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Forsmark site investigation

Pumping tests and flow logging

Boreholes HFM11 and HFM12

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April 2004

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Abstract

The percussion drilled boreholes HFM11 and HFM12 are drilled in a selected lineament called the Eckarfjärd zone. The two boreholes, which are inclined 60° from the horizontal plane, have their collaring points on each side of the lineament and are directed towards eachother.

Pumping tests and flow logging were performed in HFM11 and HFM12. In order to confirm the results from the flow logging, short injections tests were performed in those upper parts of the boreholes that could not be measured during the flow logging. Water sampling was undertaken in all boreholes in conjunction with the pumping tests. No other borehole tests had been carried out in the actual boreholes before this campaign.

The main objectives of the hydraulic tests in the percussion boreholes were to investigate the geometry, extension and hydraulic characteristics of the Eckarfjärd zone.

In HFM11 six conductive sections are identified. The transmissivity of these sections ranges from c. $3 \cdot 10^{-6}$ m^2/s to c. $1.5 \cdot 10^{-5}$ m^2/s. The total transmissivity of the borehole is c. $4.3 \cdot 10^{-5}$ m^2/s. In HFM12 two conductive sections are identified, the transmissivity of these parts ranges from c $2.5 \cdot 10^{-6}$ m^2/s to c. $1.0 \cdot 10^{-5}$ m^2/s. The total transmissivity for the borehole is c. $1.4 \cdot 10^{-5}$ m^2/s. The flow logging showed that these high transmissive sections are narrow, in HFM11 between 1–3 m and in HFM12 between 0.6–2.0 m.

Sammanfattning

Hammarborrhålen HFM11 och HFM12 är borrade i ett utvalt lineament kallat Eckarfjärdszonen. Det två borrhålen är ansatta på varsin sida om lineamentet med en lutning av 60° från horizontalplanet och är riktade mot varandra.

Pumptest och flödesloggning gjordes i HFM11 och HFM12. För att bekräfta resultaten från flödesloggningen utfördes även injektionstester i den övre delen av borrhålet som inte kunde mätas med spinner. Vattenprover togs i båda borrhålen i samband med pumptest.

Avsikten med mätningarna i hammarborrhålen var att undersöka Eckarfjärdzonens geometri, mäktighet och hydrauliska egenskaper.

I HFM11 identifierades sex konduktiva partier. Transmissiviteten i dessa varierade mellan $3\cdot10^{-6}$ m^2/s och $1.5\cdot10^{-5}$ m^2/s. Borrhålets totala transmissivitet är ca $4.3\cdot10^{-5}$ m^2/s. I HFM12 påträffades två konduktiva avsnitt med transmissiviteter på respektive $2.5\cdot10^{-6}$ m^2/s och $1\cdot10^{-5}$ m^2/s. Hålets totala transmissivitet är ca $1.4\cdot10^{-5}$ m^2/s. Flödesloggningen visade att de högtransmissiva sektionerna är smala, i HFM11 från 1 till 3 m och i HFM12 mellan 0.6–2.0 m.

Contents

1 Introduction

Two boreholes, HFM11 and HFM12, see Figure 1-1, were drilled to investigate a lineament called the Eckarfjärd zone at the SKB site investigation area in Forsmark. The boreholes which are inclined 60º from the horizontal plane, are drilled from opposite sides of the lineament and directed towards eachother. The main purpose with HFM11 and HFM12 was to provide information about the Eckarfjärd zone. Depending on the outcome of the results from HFM11 and HFM12, additional boreholes through the zone may be needed.

Pumping tests were performed to investigate hydraulic connections between HFM11–12 and possibly with some of the core drilled boreholes, see Figure 1-2, /3/. Water sampling was undertaken in both boreholes in conjunction with the tests. In addition, flow logging was performed in the boreholes. No other borehole tests had been carried out in the actual boreholes before this campaign.

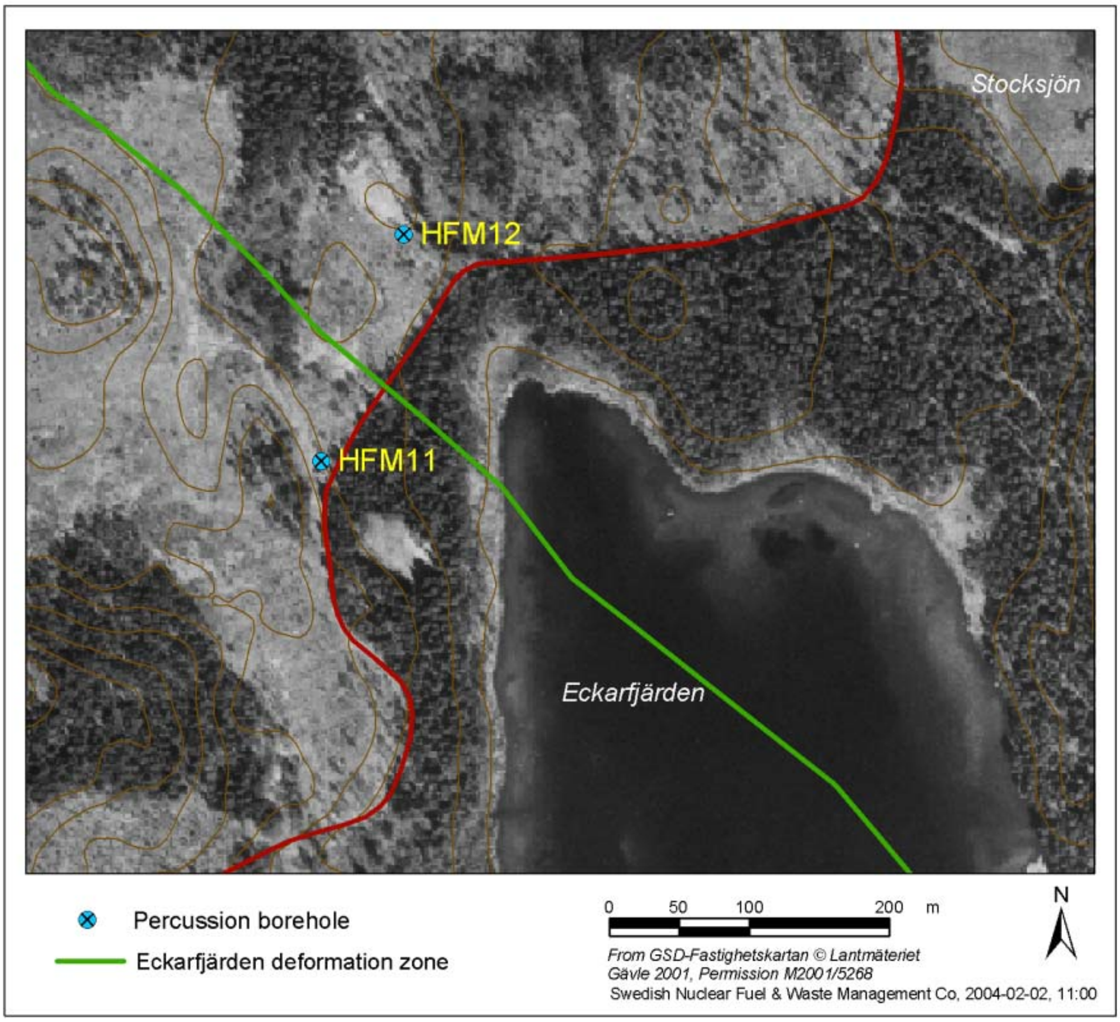


Figure 1-1. *Map showing the location of HFM11 and HFM12 at Forsmark.*

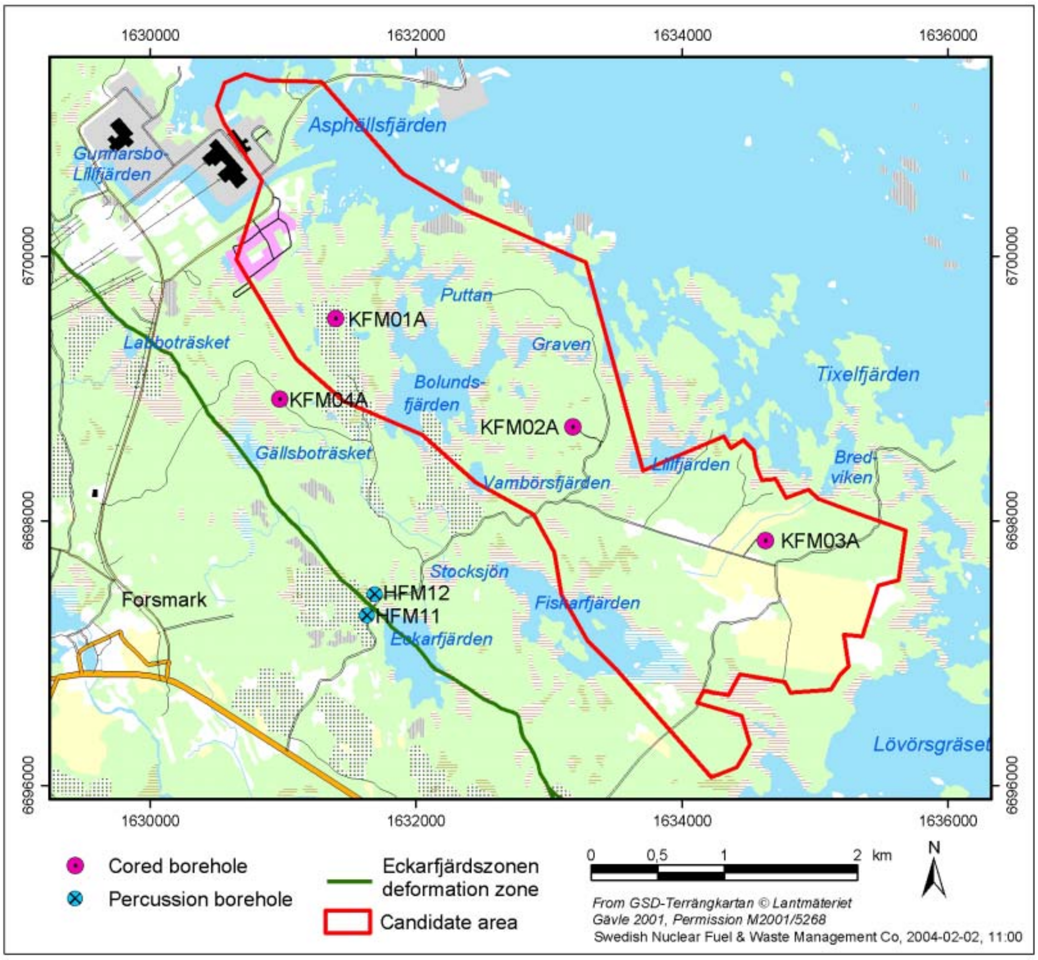


Figure 1-2. *The investigation area at Forsmark including the candidate area selected for more detailed investigations.*

This document reports the results gained by the *Hydraulic testing of the Eckarfjärd Fracture Zone, boreholes HFM11 and HFM 12*. 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 286.

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

Activity Plan	**Number**	**Version**
Hydraulic testing of the Eckarfjärd Fracture Zone. Boreholes HFM11 and HFM 12.	AP PF 400-03-78	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 hydrauliska injektionstester.	SKB MD 323.002	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

The main objectives of the single-hole pumping tests and flow logging in HFM11 and HFM12 were to:

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

3 Scope

3.1 Boreholes tested

Technical data of the boreholes tested 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 in Table 3-1 refers to the final diameter of the borehole after drilling to full depth. The borehole diameter (measured as the diameter of the drill bit) may decrease along the borehole due to proceeding wearing 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. Pertinent 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)**
HFM11	7.559	0.00–12.00	0.160	–50	60	Casing ID	
		12.00–182.35	0.139			Borehole	2003-08-21
HFM12	7.025	0–14.90	0.160	–50	240	Casing ID	
		14.90–209.50	0.135			Borehole	2002-09-16

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

Borehole data		
Bh ID	**Northing (m)**	**Easting (m)**
HFM11	6697280	1631634
HFM12	6697440	1631693

3.2 Tests performed

The tests performed in the boreholes, which are listed in Table 3-3, were performed according to Activity Plan AP PF 400-03-078 (SKB internal controlling document). Pumping tests, flow meter logging together with injection tests were carried out with the HTHB (Hydrotestutrustning i hammarborrhål) unit. All types of tests are described in the corresponding methodology descriptions (SKB internal controlling document) for single-hole pumping tests (SKB MD 321.003: Metodbeskrivning för hydrauliska enhålspumptester), flow logging (SKB MD 322.009: Metodbeskrivning för flödesloggning) and injection tests (SKB MD 323.002: Metodbeskrivning för hydrauliska injektionstester). None of the boreholes were tested previously. In conjunction with the flow logging, also temperature- and electric conductivity logging of the borehole water was performed.

During the pumping tests, water samples were collected and analysed /1/. Manual observations of the groundwater level in the pumped boreholes were also made during the tests.

Table 3-3. Borehole tests performed in HFM11 and HFM12.

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)
HFM11	12.00–182.35	1B	2003-10-02 09:04:31	2003-10-03 08:48:35
	30–182.35	6, L-Te, L-EC	2003-10-02 13:51:30	2003-10-02 18:20.10
	12.0–33.7	3	2003-10-03 11:30:04	2003-10-03 14:17:39
HFM12	14.9–209.5	1B	2003-09-26 06:58:02	2003-09-26 17:38:24
	25–209.5	6, L-Te, L-EC	2003-09-26 13:03:06	2003-09-26 17:38:24
	24.8–30.3	3	2003-09-30 13:54:27	2003-09-30 15:01:16
	19.3–24.8	3	2003-09-30 15:20:50	2003-09-30 16:18:35
	14.9–19.3	3	2003-09-30 16:34:12	2003-09-30 17:55:06

[1)] 1B: Pumping test-submersible pump, 2: Interference test, 3: Injection test, 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 with the total head of water ($p/\rho g$). 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 of equipment

4.1 Overview

The equipment used in these tests is referred to as HTHB (Swedish abbreviation for Hydraulic Test System for Percussion Boreholes). 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 constant hydraulic head or, alternatively, with constant flow rate. For injection tests, however, the upper packer can not be located 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 used. 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.

