P-04-72

Forsmark site investigation

Pumping tests and flow logging

Boreholes HFM17, HFM18 and HFM19

Jan-Erik Ludvigson, Josef Källgården, Calle Hjerne
Geosigma AB

May 2004

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

ISSN 1651-4416
SKB P-04-72

Forsmark site investigation

Pumping tests and flow logging

Boreholes HFM17, HFM18 and HFM19

Jan-Erik Ludvigson, Josef Källgården, Calle Hjerne
Geosigma AB

May 2004

Keywords: Forsmark, Hydrogeology, Hydraulic tests, Pumping tests, Flow meter logging, Water sampling, Hydraulic parameters, Transmissivity, Flow anomaly, AP PF 400-04-07, Field note no Forsmark 279.

Abstract

HFM17 is drilled between drilling site DS2 and DS6, HFM18 between drilling site DS2 and DS3. Borehole HFM19 is situated c 100 m from drilling site DS5. All drilling sites are situated at Forsmark.

The main objectives of the hydraulic tests in the percussion boreholes HFM17–19 were to investigate the hydraulic (e.g. occurrence of sub-horizontal zones) characteristics and the water chemistry of the boreholes.

Pumping tests were performed in all three boreholes together with flow logging. In order to confirm the results from flow logging, shorter hydraulic tests were performed in the upper part of the boreholes (i.e. above the highest position for flow logging). Thus, in borehole HFM17, a short pumping test above single packer was performed whereas in the boreholes HFM18 and HFM19, short injection tests were performed.

Water sampling was performed to investigate the hydrochemistry of the borehole water 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 total borehole transmissivity of HFM17 was estimated to c $4.3 \cdot 10^{-5}$ m^2/s. The flow logging indicated one single conductive section at c 30–32.5 m. The pumping test above the highest position for flow logging (8.0–21.0 m) indicated a transmissivity below c $3 \cdot 10^{-7}$ m^2/s.

The total transmissivity of borehole HFM18 was estimated to c $1.6 \cdot 10^{-4}$ m^2/s. Three conductive sections were found; at c 36.5–38 m with a transmissivity of c $7.8 \cdot 10^{-5}$ m^2/s, at c 46–46.5 m with a transmissivity of c $5.9 \cdot 10^{-5}$ m^2/s and at c 48–48.5 m with a transmissivity of c $2.5 \cdot 10^{-5}$ m^2/s. The injection test in the upper part of the borehole (9.0–24.0 m) resulted in an increasing flow rate during the flow period and a remarkably high T-value which was judged as not representative. The injection test may have influenced a fractured section in the upper part of the borehole.

The total transmissivity of borehole HFM19 was estimated to c $3.4 \cdot 10^{-4}$ m^2/s. One major inflow was found at c 170–182.5 m with a transmissivity of $2.8 \cdot 10^{-4}$ m^2/s. Two less conductive inflows were also found; at c 100–102 m with a transmissivity of c $4.0 \cdot 10^{-5}$ m^2/s and at c 148–150 m with a transmissivity of c $1.6 \cdot 10^{-5}$ m^2/s. Furthermore, an even less conductive inflow was detected at c 160–163 m with a transmissivity of c $6.2 \cdot 10^{-6}$ m^2/s. The injection test in the upper part of the borehole (12.0–21.0 m) again resulted in an increasing flow rate during the flow period but it was assumed that the estimated T-value from this test was not representative. The injection test may have influenced a fractured section in the upper part of the borehole.

Sammanfattning

HFM17 har borrats mellan borrplats 2 och 6 i Forsmark, HFM18 mellan borrplats 2 och 3. Borrhål HFM19 har borrats ca 100 m från borrplats 5 i Forsmark.

Huvudsakliga syftet med denna mätinsats i hammarborrhålen HFM17–19 var att undersöka hydrauliska egenskaperna (t.ex. förekomsten av sub-horisontella zoner) och vattenkemin hos borrhålen.

I nämnda borrhål genomfördes pumptester i kombination med flödesloggning. För att bekräfta resultaten från flödesloggningarna genomfördes hydrauliska tester i den övre delen av borrhålen (ovanför högsta position för sonden vid flödesloggning). I borrhålet HFM17 genomfördes ett pumptest ovan en enkelmanschett och de övriga borrhålen (HFM18 och HFM19) genomfördes injektionstester.

Vattenprover för undersökning av borrhålsvattnets hydrokemi togs i samband med pumptesterna i borrhålen. Före denna mätinsats hade inga andra hydrauliska tester genomförts i dessa borrhål.

Total transmissivitet för borrhålet HFM17 uppskattades till ca $4{,}3 \cdot 10^{-5}$ m^2/s. Flödesloggningen indikerade ett konduktivt avsnitt vid ca 30–32,5 m. Pumptestet ovan högsta position för flödesloggning (8,0–21,0 m) resulterade i en transmissivitet lägre än ca $3 \cdot 10^{-7}$ m^2/s.

Total transmissivitet för borrhålet HFM18 uppskattades till ca $1{,}6 \cdot 10^{-4}$ m^2/s. Tre separata konduktiva avsnitt med inflöden kunde identifieras; vid ca 36,5–38 m med en transmissivitet av ca $7{,}8 \cdot 10^{-5}$ m^2/s, vid ca 46–46,5 m med en transmissivitet av ca $5{,}9 \cdot 10^{-5}$ m^2/s och vid ca 48–48,5 m med en transmissivitet av ca $2{,}5 \cdot 10^{-5}$ m^2/s. Injektionstestet med konstant tryck i borrhålets övre del (9,0–24,0 m) resulterade i ett ökande flöde under flödesfasen och ett anmärkningsvärt högt T-värde som bedömdes icke-representativt. Injektionstestet kan ha påverkat ett sprickigt avsnitt i den övre delen av borrhålet.

Total transmissivitet för borrhålet HFM19 uppskattades till ca $3{,}4 \cdot 10^{-4}$ m^2/s. En högkonduktiv sektion identifierades vid ca 170–182,5 m med en transmissivitet av ca $2{,}8 \cdot 10^{-4}$ m^2/s. Två mindre konduktiva partier identifierades vid ca 100–102 m med en transmissivitet av ca $4{,}0 \cdot 10^{-5}$ m^2/s och vid ca 148–150 m med en transmissivitet av ca $1{,}6 \cdot 10^{-5}$ m^2/s. Ännu ett något mindre konduktivt inflöde kunde detekteras vid ca 160–163 m, transmissiviteten för detta inflöde uppskattades till ca $6{,}2 \cdot 10^{-6}$ m^2/s. Injektionstestet med konstant tryck i borrhålets övre del (12.0–21.0 m) resulterade i ett ökande flöde under flödesfasen och därav bedömdes det från injektionstestet uppskattade T-värdet som icke-representativt. Injektionstestet kan ha påverkat ett sprickigt avsnitt i den övre delen av borrhålet.

Contents

1 Introduction

Pumping tests and flow logging were performed in HFM17, HFM18 and HFM19. Water sampling was undertaken in all boreholes in conjunction with the tests. Additional hydraulic tests were performed in the boreholes above the highest position for flow logging. In HFM17, a pumping test was performed above a single packer. In the upper part of HFM18 and HFM19 (above the highest position for flow logging), injection tests were performed – one in each borehole. No other borehole hydraulic tests had been carried out in the actual boreholes before this campaign.

Borehole HFM17 is situated between drilling site DS2 and DS6, and HFM18 c 1 km southeast from drilling site DS2 (see Figure 1-1). Borehole HFM19 is situated c 100 m from drilling site DS5 (see Figure 1-1).

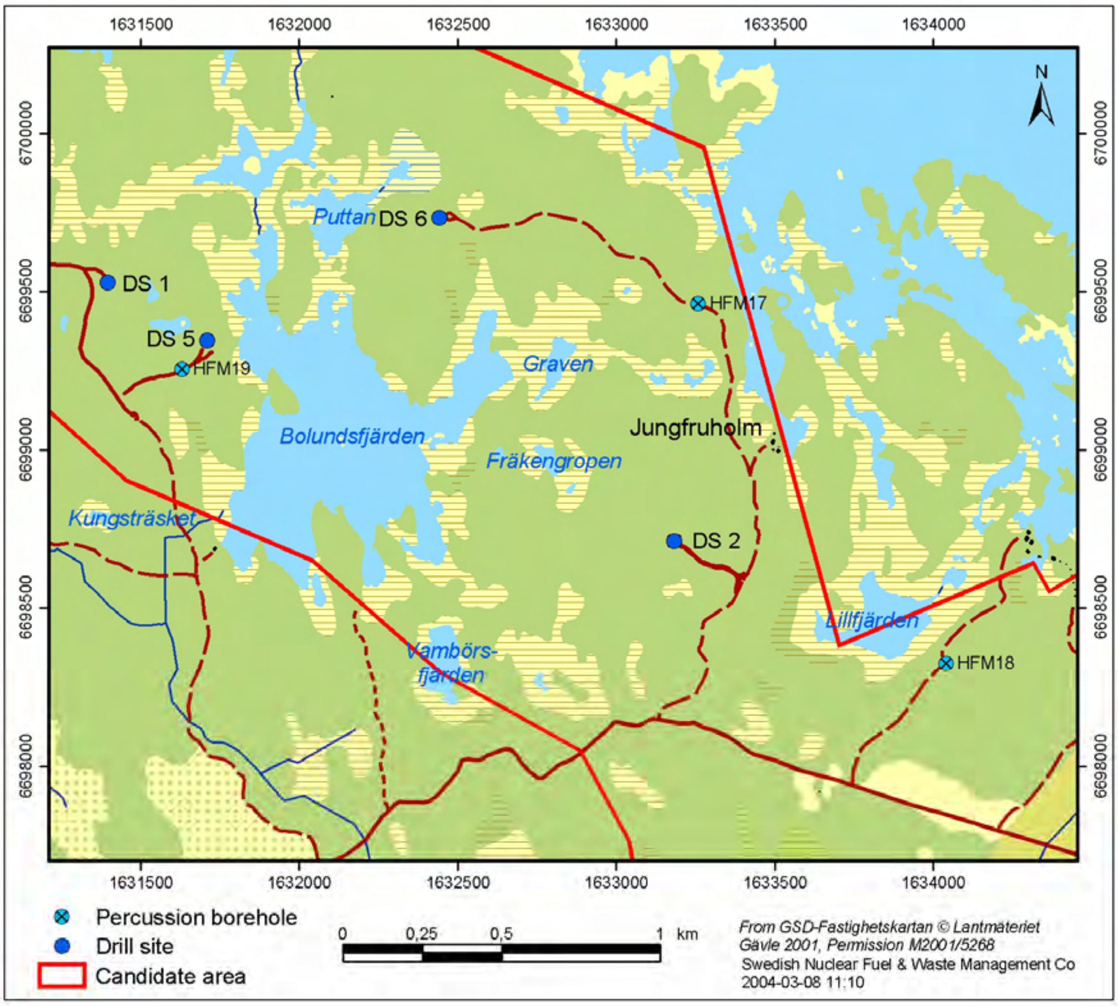


Figure 1-1. *Map showing the location of boreholes HFM17, HFM18 and HFM19.*

This document reports the results gained by the Hydraulic testing of boreholes HFM17, HFM18 and HFM19. 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 279.

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

Activity Plan	Number	Version
Hydrotester och vattenprovtagning i hammarborrhålen HFM17, HFM18 och HFM19	AP PF 400-04-07	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
Instruktion för analys av injektions- och enhålspumptester	SKB MD 320.004	1.0
Mätsystembeskrivning för HydroTestutrustning för Hammarborrhål. HTHB	SKB MD 326.001	3.0

2 Objectives

The main objectives of the pumping test in HFM17, HFM18 and HFM19 were to test the hydraulic properties of the rock in the boreholes (e.g. occurrence of sub-horizontal zones) and furthermore, to investigate the hydrochemistry of the borehole water. The position and size of the main inflows to the boreholes should be identified.

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-plane together with RHB70 in the z-direction. Northing and Easting refer to the top of the boreholes at top of casing. The borehole diameter in Table 3-1 refers to the final diameter of the boreholes 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.

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

Borehole								Casing		Drilling finished
ID	Elevation of top of casing (ToC) (m.a.s.l.)	Borehole length from ToC (m)	Bh-diam. (below casing) (m)	Inclin. -top of bh (from horizontal plane) (°)	Dip-Direction -top of bh (from local N) (°)	Northing (m)	Easting (m)	Lengt (m)	Inner diam. (m)	Date (YYYY-MM-DD)
HFM17	3.750	210.65	0.136	–84.18	318.57	6699462	1633261	8.0	0.1600	2003-12-08
HFM18	5.039	180.65	0.138	–59.35	313.29	6698327	1634037	9.0	0.1600	2003-12-16
HFM19	3.656	185.20	0.137	–58.10	280.91	6699258	1631627	12.0	0.1600	2003-12-18

3.2 Tests performed

Table 3-2. Borehole tests performed.

Bh ID	Test section (m)	Test type [1]	Test config.	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
HFM17	8.0–210.65	1B	Open hole	2004-01-27 04:02	2004-01-28 08:51
HFM17	21.0–205.0	6, L-Te, L-EC	Open hole	2004-01-27 14:00	2004-01-27 16:54
HFM17	8.0–21.0	1B	Above packer	2004-01-28 11:58	2004-01-28 14:20
HFM18	9.0–180.65	1B	Open hole	2004-02-10 09:12	2004-02-11 09:00
HFM18	24.0–175.0	6, L-Te, L-EC	Open hole	2004-02-10 13:30	2004-02-10 16:51
HFM18	9.0–24.0	3	Between packers	2004-02-11 13:12	2004-02-11 14:38
HFM19	12.0–185.2	1B	Open hole	2004-02-02 22:17	2004-02-04 08:12
HFM19	16.5–171.5	6, L-Te, L-EC	Open hole	2004-02-03 12:50	2004-02-03 16:51
HFM19	12.0–16.5	3	Between packers	2004-02-04 11:03	2004-02-04 12:36

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

During the open-hole pumping tests, water samples were collected and submitted for analysis, see Section 6.2. When possible, manual observations of the groundwater level in the pumped boreholes were also made during the tests.

3.3 Equipment check

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

To check the function of the pressure 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 displayed 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 premeasured 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) and described in the user manual of the measurement system.

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 employed. At the top of the borehole the total flow/injection rate is manually adjusted by a control valve and monitored by an electromagnetic flow meter. A data logger samples data at a frequency determined by the operator.

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

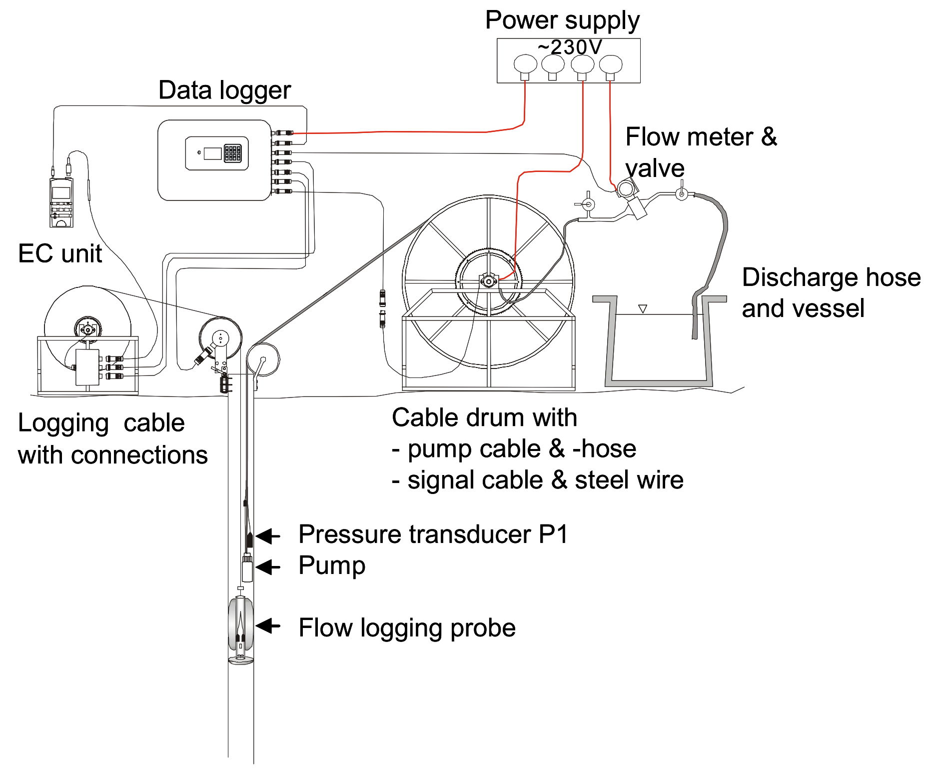


Figure 4-1. Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB. (From SKB MD 326.001, SKB internal document)

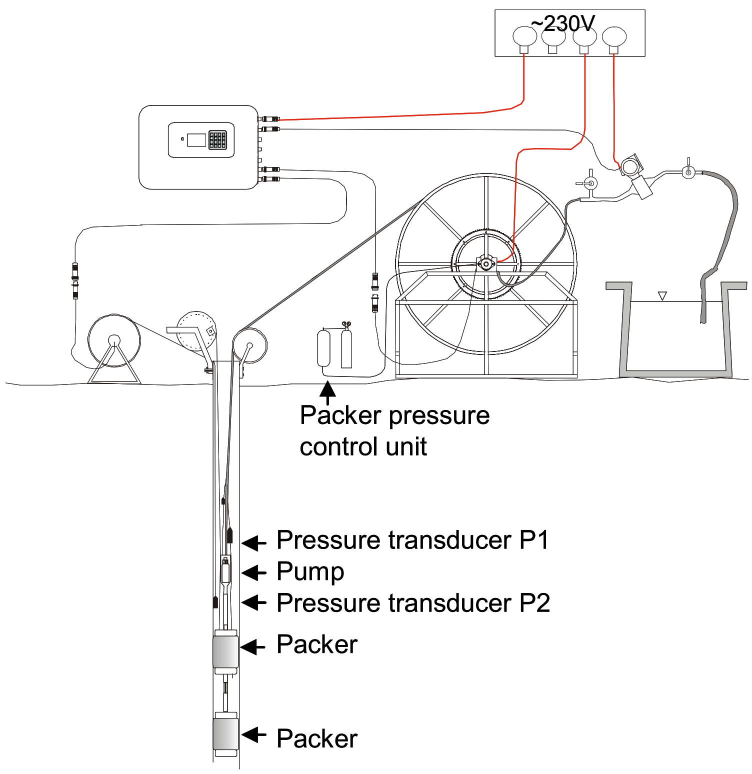


Figure 4-2. Schematic test set-up for a pumping test in an isolated borehole section with HTHB. (From SKB MD 326.001, SKB internal document)

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.

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 and 100 s sampling time
	Accuracy***	% o.r.**		± 20	
Flow (surface)	Output signal	mA	4–20		Passive
	Meas. range	L/min	1–150	5–c 80****	Pumping tests
	Resolution	L/min	0.1	0.1	
	Accuracy	% o.r.**	± 0.5	± 0.5	

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

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

The flow logging probe is calibrated for different borehole diameters (in reality different pipe diameters), i.e. 111.3, 135.5, 140 and 160 mm. During calibration the probe is installed in a vertically orientated pipe 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, cf Figure 4-3.

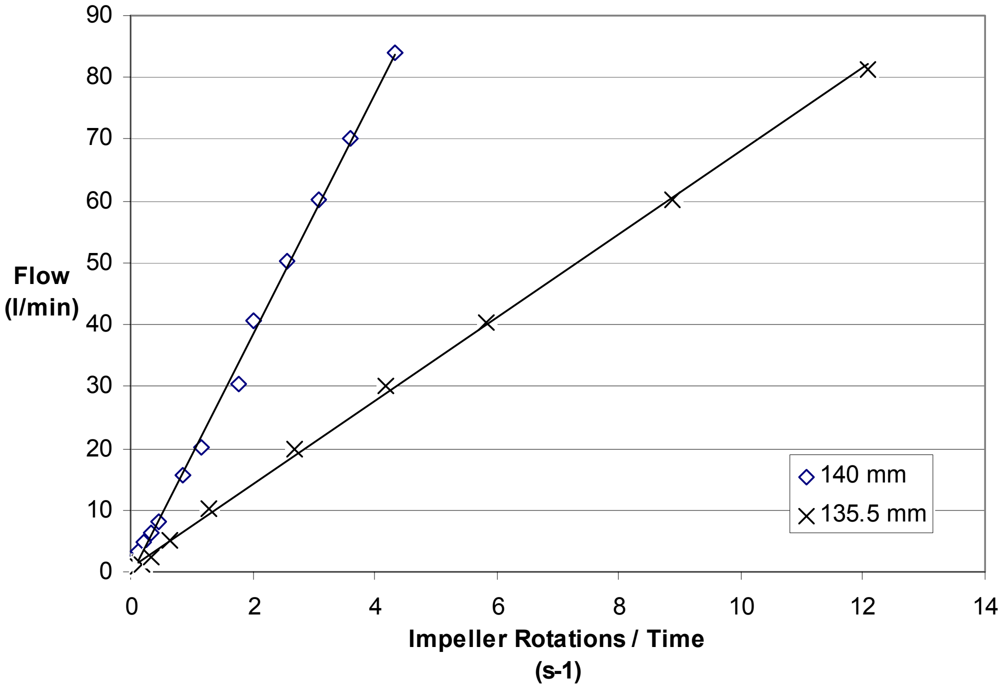


Figure 4-3. *Total flow as a function of impeller rotations for two borehole diameters (140 and 135.5 mm).*

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

Table 4-2 presents the position of sensors for each test. The following type of sensors is used: pressure (p), temperature (Te), electric conductivity (EC) together with the (lower) level of the submersible pump (Pump). Positions are given in 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 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 3-1) 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 6.

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

Borehole information				Sensors		Equipment affecting wellbore storage (WBS)			
ID	Test interval (m)	Test config	Test type[1]	Type	Positio (m b ToC)	Function	Position[2] relative test section	Outer diameter (mm)	C (m^3/Pa) for test [3]
HFM17	8.0–210.65	Open hole	1B	Pump-intake	17	Pump	In section		
			1B	P (P1)	13.72	Pump hose	In section	37	$2.0 \cdot 10^{-6}$
			6	EC-sec	21–205	Signal cable	In section	8	
			6	Te-sec	21–205	Signal cable	In section	13.5	
HFM17	31.9–71	Above a single packer	1B	Pump-intake	17	Pump	In section		
				P (P1)	13.72	Pump hose	In section	37	$2.0 \cdot 10^{-6}$
				P (P2)	20.38	Signal cable	In section	8	
						Signal cable	In section	8	
						Tecalan hose	In section	6	
						Steel wire	In section	6	
HFM18	9.0–180.65	Open hole	1B	Pump-intake	20	Pump	In section		
			1B	P (P1)	16.72	Pump hose	In section	37	$2.0 \cdot 10^{-6}$
			1B	P (P2)	16.31	Signal cable	In section	8	
			6	EC-sec	24–175	Signal cable	In section	13.5	
			6	Te-sec	24–175	Signal cable	In section		
HFM18	9.0–24.0	Between packers	3	P (P2)	7.25	Tecalan hose	In section	6	
						Aluminum bar	In section	20	$1.0 \cdot 10^{-10}$
						Steel wire	In section	6	
HFM19	12.0–185.2	Open hole	1B	Pump-intake	12.5	Pump	In section		
			1B	P (P1)	9.22	Pump hose	In section	37	$2.0 \cdot 10^{-6}$
			6	EC-sec	24–175	Signal cable	In section	8	
			6	Te-sec	24–175	Signal cable	In section	13.5	
HFM19	12.0–16.5	Between packers	3	P (P2)	9.30	Tecalan hose	In section	6	
						Aluminum bar	In section	20	$3.0 \cdot 10^{-11}$
						Steel wire	In section	36	

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

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

3) Based on the casing diameter or the nominal borehole diameter (140 mm) for open-hole tests together with the compressibility of water for the test in isolated sections, respectively (net values)

5 Execution

5.1 Preparations

All sensors included in HTHB are calibrated at the Geosigma engineering service station in Uppsala. Calibration is generally performed on a yearly basis, but more often if needed. Last calibration of spinner and flow meter was performed in March 2003, sensor for electrical conductivity in May 2003, wheel for length measurements in June 2003 and pressure sensors together with temperature sensor was last calibrated in November 2003. If a sensor is replaced at the test site, calibration of the new sensor can be carried out in the field (not the flow probe) or alternatively, in the laboratory after the measurements.

Functioning checks of the equipment used in the present test campaign were performed before each hydraulic test (cf Section 3.3). No errors were detected during these checks.

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

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

Before the tests, cleaning of equipment together with time synchronisation of clocks and data loggers was performed according to the Activity Plan.

5.2 Procedure

5.2.1 Overview

The open-hole pumping test in HFM17 was performed as a constant drawdown pumping test. The pumping tests in HFM18 and HFM19 were carried out as single-hole, constant flow rate test followed by pressure recovery periods. In all tests, the intention was to achieve approximately steady-state conditions in the borehole during the flow logging.

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

In HFM17, a single hole pumping test above a single packer was performed above the highest position for flow logging. In HFM18 and HFM19, an injection test was performed in each borehole above the highest position for flow logging.

5.2.2 Details

Single-hole pumping tests

Short flow capacity tests were carried out to select an appropriate flow rate or an appropriate drawdown for the tests. 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 HFM17, a short pumping tests (c 1h) was also carried out above a single-packer, cf Table 3-2. The latter tests constitute an option in the Activity Plan (AP PF 400-04-07, SKB internal controlling document) to roughly check the hydraulic properties in this section (Option 2–ID10 in the Activity Plan). In HFM18 and HFM19, a short injection test was carried out between packers (the upper packer in casing), cf Table 3-2. These injection tests were also options in the Activity plan (Option 1–ID9 in Activity Plan) to roughly check the hydraulic properties in these sections above highest position for flow logging.

In general, the sampling frequency of pressure during the pumping and injection tests was according to Table 5-1.The hydraulic tests in the boreholes were performed in the following order of time: HFM17, HFM19 and HFM18.

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

Time interval (s) from start/stop of pumping	Sampling interval (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 (c 15 s) at every 10 m to let the temperature and electrical conductivity stabilise.

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, cf Section 6.4.

The test program performed in the boreholes was mainly according to the Activity Plan with a few exceptions (decided by geohydrologist responsible for test performance in field):

- flow logging in HFM19 was not performed from the bottom of the borehole but from 171.5 m and upward since it was not possible to lower the probe further, and
- to reduce total measuring time, some measurements of borehole flow rate in HFM19 was shortened from 100 s to 50 s (prior to this decision, repeated checks were made to assure that no significant difference in results was obtained between a 50 s and a 100 s measurement).

