P-08-87

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Hydraulic tests, flow logging and hydrochemical sampling

Boreholes HFR101, HFR102 and HFR105

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Abstract

SKB conducts bedrock investigations for a future extension of the final repository for radioactive operational waste (SFR) at Forsmark in the Östhammar municipality. As part of this investigation boreholes HFR101, HFR102 and HFR105 were drilled.

The main objectives of the hydraulic tests in percussion boreholes were to investigate the hydraulic characteristics of the rock (e.g. occurrence and hydraulic transmissivity of different hydraulic conductors) and to obtain water samples for analysis of the water chemistry characteristics of the boreholes.

In the initial plan, pumping tests combined with flow logging was intended. However, when drilling HFR102 a very low transmissivity was indicated, making a pumping test hard to conduct. An injection test below a packer was made instead, using new equipment more adapted to low transmissivities. In HFR101 the water table was situated c. 30 m down hole and therefore, to be able to investigate the upper part of the borehole, an injection test combined with flow logging was performed. In HFR101 and HFR105 short capacity tests were made to decide whether it was meaningful to make a hydraulic test in combination with flow logging or only a pumping or injection test, and to decide a suitable flow rate for the hydraulic tests. Since the flow rate capacity was high enough, flow logging was performed in both boreholes.

Water samples were collected in HFR101 (during the capacity test) and HFR105 in conjunction with the hydraulic tests to obtain information on groundwater composition. No pumping was conducted in HFR102 and hence no water samples were obtained from this borehole.

The total borehole transmissivity of HFR101 was estimated at $2.8 \cdot 10^{-6}$ m^2/s. During the flow logging two flow anomalies could be detected.

The total borehole transmissivity of HFR102 was estimated at $2.8 \cdot 10^{-6}$ m^2/s. In this short borehole only an injection test below a packer located immediately below the casing was made.

In HFR105 the total transmissivity was estimated at $2.3 \cdot 10^{-5}$ m^2/s. A complementary pumping test above a packer was carried out in the upper part of the borehole between 21.12 and 38.0 m to ensure that all anomalies were detected by the flow logging. The transmissivity in this interval was estimated at $7.8 \cdot 10^{-7}$ m^2/s. During the flow logging, three flow anomalies were detected.

Sammanfattning

SKB bedriver bergundersökningar inför en framtida utbyggnad av slutförvaret för radioaktivt driftavfall (SFR) vid Forsmark i Östhammars kommun. Som en del av denna undersökning borrades undersökningsborrhålen HFR101, HFR102 och HFR105.

Huvudsyftet med de hydrauliska testerna i borrhålen var att undersöka de hydrauliska egenskaperna i berget (t ex förekomst av och hydraulisk transmissivitet hos olika hydrauliska ledare) och att ta vattenprover för analys av berggrundvattnets kemiska sammansättning.

Enligt den ursprungliga planen skulle pumptester kombinerade med flödesloggning utföras. Under borrningen av HFR102 fick man dock indikationer på mycket låga transmissivitetsvärden som skulle göra pumptester svåra att genomföra. Därför gjordes i stället ett injektionstest under en enkelmanschett med en utrustningen som var lämpad för ändamålet än den ordinarie. I HFR101 låg grundvattenytan ca 30 m ner i borrhålet och därför genomfördes, för att möjliggöra flödesloggning i borrhålets övre del, ett injektionstest kombinerat med flödesloggning i detta borrhål. I HFR101 och HFR105 gjordes dessutom korta kapacitetstest för att avgöra om det var meningsfullt med flödesloggning och för att bestämma lämpligt flöde under de hydrauliska testerna. Eftersom flödeskapaciteten var tillräckligt hög genomfördes flödesloggning i båda borrhålen.

Vattenprover togs i HFR101 (under kapacitetstestet) och i HFR105 i samband med de hydrauliska testerna. I HFR102 gjordes ingen pumpning och därför finns inga vattenprover från detta borrhål.

Den totala transmissiviteten i HFR101 beräknades till $2.8 \cdot 10^{-6}$ m^2/s. Under flödesloggningen identifierades två flödesanomalier.

Den totala transmissiviteten i HFR102 beräknades till $2.8 \cdot 10^{-6}$ m^2/s. I detta korta borrhål gjordes endast ett injektionstest under en manschett placerad strax under casingen.

I HFR105 beräknades den totala transmissiviteten till $2.3 \cdot 10^{-5}$ m^2/s. Ett kompletterande test gjordes i övre delen av detta borrhål (21.1–38 m) för att man ville försäkra sig om att alla större flödesanomalier hade detekterats i borrhålet. Transmissiviteten i detta intervall beräknades till $7.8 \cdot 10^{-7}$ m^2/s. Under flödesloggningen i borrhålet identifierades tre flödesanomalier.

Contents

1	**Introduction**	9
2	**Objectives**	11
3	**Scope**	13
3.1	Boreholes tested	13
3.2	Tests performed	13
3.3	Equipment check	13
4	**Description of equipment**	15
4.1	Overview	15
4.2	Measurement sensors	16
5	**Execution**	19
5.1	Preparations	19
5.2	Procedure	19
	5.2.1 Overview	19
	5.2.2 Details	19
5.3	Data handling	20
5.4	Analyses and interpretation	21
	5.4.1 Single-hole hydraulic tests	21
	5.4.2 Flow logging	23
6	**Results**	25
6.1	Nomenclature and symbols	25
6.2	Water sampling	25
6.3	Single-hole hydraulic tests	25
	6.3.1 Borehole HFR101: 8.0–209.3 m	26
	6.3.2 Borehole HFR102: 10.4–55.0 m	28
	6.3.3 Borehole HFR105: 21.1–200.5 m	30
	6.3.4 Borehole HFR105: 21.1–38.0 m	32
6.4	Flow logging	33
	6.4.1 Borehole HFR101	33
	6.4.2 Borehole HFR105	37
6.5	Summary of hydraulic tests	40
7	**References**	49
Appendix 1	List of data files	51
Appendix 2	Test diagrams	53
Appendix 3	Result tables to Sicada database	65
Appendix 4	Results from chemical analyses	77

1 Introduction

SKB conducts bedrock investigations for a future extension of the final repository for radioactive operational waste (SFR) in Forsmark in the Östhammar municipality. The extension project named ”Projekt SFR-utbyggnad” consists of a number of sub projects. One of those is the sub project Investigations to which this activity belongs.

This document reports the results of the hydraulic testing of the percussion-drilled boreholes HFR101, HFR102 and HFR105. The tests were carried out as a injection test combined with flow logging in borehole 101, a pumping test combined with flow logging in HFR105 and an injection test below a single packer in HFR102. In borehole HFR105 a complementary pumping test above a packer at 38 m was also performed. Water sampling was undertaken in conjunction with the tests in HFR101 and HFR105, in HFR101 as an additional pumping the day before the injection test. No other hydraulic tests had been carried out in the actual boreholes before this campaign.

All three boreholes are situated in the vicinity of the SFR repository, see Figure 1-1.

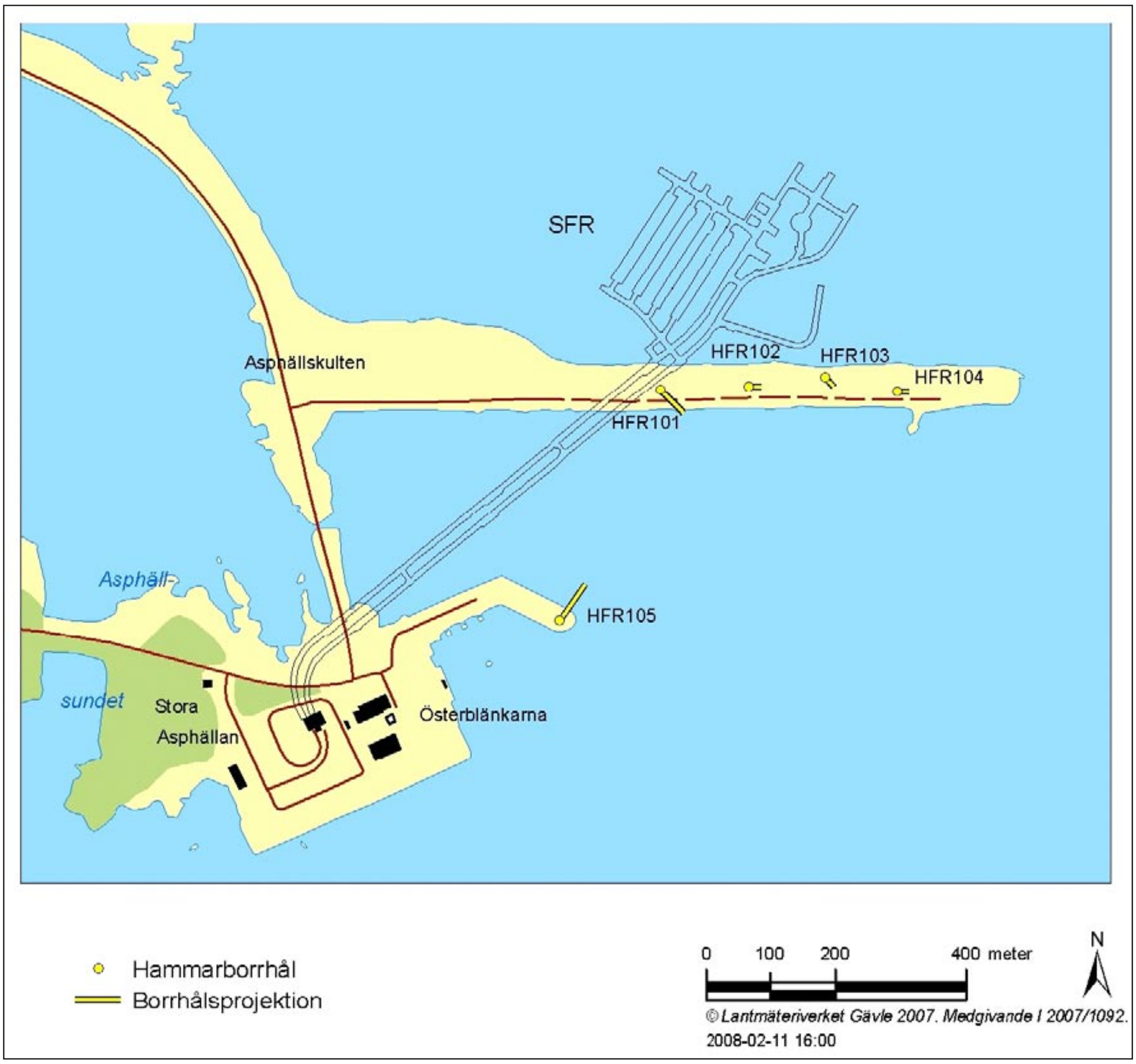


Figure 1-1. *Map showing the location of boreholes HFR101, HFR102 and HFR105.*

All time notations in this report are made according to Swedish Summer Time (SSUT), UTC +2 h.

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, where they are traceable by the Activity Plan number.

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

Activity Plan	Number	Version
Hydrotester och vattenprovtagning i hammarborrhålen HFR101, HFR102, HFR103, HFR104 och HFR105	AP SFR-08-005	1.0
Method documents	**Number**	**Version**
Metodbeskrivning för hydrauliska enhålspumptester	SKB MD 321.003	1.0
Metodbeskrivning för flödesloggning	SKB MD 322.009	1.0
Metodbeskrivning för hydrauliska injektionstester	SKB MD 323.001	
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
Metodbeskrivning för enkel vattenprovtagning i hammarborrhål och kärnborrhål	SKB MD 423.002	2.0

2 Objectives

The objective of the hydraulic tests (injection and pumping tests) and flow logging in boreholes HFR101, HFR102 and HFR105 was to investigate the hydraulic properties of the penetrated rock volumes, and to identify the position and hydraulic character of major inflows (which may represent e.g. sub-horizontal fracture zones). Furthermore, another aim was to collect water samples to obtain information on groundwater composition.

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, measured as the diameter of the drill bit, refers to the initial diameter just below the casing. The borehole diameter decreases more or less along the borehole due to wearing of the drill bit.

3.2 Tests performed

The different test types conducted in the boreholes, as well as the test periods, are presented in Table 3-2.

During an additional pumping test in HFR101 the day before the injection test and during the pumping test in borehole HFR105 water samples were collected and submitted for analysis, see Section 6.2. During the tests, manual observations of the groundwater level in the pumped boreholes were also made (if possible).

3.3 Equipment check

Prior to the tests, an equipment check was performed to establish the operating status of sensors and other equipment. In addition, calibration constants were implemented and checked. To check the function of the pressure sensor P1 (cf. Figure 4-1), the pressure in air was recorded and found to be as expected. While lowering the pressure sensor into the borehole, measured pressure coincided well with the total head of water (p/ρg). The temperature sensor displayed expected values in both air and water.

The sensor for electric conductivity displayed a zero value in air and a reasonable value in borehole water.

The measuring wheel (used to measure the position of the flow logging probe) and the sensor attached to it indicated a length that corresponded well to the pre-measured length marks on the signal cable.

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.)	Bore-hole length from ToC (m)	Bh-diam. (below casing) (m)	Inclin. -top of bh (from horizontal plane) (°)	Dip-Direction -top of bh (°)	Northing (m)	Easting (m)	Length (m)	Inner diam. (m)	Date (YYYY-MM-DD)
HFR101	2.63	209.30	0.139	–69.93	133.55	6,701,725	1,632,838	8.04	0.160	2008-05-14
HFR102	2.32	55.04	0.138	–59.36	85.00	6,701,729	1,632,975	9.04	0.160	2008-05-05
HFR105	3.27	200.50	0.141	–61.77	35.43	6,701,377	1,632,686	21.12	0.160	2008-04-22

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)
HFR101	8.0–209.3	3	Open hole	2008-05-23 09:27	2008-05-26 10:46
HFR101	8.0–207.3	6, L-EC, L-Te	Open hole	2008-05-23 13:55	2008-05-23 15:44
HFR102	10.4–55.0	3	Below packer	2008-05-28 12:43	2008-05-28 14:53
HFR105	21.1–200.5	1B	Open hole	2008-04-25 07:46	2008-04-28 11:43
HFR105	21.1–190.0	6, L-EC, L-Te	Open hole	2008-04-25 14:05	2008-04-25 15:03
HFR105	21.1–38.0	1B	Above packer	2008-04-29 13:08	2008-04-29 16:34

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

4 Description of equipment

4.1 Overview

The basic equipment used in these tests is referred to as HTHB (Swedish abbreviation for Hydraulic Test System for Percussion Boreholes) and is described in the user manual of the measurement system.

The HTHB unit is designed to perform pumping- and injection tests in open percussion drilled boreholes (Figure 4-1), and in isolated sections of the boreholes (Figure 4-2) down to a total depth (borehole length) 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). For injection tests, however, the upper packer cannot be located deeper than c. 80 m due to limitations in the number of pipes available.

All equipment that belongs to the HTHB system is, when not in use, stored on a trailer and can easily be transported by a standard car. The borehole equipment includes a submersible borehole pump with housing, expandable packers, pressure sensors and a pipe string and/or hose. During flow logging, the 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.

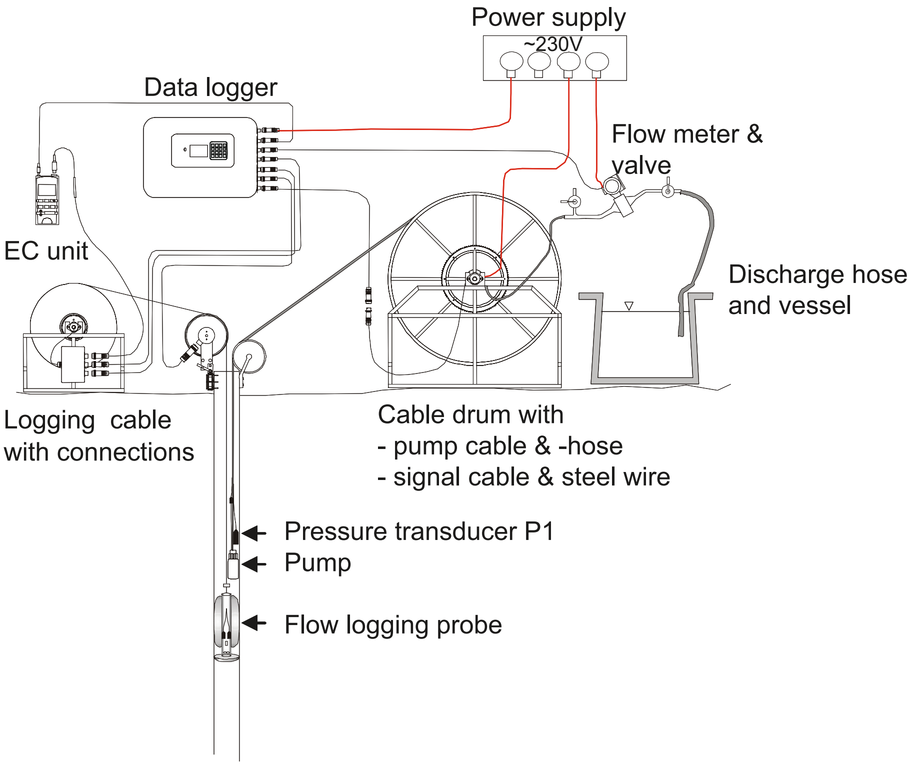


Figure 4-1. *Schematic test set-up for a pumping test in an open borehole in combination with flow logging with HTHB. (From SKB MD 326.001, SKB internal document).*

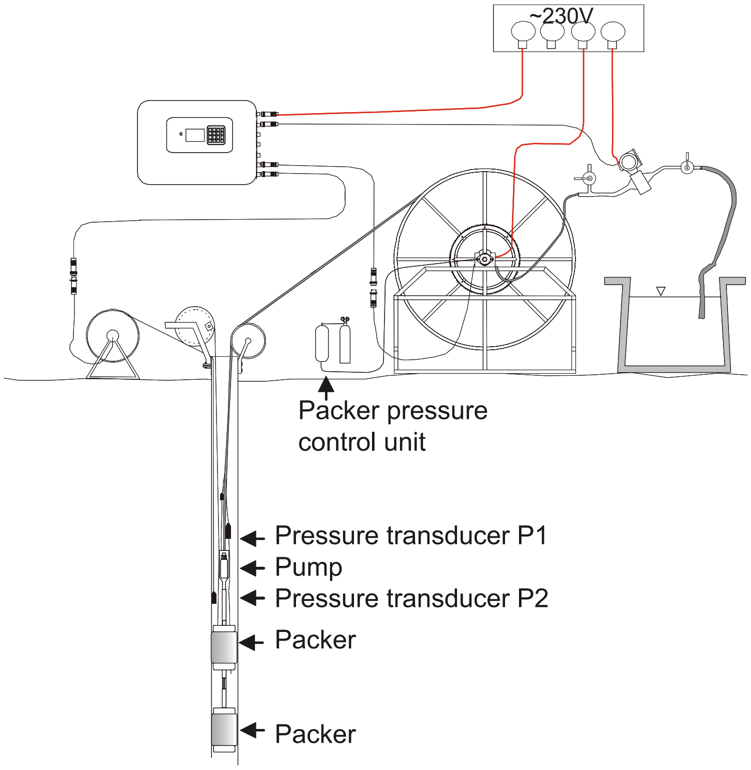


Figure 4-2. *Schematic test set-up for a pumping test in an isolated borehole section with HTHB. (From SKB MD 326.001, SKB internal document).*

The packers are normally expanded by water (nitrogen gas is used for pressurization) 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 (if required).

Since the flow logging probe in the HTHB system is manually raised or lowered, it is not suited for continuous flow logging along the borehole. Instead, the flow is measured over a certain time with the probe located at consecutive fixed positions. For different reasons though, it is advantageous to perform flow logging with a continuously moving probe. When the probe is moved in the opposite direction to the flow along the borehole the threshold flow value will always be exceeded. The location for the inflow will be more accurately determined and the flow rate between two flow anomalies determined as a mean at a number of measuring points. For these reasons, the Geosigma flow logging probe with a motor-driven cable drum was used instead of the ordinary HTHB probe and drum.

Observations of the pressure recovery after drilling indicated a very low inflow to borehole HFR102. Since the HTHB equipment cannot measure flow rates below c. 1 L/min, the injection test in HFR102 was carried out with the Geosigma WIC (Water Injection Control) equipment which a system able to perform automatically regulated constant head injection tests at very low flow rates (about 2 mL/min).

4.2 Measurement sensors

Technical data of the sensors used together with estimated data specifications of the test system (HTHB and Geosigma equipment) 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 test system for pumping tests and flow logging (based on current laboratory- and field experiences).

Parameter		Technical specification Unit	Sensor	System	Comments
Absolute pressure	Output signal	mA	4–20		
	Meas. range	kPa	0–1,500	0–1,500	
	Resolution	kPa	0.05		
	Accuracy	kPa	±1.5 *	±10	Depending on uncertainties of the sensor position
Temperature (Geosigma sensor)	Output signal	mA	4–20		
	Meas. range	°C	0–50	0–50	
	Resolution	°C	0.001		
	Accuracy	°C	± 0.6	±0.6	
Electric Conductivity (Geosigma sensor)	Output signal	V	0–9		
	Meas. range	mS/m	0–11,000	0–11,000	With conductivity meter
	Resolution	% o.r.**		1	
	Accuracy	% o.r.**		± 10	
Flow (Geosigma spinner, continuous logging)	Output signal	Pulses/s			140 mm borehole diameter
	Meas. range	L/min	c. 1–150	1–100	
	Resolution***	L/min		1	
	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	
Flow (Geosigma WIC)	Output signal	mA	4–20		
	Meas. range	L/min		0.002–64	
	Resolution	L/min		0.001	Flow rate < 1 L/min
		L/min		0.01	Flow rate > 1 L/min
	Accuracy	% o.r.**		1	Flow rate > 1 L/min

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

Table 4-2 presents the position of sensors for each test together with the level of the pump-intake of the submersible pump. The following types of sensors are used: pressure (P), temperature (Te), electric conductivity (EC). Positions are given in metres from the reference point, i.e. top of casing (ToC), to the lower part. The sensors measuring temperature and electric conductivity are located in the impeller flow-logging probe and the position is thus varying 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 not involved in the wellbore storage since the groundwater level always is kept above the top of the pump in open boreholes. Due to a failure in the pump cable attached to the pump hose an extra pump cable had to be used during the pumping tests.

In addition, the theoretical wellbore storage coefficient C for the actual test configurations and geometrical data of the boreholes were 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.

For tests where the change of water level occurs below the casing, two different values of the theoretical wellbore storage coefficient C can be estimated. One is based on the casing diameter and the other one is based on the actual borehole diameter below the casing.

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

ID	Borehole information Test interval (m)	Test config	Test type [1]	Sensors Type	Position (m b ToC)	Equipment affecting wellbore storage (WBS) Function	Position [2] relative test section	Outer diameter (mm)	C [3] (m^3/Pa)
HFR101	8.0–209.3	Open hole	3	P (P1)	31[4]	Signal cable	In section	8	$1.6 \cdot 10^{-6}$ (borehole)
	8.0– 207.3		6	EC, Te, Q	12.0–137.0	Signal cable	In section	10	$2.2 \cdot 10^{-6}$ (casing)
HFR102	10.4–55.0	Open hole	1B	P (P1)	5.72	Signal cable	Above section	8	$1.0 \cdot 10^{-10}$ (borehole)
HFR105	21.1–200.0	Open hole	1B	Pump-intake	16.25	Pump hose	In section	33.5	$2.2 \cdot 10^{-6}$ (casing)
			1B			Pump cable	In section	14.5	
			1B			Extra pump cable	In section	14.5	
			1B			Steel wire	In section	5	
			1B			Polyamide tube	In section	6	
			1B	P (P1)	15.5	Signal cable	In section	8	
	21.1–190.0		6	EC, Te, Q	21.1–190.0	Signal cable	In section	10	
HFR105	21.1–38.0	Above packer	1B	Pump-intake	36.8	Pump hose	Above section	33.5	$1.6 \cdot 10^{-6}$ (borehole)
			1B			Pump cable	Above section	14.5	$2.3 \cdot 10^{-6}$ (casing)
						Extra pump cable	Above section	14.5	
			1B			Steel wire	Above section	5	
			1B			Polyamide tube	Above section	6	
			!B			Extra Polyamide tube	Above section	6	
			1B	P (P1)	33.5	Signal cable	Above section	8	

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

[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 actual borehole diameter (Table 3-1) for open-hole tests and the compressibility of water for the test in isolated sections, respectively (net values).