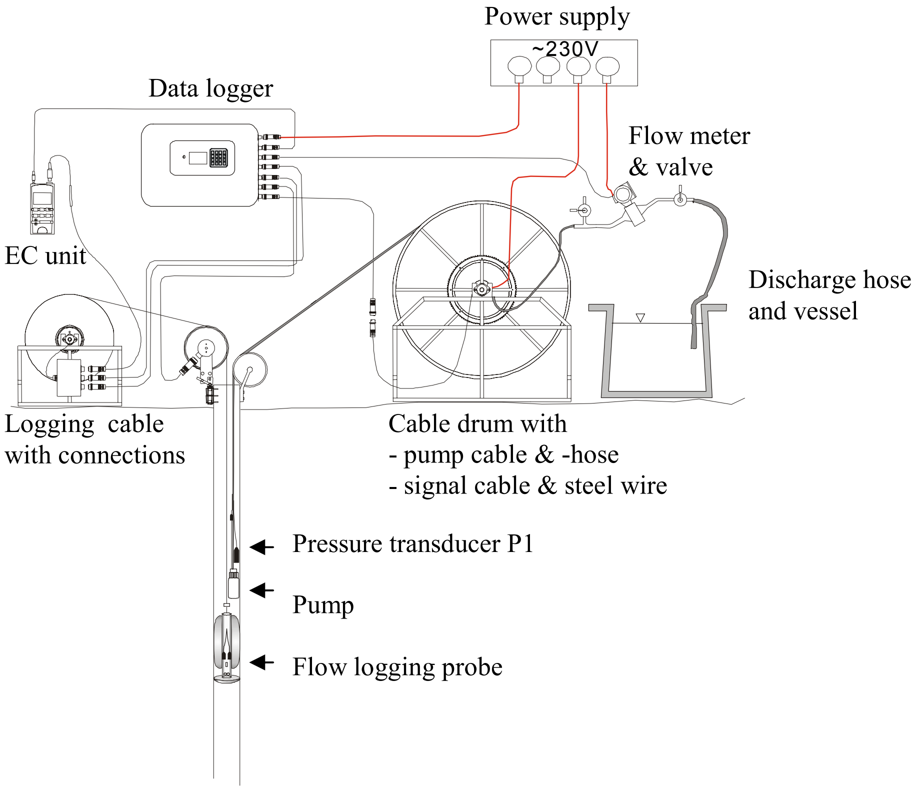


Figure 4-1. *Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB.*

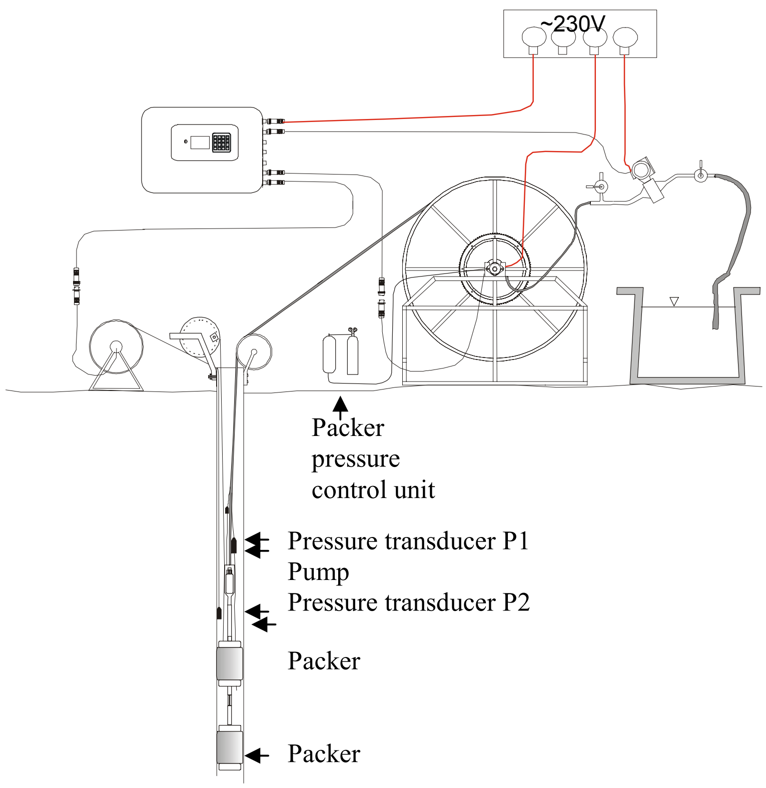


Figure 4-2*. Schematic test set-up for a pumping test in an isolated borehole section with HTHB. Additional equipment details are described in Figure 4-1.*

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 demonstrates 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 the stabilization 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	0–1500	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
	Accuracy***	% o.r.**		± 20	and 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 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

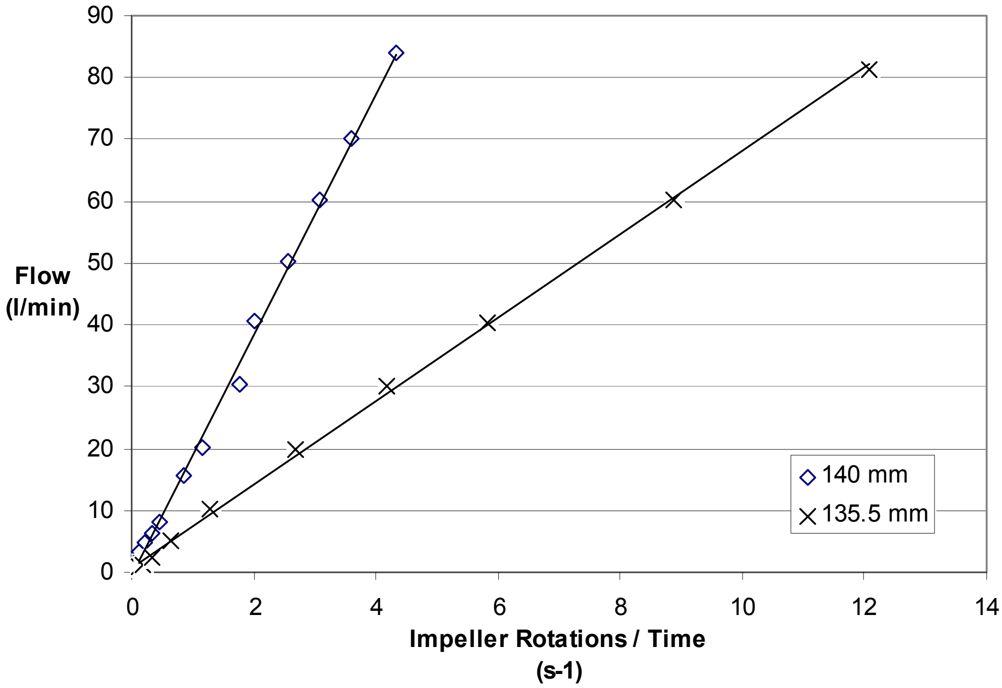


Figure 4-3. *Total flow as a function of impeller rotations for two borehole diameters (140 and 135.5 mm).*

Table 4-2 presents the position of sensors for each test. The following sensors are used: pressure (p), temperature (Te), electric conductivity (EC) together with 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 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 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 ones from the test interpretations described in Chapter 5.

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]
HFM11	12–182.35	Open hole	1B	Pump-intake	29.4	Pump	In borehole		$1.5 \cdot 10^{-6}$ (based on borehole diameter 0.139 m)
						Pump hose	In borehole	33.5	
						Pump cable	In borehole	14.5	
			1B	P (P1)	26.72	Signal cable	In borehole	8	
	33.7–175.2	Open hole	6	EC, Te, Q	33.7–175.2	Signal cable	In borehole	13.5	
	12.0–33.7	In closed section	3	P(P2)	7.46	Tecalan hose	In section	6	
						Steel wire	In section	6	
HFM12	14.9–209.5	Open hole	1B	Pump-intake	24.4	Pump	In borehole		$1.5 \cdot 10^{-6}$ (based on borehole diameter 0.135 m)
			1B			Pump hose	In borehole	33.5	
			1B			Pump cable	In borehole	14.5	
			1B	P (P1)	21.72	Signal cable	In borehole	8	
	30.5–206.5	Open hole	6	EC, Te, Q	29–209.5	Signal cable	In borehole	13.5	
	14.9–19.3	In closed section	3	P (P2)	11.4	Steel wire	In section	6	
						Tecalan hose	In section	6	
	19.3–24.8		3	P (P2)	16.9	Steel wire	In section	6	
						Tecalan hose	In section	6	
	24.8–30.3		3	P (P2)	22.4	Steel wire	In section	6	
						Tecalan hose	In section	6	

1) 1B: Pumping test-submersible pump, 3: Injection test, 6: Flow logging–Impeller incl. EC-logging (EC-sec) and temperature logging (Te-sec), 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 casing diameter and 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 400-03-59 (SKB internal controlling document) in accordance with the methodology descriptions for single-hole pumping tests, SKB MD 321.003, Version 1.0 (Metod-beskrivning för hydrauliska enhålspumptester), and flow logging, SKB MD 322.009, Version 1.0 (Metodbeskrivning för flödesloggning). The injection tests performed in the upper parts of the borehole are performed according to the methodology descriptions from injections tests, SKB MD 323.001, Version 1.0 (Metodbeskrivning för hydrauliska injektionstester).

5.1 Preparations

All sensors included in the HTHB system were calibrated at Geosigma engineering workshop in Librobäck, Uppsala. Calibration is performed on a yearly basis, or more often if needed. The last calibration of the HTHB-unit used for the tests in HFM11 and HFM12 was done in March, 2003. Before the tests, functioning checks and cleaning of equipment, together with time synchronisation of clocks and data loggers were performed according to the Activity Plan.

5.2 Procedure

5.2.1 Overview

The pumping test in HFM11 was carried out as a single-hole, constant flow rate test and in HFM12 as a constant hydraulic head test. The pumping phase was in both boreholes followed by a pressure recovery period. The intention was to achieve approximately steady-state conditions in the borehole during the flow logging.

The flow logging was performed while pumping. The inclination of the borehole made it difficult to lower the flow probe, which was the reason why discrete flow measurements were made every 0.5 m instead of every 5 m as described in MSB. The flow logging was performed from the bottom and upwards along the borehole. The position of the anomaly is determined with an accuracy of 0.5 m. After the first anomaly was detected and measured, the flow logging continued with a step length of 2 m until the next flow anomaly was encountered. 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 test, a short flow capacity test was carried out to select an appropriate flow rate for the test. All pumping tests and flow meter logging were performed 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 HFM12 the duration of the recovery period was increased over the weekend for practical reasons. However, due to problems with the logger, recovery data and the last 40 min of the pumping test are missing. In general, the sampling frequency of pressure during the pumping tests was according to Table 5-1.The single hole hydraulic tests in the boreholes were performed in the following order of time: HFM12, HFM11.

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

The recommended test time (24 h+24 h 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. The probe was halted (15 s) at every two metres 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 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. In HFM11 the flow loggning was completed in 4.5 hours and in HFM12 in 3 hours.

5.3 Data handling

Data are downloaded from the logger (Campbell 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 by the code PUMPKONV and plotted in different diagrams listed in the Instruction for analysis of injection- and single-hole pumping tests (SKB MD 320.004) by the code SKB-plot.

By the conversion to drawdown- and recovery files, different values were applied on the filter coefficient (step length) by the calculation of the pressure derivative to investigate the effect of this coefficient on the derivative. It is desired to achieve maximal smoothing of the derivative without altering the original shape of the data.

5.4 Analyses and interpretation

5.4.1 Single-hole pumping tests

As discussed in Section 5.2.1, the pumping tests were performed as a constant hydraulic head test and a constant flow rate test, respectively, followed by pressure recovery periods. 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, whereas no-flow- and constant head boundaries are reflected by an increase and decrease 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 in an equivalent porous medium were used by the evaluation of the tests. For tests indicating a fractured- or borehole storage dominated response, corresponding type curves were used by the analyses.

If possible, transient analysis was made on both the drawdown- and recovery phase of the tests. The recovery data were plotted versus equivalent time. The analysis of the drawdown- and recovery data was generally made in both log-log and lin-log diagrams according to standard methods described in the above instruction in the previous section. In addition, a preliminary steady-state analysis (e.g. Moye's formula) was made for all tests for comparison.

The transient analysis of tests dominated by wellbore storage was made according to the single-hole methods described in /2/. Estimation of the borehole storage coefficient C in appropriate pumping tests was based on the early borehole response with 1:1 slope in a log-log diagram. These values on C may be compared with the wellbore storage coefficient calculated below, based on actual borehole geometrical data and assumed fluid properties (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 properties from the anticipated, e.g. regarding the borehole diameter. Furthermore, the effective compressibility is usually higher than the water compressibility in an isolated section due to e.g. packer compliance resulting in a higher C-value.

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

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

r_{we} = borehole radius in the interval where the changes of the groundwater level occur (either r_w or r_c)

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 rate, temperature and electric conductivity of the borehole fluid) were firstly plotted versus borehole length. From these plots, flow anomalies were identified along the borehole, i.e. in this case borehole intervals over which changes of flow rate 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 rate changes are accompanied by corresponding changes in temperature and/or electric conductivity of the fluid.

Flow logging can only be carried out up to a certain distance below the submersible pump (when logging from the bottom of the hole upwards). 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 were carried out by the HTHB system in c. 5 m long sections above the flow-logged interval.

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 Methodology description for Impeller flow logging (assuming zero natural flow in the borehole):

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

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. (5-2).

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 /3/:

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

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:

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

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. (5-2):

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

In a 140 mm borehole, Q_{min}=3 L/min ($5 \cdot 10^{-5}$ m^3/s), see Table 4-1, whereas Q_p is the actual flow rate during flow logging. The upper measurement limit of borehole transmissivity is estimated from Eqn. (5-5) with Q_{max} = 100 L/min ($1.7 \cdot 10^{-3}$ m^3/s), cf. Table 4-1.

Similarly the lower measurement limit of transmissivity of a flow anomaly 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 is estimated from Eqn. (5-3) with Q_{max} = 100 L/min.

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) and Methodology description for flow logging (SKB MD 322.009), Version 1.0 (Metodbeskrivning för flödesloggning), cf. Section 3.2. Additional symbols used are explained in the text.

6.2 Water sampling

The water samples taken during the pumping tests in the boreholes and submitted for analysis are listed in Table 6-1.

