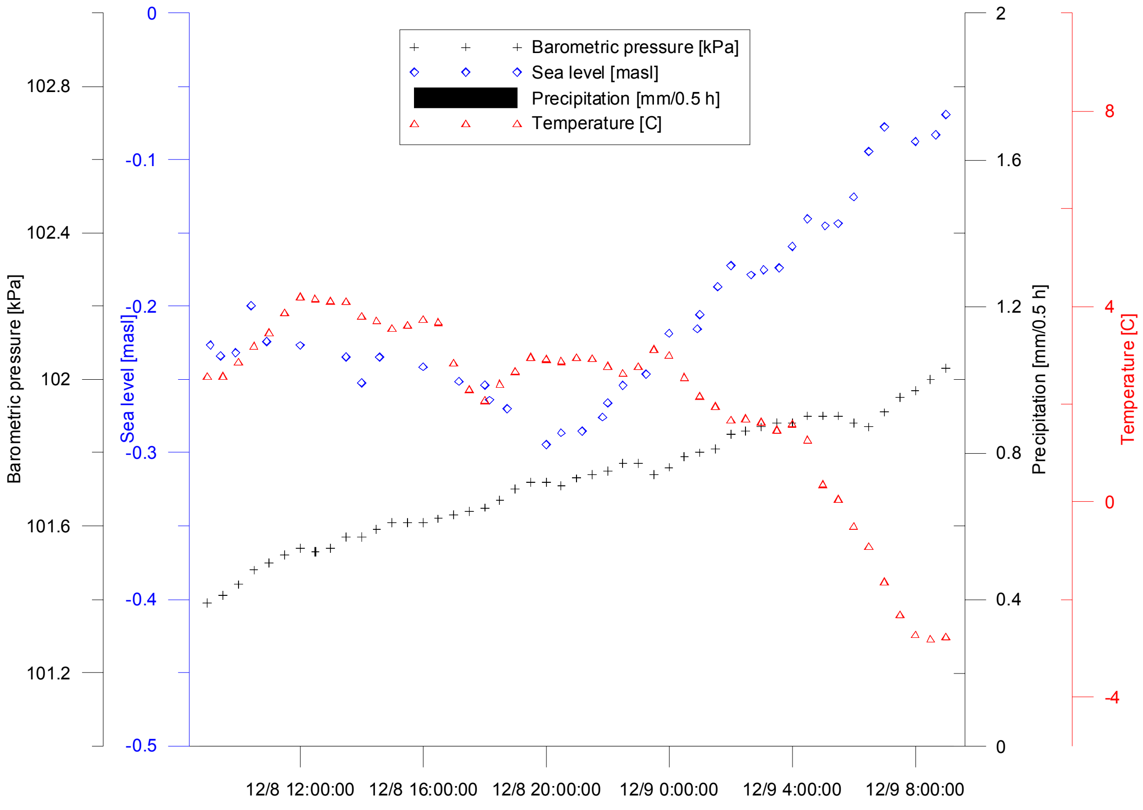


Figure 6-1. *Barometric pressure, sea level, precipitation and temperature during the test period in KFM06A.*

Comments to the test

The test was carried out as a pumping test with a constant flow rate with the intention to achieve (approximately) steady-state conditions during the flow logging. The flow rate had to be decreased from about 3.9 L/min to 2.9 L/min at c. 330 min after start of the flow period due to high drawdown, c.f. Figure A2-1 in Appendix 2. The actual drawdown was slightly increasing during the flow logging. After c. 2 min of equivalent time of the recovery period a disturbance due to a sudden movement of borehole equipment is clearly seen, c f Figure A2-4 in Appendix 2.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-1–A2-5 in Appendix 2. The initial phase of the flow period is dominated by wellbore storage effects. After that a transition to another flow regime is indicated. The change in flow rate caused the disturbance in the drawdown- and the drawdown derivative diagrams in Figures A2-2–A2-3.

After 11.9 m of recovery of the water level in the borehole, the water level reached the transition between the borehole and the casing and thus a change in diameter. This is clearly seen as a sudden change in the recovery derivative in Figures A2-4 and A2-5. After c. 50 min of equivalent time to the end of the recovery period a transition from wellbore storage towards another flow regime is indicated.

Interpreted parameters

Transient, quantitative interpretation of the flow- and recovery period of the test is shown in lin-log and log-log diagrams in Figures A2-2–A2-5 according to the methods described in Section 5.4.1. No well-defined period with pseudo radial flow occurred during either the flow- or recovery period. Therefore, the calculated hydraulic parameters are somewhat uncertain from this test. The results are shown in the Test Summary Sheets and in Tables 6-13 and 6-14 in Section 6.5. The analysis from the recovery period was selected as the representative.

6.3.2 Borehole HFM16

General test data for the open-hole pumping test in borehole HFM16 in conjunction with flow logging are presented in Table 6-3.

Table 6-3. General test data for the open-hole pumping test in HFM16 in conjunction with flow logging.

General test data			
Borehole	HFM16		
Test type1[1)]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comment	Single-hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	132.5
Casing length	Lc	m	12.02
Test section- secup	Secup	m	12.02
Test section- seclow	Seclow	m	132.5
Test section length	L_w	m	120.48
Test section diameter	$2 \cdot r_w$	mm	140
Test start (start of pressure registration)		yymmdd hh:mm	031202 08:56
Packer expanded		yymmdd hh:mm:ss	-
Start of flow period		yymmdd hh:mm:ss	031202 09:03:42
Stop of flow period		yymmdd hh:mm:ss	031202 19:04:02
Test stop (stop of pressure registration)		yymmdd hh:mm	031203 00:12:17
Total flow time	t_p	min	600.3
Total recovery time	t_F	min	308.3

[1)]: Constant Head injection and recovery or Constant Rate withdrawal and recovery

Pressure and groundwater level data

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW level (m a s l)***
Absolute pressure in borehole before start of flow period	p_i	kPa	122.28	0.74
Absolute pressure in test section before stop of flow period	p_p	kPa	113.40	–0.18
Absolute pressure in test section at stop of recovery period	p_F	kPa	120.46	0.61
Maximal pressure change during flow period	dp_p	kPa	8.88	

* Calculated from the groundwater level measurements

Manual groundwater level measurements			**GW level**	
Date YYYY-MM-DD	**Time tt:mm.ss**	**Time (min)**	**(m b. ToC)**	**(m a s l)**
2003-12-01	11:36		2.44	0.78
2003-12-01	15:53		2.46	0.76
2003-12-01	16:40		2.58	0.64
2003-12-02	08:52	–12	2.48	0.74
2003-12-02	09:42	38	2.94	0.28
2003-12-02	11:02	118	3.13	0.10
2003-12-02	12:41	217	3.22	0.01
2003-12-02	18:10	546	3.39	–0.16
2003-12-02	18:58	594	3.41	–0.18
2003-12-03	09:03	1439	2.61	0.61

Flow data

Flow data	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flowing	Q_p	m^3/s	$1.073 \cdot 10^{-3}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$1.074 \cdot 10^{-3}$
Total volume discharged during flow period	V_p	m^3	38.7

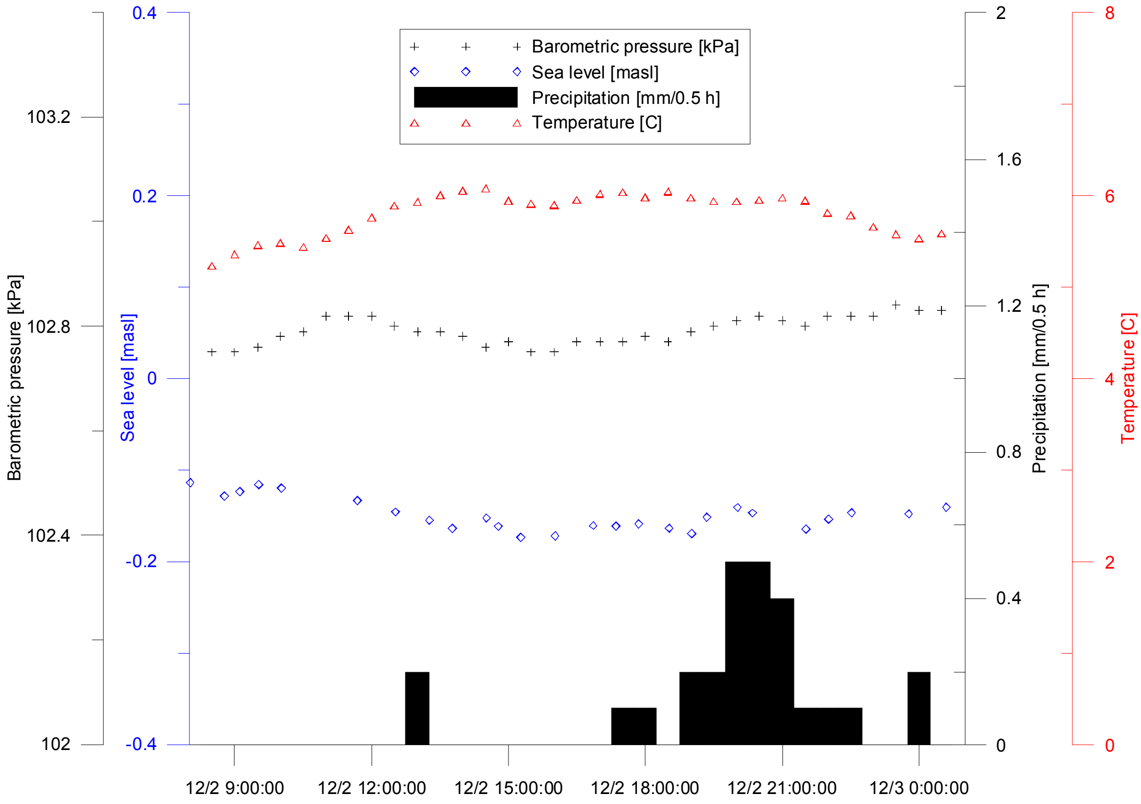


Figure 6-2. *Barometric pressure, sea level, precipitation and temperature during the test period in HFM16.*

Comments to the test

The test was carried out as a pumping test with a constant flow rate with the intention to achieve (approximately) steady-state conditions during the flow logging. The actual drawdown was slightly increasing during the flow logging. Between 400–500 min of the flow period the pumping test was affected by the flow logging which is clearly seen as a noise in the drawdown curve in Figure A2-8 in Appendix 2.

The variations in barometric pressure, sea level, precipitation and temperature during the test period in HFM16 are shown in Figure 6-2.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-6–A2-12 in Appendix 2. After the initial phase the flow regime is interpreted as pseudo-linear flow, see Figure A2-7. The drawdown derivative, in Figure A2-7, may indicate a transition towards pseudo radial flow after c. 50 min of the flow period.