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 presented 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, SKB internal document) by the code SKB-plot together with the software AQTESOLV.

5.4 Analyses and interpretation

5.4.1 Single-hole pumping tests

Firstly, a qualitative evaluation of actual flow regimes (wellbore storage, pseudo-linear, pseudo-radial and pseudo-spherical flow, respectively) and possible outer boundary conditions during the tests was performed. The qualitative evaluation was made from analyses of log-log diagrams of drawdown (or drawdown/flow rate for constant drawdown test) and/or recovery data together with the corresponding pressure (or drawdown/flow rate) derivatives versus time. In particular, pseudo-radial flow is reflected by a constant (horizontal) derivative in the diagrams. Pseudo-linear and pseudo-spherical flow is reflected by a slope of the derivative of 0.5 and –0.5, respectively in a log-log diagram. No-flow- and constant head boundaries are reflected by a rapid increase and decrease of the derivative, respectively.

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 and constant drawdown tests with radial flow in a porous medium were generally used by the evaluation of the tests. For tests indicating a fractured- or borehole storage dominated response, corresponding type curve solutions were used by the routine analyses.

If possible, transient analysis was made on both the drawdown- and recovery phase of the tests. The recovery data were plotted versus equivalent time. Transient analysis of drawdown- and recovery data was generally made in both log-log and lin-log diagrams as described in the above Instruction and in /2/ and /3/. In addition, a preliminary steady-state analysis (e.g. Moye's formula) was made for all tests for comparison.

The transient analysis was performed using a special version of the aquifer test analysis software AQTESOLV which enables both visual and automatic type curve matching with different analytical solutions for a variety of aquifer types and flow conditions. The evaluation is performed as an iterative process of type curve matching and non-linear regression on the test data. For the flow period as well as the recovery period of the constant flow rate tests, a model presented by Dougherty-Babu (1984) /4/ for constant flow rate tests with radial flow, accounting for wellbore storage and skin effects, was generally used for estimating transmissivity, storativity and skin factor for actual values on the borehole- and casing radius. For the flow period of the constant drawdown test, a model presented by Hurst Clark and Brauer (1969) /5/ for constant drawdown tests with radial flow, accounting for skin effects, was used for estimating transmissivity, storativity and skin factor. The recovery period of the constant drawdown test the model presented by Dougherty-Babu (1984) /4/ was used for estimating transmissivity, storativity and skin factor for actual values on the borehole- and casing radius. The software also includes models for discrete fractures intersecting the borehole causing pseudo-linear flow.

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

Rather than assuming a fixed value of the storativity of $1\cdot10^{-6}$ by the analysis according to the instruction SKB MD 320.004 (SKB internal document), higher values were occasionally assumed, e.g. $5\cdot10^{-5}$. This is considered as justified in this case since all tests were performed in the upper part of the bedrock in which part higher storativity sometimes may be relevant. The nomenclature used for the simulations with the AQTESOLV code is presented in the beginning of Appendix 2.

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

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

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

For an isolated pumped section (and the section below a single packer) the corresponding wellbore storage coefficient may be calculated as:

$$C = \pi \, r_w^2 \cdot L_w \cdot c_w \qquad (5\text{-}2)$$

r_{we} = borehole radius where the changes of the groundwater level occur (either r_w or r_c) or alternative, the simulated effective casing radius
r_w = nominal borehole radius (m)
r_c = inner radius of the borehole casing (m)
ρ = density of water (kg/m^3)
g = acceleration of gravity (m/s^2)
L_w = section length (m)
c_w = compressibility of water (Pa^{-1})

5.4.2 Flow logging

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

Flow logging can only be carried out in the borehole from the bottom of the hole up to a certain distance below the submersible pump. 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.

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

$$T_{FT} = \Sigma T_i = T \cdot Q_T / Q_p \qquad (5\text{-}3)$$

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 Equation (5-4).

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:

$$T_i = T \cdot dQ_i / Q_p \qquad (5\text{-}4)$$

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 borehole length (L) as determined from the flow logging may be calculated according to the methodology description for flow logging:

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

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

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

$$T_{min} = T \cdot Q_{min} / Q_p \qquad (5\text{-}6)$$

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

Similarly the lower measurement limit of transmissivity of a flow anomaly can be estimated from Equation (5-4) using $dQ_{i\ min}$ = 1 L/min ($1.7 \cdot 10^{-5}$ m^3/s) which is considered as the minimal change in borehole flow rate to identify a flow anomaly. The upper measurement limit of transmissivity of a flow anomaly corresponds to the actual transmissivity of the borehole.

5.5 Nonconformities

The test program performed in the boreholes was mainly according to the Activity Plan with one single exception (decided by geohydrologist responsible for test performance in field):

- the flow period of the short pumping test in HFM17 above a single packer was shortened to c 1 h since the flow rate was below the measurement limit for injection tests according to the methodology description (SKB MD 323.001, SKB internal document) and furthermore not detectable with the HTHB equipment.

Compared to the Methodology Description for single-hole pumping tests (SKB MD 321.003, SKB internal document), one deviation was 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 c10 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.

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 (Instruktion för analys av injektions- och enhålspumptester, SKB internal document) and the methodology description for impeller flow logging, SKB MD 322.009, Version 1.0 (Metodbeskrivning för flödesloggning, SKB internal document), cf Section 3.2. Additional symbols used are explained in the text. The nomenclature for the analyses by the AQTESOLV code is presented in Appendix 2.

6.2 Water sampling

Water samples were taken during the pumping tests in the boreholes and submitted for analysis, see Table 6-1. The results of the water analyses are described in /1/.

Table 6-1. Data of water samples taken during the pumping tests in the boreholes HFM17, HFM18 and HFM19 and submitted for analysis.

Bh ID	Date and time of sample	Pumped section (m)	Pumped volume (m3)	Sample type	Sample ID no	Remarks
HFM17	2004-01-27 10:17	8.0–210.65	4.4	WC080	8257	Open-hole test
“	2004-01-27 14:17	“	12.4	WC080	8258	Open-hole test
“	2004-01-27 17:53	“	19.3	WC080	8246	Open-hole test
HFM18	2004-02-10 10:47	12.0–180.65	4.66	WC080	8324	Open-hole test
“	2004-02-10 14:35	“	16.5	WC080	8325	Open-hole test
“	2004-02-10 18:40	“	29.4	WC080	8250	Open-hole test
HFM19	2004-02-03 09:09	9.0–185.2	2.8	WC080	8259	Open-hole test
“	2004-02-03 13:17	“	16.4	WC080	8260	Open-hole test
“	2004-02-03 18:11	“	32.7	WC080	8247	Open-hole test

6.3 Single-hole pumping tests

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

Drilling records were checked to identify possible interference on the hydraulic test data from drilling or other activities in nearby boreholes during the test periods. These records did not show any drilling and/or pumping activities during the actual test periods.

6.3.1 Borehole HFM17: 8.0–210.65 m

General test data for the open-hole pumping test in HFM17 in conjunction with flow logging are presented in Table 6-2. No manual measurements of flow rate were performed except for the functional check before the test.

The barometric pressure and sea water level during the test period in HFM17 are presented in Figure 6-1 and the air temperature together with precipitation is displayed in Figure 6-2. The air pressure varies c 1 kPa and the sea level varies c 0.1 m during the test, i.e. c 1% of total drawdown during the test and thus the effect of barometric pressure variations and sea water level variations is negligible. No substantial precipitation took place during the test period.

Table 6-2. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFM17, in conjunction with flow logging.

General test data			
Bore hole	HFM17 (8.0–210.65 m)		
Test type[1]	Constant drawdown withdrawal and recovery test		
Test section (open borehole/packed-off section):	Open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson, GEOSIGMA AB		
Test equipment system	HTHB		
General comment	Single pumping borehole		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	210.65
Casing length	L_c	m	8.0
Test section – secup	Secup	m	8.0
Test section – seclow	Seclow	m	210.65
Test section length	L_w	m	202.65
Test section diameter	$2·r_w$	mm	top 138 bottom 136 [2]
Test start (start of pressure registration)		yymmdd hh:mm	040127 04:02
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	040127 08:31:52
Stop of flow period		yymmdd hh:mm:ss	040127 18:32:59
Test stop (stop of pressure registration)		yymmdd hh:mm	040128 08:51
Total flow time	t_p	min	601.12
Total recovery time	t_F	min	858.68

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW Level (masl)** [3]
Absolute pressure in test section before start of flow period	p_i	kPa	203.47	0.85
Absolute pressure in test section at stop of flow period	p_p	kPa	115.06	–8.15
Absolute pressure in test section at stop of recovery period	p_F	kPa	202.75	0.64
Maximal pressure change in test section during the flow period	dp_p	kPa	88.41	

Manual groundwater level measurements			**GW level**	
Date YYYY-MM-DD	**Time tt:mm.ss**	**Time (min)**	**(m bToC)**	**(m a s l)**
2004-01-26	10:45:00	–1306.9	2.89	0.86
2004-01-26	16:24:00	–967.9	2.79	0.96
2004-01-26	16:52:00	–939.9	2.79	0.96
2004-01-27	08:27:00	–4.9	2.90	0.85
2004-01-27	09:45:00	73.1	11.93	–8.18
2004-01-27	11:33:00	181.1	11.91	–8.16
2004-01-27	13:54:00	322.1	11.86	–8.11
2004-01-27	18:25:40	593.8	11.90	–8.15
2004-01-28	08:49:00	1457.1	3.11	0.64

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$5.20·10^{-4}$
Mean (arithmetic) flow rate during flow period [4]	Q_m	m^3/s	$5.67·10^{-4}$
Total volume discharged during flow period [4]	V_p	m^3	20.46

1) Constant Head injection and recovery or Constant Rate withdrawal and recovery or Constant drawdown withdrawal and recovery
2) Claesson and Nilsson (2004) /7/
3) From the manual measurements of groundwater level.
4) Calculated from integration of the transient flow rate curve.

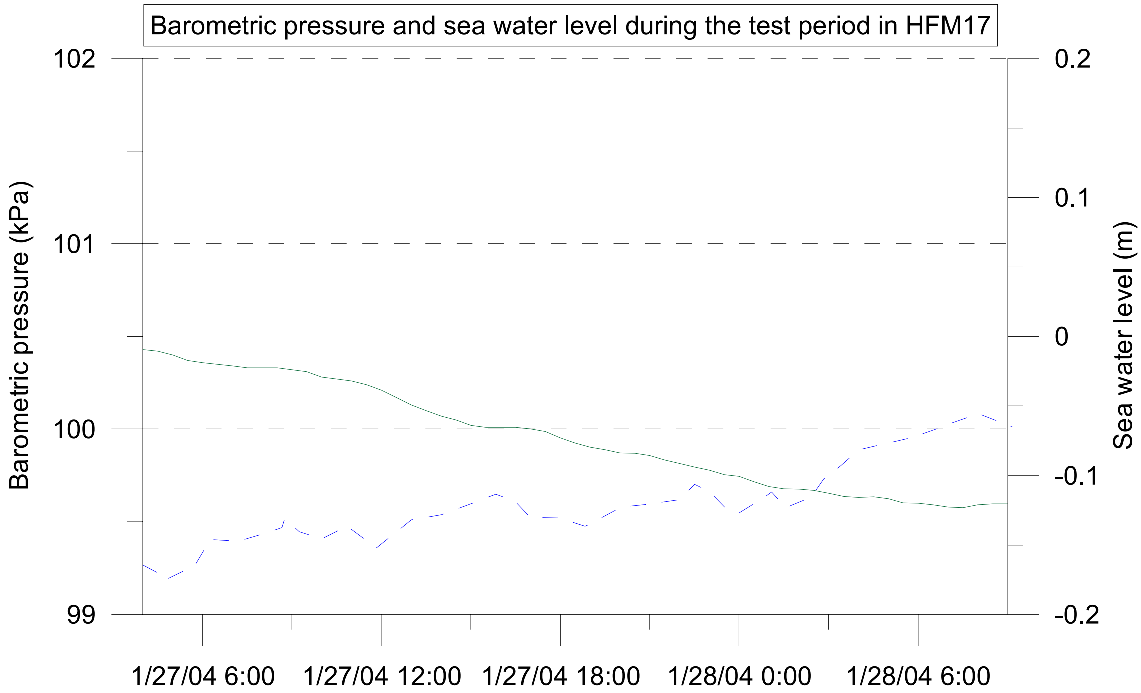


Figure 6-1. *Barometric pressure (green line) and sea water level (blue dotted line) at Forsmark during the period for pumping and flow logging in HFM17.*

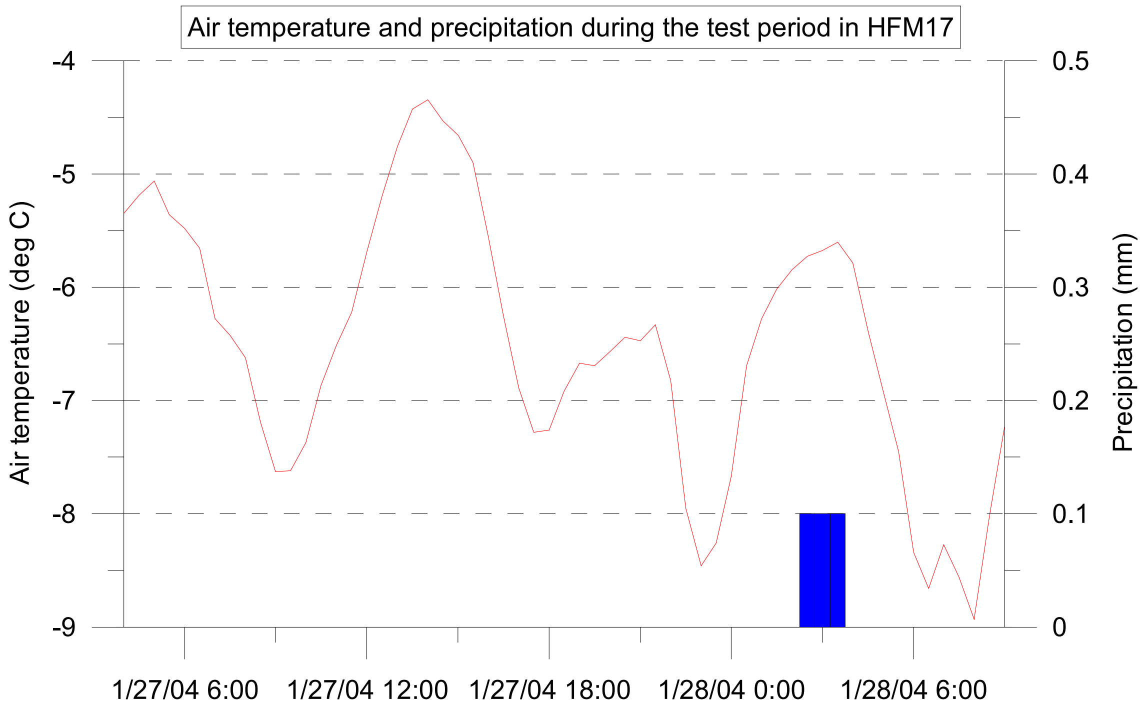


Figure 6-2. *Air temperature (red line) and precipitation (blue bars) at Forsmark during the period for pumping and flow logging in HFM17.*

Comments on test

The day before test start, a short capacity test was performed (c 20 min). By the end of the capacity test, the flow rate was c 55 L/min and the drawdown c 10 m. The actual pumping test was performed as a constant drawdown test (s = 9.0 m) with the intention to achieve (approximately) steady-state conditions during the flow logging. A comparison of the results from the capacity test and pumping test is presented in Table 6-3.

Table 6-3. Estimated specific capacity from the capacity test and pumping test in borehole HFM17: 8.0–210.65 m.

Test	Duration (min)	Flow rate, Q_p (L/min)	Drawdown, $s_w = p_i - p_p$ (m)	Specific capacity, Q_p/s_w (m^2/s)
Short capacity test	17	55.2	10.0	$9.2 \cdot 10^{-5}$
Pumping test	601	31.2	9.0	$5.8 \cdot 10^{-5}$

Table 6-3 indicates that the specific capacity from the pumping test is lower than the specific capacity from the short capacity test. This may be a result of the significantly shorter duration of the capacity test.

Interpreted flow regimes

Selected test diagrams according to the instruction for analysis of injection – and single-hole pumping tests are presented in Figures A2:1–5 in Appendix 2.

During the beginning of the flow period, a constant drawdown is regulated and hence the flow rate is scattered. A pseudo-radial flow regime is indicated from c 3 min to c 300 min, cf Figures A2:2–3. After c 300 min, a transition to a pseudo-spherical flow is indicated.

WBS effects dominate the initial phase of the recovery period. Approximate pseudo-radial flow is weakly indicated from c 30 min to c 200 min. By the end of the recovery period, a transition to pseudo-spherical flow occurs, cf Figures A2:4–5.

Interpreted parameters

The transient, quantitative interpretation of the flow- and recovery period of the test is presented in Figures A2:2–5 in Appendix 2. Quantitative analysis was applied both on the flow- and recovery period according to the methods described in Section 5.4.1. The results are exposed in the Test Summary Sheets and in Table 6-20, Table 6-21 and Table 6-22 in Section 6-5. The analysis from the recovery period was selected as the representative.

The borehole storage coefficient was estimated from the early test response with 1:1 slope in recovery log-log diagram resulting in $C = 1.6 \cdot 10^{-6}$ m^3/Pa. This result was supported by an estimate of borehole storage from Equation (5-1) and the simulated effective casing radius which resulted in exactly the same value for C.

6.3.2 Borehole HFM18: 9.0–180.65 m

General test data for the open-hole pumping test in HFM17 in conjunction with flow logging are presented in Table 6-4. No manual measurements of flow rate were performed except for a functional check before the test.

The barometric pressure and sea water level during the test period in HFM18 are presented in Figure 6-3 and the air temperature together with precipitation is displayed in Figure 6-4. The air pressure varies c 1.5 kPa and the drawdown by end of the pumping period was c 70 kPa. Thus, air pressure variations are c 2% of total drawdown during the test and thus the effect of barometric pressure variations is negligible. No substantial precipitation took place during the test period.

Table 6-4. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFM18 in conjunction with flow logging.

General test data				
Bore hole	HFM18 (9.0–180.65)			
Testtype[1]	Constant Rate withdrawal and recovery test			
Test section (open borehole/packed-off section):	Open borehole			
Test No	1			
Field crew	C. Hjerne, J. Olausson, GEOSIGMA AB			
Test equipment system	HTHB			
General comment	Single pumping borehole			
	Nomen-clature		**Nomen-clature**	
Borehole length	L	Borehole length	L	
Casing length	L_c	Casing length	L_c	
Test section – secup	Secup	Test section- secup	Secup	
Test section – seclow	Seclow	Test section- seclow	Seclow	
Test section length	L_w	Test section length	L_w	
Test section diameter	$2 \cdot r_w$	Test section diameter	$2 \cdot r_w$	
Test start (start of pressure registration)		Test start (start of pressure registration)		
Packer expanded		Packer expanded		
Start of flow period		Start of flow period		
Stop of flow period		Stop of flow period		
Test stop (stop of pressure registration)		Test stop (stop of pressure registration)		
Total flow time	t_p	Total flow time	t_p	
Total recovery time	t_F	Total recovery time	t_F	

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW Level (masl) [3]**
Absolute pressure in test section before start of flow period	p_i	kPa	195.98	1.00
Absolute pressure in test section at stop of flow period	p_p	kPa	128.26	–6.02
Absolute pressure in test section at stop of recovery period	p_F	kPa	196.78	0.93
Maximal pressure change in test section during the flow period	dp_p	kPa	67.73	

Manual groundwater level measurements

Date YYYY-MM-DD	**Time tt:mm.ss**	**Time (min)**	**GW level (m bToC)**	**(m a s l)**
2004-02-09	13:34:00	–1186.3	4.72	0.98
2004-02-09	16:20:00	–1020.3	4.73	0.97
2004-02-09	16:35:00	–1005.3	4.69	1.00
2004-02-09	17:06:10	–974.2	11.88	–5.18
2004-02-10	08:40:50	–39.5	4.73	0.97
2004-02-10	09:13:50	–6.5	4.70	1.00
2004-02-10	11:04:00	103.7	12.62	–5.82
2004-02-10	19:15:00	594.7	12.86	–6.02
2004-02-11	08:59:00	1418.7	4.78	0.93

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$8.72 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period [4]	Q_m	m^3/s	$8.74 \cdot 10^{-4}$
Total volume discharged during flow period [4]	V_p	m^3	31.5

1) Constant Head injection and recovery or Constant Rate withdrawal and recovery or Constant drawdown withdrawal and recovery
2) Claesson and Nilsson (2004) /7/
3) From the manual measurements of groundwater level.
4) Calculated from integration of the transient flow rate curve.

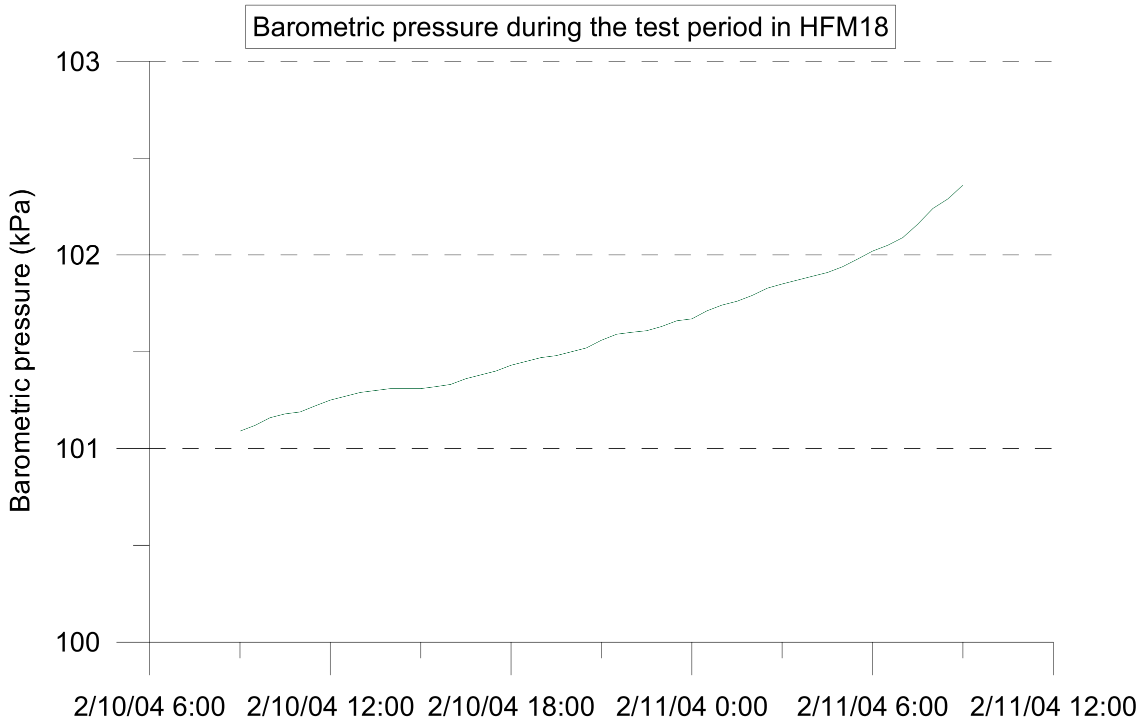


Figure 6-3. *Barometric pressure at Forsmark during the period for pumping and flow logging in HFM18.*

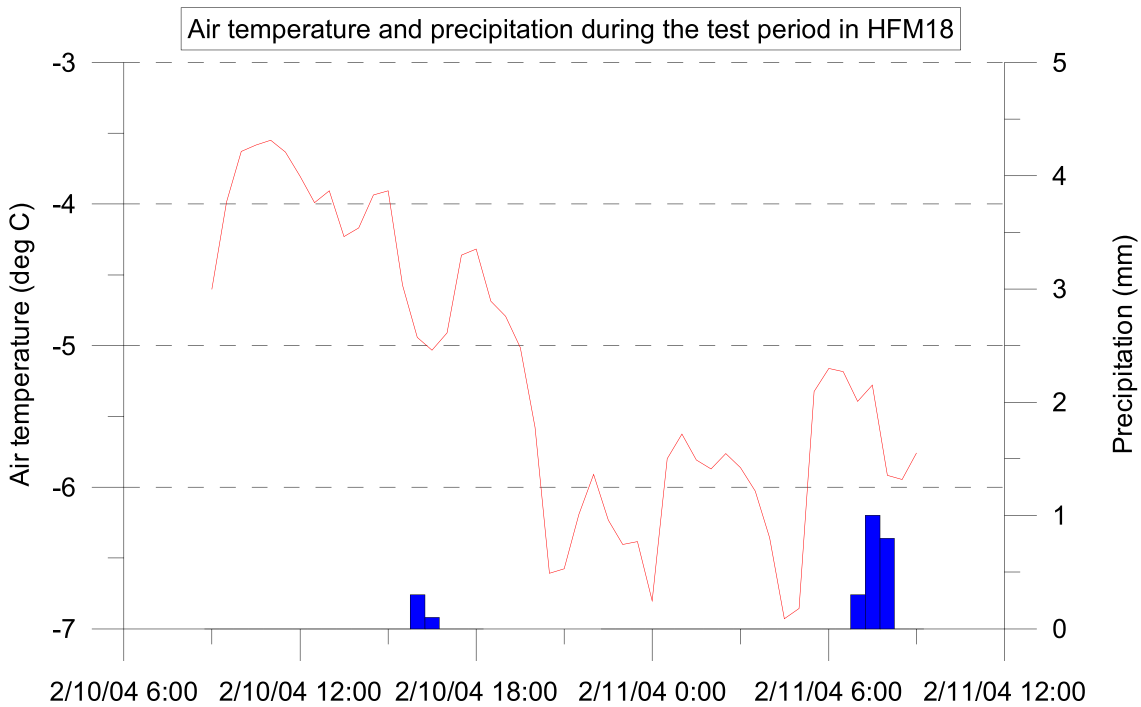


Figure 6-4. *Air temperature (red line) and precipitation (blue bars) at Forsmark during the period for pumping and flow logging in HFM18.*

Comments on test

The day before test start, a short capacity test was performed (c 20 min). By the end of the capacity test, the flow rate was c 53 L/min and the drawdown c 6 m. The actual pumping test was performed as a constant flow rate test (52.3 L/min) with the intention to achieve (approximately) steady-state conditions during the flow logging. A comparison of the results from the capacity test and pumping test is displayed in Table 6-5.

Table 6-5. Estimated specific capacity from the capacity test and pumping test in borehole HFM18: 9.0–180.65 m.