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

Bh ID	Date and time of sample	Pumped section (m)	Pumped volume (m^3)	Sample type	Sample ID no	Remarks
HFM11	2003-10-02 10:39	12.00–182.35	4.4	WC080	8036	Open-hole test
“	2003-10-02 15:00	“	16	WC080	8037	Open-hole test
“	2003-10-02 18:51	“	27	WC080	8038	Open-hole test
HFM12	2003-09-26 08:00	14.90–209.50	1	WC080	8020	Open-hole test
“	2003-09-26 11:15	“	3	WC080	8019	Open-hole test
“	2003-09-26 16:30	“	7	WC080	8018	Open-hole test

6.3 Single-hole pumping tests

Below, the results of the pumping tests are presented test by test. No corrections of measured data, e.g. for changes of the barometric pressure or tidal fluctuations, have been made by 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 records were checked to identify possible interference on test data from drilling in nearby boreholes. These records showed that core-drilling activities were in progress at drillsite 1 (KFM01B) and at drillsite 4 (KFM04). However, the drilling activities probably did not affect the hydraulic testing in HFM11 and HFM12 due to the long distance to the drillsites, cf. Figure 1-2.

6.3.1 Borehole HFM11

General test data for the open-hole pumping test in borehole HFM11 in conjunction with flow logging are presented in Table 6-2.

Table 6-2. General test data for the open-hole pumping test in HFM11 in conjunction with flow logging.

General test data			
Borehole	HFM11		
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, J. Jönsson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comment	Single hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	182.35
Casing length	L_c	m	12.00
Test section- secup	Secup	m	12.00
Test section- seclow	Seclow	m	182.35
Test section length	L_w	m	170.35
Test section diameter	$2 \cdot r_w$	mm	top 140 bottom 139
Test start (start of pressure registration)		yymmdd hh:mm	031002 09:04:31
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	031002 09:19:04
Stop of flow period		yymmdd hh:mm:ss	031002 19:19:10
Test stop (stop of pressure registration)		yymmdd hh:mm	031003 08:48:35
Total flow time	t_p	min	600
Total recovery time	t_F	min	809

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	280.0	5.89
Absolute pressure in test section before stop of flow period	p_p	kPa	145.9	–7.78 *
Absolute pressure in test section at stop of recovery period	p_F	kPa	273.1	5.08
Pressure change by the end of flow period	dp_p	kPa	134.1	13.67 **

Manual groundwater level measurements in HFM11 (0–182.35 m)			GW level	
Date YYYY-MM-DD	**Time tt:mm.ss**	**Time (min)**	**(m b. ToC)**	**(m a s l)**
2003-09-26	08:54		2.63	5.55
2003-09-30	19:03		2.18	5.89
2003-10-01	09:44		2.17	5.90
2003-10-01	14:40		2.15	5.91
2003-10-02	09.13		2.18	5.89
2003-10-03	09:16		3.24	5.08
2003-10-03	11:27		2.98	5.28
2003-10-03	12:57		2.81	5.41

* Calculated from pressure drawdown.
** Calculated from groundwater level measurements.

Flow data

Flow data	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$8.02 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$7.95 \cdot 10^{-4}$
Total volume discharged during flow period	V_p	m^3	28.76

Comments on 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. A comparison of flow rate and drawdown from the capacity test and the pumping test is shown in Table 6-3.

The barometric pressure together with the sea level and temperature during the test period in HFM11 are displayed in Figure 6-1 above. The sea level varied from 0 to 0,13 m.a.s.l. with a peak during the pumping test. The barometric pressure was fairly constant during the time for the test. No precipitation data was available for the days the pumping test and flow logging was performed.

Table 6-3 indicates a good agreement between the capacity test and pumping test, which indicates that the hydraulic borehole conditions were not altered between the tests.

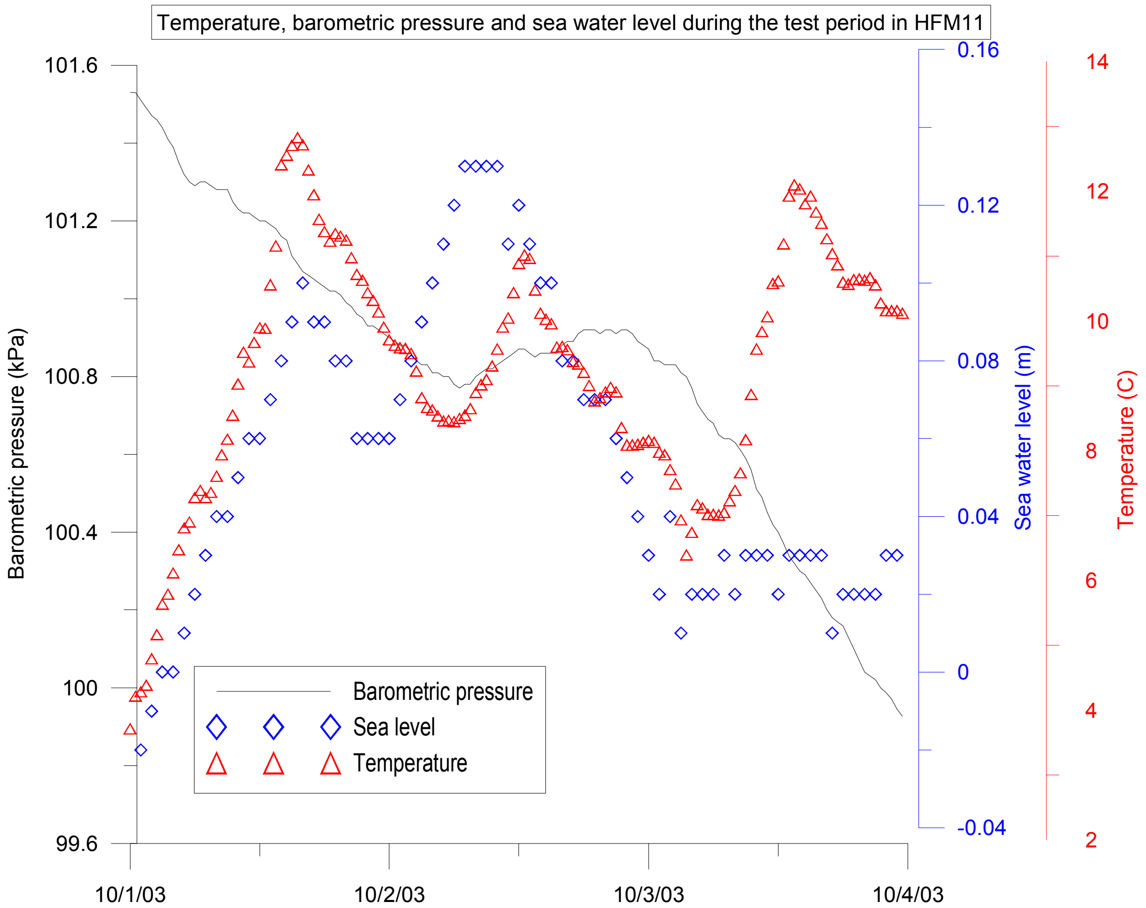


***Figure 6-1**. Barometric pressure, sea level and temperature during the test period in HFM11.*

Table 6-3. Comparison between estimated specific capacity from the capacity test and pumping test, respectively, in borehole HFM11.

Test	Duration (min)	Flow rate (L/min)	Drawdown s_w (m)	Specific capacity Q/s_w (m^2/s)
Capacity test	27	49.7	9.84	$8.4\ 10^{-5}$
Pumping test	600	48	13.47	$5.9 \cdot 10^{-5}$

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 period indicate wellbore storage from the pressure versus time diagrams in Figures A2:2 and A2:4, respectively. After initial wellbore storage, the drawdown derivative indicates a period with apparent pseudo-radial flow from c. 50 min to the end of the flow period. The jump after c 2.5 min is due to a pumping stop depending on a leakage in one of the pumping hoses caused by a missing o-ring.

The response during the recovery period basically confirms the drawdown response. After initial wellbore storage effects, pseudo-radial flow occurred from c. 50 min, cf. Figure A2:4

Interpreted parameters

Transient, quantitative interpretation of the flow- and recovery period of the test is presented in lin-log and log-log diagrams in Figures A2:2-3 and A2:3-4, respectively. Quantitative analysis was made both from the flow- and recovery period according to the methods described in Section 5.4.1. The results are exposed in the Test Summary Sheets and in Table 6-13 and 6-14 in Section 6.5.

6.3.2 Borehole HFM12

General test data for the open-hole pumping test in borehole HFM12 in conjunction with flow logging are presented in Table 6-4.

Table 6-4. General test data for the open-hole pumping test in HFM12 in conjunction with flow logging.

General test data			
Borehole	HFM12		
Test type[1]	Constant Pressure withdrawal and recovery test		
Test section (open borehole/packed-off section):	Open borehole		
Test No	1		
Field crew	J. Källgården, J. Jönsson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comment	Single-hole test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	209.5
Casing length	L_c	m	14.9
Test section- secup	Secup	m	14.9
Test section- seclow	Seclow	m	209.5
Test section length	L_w	m	194.6
Test section diameter	$2 \cdot r_w$	mm	top 138 bottom 135.3
Test start (start of pressure registration)		yymmdd hh:mm	030926 06:58:02
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	030926 07:04:39
Stop of flow period		yymmdd hh:mm:ss	030926 17:38:23
Test stop (stop of pressure registration)		yymmdd hh:mm	030926 17:38:24
Total flow time	t_p	min	633
Total recovery time	t_F	min	0 (failed)

1) Constant Head injection and recovery or Constant pressure 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	251.4	5.91
Absolute pressure in test section before stop of flow period	p_p	kPa	111.3	–8.38 *
Absolute pressure in test section at stop of recovery period	p_F	kPa	111.3	5.74
Pressure change by the end of flow period	dp_p	kPa	140.1	14.29 **

* Calculated from pressure drawdown
** Calculated from 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)
2003-09-24	13.09		1.48	5.9
2003-09-24	17:58		1.11	6.18
2003-09-25	12:43		1.41	5.95
2003-09-25	12:57		0.90	6.34
2003-09-26	07:01		1.46	5.91
2003-09-29	12:30		1.69	5.74
2003-09-30	13:46		1.29	6.04
2003-09-30	15:12		1.32	6.02
2003-09-30	16:19		1.25	6.07
2003-09-30	19:30		1.19	6.12

Flow data

Flow data	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flowing period	Q_p	m^3/s	$1.7\ 10^{-4}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	$2.55\ 10^{-4}$
Total volume discharged during flow period	V_p	m^3	7.24

Comments on the test

The pumping test was performed as a constant head test to achieve (approximately) steady-state conditions during the flow logging. Because of problems with the data logger, no recovery data were registered. An overview of the test is shown in Figure A2:1 in Appendix 2. A comparison of flow rate and drawdown from the capacity test and the pumping test is displayed in Table 6-5.

The barometric pressure together with the sea level and temperature during the test period in HFM12 are displayed in Figure 6-2 below. During the test the sea level was constant around 0.2 m, the barometric pressure increased during the day the pumping and the flow logging were performed with 0.25 kPa. No precipitation data was available for the days the test was performed.

The time needed after the flow start to reach a level with constant pressure was approximately 10 min

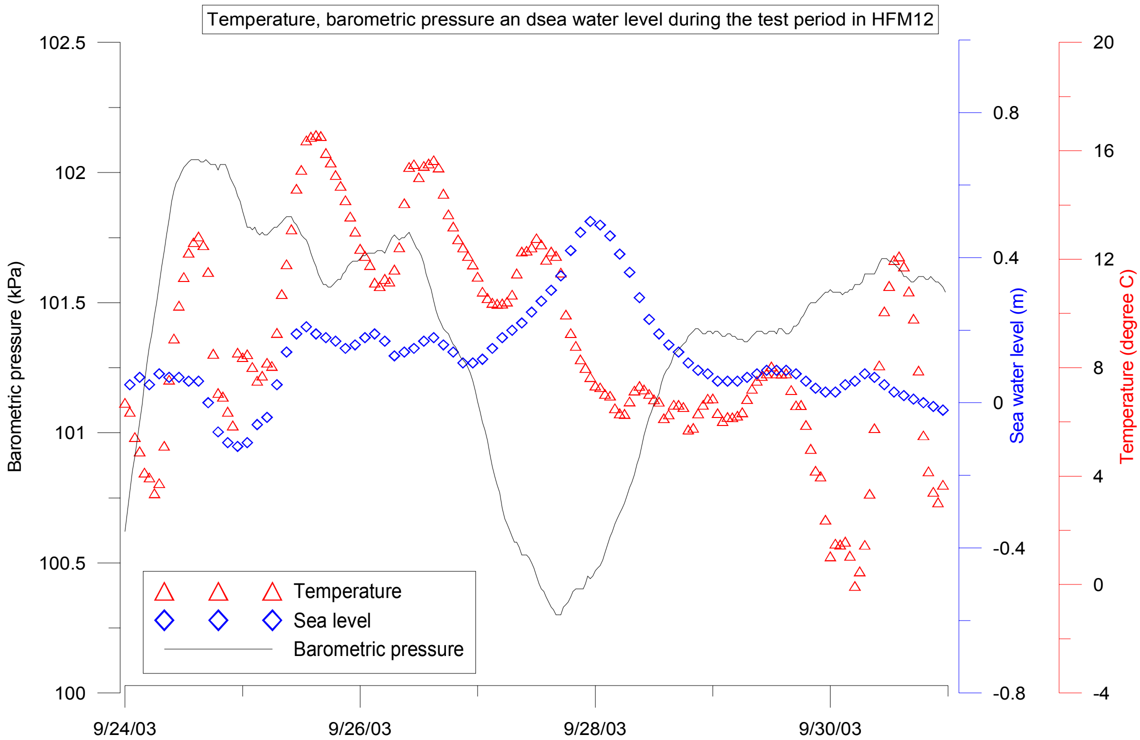


Figure 6-2*. Barometric pressure, sea level and temperature during the test period in HFM12.*

Table 6-5. Comparison of estimated specific capacity from the capacity test and pumping test, respectively, in borehole HFM12.

Test	Duration (min)	Flow rate (L/min)	Drawdown s_w (m)	Specific capacity Q/s_w (m^2/s)
Capacity test	24	10	10.8	$1.5\ 10^{-5}$
Pumping test	634	10.2	14.26	$1.21\ 10^{-5}$

Table 6-5 demonstrates a good agreement between the capacity tests 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 A2:6-8 in Appendix 2. Pseudo-radial flow occurred after c. 100 min of pumping.