The flow pattern during the recovery period is much alike that of the flow period, see Figure A2-9. The pseudo radial flow is indicated by the recovery derivative after c. 80 min of equivalent time and is more well-defined than during the flow period.

Interpreted parameters

The transient, quantitative interpretation of the flow- and recovery period of the test is shown in Figures A2-7–A2-12 in Appendix 2. Quantitative analysis was applied both on the flow- and recovery period according to the methods described in Section 5.4.1. The results are shown in the Test Summary Sheets and Table 6-11, 6-12 and 6-13 in Section 6.5. The analysis from the recovery period was selected as the representative.

6.4 Flow logging

6.4.1 Borehole KFM06A (0–100 m)

General test data for the flow logging in borehole KFM06A (0–100 m) are presented in Table 6-6.

Table 6-6. General test data for the flow logging in borehole KFM06A(0–100 m).

General test data			
Borehole	KFM06A (0–100 m)		
Test type(s)1[1)]	6, L-EC, L-Te		
Test section:	Open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comments	Single pumping borehole		
	Nomen-clature	**Unit**	**Value**
Borehole length		m	100.3
Pump position (lower level)		m	30.5
Flow logged section – Secup		m	34.5
Flow logged section – Seclow		m	66.0
Test section diameter	2·rw	mm	164
Start of flow period		yymmdd hh:mm	031208 09:19:42
Start of flow logging		yymmdd hh:mm	031208 15:21
Stop of flow logging		yymmdd hh:mm	031208 18:26
Stop of flow period		yymmdd hh:mm	031208 19:21:04

[1)] 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging

Groundwater level data

Groundwater level	Nomen-clature	Unit	G.w-level (m b ToC)	G.w-level (m a s l)
Level in borehole, at undisturbed conditions , open hole	h_i	m	3.56	1.01*
Level (steady state) in borehole, at pumping rate Q_p	h_p	m	26.30	–18.74*
Drawdown during flow logging	s_{FL}	m	-	17.98**

* Calculated from the groundwater level measurements
** Calculated from pressure measurements

Flow data

Flow data	Nomen-clature	Unit	Flow rate
Pumping rate from borehole at surface	Q_p	m^3 /s	$4.83 \cdot 10^{-5}$
Cumulative flow rate at Secup at pumping rate Q_p	Q_T	m^3 /s	-
Measurement limit for flow rate during flow logging	Q_{Measl}	m^3 /s	$6.67 \cdot 10^{-5}$
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3 /s	$1.7 \cdot 10^{-5}$

Comments to test

Due to difficulties in lowering the probe the flow logging was made from 66 m of the borehole and upward. The highest measurement position of the probe was 34.5 m. The first detectable flow was found at 48.5 m. Because of the problems with lowering the probe the step length between flow measurements was 0.5 m for the whole measured interval of the borehole.

The pumping rate at the surface was lower than the reported measurement limit (i.e. 4 L/min) which caused large uncertainties in the flow logging.

Logging results

The nomenclature used for the flow logging is according to the method description for flow logging. The measured flow distribution along the hole during the flow logging together with the electric conductivity (EC) and temperature (Te) of the borehole fluid is presented in Figure 6-3.

Due to the low transmissivity of KFM06A (0–100 m) there are large uncertainties regarding the flow logging of the borehole. All detectable borehole flow was below the given measurement limit on 4 L/min so the practical measurement limit was c. 3 l/min. The first detectable flow in the borehole was found at 48.5 m, see Figure 6-3. But at several positions below that, among others at 65.9 m, the spinner rotated for up to two minutes after relocation of the probe. The long duration of rotations can not be explained by the transport of the probe. Neither electric conductivity nor temperature measurements show any distinctive anomalies through out the measured interval. Therefore it is not possible to exclude that flow near the lower practical measurement limit existed during the flow logging in the borehole below 48.5 m. No significant flow anomalies could be identified in the borehole.

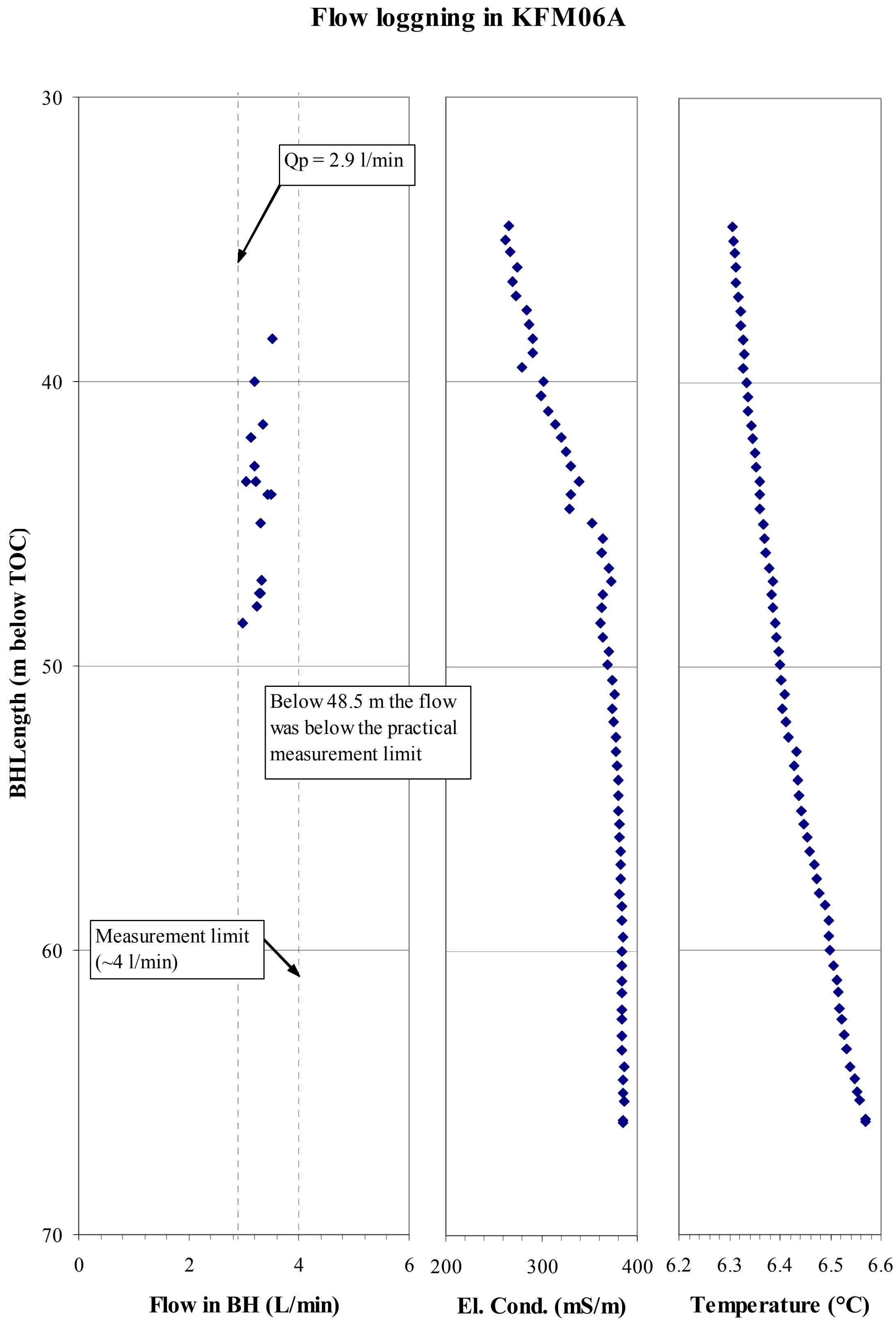


Figure 6-3. *Measured flow distribution along borehole KFM06A (0–100 m) during the flow logging together with the (temperature-compensated) electric conductivity (EC) and temperature (Te) of the borehole fluid.*

6.4.2 Borehole HFM16

General test data for the flow logging in borehole HFM16 are presented in Table 6-7.

Table 6-7. General test data for the flow logging in borehole HFM16.

General test data			
Borehole	HFM16		
Test type(s)1[1)]	6, L-EC, L-Te		
Test section:	Open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comments	Single pumping borehole		
	Nomen-clature	**Unit**	**Value**
Borehole length		m	132.5
Pump position (lower level)		m	8.0
Flow logged section – Secup		m	12.0
Flow logged section – Seclow		m	126.1
Test section diameter	2·rw	mm	140
Start of flow period		yymmdd hh:mm	031202 09:03:42
Start of flow logging		yymmdd hh:mm	031202 13:43
Stop of flow logging		yymmdd hh:mm	031202 17:38
Stop of flow period		yymmdd hh:mm	031202 19:04:02

[1)] 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging

Groundwater level data

Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)**
Level in borehole, at undisturbed conditions , open hole	h_i	m	2.48	0.74*
Level (steady state) in borehole, at pumping rate Q_p	h_p	m	3.41	–0.18*
Drawdown during flow logging	s_{FL}	m	-	0.82**

* Calculated from the groundwater level measurements
** Calculated from pressure measurements

Flow data

Flow data	**Nomen-clature**	**Unit**	**Flow rate**
Pumping rate from borehole at surface	Q_p	m^3/s	$1.073 \cdot 10^{-3}$
Cumulative flow rate at Secup at pumping rate Qp	Q_T	m^3/s	$1.073 \cdot 10^{-3}$
Measurement limit for flow rate during flow logging	Q_{Measl}	m^3/s	$5.0 \cdot 10^{-5}$
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$

Comments to test

The flow logging started near the bottom of the hole and continued upward. The first detectable flow anomaly was at 69.0 m (lower limit). The step length between flow measurements was maximally 2 m. At each flow anomaly a step length 0.5 m was used.

The measured maximal borehole flow rate at the top of the flow logged interval was approximately the same as the total flow rate pumped from the borehole at the surface.

Logging results

The nomenclature used for the flow logging is according to the method description for flow logging. The measured flow distribution along the hole during the flow logging together with the electric conductivity (EC) and temperature (Te) of the borehole fluid is presented in Figure 6-4.

Figure 6-4 indicates that HFM16 has four flow anomalies. The results of the flow logging in borehole HFM16 are presented in Table 6-8 below. There was a good agreement between Q_T and Q_p. No correction of the borehole flow rate e.g. due to deviation of the borehole diameter from the assumed in the calibration was made.