[4] The pressure transducer was lifted to ca 6.5 m below ToC during flow logging above 31 m.

5 Execution

5.1 Preparations

All sensors included in the HTHB system are calibrated at the Geosigma engineering service station in Uppsala. Calibration is generally performed on a yearly basis, but more often if needed. The latest calibration was performed in April 2008. If a sensor is replaced at the test site, calibration of the new sensor can be carried out in the field (except the flow probe) or alternatively, in the laboratory after the measurements

Functioning checks of the equipment used in the present test campaign were made prior to each hydraulic test. The results from the functioning checks are presented in Section 3.3.

Before the tests, cleaning of equipment as well as time synchronisation of clocks and data loggers were performed according to the Activity Plan.

5.2 Procedure

5.2.1 Overview

The main pumping test is normally preceded by a shorter capacity test (the day before) to determine a proper pumping flow rate. During the capacity test the flow rate is changed, considering the obtained response. Prior to the injection test in HFR101 a pumping test to collect water samples for chemical analyses was performed. No pumping test was performed in HFR102, but the recovery after drilling indicated low capacity.

Usually the main pumping is carried out as a single-hole, constant flow rate test followed by a pressure recovery period. Flow logging is performed at the end of the flow period. In borehole HFR101 the groundwater level was c. 29 m down hole, therefore, to be able to detect possible water bearing fractures above this level, a constant head injection test was made instead of a pumping test. The borehole was filled as rapidly as possible by the maximum capacity of the pump. Thereafter, a constant water level was held c. 2 m above the lower end of casing by manually operating a control valve.

Before flow logging is started, the intention is to achieve approximately steady-state conditions in the borehole. The flow logging is performed with the flow logging probe lifted (injection test) or lowered (pumping test) at a velocity of 1–3 m/min.

5.2.2 Details

Single-hole pumping and injection tests

In HFR101 the amount of water available for the injection test was restricted to 16 m^3. Therefore the length of the injection period was 6.5 h followed by a recovery period of c. 2 d and 18 h. Since the injection test was carried out on a Friday, the logger was not emptied until Monday, explaining the unusually long recovery period.

The pumping in borehole HFR105 lasted for c. 10 h followed by a recovery period of c. 2 d and 18 h (long recovery for the same reasons as for HFR101). Since the flow logging showed a very disturbed and decreasing flow in the uppermost part of the borehole a short (2 h) complementary pumping test above a packer at 38–39 m was done. The reason for the disturbed behaviour was probably that the borehole diameter, due to highly fractured rock with cavities in this part of the borehole, was somewhat greater than below.

In borehole HFR102 an injection test below a packer with an injection period of 1 h and a recovery period of ½ h was performed. The test was executed as a constant head injection test.

The sampling frequency of pressure and flow during the tests starts at 1 sample per second and increases over time according to a predefined scheme in the logger. A typically sequence for a pumping test is showed in Table 5-1. Sometimes, for practical reasons, the interval is shortened during certain periods of the test.

Flow logging

Depending on test type, injection or pumping, the flow meter probe is continuously lifted or lowered along the borehole, in the reverse direction to the borehole flow. The equipment allows for a logging velocity at 1–3 m/min. While moving the probe along the borehole, temperature, flow and electric conductivity data are sampled together with time and depth at each measuring point.

Before any pumping or injection is done, the borehole is flow logged under undisturbed conditions. This logging is later on used to correct for the spinner counts which depends on the movement of the flow logging probe, also accounting for variations in spinner counts depending on changing borehole diameter.

Flow logging is performed during the later part of the pumping or injection test. The logging starts when the pressure in the borehole is approximately stable. The time needed to complete the flow logging survey depends on the length of the borehole and the logging velocity. In general, between 1–3 hours is normal for a percussion borehole of 100–200 m length.

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 (*.DAT) are comma-separated when copied to a computer. A list of all data files from the logger is presented in Appendix 1.

Processed data files are used to create linear plots of pressure and flow versus time with the code SKBPLOT and evaluation plots with the software AQTESOLV. The flow logging is evaluated in Excel.

Table 5-1. Standard sampling intervals 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
601–3,600	60
>3,600	600

5.4 Analyses and interpretation

This section provides a comprehensive general description of the procedure used when analysing data from the hydraulic tests.

5.4.1 Single-hole hydraulic tests

Firstly, a qualitative evaluation of the actual flow regimes (wellbore storage, pseudo-linear, pseudo-radial or pseudo-spherical flow) and possible outer boundary conditions during the hydraulic tests is performed. The qualitative evaluation is made from analyses of log-log diagrams of drawdown and/or recovery data together with the corresponding derivatives versus time. In particular, pseudo-radial flow (2D) is reflected by a constant (horizontal) derivative in the diagrams. Pseudo-linear and pseudo-spherical flow are reflected by a slope of the derivative of 0.5 and –0.5, respectively, in a log-log diagram. Apparent 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 quantitative evaluation of the tests are selected. In general, a certain period with pseudo-radial flow can be identified during the pumping tests. Consequently, methods for single-hole, constant-flow rate or constant drawdown tests for radial flow in a porous medium described in Almén et al. 1986 /1/ and Morosini et al. 2001 /2/ are generally used by the evaluation of the tests. For tests indicating a fractured- or borehole storage dominated response, corresponding type curve solutions are used by the routine analyses.

If possible, transient analysis is applied on both the drawdown- and recovery phase of the tests. The recovery data are plotted versus Agarwal equivalent time. Transient analysis of drawdown- and recovery data are made in both log-log and lin-log diagrams as described in the Instruction (SKB MD 320.004). In addition, a preliminary steady-state analysis (e.g. Moye's formula) is made for all tests for comparison.

The transient analysis was performed using 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) /3/ for constant flow rate tests with radial flow, accounting for wellbore storage and skin effects, is generally used for estimating transmissivity, storativity and skin factor for actual values on the borehole- and casing radius.

AQTESOLV also includes other models, for example models for discrete fractures (horizontal and vertical, respectively) intersecting the borehole, causing pseudo-linear flow. For tests characterized by pseudo-spherical (leaky) flow relevant models are also available, e.g. Moench 1985 /4/ for single-hole pumping tests together with Hantush (1959) /5/ and Hantush (1955) /6/ for the flow and recovery period, respectively, of constant head tests. If appropriate, these models may be used in specific cases.

The effective casing radius may be estimated from the analysis of tests affected by wellbore storage. The wellbore storage coefficient can be calculated from the simulated effective casing radius, see below. The effective wellbore radius concept is used to account for negative skin factors.

An empirical regression relationship between storativity and transmissivity, Equation 5-1 is used according to the instruction SKB MD 320.004. Firstly, the transmissivity and skin factor are obtained by type curve matching on the data curve using a fixed storativity value of 10^{-6}. From the transmissivity value obtained, the storativity is then estimated according to Equation 5-1 and the type curve matching is repeated.

$S=0.0007 \cdot T^{0.5}$ (Eq. 5-1)

S=storativity (-)

T=transmissivity (m^2/s)

In most cases the change of storativity does not significantly alter the calculated transmissivity by the new type curve matching. Instead, the estimated skin factor, which is directly correlated to the storativity, is altered correspondingly.

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) and the water compressibility (for isolated sections) was 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 /2/ or alternatively, from the simulated effective casing radius according to Equation 5-2. These values on C may be compared with the net values of the wellbore storage coefficient based on actual borehole geometrical data. 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 or cavities with significant volumes and/or higher effective compressibility of the test equipment (e.g. packers).

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

$C=\pi r_{we}^2/\rho g$ (Eq. 5-2)

r_{we} = borehole radius where the changes of the groundwater level occur (either r_w or r_c) or alternatively, the simulated effective casing radius r(c)

r_w = nominal borehole radius (m)

r_c = inner radius of the borehole casing (m)

r(c) = simulated effective casing radius (m)

ρ = density of water (kg/m^3)

g = acceleration of gravity (m/s^2)

Injection tests

For injection tests with constant head, a model based on the Jacob and Lohman (1952) /7/ solution can be applied for estimating the transmissivity and skin factor for an assumed or estimated value on the storativity when a certain period with pseudo-radial flow can be identified during the injection period. The model is based on the effective wellbore radius concept to account for non-zero (negative) skin factors according to Hurst, Clark and Brauer (1969) /8/. The storativity was estimated using Equation 5-1.

For tests characterized by pseudo-spherical (leaky) flow or pseudo-stationary flow during the injection period, a model by Hantush (1959) /5/ for constant head tests can be adopted for the evaluation. In this model, the skin factor is not separated but can be calculated from the simulated effective borehole radius according to Equation 5-3. In addition, the leakage coefficient K'/b' can be calculated from the simulated leakage factor r/B.

$\xi=ln(r_w/r_{wf})$ (Eq. 5-3)

ξ = skin factor

r_w= nominal borehole radius (m)

r_{wf}= effective borehole radius

For transient analysis of the recovery period, the model presented by Dougherty-Babu (1984) /3/ can be used when a certain period with pseudo-radial flow could be identified. This model accounts for wellbore storage and skin effects. The solution for wellbore storage and skin effects is analogous to the corresponding solution presented in Earlougher (1977) /10/ based on the effective wellbore radius concept to account for non-zero (negative) skin factors. For tests in isolated test sections, a radius of a fictive standpipe connected to the test section, denoted fictive casing radius, r(c), represents wellbore storage. The wellbore storage coefficient is estimated from Equation 5-2 using r(c). This concept is equivalent to calculating the wellbore storage coefficient C from the compressibility and geometrical data of an isolated test section. The storativity was estimated using Equation 5-1 in the same way as described above for the transient analysis of the injection period.

For tests showing pseudo-spherical- or pseudo-stationary flow during the recovery period a model for constant flow rate tests, Hantush (1955) can be applied for evaluation of this period. The model also allows calculation of the wellbore storage coefficient C according to Equation 5-2. The skin factor is calculated from Equation 5-3.

5.4.2 Flow logging

The actual borehole diameter in a percussion drilled borehole, measured as the diameter of the drill bit, is most often deviating from the nominal diameter. Furthermore, the borehole diameter is normally somewhat larger than the diameter of the drill bit, depending, among other things, on the rock type. The diameter is also decreasing towards depth due to successive wearing of the drill bit. Therefore, since the number of counts registered by the spinner in the flow logging probe to a high degree is depending on the borehole diameter, it is generally not possible to use a calibration of the spinner for a single diameter.

For the above reasons the spinner counts, corrected for logging in the undisturbed borehole, are used as relative flow measurements and the flow at a certain borehole length (Q(L)) is determined according to:

$$Q(L) = C(L)/\, C_T \cdot Q_{FT} \qquad \text{(Eq. 5-4)}$$

where

C(L) = spinner counts per sec at length L

C_T = spinner counts per sec at top of logged interval

Q_{FT} = Flow at top of logged interval

If the flow logging can be carried out all the way from the lower end of the casing to the bottom of the borehole (or reverse) or if no flow exists above the top of the flow logged interval, Q_{FT} will be equal to the total pumped flow measured at the surface (Q_p).

During pumping, flow logging can only be carried out from the borehole bottom up to a certain distance below the submersible pump (c. 2.5 m). If it is not possible to place the pump high enough in the casing there will be a remaining part of the borehole (i.e. from the pump to the casing) that cannot be flow-logged, although high inflow zones may sometimes be located here. In such cases it is necessary to supplement the flow logging with injection or pumping tests above the highest logged level to be able to determine the flow at top of the flow logged interval (Q_{FT}). Alternatively, if other information (e.g. BIPS logging or drilling information) clearly shows that no inflow occurs in this part of the borehole, no supplementary tests are necessary.

Flow along the borehole, calculated according to Equation 5-4, is plotted, together with temperature and electric conductivity of the borehole fluid, versus borehole length. From these plots, flow anomalies are identified, i.e. borehole intervals over which changes of flow exceeding c. 1 L/min occur. The size of the inflow at a flow anomaly is determined by the actual change in flow rate across the anomaly. In most cases, the flow changes are accompanied by changes in temperature and/or electric conductivity of the fluid.

Depending on if supplementary tests are carried out, two different methods are employed for estimating the transmissivity of individual flow anomalies in the flow logged interval of the borehole. In both cases the transmissivity of the entire borehole (T) is estimated from the transient analysis of the pumping or injection test.

Method 1

If no significant inflow exists above the flow logged interval, the transmissivity of an individual flow anomaly (T_i) is calculated from the measured inflow (dQ_i) at the anomaly, the discharge Q_p and the calculated transmissivity of the entire borehole (T) according to:

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

The cumulative transmissivity $T_F(L)$ versus the borehole length (L) as determined from the flow logging may be calculated according to:

$$T_F(L) = Q(L) / Q_p \cdot T \qquad \text{(Eq. 5-6)}$$

Method 2

If additional hydraulic tests show that there exist significant flow anomalies above the flow logged interval, the transmissivity T_A for the non flow logged interval is estimated from these tests. In this case the resulting transmissivity of the flow-logged interval (T_{FT}) is calculated according to:

$$T_{FT} = \Sigma T_i = (T - T_A) \qquad \text{(Eq. 5-7)}$$

where T_A is the transmissivity of the non flow-logged interval.

The resulting flow at the top of the flow logged interval Q_{FT} may be calculated from:

$$Q_{FT} = Q_p \cdot T_{FT}/T \qquad \text{(Eq. 5-8)}$$

The transmissivity of an individual flow anomaly (T_i) is calculated from the relative contribution of the anomaly to the total flow at the top of the flow logged interval (dQ_i/Q_{FT}) and the calculated transmissivity of the entire flow-logged interval (T_{FT}) according to:

$$T_i = dQ_i / Q_{FT} \cdot T_{FT} \qquad \text{(Eq. 5-9)}$$

The cumulative transmissivity $T_F(L)$ at the borehole length (L) as determined from the flow logging may be calculated according to:

$$T_F(L) = Q(L) / Q_{FT} \cdot T_{FT} \qquad \text{(Eq. 5-10)}$$

The lower measurement limit of transmissivity of a flow anomaly can be estimated 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.

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, and the methodology description for impeller flow logging, SKB MD 322.009. Additional symbols used are explained in the text. The nomenclature for the analyses of the hydraulic tests by the AQTESOLV code is presented in Appendix 2.

6.2 Water sampling

Water samples were collected according to SKB chemistry class 3, SKB MD 423.002, during the combined flow logging and pumping test in HFR105 and during a separate pumping for this purpose in borehole HFR101, see Table 6-1. No pumping was conducted in HFR102 and hence there are no water samples from this borehole. The results from chemical analyses are presented in appendix 4.

6.3 Single-hole hydraulic tests

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

Drilling records and other activities were checked in the SKB database Sicada to identify possible interference on the hydraulic test data from activities in nearby boreholes during the test periods. No such activities with possible influence on the hydraulic tests were found in the Sicada database and no responses typical for drilling activities were found in the pressure measurements.

Table 6-1. Water samples collected in boreholes HFR101 and HFR105 and submitted for analysis.

Bh ID	Date and time of sample	Pumped section (m)	Pumped volume (m^3)	Sample type	Sample ID no	Remarks
HFR101	2008-05-22 16:30	8.0–209.3	4.6	WC080	16020	Open-hole test
HFR101	2008-05-22 17:50	8.0–209.3	5.9	WC080	16021	Open-hole test
HFR101	2008-05-22 18:30	8.0–209.3	6.6	WC080	16022	Open-hole test
HFR105	2008-04-25 09:00	21.1–200.5	0.83	WC080	16017	Open-hole test
HFR105	2008-04-25 13:05	21.1–200.5	4.5	WC080	16018	Open-hole test
HFR105	2008-04-25 17:50	21.1–200.5	8.78	WC080	16019	Open-hole test

6.3.1 Borehole HFR101: 8.0–209.3 m

General test data for the open-hole injection test in HFR101 are presented in Table 6-2.

The atmospheric pressure during the test period in HFR101, which is presented in Figure 6-1, varied c. 4 kPa, i.e. only c. 2% of the total displacement of c. 20 m, and thus the effect of atmospheric pressure variations on the test results is considered negligible. No rain immediately before or during the test period has affected the groundwater levels.

Table 6-2. General test data, pressure, groundwater level and flow data for the open-hole injection test in borehole HFR101.

General test data				
Borehole	HFR101			
Test type	Constant head injection and recovery test			
Test section (open borehole/packed-off section):	Open borehole			
Test No	1			
Field crew	J. Harrström and S. Jönsson, GEOSIGMA AB			
Test equipment system	HTHB			
General comment				
	Nomenclature	**Unit**	**Value**	
Borehole length	L	M	209.30	
Casing length	L_c	M	8.0	
Test section- secup	Secup	M	8.0	
Test section- seclow	Seclow	M	209.3	
Test section length	L_w	M	201.3	
Test section diameter	$2{\cdot}r_w$	Mm	top 139.5 bottom 137.8	
Test start (start of pressure registration)		yymmdd hh:mm:ss	080523 09:27:10	
Packer expanded		yymmdd hh:mm:ss		
Start of flow period		yymmdd hh:mm:ss	080523 09:52:57	
Stop of flow period		yymmdd hh:mm:ss	080523 15:57:02	
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	080526 10:46:14	
Total flow time	t_p	Min	364	
Total recovery time	t_F	Min	4,009	

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)** [1]
Absolute pressure in test section before start of flow period	p_i	kPa	123.8	–25.72
Absolute pressure in test section at stop of flow period	p_p	kPa	340.8	–3.01
Absolute pressure in test section at stop of recovery period	p_F	kPa	130.7	
Maximal pressure change in test section during the flow period	dp_p	kPa	217.0	22.71

Manual groundwater level measurements **Date YYYY-MM-DD**	**Time tt:mm:ss**	**Time (min)**	**GW level** **(m b ToC)**	**(m a s l)**
2008-05-21	08:55:00	–2,938	27.70	–23.39
2008-05-21	15:33:00	–2,540	27.70	–23.39
2008-05-22	08:50:00	–1,503	27.65	–23.34
2008-05-23	08:46:00	–67	30.18	–25.72

Flow data	**Nomenclature**	**Unit**	**Value**
Injection flow rate to test section just before stop of injection period	Q_p	m^3/s	$3.74{\cdot}10^{-4}$
Mean (arithmetic) flow rate during injection period [2]	Q_m	m^3/s	$5.39{\cdot}10^{-4}$
Total volume injected [2]	V_p	m^3	11.77

[1] From the manual measurements of groundwater level.
[2] Calculated from integration of the transient flow rate curve during the injection period.

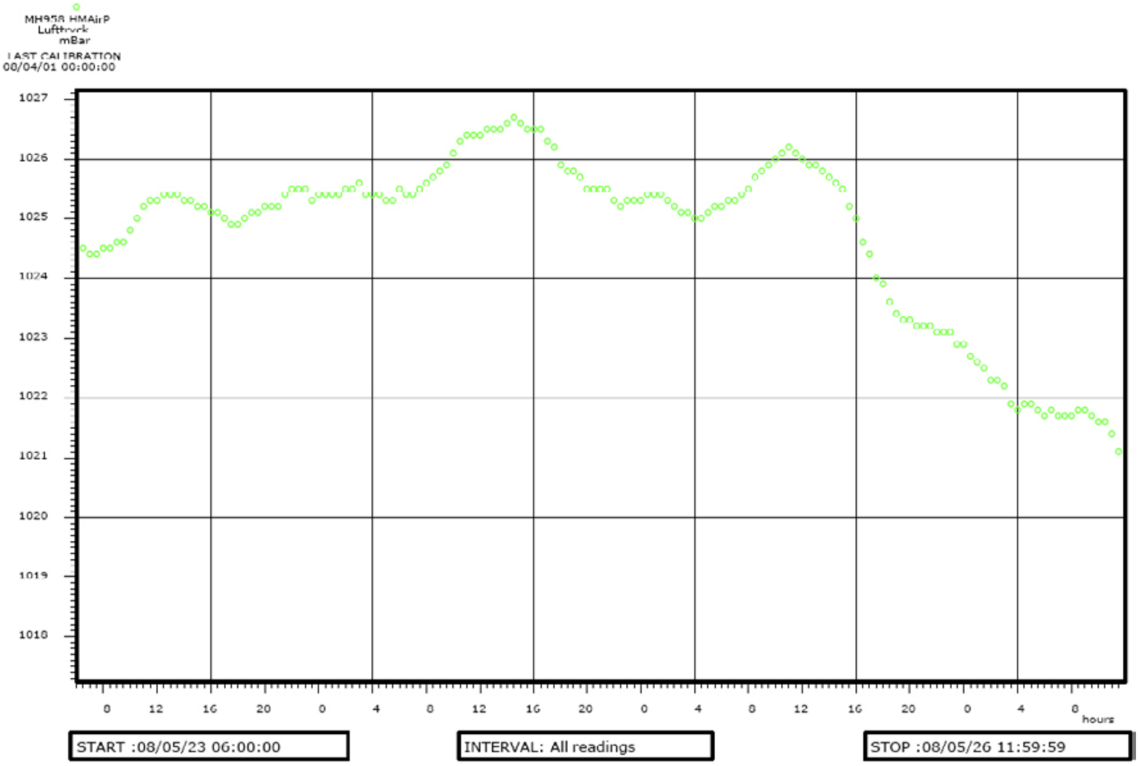


Figure 6-1. *Atmospheric pressure during the test period in HFR101.*

Comments on test

Due to influence from the SFR repository, the groundwater level in the borehole was ca 30 m below top of casing. To be able to include hydraulically conductive fractures or fracture zones above this level during the flow logging, the test was performed as a constant head injection test by keeping a constant level ca 2 m above the lower end of casing. During the time period to fill the borehole to that level (c. 17 min) the injection was made at the maximum capacity of the pump (c. 72 L/min). The water used for injection was contained in a tank and the amount of water available put a limit on the length of the injection period which was c. 6 hours.

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.

The early phase of the flow period is strongly affected by the filling of the borehole to the target level but then a pseudo-linear flow may be interpreted after c. 1,000 s. During the recovery a transition from wellbore storage dominated flow to an apparent pseudo-linear flow can be seen after c. 1,000 sec. The response is indicating a single dominating fracture, which is supported by an alternative model for a vertical fracture /9/ which gives almost the same result.

Interpreted parameters

Transient evaluation of transmissivity was performed for both the flow- and recovery period. The quantitative interpretation is presented in Figures A2:2–5 in Appendix 2. The quantitative analysis was performed according to the methods described in Section 5.4.1. The transmissivity was estimated by a model assuming pseudo-radial flow in combination with a strong negative skin factor for both the flow- /8/ and recovery /3/ period. The representative transmissivity (T_T) is chosen from the transient evaluation of the recovery period. The agreement between the flow and the recovery period regarding transmissivity and skin factor is good.

The results are summarized in Tables 6-10, 6-11, 6-12 and in a Test Summary Sheet (Table 6-13).

6.3.2 Borehole HFR102: 10.4–55.0 m

General test data for the injection test below a packer in HFR102 are presented in Table 6-3.

The atmospheric pressure during the test period in HFR102, which is presented in Figure 6-2, varied only c. 0.7 kPa during the test, compared to a total displacement of c. 200 kPa, and thus the effect of atmospheric pressure variations on the test results is considered negligible. No rain immediately before or during the test period has affected the groundwater levels.

Table 6-3. General test data, pressure, groundwater level and flow data for the open-hole injection test in borehole HFR102.