No evaluation of the recovery period could be made due to lack of data.

Interpreted parameters

The transient, quantitative interpretation of the flow- and recovery period of the test is shown in Figures A2:7-8 in Appendix 2. Quantitative analysis was made from the flow period in lin-log and log-log diagrams according to the methods described in Section 5.4.1.

6.4 Flow logging

6.4.1 Borehole HFM11

General test data for the flow logging in borehole HFM11 are presented in Table 6-6.

Table 6-6. General test data for the flow logging in borehole HFM11.

General test data			
Borehole	HFM11		
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		
	Nomen-clature	**Unit**	**Value**
Borehole length		m	182.35
Casing length		m	12.00
Pump position (lower level)		m	30
Flow logged section – Secup		m	33.50
Flow logged section – Seclow		m	175
Test section diameter	$2 \cdot r_w$	mm	top 140 bottom 139
Start of flow period		yymmdd hh:mm	031002 09:19:04
Start of flow logging		yymmdd hh:mm	031002 13:51:30
Stop of flow logging		yymmdd hh:mm	031002 18:20:01
Stop of flow period		yymmdd hh:mm	031002 19:19.10

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

Pressure, groundwater level and flow data

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GWL (masl)**
Absolute pressure in borehole before start of flow period	p_i	kPa	280.0	5.89
Absolute pressure in test section before stop of flow period	p_p	kPa	145.9	–7.78*
Absolute pressure in test section at stop of recovery period	p_F	kPa	273.1	5.08
Pressure drawdown at stop of flow period	dp_p	kPa	134.1	
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	2.18	5.89
Level (steady state) in borehole, at pumping rate Q_p	h_p	m		–7.78*
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	13.47	13.67
Flow data	**Nomen-clature**	**Unit**	**Flow rate**	
Final pumping rate at surface	Q_p	m^3/s	$8.00 \cdot 10^{-4}$	
Cumulative flow rate at Secup at pumping rate Q_p	Q_T	m^3/s	$8.08 \cdot 10^{-4}$	
Lower measurement limit for flow rate during flow logging	Q_{Measl}	m^3/s	$5 \cdot 10^{-5}$	
Minimal change in borehole flow rate to detect flow anomaly	dQ_{anom}	m^3/s	$1.7 \cdot 10^{-5}$	

* Calculated from pressure drawdown.

Comments on the test

The flow logging was made from the bottom of the hole upwards. The first detectable flow anomaly was found at 146.2 m. The step length between flow measurements was maximally 2 m.

The measured electric conductivity was not temperature-compensated due to a broken temperature recorder. The measured cumulative borehole flow rate at the top of the flow logged interval was equal to the total flow rate pumped from the borehole at the surface. This fact indicates that no flow anomaly is present above the flow logged interval.

Logging results

The nomenclature used for the flow logging is according to the methodology description for flow logging. The measured flow distribution along the hole together with the uncorrected electric conductivity (EC) of the borehole fluid is presented in Figure 6-1. The values presented in Figure 6-2 have not been temperature compensated due to problems with the temperature sensor.

The results of the flow logging in borehole HFM11 are also presented in Table 6-7 below. Six flow anomalies were identified in the borehole. The measured inflow at the identified flow anomalies (dQ_i) is shown. The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Eqn. (5-2) and the transmissivity of individual flow anomalies (T_i) from Eqn. (5-3). An estimation of the transmissivity of the interpreted flow anomalies 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.

As can be seen from Table 6-7, all of the total flow at the surface was measured within the flow logged interval. This fact indicates that there is no flow anomaly above the flow logged interval. The largest inflow was encountered within the interval 40.7–43.7 m. A small inflow below the measurement limit occurred in the interval 146.2–147.3 m.

Table 6-7. Results of the flow logging in borehole HFM11. 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 pumping test evaluation.

HFM11 Flow anom.		$Q_T=8.15\cdot10^{-4}$ (m^3/s)	$T=4.31\cdot10^{-5}$ (m^2/s)	s_{FL}=13.47 m	$Q_p=8.00\cdot10^{-4}$ (m^3/s)
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**
37.7–38.7	1	$1.17\cdot10^{-4}$	$7.27\cdot10^{-6}$	$8.66\cdot10^{-6}$	EC
40.7–43.7	3	$2.43\cdot10^{-4}$	$1.52\cdot10^{-5}$	$1.81\cdot10^{-5}$	EC
108.2–110.2	2	$1.65\cdot10^{-4}$	$1.03\cdot10^{-5}$	$1.23\cdot10^{-5}$	EC
135.7–136.7	1	$4.67\cdot10^{-5}$	$2.91\cdot10^{-6}$	$3.46\cdot10^{-6}$	EC
141.2–143.7	2.5	$1.63\cdot10^{-4}$	$1.02\cdot10^{-5}$	$1.21\cdot10^{-5}$	EC
146.2–147.3	1.1	$7.33\cdot10^{-5}$	$4.57\cdot10^{-6}$	$5.44\cdot10^{-6}$	EC
Total		**$\Sigma=8.08\cdot10^{-4}$**	**$\Sigma=5.04\cdot10^{-5}$**	**$\Sigma=6.00\cdot10^{-5}$**	
Difference		$Q_T - Q_p = 1.5\cdot10^{-5}$			

Injection test

To confirm the result from the flow logging, an injection test was performed in the upper part of the borehole. Water collected from the borehole during pumping was injected in a borehole section between two packers. The measured section was between 12.0–33.7 m, i.e. 22 m long. The low injection rate in this section confirms the results from the flow logging. The results from the injection test are shown in Table 6-8 below. Only a steady-state evaluation of the transmissivity by Moye's formula was made.

Table 6-8. Results of the injection tests in section 12.0–33.7 m in borehole HFM11 in conjunction with the flow logging.

Injection test	Nomen-clature	Unit	Value
Injection rate at surface	Q_p	m^3/s	$<1.7 \cdot 10^{-5}$
Absolute pressure in borehole before start of flow period	p_i	kPa	137.7
Absolute pressure in test section before stop of flow period	p_p	kPa	339.5
Absolute pressure in test section at stop of recovery period	p_F	kPa	133.9
Pressure change by the end of flow period	dp_p	kPa	201.8
Specific flow rate	Q_p/ dp_p	m^2/s	$<2.85 \cdot 10^{-7}$
Transmissivity (Moye)	T_M	m^2/s	$<4.83 \cdot 10^{-8}$

Summary of results

Table 6-9 presents an overview of the results from the tests performed in the borehole. The results in Table 6-9 are consistent and demonstrate that all specific flow and transmissivity is restricted to the flow-logged interval.

The borehole diameter used in the calibration of the borehole flow rate, 140 mm, is close to the top diameter for the borehole and no correction for the small difference between Q_{FT} and Q_p were made.

Table 6-9. Compilation of results from pumping test and flow logging including injection tests in the upper part of borehole HFM11.

Test type	Interval (m)	Specific flow Q/s* (m^2/s)	T (m^2/s)
Flow logging	33.5–175	$6.00 \cdot 10^{-5}$	$5.04 \cdot 10^{-5}$
Injection test	12.0–33.7	$<2.85 \cdot 10^{-7}$	$<4.83 \cdot 10^{-8}$ **
Pumping test	12–182.35	$5.98 \cdot 10^{-5}$	$4.31 \cdot 10^{-5}$

* calculated as Qp/dp for the injections test interval
** transmissivity from the evaluation with Moye's formula

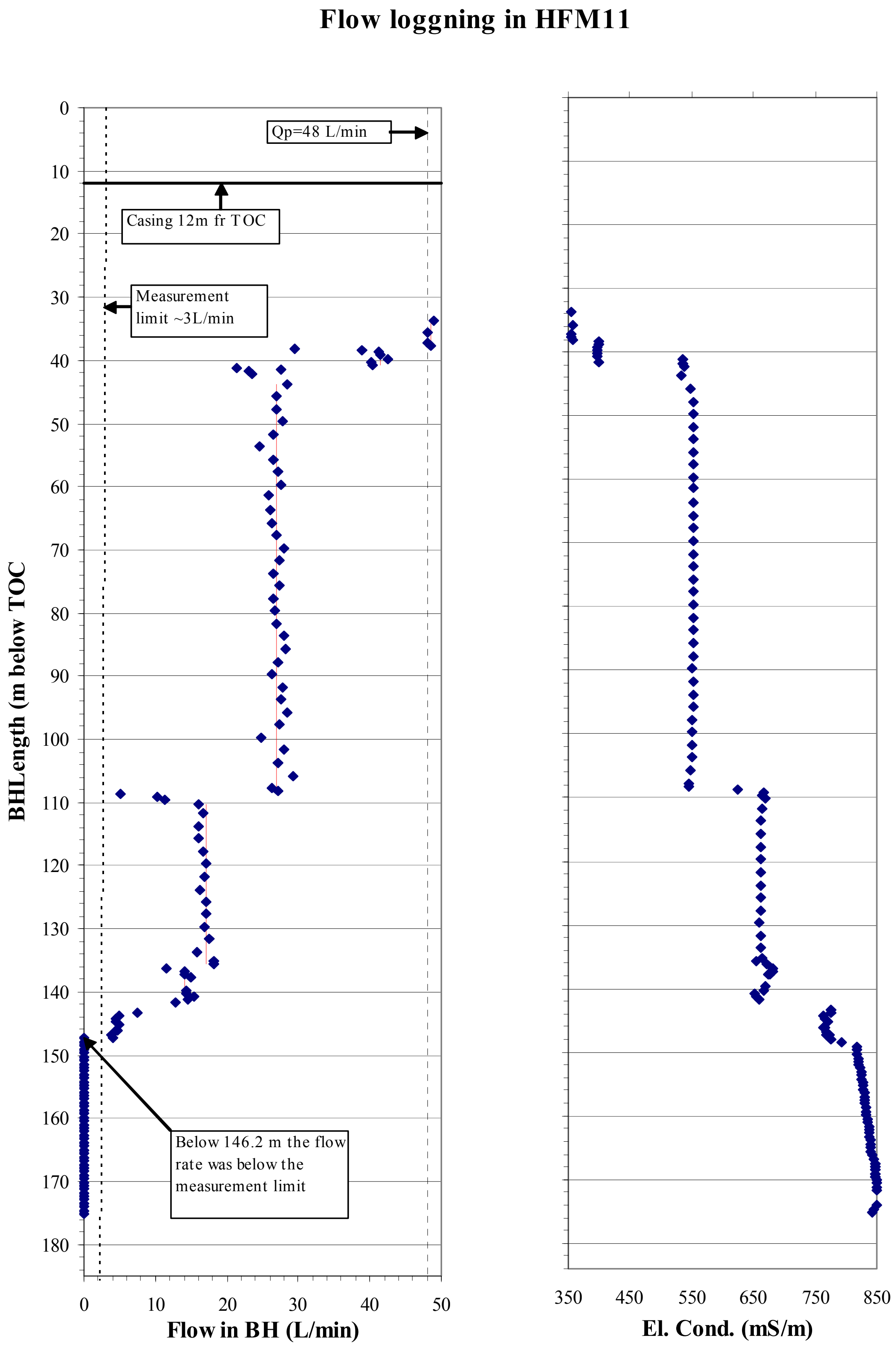


Figure 6-1. *Measured flow distribution along borehole HMF11 during the flow logging together with the uncorrected electric conductivity (EC).*

Figure 6-2 displays the cumulative transmissivity $T_F(L)$ along the borehole length (L) from the flow logging calculated from Eqn. (6-5). Since the width of the flow anomaly 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 T of the borehole are also shown in the figure, cf. Section 6.4.2.

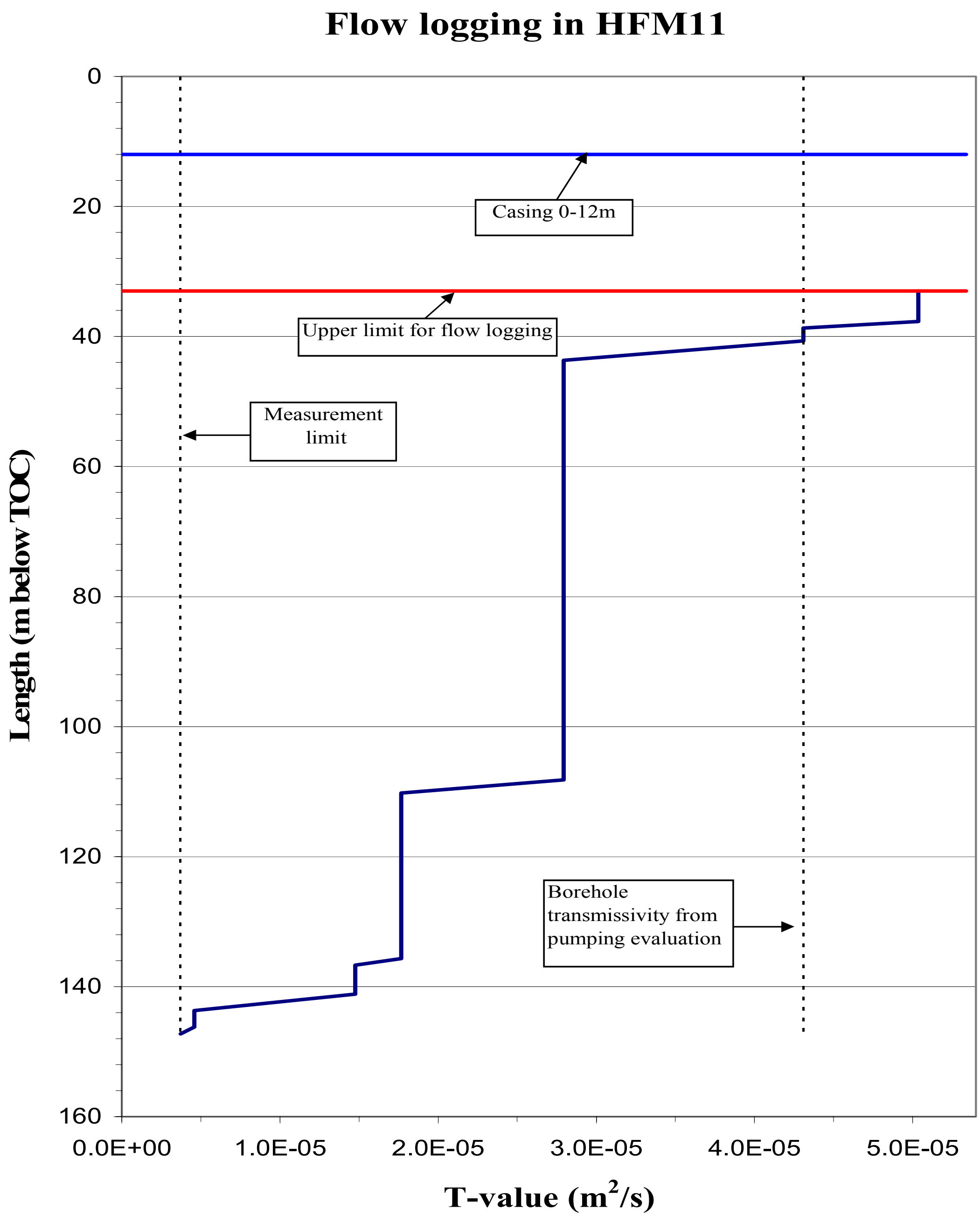


***Figure 6-2**. Calculated, cumulative transmissivity along the flow-logged interval of borehole HFM11. Below c. 146.2 m, the borehole transmissivity fell below the measurement limit. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.4.2 Borehole HFM12

General test data for the flow logging in borehole HFM12 are presented in Table 6-10.