The first anomaly is located in the interval 69.0–69.5 m which is also supported by the electric conductivity measurements. The largest flow anomaly in the borehole is located between 58.5 and 59.5. This anomaly is supported by both temperature and electrical conductivity. At flow anomaly number three, 56.0–56.5 m, there is only a small change in electrical conductivity. Flow anomaly number two and three could be interpreted as one anomaly but here there are presented individually. The fourth flow anomaly is supported with a small change in both temperature and electrical conductivity and is located at 41.0–41.5 m in the borehole. The first, second and the fourth flow anomaly is supported by observations during drilling, c.f. Chapter 1.

The estimated transmissivity of individual flow anomalies (T_i) are calculated from Eqn. (5-3). An estimation of the transmissivity of the interpreted flow anomaly was 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 6-8. Results of the flow logging in borehole HFM16. Q_T=cumulative flow at the top of the logged interval, s_{FL}= drawdown during flow logging.

HFM16 Flow anom.		Q_T=1.073·10^{-3} (m^3/s)	T=5.26·10^{-4} (m^2/s)	s_{FL}=0.82 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**
41.0–41.5	0.5	2.40·10^{-4}	1.18·10^{-4}	2.93·10^{-4}	Te , EC
56.0–56.5	0.5	8.33·10^{-5}	4.08·10^{-5}	1.02·10^{-4}	(EC)
58.5–59.5	1.0	6.33·10^{-4}	3.10·10^{-4}	7.72·10^{-4}	Te, EC
69.0–69.5	0.5	1.17·10^{-4}	5.72·10^{-5}	1.42·10^{-4}	EC
Total		∑ = 1.073·10^{-3}	∑ = 5.26·10^{-4}	∑ = 1.31·10^{-3}	
Difference		Q_T–Q_p= 0	-	-	

Flow loggning in HFM16

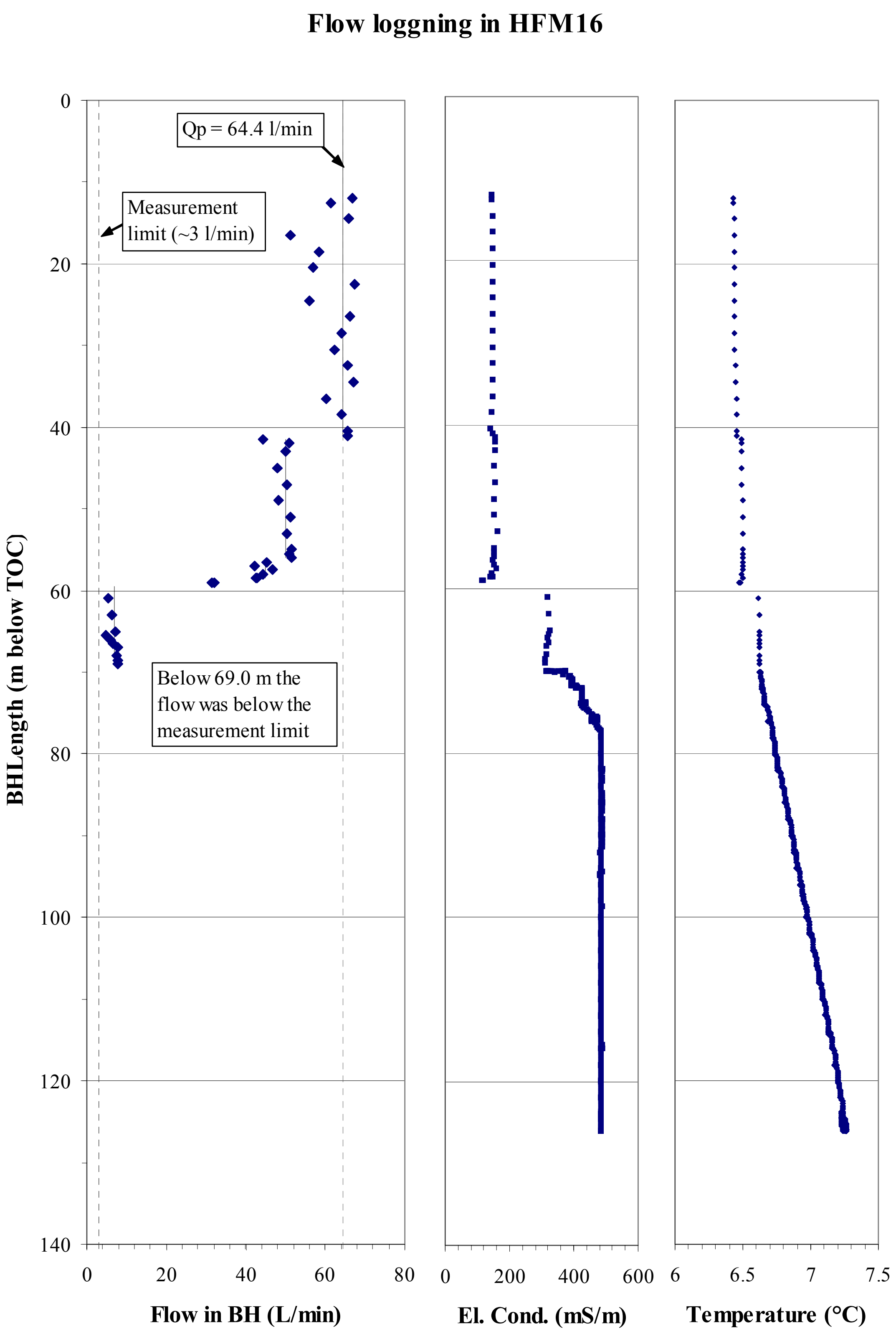


Figure 6-4. *Measured flow distribution along borehole HFM16 during the flow logging together with the (temperature-compensated) electric conductivity (EC) and temperature (Te) of the borehole fluid.*

Figure 6-5 shows the calculated, cumulative transmissivity $T_F(L)$ along the borehole length (L) from the flow logging from Eqn. (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, c.f. Section 5.4.2.

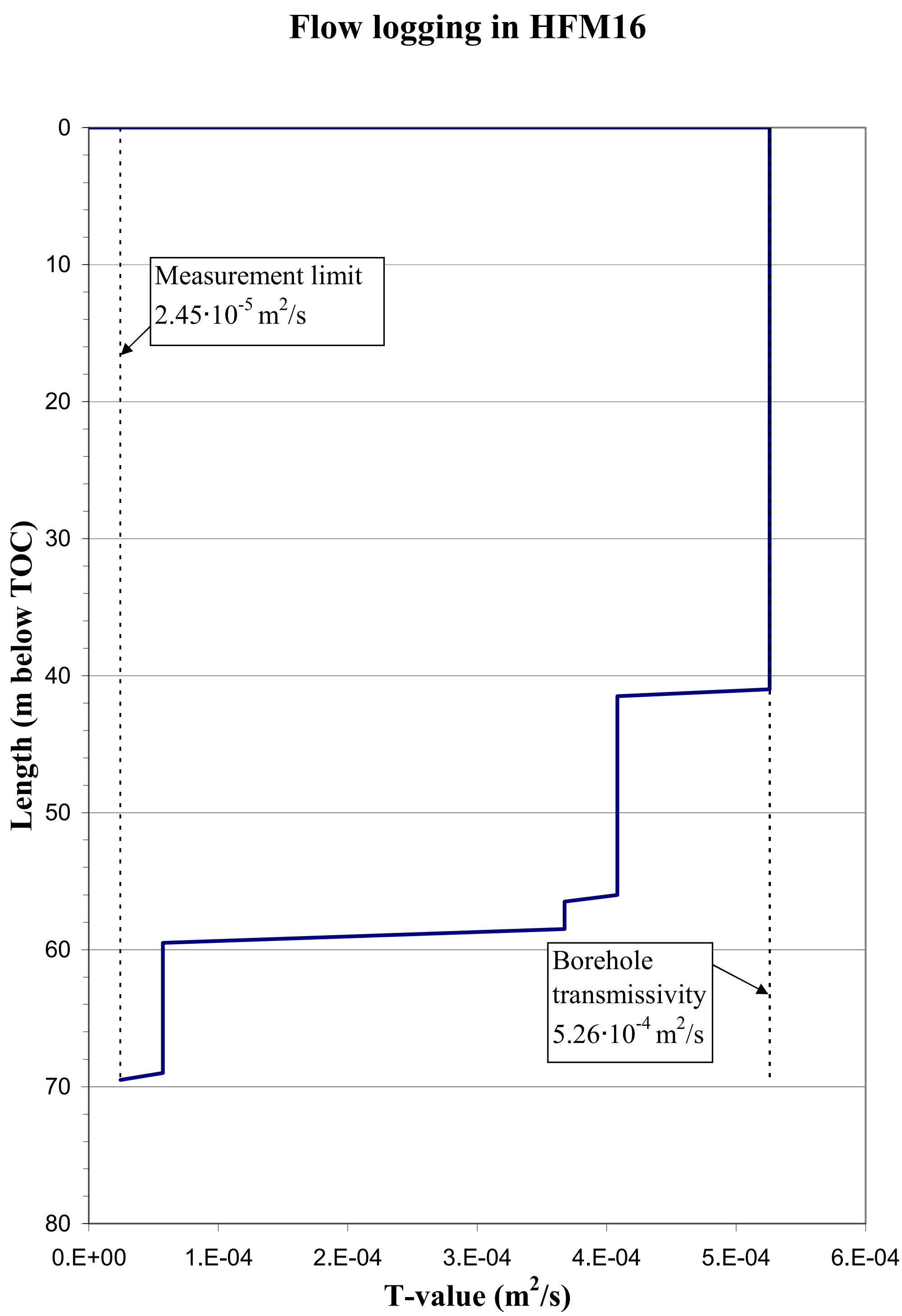


Figure 6-5. *Calculated, cumulative transmissivity along the flow-logged interval of borehole HFM16.*

6.5 Summary of hydraulic tests

A compilation of measured test data from the hydraulic tests carried out in the test campaign is shown in Table 6-10. In Table 6-11 and 6-12 calculated hydraulic parameters of the formation and borehole from the tests, respectively, are shown. The results of the flow logging are presented 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 practical lower limit is based on the minimal flow rate Q, for which the system is designed (5 L/min) and an estimated maximal allowed drawdown for practical purposes (c. 50 m) in a percussion borehole, c.f. 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 e.g. background fluctuations of the pressure before and during the test. These values correspond to an estimated, practical upper measurement limit of Q/s–U=2·10–3 m^2/s for both pumping tests and injection tests.