General test data				
Borehole	HFR102			
Test type	Constant head injection and recovery test			
Test section (open borehole/packed-off section):	Below a single packer			
Test No	1			
Field crew	J. Harrström and Jan Sundberg, GEOSIGMA AB			
Test equipment system	Geosigma WIC			
General comment				
	Nomenclature	**Unit**	**Value**	
Borehole length	L	M	55.0	
Casing length	Lc	M	9.0	
Test section- secup	Secup	M	10.4	
Test section- seclow	Seclow	M	55.0	
Test section length	Lw	M	44.6	
Test section diameter	$2 \cdot r_w$	Mm	top 138.3 bottom 138.0	
Test start (start of pressure registration)		yymmdd hh:mm:ss	080528 12:43:52	
Packer expanded		yymmdd hh:mm:ss	080528 12:52:00	
Start of flow period		yymmdd hh:mm:ss	080528 13:20:01	
Stop of flow period		yymmdd hh:mm:ss	080528 14:20:01	
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	080528 14:53:14	
Total flow time	t_p	Min	60	
Total recovery time	t_F	Min	33.2	

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)** [1]
Absolute pressure in test section before start of flow period	p_i	kPa	161.1	
Absolute pressure in test section at stop of flow period	p_p	kPa	356.9	
Absolute pressure in test section at stop of recovery period	p_F	kPa	166.0	
Maximal pressure change in test section during the flow period	d_{pp}	kPa	195.8	

Manual groundwater level measurements **Date YYYY-MM-DD**	**Time tt:mm:ss**	**Time (min)**	**GW level** **(m b ToC)**	**(m a s l)**
2008-05-28	09:40:00	–220	4.0	–1.12
2008-05-28	14:58:00	98	3.30	–0.52
2008-05-28	15:40:00	140	3.69	–0.85

Flow data	**Nomenclature**	**Unit**	**Value**
Injection flow rate to test section just before stop of injection period	Q_p	m^3/s	$6.61 \cdot 10^{-5}$
Mean (arithmetic) flow rate during injection period [2]	Q_m	m^3/s	$7.11 \cdot 10^{-5}$
Total volume injected [2]	V_p	m^3	0.256

[1] From the manual measurements of groundwater level.
[2] Calculated from integration of the transient flow rate curve during the injection period.

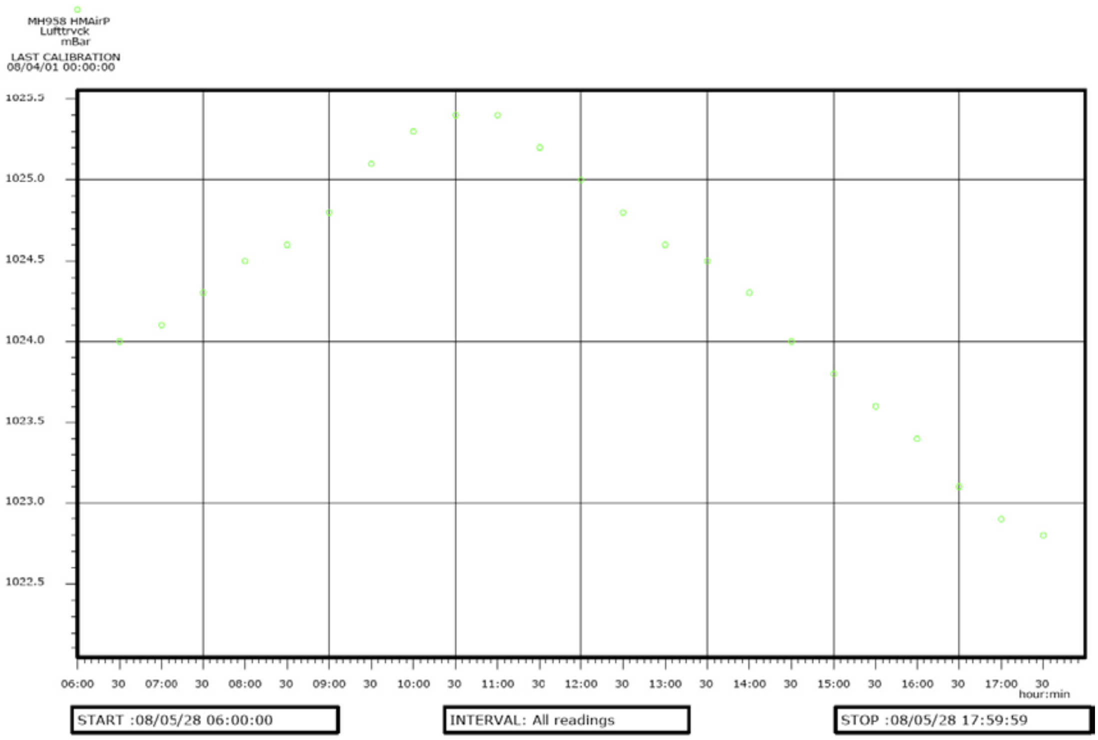


Figure 6-2. *Atmospheric pressure during the test period in HFR102.*

Comments on test

Due to expected low pumping flow rates the test was performed as a constant head injection test with the Geosigma WIC (Water Injection Control) equipment (see section 4.1) which is able to measure flow rates at a few mL/min. No down-hole test-valve was used, but a valve at the WIC equipment opened and closed the flow to the test section. The packer was placed immediately below the end of casing meaning that a borehole section of c. 1.4 m below the end of casing was not included in the test section.

The test was carried out with a flow period of 60 minutes followed by a 30 minutes recovery period.

Interpreted flow regimes

Selected test diagrams according to the Instruction for analysis of injection – and single-hole pumping tests are presented in Figures A2:6–10 in Appendix 2.

During the flow period slightly pseudo-spherical (leaky) flow was seen after c. 200 s.

Interpreted parameters

Transient evaluation of transmissivity was performed for both the flow- and recovery period. The quantitative interpretation is presented in Figures A2:7–10 in Appendix 2. The quantitative analysis was performed according to the methods described in Section 5.4.1. The transmissivity was estimated by a model for pseudo-spherical (leaky) flow for both the flow- /7/ and recovery /8/ period. The representative transmissivity (T_T) is chosen from the transient evaluation of the recovery period. The agreement between the flow and the recovery period regarding transmissivity and skin factor is good.

The results are shown in Tables 6-10, 6-11, 6-12 and in a Test Summary Sheet (Table 6-14) and.

6.3.3 Borehole HFR105: 21.1–200.5 m

The atmospheric pressure during the test period in HFR105, seen in Figure 6-3, varied less than 0.7 kPa, i.e. only c. 2% of the total drawdown of c. 4 m, and thus the effect of atmospheric pressure variations on the test results is considered negligible. No rain immediately before or during the test period has affected the groundwater levels.

General test data for the open-hole pumping test in HFR105 are presented in Table 6-4.

Table 6-4. General test data, pressure, groundwater level and flow data for the open-hole pumping test in borehole HFR105.

General test data					
Borehole	HFR105 (21.12–200.50 m)				
Test type	Constant rate withdrawal and recovery test				
Test section (open borehole/packed-off section):	Open borehole				
Test No	1				
Field crew	T. Svensson, GEOSIGMA AB				
Test equipment system	HTHB				
General comment	Single pumping borehole				
	Nomenclature	**Unit**	**Value**		
Borehole length	L	m	200.5		
Casing length	Lc	m	21.1		
Test section- secup	Secup	m	21.1		
Test section- seclow	Seclow	m	200.5		
Test section length	Lw	m	179.4		
Test section diameter	2·rw	mm	top 141.3 bottom 139.8		
Test start (start of pressure registration)		yymmdd hh:mm:ss	080425 07:46:53		
Packer expanded		yymmdd hh:mm:ss			
Start of flow period		yymmdd hh:mm:ss	080425 08:05:02		
Stop of flow period		yymmdd hh:mm:ss	080425 18:06:01		
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	080428 11:43:57		
Total flow time	t_p	Min	601		
Total recovery time	t_F	Min	3,938		

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)** [1)]
Absolute pressure in test section before start of flow period	p_i	kPa	153.8	–5.74
Absolute pressure in test section at stop of flow period	p_p	kPa	113.9	–9.98
Absolute pressure in test section at stop of recovery period	p_F	kPa	159.7	
Maximal pressure change in test section during the flow period	d_{pp}	kPa	39.9	

Manual groundwater level measurements **Date YYYY-MM-DD**	**Time tt:mm:ss**	**Time (min)**	**GW level** **(m b ToC)**	**(m a s l)**
2008-04-23	09:58:00	–2,749	10.6	–6.07
2008-04-23	16:38:00	–2,349	10.4	–5.89
2008-04-23	19:42:00	–2,165	10.37	–5.86
2008-04-24	13:41:00	–567	10.35	–5.85
2008-04-24	16:06:00	–422	11.25	–6.64
2008-04-25	07:47:00	–21	10.3	–5.80
2008-04-25	10:59:00	174	13.65	–8.76
2008-04-25	18:01:00	596	15.15	–10.08
2008-04-29	12:13:00	6,008	10.20	–5.72

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m^3/s	$2.47 \cdot 10^{-4}$
Mean (arithmetic) flow rate during flow period [2)]	Q_m	m^3/s	$2.49 \cdot 10^{-4}$
Total volume discharged during flow period [2)]	V_p	m^3	8.98

[1)] From the manual measurements of groundwater level.
[2)] Calculated from integration of the transient flow rate curve during the injection period.

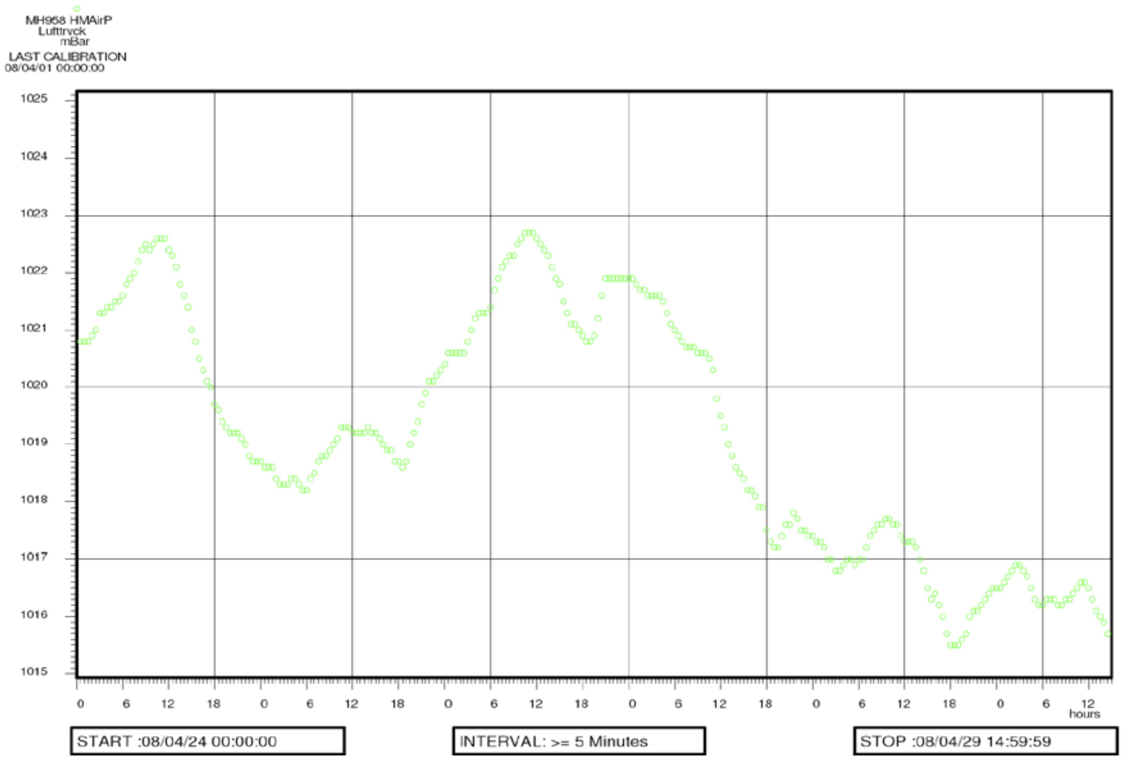


Figure 6-3. *Atmospheric pressure during the test period in HFR105.*

Comments on test

The day before test start, a short capacity test was performed in HFR105 during observation of the drawdown response. The flow rate was first set to 30 L/min for about 15 minutes and then lowered to 15 L/min for another 25 minutes. By the end of the capacity test, the drawdown was c. 3.1 m. The actual pumping test was conducted as a constant flow rate test (c. 15 L/min) with the intention to achieve (approximately) steady-state conditions during the flow logging. The pump was started twice shortly before the actual test was initiated, hence the early part of the test give a somewhat uncertain result. The drawdown at the end of the 10-hour pumping period was c. 4 m.

Interpreted flow regimes

Selected test diagrams according to the Instruction for analysis of injection – and single-hole pumping tests are presented in Figures A2:11–19 in Appendix 2.

After initial wellbore storage a first pseudo-radial flow regime (PRF1) is seen after c. 10 min. After a transition period a second period with pseudo-radial flow regime (PRF2) occurs after about 200 min and continues throughout the test. The recovery period displays the same pattern with two consecutive PRF:s developing at about the same times as during the flow period although PFR2 is less developed during recovery. This behavior indicates probably two intersecting fractures with slightly different transmissivity or alternatively, decreasing aperture of the same fracture away from the borehole.

Interpreted parameters

Transient evaluation of transmissivity was performed for both the flow- and recovery period. The quantitative interpretations for both the early and late responses are presented in Figures A2:12–19 in Appendix 2. The quantitative analysis was performed according to the methods described in Section 5.4.1. The transmissivity for both the flow and recovery period is evaluated with the Dougherty-Babu model assuming pseudo-radial flow /3/. The evaluated data from the flow and recovery period give consistent results. Since the flow logging is conducted during the period of the test when the second PRF occurs, the evaluation of the late PRF during the flow period is chosen to provide the most representative transmissivity (T_T) for this borehole. The calculation of the wellbore storage coefficient (C) is made with the fictive radius (r_c) evaluated from the first PRF during the flow period.

The results are shown in Tables 6-10, 6-11, 6-12 and in a the Test Summary Sheet (Table 6-15).

6.3.4 Borehole HFR105: 21.1–38.0 m

A complementary test was conducted in the upper part of the borehole to ensure that the flow logging conducted in the entire borehole covered all flow anomalies. The borehole was sealed off with a packer at the depth of 38–39 m and a pumping test was then performed above this packer. General test data for the test is presented in Table 6-5.

Table 6-5. General test data, pressure, groundwater level and flow data for the open-hole pumping test above the packer in borehole HFR105.

General test data				
Borehole	HFR105 (21.12–38.0 m)			
Test type	Constant rate withdrawal and recovery test			
Test section (open borehole/packed-off section):	Packed off below the section			
Test No	1			
Field crew	S. Jönsson, GEOSIGMA AB			
Test equipment system	HTHB			
General comment				
	Nomenclature	**Unit**	**Value**	
Borehole length	L	M	200.5	
Casing length	L_c	M	21.1	
Test section- secup	Secup	M	21.1	
Test section- seclow	Seclow	M	38.0	
Test section length	L_w	M	16.9	
Test section diameter	$2 \cdot r_w$	Mm	141.3	
Test start (start of pressure registration)		yymmdd hh:mm:ss	080429 13:08:40	
Packer expanded		yymmdd hh:mm:ss	080429 12:46:00	
Start of flow period		yymmdd hh:mm:ss	080429 13:50:06	
Stop of flow period		yymmdd hh:mm:ss	080429 15:52:04	
Test stop (stop of pressure registration)		yymmdd hh:mm:ss	080429 16:34:23	
Total flow time	t_p	Min	122	
Total recovery time	t_F	Min	42	

Pressure data	**Nomenclature**	**Unit**	**Value**	**GW Level (masl)**
Absolute pressure in test section before start of flow period	p_i	kPa	322.3	–5.72
Absolute pressure in test section at stop of flow period	p_p	kPa	122.6	
Absolute pressure in test section at stop of recovery period	p_F	kPa	154.8	
Maximal pressure change in test section during the flow period	d_{pp}	kPa	199.7	

Manual groundwater level measurements			**GW level**	
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**(m b ToC)**	**(m a s l)**
2008-04-29	12:13:00	–97	10.2	–5.72

Flow data	**Nomenclature**	**Unit**	**Value**
Flow rate from test section just before stop of flow period	Q_p	m_3/s	$4.67 \cdot 10^{-5}$
Mean (arithmetic) flow rate during flow period	Q_m	m_3/s	$6.52 \cdot 10^{-5}$
Total volume discharged during flow period	V_p	m^3	0.47

Comments on test

The section between 21.1 (casing end) and 38 m was pumped at a constant rate of c. 4.75 L/min during the first 70 min. Due to low transmissivity the flow rate was lowered to about 3 L/min for the rest of the test. The flow period was 122 minutes followed by 42 minutes of pressure recovery.

Interpreted flow regimes

Since the recovery period for this test was short, both the injection and recovery period is evaluated together. Selected test diagrams according to the Instruction for analysis of injection tests are presented in Figures A2:20–22 in Appendix 2.

The dominating flow regime during the injection test is well-bore storage.

Interpreted parameters

Transient evaluation of transmissivity was performed for the combined flow- and recovery period. Plots of the quantitative interpretation is presented in Figures A2:21–22 in Appendix 2. The quantitative analysis was performed according to the methods described in Section 5.4.1. The transmissivity was estimated by the Dougherty-Babu model assuming pseudo-radial flow /3/. The representative transmissivity (T_T) is considered from the transient evaluation assuming pseudo-radial flow including wellbore storage and skin. The results are shown in Tables 6-10, 6-11, 6-12 and in the Test Summary Sheet (Table 6-16).

6.4 Flow logging

6.4.1 Borehole HFR101

General test data for the flow logging in borehole HFR101 are presented in Table 6-6.

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 of the borehole fluid are presented in Figure 6-4.

The figure presents calculated borehole flow rates according to Eq. 5-4. In this case, it was possible to extend the flow logging to slightly above the end of the casing and therefore Method 1 in section 5.4.2 was used to evaluate the flow logging.

Figure 6-4 shows a major flow anomaly at c. 107–108 m borehole length. A small change in temperature during the logging under undisturbed conditions indicates a slightly warmer water from this anomaly. A small flow of c. 2 L/min can be seen below c. 140 m. It is difficult to explain why this flow ceases at 140 m, but a possible explanation could be that the flow derives from a limited storage, which is emptied during the logging. Another explanation could be that there is some mechanical shortcoming in the spinner between c. 110–140 m. Comparing the temperature curves during logging under undisturbed conditions and during injection one can see a mismatch ceasing at c. 197 m. This indicates an outflow at this location causing a downward movement of the original temperature profile in the borehole. An outflow at depth is also supported by the electric conductivity profile showing that the fresh water front has reached a level below the major anomaly during the injection. Rough calculations with the assumption of a piston flow below 110 m supports the estimated magnitude derived from the flow logging.

Table 6-6. General test data, groundwater level and flow data for the flow logging in borehole HFR101.

General test data				
Borehole	HFM101			
Test type(s) [1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	J. Harrström and S. Jönsson, GEOSIGMA AB			
Test equipment system	HTHB + Geosigma spinner			
General comments				
	Nomenclature	**Unit**	**Value**	
Borehole length		m	209.3	
Pump position (lower level)		m	At surface	
Flow logged section – Secup		m	8.0	
Flow logged section – Seclow		m	207.3	
Test section diameter	2·rw	mm	top 139.5 bottom 137.0	
Start of flow period		yymmdd hh:mm	080523 09:52	
Start of flow logging		yymmdd hh:mm	080523 13:55	
Stop of flow logging		yymmdd hh:mm	080523 15:46	
Stop of flow period		yymmdd hh:mm	800523 15:57	
Groundwater level	**Nomenclature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l) [2]**
Groundwater level in borehole, at undisturbed conditions, open hole	h_i	m	30.18	–25.72
Groundwater level (steady state) in borehole, at injection rate Q_p	h_p	m	6.00	–3.01
Displacement during flow logging at pumping rate Q_p	s_{FL}	m		22.71
Flow data	**Nomenclature**	**Unit**	**Flow rate**	
Injection flow rate at the end of injection period	Q_p	m^3/s	$3.74 \cdot 10^{-4}$	
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$	

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

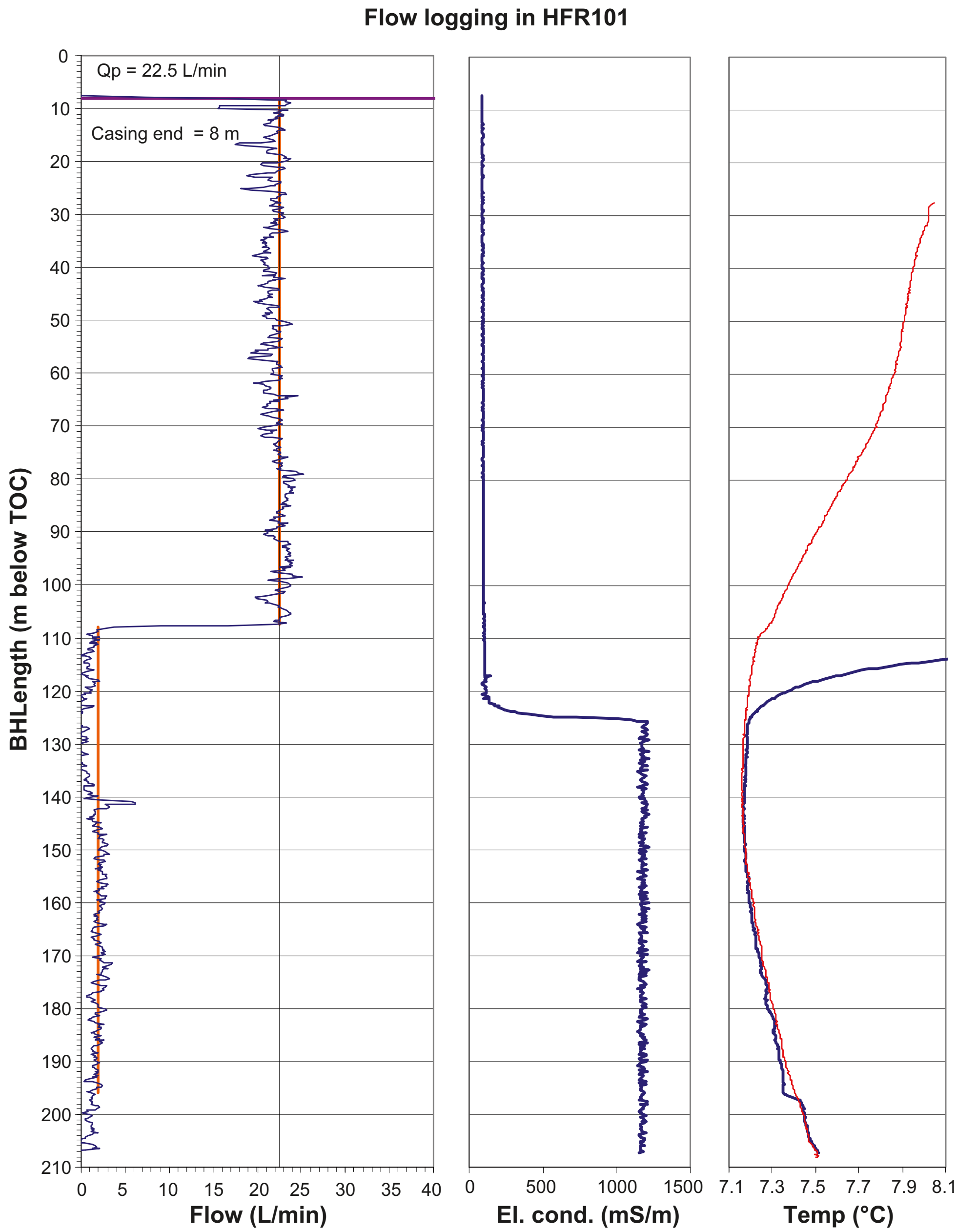


Figure 6-4. *Inflow distribution together with electrical conductivity and temperature of the borehole fluid along borehole HFR101 during flow logging. Red temperature curve shows temperature during logging in undisturbed borehole.*

The results of the flow logging in borehole HFR101 are presented in Table 6-7 below. The inflow from the individual flow anomalies (dQ_i) are calculated as the difference between the borehole flow above and below the anomaly, calculated from Eq. (5-4). The corresponding transmissivity values (T_i) are then calculated from Eq. (5-5). The borehole transmissivity for the entire borehole (T) is taken from the transient evaluation of the injection test, performed in conjunction with the flow logging (cf. Section 6.3.1). An estimation of the transmissivity of the interpreted flow anomalies was also made by calculating the specific flow (dQ_i/s_{FL}). S_{FL} in Table 6-7 is calculated from measured pressure difference between stop and start of flow period (p_p–p_i).