Table 6-10. General test data for the flow logging in borehole HFM12.

General test data			
Borehole	HFM12		
Test type(s)[1]	6, L-EC, L-Te		
Test section:	Open borehole		
Test No	1		
Field crew	J. Källgården, J Jönsson (GEOSIGMA AB)		
Test equipment system	HTHB1		
General comments	Single pumping borehole		
	Nomen-clature	**Unit**	**Value**
Borehole length		m	209.5
Casing length		m	14.9
Pump position (lower level)		m	25
Flow logged section – Secup		m	30.5
Flow logged section – Seclow		m	206.5
Test section diameter	$2 \cdot r_w$	mm	top 138 bottom 135.3
Start of flow period		yymmdd hh:mm	030926 07:04:39
Start of flow logging		yymmdd hh:mm	030926 13:03:06
Stop of flow logging		yymmdd hh:mm	030926 17:38:24
Stop of flow period		yymmdd hh:mm	030926 17:38:23

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

Pressure, groundwater level and flow data

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GWL (masl)**
Absolute pressure in borehole before start of flow period	p_i	kPa	251.4	5.91
Absolute pressure in test section before stop of flow period	p_p	kPa	111.3	–8.38 *
Absolute pressure in test section at stop of recovery period	p_F	kPa	111.3	5.74
Pressure drawdown at stop of flow period	dp_p	kPa	140.1	
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	1.46	5.91
Level (steady state) in borehole, at pumping rate Q_p	h_p	m		–8.38 *
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	14.26	14.29
Flow data	**Nomen-clature**	**Unit**	**Flow rate**	
Final pumping rate at surface	Q_p	m^3 /s	$1.7 \cdot 10^{-4}$	
Cumulative flow rate at Secup at pumping rate Q_p	Q_T	m^3 /s	$9.35 \cdot 10^{-5}$	
Lower measurement limit for flow rate during flow logging	Q_{measl}	m^3 /s	$5 \cdot 10^{-5}$	
Minimal rate in borehole flow rate to detect flow anomaly	dQ_{anom}	m^3 /s	$1.7 \cdot 10^{-5}$	

* Calculated from pressure drawdown.

Comments on the test

The flow logging was made from the bottom of the hole upwards. The first detectable flow anomaly was at 123.2 m (lower limit). The step length between flow measurements was maximally 2 m. At each flow anomaly the step length was decreased to 0.5 m.

The measured electric conductivity was temperature-compensated and the result is shown in Figure 6-3. The measured cumulative borehole flow rate at the top of the flow logged interval was significantly lower than the total flow rate pumped from the borehole at the surface. Injection tests were made to investigate if additional flow anomalies are present above the flow logged interval.

Logging results

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

The results of the flow logging in borehole HFM12 are also presented in Table 6-11 below. One major flow anomaly and one minor anomaly were identified. The measured inflow at the identified flow anomalies (dQ_i) is shown. As can be seen from Figure 6-3 most of the measured inflow to the borehole during the flow logging occurs in the borehole interval 123.2–123.8 m and below this interval. A small flow anomaly also occurs at 110.2–112.2 m.

Table 6-11 shows that Q_T is lower than Q_p which indicates that there may be an additional anomaly above the flow logged interval. However, there are reasons to believe that Q_{FT} is underestimated, since the calibration constants used match the diameter at the bottom of the borehole (135.3 mm) but not at the top (138 mm) which means that the total flow from the logged interval might be larger. Calibration constants for a test tube with the diameter of 135.5 mm were used by the flow logging.

Table 6-11. Results of the flow logging in borehole HFM12. 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 pumping test evaluation.

HFM12 Flow anomalies		Q_T=9.33·10^{-5} (m^3/s)	T=1.43·10^{-5} (m^2/s)	s_{FL}=14.26m	Qp=1.7·10^{-4} (m^3/s)
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**
110.2–112.2	2	1.60·10^{-5}	1.36·10^{-6}	1.12·10^{-6}	EC
123.2–123.8	0.6	7.73·10^{-5}	6.51·10^{-6}	5.42·10^{-6}	EC
Total		**Σ=9.33·10^{-5}**	**Σ=7.85·10^{-6}**	**Σ=6.55·10^{-6}**	
Difference		Q_p–Q_T=7.65·10^{-5}			

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

Injection test

Three injection tests were performed in the upper part of the borehole to confirm the results from the flow logging. Water collected from the borehole during pumping was injected in sections between two packers. The measured total interval was 14.9–30.3 m with a section length of 4.4 m for the uppermost section and 5.5 m for the other sections. In the uppermost section a high flow rate was injected. The results of the injection tests are shown in Table 6-12.

Table 6-12. Results of the injection tests in borehole HFM12 in conjunction with the flow logging.

Injection test	**Nomen-clature**	**Unit**	**Value for section:**		
			14.9–19.3 m	19.3–24.8 m	24.8–30.3 m
Pumping rate at surface	Q_p	m^3/s	$2.03\cdot10^{-4}$	$2.05\cdot10^{-5}$	$6.67\cdot10^{-6}$
Absolute pressure in borehole before start of flow period	p_i	kPa	206.8	242.8	270.9
Absolute pressure in test section before stop of flow period	p_p	kPa	387.9	429.3	549.4
Absolute pressure in test section at stop of recovery period	p_F	kPa	190.1	227.8	266.3
Pressure change by the end flow period	dp_p	kPa	197.8	201.5	283.1
Specific flow rate	Q_p/dp_p	m^2/s	$1.1\cdot10^{-5}$	$1.07\cdot10^{-6}$	$2.35\cdot10^{-7}$
Transmissivity (Moye)	T_M	m^2/s	$8.01\cdot10^{-6}$	$8.18\cdot10^{-7}$	$1.8\cdot10^{-7}$

Summary of results

Table 6-13 gives an overview of the results from the tests performed in the borehole. To be able to compare the results from the different tests and to estimate the transmissivity of the potential flow anomaly above the flow logged interval, the specific flows (Q/s) and transmissivity of the tests were calculated.

No correction of the borehole flow rate due to increased borehole diameter (138 mm) at the top of the flow logged interval was made. The calibration constants are close to the bottom diameter of the borehole (135.3 mm). The estimated specific flow and transmissivity of the interval above the flow logged interval (14.9–30.3 m) from the difference between the pumping test and the flow logging and from the injection tests, respectively, in Table 6-13 are consistent, although the injection test in the uppermost section 14.9–19.3 m indicated slightly higher values. It should be pointed out that the potential flow anomaly in this section is uncertain. It may possibly represent a slight leakage at the casing shoe.

Table 6-13. Compilation of results from pumping test and flow logging including injection tests in the upper part of borehole HFM12.

Test type	Interval (m)	Specific flow Q/s* (m^2/s)	T (m^2/s)	Remarks
Flow logging	30.5–206.5	$6.55\cdot10^{-6}$	$7.85\cdot10^{-6}$	Logged interval
Pumping test	14.9–209.5	$1.19\cdot10^{-5}$	$1.43\cdot10^{-5}$	Entire borehole
Injection tests total interval	14.9–30.3	$1.23\cdot10^{-5}$	$9.00\cdot10^{-6}$ **	Interval above logged interval
Difference (pumping test-flow logging)	14.9–30.3	$5.35\cdot10^{-6}$	$6.45\cdot10^{-6}$	Interval above logged interval

* calculated as Qp/dp for each interval
** transmissivity from evaluation with Moye's formula

Figure 6-4 illustrates the cumulative transmissivity T_F (L) along the borehole length (L) from the flow logging calculated from Eqn. (5-3). 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.

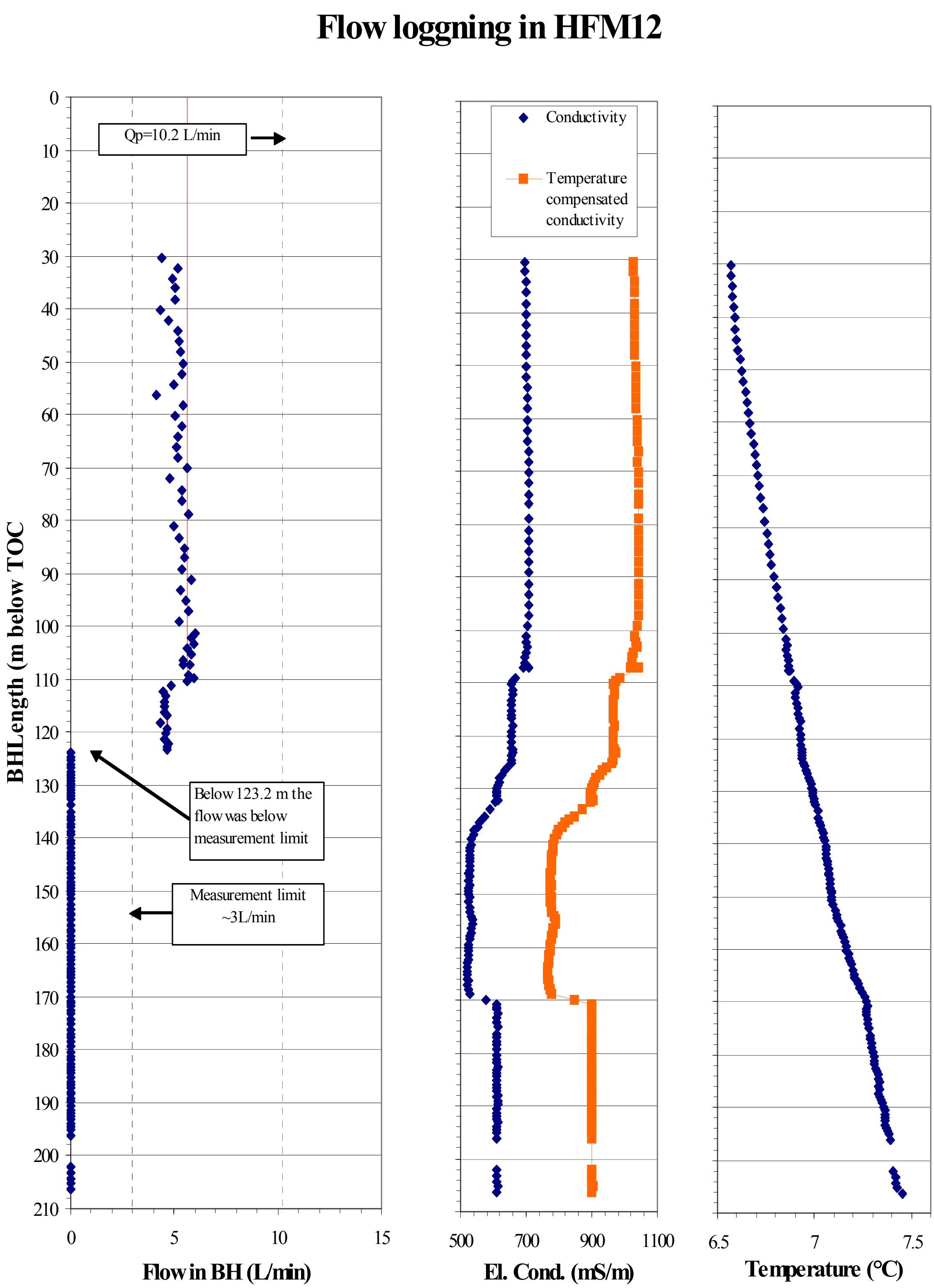


Figure 6-3. *Measured flow distribution along borehole HFM12 during the flow logging together with the relative electric conductivity (EC) and temperature (Te) of the borehole fluid.*