In Tables 6-10 to 6-12, the parameter explanations are according to the Instruction for analysis of injection tests and single-hole pumping tests SKB MD 320.004, Version 1.0 (Metodinstruktion för analys av injektions- och enhålspumptester, SKB internal document). The parameters are also explained in the text above, except the following parameters:

T_M = steady-state transmissivity calculated from Moye's formula
T_T = transmissivity of formation from transient evaluation
T_i = estimated transmissivity of flow anomaly
S* = assumed value on storativity by calculation of the skin factor.
C = wellbore storage coefficient
ζ = skin factor

Table 6-10. Summary of test data for the hydraulic tests performed in boreholes at drillsite DS6 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)
KFM06A	12.3–100.3	1B	299.48	108.55	294.67	$4.92\cdot10^{-5}$	$5.71\cdot10^{-5}$	2.06
HFM16	12.02–132.50	1B	122.28	113.40	120.46	$1.07\cdot10^{-3}$	$1.07\cdot10^{-3}$	38.7

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

Table 6-11. Summary of calculated hydraulic parameters of the formation from the hydraulic tests performed at drill site DS6 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* (-)
KFM06A	12.3–100.3		1B	$2.53\cdot10^{-6}$	$2.93\cdot10^{-6}$	$1.41\cdot10^{-6}$		$1.0\cdot10^{-6}$
KFM06A	34.5–66.0		6				-	
HFM16	12.02–132.50		1B	$1.19\cdot10^{-3}$	$1.46\cdot10^{-3}$	$5.26\cdot10^{-4}$		$5.5\cdot10^{-5}$
HFM16	12.0–126.0	41.0–41.5	6				$1.18\cdot10^{-4}$	
HFM16	12.0–126.0	56.0–56.5	6				$4.08\cdot10^{-5}$	
HFM16	12.0–126.0	58.5–59.5	6				$3.10\cdot10^{-4}$	
HFM16	12.0–126.0	69.0–69.5	6				$5.72\cdot10^{-5}$	

Table 6-12. Summary of calculated hydraulic parameters of the borehole from hydraulic test performed in boreholes within drillsite DS6 in the Forsmark area.

Borehole ID	Section (m)	Test type	S* (-)	C (m^3/Pa)	ζ (-)
KFM06A	12.3–100.3	1B	$1\cdot10^{-6}$	$2.15\cdot10^{-6}$ *	–1.66
HFM16	12.02–132.50	1B	$5.5\cdot10^{-5}$	-	–6.78

* Calculated from the simulated effective casing radius

Table 6-13. Summary of calculated hydraulic parameters of the formation using a horizontal fracture model from the hydraulic tests performed at drill site DS6 in the Forsmark area.

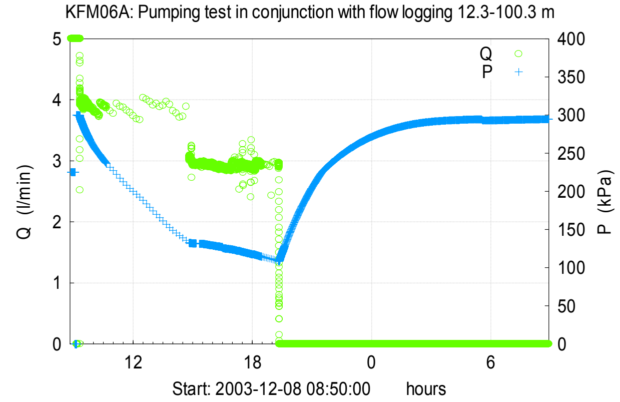
Borehole ID	Section (m)	Test type	K_r (m/s)	T_r (m^2/s)	S_s* (1/m)	S* (-)	R_f (m)
HFM16	12.02–132.50	1B	$4.90\cdot10^{-6}$	$5.87\cdot10^{-4}$	$4.17\cdot10^{-7}$	$5.5\cdot10^{-5}$	135

K_r = hydraulic conductivity of the formation in the radial (horizontal) direction
T_r = transmissivity of the formation in the radial (horizontal) direction
S_s* = assumed specific storage of the formation
R_f = estimated radius of horizontal fracture

Test Summary Sheet

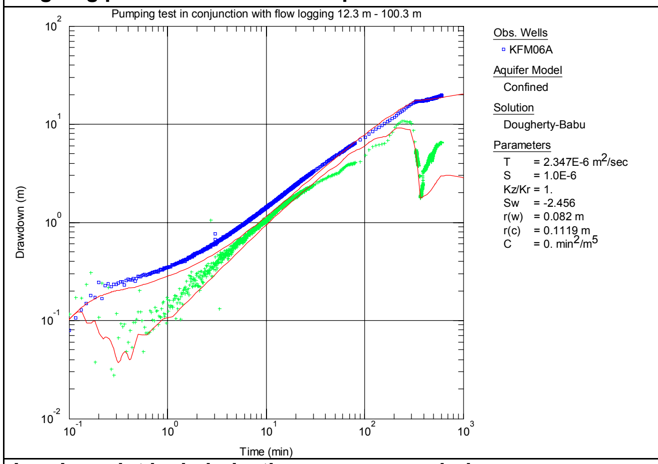
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	KFM06A (0–100 m)	Test start:	2003-12-08 09:10
Test section (m):	12.3–100.3	Responsible for test performance:	GEOSIGMA AB C. Hjerne/J. Olausson
Section diameter, $2 \cdot r_w$ (m):	0.164	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

Linear plot Q and p

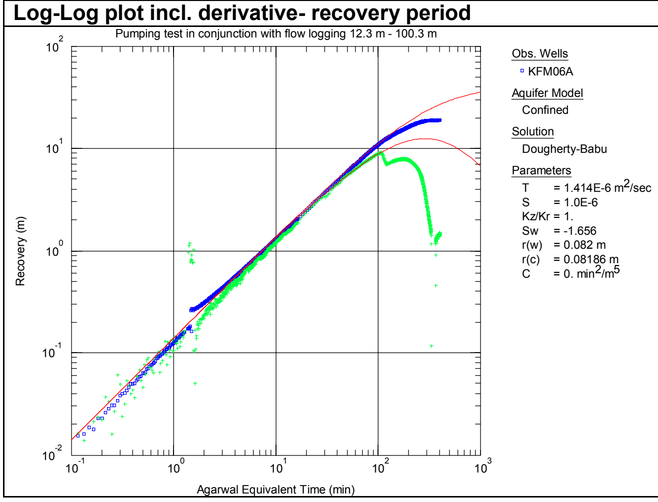


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	299.48		
p_i (kPa)	299.48		
p_p(kPa)	108.55	p_F (kPa)	294.67
Q_p (m^3/s)	$4.92 \cdot 10^{-5}$		
t_p (min)	601.37	t_F (min)	813.77
S*	$1 \cdot 10^{-6}$	S*	$1 \cdot 10^{-6}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.1	Derivative fact.	0.05
Results		**Results**	
Q/s (m^2/s)	$2.53 \cdot 10^{-6}$		
T_{Moye}(m^2/s)	$2.93 \cdot 10^{-6}$		
Flow regime:	WBS	Flow regime:	WBS
t_1 (min)	0.3	dt_{e1} (min)	0.1
t_2 (min)	601	dt_{e2} (min)	100
T_w (m^2/s	$2.35 \cdot 10^{-6}$	T_w (m^2/s	$1.41 \cdot 10^{-6}$
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	$4.01 \cdot 10^{-6}$	C (m^3/Pa)	$2.15 \cdot 10^{-6}$
C_D (-)	-	C_D (-)	-
ξ (-)	–2.46	ξ (-)	–1.66
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.

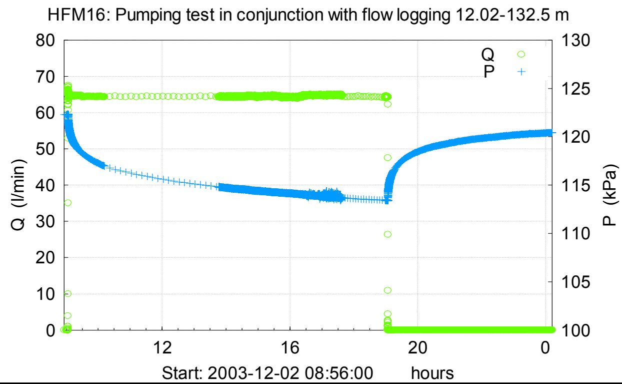
Flow regime:	WBS	C (m^3/Pa)	$2.15 \cdot 10^{-6}$
dt_{e1} (min)	0.1	C_D (-)	
dt_{e2} (min)	100	ξ (-)	–1.66
T_T (m^2/s)	$1.41 \cdot 10^{-6}$		
S (-)			
K_s (m/s)			
S_s (1/m)			

Comments: Change in the flow rate at 330 min from about 3.9 L/min to about 2.9 L/min. Dominating wellbore effects occurred during both the flow- and recovery period followed by a transition period. No pseudo-radial flow was developed.

Test Summary Sheet

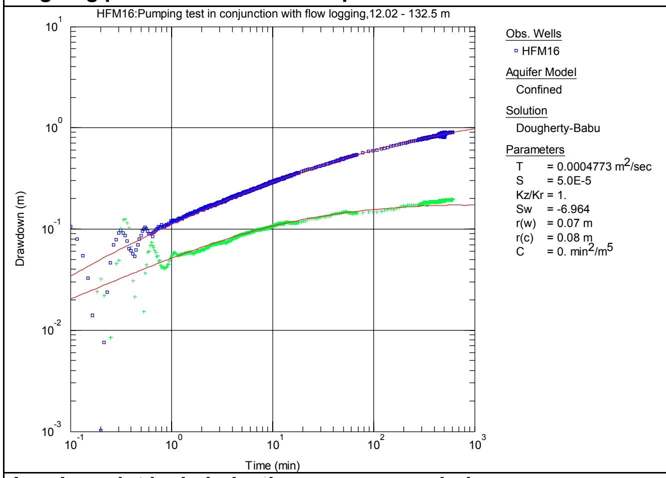
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM16	Test start:	2003-12-02 08:56
Test section (m):	12.02–132.5	Responsible for test performance:	GEOSIGMA AB C. Hjerne/ J. Olausson
Section diameter, $2 \cdot r_w$ (m):	0.140	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

Linear plot Q and p

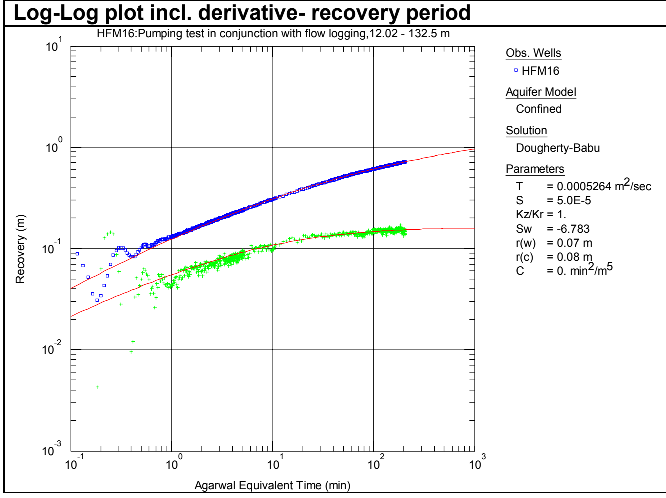


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	122.28		
p_i (kPa)	122.28		
p_p(kPa)	113.40	p_F (kPa)	120.46
Q_p (m^3/s)	$1.07 \cdot 10^{-3}$		
t_p (min)	600.3	t_F (min)	308
S*	$5 \cdot 10^{-5}$	S*	$5 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.5	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$1.19 \cdot 10^{-3}$		
T_{Moye}(m^2/s)	$1.46 \cdot 10^{-3}$		
Flow regime:	PLF→PRF	Flow regime:	PLF→PRF
t_1 (min)	0.8	dt_{e1} (min)	0.8
t_2 (min)	600	dt_{e2} (min)	204
T_w (m^2/s)	$4.77 \cdot 10^{-4}$	T_w (m^2/s)	$5.26 \cdot 10^{-4}$
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 (-)	–6.96	ξ (-)	–6.78
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:	PLF→PRF	C (m^3/Pa)	-
dt_{e1} (min)	0.8	C_D (-)	-
dt_{e2} (min)	204	ξ (-)	–6.78
T_T (m^2/s)	$5.26 \cdot 10^{-4}$		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: During both the flow- and the recovery period pseudo-linear flow regime existed, approaching a pseudo-radial flow regime towards the end of each period.