Table 6-7. Results of the flow logging in borehole HFR101. T=transmissivity from the pumping test, s_{FL}= displacement during flow logging and Q_p=pumped flow rate from borehole.

Flow anomalies			$T=2.8\cdot10^{-6}$ (m²/s)	s_{FL}= 22.11 m	$Q_p=3.74\cdot10^{-4}$ (m³/s)	
Interval (m b ToC)	Length (m)	dQ_i (m³/s)	T_i (m²/s)	dQ_i/s_{FL} (m²/s)	dQ_i/Q_p (%)	Supporting information
107.3–108	1	$3.4\cdot10^{-04}$	$2.6\cdot10^{-06}$	$1.5\cdot10^{-05}$	91.1	Temp
196–197	1	$3.3\cdot10^{-05}$	$2.5\cdot10^{-07}$	$1.5\cdot10^{-06}$	8.9	EC, Temp
Total		**$3.7\cdot10^{-04}$**	**$2.8\cdot10^{-06}$**	$1.7\cdot10^{-05}$	100	

Figure 6-5 presents the transmissivity of the flow anomalies (T_i) along the borehole. The estimated width of the flow anomaly in the borehole is represented by the bar with. The estimated threshold value of T, cf. Section 5.4.2, and the total transmissivity of the borehole are also presented in the figure.

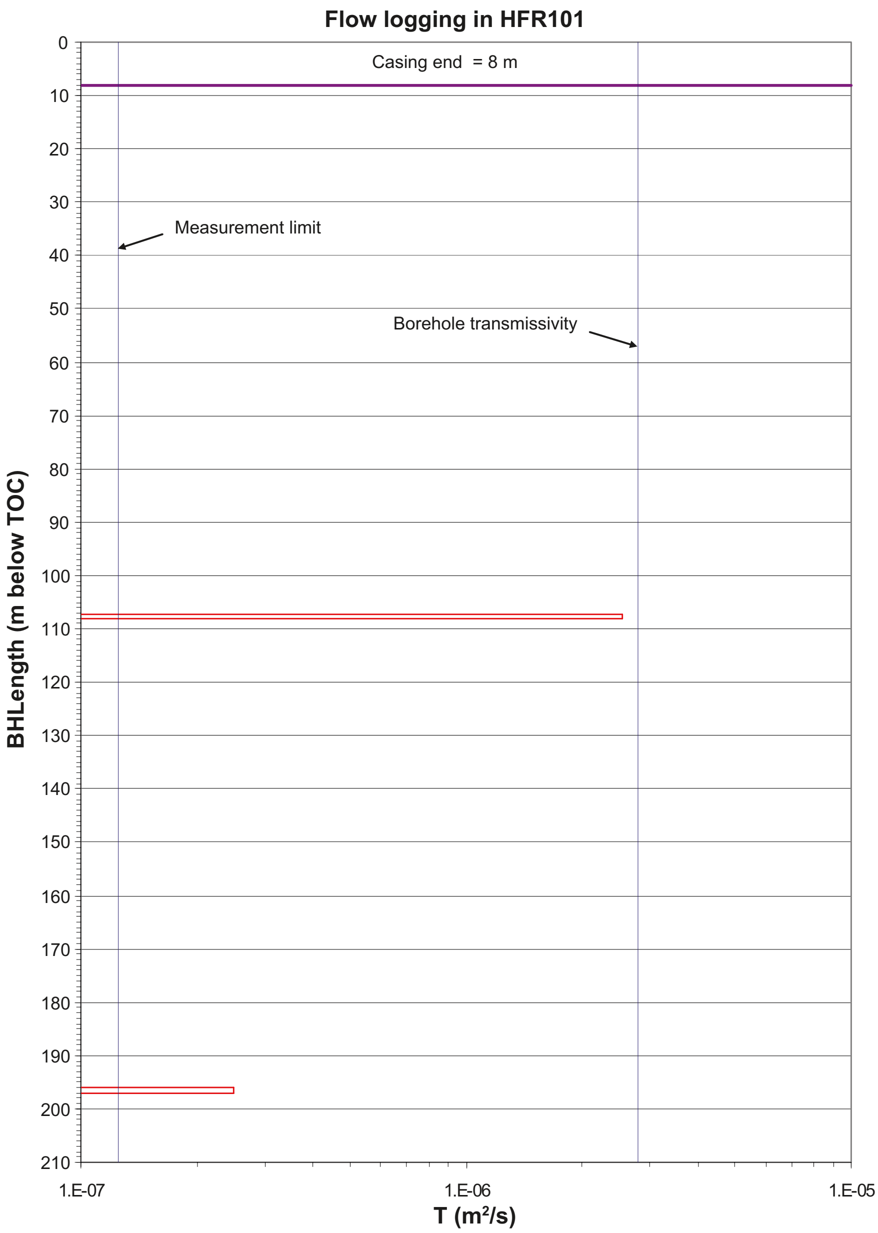


Figure 6-5. *Calculated transmissivity of the located flow anomalies along the flow logged interval of borehole HFR101. The total borehole transmissivity was calculated from the injection test during flow logging.*

6.4.2 Borehole HFR105

General test data for the flow logging in borehole HFR105 are presented in Table 6-8.

Table 6-8. General test data, groundwater level and flow data for the flow logging in borehole HFR105.

General test data				
Borehole	HFM105			
Test type(s) [1]	6, L-EC, L-Te			
Test section:	Open borehole			
Test No	1			
Field crew	Tomas Svensson, GEOSIGMA AB			
Test equipment system	HTHB + Geosigma spinner			
General comments				
	Nomenclature	**Unit**	**Value**	
Borehole length		m	200.5	
Pump position (lower level)		m	16.8	
Flow logged section – Secup		m	21.1	
Flow logged section – Seclow		m	190.0	
Test section diameter	2·rw	mm	top 141.3 bottom 139.8	
Start of flow period		yymmdd hh:mm	080425 08:05	
Start of flow logging		yymmdd hh:mm	080425 14:05	
Stop of flow logging		yymmdd hh:mm	080425 15:02	
Stop of flow period		yymmdd hh:mm	080425 18:06	

Groundwater level	**Nomen-clature**	**Unit**	**G.w-level (m b ToC)**	**G.w-level (m a s l) [2]**
Groundwater level in borehole, at undisturbed conditions , open hole	h_i	m	10.30	–5.80
Groundwater level (steady state) in borehole, at pumping rate Q_p	h_p	m	15.15	–10.08
Drawdown during flow logging at pumping rate Q_p	s_{FL}	m		4.28

Flow data	**Nomen-clature**	**Unit**	**Flow rate**
Pumping rate at surface	Q_p	m^3/s	$2.47 \cdot 10^{-4}$
Minimal change of borehole flow rate to detect flow anomaly	dQ_{Anom}	m^3/s	$1.7 \cdot 10^{-5}$

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

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 of the borehole fluid are presented in Figure 6-6.

The figure presents calculated borehole flow rates according to Eq. 5-4. In this case, it was possible to extend the flow logging to slightly above the end of the casing. As can be seen from Figure 6-6 the measured borehole flow decreases above c. 36 m. This is probably an effect of increasing borehole diameter due to crushed rock in the uppermost part of the borehole. Due to this fact it was not possible to confirm that all inflow anomalies had been found above this level. Therefore a complementary pumping test (see section 5.2.2) above a packer at 38–39 m was performed. The test showed that the transmissivity in this part of the borehole was very low and would correspond to an inflow of only c. 0.2 L/min with a drawdown at the same level as during the flow logging. Although the portion of the total borehole transmissivity from this part of the borehole was small, Method 2 in section 5.4.2, reducing the calculated flow for inflow above c. 38 m, was used when evaluating the flow logging measurements.

Figure 6-6 shows three inflow anomalies at c. 56, 89 and 120 m borehole length. None of them was supported by changes in electric conductivity or temperature of the borehole fluid, indicating a rather homogeneous water in this part of the rock.

It should be mentioned though, that the magnitude of the Electric conductivity derived from the flow logging differs from the results from the analyses of the water samples taken during the pumping. The difference is c. 350 mS/m. No explanation to this has been found, but greather relative changes indicating variations in Electric conductivity would probably still have been possible to observe.

The results of the flow logging in borehole HFR105 are presented in Table 6-9 below. The inflow from the individual flow anomalies (dQ_i) are calculated as the difference between the borehole flow above and below the anomaly, calculated from Eq. (5-4). The corresponding transmissivity values (T_i) are then calculated from Eq. (5-9). The borehole transmissivity for the entire borehole (T) is taken from the transient evaluation of the pumping test, in conjunction with the flow logging (cf. Section 6.3.3). An estimation of the transmissivity of the interpreted flow anomalies was also made by calculating the specific flow (dQ_i/s_{FL}). S_{FL} in Table 6-7 is calculated from measured pressure difference between start and stop of flow period (p_i-p_p).

Figure 6-7 presents the transmissivity of the flow anomalies (T_i) along the borehole. The estimated width of the flow anomalies in the borehole is represented by the bar width. The estimated threshold value of T, cf. Section 5.4.2, and the total transmissivity of the borehole are also presented in the figure.

Table 6-9. Results of the flow logging in borehole HFR105. T=transmissivity from the pumping test, s_{FL}= drawdown during flow logging and Q_p=pumped flow rate from borehole.

Flow anomalies			**T=2.26·10⁻⁵ (m²/s)**	**s_{FL}= 4.07 m**	**Q_p=2.47·10⁻⁴ (m³/s)**	
Interval (m b ToC)	**Length (m)**	**dQ_i (m³/s)**	**T_i (m²/s)**	**dQ_i/s_{FL} (m²/s)**	**dQ_i/Q_p (%)**	**Supporting information**
55.6–55.8	0.2	$6.3·10^{-05}$	$5.7·10^{-06}$	$1.6·10^{-05}$	26	
89.1–89.5	0.4	$6.7·10^{-05}$	$6.0·10^{-06}$	$1.6·10^{-05}$	27	
119.4–120	0.6	$1.2·10^{-04}$	$1.1·10^{-05}$	$2.9·10^{-05}$	47	
Total		**$2.5·10^{-04}$**	**$2.2·10^{-05}$**	**$6.1·10^{-05}$**	**100**	

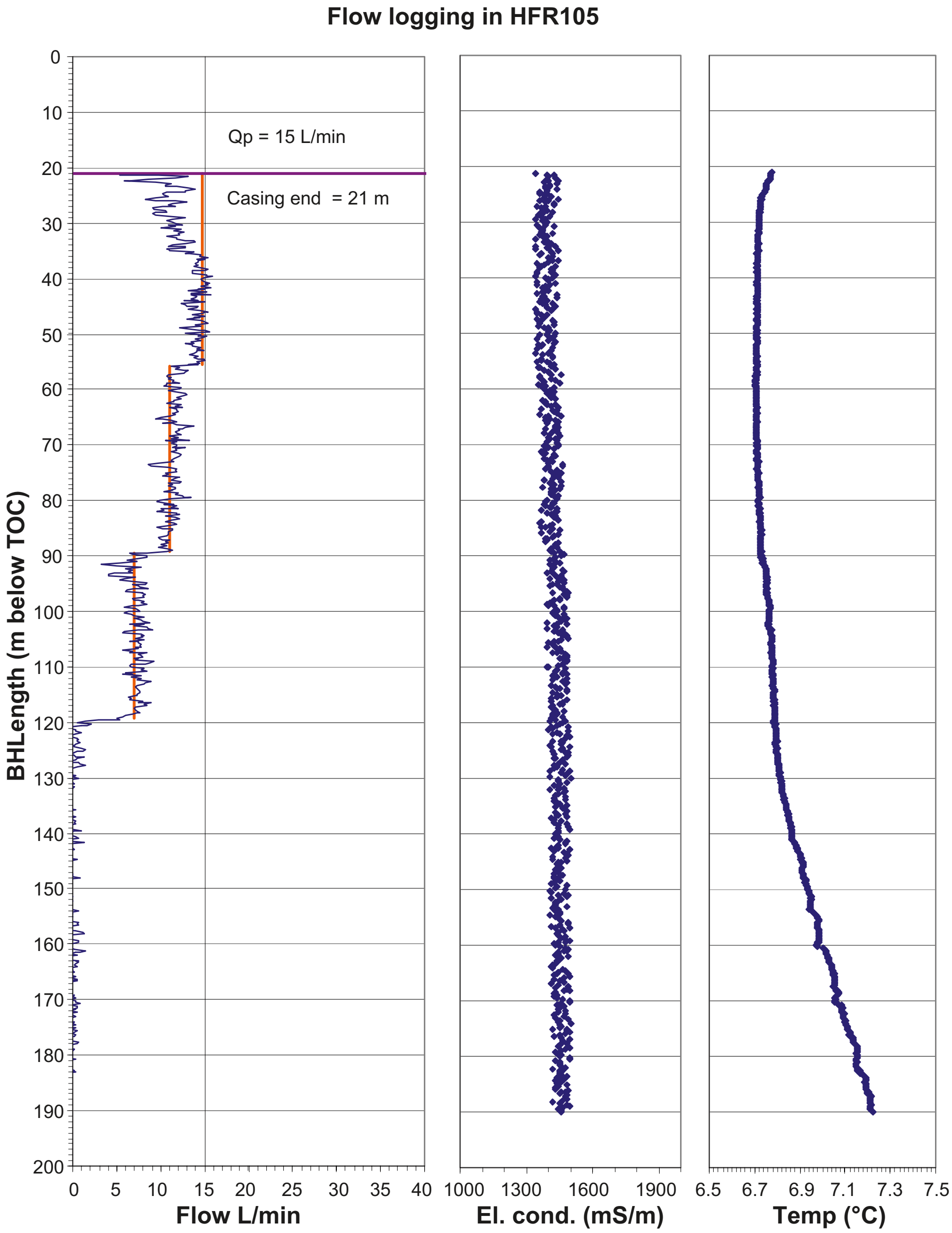


Figure 6-6. *Inflow distribution together with electrical conductivity and temperature of the borehole fluid along borehole HFR105 during flow logging.*

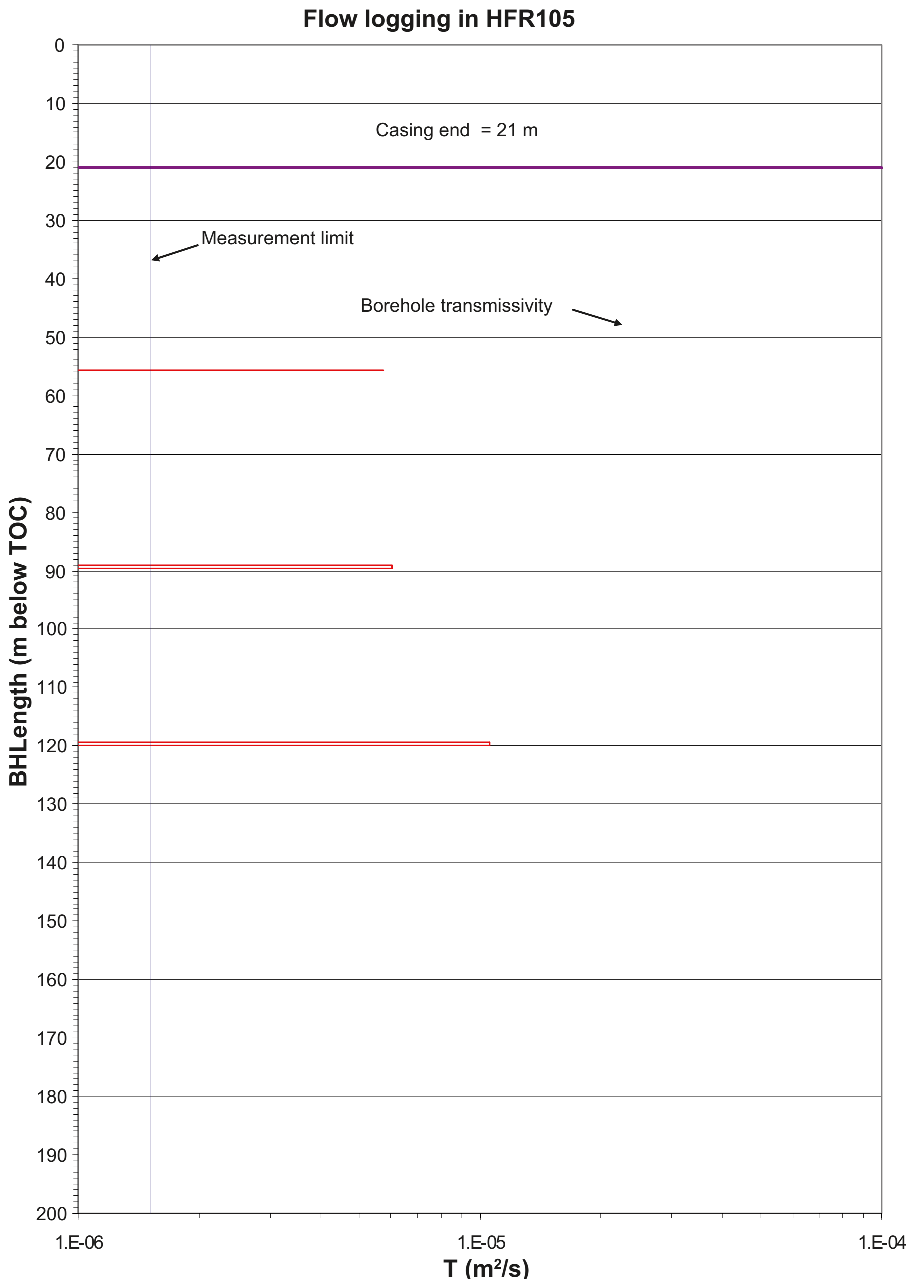


Figure 6-7. *Calculated transmissivity of the located flow anomalies along the flow logged interval of borehole HFR105. The total borehole transmissivity was calculated from the pumping test during flow logging.*

6.5 Summary of hydraulic tests

A compilation of measured test data from the hydraulic tests in the three boreholes is presented in Table 6-10. In Tables 6-11, 6-12 and in the test summary sheets in Tables 6-13, 6-14, 6-15 and 6-16, hydraulic parameters calculated from the tests are shown.

In Tables 6-10, 6-11 and 6-12 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 respectively

T_M = steady-state transmissivity calculated from Moye's formula

T_T = judged best estimate of transmissivity (from transient evaluation of hydraulic test)

T_i = estimated transmissivity of flow anomaly

S* = assumed value on storativity used in single-hole tests

C = wellbore storage coefficient

ξ = skin factor

Table 6-10. Summary of test data for the hydraulic tests performed in boreholes HFR101, HFR102 and HFR105 in the SFR area.

Borehole ID	Section (m)	Test type [1]	pi (kPa)	pp (kPa)	pF (kPa)	Qp (m³/s)	Qm (m³/s)	Vp (m³)
HFR101	8.0–209.3	3	123.8	340.8	130.7	$3.74 \cdot 10^{-4}$	$5.39 \cdot 10^{-4}$	11.77
HFR102	10.4–55.0	3	161.1	356.9	166.0	$6.61 \cdot 10^{-5}$	$7.11 \cdot 10^{-5}$	0.256
HFR105	21.1–200.5	1B	153.8	113.9	159.7	$2.47 \cdot 10^{-4}$	$2.49 \cdot 10^{-4}$	8.98
HFR105	21.1–38.0	1B	322.3	122.6	154.8	$4.67 \cdot 10^{-5}$	$6.52 \cdot 10^{-5}$	0.47

[1] 1B: Pumping test-submersible pump, 3: Injection test.

Table 6-11. Summary of calculated hydraulic parameters from the hydraulic tests performed in boreholes HFR101, HFR102 and HFR105 in the SFR area.

Borehole ID	Section (m)	Flow Anomaly interval (m)	Test type [1]	Q/s (m²/s)	TM (m²/s)	TT (m²/s)	Ti (m²/s)
HFR101	8.0–209.3		3	$1.7 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	$2.8 \cdot 10^{-6}$	
	8.0–207.3 (f)	107.3–108	6	$1.5 \cdot 10^{-5}$			$2.6 \cdot 10^{-6}$
	8.0–207.3 (f)	196–197	6	$1.5 \cdot 10^{-6}$			$2.5 \cdot 10^{-7}$
HFR102	10.4–55.0		3	$3.3 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$	$2.8 \cdot 10^{-6}$	
HFR105	21.12–200.5		1B	$6.1 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$	$2.3 \cdot 10^{-5}$	
HFR105	21.12–200.5 (f)	55.6–55.8	6	$1.6 \cdot 10^{-5}$			$5.7 \cdot 10^{-6}$
HFR105	21.12–200.5 (f)	89.1–89.5	6	$1.6 \cdot 10^{-5}$			$6.0 \cdot 10^{-6}$
HFR105	21.12–200.5 (f)	119.4–120	6	$2.9 \cdot 10^{-5}$			$1.1 \cdot 10^{-5}$
HFR105	21.12–38.0		1B	-	-	$7.8 \cdot 10^{-7}$	

1) 1B: Pumping test-submersible pump, 3: Injection test, 6: Flow logging–Impeller.
(f) Flowlogged interval.

Table 6-12. Summary of calculated hydraulic parameters from the hydraulic tests performed in boreholes HFR101, HFR102 and HFR105 in the SFR area.

Borehole ID	Section (m)	Test type[1]	S* (-)	C [2] (m³/Pa)	ξ (-)
HFR101	8.0–209.3	3	$1.2 \cdot 10^{-6}$	$1.6 \cdot 10^{-6}$	–7.6
HFR102	10.4–55.0	3	$1.2 \cdot 10^{-6}$	$5.7 \cdot 10^{-9}$	–1.5
HFR105	21.1–200.5	1B	$3.2 \cdot 10^{-6}$	$1.9 \cdot 10^{-6}$	–7.01
HFR105	21.1–38.0	1B	$6.1 \cdot 10^{-7}$	$2.2 \cdot 10^{-6}$	0

[1] 1B: Pumping test-submersible pump, 3: Injection test.
[2] When the fictive casing radius r(c) can be obtained from the parameter estimation in the transient analyses, C is calculated according to Equation 5-2.

Appendix 3 includes the result tables delivered to the database SICADA. The lower measurement limit for the pumping tests with the HTHB system, presented in the result tables, is expressed in terms of specific flow (Q/s). For pumping tests, the practical lower limit is based on the minimum flow rate for which the system is designed (5 L/min) and an estimated maximum 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 (Q/s-L) of $2 \cdot 10^{-6}$ m^2/s of the pumping tests with HTHB.