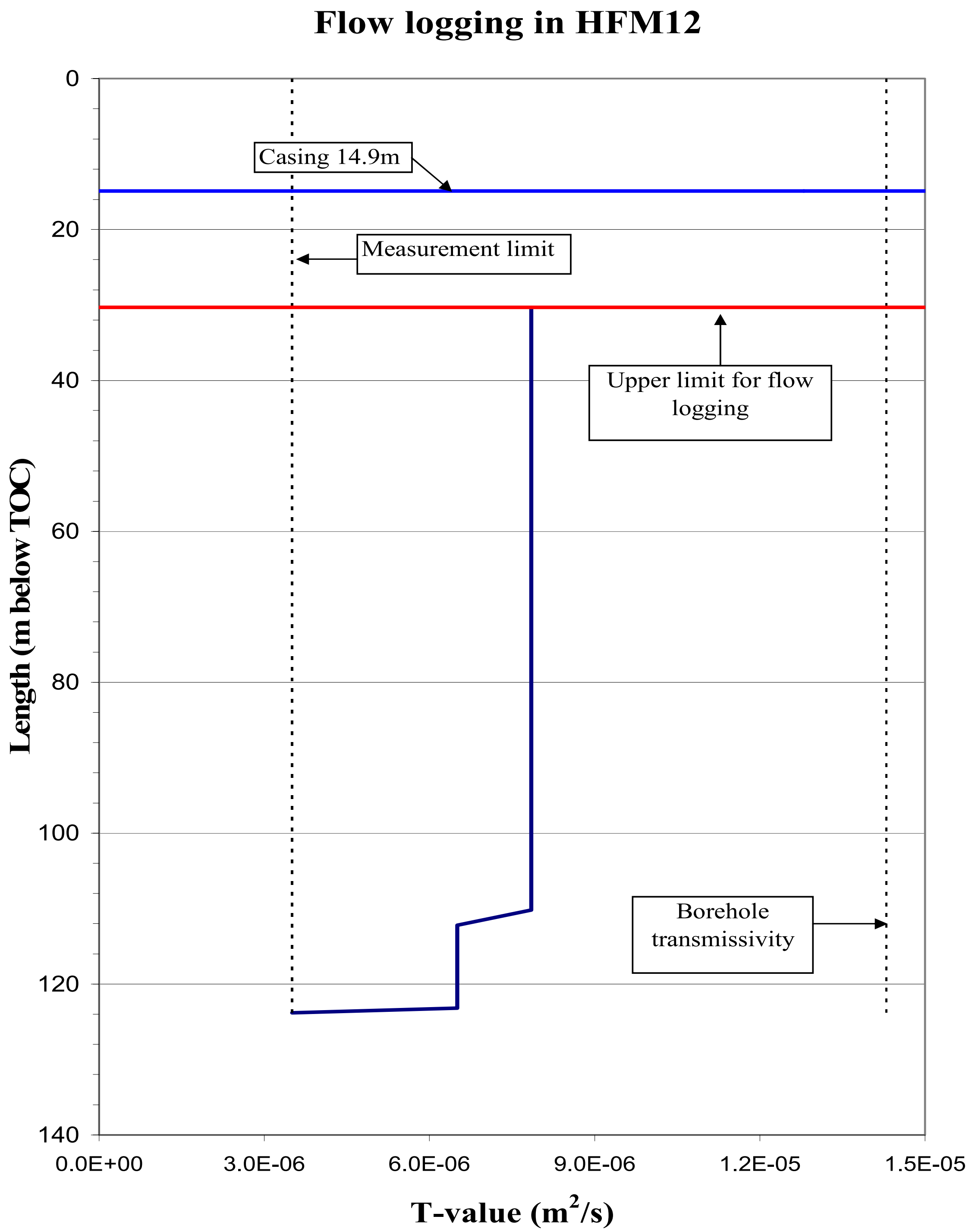


Figure 6-4*. Calculated, cumulative transmissivity along the flow logged interval of borehole HFM12. The total borehole transmissivity was calculated from the pumping test during flow logging.*

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 6-14. In Table 6-15 and 6-16 hydraulic parameters calculated from the tests in HFM11 and HFM12 are exposed. 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 for practical purposes 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 $Q/s\text{–}L=2\cdot10^{-6}$ 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 $Q/s\text{–}U=2\cdot10^{-3}$ m^2/s for both pumping tests and injection tests.

In Table 6-15 and 6-16, 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_1 = transient transmissivity from the first pseudo-radial flow regime

T_2 = transient transmissivity from the second pseudo-radial flow regime

T_i = estimated transmissivity of flow anomaly

S* = assumed value on storativity used for calculation of the skin factor

C = wellbore storage coefficient

ζ = skin factor

Table 6-14. Summary of test data for the hydraulic tests performed in boreholes HFM11 and HFM12 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)
HFM11	12.00–182.35	1B	280.0	145.9	273.1	8·10–4	7,95E–4	28,76
HFM12	14.9–209.5	1B	251.4	111.3	111.3	1.7E–4	2.55E–4	7.24

[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 of the formation from the hydraulic tests performed in HFM11–12 in the Forsmark area.

Borehole ID	Section (m)	Flow Anomaly interval (m)	Test type [1]	Q/s (m^2/s)	T_M (m^2/s)	T_1 (m^2/s)	T_2 (m^2/s)	T_i (m^2/s)	S* (-)
HFM11	12.00–182.35		1B	$5.98\cdot10^{-5}$	7.66E–05	$4.31\cdot10^{-5}$			$5.0\cdot10^{-5}$
HFM11	33.5–175	37.7–38.7	6	$8.66\cdot10^{-6}$				$7.27\cdot10^{-6}$	$5.0\cdot10^{-5}$
HFM11		40.7–43.7	6	$1.81\cdot10^{-5}$				$1.52\cdot10^{-5}$	$5.0\cdot10^{-5}$
HFM11		108.2–110.2	6	$1.23\cdot10^{-5}$				$1.03\cdot10^{-5}$	$5.0\cdot10^{-5}$
HFM11		135.7–136.7	6	$3.46\cdot10^{-6}$				$2.91\cdot10^{-6}$	$5.0\cdot10^{-5}$
HFM11		141.2–143.7	6	$1.21\cdot10^{-5}$				$1.02\cdot10^{-5}$	$5.0\cdot10^{-5}$
HFM11		146.2–182.35	6	$5.44\cdot10^{-6}$				$4.57\cdot10^{-6}$	$5.0\cdot10^{-5}$
HFM11	12.0–33.7m	12.0–33.7	3	$1.98\cdot10^{-7}$	$4.83\cdot10^{-8}$				
HFM12	14.9–209.5		1B	$1.20\cdot10^{-5}$	$1.57\cdot10^{-5}$	$1.43\cdot10^{-5}$			$5.0\cdot10^{-5}$
HFM12	30.5–206.5	110.2–112.2	6	$1.12\cdot10^{-6}$				$1.36\cdot10^{-6}$	$5.0\cdot10^{-5}$
HFM12		123.2–209.5	6	$5.42\cdot10^{-6}$				$6.51\cdot10^{-6}$	$5.0\cdot10^{-5}$
HFM12		14.9–19.3	3	$1.12\cdot10^{-5}$	$8.00\cdot10^{-6}$				$5.0\cdot10^{-5}$
HFM12		19.3–24.8	3	$1.10\cdot10^{-6}$	$8.18\cdot10^{-7}$				$5.0\cdot10^{-5}$
HFM12		24.8–30.3	3	$2.40\cdot10^{-7}$	$1.79\cdot10^{-7}$				$5.0\cdot10^{-5}$

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

Table 6-16. Summary of calculated hydraulic parameters of the borehole from hydraulic tests performed in boreholes HFM11 and HFM12 in the Forsmark area.

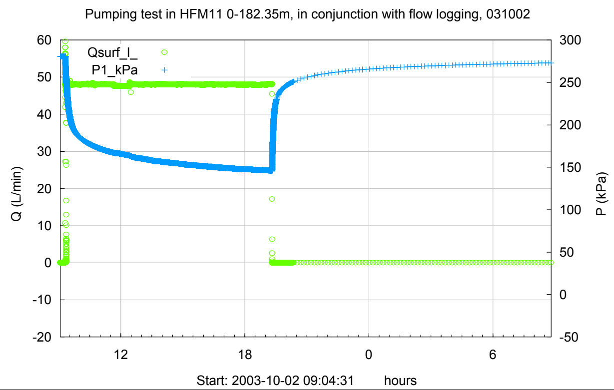
Borehole ID	Section (m)	Test type	S* (-)	C (m^3/Pa)	ζ (-)
HFM11	12.00–182.35	1B	$5\cdot10^{-5}$	$2.4\cdot10^{-6}$	–4.69*
HFM12	14.9–209.5	1B	$5\cdot10^{-5}$		–0.71**

* Calculated from s vs. log(t) during drawdown phase.
** Calculated from 1/Q vs. log(t) during drawdown phase.

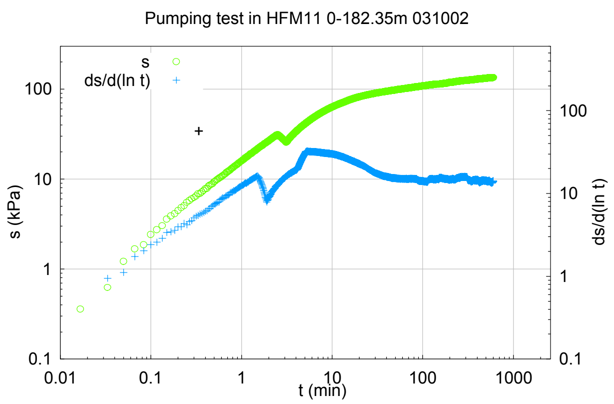
Test Summary Sheet

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM11	Test start:	2003-10-02 09:19:04
Test section (m):	12.00–182.35	Responsible for test performance:	GEOSIGMA AB T. Svensson, J. Jönsson
Section diameter, 2·rw (m):	top 0.140 bottom 0.139	Responsible for test evaluation:	GEOSIGMA AB J-E. Ludvigson

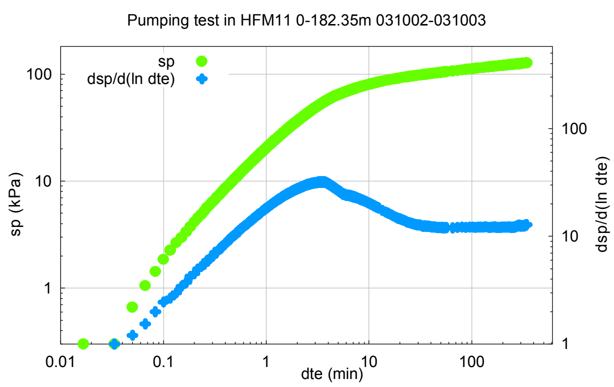
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)	280.0		
p_i (kPa)	280.0		
p_p(kPa)	145.9	p_F (kPa)	273.1
Q_p (m^3/s)	$8.0 \cdot 10^{-4}$		
tp (min)	600.1	t_F (min)	809.4
S*	$5 \cdot 10^{-5}$	S*	$5 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.5	Derivative fact.	0.5
Results		**Results**	
Q/s (m^2/s)	$5.98 \cdot 10^{-5}$		
T_{Moye}(m^2/s)	$7.66 \cdot 10^{-5}$		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	50	dt_{e1} (min)	50
t_2 (min)	600	dt_{e2} (min)	350
T_w (m^2/s)	$4.31 \cdot 10^{-5}$	T_w (m^2/s)	$4.88 \cdot 10^{-5}$
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)	$2.40 \cdot 10^{-6}$	C (m^3/Pa)	$2.40 \cdot 10^{-6}$
C_D (-)	78513	C_D (-)	78513
ξ (-)	–4.69	ξ (-)	–3.83
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

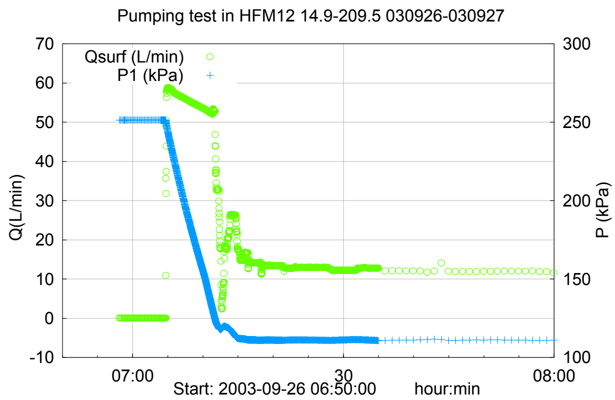
Interpreted formation and well parameters.			
Flow regime:	PRF	C (m^3/Pa)	$2.40 \cdot 10^{-6}$
t_1 (min)	50	C_D (-)	
t_2 (min)	600	ξ (-)	–4.69
T_T (m^2/s)	$4.31 \cdot 10^{-5}$		
S (-)			
K_s (m/s)			
S_s (1/m)			

Comments: Initial flow transiting to a pseudo-radial flow during both the flow- and recovery period.

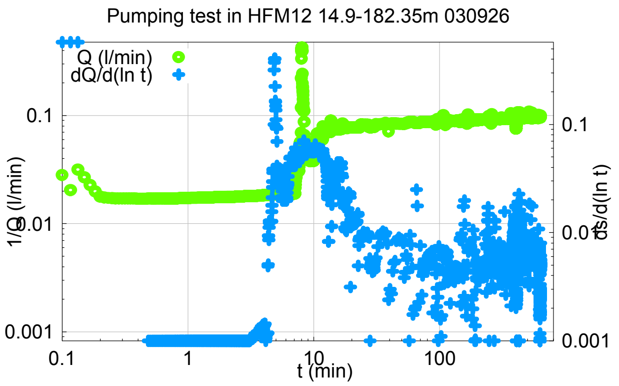
Test Summary Sheet

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM12	Test start:	2003-09-26 06:58:02
Test section (m):	14.9–209.5	Responsible for test performance:	GEOSIGMA AB J. Källgården, J. Jönsson
Section diameter, 2·rw (m):	top 0.138 bottom 0.135	Responsible for test evaluation:	GEOSIGMA AB J-E. Ludvigson

Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period

Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)	251.4		
p_i (kPa)	251.4		
p_p(kPa)	111.3	p_F (kPa)	
Q_p (m^3/s)	$1.4\cdot10^{-4}$		
tp (min)	633.7	t_F (s)	
S*	$5\cdot10^{-5}$	S*	
Ecw (mS/m)			
Tew(gr C)			
Derivative fact.	0.5	Derivative fact.	
Results		**Results**	
Q/s (m^2/s)	$1.2\cdot10^{-5}$		
T_{Moye}(m^2/s)	$1.57\cdot10^{-5}$		
Flow regime:	PRF	Flow regime:	
t_1 (min)	100	dt_{e1} (min)	
t_2 (min)	600	dt_{e2} (min)	
T_w (m^2/s)	$1.43\cdot10^{-5}$	T_w (m^2/s)	
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)		C (m^3/Pa)	
C_D (-)	0	C_D (-)	
ξ (-)	–0.71	ξ (-)	
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

Flow regime:	PRF	C (m^3/Pa)	
t_1 (min)	100	C_D (-)	
t_2 (min)	600	ξ (-)	–0.71
T_T (m^2/s)	$1.43\cdot10^{-5}$		
S (-)			
K_s (m/s)			
S_s (1/m)			

Comments: No recovery data registered because of logger problems. The pumping test was performed as a constant head test where pseudo-radial flow was reached after c. 100 min.

7 References

1 **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-report in progress. Svensk kärnbränslehantering AB.

2 **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.

3 **Claesson L-Å, Nilsson G, 2003.** Forsmark site investigation. Drilling of six percussion drillholes on different lineaments, HFM11–13 and HFM17–19. SKB P-report in progress. Svensk kärnbränslehantering AB.