Test	Duration (min)	Flow rate, Q_p (L/min)	Drawdown, $s_w = p_i – p_p$ (m)	Specific capacity, Q_p/s_w (m^2/s)
Short capacity test	24	53.0	6.1	$1.4 \cdot 10^{-4}$
Pumping test	601	52.3	6.9	$1.3 \cdot 10^{-4}$

Table 6-5 indicates that the specific capacity from the short capacity test is in accordance with the specific capacity from the pumping test.

One of the pressure sensors (P1, Section 4) stopped working properly during pressure registration before start of pumping and was replaced by the other pressure sensor (P2, Section 4). The calibration constants were changed to those valid for P2 and the only effect on the measurements from this sensor change is that registration time for undisturbed pressure in the borehole before pumping start is shortened.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2:6–10 in Appendix 2.

The initial phase of the flow and recovery period is dominated by WBS effects, cf Figures A2:7 and A2:9. The WBS-dominated initial phase is followed by a transition stage to a pseudo-spherical flow, indicated both during the flow and the recovery period. For the flow period, the pseudo-spherical flow is followed by indications of a transition to pseudo-stationary flow, cf Figure A2:7. The end of the recovery is probably disturbed from external effects, possibly tidal effects, cf Figure A2:9. The increased recovery derivative corresponds to a pressure change of c 2 kPa.

Interpreted parameters

The results are presented in the Test summary sheets below and in Table 6-20, Table 6-21 and Table 6-22 in Section 6.5.

Transient evaluation was attempted on both the flow and the recovery period. No reliable fit of the type curve to the data set was obtained. The resulting skin factor was very high for both periods. These results indicate that no pseudo-radial flow regime is developed but rather a pseudo-spherical flow regime in accordance with the interpreted flow regimes presented above.

Accordingly, the judged best representative estimate of T is the steady-state evalutation of transmissivity according to Moye.

6.3.3 Borehole HFM19: 12.0–185.2 m

General test data for the open-hole pumping test in the borehole HFM19 in conjunction with flow logging are presented in Table 6-6. No manual measurements of the groundwater level was performed since the presence of the pump hose and signal cable made it impossible to lower the water leveller in the borehole. Neither manual measurements of flow rate were performed except for the functional check before the test.

The barometric pressure and sea water level during the test period in HFM19 are presented in Figure 6-5 and the air temperature together with precipitation is displayed in Figure 6-6.

Table 6-6. General test data, pressure and flow data for the open-hole pumping test in borehole HFM19 in conjunction with flow logging.

General test data				
Bore hole	HFM19 (12.0–185.2 m)			
Testtype[1]	Constant Rate withdrawal and recovery test			
Test section (open borehole/packed-off section):	Open borehole			
Test No	1			
Field crew	J. Källgården, J. Olausson, GEOSIGMA AB			
Test equipment system	HTHB			
General comment	Single pumping borehole			
	Nomen-clature	**Unit**	**Value**	
Borehole length	L	m	185.2	
Casing length	L_c	m	12.0	
Test section – secup	Secup	m	12.0	
Test section – seclow	Seclow	m	185.2	
Test section length	L_w	m	173.2	
Test section diameter	$2{\cdot}r_w$	mm	top 140 bottom 137 [2]	
Test start (start of pressure registration)		yymmdd hh:mm	040202 22:17	
Packer expanded		yymmdd hh:mm:ss	–	
Start of flow period		yymmdd hh:mm:ss	040203 08:17:49	
Stop of flow period		yymmdd hh:mm:ss	040203 18:21:55	
Test stop (stop of pressure registration)		yymmdd hh:mm	040204 08:12	
Total flow time	t_p	min	604	
Total recovery time	t_F	min	830	

Pressure data	**Nomen-clature**	**Unit**	**Value**	**GW Level (masl)** [3]
Absolute pressure in test section before start of flow period	p_i	kPa	147.97	0.85
Absolute pressure in test section at stop of flow period	p_p	kPa	131.88	–0.79
Absolute pressure in test section at stop of recovery period	p_F	kPa	143.67	0.41
Maximal pressure change in test section during the flow period	dp_p	kPa	16.09	

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$9.08{\cdot}10^{-4}$
Mean (arithmetic) flow rate during flow period [4]	Q_m	m^3/s	$9.08{\cdot}10^{-4}$
Total volume discharged during flow period [4]	V_p	m^3	32.9

1) Constant Head injection and recovery or Constant Rate withdrawal and recovery or Constant drawdown withdrawal and recovery
2) Claesson and Nilsson (2004) /7/
3) Calculated from pressure data.
4) Calculated from integration of the transient flow rate curve.

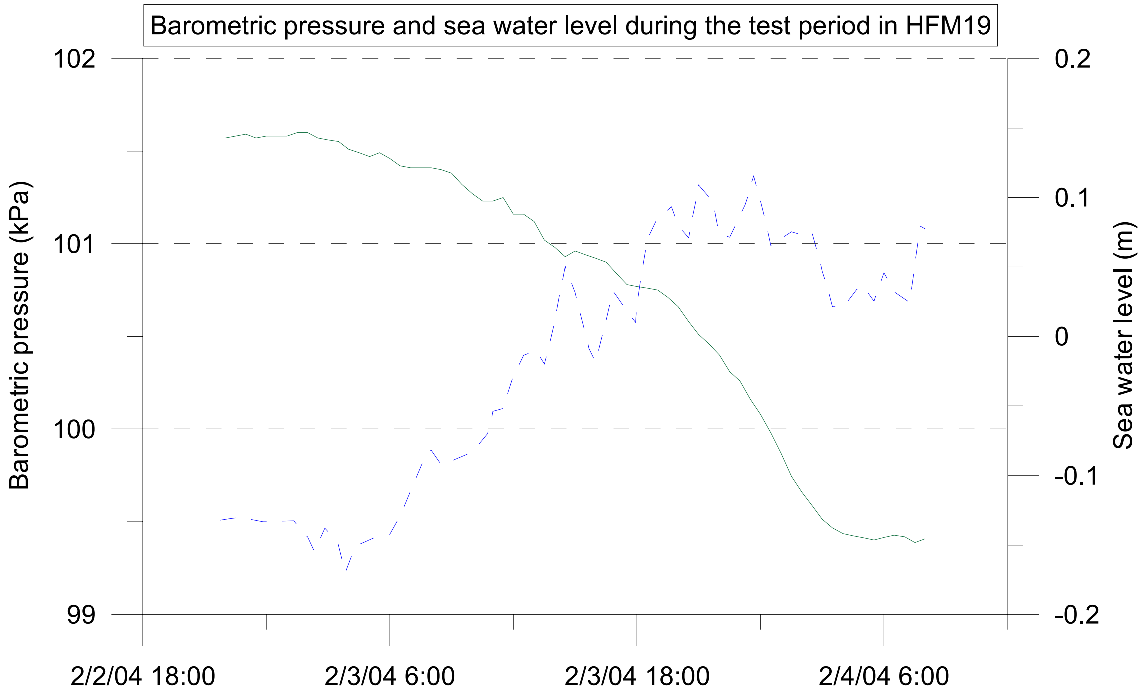


Figure 6-5. *Barometric pressure (green line) and sea water level (blue dotted line) at Forsmark during the period for pumping and flow logging in HFM19.*

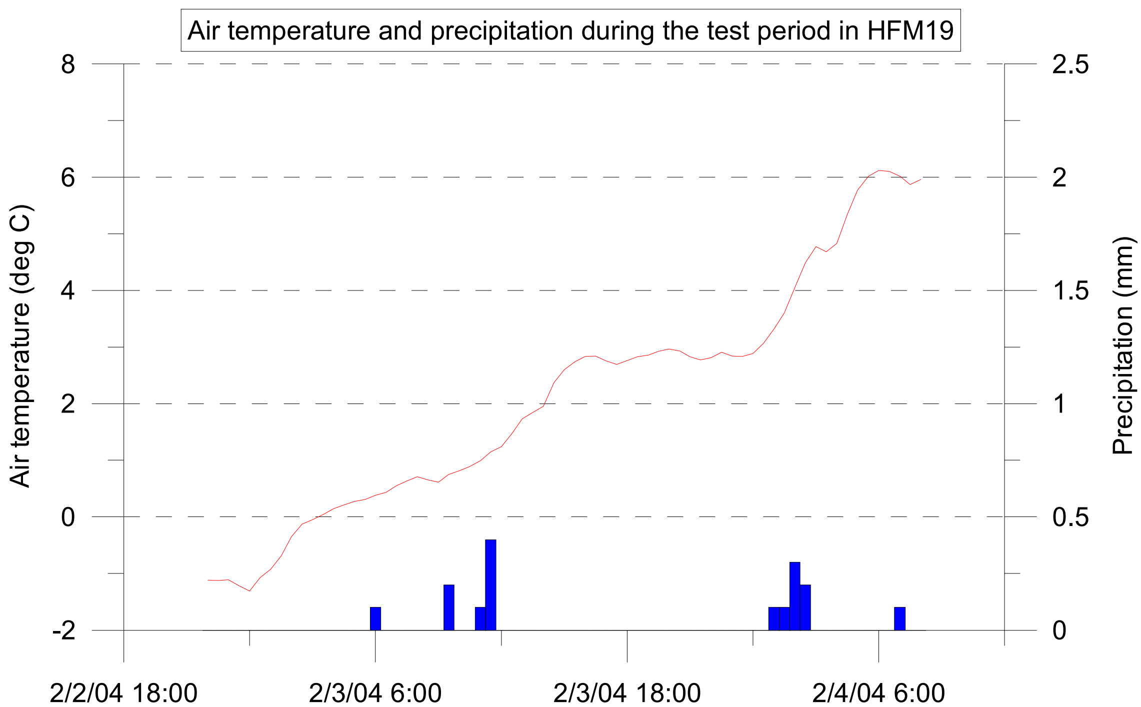


Figure 6-6. *Air temperature (red line) and precipitation (blue bars) at Forsmark during the period for pumping and flow logging in HFM19.*

Comments on test

The day before test start, a short capacity test was performed (c 30 min). The capacity test indicated relatively high transmissivity (flow rate c 60 L/min and a drawdown of c 1.4 m). The pumping test was performed as a constant flow rate (c 54.5 L/min) test with the intention to achieve (approximately) steady-state conditions during the flow logging. A comparison of the results from the capacity test and pumping test is presented in Table 6-7.

Table 6-7. Estimated specific capacity from the capacity test and pumping test in borehole HFM19: 12.0–185.2 m.

Test	Duration (min)	Flow rate, Q_p (L/min)	Drawdown, $s_w = p_i – p_p$ (m)	Specific capacity, Q_p/s_w (m^2/s)
Short capacity test	31	60.0	1.4	$7.1 \cdot 10^{-4}$
Pumping test	604	54.5	1.6	$5.5 \cdot 10^{-4}$

Table 6-7 indicates that the specific capacity from the short capacity test is in accordance with the specific capacity from the pumping test.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2:11–17 in Appendix 2. Both the flow and recovery period indicate pseudo-linear flow (i.e. fracture response) in the beginning of each period. No WBS effects are observed. During the flow period, a pseudo-radial flow regime is indicated from c 5 min. A disturbance occurs at c 30 min during the flow period.

During the recovery period, a pseudo-linear flow persists much longer (throughout the period) and no well-defined pseudo-radial flow regime is developed. The end of the recovery is probably disturbed from external effects, possibly tidal effects. The increased recovery derivative corresponds to a pressure change of c 1.5 kPa.

Interpreted parameters

The results are presented in the Test summary sheets below and in Table 6-20, Table 6-21 and Table 6-22 in Section 6.5.

Transient evaluation of transmissivity has been performed for both the flow and the recovery period. The transmissivity was estimated by a model assuming pseudo-radial flow /4/ on the flow period and a model assuming a horizontal fracture intersecting the borehole /6/ on the recovery period. The representative transmissivity (i.e. T_T) is considered from the transient evaluation of the flow period, assuming pseudo-radial flow. The storativity S, is assumed to be $5 \cdot 10^{-4}$. The transmissivity obtained when assuming horizontal fracture shows good agreement with the transmissivity estimated from the pseudo-radial flow model. The fictive length of the assumed horizontal fracture is c 100 m).

6.4 Flow logging

6.4.1 Borehole HFM17

General test data for the flow logging in borehole HFM17 are presented in Table 6-8.

Table 6-8. General test data, groundwater level and flow data for the flow logging in borehole HFM17.

General test data				
Borehole	HFM17			
Test type(s)[1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	C. Hjerne, J. Olausson (GEOSIGMA AB)			
Test equipment system	HTHB			
General comments	Single pumping borehole			
	Nomenclature	**Unit**	**Value**	
Borehole length		m	210.65	
Pump position (lower level)		m	17	
Flow logged section – Secup		m	21	
Flow logged section – Seclow		m	205	
Test section diameter	2·rw	mm	top 138 bottom 136 [2]	
Start of flow period		yymmdd hh:mm	040127 08:31	
Start of flow logging		yymmdd hh:mm	040127 14:00	
Stop of flow logging		yymmdd hh:mm	040127 16:55	
Stop of flow period		yymmdd hh:mm	040127 18:32	

Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)**
Groundwater level in borehole, at undisturbed conditions, open hole	h_i	m	2.90	0.85
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m	11.90	–8.15
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	8.97	

Flow data	**Nomen-clature**	**Unit**	**Flow rate**
Pumping rate at surface	Q_p	m3 /s	5.2·10–4
Corrected cumulative flow rate at Secup at pumping rate Q_p	Q_{Tcorr}	m3 /s	5.2·10–4
Measurement limit for borehole flow rate during flow logging	Q_{Measl}	m3 /s	5.0·10–5
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m3 /s	1.7·10–5

1) 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging
2) Claesson and Nilsson (2004) /7/

Comments on test

The flow logging was made from the bottom of the hole and upwards. The step length between flow logging measurements was maximally 5 m in the borehole interval 205–32 m. Above 32 m, the step length was maximally 2 m.

The measured electric conductivity is used as supporting information when interpreting flow anomalies and for this purpose the electrical conductivity is compensated for temperature (see Figure 6-7).

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 during the flow logging together with the electric conductivity (EC) and temperature (Te) of the borehole fluid is presented in Figure 6-7. The figure presents one data set of borehole flow rate with calibration constants for a 135.5 mm pipe (according to the drilling record, the borehole diameter in upper part is 138.2 mm) and another with corrected borehole flow rate. The correction is performed as a scaling of all borehole flow rate data to achieve $Q_{Tcorr} = Q_p$. The correction is performed under the assumption of no inflow above the highest position for flow logging. This assumption is supported by the result of the pumping test above a single packer, see below.

Figure 6-7 shows that the only detected inflow occurs over the interval 30–32.5 m. The inflow is supported by the EC-measurements.

The results of the flow logging in borehole HFM17 are presented in Table 6-9 below. The measured inflow at the identified flow anomaly (dQ_i) together with its estimated percentage of the total flow is presented.

The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Equation (5-3) and the transmissivity of individual flow anomalies (T_i) from Equation (5-4). Transmissivity for the entire borehole used in Equation (5-4) was taken from the transient evaluation of the recovery period for the pumping test performed in conjunction with the flow logging (cf Section 6.3.1). An estimation of the transmissivity of the interpreted flow anomaly was also made by the specific flow (dQ_i/s_{FL}). The transmissivity of the entire borehole was calculated from the transient interpretation of the pumping test during flow logging, cf Section 6.3.1.

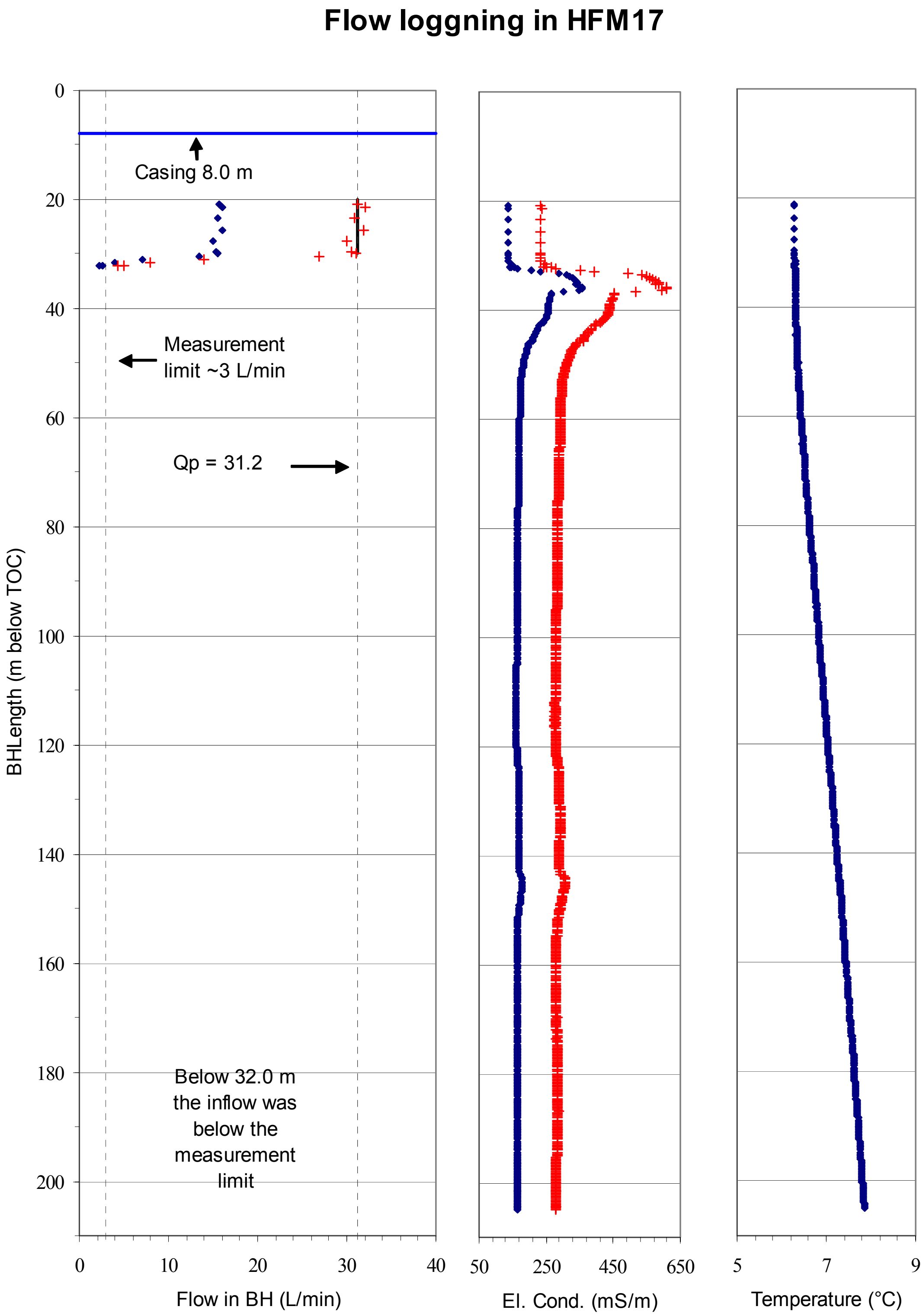


Figure 6-7. *Measured (blue) and corrected (red+) inflow distribution together with electrical conductivity (blue), temperature-compensated electric conductivity (red+) and temperature (Te) distribution of the borehole fluid along borehole HMF17 during flow logging.*

Table 6-9. Results of the flow logging in borehole HFM17. Q_{Tcorr}=cumulative flow at the top of the logged interval, corrected due to the deviation of the actual borehole diameter from the one used for calibration. Q_p=pumped flow rate from borehole, s_{FL}= drawdown during flow logging. T=transmissivity from the pumping test.

HFM17 **Flow anomalies**		**Q_{Tcorr} =5.20·10^{-4}** **(m^3/s)**	**T=3.93·10^{-5}** **(m^2/s)**	**s_{FL}=8.97 m**	**Q_p=5.20·10^{-4}** **(m^3/s)**	
Interval (m b ToC)	**B.h. length (m)**	**dQ_{icorr}*** **(m^3/s)**	**T_i** **(m^2/s)**	**dQ_{icorr}/s_{FL}** **(m^2/s)**	**dQ_{icorr}/Q_p** **(%)**	**Supporting information**
30–32.5	2.5	5.2·10^{-4}	3.93·10^{-5}	5.80·10^{-5}	100	EC
Total		**Σ= 5.2·10^{-4}**	**Σ= 3.9·10^{-5}**	**Σ5.8·10^{-4}**	**Σ100**	
Difference		Q_p–Q_{Tcorr}=0	–	–		

* The corrected flow is based on the assumption that all inflow occurs within the flow logged interval, i.e. QT= Q_p=ΣdQ_{icorr} and that the difference in flow is only due to the borehole diameter.

Pumping test in the upper part of the borehole

To confirm the result from the flow logging, a constant drawdown pumping test was performed in the uppermost part of the borehole. The measured section was between 8.0–21.0 m, i.e. 13 m long. The pumped flow rate was below the measurement limit (for this test, a major part of the pumped water was shunted back to the borehole and the practical lower measurement limit was 0.5 L/min), a rough estimate of the flow rate gave 0.2 L/min although a more correct value is <0.5 L/min. The results from the pumping test are presented in Table 6-10 below. Only a steady-state evaluation of the transmissivity by Moye's formula was made (based on the measurement limit as Q_p).

Table 6-10. Results of the pumping test in the section 8.0–21.0 m in borehole HFM17 in conjunction with flow logging.

Pumping test in upper part of borehole HFM17	**Nomen-clature**	**Unit**	**Value**
Flow rate at surface	Q_p	m^3/s	<8.33·10^{-6}
Absolute pressure in borehole before start of flow period	p_i	kPa	203.07
Pressure in section below the packer before start of flow period	p_{bi}	kPa	276.11
Absolute pressure in test section before stop of flow period	p_p	kPa	102.67
Pressure in section below the packer at stop of flow period	p_{bp}	kPa	275.98
Absolute pressure in test section at stop of recovery period	p_F	kPa	122.6
Pressure in section below the packer at stop of recovery period	p_{bF}	kPa	275.95
Pressure change by the end of flow period	dp_p	kPa	100.4
Specific flow	Q_p/ dp_p	m^2/s	<8.14·10^{-7}
Transmissivity (Moye)	T_M	m^2/s	<2.87·10^{-7}

Summary of results

Table 6-11 presents a summary of the results from the pumping test and corrected results from the flow logging together with the results of the pumping test in the upper part of the borehole. The results in Table 6-11 are consistent and show that the major part of the borehole transmissivity is restricted to the flow-logged interval.

Table 6-11. Compilation of results from the different hydraulic tests performed in borehole HFM17.

Test type	Interval (m)	Specific flow Q/s (m2/s)	T (m2/s)
Flow logging	21.0–205.0	5.80·10–5	3.93·10–5
Pumping test	8.0–210.65	5.77·10–5	3.93·10–5
Pumping test in upper part of the borehole	5.0–21.0	<8.14·10–7	<7.18·10–7

Figure 6-8 presents the cumulative transmissivity $T_F(L)$ along the borehole length (L) from the flow logging calculated from Equation (5-5). 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 transmissivity of the borehole are also presented in the figure, cf Section 5.4.2.

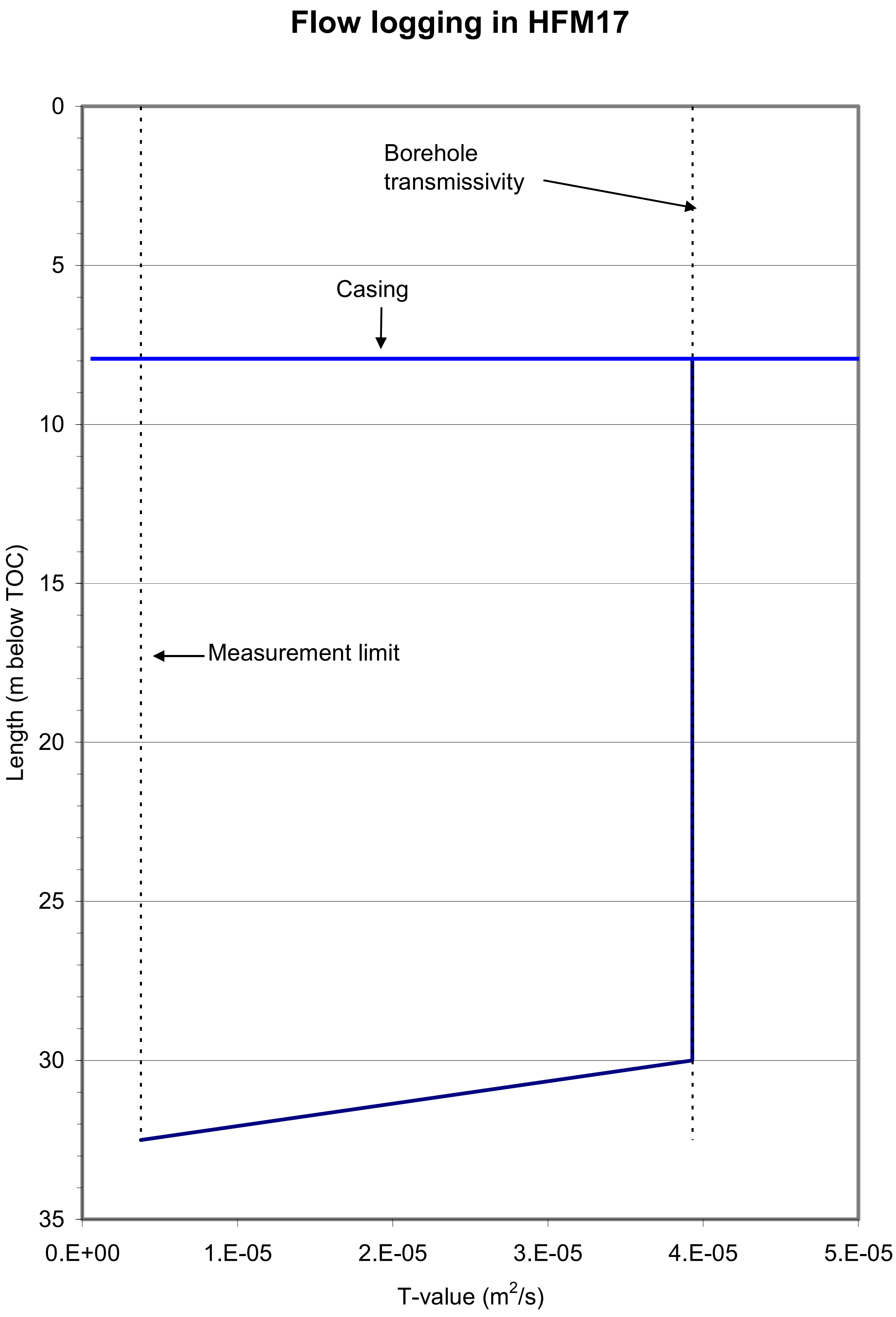


Figure 6-8. *Calculated, cumulative transmissivity along the flow logged interval of borehole HFM17. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.4.2 Borehole HFM18

General test data for the flow logging in borehole HFM18 are presented in Table 6-12.