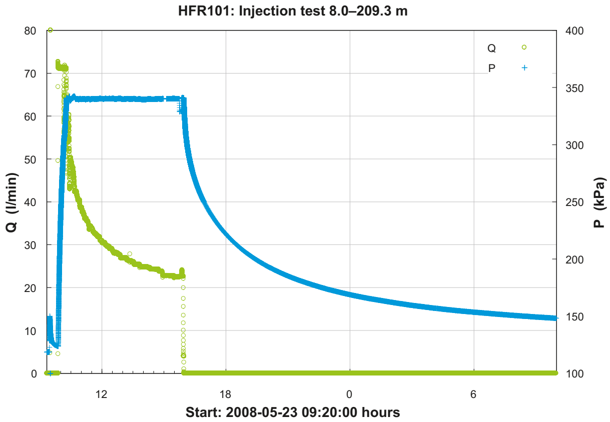
Similarly, the practical, upper measurement limit of the HTHB-system is estimated from the maximal flow rate (c. 80 L/min) and a minimal drawdown of c. 0.5 m, which is considered significant in relation to e.g. background fluctuations of the pressure before and during the test. These values correspond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

Table 6-13. Test Summary Sheet for the injection test in HFR101, section 8.04–209.30 m.

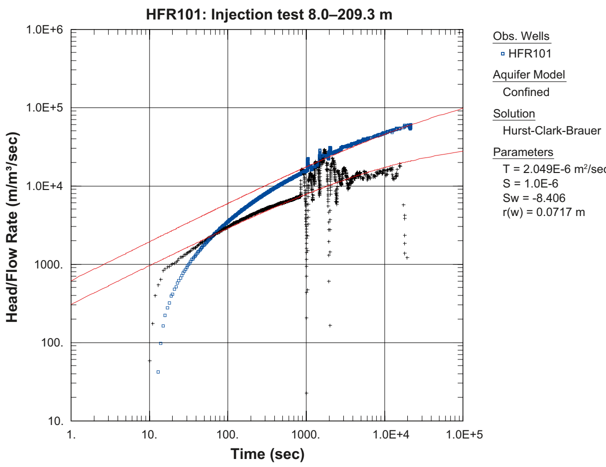
Test Summary Sheet

Project:	SFR – utbyggnad	Test type:	3
Area:	Forsmark	Test no:	1
Borehole ID:	HFR101	Test start:	2008-05-23 09:27
Test section (m):	8.04–209.30	Responsible for test performance:	Geosigma AB J. Harrström S. Jönsson
Section diameter, $2 \cdot r_w$ (m):	top 0.1395 bottom 0.1378	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

Linear plot Q and p



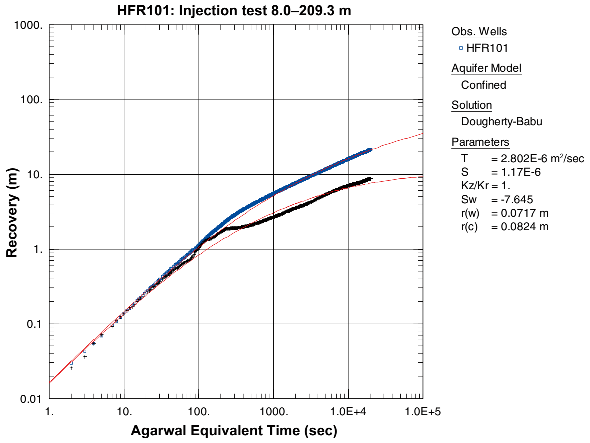
Log-Log plot incl. derivate- flow period



Flow period*		**Recovery period***	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	123.8		
p_p(kPa)	340.8	p_F (kPa)	130.7
Q_p (m^3/s)	$3.74 \cdot 10^{-4}$		
tp (min)	364	t_F (min)	4,009
S*	$1.0 \cdot 10^{-6}$	S*	$1.2 \cdot 10^{-6}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.2	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$1.7 \cdot 10^{-5}$		
T_{Moye}(m^2/s)	$2.2 \cdot 10^{-5}$		
Flow regime:	->PLF	Flow regime:	WBS->PLF
t_1 (min)		dt_{e1} (min)	
t_2 (min)		dt_{e2} (min)	
T_w (m^2/s)	$2.0 \cdot 10^{-6}$	T_w (m^2/s)	$2.8 \cdot 10^{-6}$
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)		C (m^3/Pa)	$1.6 \cdot 10^{-6}$
C_D (-)		C_D (-)	
ξ (-)	–8.4	ξ (-)	–7.6
T_{GRF} (m^2/s)		T_{GRF} (m^2/s)	
S_{GRF} (-)		S_{GRF} (-)	
D_{GRF} (-)		D_{GRF} (-)	

Test Summary Sheet

Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters

Flow regime:	WBS->PLF	C (m^3/Pa)	1.6· 10^{-6}
t_1 (min)		C_D (-)	
t_2 (min)		ξ (-)	–7.6
T_T (m^2/s)	2.8·10^{-6}		
S (-)	1.2·10^{-6}		
K_s (m/s)			
S_s (1/m)			

Comments:

A transition to pseudo-linear flow may be seen after c. 1,000 sec. during the recovery. The early phase of the flow period is strongly disturbed by the filling of the borehole to a constant water level, but after c. 1,000 sec. (17 min) a transition to pseudo-linear flow is obvious also during the flow period.

The results from the recovery period are chosen as the most representative.

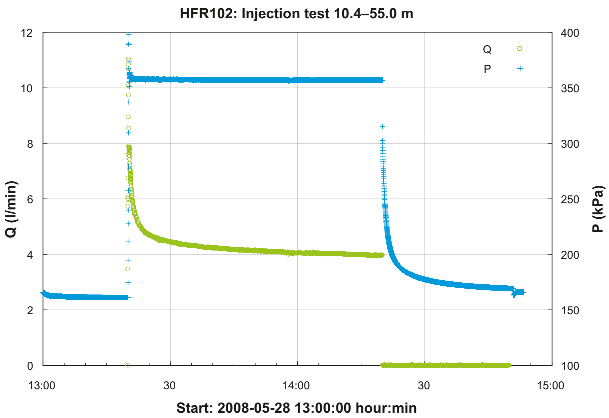
An alternative evaluation can be made using a model for a single fracture.

Table 6-14. Test Summary Sheet for the injection test in HFR102 section 9.04–55.04 m.

Test Summary Sheet

Project:	SFR – utbyggnad	Test type:	3
Area:	Forsmark	Test no:	1
Borehole ID:	HFR102	Test start:	2008-05-28 12:43
Test section (m):	10.4–55.0	Responsible for test performance:	Geosigma AB J. Harrström S. Jönsson
Section diameter, 2·r_w (m):	top 0.1383 bottom 0.1380	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

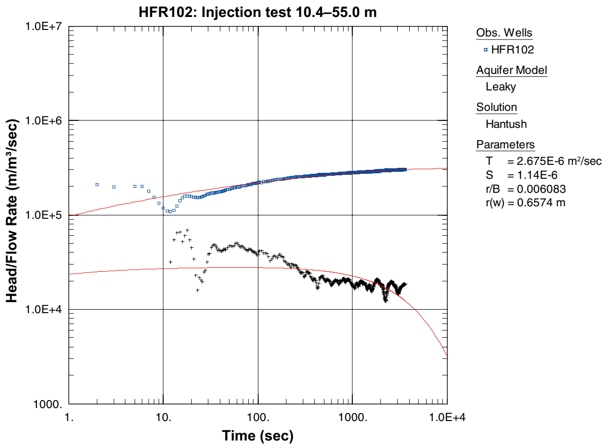
Linear plot Q and p



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	161.1		
p_p(kPa)	356.9	p_F (kPa)	166.0
Q_p (m^3/s)	6.61·10^{-5}		
tp (min)	60	t_F (min)	33.2
S*	1.1·10^{-6}	S*	1.2·10^{-6}
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.3	Derivative fact.	0.05
Results		**Results**	
Q/s (m^2/s)	3.3·10^{-6}		

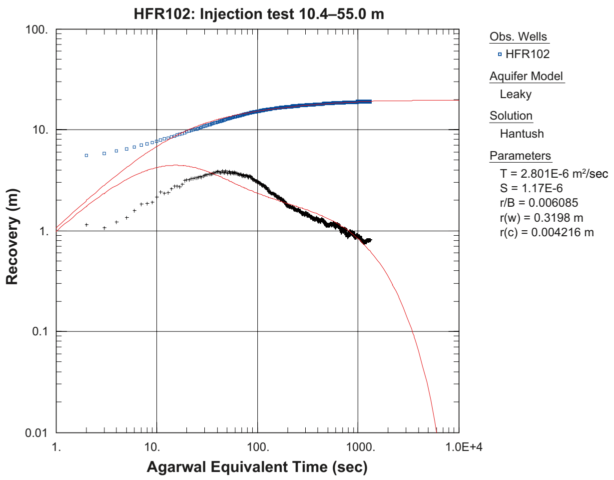
Test Summary Sheet

Log-Log plot incl. derivate- flow period



T_{Moye}(m²/s)	$3.7 \cdot 10^{-6}$		
Flow regime:	WBS->PSF	Flow regime:	WBS->PSF
t_1 (min)		dt_{e1} (min)	
t_2 (min)		dt_{e2} (min)	
T_w (m²/s)	$2.7 \cdot 10^{-6}$	T_w (m²/s)	$2.8 \cdot 10^{-6}$
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m³/Pa)		C (m³/Pa)	$5.7 \cdot 10^{-9}$
C_D (-)		C_D (-)	
ξ (-)	–2.3	ξ (-)	–1.5
T_{GRF}(m²/s)		T_{GRF}(m²/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Log-Log plot incl. derivative- recovery period



Interpreted formation and well parameters

Flow regime:	WBS->PSF	C (m³/Pa)	$5.7 \cdot 10^{-9}$
t_1 (min)		C_D (-)	
t_2 (min)		ξ (-)	–1.5
T_T (m²/s)	$2.8 \cdot 10^{-6}$		
S (-)	$1.2 \cdot 10^{-6}$		
K_s (m/s)			
S_s (1/m)			

Comments:

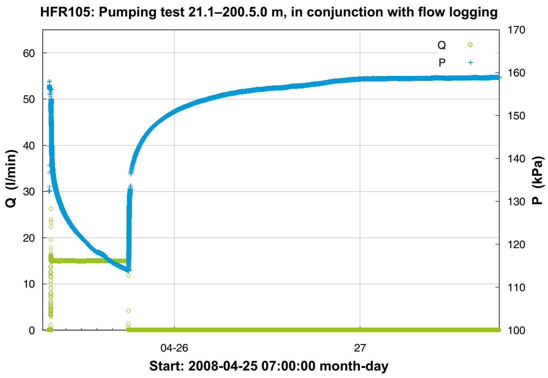
A transition to pseudo-spherical flow may be seen after c. 200 seconds both during the flow and the recovery period.
The results from the recovery period are chosen as the most representative.

Table 6-15. Test Summary Sheet for the pumping test in HFR105, section 21.12–200.50 m.

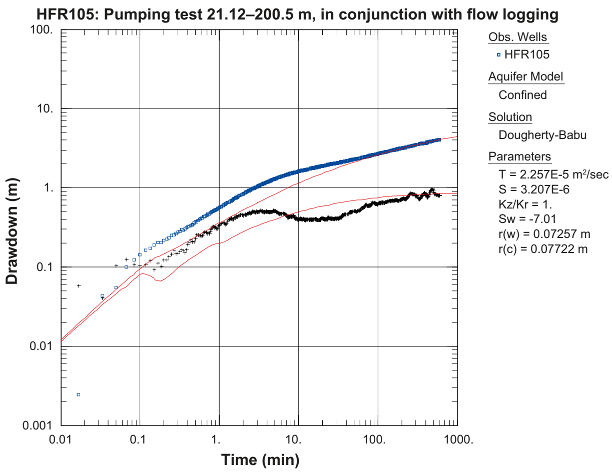
Test Summary Sheet

Project:	SFR – utbyggnad	Test type:	3
Area:	Forsmark	Test no:	1
Borehole ID:	HFR105	Test start:	080425 07:46:53
Test section (m):	21.1–200.5	Responsible for test performance:	Geosigma AB T. Svensson
Section diameter, $2 \cdot r_w$ (m):	top 0.1413 bottom 0.1398	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

Linear plot Q and p



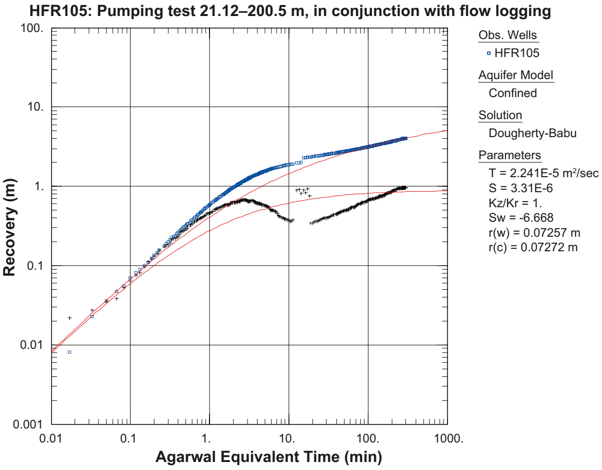
Log-Log plot incl. derivate- flow period – late response



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	153.8		
p_p(kPa)	113.9	p_F (kPa)	159.7
Q_p (m^3/s)	$2.47 \cdot 10^{-4}$		
tp (min)	601	t_F (min)	3,938
S*	$3.2 \cdot 10^{-6}$	S*	$3.3 \cdot 10^{-6}$
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.2	Derivative fact.	0.2
Results		**Results**	
Q/s (m^2/s)	$6.1 \cdot 10^{-5}$		
T_{Moye}(m^2/s)	$5.06 \cdot 10^{-5}$		
Flow regime:	WBS-> PRF1 -> PRF2	Flow regime:	WBS-> PRF1 -> PRF2
t_1 (min)	200	dt_{e1} (min)	100
t_2 (min)	601	dt_{e2} (min)	3,938+
T_w (m^2/s)	$2.3 \cdot 10^{-5}$	T_w (m^2/s)	$2.2 \cdot 10^{-5}$
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m^3/Pa)	$1.9 \cdot 10^{-6}$	C (m^3/Pa)	$1.7 \cdot 10^{-6}$
C_D (-)		C_D (-)	
ξ (-)	–7.0	ξ (-)	–6.7
T_{GRF} (m^2/s)		T_{GRF} (m^2/s)	
S_{GRF} (-)		S_{GRF} (-)	
D_{GRF} (-)		D_{GRF} (-)	

Test Summary Sheet

Log-Log plot incl. derivative- recovery period – late response



Interpreted formation and well parameters.

Flow regime:	WBS-> PRF1 -> PRF2	C (m^3/Pa)	$1.9 \cdot 10^{-6}$
t_1 (min)	200	C_D (-)	
t_2 (min)	601	ξ (-)	–7.0
T_T (m^2/s)	$2.3 \cdot 10^{-5}$		
S (-)	$3.2 \cdot 10^{-6}$		
K_s (m/s)			
S_s (1/m)			

Comments:
Initially both the drawdown and recovery are influenced by wellbore storage. A first pseudo-radial flow (PRF) develops early and a second PRF, fully developed after about 200 min, continues for the rest of the drawdown period. The recovery period indicates the same flow regimes and times. This response indicates two intersecting fractures with slightly different transmissivity or alternatively, one fracture with decreasing transmissivity away from the borehole.

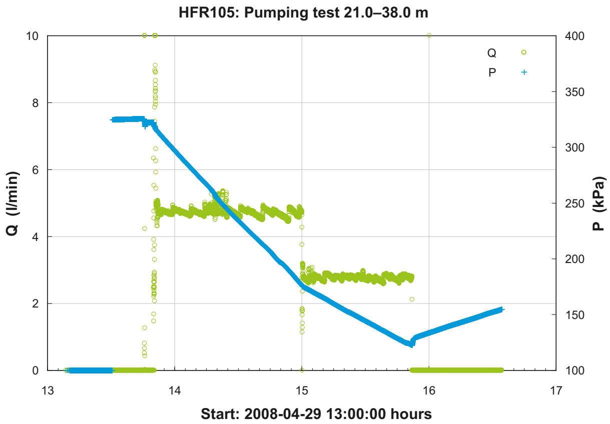
The results from the evaluation of the late PRF during the flow period are chosen as the most representative.

Table 6-16. Test Summary Sheet for the pumping test in HFR105, section 21.12–38.0 m.

Test Summary Sheet

Project:	SFR – utbyggnad	Test type:	1B
Area:	Forsmark	Test no:	1
Borehole ID:	HFR105	Test start:	080429 07:46:53
Test section (m):	21.12–38.0	Responsible for test performance:	Geosigma AB S. Jönsson
Section diameter, $2 \cdot r_w$ (m):	0.1413	Responsible for test evaluation:	Geosigma AB J-E Ludvigson

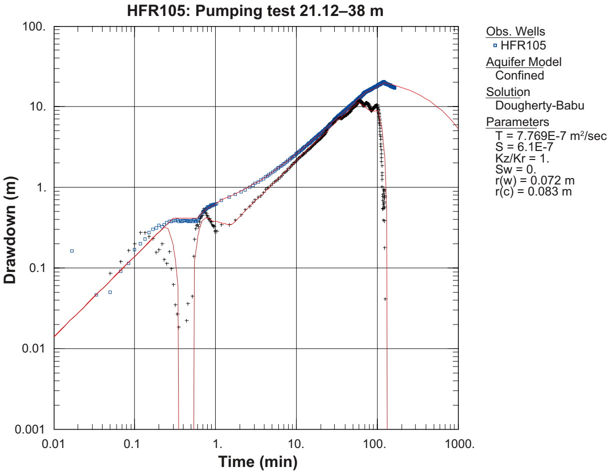
Linear plot Q and p



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	322.3		
p_p(kPa)	122.6	p_F (kPa)	154.8
Q_p (m^3/s)			
tp (min)	122	t_F (min)	42
S*	$6.1 \cdot 10^{-7}$	S*	
EC_w (mS/m)			
Te_w(gr C)			
Derivative fact.	0.2	Derivative fact.	
Results		**Results**	
Q/s (m^2/s)			

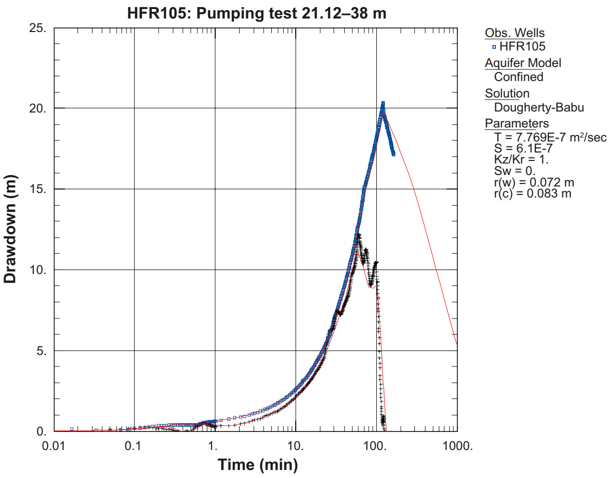
Test Summary Sheet

Log-Log plot incl. derivate – flow and recovery period



T_{Moye} (m²/s)			
Flow regime:	WBS	Flow regime:	
t_1 (min)		dt_{e1} (min)	
t_2 (min)		dt_{e2} (min)	
T_w (m²/s)	$7.8\cdot10^{-7}$	T_w (m²/s)	
S_w (-)		S_w (-)	
K_{sw} (m/s)		K_{sw} (m/s)	
S_{sw} (1/m)		S_{sw} (1/m)	
C (m³/Pa)	$2.2\cdot10^{-6}$	C (m³/Pa)	
C_D (-)		C_D (-)	
ξ (-)	0	ξ (-)	
T_{GRF} (m²/s)		T_{GRF} (m²/s)	
S_{GRF} (-)		S_{GRF} (-)	
D_{GRF} (-)		D_{GRF} (-)	

Log-Lin plot incl. derivate – flow and recovery period



Interpreted formation and well parameters

Flow regime:	WBS	C (m³/Pa)	$2.2\cdot10^{-6}$
t_1 (min)		C_D (-)	
t_2 (min)		ξ (-)	0
T_T (m²/s)	$7.8\cdot10^{-7}$		
S (-)	$6.1\cdot10^{-7}$		
K_s (m/s)			
S_s (1/m)			

Comments:
Due to the short recovery, both the injection and the recovery period is evaluated together for this pumping test. Wellbore storage (WBS) dominates the entire test, indicating low transmissivity of this borehole interval.

7 References

/1/ **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.

/2/ **Morosini M, Almén K-E, Follin S, Hansson K, Ludvigson J-E and Rhén I, 2001.** Metoder och utrustningar för hydrauliska enhålstester. Metod och programaspekter för geovetenskapliga platsundersökningar. Tekniskt Dokument TD-01-63, Svensk Kärnbränslehantering AB.

/3/ **Dougherty, D E and D K Babu, 1984.** Flow to a partially penetrating well in a double-porosity reservoir, Water Resour. Res. 20 (8), 1116–1122.

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/5/ **Hantush M S, 1959.** Nonsteady flow to flowing wells in leaky aquifer. Jour. Geophys. Research, v. 64, no 8, pp 1043–1052.

/6/ **Hantush M S, 1955.** Nonsteady radial flow in an infinite leaky aquifer. Am. Geophys. Union Trans. v. 36, no 1, pp 95–100.

/7/ **Jacob C E and Lohman S W, 1952.** Nonsteady flow to a well of constant drawdown in an extensive aquifer. Trans. AGU (Aug. 1952), pp. 559–569.

/8/ **Hurst W, Clark J D, Brauer E B, 1969.** The skin effect in producing wells. J. Peth. Tech. Nov. 1969, pp. 1483–1489.

/9/ **Ozkan E, Raghavan R, 1991.** New solutions for well testing analysis; Part 1, Analytical considerations. SPE Formation Evaluation vol 6, no 3, pp.359–368.

/10/ **Earlougher R C Jr, 1977.** Advances in well test analysis. Monogr. Ser., vol. 5, Soc. Petrol. Engrs., Dallas, 1977.

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 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
HFR101					2008-05-21 09:09:10	2008-05-26 15:07:58	HFR101_080521_Ref_Da03.DAT		Reference file
	8.04–209.30	1B	2008-05-22 09:33:21	2008-05-22 18:36:09	2008-04-25 09:44:00	2008-04-28 18:35:04	HFR101_080522_Pumpin03.DAT	P, Q, T, EC	
	8.04–209.30	6, L-EC, L-T	2008-05-23 15:48:28.3	2008-05-23 15:48:28.3			HFR101_080523_Spinne03.DAT	P, Q, T, EC, SP	
	8.04–209.30	1B	2008-05-23 09:27:10	2008-05-23 16:28:20	2008-05-21 10:04:25	2008-05-26 10:46:14	HFR101_080521_FlowLo03.DAT	P, Q, T, EC	Capacity test
HFR102					2008-05-28 09:49:47	2008-05-28 14:53:20	HFR102_10.32_080528_Ref_Da03.DAT		Reference file
	10.38–55.04	3	2008-05-28 13:20:00	2008-05-28 14:49:57	2008-05-28 13:19:59	2008-05-28 14:49:57	HFR102_10.32_080528_loggdata_WIC.xls	Q	
	10.38–55.04	3	2008-05-28 13:20:00	2008-05-28 14:50:00	2008-05-28 12:44:52	2008-05-28 14:53:14	HFR102_10.38_080528_Inject03.DAT	P	
HFR105	21.12–200.5	1B, 6, L-EC, L-T	2008-04-25 08:05:00	2008-04-28 11:43:57	2008-04-25 07:46:53	2008-04-28 11:43:57	HFR105_080428_FlowLo00.DAT	P, Q, T, EC	
					080423 15:43:34	080429 15:58:11	HFR105_080429_Ref_Da00.DAT		Reference file
	21.12–38.0	3	2008-04-29 13:50:00	2008-04-29 16:34:23	2008-04-29 13:08:40	2008-04-29 16:34:23	HFR105_080429_Pumpin00.DAT	P,Q	

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.