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, etc) 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**
HFM11	0–182.35	1B, 6,L-EC, L-T		2003-10-02 08:28:13	2003-10-03 08:48:35	2003-10-01 11:03:38	200-10-03 08:48:35	HFM11_000_031002_FlowLo00.DAT	P, Q, T, EC	
HFM11						2003-09-30 08.03:41	2003-10-03 08:48:38	HFM11_000_031002_Ref_Da00.DAT	R	
HFM11	182.35–33	6 L-EC L-T		2003-10-02 13:51:30	2003-10-02 18:20:01	2003-10-02 13:51:30	2003-10-02 18:20:01	HFM11_33_031002_Spinne00.DAT	P, Q, Sp, T, EC	
				2003-10-02 08:28:13	2003-10-03 08:48:35	2003-10-01 11:03:38	2003-10-03 08:48:35	HFM11_33_031002_FlowLo00.DAT	P, Q, T, EC	
						2003-09-30 08:03:41	2003-10-02 13:23:52	HFM11_33_031002_Ref_Da00.DAT	R	
HFM11	33.7–12.0	3		2003-10-03 13:13:29	2003-10-03 14:17:39	2003-10-03 11:30:04	2003-10-03 14:17:39	HFM11_11.7_031003_Inject00.DAT	P, Q	
						2003-09-30 08:03:41	2003-10-03 14:17:51	HFM11_11.7_031003_Ref_Da00.DAT		
HFM12	0–209.5	1B, 6,L-EC, L-T		2003-09-25 13:29:49	2003-09-26 17:38:24	2003-09-25 13:29:49	2003-09-26 17:38:24	HFM12_000_030926_FlowLo00.DAT	P, Q, T, EC	No recovery data registered because of logger problems.

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**
HFM12						2003-09-24 13:19:09	2003-09-29 20:03:31	HFM12_000_030926_Ref_Da00.DAT	R	
HFM12	206.5–30.3	6 L-EC L-T		2003-09-26 15:31:55	2003-09-26 18:17:59	2003-09-26 15:31:55	2003-09-26 18:17:59	HFM12_30.3_030926_Spinne00.DAT	P, Q, Sp, T, EC	
HFM12				2003-09-25 13:29:49	2003-09-26 17:38:24	2003-09-25 13:29:49	2003-09-26 17:38:24	HFM12_30.3_030926_FlowLo00.DAT	P, Q, T, EC	
HFM12						2003-09-24 13:19:09	2003-09-29 20:03:31	HFM12_30.3_030926_Ref_Da00.DAT	R	
HFM12	30.3–24.8	3		2003-09-30 13:54:27	2003-10-03 15:01:16	2003-09-30 13:54:27	2003-10-03 15:01:16	HFM12_24.8_030930_Inject00.DAT	P, Q	
HFM12						2003-09-30 08:03:41	2003-09-30 17:55:06	HFM12_24.8_030930_Ref_Da00.DAT		
HFM12	24.8–19.3	3		2003-09-30 15:20:50	2003-09-30 16:18:35	2003-09-30 15:20:50	2003-09-30 16:18:35	HFM12_19.3_030930_Inject00.DAT	P, Q	
HFM12						2003-09-30 08:03:41	2003-09-30 17:55:06	HFM12_19.3_030930_Ref_Da00.DAT		
HFM12	19.3–14.9	3		2003-09-30 16:34:12	2003-09-30 17:55:06	2003-09-30 16:34:12	2003-09-30 17:55:06	HFM12_14.9_030930_Inject00.DAT	P, Q	
HFM12						2003-09-30 08:03:41	2003-09-30 17:55:06	HFM12_14.9_030930_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 HFM11 12.00–182.50 m

2. Pumping test in HFM12:14.9–209.5 m

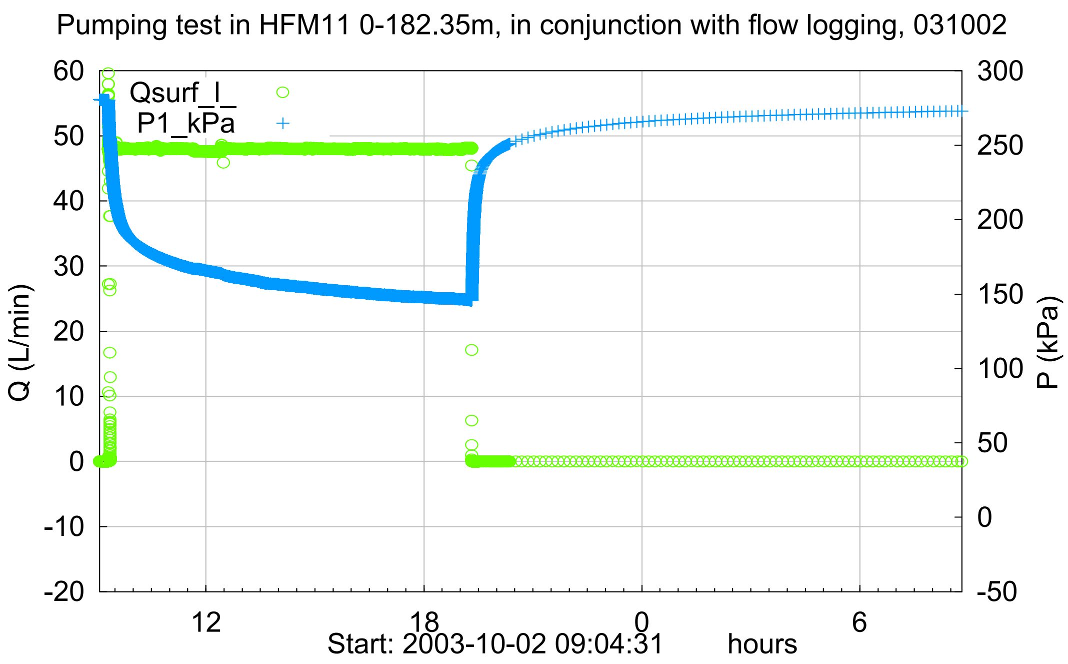


Figure A2:1. *Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM11 in conjunction with flow logging.*

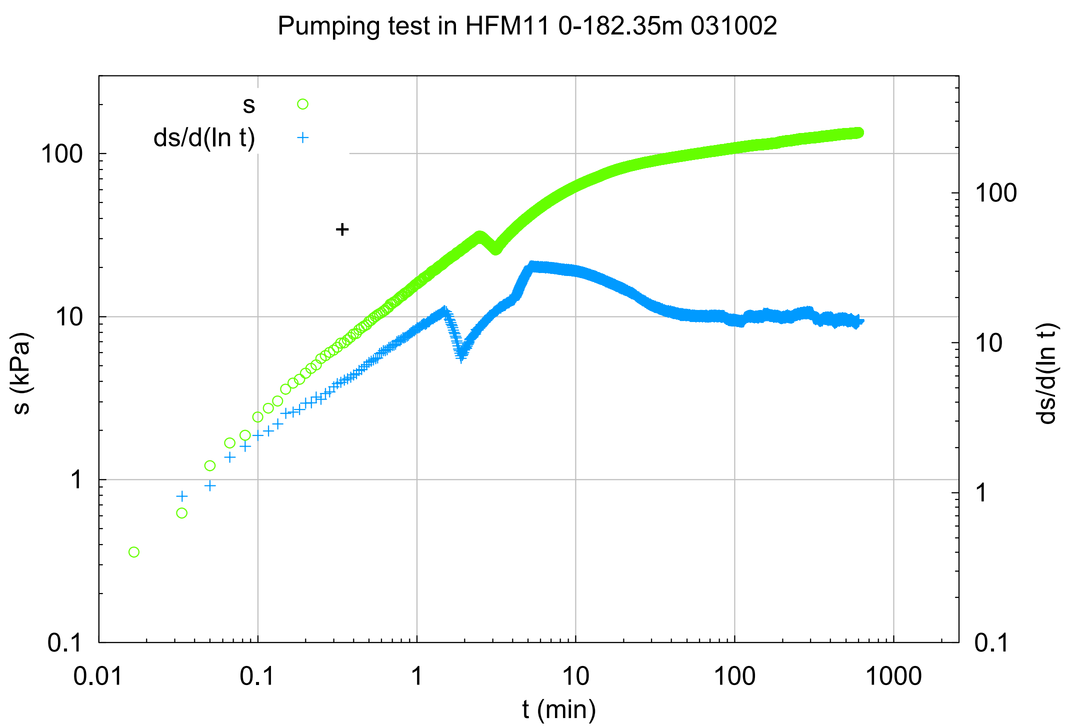


Figure A2:2. *Log-log plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) during the open-hole pumping test in HFM11.*

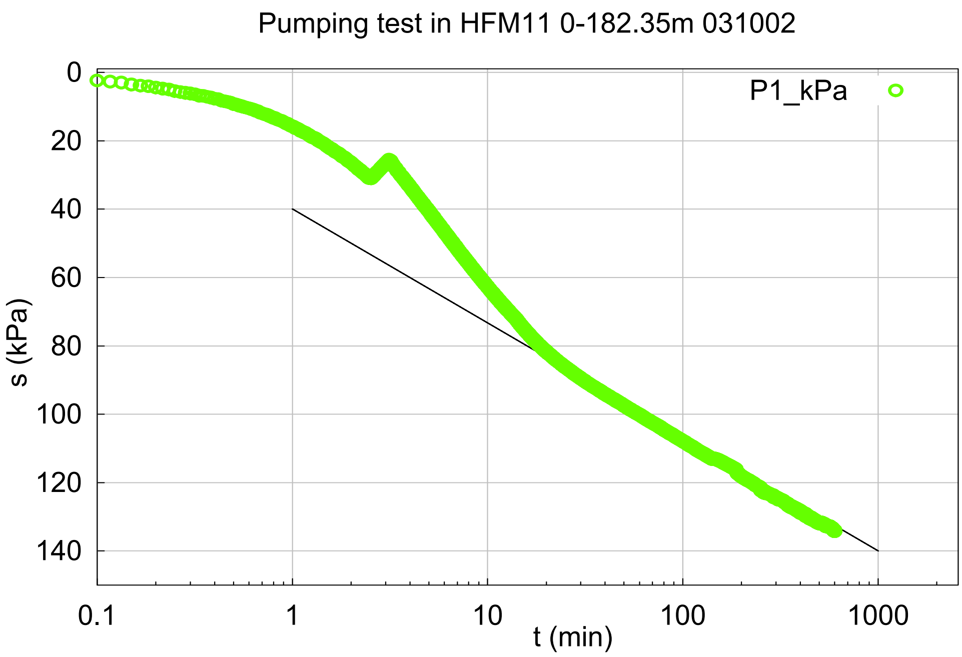


Figure A2:3. *Lin-log plot of drawdown (s) versus time (t) during the open-hole pumping test in HFM11.*

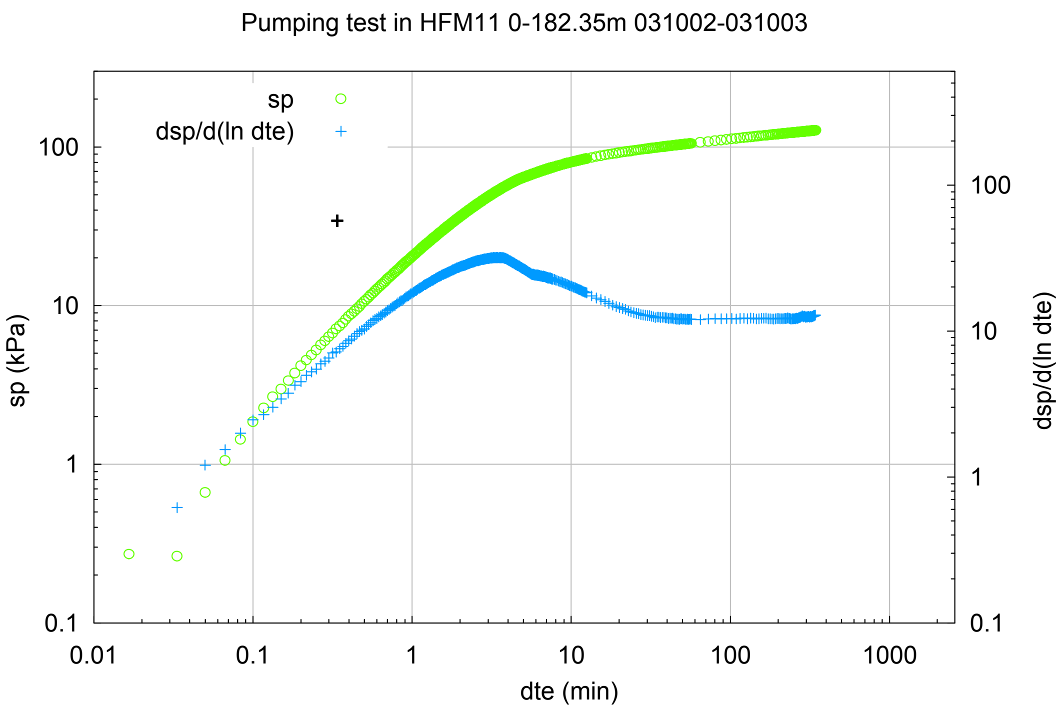


Figure A2:4. *Log-log plot of pressure recovery (sp) and – derivative, dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM11.*