Table 6-12. General test data, groundwater level and flow data for the flow logging in borehole HFM18.

General test data			
Borehole	HFM18		
Test type(s) [1]	6, L-EC, L-Te		
Test section:	Open borehole		
Test No	1		
Field crew	C. Hjerne, J. Olausson, GEOSIGMA AB		
Test equipment system	HTHB		
General comments	Single pumping borehole		
	Nomenclature	**Unit**	**Value**
Borehole length		m	180.65
Pump position (lower level)		m	20
Flow logged section – Secup		m	24
Flow logged section – Seclow		m	175
Test section diameter	2·rw	mm	top 140 bottom 138 [2]
Start of flow period		yymmdd hh:mm	040210 09:20
Start of flow logging		yymmdd hh:mm	040210 13:30
Stop of flow logging		yymmdd hh:mm	040210 16:51
Stop of flow period		yymmdd hh:mm	040210 19:21

Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)**
Groundwater level in borehole, at undisturbed conditions, open hole	h_i	m	4.70	1.00
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m	12.86	–6.02
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m	6.92	

Flow data	**Nomen-clature**	**Unit**	**Flow rate**
Pumping rate at surface	Q_p	m^3/s	$8.7 \cdot 10^{-4}$
Cumulative flow rate at Secup at pumping rate Qp	Q_T	m^3/s	$8.7 \cdot 10^{-4}$
Measurement limit for borehole flow rate during flow logging	Q_{Measl}	m^3/s	$5.0 \cdot 10^{-5}$
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$

1) 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging
2) Claesson and Nilsson (2004) /7/

Comments on test

The flow logging was made from the bottom of the borehole and upwards. The step length between positions for flow logging measurements was maximally 5 m in the borehole interval 175–50 m. Above 50 m, the step length was maximally 2 m.

The measured electric conductivity is used as supporting information when interpreting flow anomalies and for this purpose the electrical conductivity is compensated for temperature (see Figure 6-9 and Figure 6-10).

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 during the flow logging together with the electric conductivity (EC) and temperature (Te) of the borehole fluid is presented in Figure 6-9. A detailed plot of the flow logging results in the upper part of the borehole together with electric conductivity is presented in Figure 6-10.

Three separate flow anomalies were identified, the first at 48–48.5 m, the second at 46–46.5 m and the last at 36.5–38 m. The flow anomalies are supported by anomalies in electrical conductivity.

The results of the flow logging in borehole HFM18 are presented in Table 6-13 below. The measured inflows at the identified flow anomalies (dQ_i) together with their estimated percentages of the total flow are shown. In the borehole HFM18, the cumulative flow rate at the top of the flow logged interval (ΣdQi) was almost identical to the total flow rate (Qp) pumped from the borehole.

The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Equation (5-3) and the transmissivity of individual flow anomalies (T_i) from Equation (5-4). Transmissivity for the entire borehole used in Equation (5-4) was taken from the steady-state evaluation (according to Moye) of the pumping test performed in conjunction with the flow logging (cf Section 6.3.2). An estimation of the transmissivity of the interpreted flow anomaly was also made by the specific flow (dQ_i/s_{FL}). The transmissivity of the entire borehole was calculated from the transient interpretation of the pumping test during flow logging.

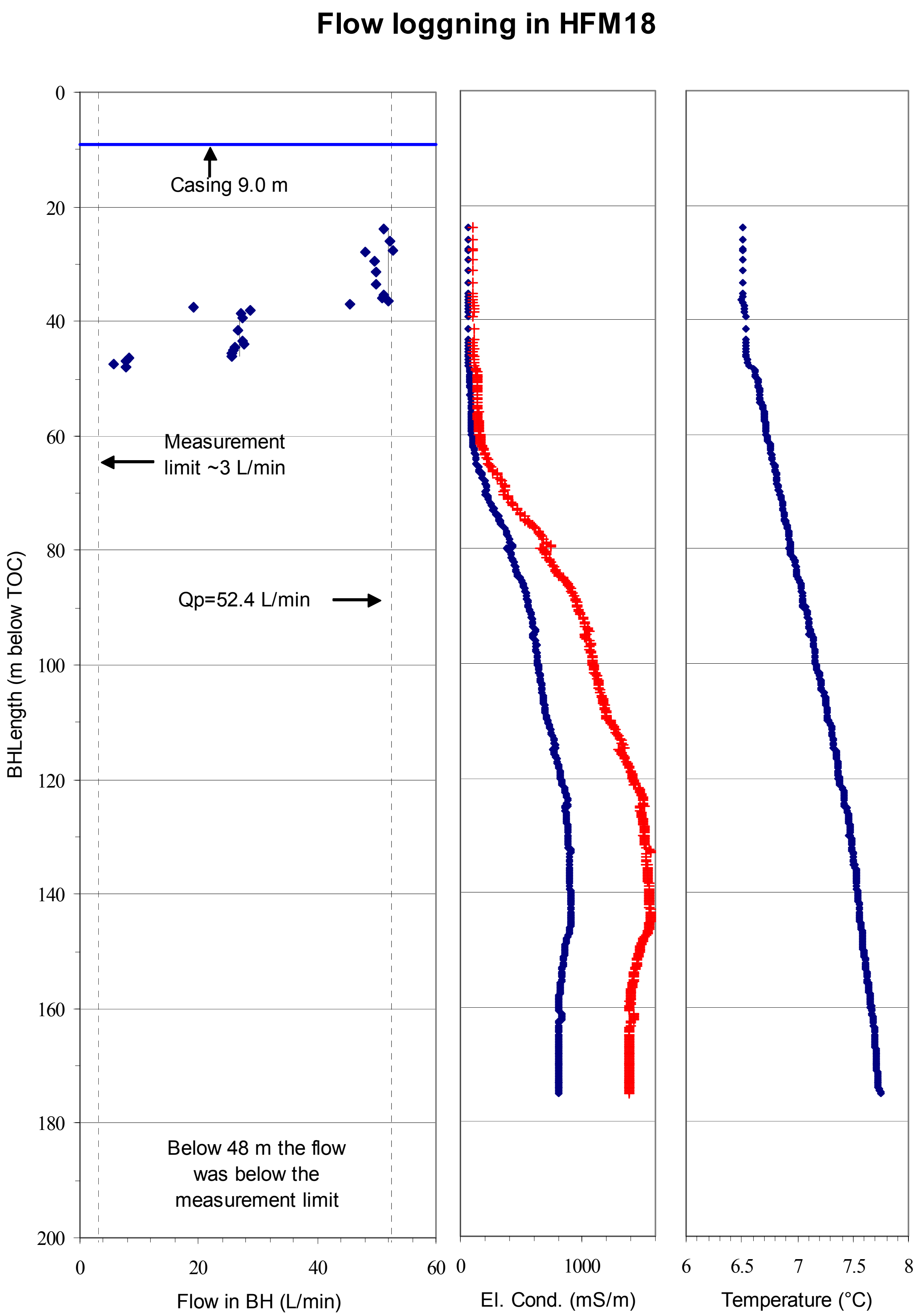


Figure 6-9. *Measured inflow distribution together with electrical conductivity (blue), temperature-compensated electric conductivity (red+) and temperature (Te) distribution of the borehole fluid along borehole HMF18 during flow logging.*

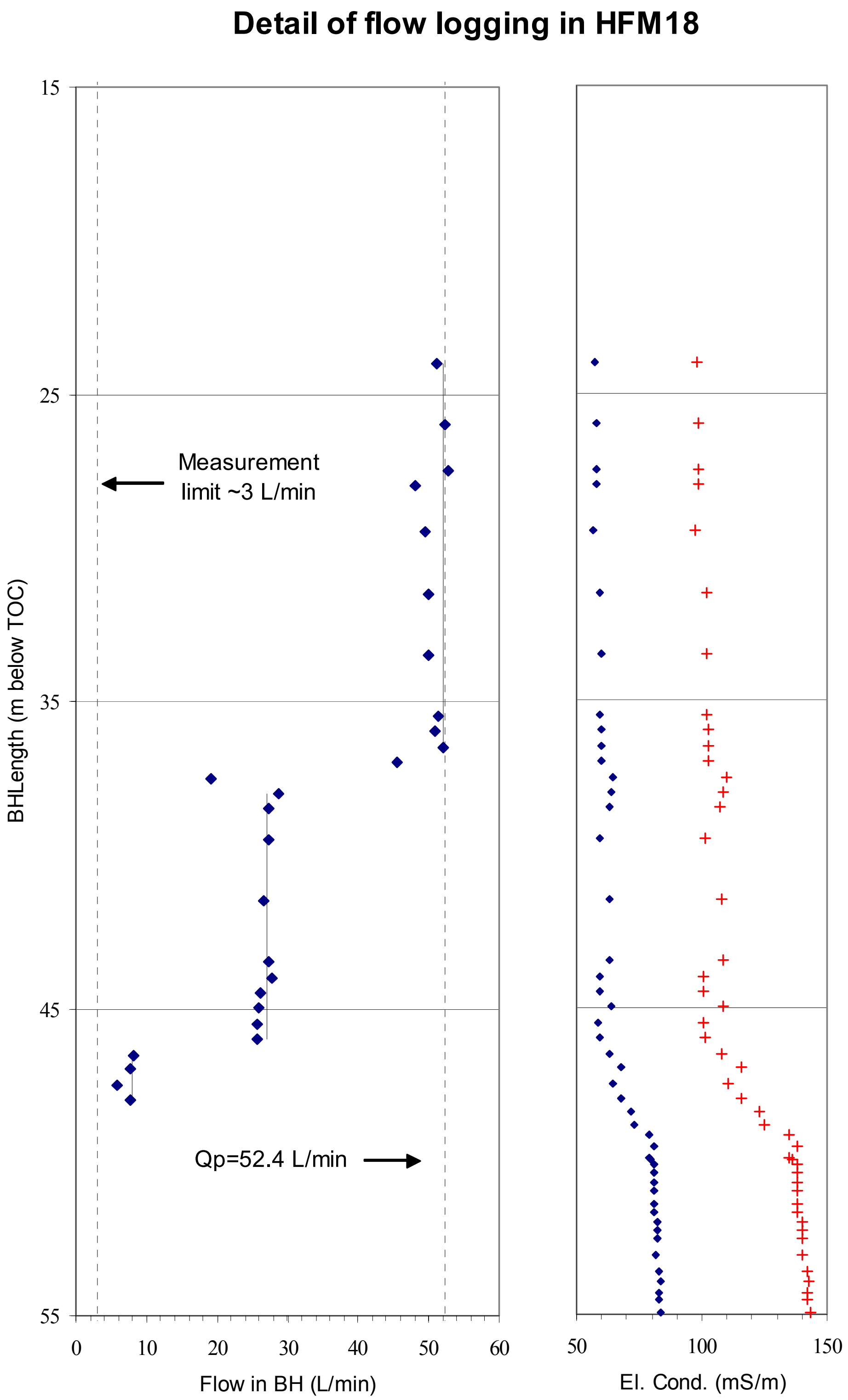


Figure 6-10. *Detail of measured inflow distribution together with electrical conductivity (blue), temperature-compensated electric conductivity (red+) distribution of the borehole fluid along borehole HMF18 during flow logging.*

Table 6-13. Results of the flow logging in borehole HFM18. Q_T=cumulative flow at the top of the logged interval. Q_p=pumped flow rate from borehole, s_{FL}= drawdown during flow logging. T=transmissivity from the pumping test.

HFM18 Flow anomalies		Q_T =8.67·10^{-4} (m^3/s)	Qp=8.73·10^{-4} (m^3/s)	T=1.63·10^{-4} (m^2/s)	s_{FL}=6.92 m	
Interval (m b ToC)	**B.h. length (m)**	**dQ_i (m^3/s)**	**dQ_i/Q_p (%)**	**T_i (m^2/s)**	**dQ_i/s_{FL} (m^2/s)**	**Supporting information**
36.5–38	1.5	4.17·10^{-4}	47.7	7.78·10^{-5}	6.02·10^{-5}	
46–46.5	0.5	3.17·10^{-4}	36.3	5.91·10^{-5}	4.58·10^{-5}	EC
48–48.5	0.5	1.33·10^{-4}	15.3	2.49·10^{-5}	1.93·10^{-5}	EC
Total		**ΣdQ_i= 8.7·10^{-4}**	**Σ99**	**ΣT_i= 1.6·10^{-4}**	**Σ1.3·10^{-4}**	
Difference		Q_p–Q_T=6·10^{-6}		–	–	

Injection test in the upper part of the borehole

To confirm the results from the flow logging, an injection test was performed in the uppermost part of the borehole. The measured section was between 9.0–24.0 m, i.e. 15 m long. The results of the injection test are presented in Table 6-14. An overview of the injection test is presented in Figure A2:18.

The injection test was performed with a constant head of c 23 m. Flow rate increased from c 25 L/min to c 35 L/min during the flow period prevailing for c 15 min. No reasonable explanation to the increased flow rate based on the hydraulic properties of the natural rock matrix or fracture zones adjacent to the borehole is found. A possible explanation to the increased flow rate may be that the injection test opened a channel in a conductive section within the test interval.

The estimated transmissivity for section 9.0–24.0 m in HFM18 can be compared to the specific flow c 1·10^{-6} m^2/s, estimated from the difference between borehole flow rate at 24.0 m and the pumped flow rate at surface. The borehole flow rate at 24 m is assumed to be reliable since borehole diameter is 140 mm in the upper part of the borehole (Claesson and Nilsson, 2004 /7/). Thus, the results of this injection test are not considered as fully reliable due to the increased flow rate during the injection test and the discrepancy between flow logging results and injection test results. Hereby, the injection test results are not presented in the results tables to SICADA. Still, a steady-state evaluation of the transmissivity by Moye’s formula was made.

Table 6-14. Results of the injection test in the section 9.0–24.0 m in borehole HFM18 in conjunction with flow logging.

Injection test in upper part of borehole HFM18	Nomen-clature	Unit	Value
Injection rate at surface	Q_p	m^3/s	$7.02 \cdot 10^{-4}$
Absolute pressure in borehole before start of flow period	p_i	kPa	114.9
Absolute pressure in test section before stop of flow period	p_p	kPa	343.0
Absolute pressure in test section at stop of recovery period	p_F	kPa	137.5
Pressure change by the end of flow period	dp_p	kPa	228.1
Specific flow	Q_p/ dp_p	m^2/s	$3.02 \cdot 10^{-5}$
Transmissivity (Moye)	T_M	m^2/s	$2.73 \cdot 10^{-5}$

Summary of results

Table 6-15 presents a summary of the results from the pumping test and flow logging together with the results from the injection test in the upper part of the borehole. The results in Table 6-15 are consistent and show that nearly the entire transmissivity of the borehole is located within the flow-logged interval, despite the uncertainty of the results from the injection tests.

Table 6-15. Compilation of results from the different hydraulic tests performed in borehole HFM18.

Test type	Interval (m)	Specific flow Q/s (m^2/s)	T (m^2/s)
Flow logging	24.0–175.0	$1.25 \cdot 10^{-4}$	$1.62 \cdot 10^{-4}$
Pumping test	9.0–180.65	$1.27 \cdot 10^{-4}$	$1.63 \cdot 10^{-4}$
Injection test	9.0–24.0	$3.02 \cdot 10^{-5}$	$2.73 \cdot 10^{-5}$

Figure 6-11 presents the cumulative transmissivity $T_F(L)$ along the borehole length (L) from the flow logging calculated from Equation (5-5). 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 transmissivity of the borehole are also shown in the figure, cf Section 5.4.2.

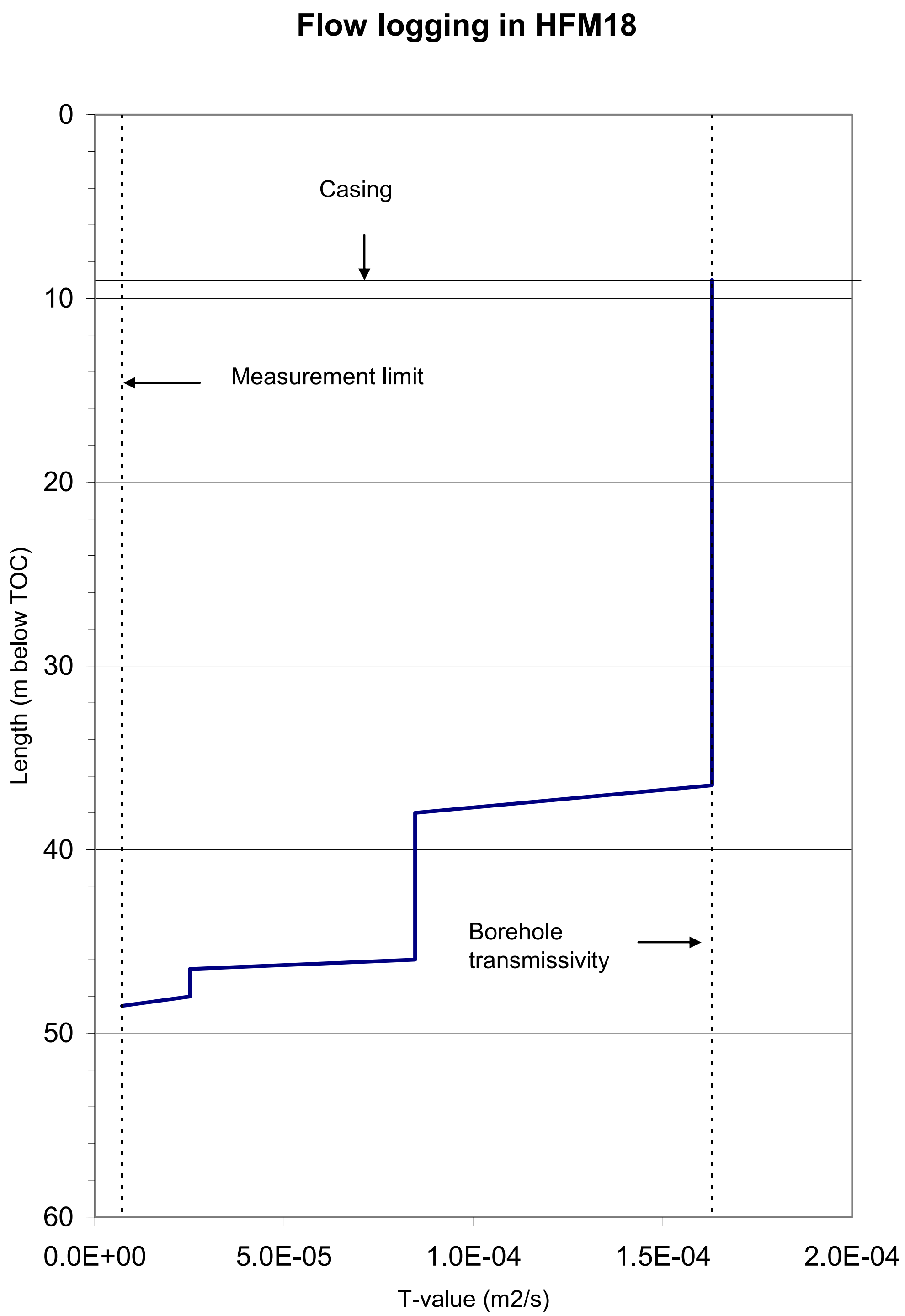


Figure 6-11. *Calculated, cumulative transmissivity along the flow logged interval of borehole HFM18. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.4.3 Borehole HFM19

General test data for the flow logging in borehole HFM19 are presented in Table 6-16.

Table 6-16. General test data, groundwater level and flow data for the flow logging in borehole HFM19.

General test data				
Borehole	HFM19			
Test type(s) [1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	J. Källgården, J. Olausson, GEOSIGMA AB			
Test equipment system	HTHB			
General comments	Single pumping borehole			
	Nomen-clature	**Unit**	**Value**	
Borehole length		m	185.2	
Pump position (lower level)		m	12.5	
Flow logged section – Secup		m	16.5	
Flow logged section – Seclow		m	171.5	
Test section diameter	2·rw	mm	top 140 bottom 137 [2]	
Start of flow period		yymmdd hh:mm	040203 08:17	
Start of flow logging		yymmdd hh:mm	040203 12:50	
Stop of flow logging		yymmdd hh:mm	040203 16:51	
Stop of flow period		yymmdd hh:mm	040203 18:21	
Groundwater level [3]	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l)**
Groundwater level in borehole, at undisturbed conditions, open hole	hi	m	–	0.85
Groundwater level (steady state) in borehole, at pumping rate Qp [4]	hp	m	–	–0.79
Drawdown during flow logging at pumping rate Qp [5]	sFL	m	1.53	
Flow data	**Nomen-clature**	**Unit**	**Flow rate**	
Pumping rate at surface	Q_p	m^3/s	$9.08 \cdot 10^{-4}$	
Corrected cumulative flow rate at Secup at pumping rate Qp	Q_{Tcorr}	m^3/s	$9.08 \cdot 10^{-4}$	
Measurement limit for borehole flow rate during flow logging	Q_{Measl}	m^3/s	$5.0 \cdot 10^{-5}$	
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$	

[1)] 6: Flow logging-Impeller, L-EC: EC-logging, L-TE: temperature logging
[2)] Claesson and Nilsson (2004) /7/
[3)] Calculated from pressure sensor data.
[4)] Steady-state was not achieved during the pumping, this groundwater level is caculated from p_p.
[5)] The drawdown increased from 1.46 m to 1.60 m during the flow logging.

Comments on test

The flow logging was made from c 171.5 m and upwards. Due to an obstacle in the borehole it was not possible to lower the flow logging probe further down than 171.5 m. The step length between flow measurements was maximally 2 m in the borehole interval 171.5–16.5 m. A significant borehole flow rate was detected already at the first position for flow logging (171.5 m). Thus, a major inflow to the borehole is present below 171.5 m.

The measured electric conductivity is used as supporting information when interpreting flow anomalies and for this purpose the electrical conductivity is compensated for temperature (see Figure 6-12). Before start of flow logging, the flow logging probe was lowered in the undisturbed borehole HFM19 and thus a profile of temperature and electrical conductivity under undisturbed conditions was measured (see Figure 6-13).

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 during the flow logging together with the electric conductivity (EC) and temperature (Te) of the borehole fluid is presented in Figure 6-12.

In Figure 6-12 an apparent increase in borehole flow rate with borehole length is indicated. This is a result of the decrease in borehole diameter with depth (according to the drilling record, borehole diameter at top is 140.2 mm and at bottom 137.0 mm). Also, when the flow logging probe is lowered into an undisturbed borehole (no pumping) the decreasing borehole diameter is clearly seen as an increasing number of spinner rotations per meter with depth.

The flow in the borehole is calculated from a linear calibration equation where the flow is proportional to the number of spinner rotations per time. Using the logging in the undisturbed borehole together with known calibration constants at two certain borehole diameters it is possible to estimate a relationship between the proportionality factor (gain) in the calibration equation and borehole length. This has been done to correct the measured flow in Figure 6-12, calculated with calibration constants for a borehole with 140 mm diameter, for increasing diameter at depth.

The final borehole flow rate data are denoted Q_{icorr} and shown as red crosses in Figure 6-12. The corresponding borehole flow rate at the uppermost position for flow logging is denoted Q_{Tcorr}. The corrected borehole flow rates were used for interpreting flow anomalies.