Test diagrams

Diagrams are presented for the following tests:	Page
1. Pumping test in HFR101: 8.0–209.3 m	53
2. Pumping test in HFR102: 10.4–55.0 m	56
3. Pumping test in HFR105: 21.1–200.5 m	58
4. Pumping test in HFR105: 21.1–38.0 m	63

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)

K_r = hydraulic conductivity, radial direction (m/s)

S_s = specific storage (1/m)

R_f = fracture radius (m)

1. Pumping test in HFR101: 8.04–209.30 m

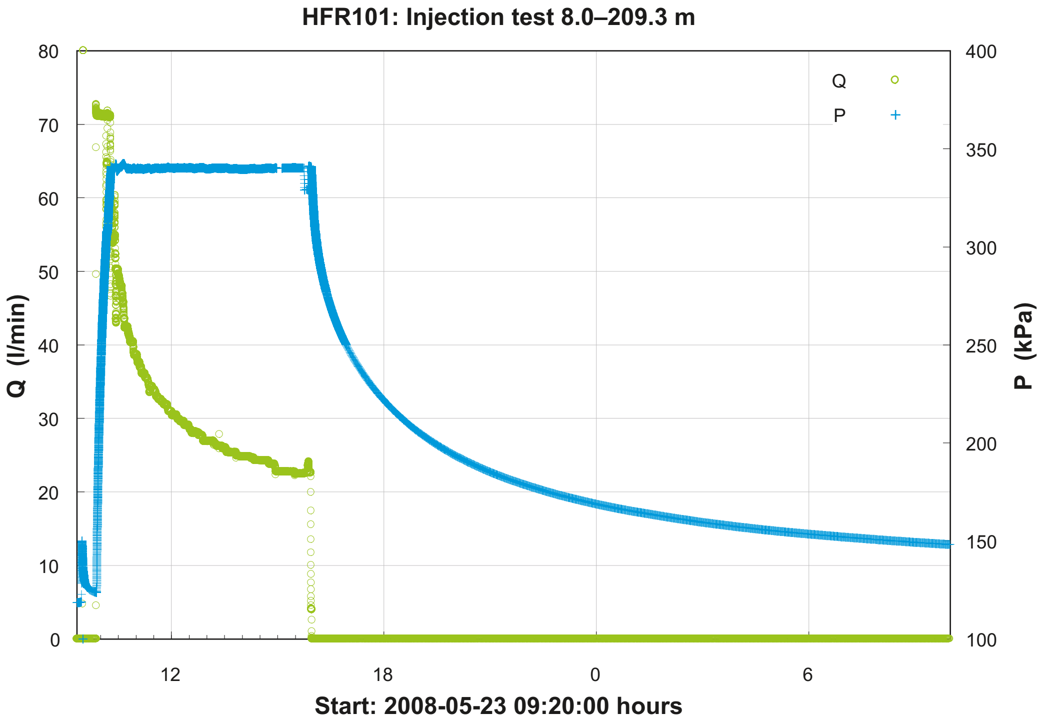

Figure A2-1. *Linear plot of flow rate (Q) and pressure (P) versus time during the open-hole injection test in HFR101 in conjunction with flow logging.*

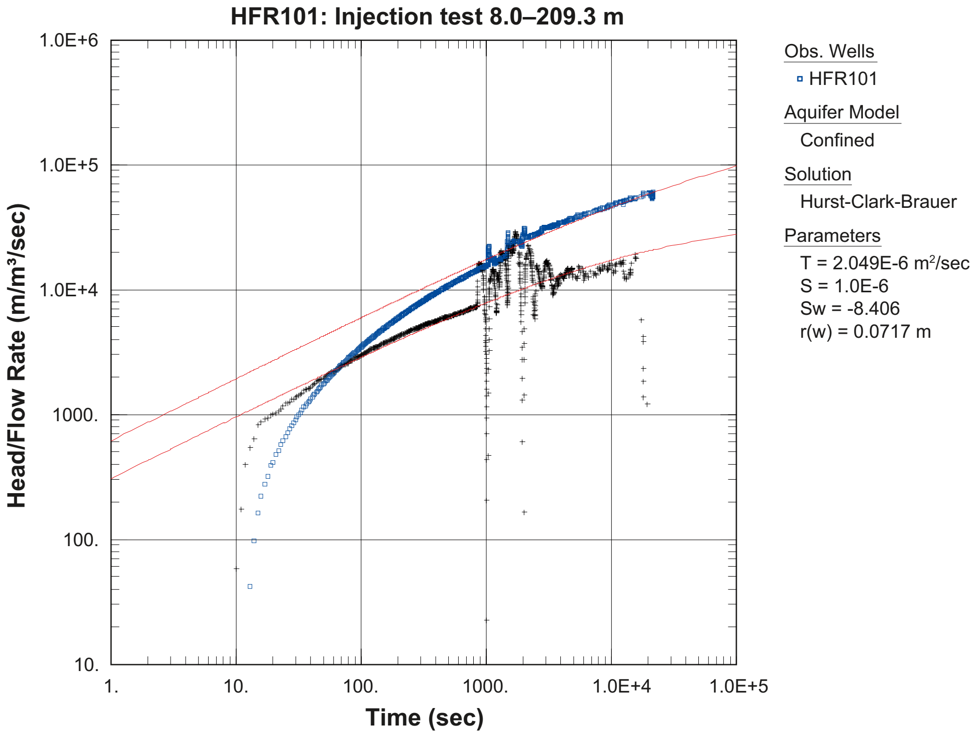

Figure A2-2. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole injection test in HFR101.*

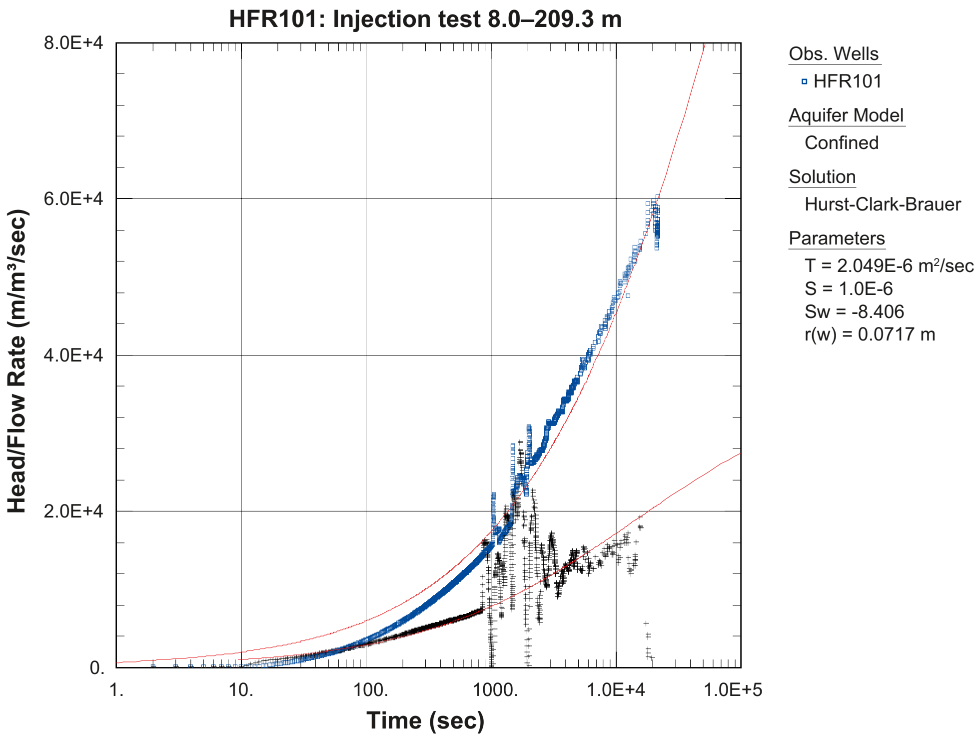

Figure A2-3. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole injection test in HFR101.*

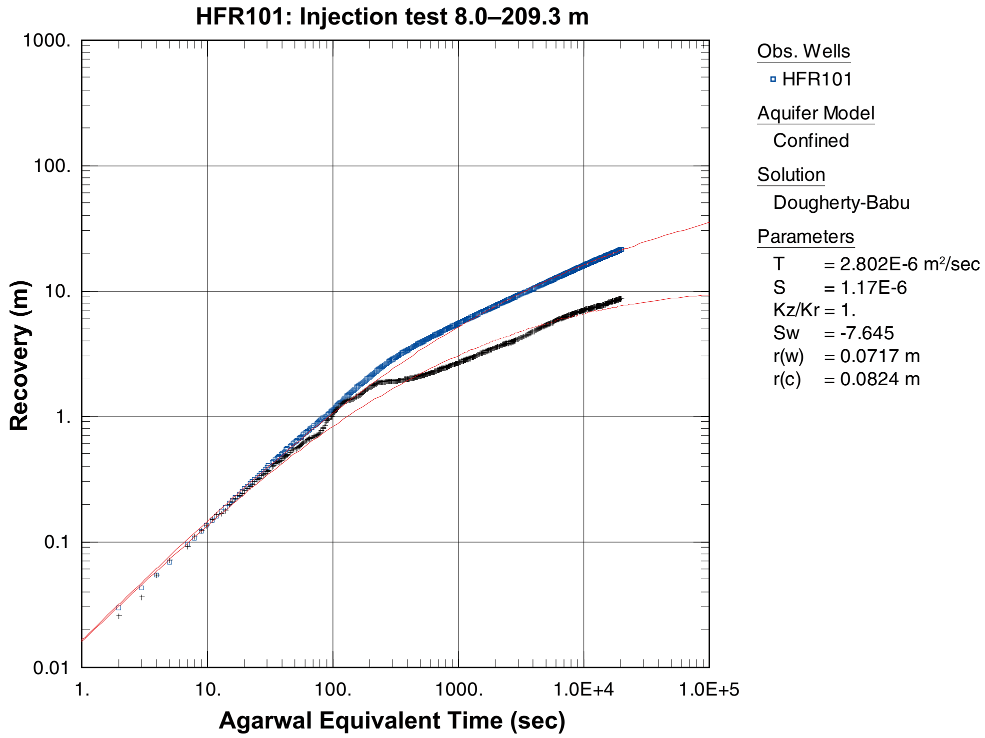

Figure A2-4. *Log-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole injection test in HFR101.*

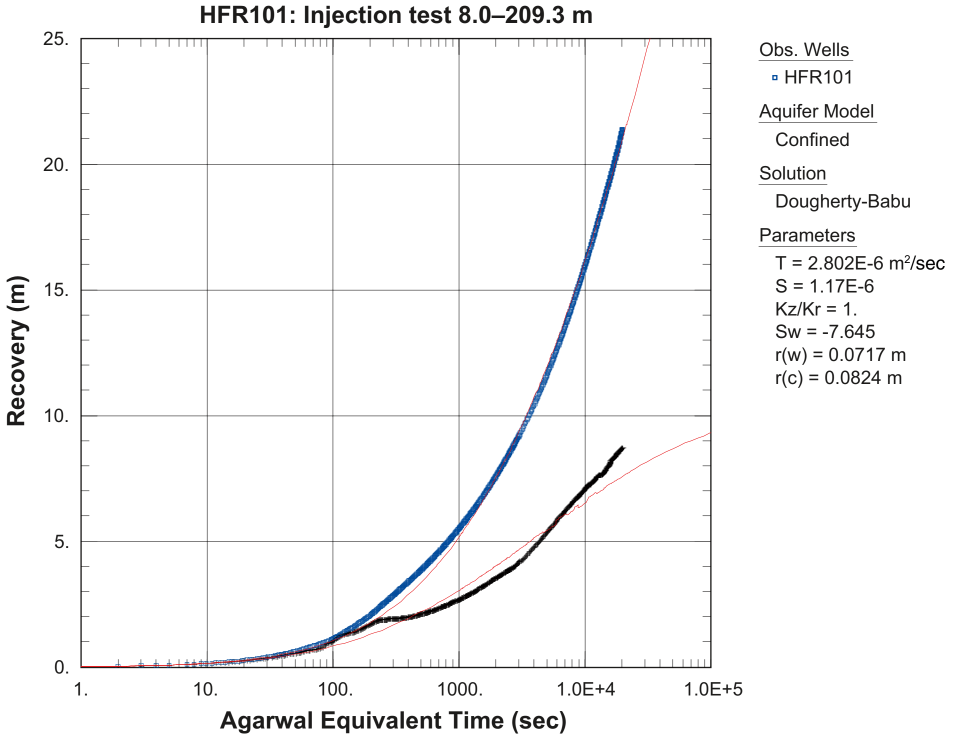

Figure A2-5. *Lin-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole injection test in HFR101.*

2. Pumping test in HFR102: 10.4–55.0 m

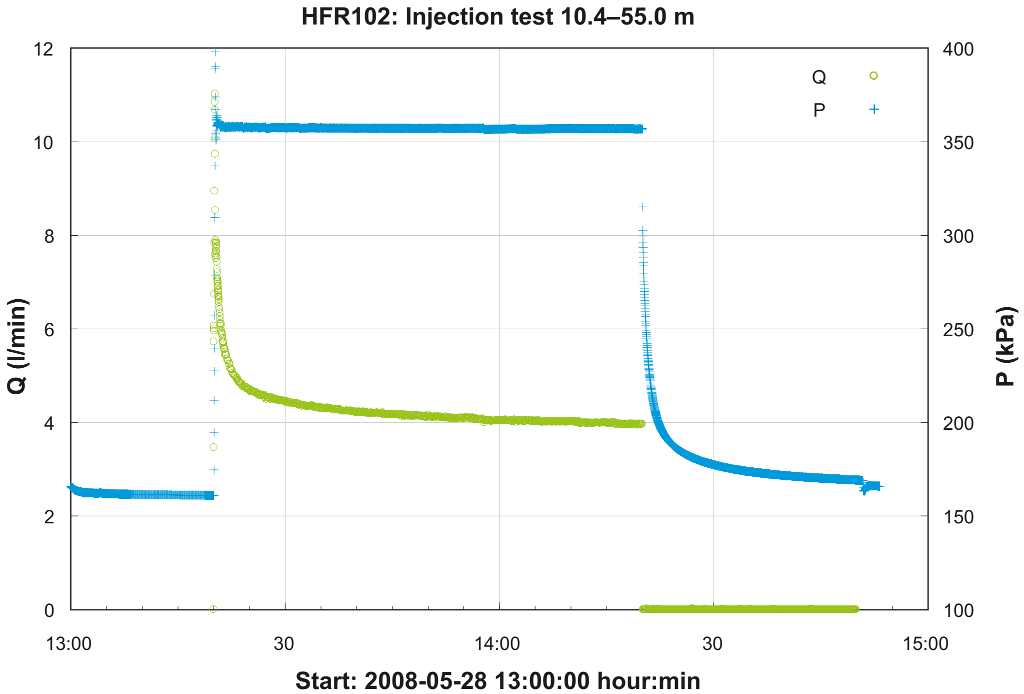

Figure A2-6. *Linear plot of flow rate (Q) and pressure (P) versus time during the injection test below a packer in HFR102.*

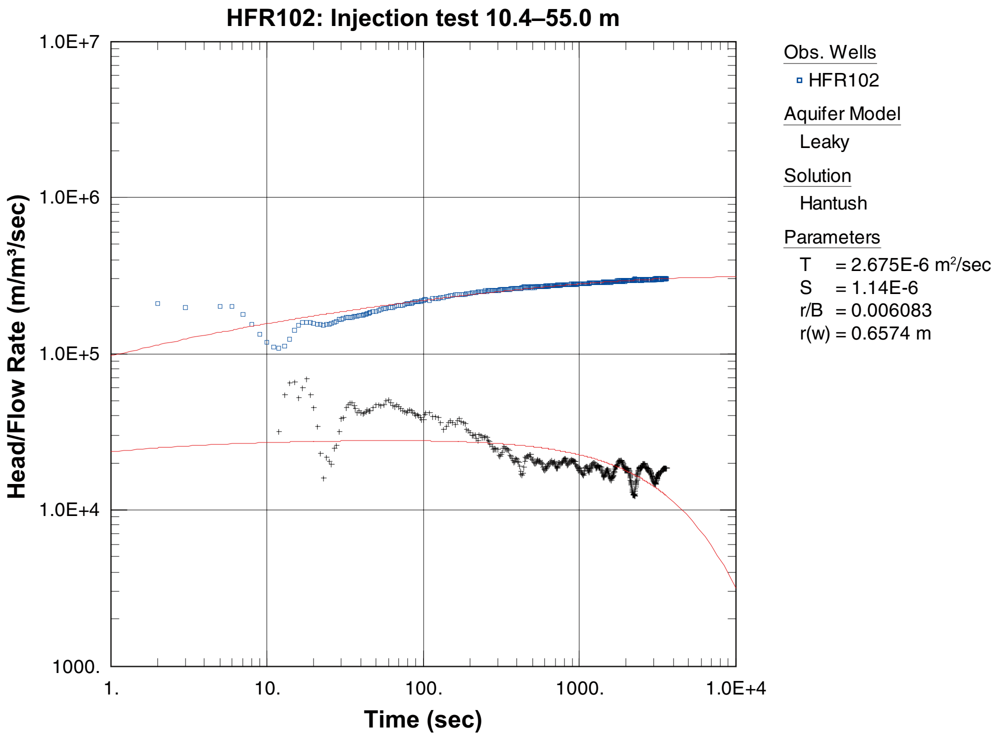

Figure A2-7. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the injection test below a packer in HFR102.*

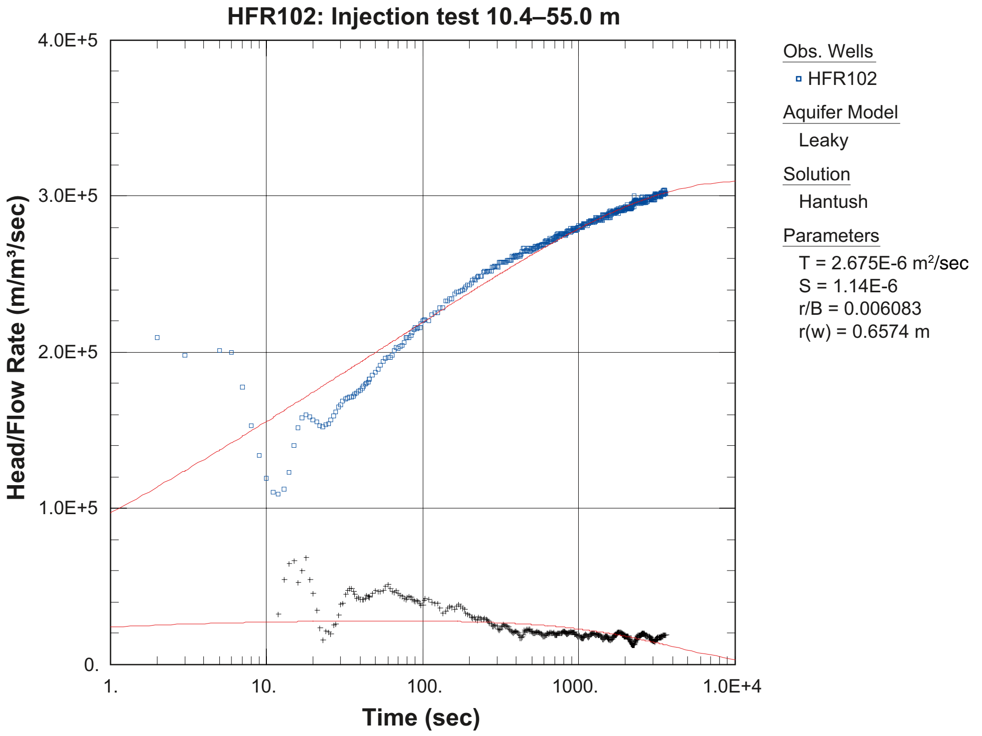

Figure A2-8. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole injection test in HFR102.*

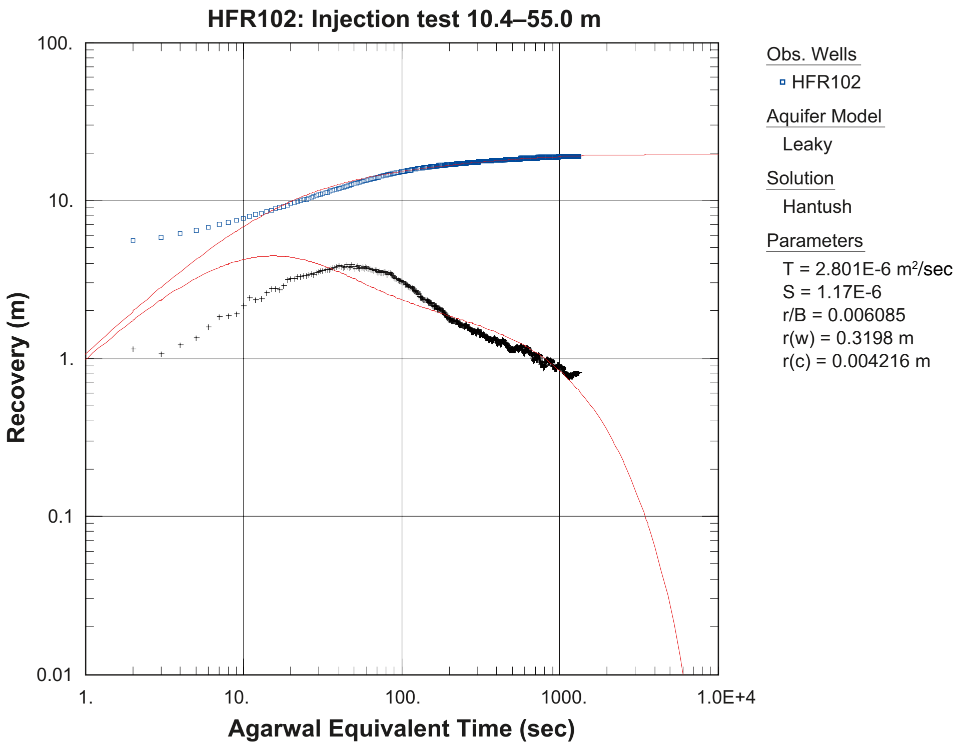

Figure A2-9. *Log-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the injection test below a packer in HFR102.*

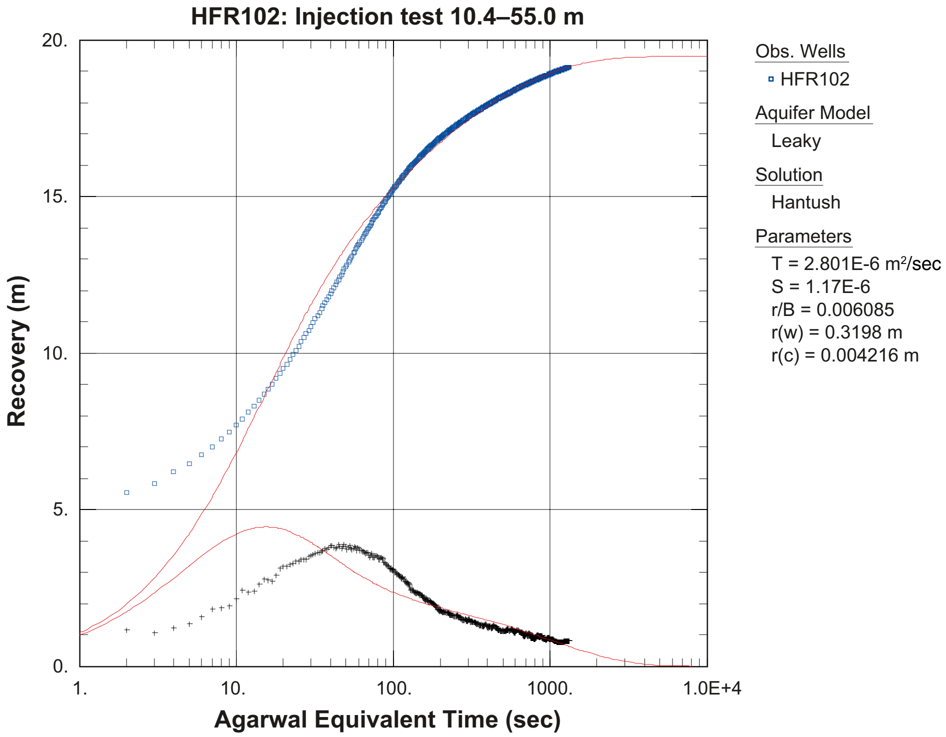

Figure A2-10. *Lin-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole injection test in HFR102.*