7 References

/1/ **Nilsson A-C, 2004.** Sampling and analyses of groundwater in percussion drilled boreholes. Results from the percussion boreholes HFM09 to HFM19 and the percussion drilled parts of KFM05A and KFM06A (in prep).

/2/ **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. Tekniskt Dokument TD-01-63, 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/ **Dougherty D E, Babu D K, 1984.** Flow to a partially penetrating well in a double-porosity reservoir, Water Resour. Res., 20 (8), 1116–1122.

/5/ **Gringarten A C, Ramey H J, 1974.** Unsteady- state pressure distributions created by a well with a single horizontal fracture, partial penetration, or restricted entry. Soc. Pet. Eng. J. (Aug. 1974) pp. 413–426, Trans., AIME, 257.

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	Datafile, stop Date, time YYYY-MM-DD tt:mm:ss	Data files of raw and primary data	Content (parameters)[2]	Comments
HFM16	0–132.5	1B,6 L-EC L-T		2003-12-02 08:56:30	2003-12-03 00:12:17	2003-12-02 08:56:30	2003-12-03 00:12:17	HFM16_000_031202_FlowLo00.DAT	P, Q, T, EC	
HFM16	0–132.5	1B				2003-12-02 08:41:45	2003-12-02 19:15:06	HFM16_000_031202_Ref_Da00.DAT		
HFM16	12.0–126.0	6 L-EC L-T		2003-12-02 13:43	2003-12-02 17:38	2003-12-02 15:06:43	2003-12-02 17:37:25	HFM16_12.0_031202_Spinne00.DAT	P, Q, T, EC, Sp	
HFM16	12.0–126.0	6				2003-12-02 08:41:45	2003-12-02 19:15:06	HFM16_12.0_031202_Ref_Da00.DAT		
KFM06A	0–100.3	1B,6 L-EC L-T		2003-12-08 09:10:02	2003-12-09 08:54:50	2003-12-08 09:10:02	2003-12-09 08:54:50	KFM06A_000_031208_FlowLo00.DAT	P, Q, T, EC	
KFM06A	0–100.3	1B				2003-12-08 08:51:51	2003-12-09 09:11:58	KFM06A_000_031208_Ref_Da00.DAT		
KFM06A	34.5–66.0	6 L-EC L-T		2003-12-08 15:21	2003-12-08 18:26	2003-12-08 16:53:08	2003-12-08 18:14:06	KFM06A_34.5_031208_ Spinne00.DAT	P, Q, T, EC, Sp	
KFM06A	34.5–66.0	6				2003-12-08 08:51:51	2003-12-09 09:11:58	KFM06A_34.5_031208_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

Nomenclature:

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)

Kr= radial (horizontal) hydraulic conductivity (m/s)

Ss= specific storage (1/m)

Rf= radius of horizontal fracture (m)

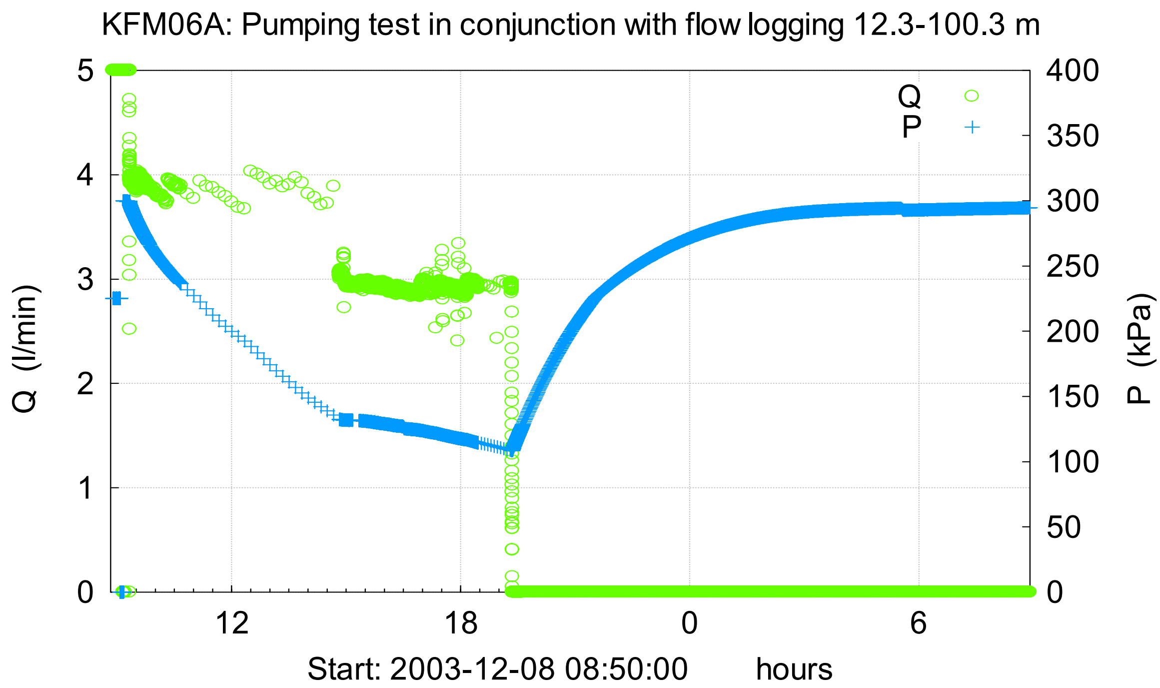


Figure A2-1. *Linear plot of flow rate (Q) and pressure (P) versus time during the open-hole pumping test in KFM06A (0–100 m) in conjunction with flow logging.*

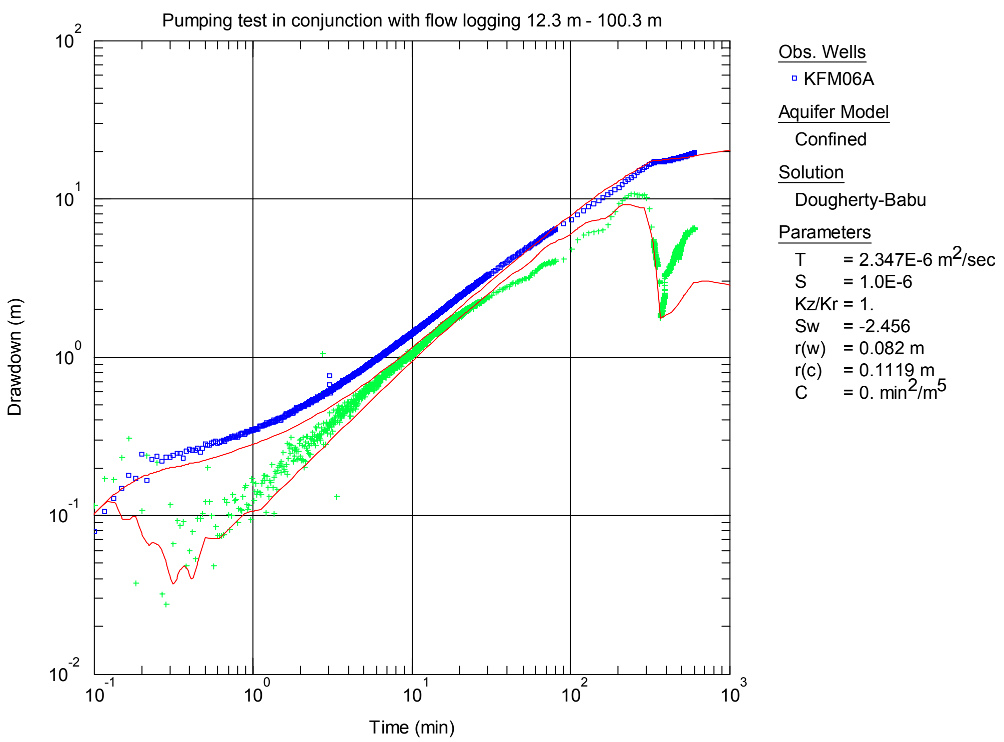


Figure A2-2. *Log-log plot of drawdown (□) and drawdown derivative, (+), versus time during the open-hole pumping test in KFM06A (0–100 m). Displaying fit to Dougherty-Babu solution (solid line).*