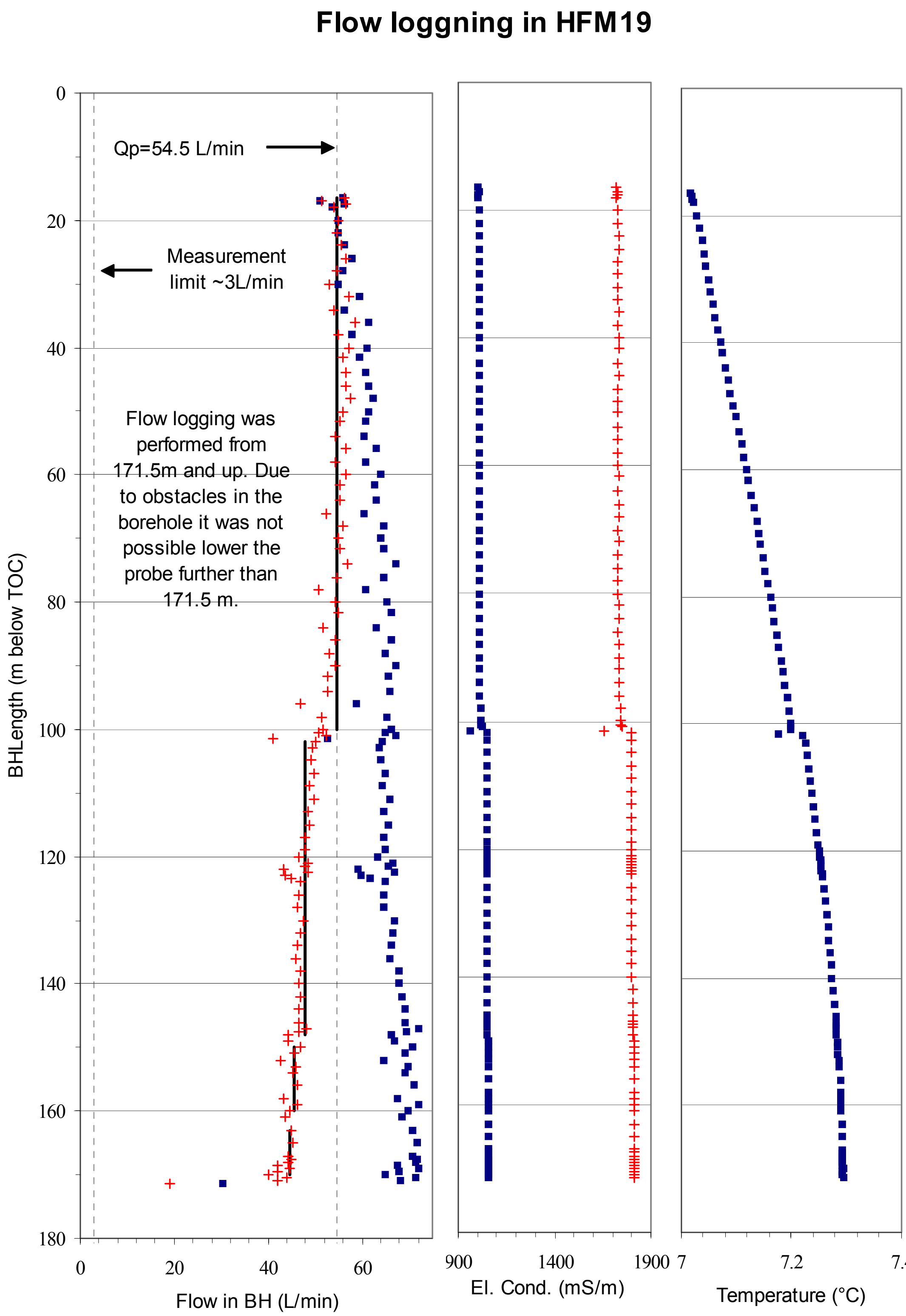


***Figure 6-12.** Measured (blue square) and corrected (red cross) inflow distribution together with electrical conductivity (blue square), temperature-compensated electric conductivity (red cross) and temperature (Te) distribution of the borehole fluid along borehole HMF19 during flow logging.*

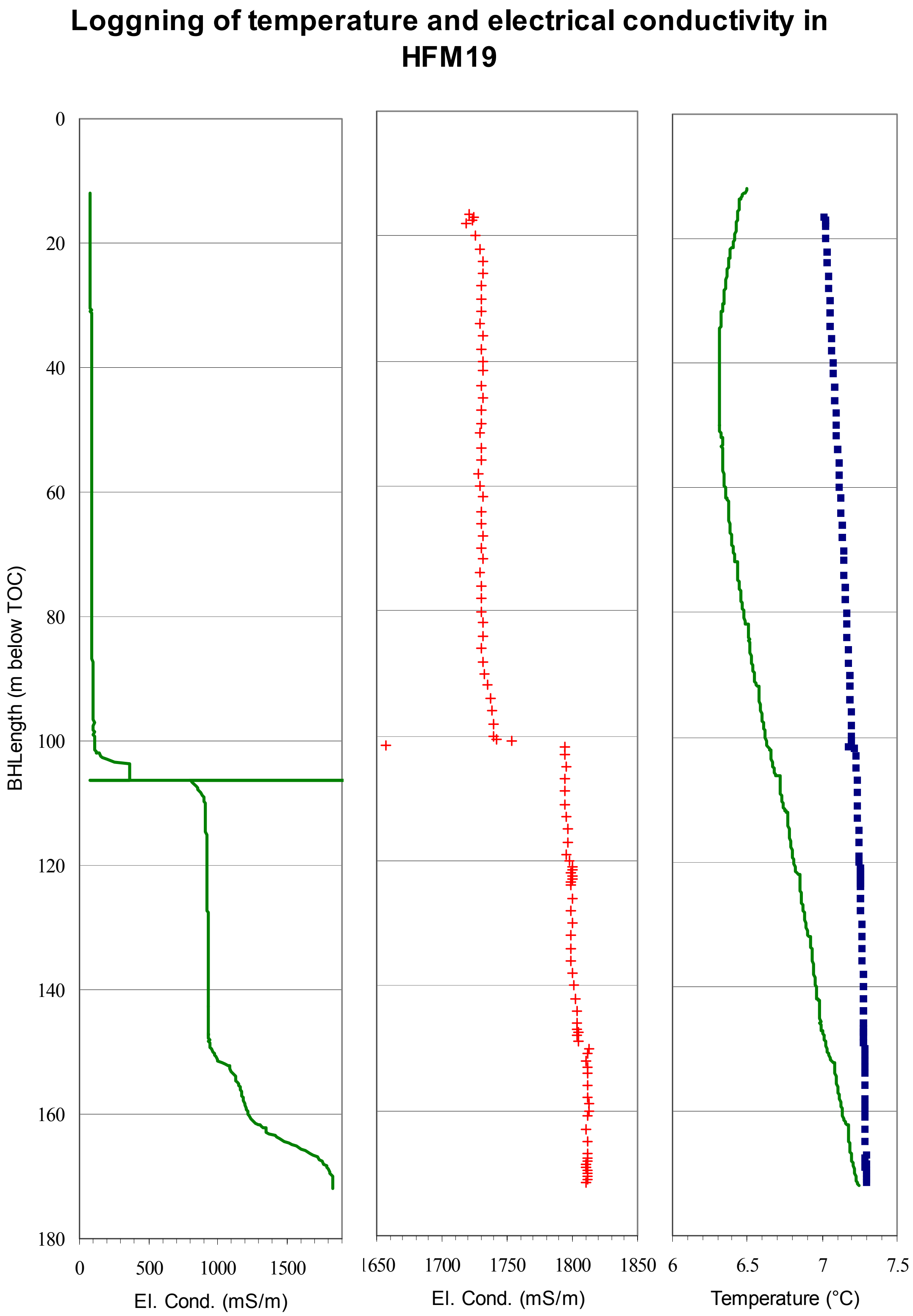


Figure 6-13. *Electrical conductivity (EC) and temperature (Te) in HFM19. Temperature compensated electric conductivity during undisturbed conditions (green line). Temperature compensated electrical conductivity during flow logging (red cross). Temperature during undisturbed conditions (green line) and temperature during flow logging (blue square).*

It should be pointed out that the borehole flow rate correction assumes no inflow to borehole above the highest position for flow logging. As seen from the injection test presented below, a small inflow above the highest position for flow logging is present although it is below the measurement limit for detecting flow anomalies.

In Figure 6-13 the profiles of temperature-compensated electrical conductivity and temperature are presented during both pumped and undisturbed conditions. Those data sets are used as supporting information when interpreting flow anomalies. The results of the flow logging in borehole HFM19 are presented in Table 6-17 below. The measured, corrected inflows at the identified flow anomalies (dQ_{icorr}) together with their estimated percentages of the total flow are shown. As can be seen from Figure 6-12 most of the measured inflow to the borehole occurs below 170 m and three minor inflows are indicated within the flow logged interval. These flow anomalies are supported by anomalies in electrical conductivity although the EC anomaly at 160–163 m is very weak. The EC anomalies are also indicated in the profile obtained while lowering the flow probe in the undisturbed borehole, cf Figure 6-13. At c 120 m, another flow anomaly is weakly indicated but not interpreted as a real anomaly since dQ_{icorr} at c 120 m is less than the detection limit (i.e. <1 L/min), cf Table 6-16.

The cumulative transmissivity (T_{FT}) at the top of the flow-logged borehole interval was calculated from Equation (5-3) with Q_T replaced by Q_{Tcorr} and since $Q_{Tcorr} = Q_p$, $T_{FT} = T$. The transmissivity of individual flow anomalies (T_i) were calculated from Equation (5-4) with dQ_i replaced by dQ_{icorr}. Transmissivity for the entire borehole used in Equation (5-4) was taken from the transient evaluation of the flow period for the pumping test performed in conjunction with the flow logging (cf Section 6.3.3). An estimation of the transmissivity of the interpreted flow anomaly was also made by the specific flow (dQ_{icorr}/s_{FL}). The transmissivity of the entire borehole (T) was calculated from the transient interpretation of the pumping test during flow logging.

Table 6-17. Results of the flow logging in borehole HFM19. Q_{Tcorr}=cumulative flow at the top of the logged interval, corrected due to the deviations of borehole diameter. Q_p=pumped flow rate from borehole, s_{FL}= drawdown during flow logging. T=transmissivity from the pumping test.

HFM19 Flow anomalies		**$Q_{Tcorr}=9.08\cdot10^{-4}$ (m^3/s)**	**$T=3.37\cdot10^{-4}$ (m^2/s)**	**s_{FL}=1.53 m**	**$Q_p=9.08\cdot10^{-4}$ (m^3/s)**	
Interval (m b ToC)	**B.h. length (m)**	**dQ_{icorr}* (m^3/s)**	**T_i (m^2/s)**	**dQ_{icorr}/s_{FL} (m^2/s)**	**dQ_{icorr}/Q_p (%)**	**Supporting information**
100–102	2	$1.08\cdot10^{-4}$	$4.02\cdot10^{-5}$	$7.08\cdot10^{-5}$	11.9	EC
148–150	2	$4.17\cdot10^{-5}$	$1.55\cdot10^{-5}$	$2.72\cdot10^{-5}$	4.6	EC
160–163	3	$1.67\cdot10^{-5}$	$6.18\cdot10^{-6}$	$1.09\cdot10^{-5}$	1.8	EC
170–182.5	15.2	$7.42\cdot10^{-4}$	$2.75\cdot10^{-4}$	$4.85\cdot10^{-4}$	81.7	EC
Total		**$\Sigma= 9.1\cdot10^{-4}$**	**$\Sigma= 3.4\cdot10^{-4}$**	**$\Sigma5.9\cdot10^{-4}$**	**$\Sigma100$**	
Difference		$Q_p–Q_{Tcorr}=0$	–	–		

* The corrected flow is based on estimates of borehole diameter variations, calibration constants for different borehole diameters and the assumption that all inflow occurs within the flow logged interval, i.e. $Q_{Tcorr}= Q_p=\Sigma dQ_{icorr}$.

Injection test in the upper part of the borehole

To confirm the result from the flow logging, an injection test was performed in the uppermost part of the borehole. The measured section was between 12.0–16.5 m, i.e. 4.5 m long. A summary of the results of the injection test is presented in Table 6-18. An overview of the injection test is presented in Figure A2:19 in Appendix 2.

The injection test was performed at a constant head of c 20 m. In a similar way as in borehole HFM18, the flow rate increased from c 2 L/min to c 4 L/min during the flow period prevailing for c 20 min. A possible explanation to the increased flow rate may be that the injection test opened a channel in a fractured section of the upper part of borehole. The constant head of c 20 m was higher than the drawdown during the open-hole pumping test (c 1.4 m) and it is possible that the higher head during the injection test opened a channel that was not present during the open-hole pumping test. Since the results of this injection test is not fully reliable, they are not presented in the results table to SICADA. Still, a steady-state evaluation of the transmissivity by Moye's formula was made.

Table 6-18. Results of the injection test in the section 12.0–16.5 m in borehole HFM19 in conjunction with flow logging.

Injection test	Nomen-clature	Unit	Value
Injection rate at surface	Q_p	m^3/s	$6.18 \cdot 10^{-5}$
Absolute pressure in borehole before start of flow period	p_i	kPa	161.70
Absolute pressure in test section before stop of flow period	p_p	kPa	361.50
Absolute pressure in test section at stop of recovery period	p_F	kPa	182.50
Pressure change by the end of flow period	dp_p	kPa	199.80
Specific flow	Q_p/dp_p	m^2/s	$3.04 \cdot 10^{-6}$
Transmissivity (Moye)	T_M	m^2/s	$2.16 \cdot 10^{-6}$

Summary of results

Table 6-19 gives a summary of the results from the pumping test and corrected results from the flow logging. The low transmissivity in the injection section (see above) corresponds to an inflow to the borehole during flow logging that would be below the detection limit for an anomaly. Thus, the assumption of no inflow above the highest position for flow logging when correcting borehole flow rate can be considered as relevant.

Table 6-19. Compilation of results from the different hydraulic tests performed in borehole HFM19.

Test type	Interval (m)	Specific flow Q/s (m^2/s)	T (m^2/s)
Flow logging	16.5–171.5	$5.94 \cdot 10^{-4}$	$3.37 \cdot 10^{-4}$
Pumping test	12.0–185.2	$5.94 \cdot 10^{-4}$	$3.37 \cdot 10^{-4}$
Injection test	12.0–16.5	$3.04 \cdot 10^{-6}$	$2.16 \cdot 10^{-6}$

Figure 6-14 displays the cumulative transmissivity $T_F(L)$ along the borehole length (L) from the flow logging calculated from Equation (5-5). 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 presented in the figure, cf Section 5.4.2.

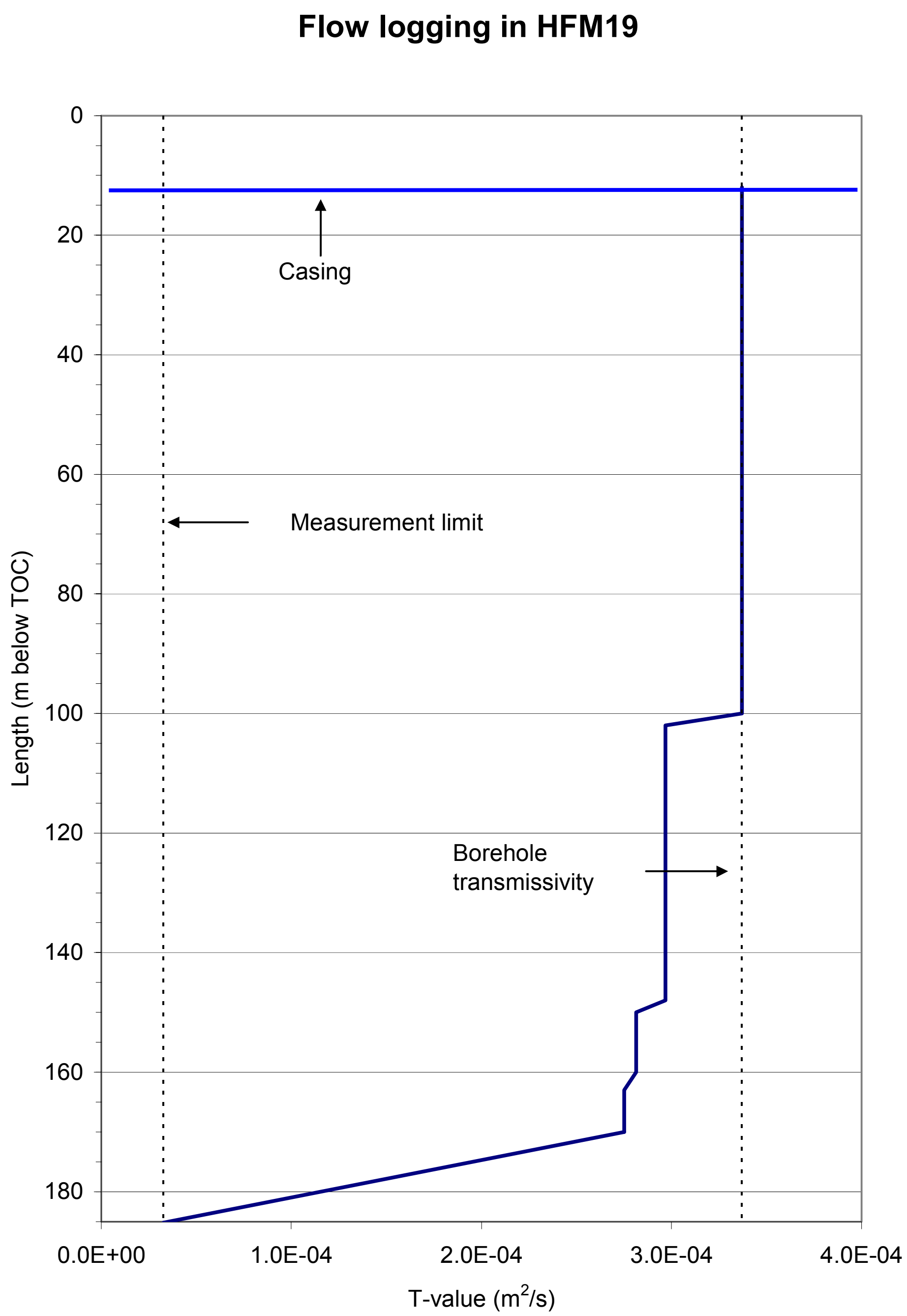


Figure 6-14. *Calculated, cumulative transmissivity along the flow logged interval of borehole HFM19. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.5 Summary of hydraulic tests

A compilation of measured test data from the hydraulic tests carried out in the test campaign is presented in Table 6-20. In Table 6-21 and Table 6-22, hydraulic parameters calculated from the tests in HFM17, HFM18 and HFM19 are shown. The results of the flow logging are presented in Section 6.4.

The lower measurement limit for the HTHB system, presented in the tables below, is expressed in terms of specific flow (Q/s). For pumping tests, the practical lower limit is based on the minimal flow rate Q, for which the system is designed (5 L/min) and an estimated maximal allowed drawdown for practical purposes (c 50 m) in a percussion borehole, cf Table 4-1. These values correspond to a practical lower measurement limit of Q/s–L = $2{\cdot}10^{-6}$ m^2/s of the pumping tests. For the pumping test 8.0–21.0 m in HFM17, a special test setup was used that lowered the measurement limit to 0.5 L/min (cf Section 6.4.1). Maximal possible drawdown was in this particular case restricted to c 15 m, corresponding to a practical lower measurement limit of Q/s–L = $8{\cdot}10^{-7}$ m^2/s. For injection tests, the practical lower measurement limit is based on the minimal flow rate Q, for which the system is designed (1 L/min) and a head of 20 m according to the methodology description for injection tests (SKB MD 323.001, SKB internal document). These values correspond to a practical lower measurement limit of Q/s–L = $8{\cdot}10^{-7}$ m^2/s of the injection tests.

Similarly, the practical, upper measurement limit of the HTHB-system is estimated from the maximal flow rate (c 80 L/min) and a minimal drawdown of c 0.5 m, which is considered significant in relation to e.g. background fluctuations of the pressure before and during the test. These values correspond to an estimated, practical upper measurement limit of Q/s–U = $2{\cdot}10^{-3}$ m^2/s for both pumping tests and injection tests.

Table 6-20. Summary of test data for the open-hole pumping tests performed with the HTHB system in boreholes HFM17, HFM18 and HFM19 in the Forsmark candidate 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)
HFM17	8.0–210.65	1B	203.47	115.06	202.75	$5.20{\cdot}10^{-4}$	$5.67{\cdot}10^{-4}$	20.5
HFM18	9.0–180.65	1B	195.98	128.26	196.78	$8.72{\cdot}10^{-4}$	$8.74{\cdot}10^{-4}$	31.5
HFM19	12.0–185.2	1B	147.97	131.88	143.67	$9.08{\cdot}10^{-4}$	$9.08{\cdot}10^{-4}$	32.9

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

Table 6-21. Summary of calculated hydraulic parameters of the formation from the hydraulic tests performed with the HTHB system in boreholes HFM17, HFM18 and HFM19 in the Forsmark candidate area.

Borehole ID	Section (m)	Flow Anomaly interval (m)	Test type[1)]	Q/s (m^2/s)	T_M (m^2/s)	T_T (m^2/s)	T_i (m^2/s)	S* (–)
HFM17	8.0–210.65		1B	$5.77{\cdot}10^{-5}$	$7.61{\cdot}10^{-5}$	$3.93{\cdot}10^{-5}$		$5.00{\cdot}10^{-5}$
HFM17	8.0–21.0		1B	$<8.14{\cdot}10^{-7}$	$<7.18{\cdot}10^{-7}$			
HFM17	21.0–205.0 (f)	30–32.5	6	$5.79{\cdot}10^{-5}$			$3.93{\cdot}10^{-5}$	
HFM18	9.0–180.65		1B	$1.27{\cdot}10^{-4}$	$1.63{\cdot}10^{-4}$			$5.00{\cdot}10^{-5}$
HFM18	9.0–24.0		3	$3.02{\cdot}10^{-5}$	$2.73{\cdot}10^{-5}$			
HFM18	24.0–175.0 (f)	36.5–38	6	$6.02{\cdot}10^{-5}$			$7.78{\cdot}10^{-5}$	
HFM18		46–46.5	6	$4.58{\cdot}10^{-5}$			$5.91{\cdot}10^{-5}$	
HFM18		48–48.5	6	$1.93{\cdot}10^{-5}$			$2.49{\cdot}10^{-5}$	
HFM19	12.0–185.2		1B	$5.54{\cdot}10^{-4}$	$7.17{\cdot}10^{-4}$	$3.37{\cdot}10^{-4}$		$5.00{\cdot}10^{-5}$
HFM19	12.0–16.5		3	$3.04{\cdot}10^{-6}$	$2.16{\cdot}10^{-6}$			
HFM19	16.5–171.5 (f)	100–102	6	$7.08{\cdot}10^{-5}$			$4.02{\cdot}10^{-5}$	
HFM19		148–150	6	$2.72{\cdot}10^{-5}$			$1.55{\cdot}10^{-5}$	
HFM19		160–163	6	$1.09{\cdot}10^{-5}$			$6.18{\cdot}10^{-6}$	
HFM19		170–182.5	6	$4.85{\cdot}10^{-4}$			$2.75{\cdot}10^{-4}$	

(f)= flow logged interval
1) 1B: Pumping test-submersible pump, 3: Injection test, 6: Flow logging–Impeller. L-EC: EC-logging, L-Te: temperature logging

In Table 6-20, Table 6-21 and Table 6-22, the parameter explanations are according to the instruction for injection- and single-hole pumping tests. The parameters are also explained in the text above, except the following:

Q/s = specific flow for the borehole and flow anomalies (for the latter ones, the corrected specific flow for the borehole diameter is listed)
T_M = steady-state transmissivity calculated from Moye's formula
T_T = judged best estimate of transmissivity (from transient evaluation of hydraulic test or from Moye's formula)
T_i = estimated transmissivity of flow anomaly
S* = assumed value on storativity used in single-hole tests

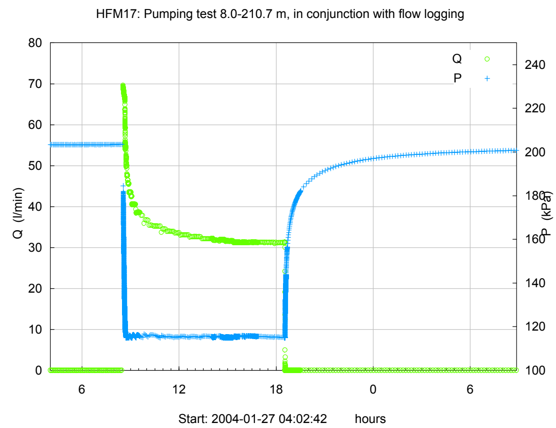
Table 6-22. Summary of calculated hydraulic parameters of the borehole from hydraulic test performed with the HTHB system in boreholes HFM17, HFM18 and HFM19 in the Forsmark candidate area.

Borehole ID	Section (m)	Test type	S* (–)	C (m3/Pa)	ζ (–)
HFM17	8.0–210.65	1B	5·10–5	$1.6{\cdot}10^{-6}$	–3.5
HFM18	9.0–180.65	1B	5·10–5	–	–
HFM19	12.0–185.2	1B	5·10–5	$2.7{\cdot}10^{-6}$	–

Test Summary Sheet

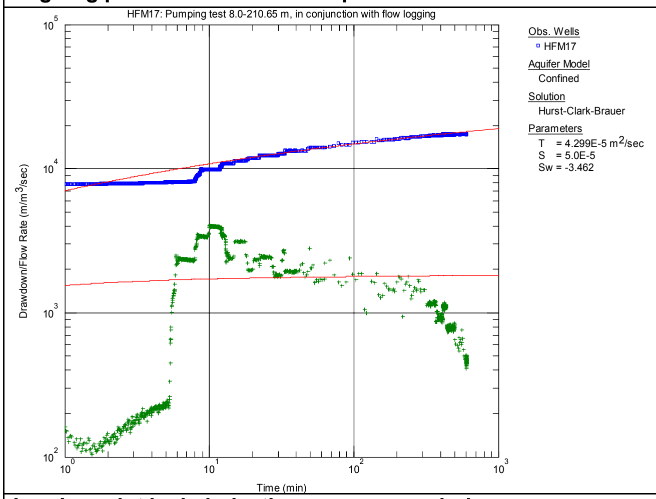
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM17	Test start:	2004-01-27 04:02:42
Test section (m):	202.65	Responsible for test performance:	Geosigma AB C. Hjerne
Section diameter, 2·r_w (m):	top 0.138 bottom 0.136	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

Linear plot Q and p

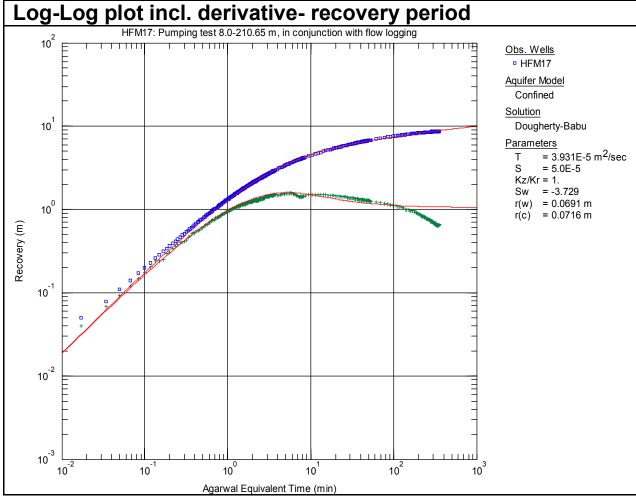


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	203.47		
p_i (kPa)	203.47		
p_p(kPa)	115.06	pF (kPa)	202.75
Q_p (m^3/s)	$5.2 \cdot 10^{-4}$		
tp (min)	601	tF (min)	859
S*	$5 \cdot 10^{-5}$	S*	$5 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.4	Derivative fact.	0.1
Results		**Results**	
Q/s (m2/s)	$5.77 \cdot 10^{-5}$		
T_{Moye}(m^2/s)	$7.61 \cdot 10^{-5}$		
Flow regime:	PRF	Flow regime:	WBS –>PRF
t_1 (min)	30	dt_{e1} (min)	10
t_2 (min)	300	dt_{e2} (min)	100
T_w (m^2/s)	$4.3 \cdot 10^{-5}$	T_w (m^2/s)	$3.9 \cdot 10^{-5}$
S_w (–)		S_w (–)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)		C (m^3/Pa)	$1.6 \cdot 10^{-6}$
C_D (–)		C_D (–)	
ξ (–)	–3.5	ξ (–)	–3.7
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters.

Flow regime:	PRF	C (m^3/Pa)	$1.6 \cdot 10^{-6}$
t_1 (min)	10	C_D (–)	
t_2 (min)	100	ξ (–)	–3.7
T_T (m^2/s)	$3.9 \cdot 10^{-5}$		
S (–)			
K_s (m/s)			
S_s (1/m)			

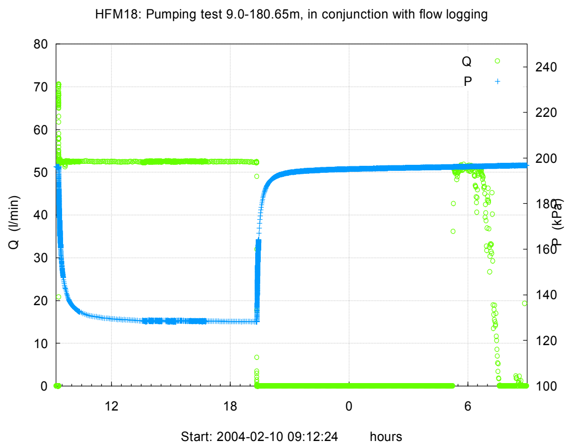
Comments:

The test was performed as a constant drawdown test. A pseudo-radial flow regime is indicated from c 30 to c 300 min during the flow period. By the end of the flow period, a transition to pseudo-spherical flow is indicated. The initial phase of recovery is dominated by WBS effects followed by a transition to pseudo-radial flow. By end of recovery, a transition to pseudo-spherical flow is indicated.