3. Pumping test in HFR105: 21.1–200.5 m

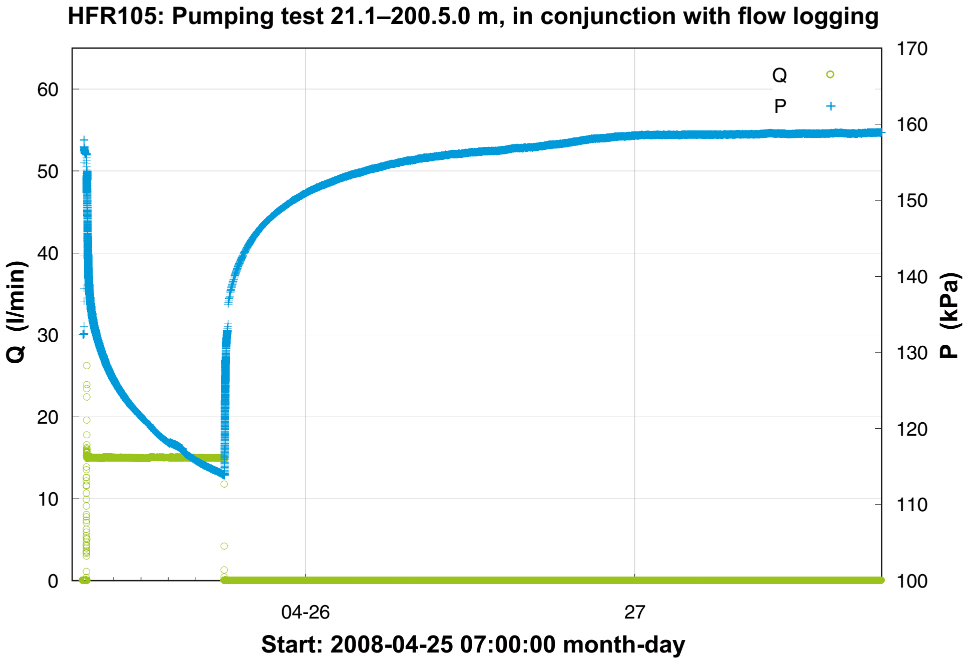

Figure A2-11. *Linear plot of flow rate (Q) and pressure (P) versus time during the open-hole pumping test in HFR105.*

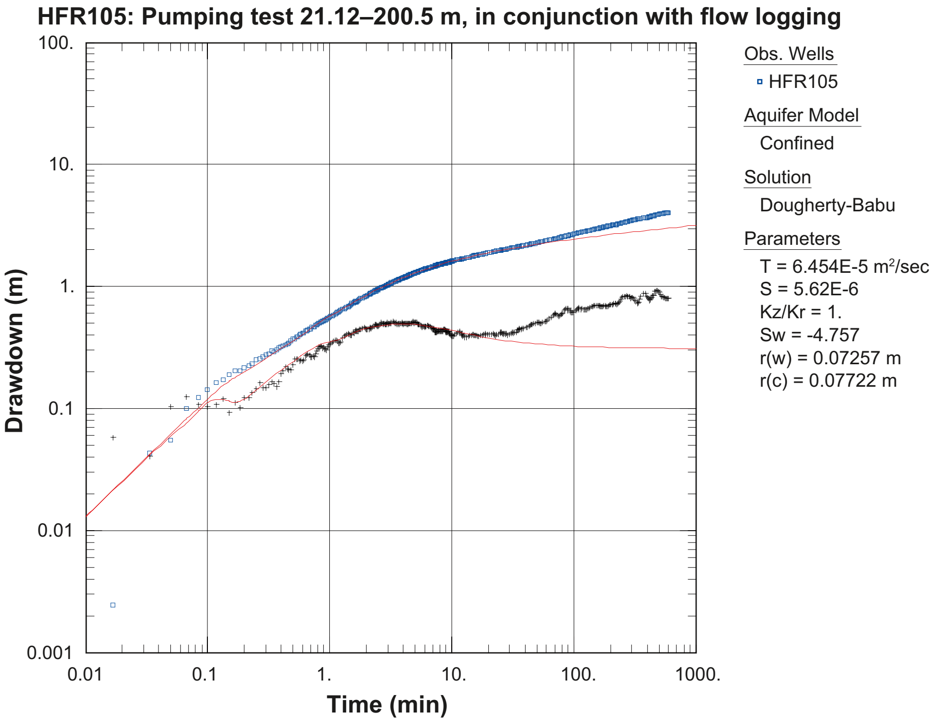

Figure A2-12. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR105. The interpretation is made on the early part.*

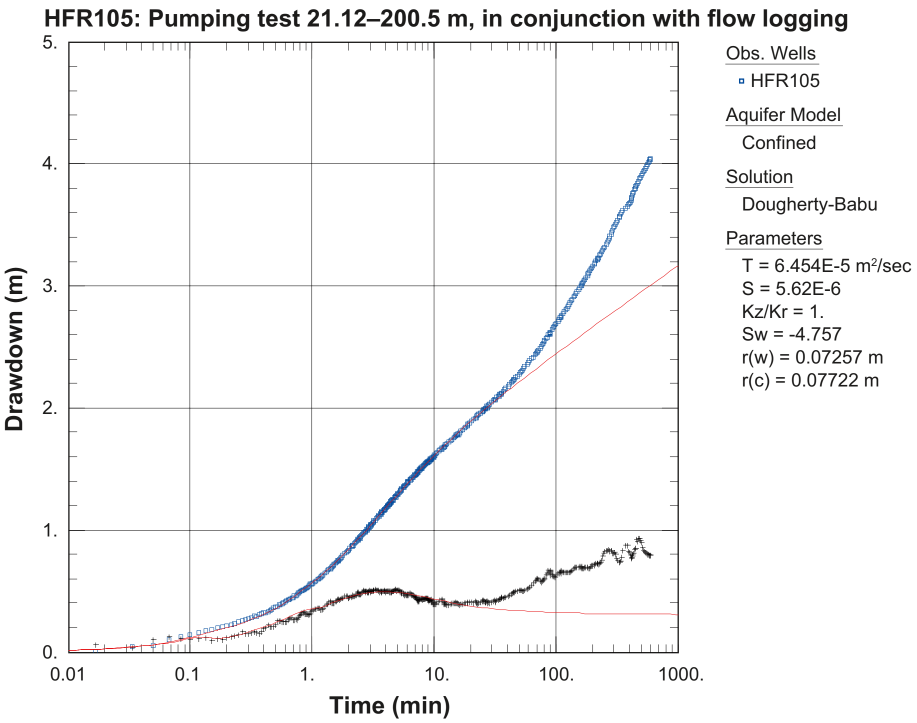

Figure A2-13. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR105. The interpretation is made on the early part*

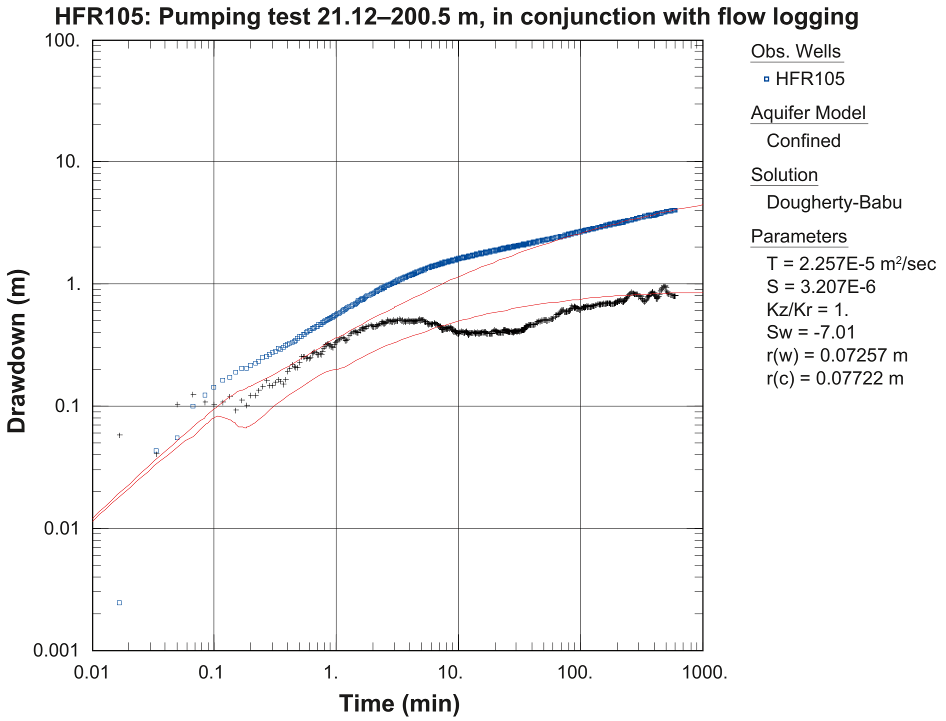

Figure A2-14. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR105. The interpretation is made on the later part when flow logging was conducted.*

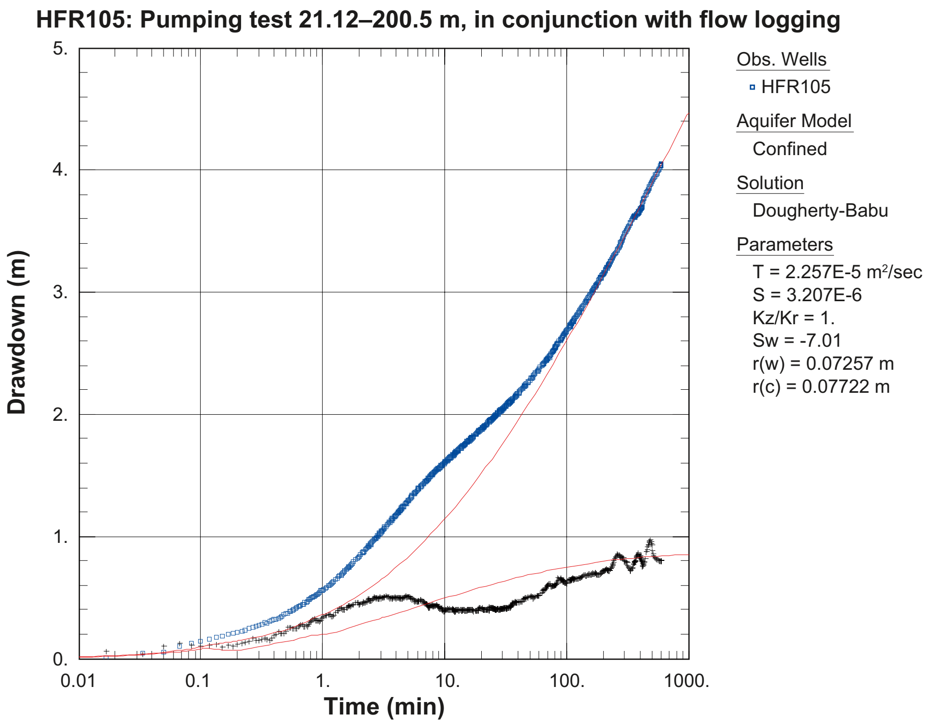

Figure A2-15. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFR105. The interpretation is made on the later part when flow logging was conducted.*

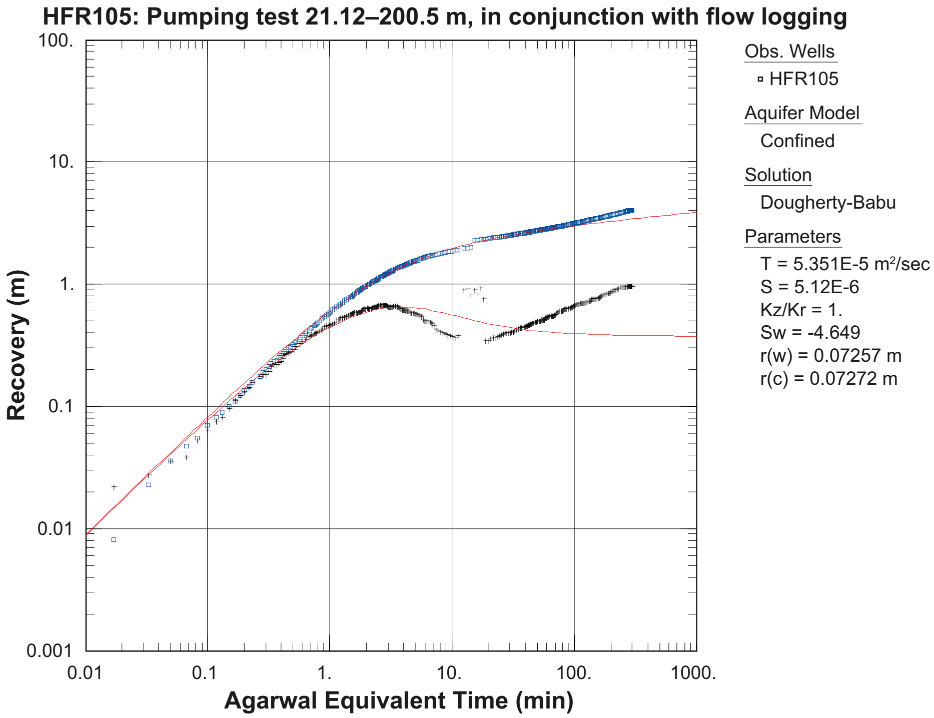

Figure A2-16. *Log-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole pumping test in HFR105. The interpretation is made on the early part.*

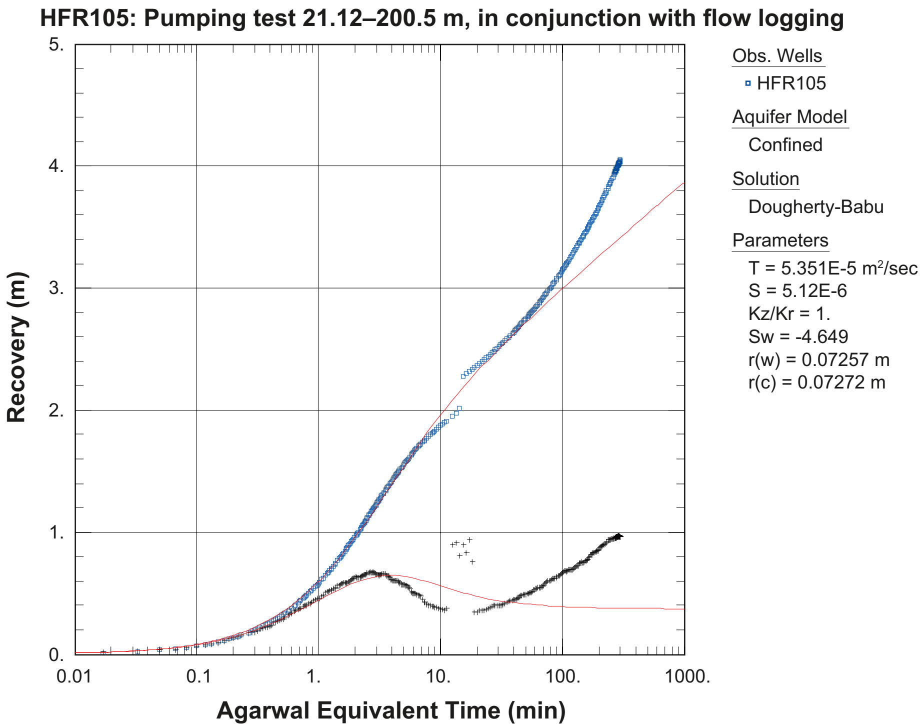

Figure A2-17. *Lin-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole pumping test in HFR105. The interpretation is made on the early part.*

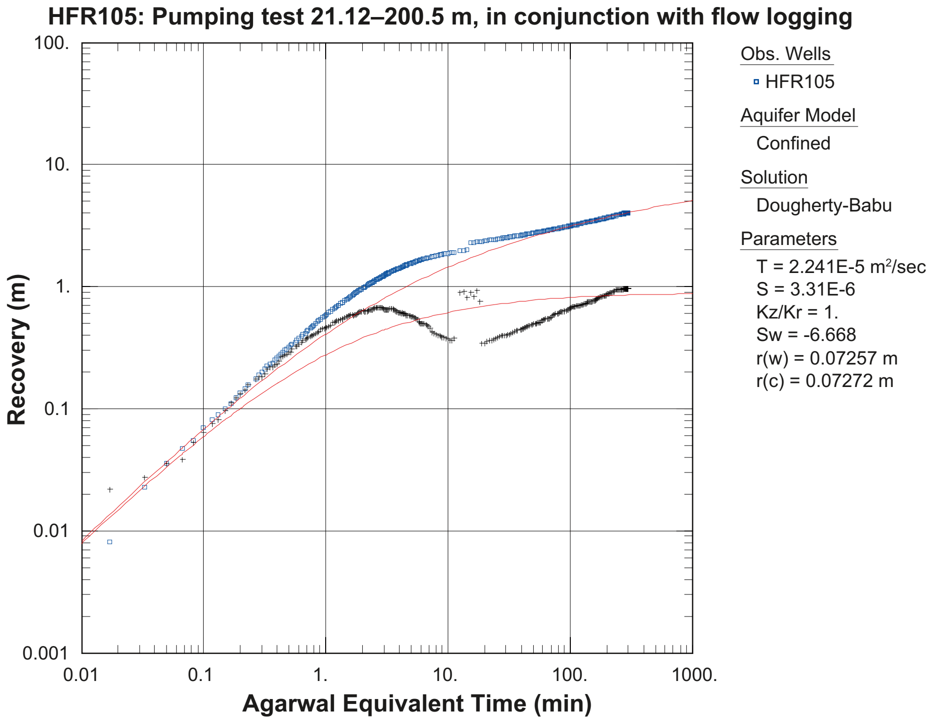

Figure A2-18. *Log-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole pumping test in HFR105.*

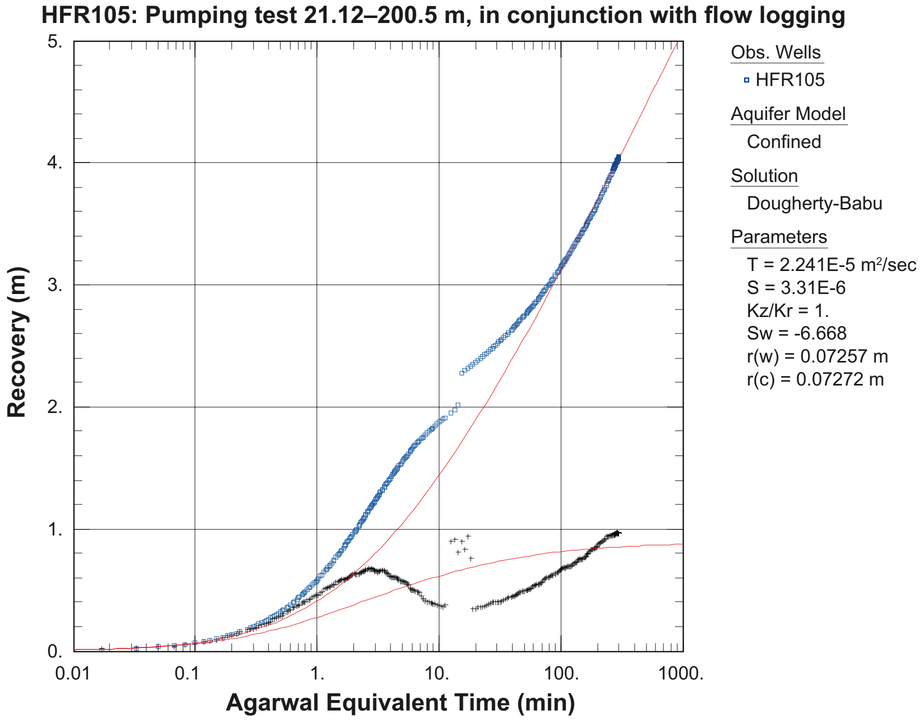

Figure A2-19. *Lin-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) from the open-hole pumping test in HFR105.*

4. Pumping test in HFR105: 21.12–38.0 m

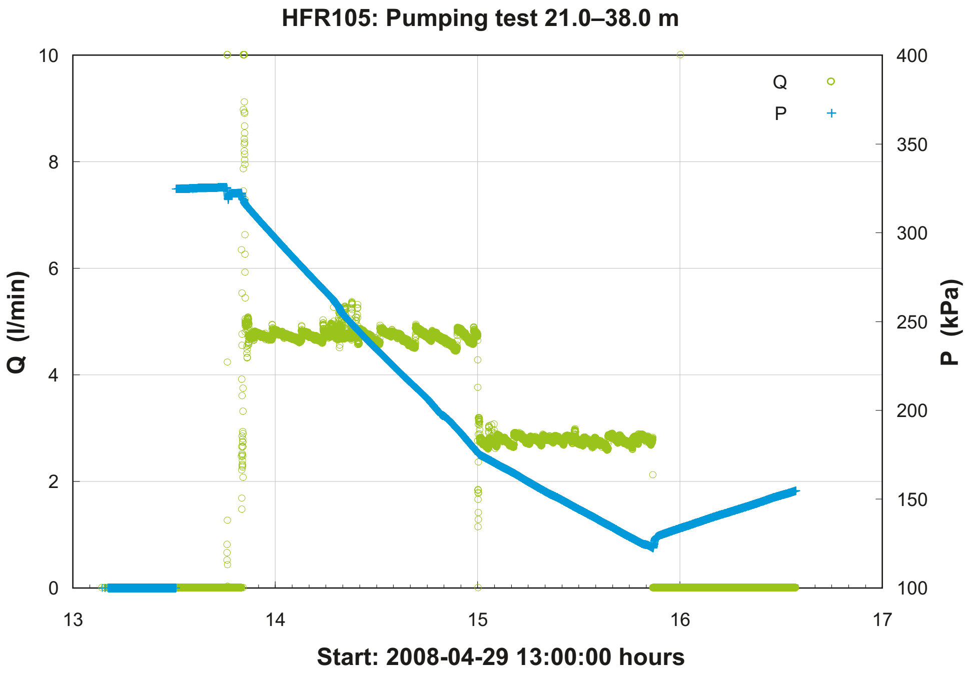

Figure A2-20. *Linear plot of flow rate (Q) and pressure (P) versus time during the pumping test above a packer in HFR105.*