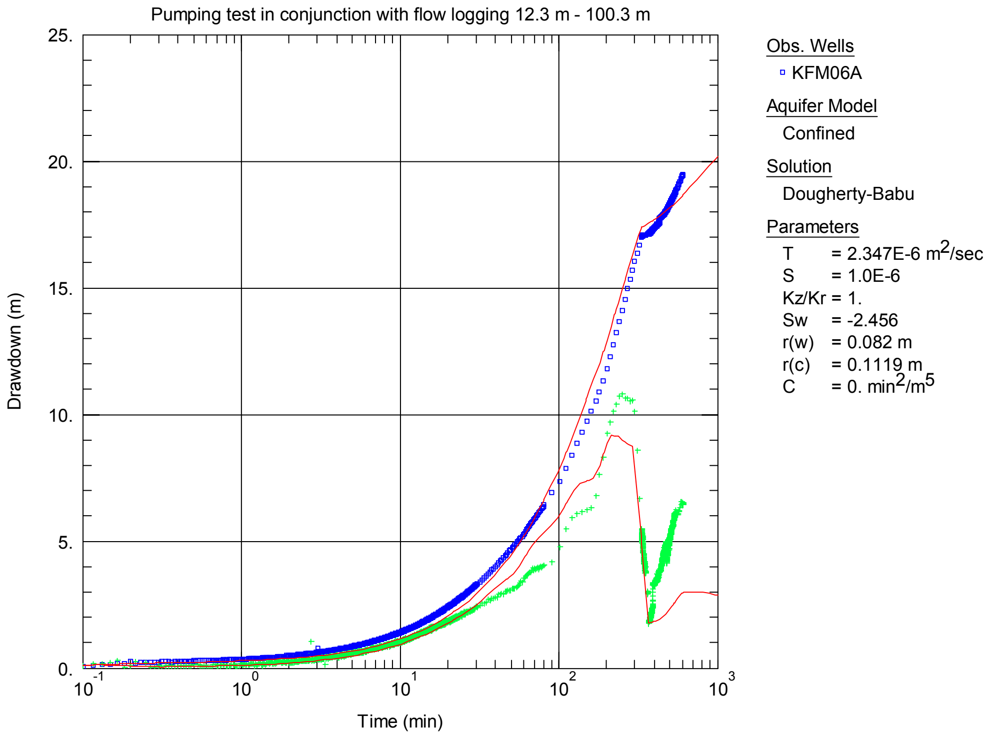


Figure A2-3. *Lin-log plot of drawdown (□) and drawdown derivative, (+), versus time during the open-hole pumping test in KFM06A (0–100 m). Displaying fit to Dougherty-Babu solution (solid line).*

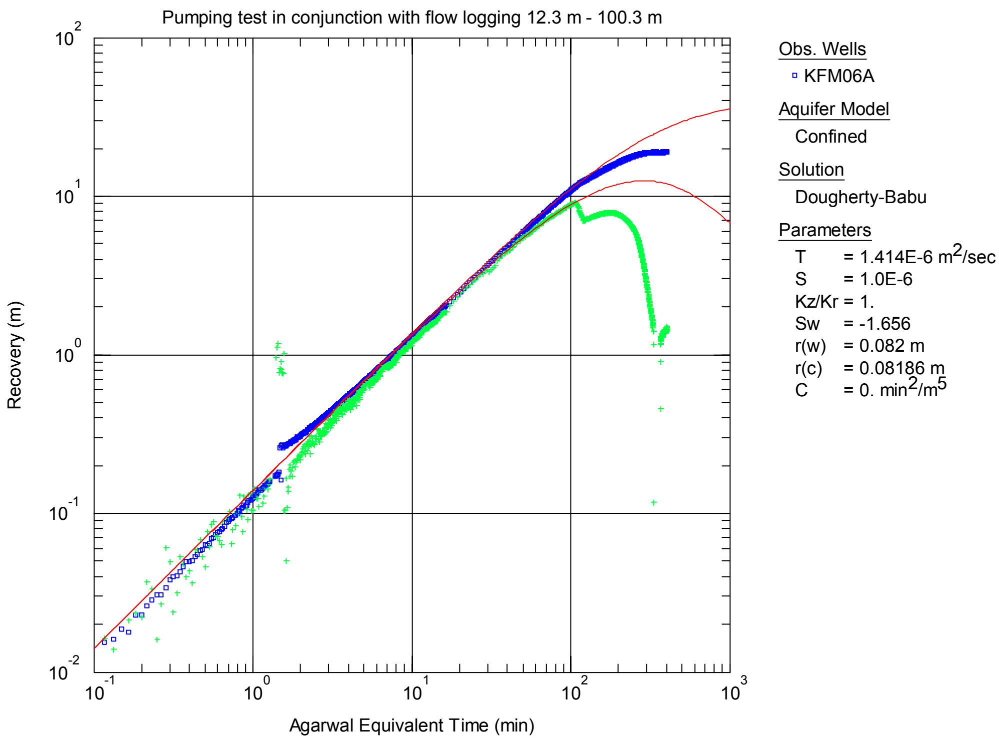


Figure A2-4. *Log-log plot of recovery (□) and recovery derivative, (+), versus equivalent time from the open-hole pumping test in KFM06A(0–100 m). Displaying fit to Dougherty-Babu solution (solid line).*

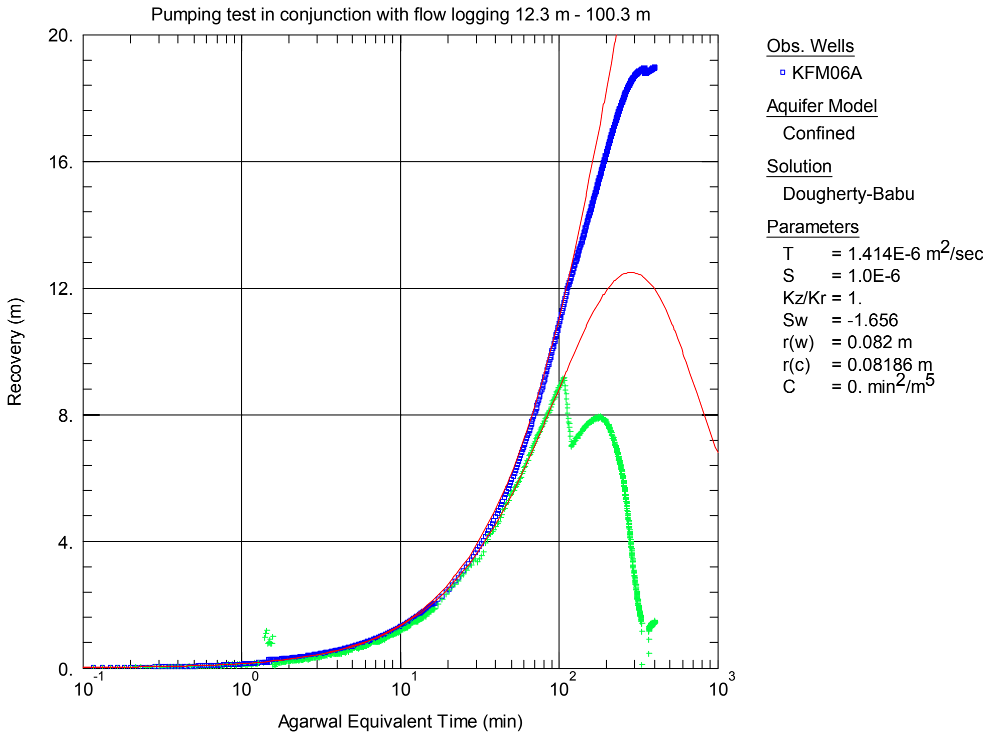


Figure A2-5. *Lin-log plot of recovery (□) and recovery derivative, (+), versus equivalent time from the open-hole pumping test in KFM06A (0–100 m). Displaying fit to Dougherty-Babu solution (solid line).*

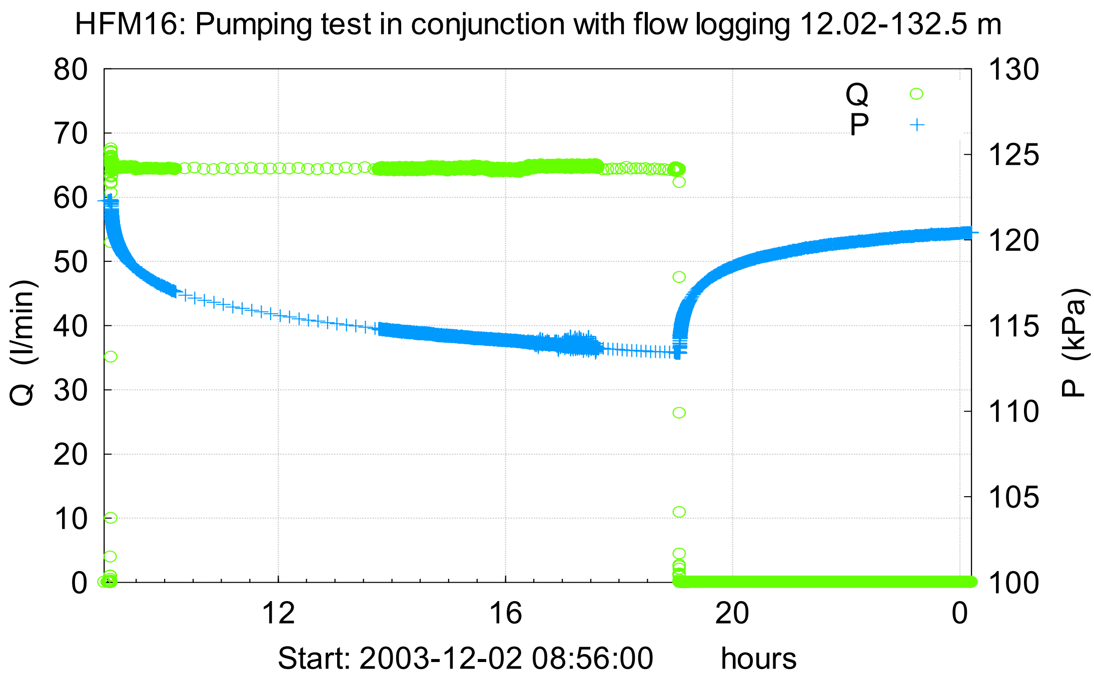


Figure A2-6. *Linear plot of flow rate (Q) and pressure (P) versus time during the open-hole pumping test in HFM16 in conjunction with flow logging.*