Test Summary Sheet

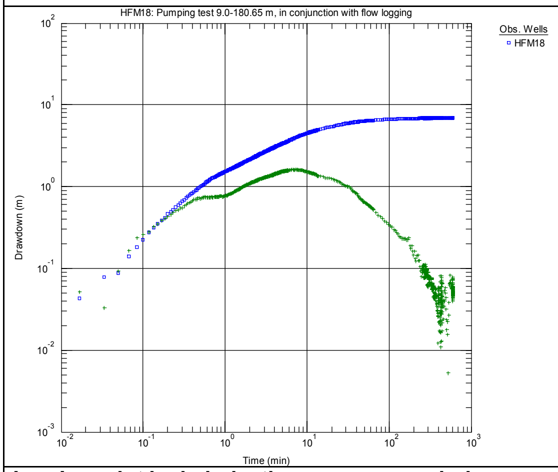
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM18	Test start:	2004-02-10 09:12
Test section (m):	171.65	Responsible for test performance:	Geosigma AB C. Hjerne
Section diameter, $2 \cdot r_w$ (m):	top 0.140 bottom 0.138	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

Linear plot Q and p

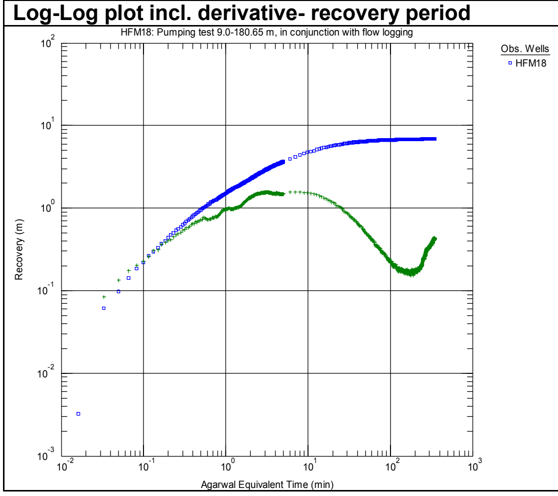


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	195.98		
p_i (kPa)	195.98		
p_p(kPa)	128.26	pF (kPa)	196.78
Q_p (m^3/s)	$8.72 \cdot 10^{-4}$		
tp (min)	601	tF (min)	819
S*	$5.0 \cdot 10^{-5}$	S*	$5.0 \cdot 10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.4	Derivative fact.	0.2
Results		**Results**	
Q/s (m2/s)	$1.27 \cdot 10^{-4}$		
T_{Moye}(m^2/s)	$1.63 \cdot 10^{-4}$		
Flow regime:	WBS–> PSF	Flow regime:	WBS–> PSF
t_1 (min)		dt_{e1} (min)	
t_2 (min)		dt_{e2} (min)	
T_w (m^2/s)		T_w (m^2/s)	
S_w (–)		S_w (–)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)	$2.7 \cdot 10^{-6}$	C (m^3/Pa)	$2.7 \cdot 10^{-6}$
C_D (–)		C_D (–)	
ξ (–)		ξ (–)	
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters.

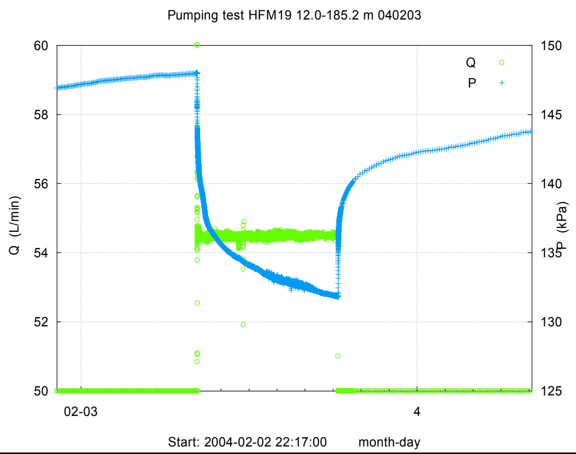
Flow regime:		C (m^3/Pa)	$2.7 \cdot 10^{-6}$
t_1 (min)		C_D (–)	
t_2 (min)		ξ (–)	
T_T (m^2/s)			
S (–)			
K_s (m/s)			
S_s (1/m)			

Comments:
The intial phase of both flow and recovery period is affected by WBS. After a transition stage, pseudo-spherical flow is indicated during both periods.

Test Summary Sheet

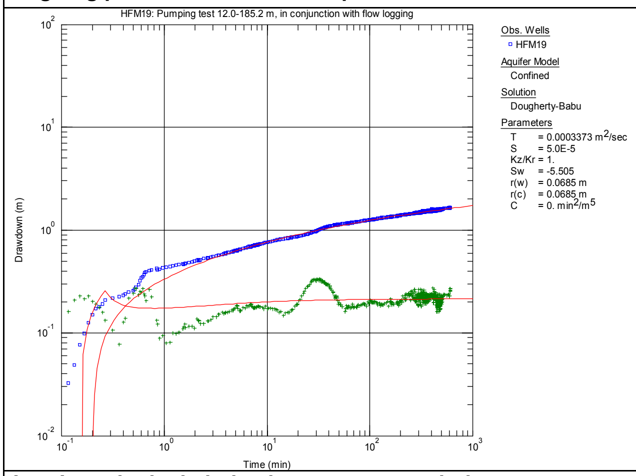
Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFM19	Test start:	2004-02-02 22:17:08
Test section (m):	12.0–185.2	Responsible for test performance:	Geosigma AB J. Källgården
Section diameter, 2·r_w (m):	top 0.140 bottom 137.0	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

Linear plot Q and p

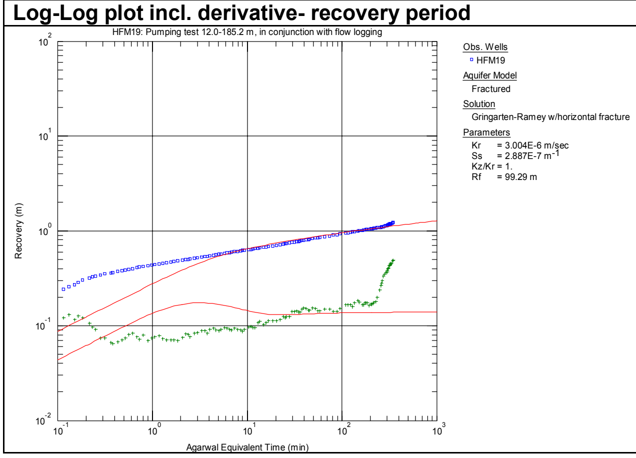


Flow period		Recovery period	
Indata		**Indata**	
p_0 (kPa)	147.97		
p_i (kPa)	147.97		
p_p(kPa)	131.88	p_F (kPa)	143.67
Q_p (m^3/s)	$9.08·10^{-4}$		
tp (min)	604	tF (min)	830
S*	$5·10^{-5}$	S*	$5·10^{-5}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.3	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$5.54·10^{-4}$		
T_{Moye}(m^2/s)	$7.17·10^{-4}$		
Flow regime:	PRF	Flow regime:	PLF
t_1 (min)	5	dt_{e1} (min)	10
t_2 (min)	600	dt_{e2} (min)	250
T_w (m^2/s)	$3.37·10^{-4}$	T_w (m^2/s)	$5.20·10^{-4}$
S_w (–)		S_w (–)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)		C (m^3/Pa)	
C_D (–)		C_D (–)	
ξ (–)	–5.5	ξ (–)	
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters.

Flow regime:	PRF	C (m^3/Pa)	
t_1 (min)	5	C_D (–)	
t_2 (min)	600	ξ (–)	–5.5
T_T (m^2/s)	$3.37·10^{-4}$		
S (–)			
K_s (m/s)			
S_s (1/m)			

Comments:

Both the flow and the recovery period indicates pseudo-linear flow although evaluation of T_T is performed assuming pseudo-radial flow from the flow period.

By the end of recovery period, a disturbance is indicated, possibly due to tidal effects.

7 References

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

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

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

5 **Hurst W, J D Clark, E B Brauer, 1969.** The skin effect in producing wells. J. Pet. Tech, Nov.1969, pp1483–1489.

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

7 **Claesson L-Å, Nilsson, G, 2004.** Forsmark site investigation. Drilling of five percussion boreholes, HFM11–12 and HFM17–19, on different lineaments. SKB P-04-XX. Svensk kärnbränslehantering AB. P-report in progress.

Appendix 1

List of data files

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

Bh ID	Test section (m)	Test type[1]	Test no	Test start Date, time YYYY-MM-DD tt:mm:ss	Test stop Date, time YYYY-MM-DD tt:mm:ss	Datafile, start Date, time YYYY-MM-DD tt:mm:ss	Datafile, stop Date, time YYYY-MM-DD tt:mm:ss	Data files of raw and primary data	Content (para-meters)[2]	Comments
HFM17	8.0–210.65	1B		2004-01-27 04:02:42	2004-01-28 08:51:40	2004-01-26 15:34:38	2004-01-28 08:59:15	HFM17_08.0_040127_FlowLo00.DAT	P, Q, Te, EC	A short pumping test was performed 040126 with flow period start. 17:01:45 /CH
		1B				2004-01-26 13:57:02	2004-01-28 09:12:29	HFM17_08.0_040127_Ref_Da00.DAT		
HFM17	21.0–205.0	6		2004-01-27 14:00:00	2004-01-27 16:54:43	2004-01-27 16:09:10	2004-01-27 16:54:43	HFM17_21.0_040127_Spinne00.DAT	P, Q, Te, EC, Sp	
		6				2004-01-26 13:57:02	2004-01-27 18:31:40	HFM17_21.0_040127_Ref_Da00.DAT		
HFM17	8.0–21.0	1B		2004-01-28 11:58:04	2004-01-28 14:20:10	2004-01-28 10:57:13	2004-01-28 14:22:45	HFM17_08.0_040128_Pumpin00.DAT	P, Q	Short pumping test in upper part of borehole/CH
		1B				2004-01-28 10:57:13	2004-01-28 14:22:57	HFM17_08.0_040128_Ref_Da00.DAT		
HFM18	9.0-180.65	1B		2004-02-10 09:12:24	2004-02-11 09:00:14	2004-02-09 15:00	2004-02-11 09:00	HFM18_09.0_040210_FlowLo00.DAT	P, Q, T, EC	A short pumping test was performed 040209 with flow period start. 16:44:32 /CH
	9.0-180.65	1B				2004-02-09 14:41	2004-02-11 09:32	HFM18_09.0_040210_Ref_Da00.DAT		

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 (para-meters)[2]	Comments
HFM18	24.0-175.0	6		2004-02-10 13:30:00	2004-02-10 16:51:25	2004-02-10 15:17	2004-02-10 16:51	HFM18_24.0_040210_Spinne00.DAT	P, Q, T, Sp, EC	
	24.0-175.0	6				2004-02-10 10:24	2004-02-10 19:19	HFM18_24.0_040210_Ref_Da00.DAT		
HFM18	9.0-24.0	3		2004-02-11 13:12:08	2004-02-11 14:38:47	2004-02-11 13:10	2004-02-11 14:38	HFM18_09.0_040211_Inject00.DAT	P, Q	Injection test in upper part of borehole /CH
	9.0-24.0	3				2004-02-11 09:32	2004-02-11 16:04	HFM18_09.0_040211_Ref_Da00.DAT		
HFM19	12.0-185.2	1B		2004-02-02 22:17:08	2004-02-04 08:12:45	2004-02-02 12:52	2004-02-04 10:13	HFM19_12.0_040202_FlowLo00.DAT	P, Q, T, EC	A short pumping test was performed 040202 with flow period start 14:51:13/JK
	12.0-185.2	1B				2004-02-02 12:44	2004-02-04 10:13	HFM19_12.0_040202_Ref_Da00.DAT		
HFM19	16.5-171.5	6		2004-02-03 12:50:44	2004-02-03 16:51:28	2004-02-03 12:50	2004-02-03 16:51	HFM19_16.5_040203_Spinne00.DAT	P, Q, T, Sp, EC	
	16.5-171.5	6				2004-02-03 10:47	2004-02-03 18:20	HFM19_16.5_040203_Ref_Da00.DAT		
HFM19	12.0-16.5	3		2004-02-04 11:03:08	2004-02-04 12:36:08	2004-02-04 10:13	2004-02-04 12:36	HFM19_12.0_040204_Inject00.DAT	P, Q	Injection test in upper part of borehole/JK
	12.0-16.5	3				2004-02-04 10:13	2004-02-04 12:36	HFM19_12.0_040204_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 HFM17:8.0-210.65 m
2. Pumping test in HFM18:9.0-185.65 m
3. Pumping test in HFM19:12.0-185.2 m
4. Injection tests in HFM18 and HFM19

Nomenclature in AQTESOLV:

T=transmissivity (m^2/s)

S=storativity (-)

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

S_w=skin factor

r(w)=borehole radius (m)

r(c)= effective casing radius (m)

C= well loss constant (not used, set to 0)

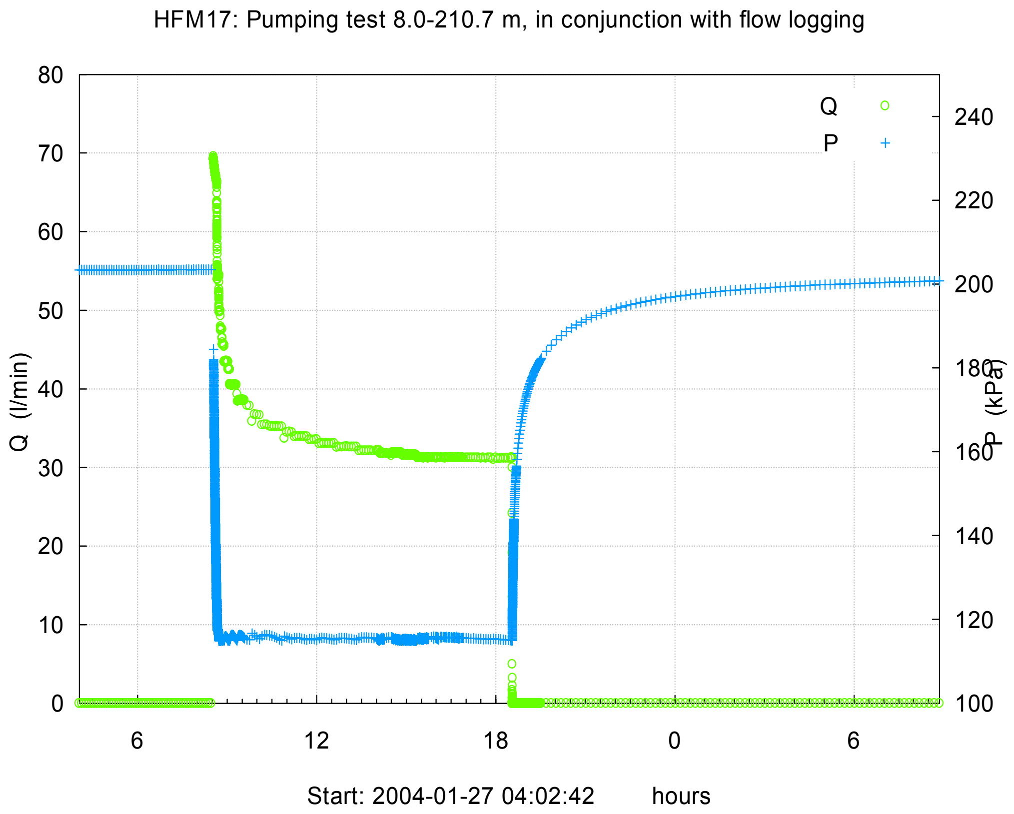


Figure A2-1. *Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM17 in conjunction with flow logging.*

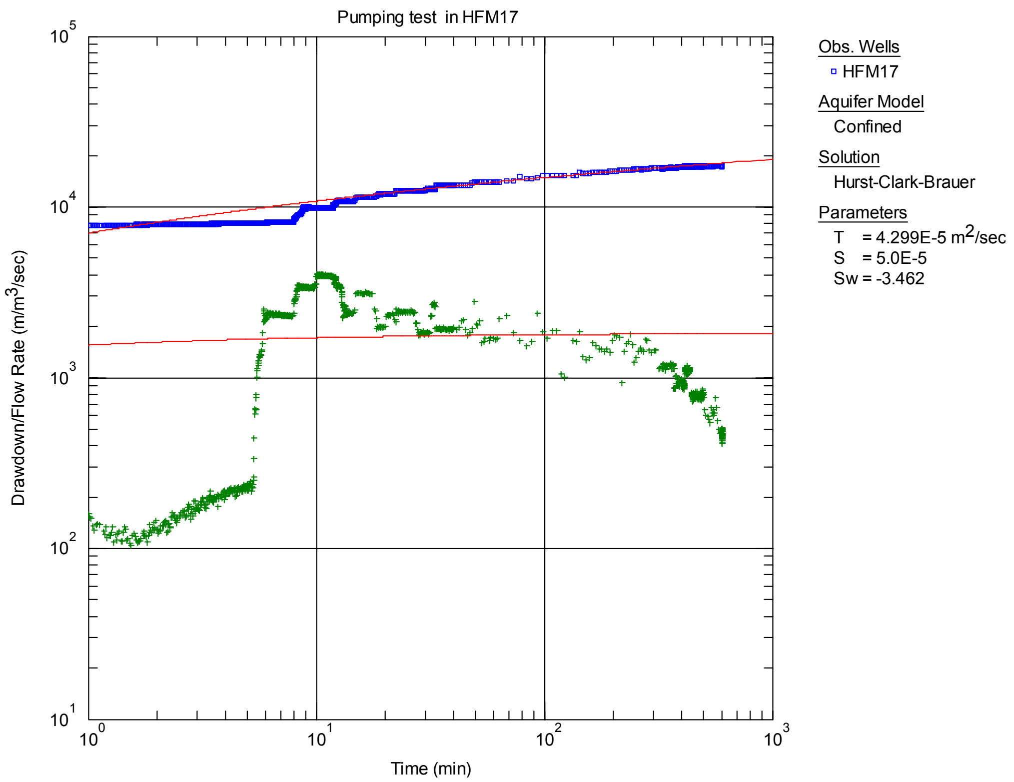
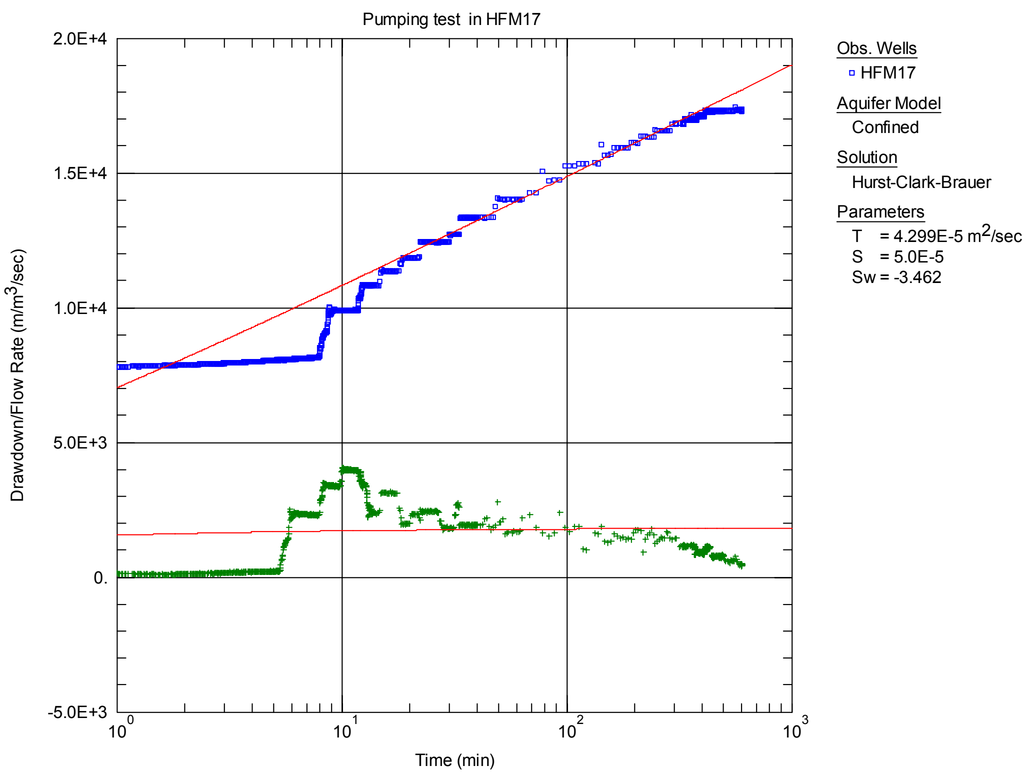
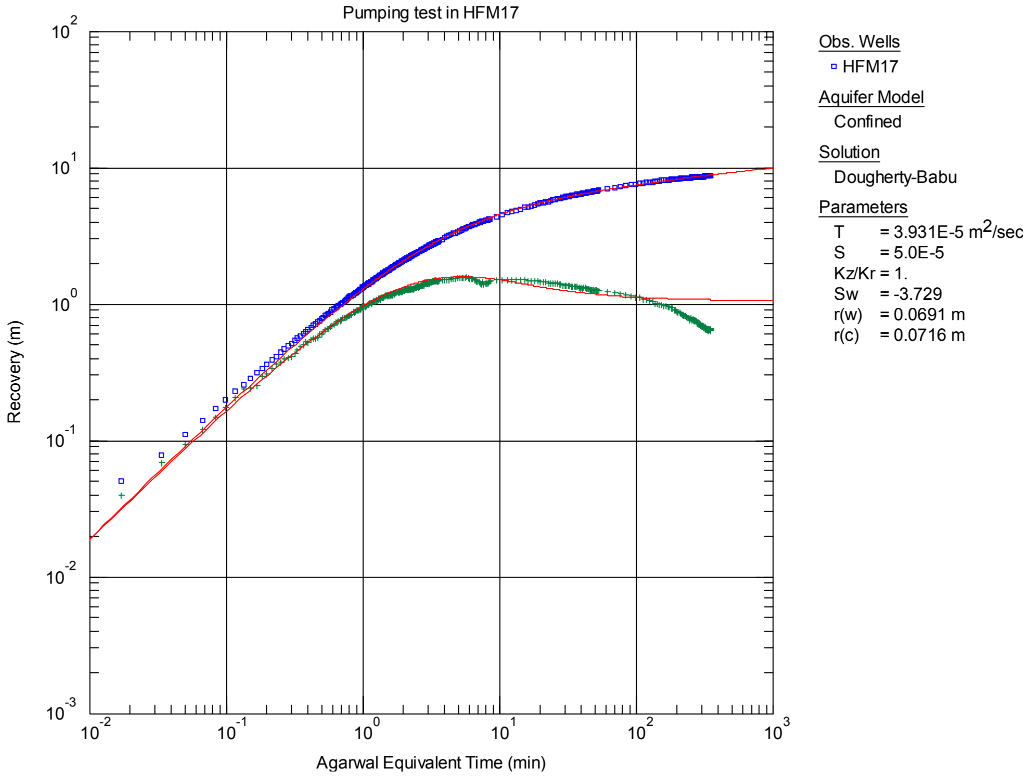


Figure A2-2. *Log-log plot of drawdown/flow rate (blue □) and drawdown/flow rate-derivative (green +) versus time during the open-hole pumping test in HFM17.*



FigureA2-3. *Lin-log plot of drawdown/flow rate (blue □) and drawdown/flow rate-derivative (green +) versus time during the open-hole pumping test in HFM17.*



FigureA2-4. *Log-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM17.*

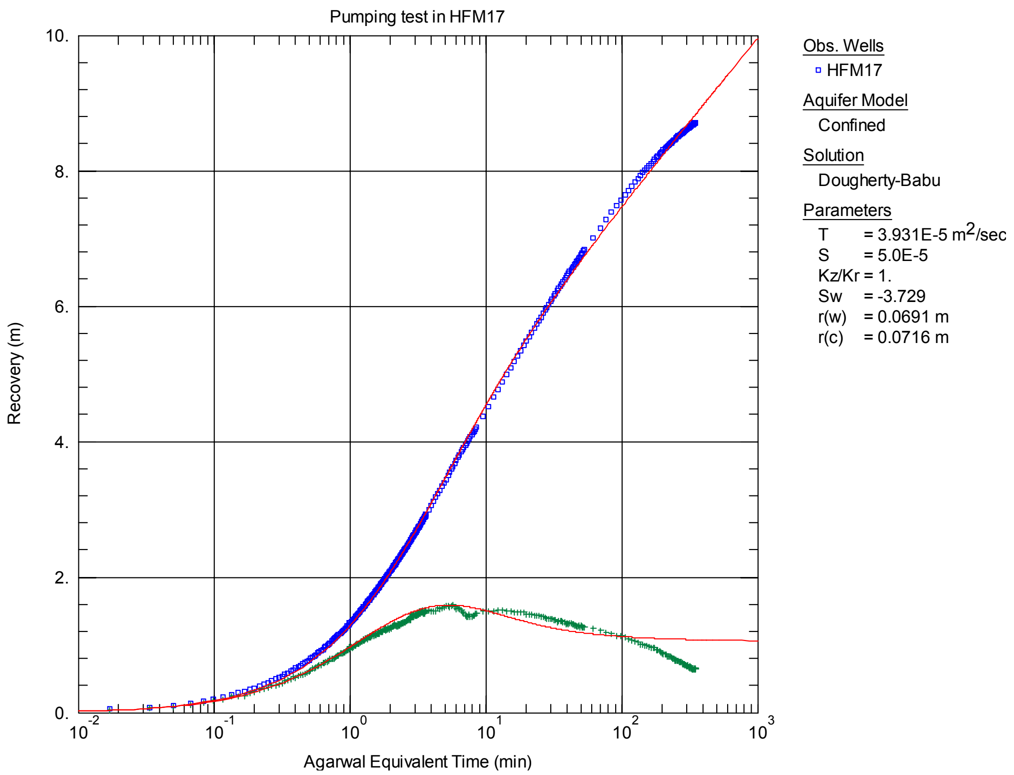


Figure A2-5. *Lin-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM17.*

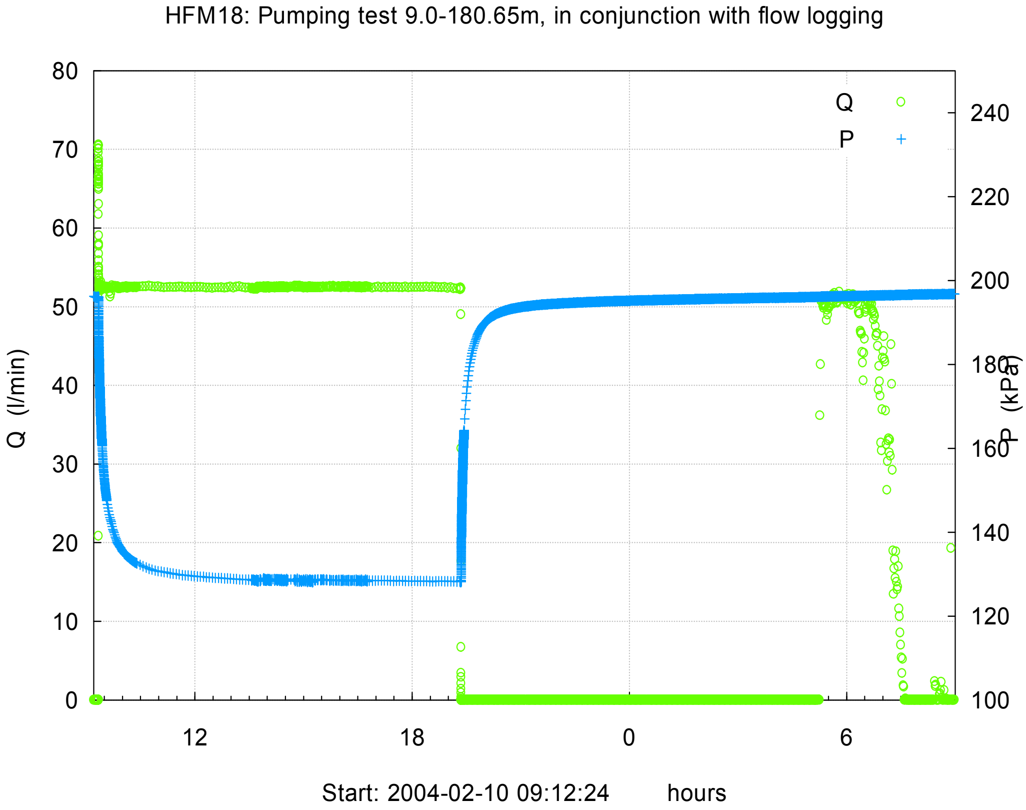


Figure A2-6. *Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM18 in conjunction with flow logging.*