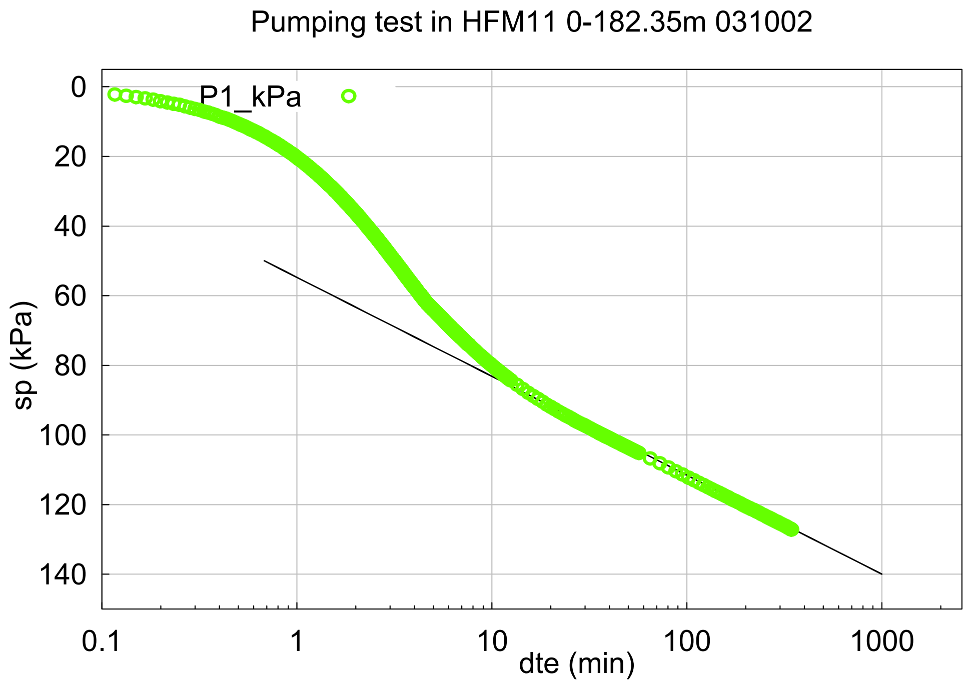


Figure A2:5*. Lin-log plot of pressure recovery (sp) versus equivalent time (dte) from the open-hole pumping test in HFM11.*

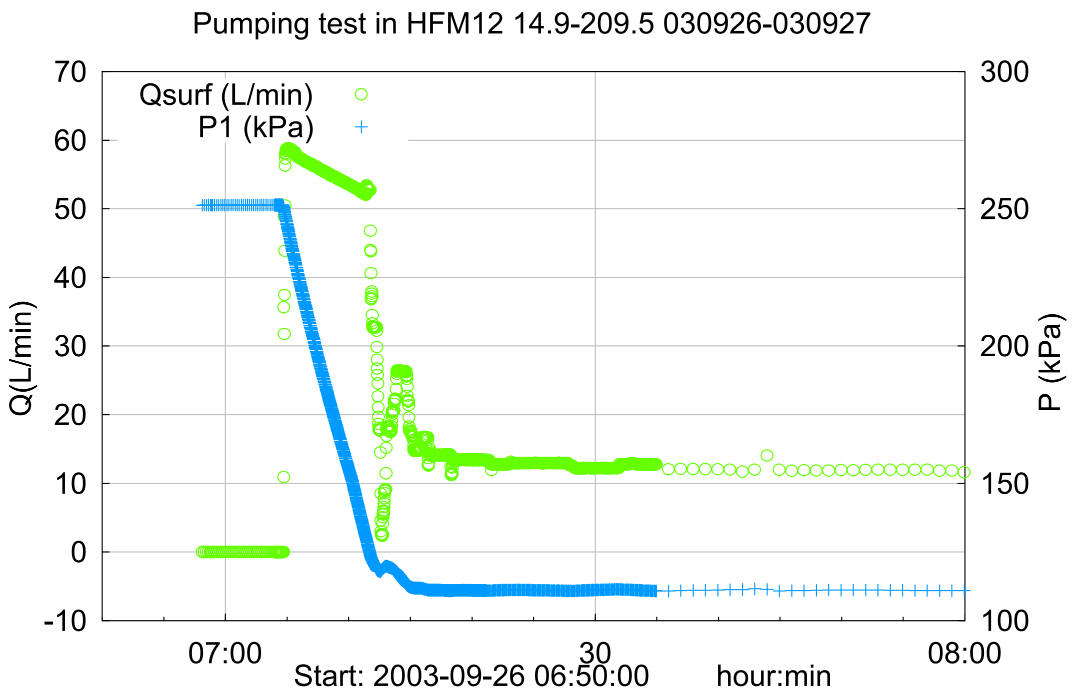


Figure A2:6*. Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM12 in conjunction with flow logging.*

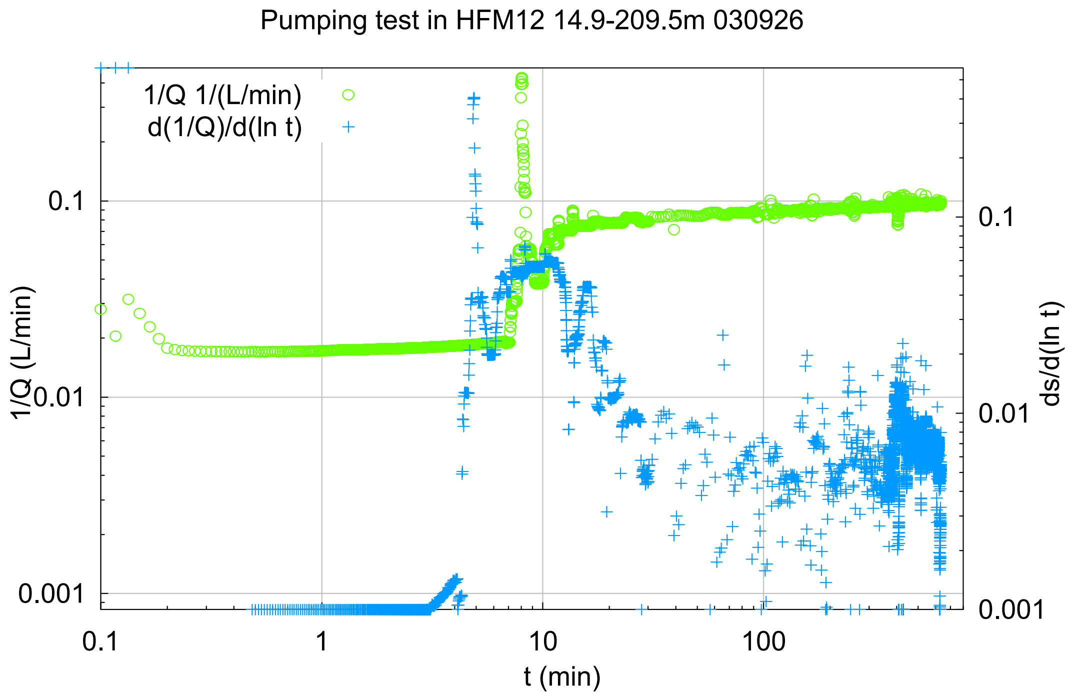


Figure A2:7. *Log-log plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) during the open-hole pumping test in HFM12.*

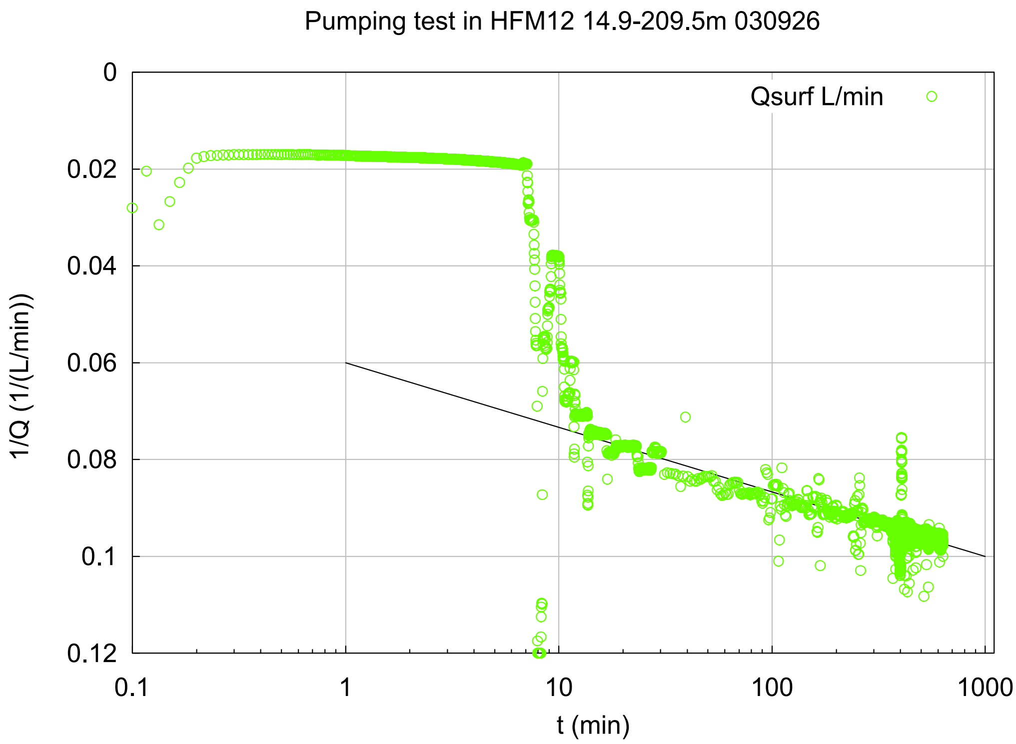


Figure A2:8. *Lin-log plot of drawdown (s) versus time (t) during the open-hole pumping test in HFM12.*

Appendix 3

Result tables to SICADA database

The following Result Tables are presented:

1. Result Tables for Single-hole pumping and injection tests
2. Result Tables for flow meter logging

Result Table for Single hole tests at Drill Site 2 at Forsmark for submission to Sicada

SINGLE HOLE 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	V_p (m**3)
HFM11	12.00	182.35	1B	1	2003-10-02 09:04	2003-10-03 08:48	2003-10-02 09:19:04	2003-10-02 19:19:10	8.02E-04	0	8.3E-05	1.3E-03	28.8
HFM12	14.90	209.50	1B	1	2003-09-26 06:58	2003-09-26 17:38	2003-09-26 07:04:39	2003-09-29 08:43:00	1.70E-04	0	8.3E-05	1.3E-03	7.2

cont.

Q_m (m**3/s)	tp (s)	t_F (s)	h_i (m a sl)	h_p (m a sl)	h_F (m a sl)	p_i (kPa)	p_p (kPa)	p_F (kPa)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/L)	TDS_{wm} (mg/L)	Reference	Comments (-)
7.95E-04	36000	19740	4.88	-7.78	4.86	280.0	145.90	273.10					P-03	
2.55E-04	37980	16518	5.05	-8.38		251.4	111.30	111.30					P-03	

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-mea (1D) (m^3/s)	TB-meas (1D) (m^3/s)	SB (1D) (m)	SB* (1D) (m)	L_f (1D) (m)	T_T (2D) (m^2/s)	Value type (-1, 0 or 1)
HFM11	12.00	182.35	2003-10-02 08:28	5.98E-05	0		7.66E-05	170.35								4.31E-05	0
HFM12	14.90	209.50	2003-09-26 06:58	1.20E-05	0		1.57E-05	194.6								1.43E-05	0

cont.

Q/s-measl-L (m^2/s)	Q/s-measl-U (m^2/s)	S (2D) (-)	S* (2D) (-)	K´/b´ (2D) (1/s)	K_S (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	L_p (m)	C (m**3/Pa)	C_D (-)	ζ (2D) (-)	ώ (-)	λ (-)	t_1 (s)	t_2 (s)	Comments (-)
2.0E-06	2.0E-03		5.00E-05								2.40E-06		-4.69			3000	36000	
2.0E-06	2.0E-03		5.00E-05										-0.71			6000	36000	

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 – 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
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 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.
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 function for T=f (Q/s). The function used should be referred in "Comments"
T_M	m2/s	Transmissivity based on Moye (1967)
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
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 application, 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

Result Table for Flow logging at Drill Site 2 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:ss	Date and time of flowl., stop YYYYMMDD hh:mm:ss
HFM11	33.50	175.00	6	1	2003-10-02 09:04:31	2003-10-03 08:48:35	2003-10-02 13:51:30	2003-10-02 18:20:01
HFM12	30.50	206.50	6	1	2003-09-26 06:58:02	2003-09-26 17:38:24	2003-09-26 13:03:06	2003-09-26 17:38:24

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	8.00E-04	36000	19740	4.86	-7.78	13.47	P-03	
5.0E-05	1.7E-03	1.70E-04	37980	16518	5.05	-8.38	14.26	P-03	

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)	T Entire hole (m^2/s)	T_{FT} (m^2/s)
HFM11	33.50	175.00									8.15E-04	8.15E-04	4.31E-05	5.04E-05
HFM12	30.50	206.50									9.35E-05	9.35E-05	1.43E-05	7.85E-06

cont.

T_F-measl-L (m^2/s)	T_F-measl-U (m^2/s)	Reference (-)	Comments (-)
2.0E-06	2.0E-03	P-03	
2.0E-06	2.0E-03	P-03	

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)	$deltaQ_i/s_{FL}$ (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 (-)
HFM11	33.50	175.00	37.7	38.7				1.17E-04	8.66E-06	1	7.27E-06	9.20E-07	8.98E-05	P-03	
			40.73	43.7				2.43E-04	1.81E-05	3	1.52E-05	9.20E-07	8.98E-05	P-03	
			108.2	110.2				1.65E-04	1.23E-05	2	1.03E-05	9.20E-07	8.98E-05	P-03	
			135.7	136.7				4.67E-05	3.46E-06	1	2.91E-06	9.20E-07	8.98E-05	P-03	
			141.2	143.7				1.63E-04	1.21E-05	2.5	1.02E-05	9.20E-07	8.98E-05	P-03	
			146.2	147.3				7.33E-05	5.44E-06	1.1	4.57E-06	9.20E-07	8.98E-05	P-03	
HFM12	30.50	206.50	110.2	112.2				1.60E-05	1.12E-06	2	1.36E-06	1.40E-06	1.43E-04	P-03	
			123.2	123.8				7.73E-05	5.42E-06	0.6	6.51E-06	1.40E-06	1.43E-04	P-03	

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	m3/s	Estimated lower measurement limit for borehole flow rate in flow logging probe
Q-measl-U	m3/s	Estimated upper measurement limit for borehole flow rate in flow logging probe
Qp	m3/s	Flow rate at surface during flow logging
tp	s	Time for the flowing phase of the test
tFL	s	Duration of the flow logging survey
sFL	m	Average drawdown of the water level in open borehole during flow logging
h0	masl	Initial hydraulic head. Measured as water level in open borehole with reference level in the local coordinates system with z=0 m.
hp	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
$Q_T$corr	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 Ti. If estimated Ti equals T-measlim in the table actual Ti is considered to be equal or less than Ti-measlim
T_i-measlim-L	m**2/s	Estimated upper measurement limit for evaluated Ti. If estimated Ti equals Ti-measlim in the table actual Ti is considered to be equal or greater than Ti-measlim
Reference		SKB number for reports describing data and results
Comments		Short comment on evaluated parameters