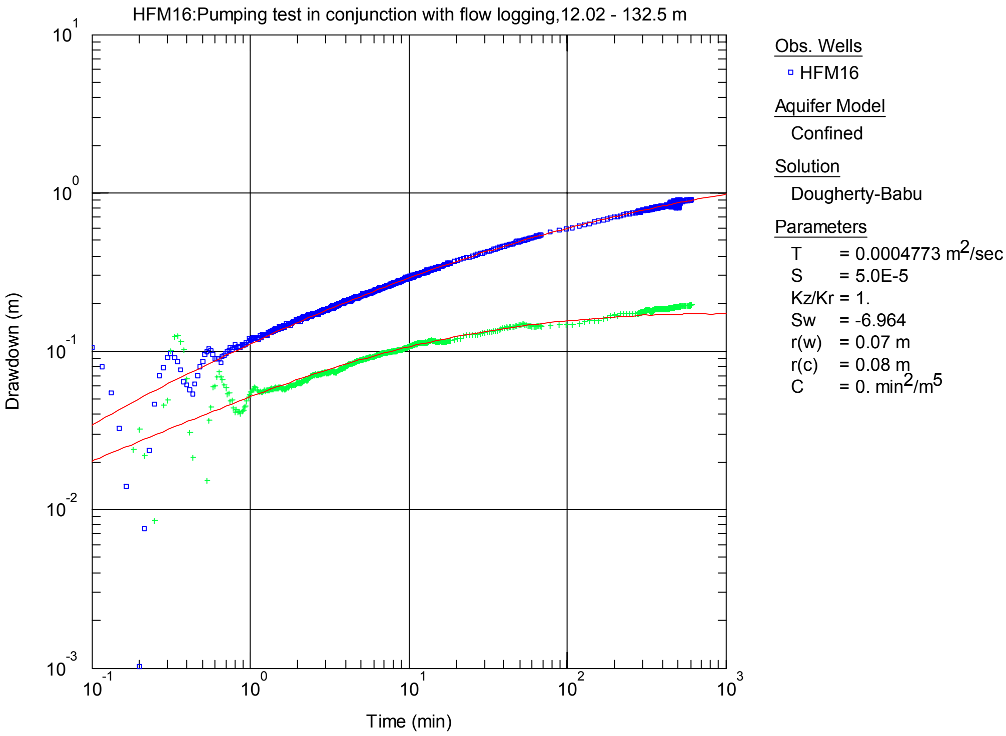


Figure A2-7. *Log-log plot of drawdown (□) and drawdown derivative, (+), versus time during the open-hole pumping test in HFM16. Displaying fit to Dougherty-Babu solution (solid line).*

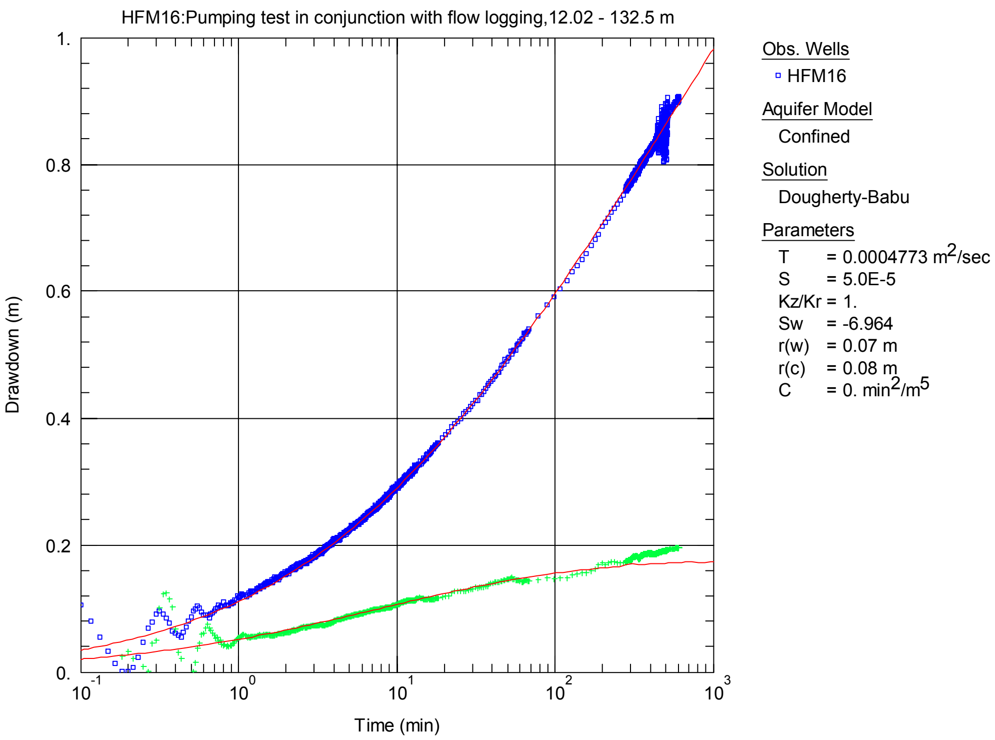


Figure A2-8. *Lin-log plot of drawdown (□) and drawdown derivative, (+), versus time during the open-hole pumping test in HFM16. Displaying fit to Dougherty-Babu solution (solid line).*

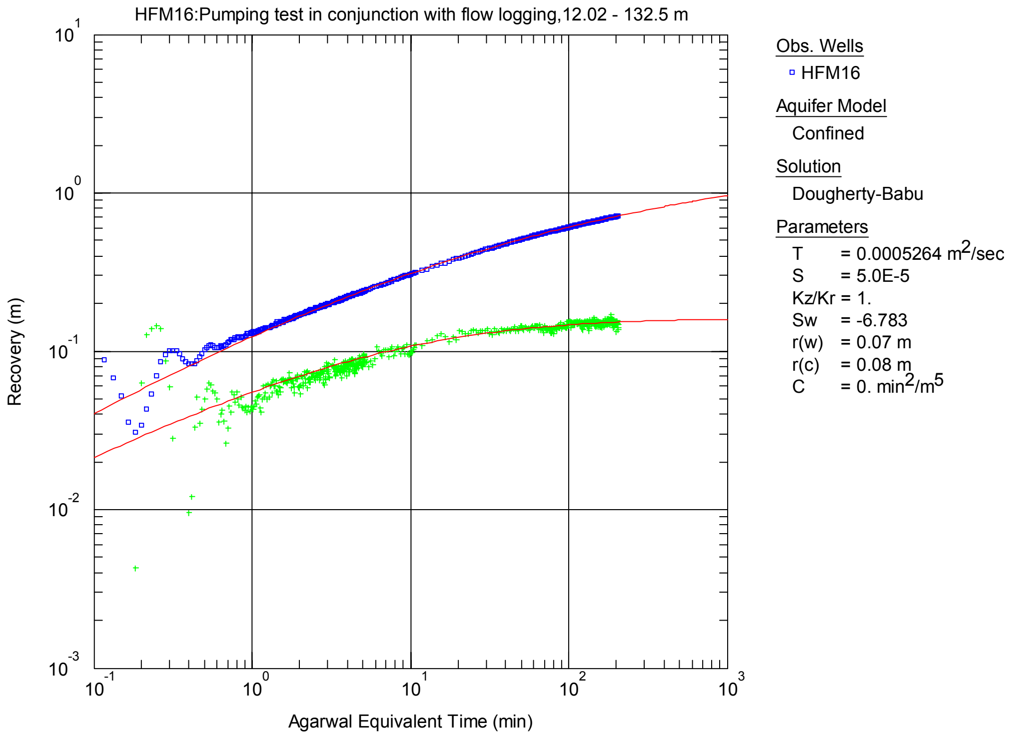


Figure A2-9. *Log-log plot of recovery (□) and recovery derivative, (+), versus equivalent time from the open-hole pumping test in HFM16. Displaying fit to Dougherty-Babu solution (solid line).*

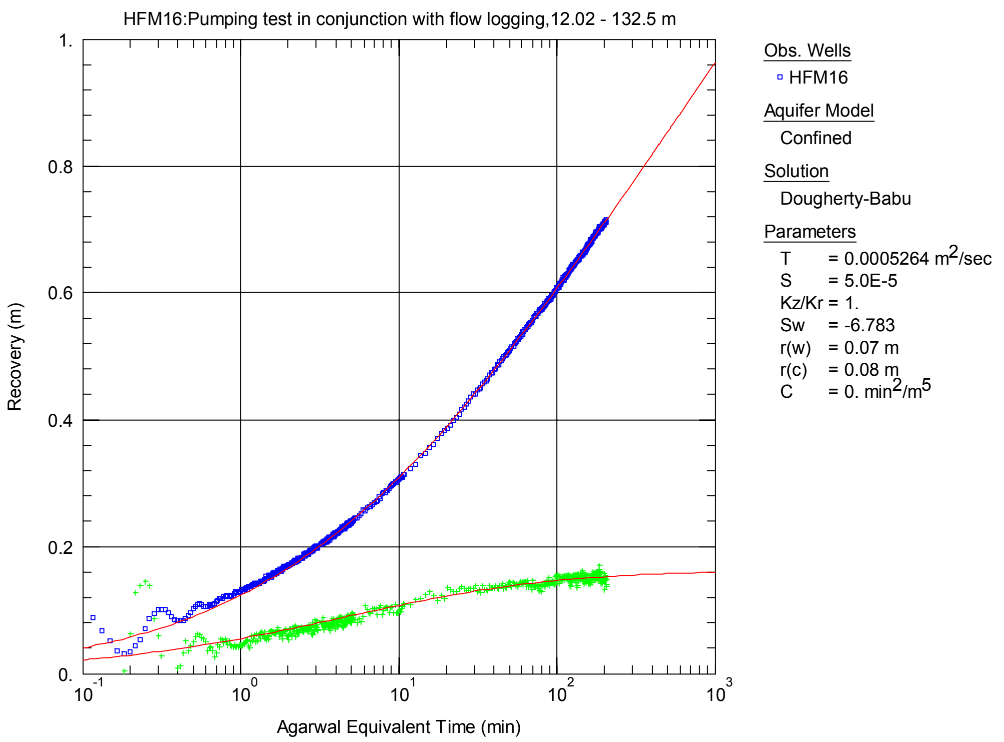


Figure A2-10. *Lin-log plot of recovery (□) and recovery derivative, (+), versus equivalent time from the open-hole pumping test in HFM16. Displaying fit to Dougherty-Babu solution (solid line).*