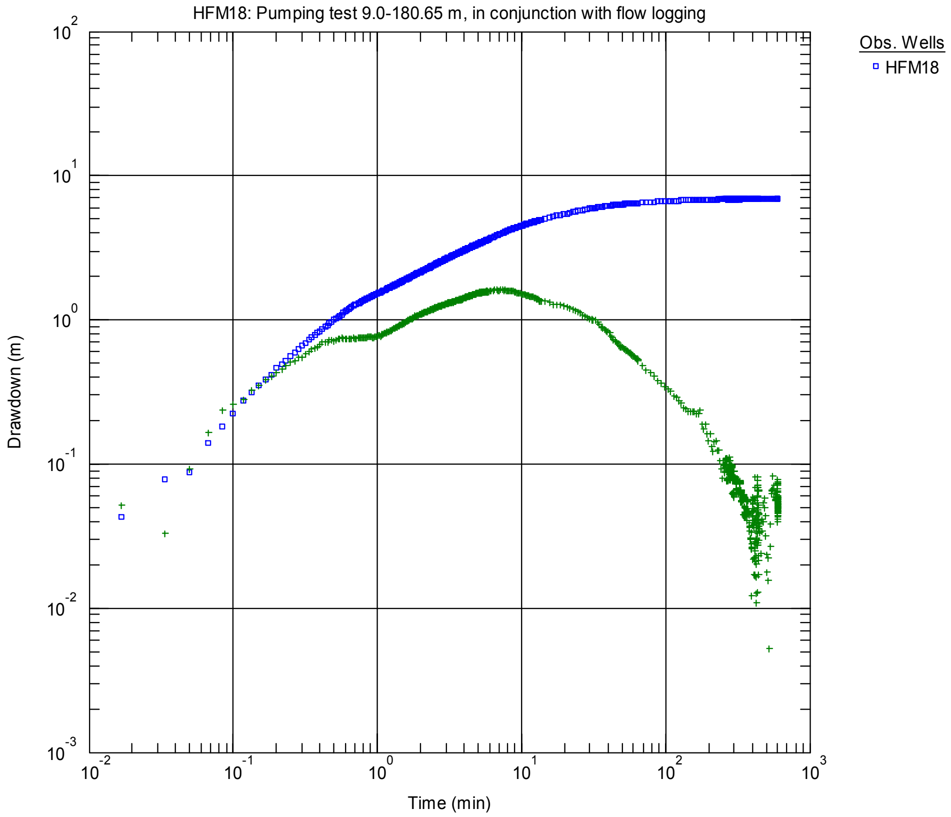


Figure A2-7. *Log-log plot of drawdown (blue □) and drawdown derivative (green +) versus time during the open-hole pumping test in HFM18.*

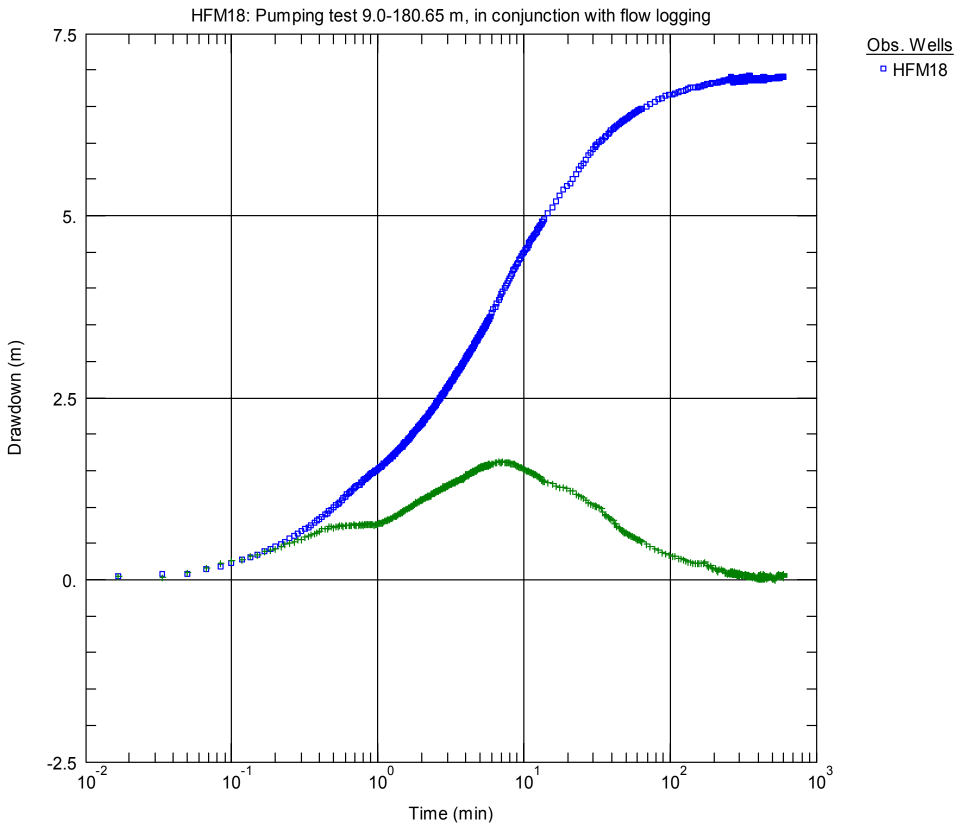


Figure A2-8. *Lin-log plot of drawdown (blue □) and drawdown derivative (green +) versus time during the open-hole pumping test in HFM18.*

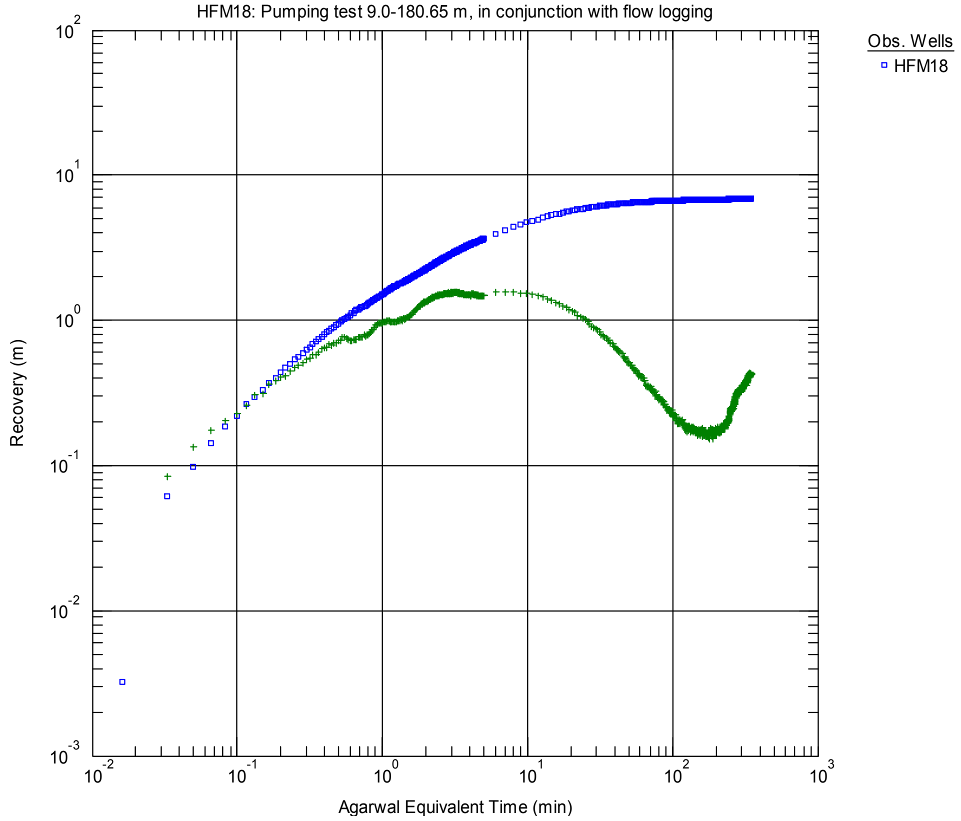


Figure A2-9. *Log-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM18.*

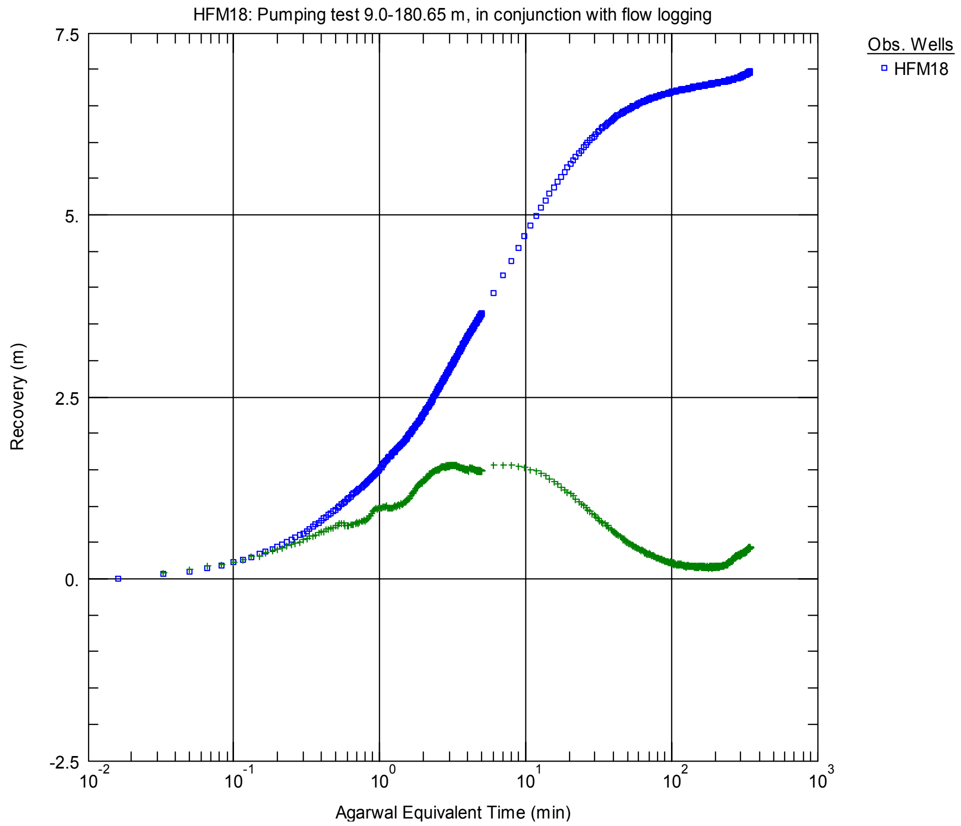


Figure A2-10. *Lin-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM18.*

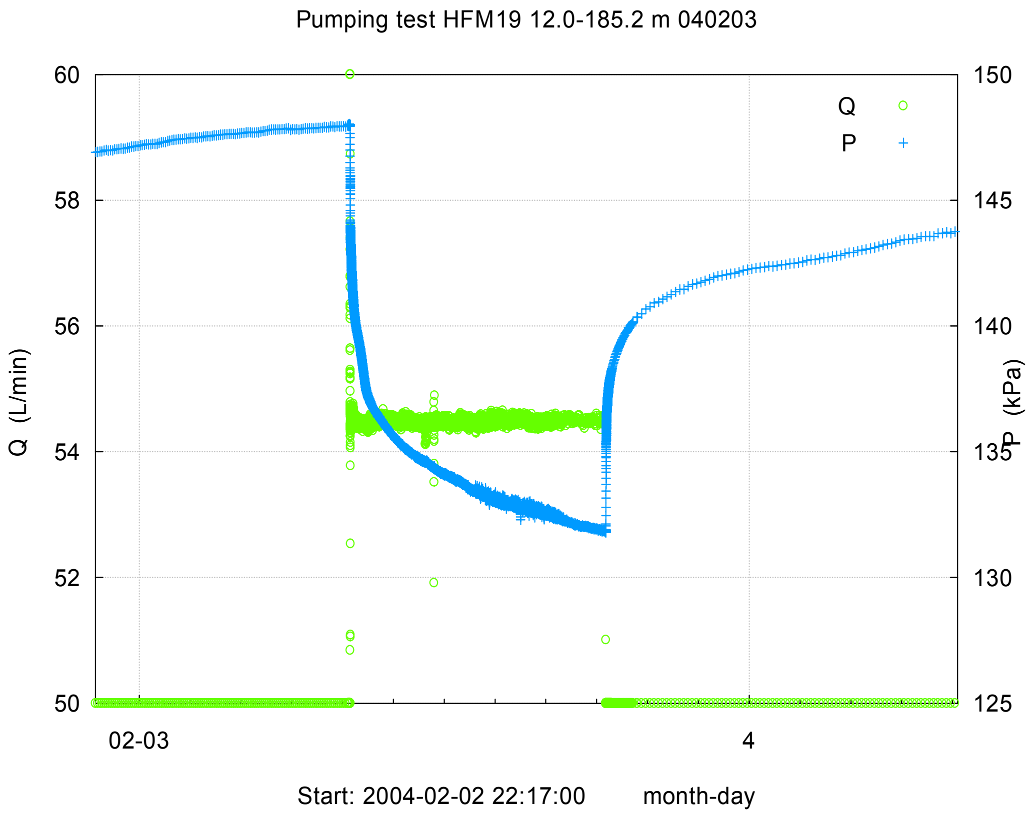


Figure A2-11. *Linear plot of flow rate (Q) and pressure (p) versus time during the open-hole pumping test in HFM19 in conjunction with flow logging.*

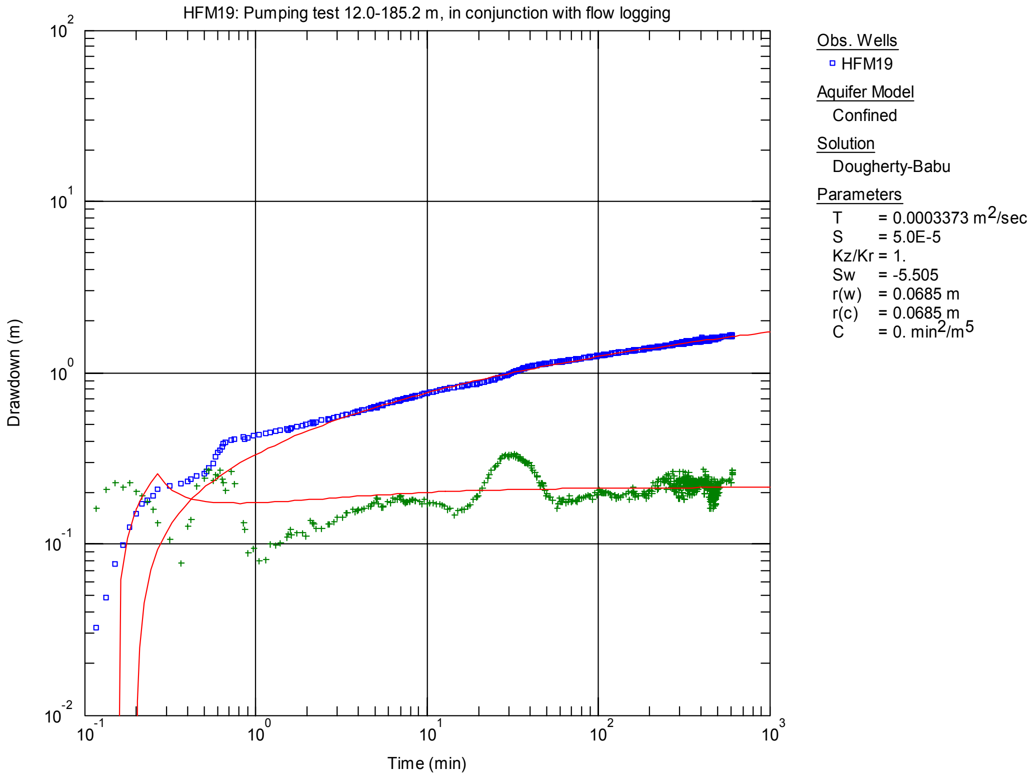


Figure A2-12. *Log-log plot of drawdown (blue □) and drawdown derivative (green +) versus time during the open-hole pumping test in HFM19. Displaying fit to Dougherty-Babu solution.*

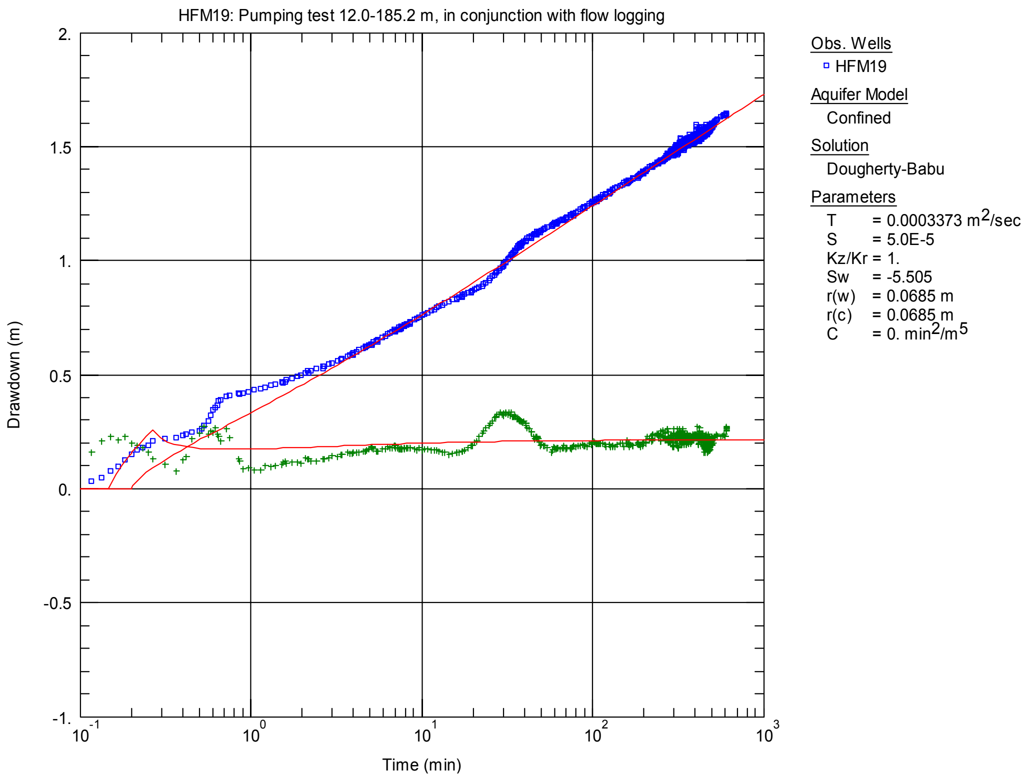


Figure A2-13. *Lin-log plot of drawdown (blue □) and drawdown derivative (green +) versus time during the open-hole pumping test in HFM19. Displaying fit to Dougherty-Babu solution.*

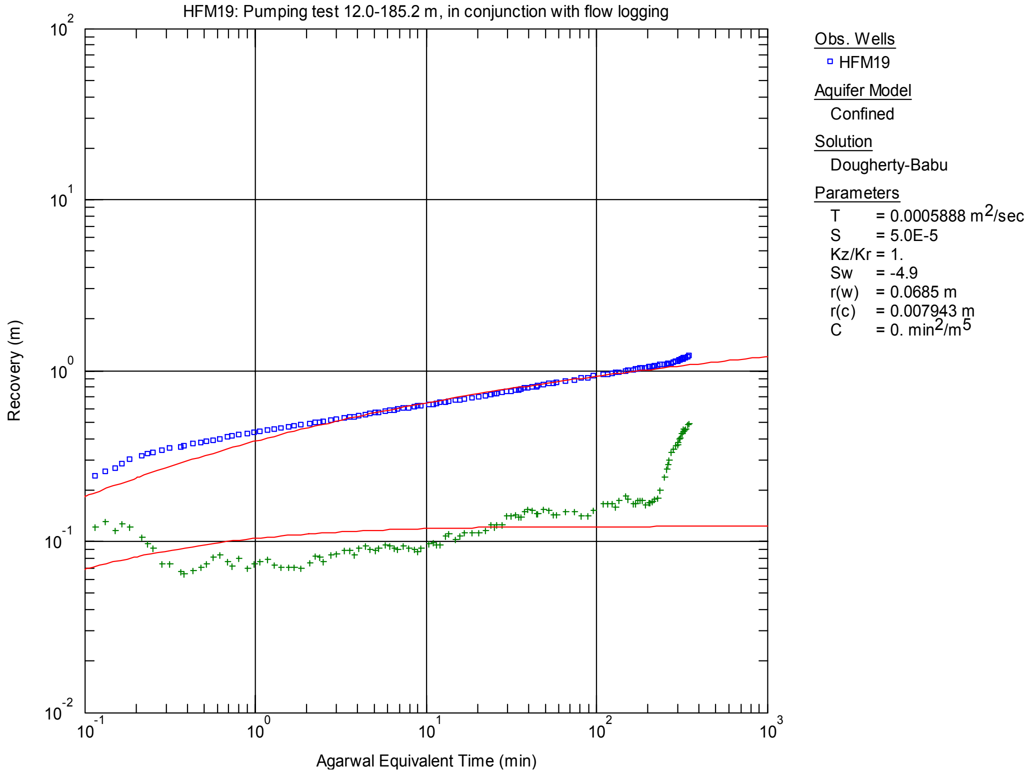


Figure A2-14. *Log-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM19. Displaying fit to Dougherty-Babu solution.*

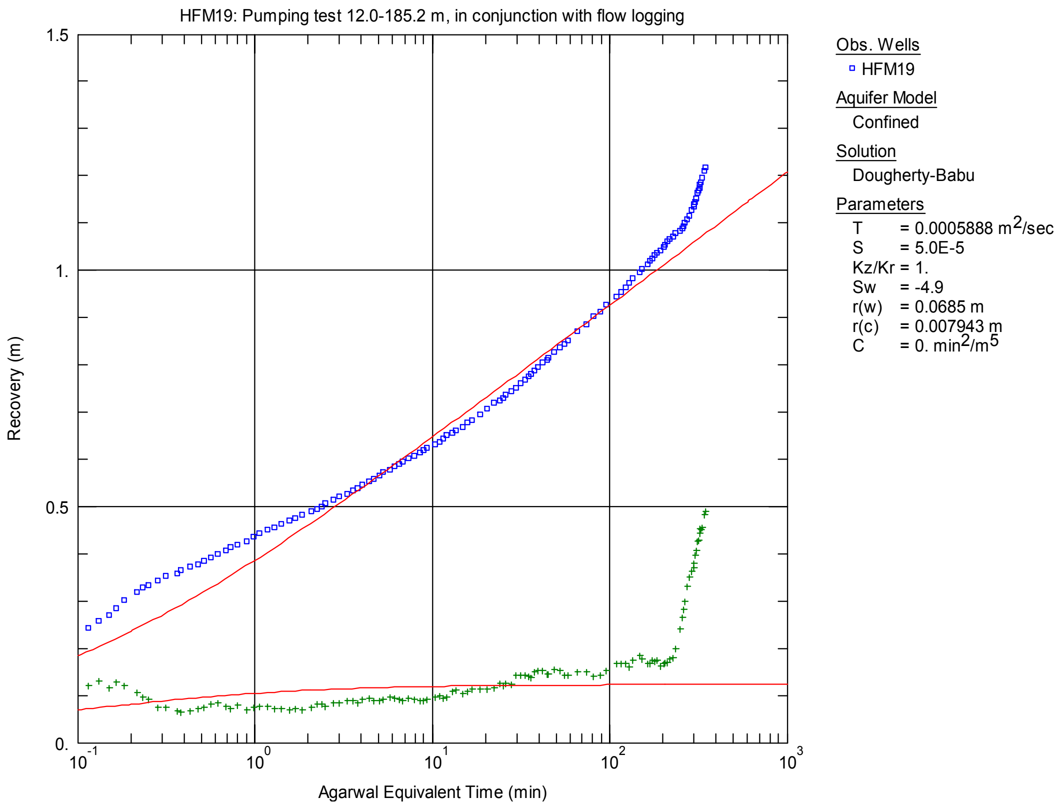


Figure A2-15. *Lin-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM19. Displaying fit to Dougherty-Babu solution.*