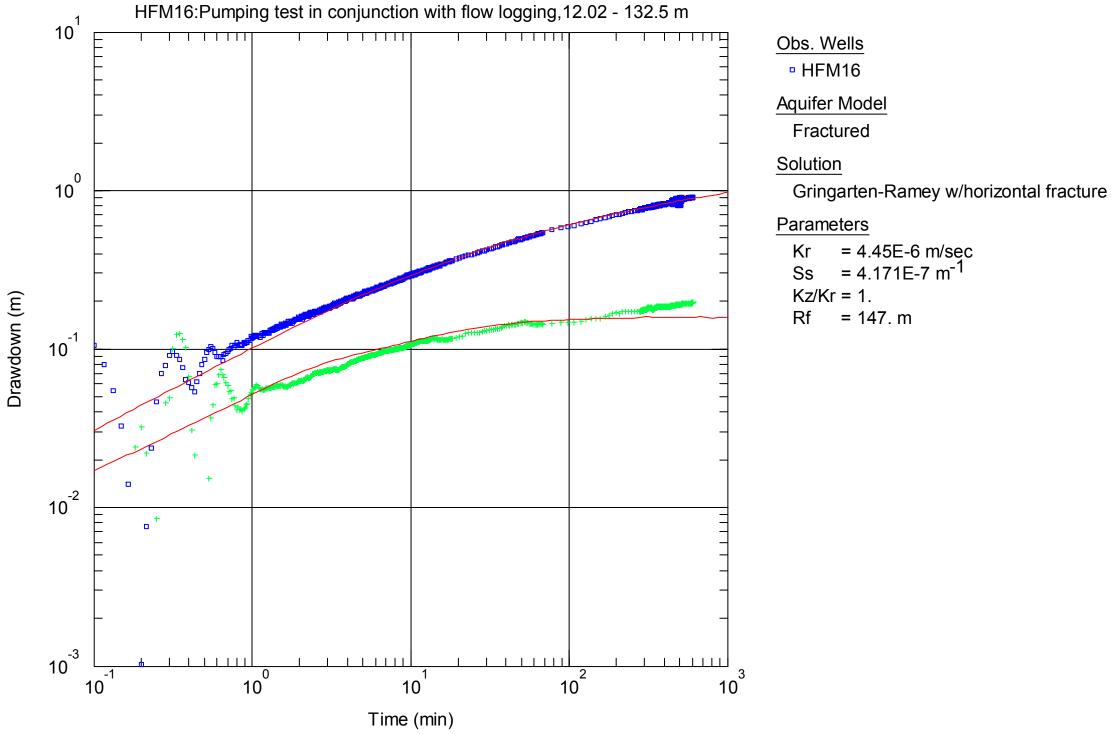


Figure A2-11. *Log-log plot of drawdown (□) and drawdown derivative, (+), versus time during the open-hole pumping test in HFM16. Displaying fit to alternative solution, Gringarten-Ramey.*

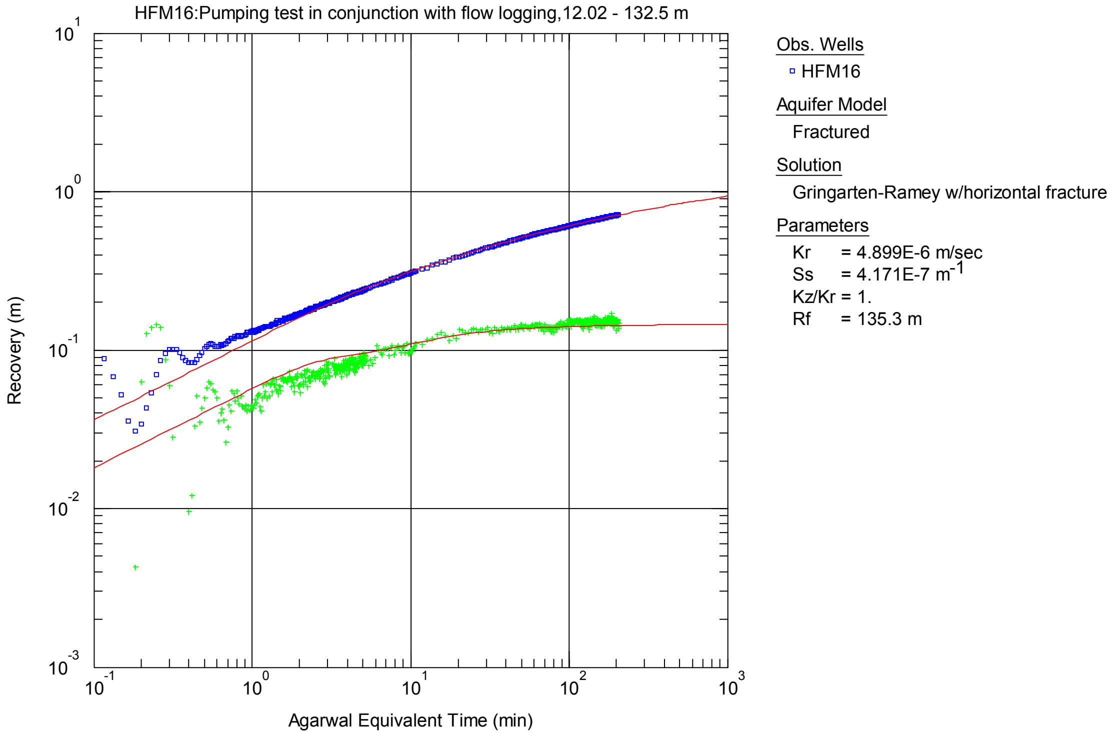


Figure A2-12. *Log-log plot of recovery (□) and recovery derivative, (+), versus equivalent time from the open-hole pumping test in HFM16. Displaying fit to alternative solution, Gringarten-Ramey.*

Appendix 3

Result tables to Sicada database

Result Table for Single hole tests at drillsite DS6 at Forsmark for submission to Sicada

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_d; General information

Borehole idcode	Borehole secup (m)	Borehole seclow (m)	Test type (1-6)	Formation type (-)	Date and time for test, start YYYYMMDD hh:mm	Date and time for test, stop YYYYMMDD hh:mm	Date and time for flow period, start YYYYMMDD hh:mm:ss	Date and time for flow period, stop YYYYMMDD hh:mm:ss	Qp (m**3/s)	Value type (-1, 0 or 1)	Q-measl-L (m**3)/s	Q-measl-U (m**3)/s
KFM06A	12.30	100.30	1B	1	20031208 09:10	20031209 08:55	20031208 09:19:42	20031208 19:21:04	4.92E-05	-1	8.3E-05	1.3E-03
HFM16	12.02	132.50	1B	1	20031202 08:56	20031203 00:12	20031202 09:03:42	20031202 19:04:02	1.07E-03	0	8.3E-05	1.3E-03

cont.

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 (^oC)	EC_w (mS/m)	TDS_w (mg/ L)	TDS_{wm} (mg/ L)	Reference	Comments (-)
36082	48826	1.01	-18.74	0.37	299.48	108.55	294.67						
36020	18495	0.74	-0.18	0.61	122.28	113.40	120.46						

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 (-1, 0 or 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)
KFM06A	12.30	100.30	20031208 09:10	2.53E-06	0		2.93E-06	80							
HFM16	12.02	132.50	20031202 08:56	1.19E-03	0		1.46E-03	120.48							

cont.

T_T (2D) (m^2/ s)	Value type (-1, 0 or 1)	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 (-)	dt_1 (s)	dt_2 (s)	Comments (-)
1.41E-06	0	2.0E-06	2.0E-03		1.0E-06								2.15E-06		-1.66			0.1	100	
5.26E-04	0	2.0E-06	2.0E-03		5.5E-05										-6.78			0.8	204	

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	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 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	Transmissivity based on specific capacity and a a function for T=f(Q/s). The function used should be refered in "Comments"
T_M	m2/s	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
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
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

B. Result Table for Flow logging at drillsite DS6 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 stop of flow period YYYYMMDD hh:mm	Date and time of flowl., start YYYYMMDD hh:mm:ss	Date and time of flowl., stop YYYYMMDD hh:mm:ss	Q-measl-L (m^3/s)	Q-measl-U (m^3/s)	Q_p (m^3/s)
KFM06A	34.5	66.0	6	1	20031208 09:10	20031208 19:21	20031208 15:21	20031208 18:26	6.7E-05	1.7E-03	4.83E-05
HFM16	12.00	126.10	6	1	20031202 08:56	20031202 19:04	20031202 13:43	20031202 17:38	5.0E-05	1.7E-03	1.07E-03

cont.

tp (s)	t_{FL} (s)	h_0 (m a s l)	h_p (m a s l)	s_{FL} (m)	Reference (-)	Comments (-)
36082	11100	1.01	-18.74	17.98		
36020	14100	0.74	-0.18	0.82		

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)	Q_{Tcorr}	T Entire hole (m^2/ s)	T_{FT} (m^2/ s)	T_F-measl-L (m^2/ s)
KFM06A	34.5	66.0												1.41E-06		2.0E-06
HFM16	12.0	126.1										1.07E-03	1.07E-03	5.26E-04	5.26E-04	2.0E-06

cont.

Reference (-)	Comments (-)
	Final bh. Diam=164 mm, Flow calibration=160 mm
	Final bh. Diam=140 mm, Flow calibration=140 mm

FLOWLOGG-IMPELLER TESTS plu_impeller_anomaly

Borehole	Borehole secup (m)	Borehole seclow (m)	Upper limit L (m)	Lower limit L (m)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	$deltaQ_i$ (m**3/s)	$deltaQ_{icorr}$ (m**3/s)	$deltaQ_{icorr}/s_{FL}$ (m**2/s)	b_i (m)	T_i (m^2/ s)	T_i-measl-L (m^2/ s)	T_i-measl-U (m^2/ s)	Reference (-)	Comments (-)
HFM16	12.0	126.1	41.0	41.5				2.40E-04	2.40E-04	2.93E-04	0.5	1.18E-04	8.3E-06			
HFM16	12.0	126.1	56.0	56.5				8.33E-05	8.33E-05	1.02E-04	0.5	1.02E-04	8.3E-06			
HFM16	12.0	126.1	58.5	59.5				6.33E-04	6.33E-04	7.72E-04	1.0	7.72E-04	8.3E-06			
HFM16	12.0	126.1	69.0	69.5				1.17E-04	1.17E-04	1.42E-04	0.5	1.42E-04	8.3E-06			

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	Lengt coordinate along the borehole for the upper limit of the logged section (Based on corrected length L)
Borehole seclow	m	Lengt coordinate 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 flowlogging start (YYYY-MM-DD hh:mm:ss)
date and time, stop	date_s	Date and time of flowlogging stop (YYYY-MM-DD hh:mm:ss)
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-comb.Sequentia, 5B: Difference flow logging-PFL-DIFF-Overlapping, 6: Flow logging-Impeller 7: Grain size analysis
Formation type		1: Rock, 2: Soil (supeficial deposits)
Q-measl-L	m^3/s	Estimated lower measurement limit for borehole flow rate in flowlogging probe
Q-measl-U	m^3/s	Estimated upper measurement limit for borehole flow rate in flowlogging probe
Q_p	m^3/s	Flow rate at surface during flowlogging
tp	s	Time for the flowing phase of the test
t_{FL}	s	Duration of the flowlogging survey
s_{FL}	m	Average drawdown of the water level in open borehole during flowlogging
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	Stabilised 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 cummulative flow rate. Position for measurement is related to L (corrected lenght)
Q_1	m^3/s	Cumulative flow rate during pumping. Position for measurement is related to L (corrected length)
Q_{1T}	m^3/s	Cummulative flow rate:Q_1 at the top of measured interval
Q_T	m^3/s	Cummulative flow rate:Q at the top of measured interval
$Q_T$corr	m^3/s	Cummulative flow rate:QTat 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 flowlogging (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 lenght)
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 lenght)

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 lenght)
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 lenght)
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 thanT_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 thanT_i-measlim
Reference		SKB number for reports describing data and results
Comments		Short comment on evaluated parameters