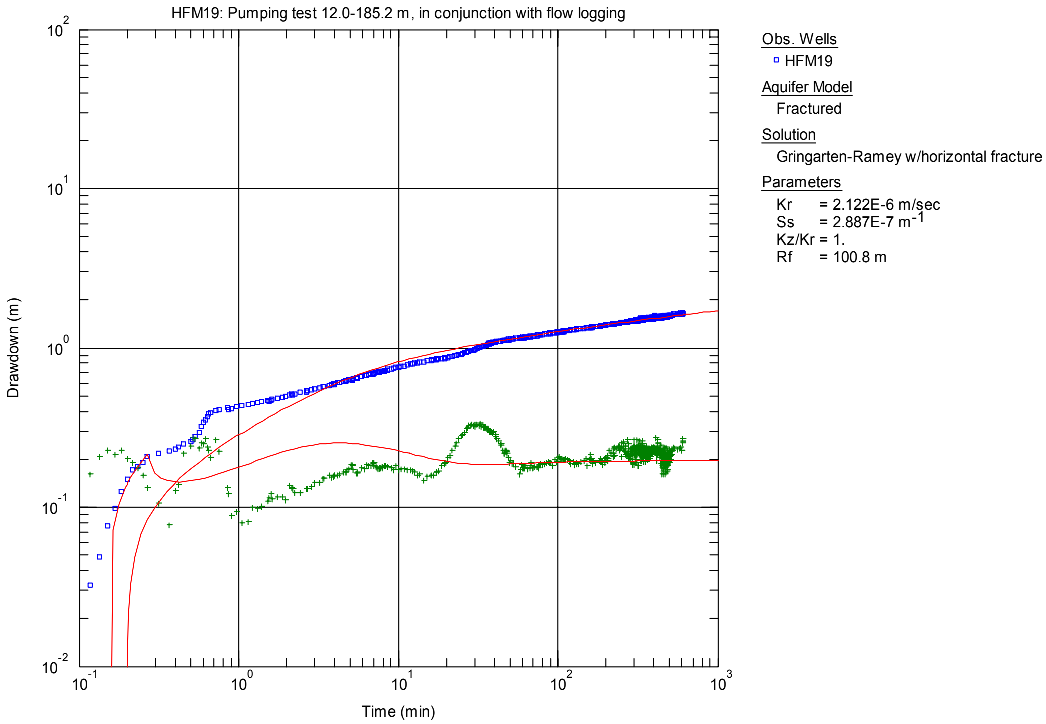


***Figure A2-16.** Log-log plot of drawdown (blue □) and drawdown derivative (green +) versus time during the open-hole pumping test in HFM19. Displaying fit to alternative solution, Gringarten-Ramey, the values for K_r and S_s are under assumption of the formation thickness 173.2 m.*

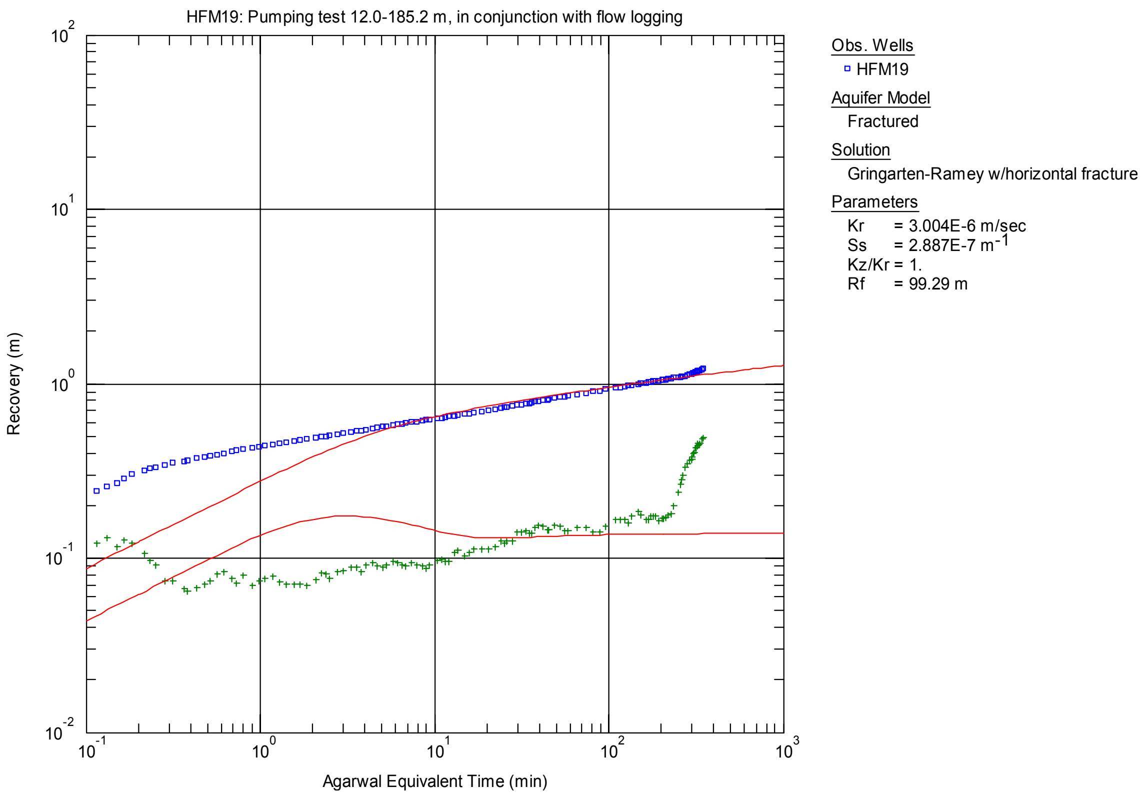


***Figure A2-17.** Log-log plot of pressure recovery (blue □) and - derivative (green +) dsp/d(ln dte) versus equivalent time (dte) from the open-hole pumping test in HFM19. Displaying fit to alternative solution Gringarten-Ramey, the values for K_r and S_s are under assumption of the formation thickness 173.2 m.*

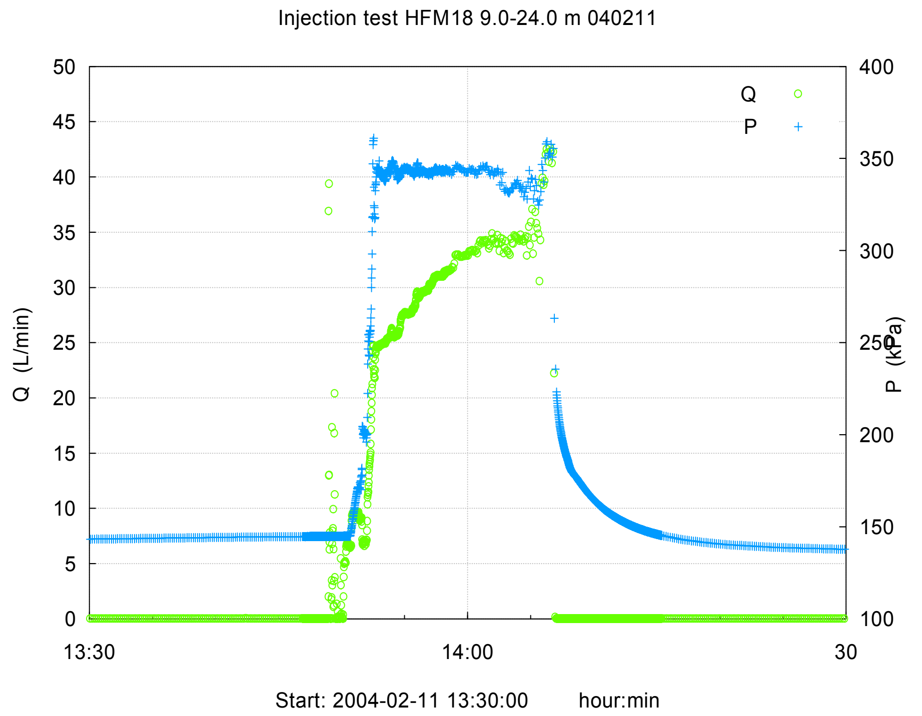


Figure A2-18. *Linear plot of flow rate (Q) and pressure (p) versus time during the injection test in the interval 9.0-24.0 m in HFM18.*

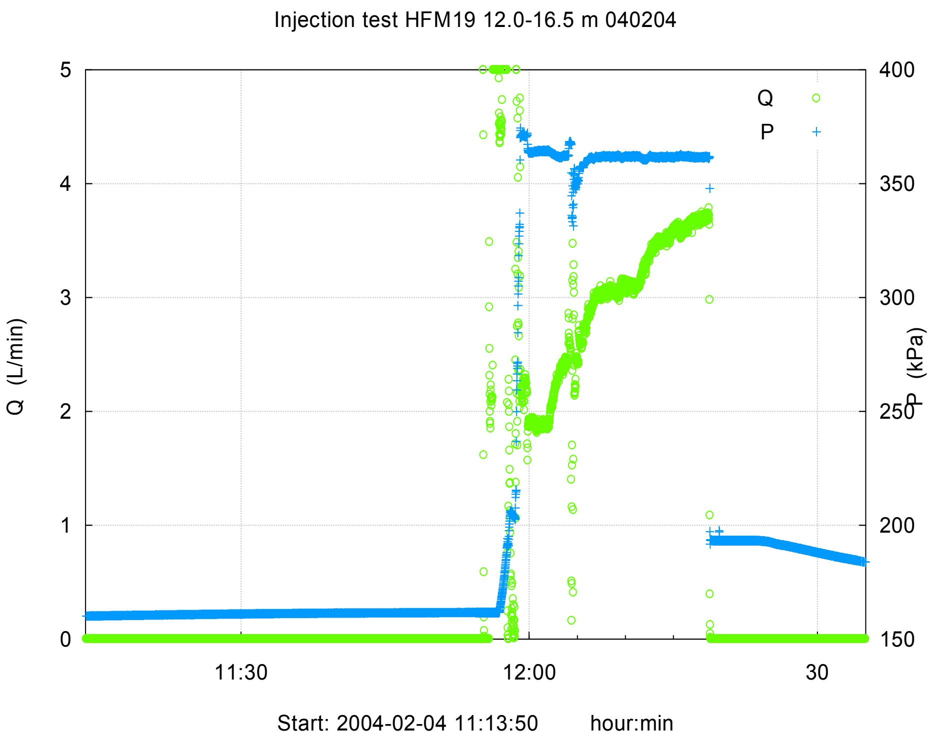


Figure A2-19. *Linear plot of flow rate (Q) and pressure (p) versus time during the injection test in the interval 12.0-16.5 m in HFM19.*

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 logging

A. Result Table for Single-hole tests for submission to the Sicada database

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_d; General information

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	Date and time for test, start YYYYMMDD hh:mm	Date and time for test, stop YYYYMMDD hh:mm	Start flow/ injection hhmmss	Stop flow/ injection hhmmss	Q_p (m^3/s)	Value type	Q-measl-L (m^3)/s	Q-measl-U (m^3)/s	V_p (m^3)	Q_m (m^3/s)
HFM17	8.00	210.65	1B	open-hole	20040127 04:02	20040128 08:51	20040127 08:31:52	20040127 18:32:59	5.20E-04	0	8.3E-05	1.3E-03	20.5	5.67E-04
HFM17	8.00	21.00	1B	above packer	20040128 11:58	20040128 14:20	20040128 12:06:00	20040128 13:12:04	<8.33E-06	-1	8.3E-06	1.3E-03	0.03	<8.33E-06
HFM18	9.00	180.65	1B	open-hole	20040210 09:12	20040211 09:00	20040210 09:20:20	20040210 19:21:03	8.72E-04	0	8.3E-05	1.3E-03	31.5	8.74E-04
HFM19	12.00	185.20	1B	open-hole	20040202 22:17	20040204 08:12	20040203 08:17:49	20040203 18:21:55	9.08E-04	0	8.3E-05	1.3E-03	32.9	9.08E-04

cont.

t_p (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 (-)
36067	51540	0.85	-8.15	0.64	203.47	115.06	202.75	-	-	-	-		
3964	4080	-	-	-	203.07	102.67	122.60	-	-	-	-		
36043	49152	1.00	-6.02	0.93	195.98	128.26	196.78	-	-	-	-		
36253	49800	0.85	-0.79	0.41	148	131.88	143.67	-	-	-	-		

Test Type: 1B: Pumping test-submersible pump,

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_obs

Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YYYYMMDD hh:mm	Section Above		Section below		p_{ai} (kPa)	p_{ap} (kPa)	p_{aF} (kPa)	p_{bi} (kPa)	p_{bp} (kPa)	p_{bF} (kPa)
				secup (m)	seclow (m)	secup (m)	seclow (m)						
HFM17	8.00	21.00	20040128 11:58			22.00	210.65				276.11	275.98	275.95

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_ed1; Basic evaluation

Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YYYYMMDD hh:mm	Q/s (m^2/s)	Value type (-1, 0 or 1)	T_Q (m^2/s)	T_M (m^2/s)	b (m)	B (m)	TB (1D) (m^3/s)	TB-measl-L (1D) (m^3/s)	TB-measl-U (1D) (m^3/s)	SB (1D) (m)	SB* (1D) (m)	L_f (1D) (m)	T_T (2D) (m^2/s)	Value type (-1, 0 or 1)
HFM17	8.00	210.65	20040127 04:02	5.77E-05	0	-	7.61E-05	202.65	-	-	-	-	-	-	-	3.93E-05	0
HFM17	8.00	21.00	20040128 11:58	<8.14E-07	-1	-	<7.18E-07	13.00	-	-	-	-	-	-	-	-	-
HFM18	9.00	180.65	20040210 09:12	1.26E-04	0	-	1.63E-04	171.65	-	-	-	-	-	-	-	-	-
HFM19	12.00	185.20	20040202 22:17	5.54E-04	0	-	7.17E-04	173.20	-	-	-	-	-	-	-	3.37E-04	0

cont.

Q/s-measl-L (m^2/s)	Q/s-measl-U (m^2/s)	S (2D) (-)	S* (2D) (-)	K´/b´ (2D) (1/s)	K_S (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	L_p (m)	C (m^3/Pa)	C_D (-)	ξ (2D) (-)	ω (-)	λ (-)	t_1 (s)	t_2 (s)	Comments (-)
2E-06	2E-03	-	5.0E-05	-	-	-	-	-	-	-	1.6E-06	-	-3.7	-	-	600	6000	
6E-07	2E-03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
2E-06	2E-03	-	-	-	-	-	-	-	-	-	2.7E-06	-	-	-	-	-	-	
2E-06	2E-03	-	5.0E-05	-	-	-	-	-	-	-	-	-	-5.5	-	-	300	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 - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumpingtest-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-sequential, 5B: Difference flow logging-PFL-DIFF-overlapping, 6:Flow logging_Impeller,7:Grain size analysis
Date for test start		Date for the start of the pumping or injection test (YYYYMMDD hh:mm)
Start flow / injection		Date and time for the start of the pumping or injection period (YYMMDD hh:mm:ss)
Start flow / injection		Date and time for the end of the pumping or injection period (YYMMDD hh:mm:ss)
Q_m	m^3/s	Arithmetric mean flow rate of the pumping/injection period.
Q_p	m^3/s	Flow rate at the end of the pumping/injection period.
Value type	-	Code for Q_p-value; -1 means Q_p<lower measurement limit, 0 means measured value, 1 means Q_p> upper measurement value of flowrate
Q-measl_L	m^3/s	Estimated lower measurement limit for flow rate
Q-measl_U	m^3/s	Estimated upper measurement limit for flow rate
V_p	m^3	Total volume pumped (positive) or injected (negative) water during the flow period.
t_p	s	Time for the flowing phase of the test
t_F	s	Time for the recovery phase of the test
h_i	m	Initial formation hydraulic head. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_p	m	Final hydraulic head at the end of the pumping/injection period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_F	m	Final hydraulic head at the end of the recovery period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
p_i	kPa	Initial formation pressure.
p_p	kPa	Final pressure at the end of the pumping/injection period.
p_F	kPa	Final pressure at the end of the recovery period.
Te_w	gr C	Fluid temperature in the test section representative for the evaluated parameters
EC_w	mS/m	Electrical conductivity of the fluid in the test section representative for the evaluated parameters
TDS_w	mg/L	Total salinity of the fluid in formation at test section based on EC.

Header	Unit	Explanation
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	m^2/s	Specific capacity, based on Qp and s=abs(pi-pp). Only given for test section (label 1) in interference test.
T_Q	m^2/s	Transmissivity based on specific capacity and a a function for T=f(Q/s). The fuction used should be refered in "Comments"
T_M	m^2/s	Transmissivity based on Moye (1967)
b	m	Interpreted formation thickness representative for evaluated T ot TB.
B	m	Interpreted witdth of a formation with evaluated TB
TB	m^3/s	1D model for evaluation of formation properties. T=transmissivity, B=width of formation
TB-measl-L	m^2/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	m^2/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	m^2/s	2D model for evaluation of formation properties. T=transmissivity
T-measl-L	m^2/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	m^2/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

Header	Unit	Explanation
S_S*	1/m	3D model for evaluation of formation properties. Assumed Ss. Ss=Specific Storage
L_p	m	Hydraulic point of appication, based on hydraulic conductivity distribution (if available) or the midpoint of the borehole test section
C	(m^3/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
Borehole secup	m	Length coordinate along the borehole for the upper limit of the observation section
Borehole seclow	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

B. Result Table for Flow logging at drill site 1 at Forsmark site investigation for submission to the Sicada database

FLOWLOGG-IMPELLER TESTS-Main

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	Date and time of test, start YYYYMMDD hh:mm	Date and time of stop of flow period YYYYMMDD hh:mm	Date and time of flowl., start YYYYMMDD hh:mm	Date and time of flowl., stop YYYYMMDD hh:mm	Q-measl-L (m^3/s)	Q-measl-U (m^3/s)	Q_p (m^3/s)
HFM17	21	205	6	1	20040127 04:02	20040127 18:32	040127 14:00	040127 16:55	5.00E-05	1.67E-03	5.20E-04
HFM18	24	175	6	1	20040210 09:12	20040210 19:21	040210 13:30	040210 16:51	5.00E-05	1.67E-03	8.73E-04
HFM19	16.5	171.5	6	1	20040202 22:17	20040203 18:21	040203 12:50	040203 16:51	5.00E-05	1.67E-03	9.08E-04

cont.

tp (s)	t_{FL} (s)	h_0 (m a s l)	h_p (m a s l)	s_{FL} (m)	Reference (-)	Comments (-)
36060	10500	0.85	-8.15	8.97		
36060	12060	1	-6.02	6.92		
36240	14460			1.53		

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

plu_impell-main_res

Borehole	Borehole secup (m)	Borehole seclow (m)	Te_{w0} (° C)	EC_{w0} (mS/m)	TDS_{w0} (mg/ L)	Q_0 (m^3/s)	Te_w (° C)	EC_w (mS/m)	TDS_w (mg/ L)	Q_{1T} (m^3/s)	Q_T (m^3/s)	Q_{Tcorr} (m^3/s)	T Entire hole (m^2/ s)	T_{FT} (m^2/ s)
HFM17	21	205	-	-	-	-	-	-	-	2.58E-04	2.58E-04	5.20E-04	3.93E-05	3.93E-05
HFM18	24	175	-	-	-	-	-	-	-	8.67E-04	8.67E-04	8.67E-04	1.63E-04	1.62E-04
HFM19	16.5	171.5	-	-	-	-	-	-	-	-	-	9.08E-04	3.37E-04	3.37E-04

continued plu_impell-main_res

T_F-measl-L (m^2/ s)	T_F-measl-U (m^2/ s)	Reference (-)	Comments (-)
2E-06	2E-03		bh. diam=138.2-135.5 mm, flow calibr.=135.5 mm
2E-06	2E-03		bh. diam=140.0-137.7 mm, flow calibr.=140.0 mm
2E-06	2E-03		bh. diam=140.2-137.0 mm, flow calibr.=140.0 mm

FLOWLOGG-IMPELLER TESTS plu_impeller_anomaly

Borehole	Borehole secup (m)	Borehole seclow (m)	Upper limit L (m)	Lower limit L (m)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	$deltaQ_i$ (m^3/s)	$deltaQ_{icorr}$ (m^3/s)	$deltaQ_{icorr}/s_{FL}$ (m^2/s)	b_i (m)	T_i (m^2/s)	T_i-measl-L (m^2/s)	T_i-measl-U (m^2/s)	Ref-erence (-)	Comments (-)
HFM17	21	205	30	32.5	-	-	-	2.58E-04	5.20E-04	5.80E-05	2.5	3.93E-05	1.26E-06	3.93E-05	-	Assumption $Q_T = Q_p$
HFM18	24	175	36.5	38	-	-	-	4.17E-04	4.17E-04	6.02E-05	1.5	7.78E-05	3.11E-06	1.63E-04	-	
HFM18	24	175	46	46.5	-	-	-	3.17E-04	3.17E-04	4.58E-05	0.5	5.91E-05	3.11E-06	1.63E-04	-	
HFM18	24	175	48	48.5	-	-	-	1.33E-04	1.33E-04	1.93E-05	0.5	2.49E-05	3.11E-06	1.63E-04	-	
HFM19	16.50	171.50	100	102	-	-	-	-	1.08E-04	7.08E-05	2	4.02E-05	6.19E-06	3.37E-04	-	Assumption $Q_T = Q_p$
HFM19	16.50	171.50	148	150	-	-	-	-	4.17E-05	2.72E-05	2	1.55E-05	6.19E-06	3.37E-04	-	Assumption $Q_T = Q_p$
HFM19	16.50	171.50	160	163	-	-	-	-	1.67E-05	1.09E-05	3	6.18E-06	6.19E-06	3.37E-04	-	Assumption $Q_T = Q_p$
HFM19	16.50	171.50	170	182.5	-	-	-	-	7.42E-04	4.85E-04	13	2.75E-04	6.19E-06	3.37E-04	-	Assumption $Q_T = Q_p$

Header	Unit	Description
Date/time test start	date	Date for the stop of the test (YYYY-MM-DD hh:mm)
Date/time test stop	date	Date for the stop of the test (YYYY-MM-DD hh:mm)
Borehole	idcode	Object or borehole identification code
Borehole secup	m	Lengt coordinate along the borehole for the upper limit of the logged section (Based on corrected length L)
Borehole seclow	m	Lengt coordinate along the borehole for the lower limit of the logged section. (Based on corrected length L)
date and time, start	date_s	Date and time of flowlogging start (YYYY-MM-DD hh:mm:ss)
date and time, stop	date_s	Date and time of flowlogging stop (YYYY-MM-DD hh:mm:ss)
Test type (1-7)	code_chr_2	1A: Pumping test - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumpingtest-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-comb.Sequentia, 5B: Difference flow logging-PFL-DIFF-Overlapping, 6: Flow logging-Impeller 7: Grain size analysis
Formation type	code_chr_2	1: Rock, 2: Soil (supeficial deposits)
Q-measl-L	m^3/s	Estimated lower measurement limit for borehole flow rate in flowlogging probe
Q-measl-U	m^3/s	Estimated upper measurement limit for borehole flow rate in flowlogging probe
Q_p	m^3/s	Flow rate at surface during flowlogging
tp	s	Time for the flowing phase of the test
t_{FL}	s	Duration of the flowlogging survey
s_{FL}	m	Average drawdown of the water level in open borehole during flowlogging
h_0	masl	Initial hydraulic head. Measured as water level in open borehole with reference level in the local coordinates system with z=0 m.
h_p	masl	Stabilised hydraulic head during first pumping period. Measured as water level in open borehole with reference level in the local coordinates system with z=0 m.
L, Corrected	m	Corrected length to point considered representative for measured value
Q	m^3/s	Cumulative flow rate:Q1-Qo. Position for measurement is related to L (corrected length)
Q_0	m^3/s	Natural (undisturbed) measured cummulative flow rate. Position for measurement is related to L (corrected lenght)
Q_1	m^3/s	Cumulative flow rate during pumping. Position for measurement is related to L (corrected length)
Q_{1T}	m^3/s	Cummulative flow rate:Q_1 at the top of measured interval
Q_T	m^3/s	Cummulative flow rate:Q at the top of measured interval
$Q_T$corr	m^3/s	Cummulative flow rate:QTat the top of measured interval, based on corrected borehole diameter

Header	Unit	Description
T(Entire hole)	m^2/s	Evaluated transmissivity for the entire hole section that is considered representative for the flowlogging (also reported in data file for single-hole interpretation)
T_F	m^2/s	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/s	Cumulative transmissivity of the entire measured interval, based on impeller measurement
T_F-measl-L	m^2/s	Estimated lower measurement limit for evaluated T_F. If estimated T_F equals T-measlim in the table, the actual T_F is considered to be equal or less than T_F - measlim
T_F-measl-U	m^2/s	Estimated upper measurement limit for evaluated T_F. If estimated T_F equals T-measlim in the table, the actual T_F is considered to be equal or greater than T_F - measlim
Te_{w0}	gr C	Natural (undisturbed) fluid temperature in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected lenght)
EC_{w0}	mS/m	Natural (undisturbed) electrical conductivity of the fluid in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected lenght)
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 lenght)
Upper limit	m	Corrected length coordinate along the borehole for the upper limit of the flow anomaly
Lower limit	m	Corrected length coordinate along the borehole for the lower limit of the flow anomaly
Te_w	centigrade	Natural (undisturbed) fluid temperature in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected lenght)
EC_w	mS/m	Natural (undisturbed) electrical conductivity of the fluid in the test section representative for the evaluated parameters. Position for measurement is related to L (corrected lenght)
TDS_w	mg/L	Natural (undisturbed) total salinity of the fluid in the test section representative for the evaluated parameters based on EC. Position for measurement is related to L (corrected lenght)
deltaQ_i	m^3/s	deltaQi : Flow rate of interpreted flow anomaly i
deltaQ_{icorr}	m^3/s	deltaQicorr : Flow rate of interpreted flow anomaly calculated with corrected borehole diameter.
deltaQ_i/S_{FL}	m^2/s	deltaQi/s_{FL}: Specific capacity of interpreted flow anomaly
b_i	m	Interpreted formation thickness representative for evaluated Ti of anomaly i.
T_i	m^2/s	Evaluated transmissivity of flow anomaly i considered representative for the flow logging
T_i-measlim-L	m^2/s	Estimated lower measurement limit for evaluated T_i. If estimated T_i equals T-measlim in the table actual T_i is considered to be equal or less thanT_i-measlim
T_i-measlim-L	m^2/s	Estimated upper measurement limit for evaluated T_i. If estimated T_i equals T_i-measlim in the table actual T_i is considered to be equal or greater thanT_i-measlim

Header	**Unit**	**Description**
Reference	text_30	SKB number for reports describing data and results
Comments	text_50	Short comment on evaluated parameters