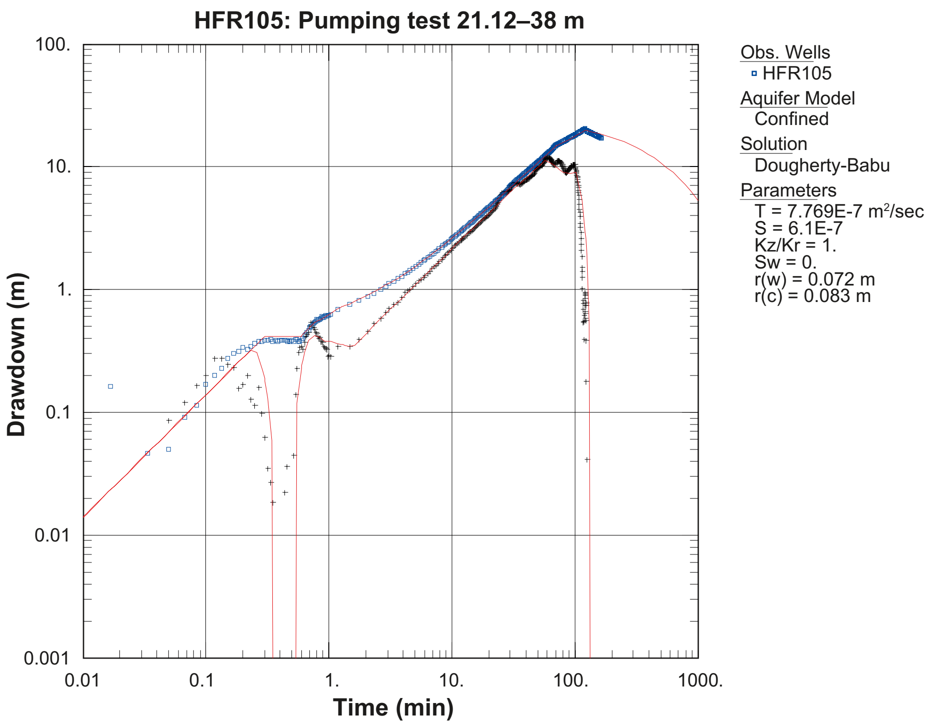

Figure A2-21. *Log-log plot of the entire test with pressure drawdown and recovery (blue □) and the derivative (black +) versus time during the pumping test above a packer in HFR105.*

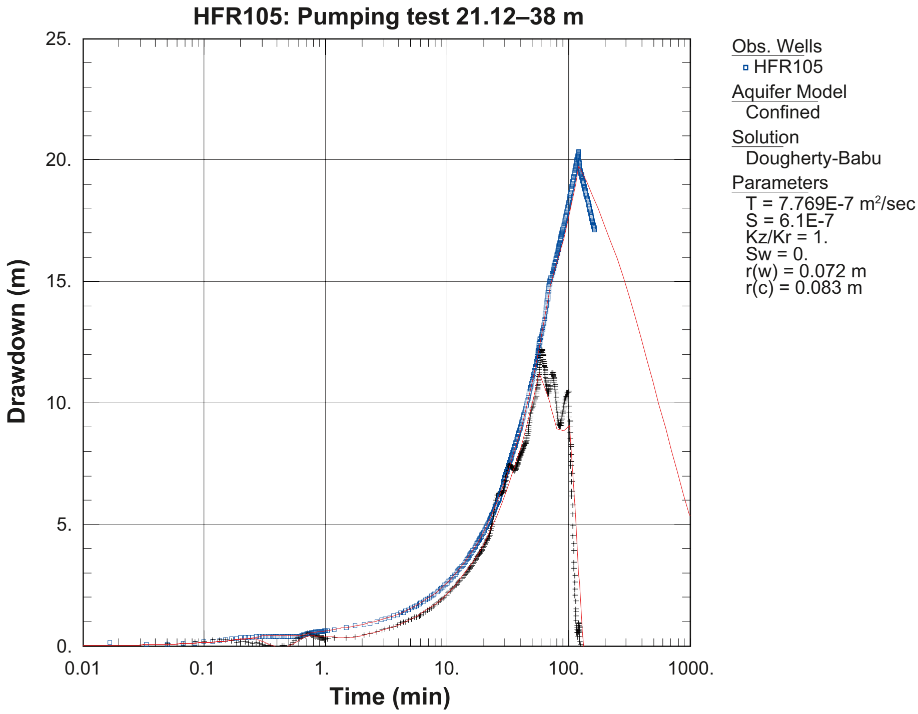

Figure A2-22. *Lin-log plot of the entire test with pressure drawdown and recovery (blue □) and the derivative (black +) versus time during the pumping test above a packer in HFR105.*

Appendix 3

Result tables to Sicada database

The following Result Tables are presented:	Page
A. Result Tables for Single-hole pumping tests	66
B. Result Tables for flow logging	71

A. Result Table for Single-hole tests for submission to the Sicada database SINGLEHOLE TESTS, Pumping and injection, plu_s_hole_test_d; General information.

idcode	start_date	stop_date	secup (m)	seclow (m)	section_no	test_type	formation_type	start_flow_period (YYYY-MM-DD hh:mm:ss)	stop_flow_period (YYYY-MM-DD hh:mm:ss)	flow_rate_end_qp (m**3/s)
HFR101	080523 09:27:10	080526 10:46:14	8.0	209.3		3	1	2008-05-23 09:52	2008-05-23 15:57	3.74E-04
HFR102	080528 12:43:52	080528 14:53:14	9.0	55.0		3	1	2008-05-28 13:20	2008-05-28 14:20	6.61E-05
HFR105	080425 07:46:53	080428 11:43:57	21.1	200.5		1B	1	2008-04-25 08:05	2008-04-25 18:06	2.47E-04
HFR105	080429 13:08:40	080429 16:34:23	21.1	38.0		1B	1	2008-04-29 13:50	2008-04-29 15:52	4.67E-05

cont.

value_type_qp	mean_flow_rate_qm (m**3/s)	q_measl_l (m**3/s)	q_measl_u (m**3/s)	tot_volume_vp (m**3)	dur_flow_phase_tp (s)	dur_rec_phase_tf (s)	initial_head_hi (m)	head_at_flow_end_hp (m)	final_head_hf (m)	initial_press_pi (kPa)	initial_press_pi_corr (kPa)	press_at_flow_end_pp (kPa)	press_flowend_pp_corr (kPa)	final_press_pf (kPa)	final_press_pf_corr (kPa)
0	5.39E-04	2.E-06	2.E-03	11.77	21840	240540	-25.73	-3.01	-25.02	123.80		340.80		130.70	
0	7.11E-05	4.20E-09	2.E-03	0.26	3600	1992				161.10		356.90		166.00	
0	2.49E-04	2.E-06	2.E-03	8.98	36060	236280	-5.74	-9.98		153.80		113.90		159.70	
0	6.52E-05	2.E-06	2.E-03	0.47	7320	2520	-7.56			322.25		122.60		154.80	

cont.

fluid_temp_tew (oC)	fluid_elcond_ecw (mS/m)	fluid_salinity_tdsw (mg/l)	fluid_salinity_tdswm (mg/l)	reference	comments (no_unit)	lp (m)
						107.50
						32.70
						119.50
						29.60

Column	Datatype	Unit	Column Description
Site	CHAR		Investigation site name
Activity_type	CHAR		Activity type code
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
Project	CHAR		project code
Idcode	CHAR		Object or borehole identification code
Secup	FLOAT	m	Upper section limit (m)
Seclow	FLOAT	m	Lower section limit (m)
Section_no	INTEGER	number	Section number
test_type	CHAR		Test type code (1-7), see table description
formation_type	CHAR		1: Rock, 2: Soil (superficial deposits)
start_flow_period	DATE	yyyymmdd	Date & time of pumping/injection start (YYYY-MM-DD hh:mm:ss)
stop_flow_period	DATE	yyyymmdd	Date & time of pumping/injection stop (YYYY-MM-DD hh:mm:ss)
flow_rate_end_qp	FLOAT	m**3/s	Flow rate at the end of the flowing period
value_type_qp	CHAR		0:true value,–1<lower meas.limit1:>upper meas.limit
mean_flow_rate_qm	FLOAT	m**3/s	Arithmetic mean flow rate during flow period
q_measl__l	FLOAT	m**3/s	Estimated lower measurement limit of flow rate
q_measl__u	FLOAT	m**3/s	Estimated upper measurement limit of flow rate
tot_volume_vp	FLOAT	m**3	Total volume of pumped or injected water
dur_flow_phase_tp	FLOAT	s	Duration of the flowing period of the test
dur_rec_phase_tf	FLOAT	s	Duration of the recovery period of the test
initial_head_hi	FLOAT	m	Hydraulic head in test section at start of the flow period
head_at_flow_end_hp	FLOAT	m	Hydraulic head in test section at stop of the flow period.
final_head_hf	FLOAT	m	Hydraulic head in test section at stop of recovery period.
initial_press_pi	FLOAT	kPa	Groundwater pressure in test section at start of flow period
press_at_flow_end_pp	FLOAT	kPa	Groundwater pressure in test section at stop of flow period.
final_press_pf	FLOAT	kPa	Groundwater pressure at the end of the recovery period.
fluid_temp_tew	FLOAT	oC	Measured section fluid temperature, see table description
fluid_elcond_ecw	FLOAT	mS/m	Measured section fluid el. conductivity,see table descr.
fluid_salinity_tdsw	FLOAT	mg/l	Total salinity of section fluid based on EC,see table descr.
fluid_salinity_tdswm	FLOAT	mg/l	Tot. section fluid salinity based on water sampling,see...
reference	CHAR		SKB report No for reports describing data and evaluation
comments	VARCHAR		Short comment to data
error_flag	CHAR		If error_flag = "*" then an error occured and an error
in_use	CHAR		If in_use = "*" then the activity has been selected as
Sign	CHAR		Activity QA signature
Lp	FLOAT	m	Hydraulic point of application

SINGLEHOLE TESTS, Pumping and injection, plu_s_hole_test_ed1; Basic evaluation

idcode	start_date	stop_date	secup (m)	seclow (m)	section_no	test_type	formation_type	lp (m)	seclen_class (m)	spec_capacity_q_s (m**2/s)	value_type_q_s
HFR101	080523 09:27:10	080526 10:46:14	8.0	209.3		3	1	107.5		1.7E-05	0
HFR102	080528 12:43:52	080528 14:53:14	9.0	55.0		3	1	32.7		3.3E-06	0
HFR105	080425 07:46:53	080428 11:43:57	21.1	200.5		1B	1	119.5		6.1E-05	0
HFR105	080429 13:08:40	080429 16:34:23	21.1	38.0		3	1	29.6			

cont.

transmissivity_tq (m**2/s)	value_type_tq	bc_tq	transmissivity_moye (m**2/s)	value_type_tm	bc_tm	hydr_cond_moye (m/s)	formation_width_b (m)	width_of_channel_b (m)	tb (m**3/s)	l_measl_tb (m**3/s)	u_measl_tb (m**3/s)	sb (m)	assumed_sb (m)	leakage_factor_lf (m)	transmissivity_tt (m**2/s)	value_type_tt	bc_tt
			2.2E-05	0	0										2.80E-06	0	1
			3.7E-06	0	0										2.80E-06	0	1
			5.1E-05	0	0										2.26E-05	0	1
															7.80E-07	0	1

cont.

l_measl_q_s (m**2/s)	u_measl_q_s (m**2/s)	storativity_s	assumed_s	s_bc	ri (m)	ri_index	leakage_coeff (1/s)	hydr_cond_ksf (m/s)	value_type_ksf	l_measl_ksf (m/s)	u_measl_ksf (m/s)	spec_storage_ssf (1/m)	assumed_ssf (1/m)	c (m**3/pa)	cd	skin	dt1 (s)	dt2 (s)
2.E-06	2.E-03	1.20E-05			107.00	1								1.64E-06		-7.60		
4.20E-09	2.E-03	1.20E-06			137.00	0								1.00E-10		-1.50		
2.E-06	2.E-03	3.21E-06			756.00	0								1.90E-06		-7.00		
2.E-06	2.E-03	6.10E-07			145.00	-1								2.20E-06		0.00		

cont.

t1 (s)	t2 (s)	dte1 (s)	dte2 (s)	p_horner (kPa)	transmissivity_t_nlr (m**2/s)	storativity_s_nlr	value_type_t_nlr	bc_t_nlr	c_nlr (m**3/pa)	cd_nlr	skin_nlr	transmissivity_t_grf (m**2/s)	value_type_t_grf	bc_t_grf	storativity_s_grf	flow_dim_grf	comment
12000	36060	6000	236280														

Column	Datatype	Unit	Column Description
Site	CHAR		Investigation site name
Activity_type	CHAR		Activity type code
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
Project	CHAR		project code
Idcode	CHAR		Object or borehole identification code
Secup	FLOAT	m	Upper section limit (m)
Seclow	FLOAT	m	Lower section limit (m)
Section_no	INTEGER	number	Section number
test_type	CHAR		Test type code (1-7), see table description!
formation_type	CHAR		Formation type code. 1: Rock, 2: Soil (superficial deposits)
Lp	FLOAT	m	Hydraulic point of application for test section, see descr.
seclen_class	FLOAT	m	Planned ordinary test interval during test campaign.
spec_capacity_q_s	FLOAT	m**2/s	Specific capacity (Q/s) of test section, see table descript.
value_type_q_s	CHAR		0:true value,–1:Q/s<lower meas.limit,1:Q/s>upper meas.limit
transmissivity_tq	FLOAT	m**2/s	Tranmissivity based on Q/s, see table description
value_type_tq	CHAR		0:true value,–1:TQ<lower meas.limit,1:TQ>upper meas.limit.
bc_tq	CHAR		Best choice code. 1 means TQ is best choice of T, else 0
transmissivity_moye	FLOAT	m**2/s	Transmissivity,TM, based on Moye (1967)
bc_tm	CHAR		Best choice code. 1 means Tmoye is best choice of T, else 0
value_type_tm	CHAR		0:true value,–1:TM<lower meas.limit,1:TM>upper meas.limit.
hydr_cond_moye	FLOAT	m/s	K_M: Hydraulic conductivity based on Moye (1967)
formation_width_b	FLOAT	m	b:Aquifer thickness repr. for T(generally b=Lw) ,see descr.
width_of_channel_b	FLOAT	m	B:Inferred width of formation for evaluated TB
Tb	FLOAT	m**3/s	TB:Flow capacity in 1D formation of T & width B, see descr.
l_measl_tb	FLOAT	m**3/s	Estimated lower meas. limit for evaluated TB,see description
u_measl_tb	FLOAT	m**3/s	Estimated upper meas. limit of evaluated TB,see description
Sb	FLOAT	m	SB:S=storativity,B=width of formation,1D model,see descript.
assumed_sb	FLOAT	m	SB* : Assumed SB,S=storativity,B=width of formation,see...
Leakage_factor_lf	FLOAT	m	Lf:1D model for evaluation of Leakage factor
transmissivity_tt	FLOAT	m**2/s	TT:Transmissivity of formation, 2D radial flow model,see...
value_type_tt	CHAR		0:true value,–1:TT<lower meas.limit,1:TT>upper meas.limit,
bc_tt	CHAR		Best choice code. 1 means TT is best choice of T, else 0
l_measl_q_s	FLOAT	m**2/s	Estimated lower meas. limit for evaluated TT,see table descr
u_measl_q_s	FLOAT	m**2/s	Estimated upper meas. limit for evaluated TT,see description
storativity_s	FLOAT		S:Storativity of formation based on 2D rad flow,see descr.
assumed_s	FLOAT		Assumed Storativity,2D model evaluation,see table descr.
s_bc	FLOAT		Best choice of S (Storativity) ,see descr.
Ri	FLOAT	m	Radius of influence
ri_index	CHAR		ri index=index of radius of influence :–1,0 or 1, see descr.
Leakage_coeff	FLOAT	1/s	K'/b':2D rad flow model evaluation of leakage coeff,see desc
hydr_cond_ksf	FLOAT	m/s	Ksf:3D model evaluation of hydraulic conductivity,see desc.
value_type_ksf	CHAR		0:true value,–1:Ksf<lower meas.limit,1:Ksf>upper meas.limit,
l_measl_ksf	FLOAT	m/s	Estimated lower meas.limit for evaluated Ksf,see table desc.
u_measl_ksf	FLOAT	m/s	Estimated upper meas.limit for evaluated Ksf,see table descr
spec_storage_ssf	FLOAT	1/m	Ssf:Specific storage,3D model evaluation,see table descr.
assumed_ssf	FLOAT	1/m	Ssf*:Assumed Spec.storage,3D model evaluation,see table des.
C	FLOAT	m**3/pa	C: Wellbore storage coefficient; flow or recovery period
Cd	FLOAT		CD: Dimensionless wellbore storage coefficient

Column	Datatype	Unit	Column Description
Skin	FLOAT		Skin factor;best estimate of flow/recovery period,see descr.
dt1	FLOAT	s	Estimated start time of evaluation, see table description
dt2	FLOAT	s	Estimated stop time of evaluation. see table description
t1	FLOAT	s	Start time for evaluated parameter from start flow period
t2	FLOAT	s	Stop time for evaluated parameter from start of flow period
dte1	FLOAT	s	Start time for evaluated parameter from start of recovery
dte2	FLOAT	s	Stop time for evaluated parameter from start of recovery
p_horner	FLOAT	kPa	p*:Horner extrapolated pressure, see table description
transmissivity_t_nlr	FLOAT	m**2/s	T_NLR Transmissivity based on None Linear Regression...
storativity_s_nlr	FLOAT		S_NLR=storativity based on None Linear Regression,see..
value_type_t_nlr	CHAR		0:true value,–1:T_NLR<lower meas.limit,1:>upper meas.limit
bc_t_nlr	CHAR		Best choice code. 1 means T_NLR is best choice of T, else 0
c_nlr	FLOAT	m**3/pa	Wellbore storage coefficient, based on NLR, see descr.
cd_nlr	FLOAT		Dimensionless wellbore storage constant, see table descrip.
skin_nlr	FLOAT		Skin factor based on Non Linear Regression,see desc.
transmissivity_t_grf	FLOAT	m**2/s	T_GRF:Transmissivity based on Genelized Radial Flow,see...
value_type_t_grf	CHAR		0:true value,–1:T_GRF<lower meas.limit,1:>upper meas.limit
bc_t_grf	CHAR		Best choice code. 1 means T_GRF is best choice of T, else 0
storativity_s_grf	FLOAT		S_GRF:Storativity based on Generalized Radial Flow, see des.
flow_dim_grf	FLOAT		Inferred flow dimesion based on Generalized Rad. Flow model
comment	VARCHAR	no_unit	Short comment to the evaluated parameters
error_flag	CHAR		If error_flag = "*" then an error occured and an error
in_use	CHAR		If in_use = "*" then the activity has been selected as
Sign	CHAR		Activity QA signature

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

Plu_impeller_basic_d

idcode	start_date	stop_date	secup (m)	seclow (m)	section_no	start_flowlogging (YYYY-MM-DD hh:mm:ss)	stop_flowlogging (YYYY-MM-DD hh:mm:ss)	l (m)	test_type	formation_type
HFR101	080523 09:27:10	080526 10:46:14	8.0	207.3		2008-05-23 13:55	2008-05-23 15:46	209.30	6	1
HFR105	080425 07:46:53	080428 11:43:57	21.1	190.0		2008-04-25 14:04	2008-04-25 15:02	200.50	6	1

cont.

q_measl_l (m**3/s)	q_measl_u (m**3/s)	pump_flow_q1 (m**3/s)	pump_flow_q2 (m**3/s)	dur_flow_phase_tp1 (s)	dur_flow_phase_tp2 (s)	dur_flowlog_tfl_1 (s)	dur_flowlog_tfl_2 (s)	drawdown_s1 (m)	drawdown_s2 (m)	initial_head_ho (m.a.s.l.)	hydraulic_head_h1 (m.a.s.l.)	hydraulic_head_h2 (m.a.s.l.)	reference	comments
5.00E-05	1.33E-03	5.39E-04		21840		6660		22.11		-25.73	-3.01			
5.00E-05	1.33E-03	6.52E-05		7320		3660		4.07		-7.46				

Column	Datatype	Unit	Column Description
Site	CHAR		Investigation site name
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
Secup	FLOAT	m	Upper section limit (m)
Seclow	FLOAT	m	Lower section limit (m)
Sign	CHAR		Activity QA signature
start_flowlogging	DATE	yyyymmdd	Date and time of flowlogging start (YYYY-MM-DD hh:mm:ss)
stop_flowlogging	DATE	yyyymmdd	Date and time of flowlogging stop (YYYY-MM-DD hh:mm:ss)
L	FLOAT	m	Corrected borehole length during logging, see table descr.
test_type	CHAR		Type of test,(1- 7); see table description
formation_type	CHAR		1: Rock, 2: Soil (supeficial deposits)
q_measl_l	FLOAT	m**3/s	Estimated lower measurement limit of borehole flow,see des.
q_measl_u	FLOAT	m**3/s	Estimated upper measurement limit of borehole flow,see desc.
pump_flow_q1	FLOAT	m**3/s	Flow rate at surface during flow logging period 1
pump_flow_q2	FLOAT	m**3/s	Flow rate at surface during flow logging period 2
dur_flow_phase_tp1	FLOAT	s	Duration of flow period 1
dur_flow_phase_tp2	FLOAT	s	Duration of flow period 2
dur_flowlog_tfl_1	FLOAT	s	Duration of the flowlogging survey 1
dur_flowlog_tfl_2	FLOAT	s	Duration of the flowlogging survey 2
drawdown_s1	FLOAT	m	Representative drawdown in borehole during flowlog period 1
drawdown_s2	FLOAT	m	Representative drawdown in borehole during flowlog period 2
initial_head_ho	FLOAT	m.a.s.l.	Initial hydraulic head (open borehole),see table description
hydraulic_head_h1	FLOAT	m.a.s.l.	Represen. hydr.head during flow period 1,see table descr.
hydraulic_head_h2	FLOAT	m.a.s.l.	Represen. hydr.head during flow period 2,see table descr.
reference	CHAR		SKB report number for reports describing data & evaluation
comments	VARCHAR		Short comment to the evaluated parameters (optional))

Plu_impell_main_res

idcode	start_date	stop_date	secup (m)	seclow (m)	section_no	l (m)	cum_flow_q0 (m**3/s)	cum_flow_q1 (m**3/s)	cum_flow_q2 (m**3/s)	cum_flow_q1t (m**3/s)	cum_flow_q2t (m**3/s)	corr_cum_flow_q1c (m**3/s)	corr_cum_flow_q2c (m**3/s)	corr_cum_flow_q1tc (m**3/s)
HFR101	080523 09:27:10	080526 10:46:14	8.0	207.3		209.3				3.74E-04				
HFR105	080425 07:46:53	080428 11:43:57	21.1	190.0		200.5				2.47E-04				

cont.

corr_com_flow_q1tcr (m**3/s)	corr_com_flow_q2tcr (m**3/s)	transmissivy_hole_t (m**2/s)	value_type_t	bc_t	cum_transmissivity_tf (m**2)	value_type_tf	bc_tf	l_measl_tf (m**2/s)	cum_transmissivity_tft (m**2)	value_type_tft	bc_tft	u_measl_tf (m**2/s)	reference	comments
		2.8E-06	0	1				1.67E-06	2.8E-06	0	0			
		2.3E-05	0	1				1.67E-06	2.3E-06	0	0			

Column	Datatype	Unit	Column Description
Site	CHAR		Investigation site name
Activity_type	CHAR		Activity type code
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
Project	CHAR		project code
Idcode	CHAR		Object or borehole identification code
Secup	FLOAT	m	Upper section limit (m)
Seclow	FLOAT	m	Lower section limit (m)
Section_no	INTEGER	number	Section number
L	FLOAT	m	Corrected borehole length
cum_flow_q0	FLOAT	m**3/s	Undisturbed cumulative flow rate, see table description
cum_flow_q1	FLOAT	m**3/s	Cumulative flow rate at pumping flow Q1/head h1,see descr.
cum_flow_q2	FLOAT	m**3/s	Cumulative flow rate at pumping flow Q2/head h2, see descr.
cum_flow_q1t	FLOAT	m**3/s	Cumulative flow at the top of measured interval,pump flow Q1
cum_flow_q2t	FLOAT	m**3/s	Cumulative flow at the top of measured interval,pump flow Q2
corr_cum_flow_q1c	FLOAT	m**3/s	Corrected cumulative flow q1 at pump flow Q1,see tabledescr.
corr_cum_flow_q2c	FLOAT	m**3/s	Corrected cumulative flow q2 at pump flow Q2,see tabledescr.
corr_cum_flow_q1tc	FLOAT	m**3/s	Corrected cumulative flow q1T at pump flow Q1,see...
corr_cum_flow_q2tc	FLOAT	m**3/s	Corrected cumulative flow q2T at pump flow Q2,see...
corr_com_flow_q1tcr	FLOAT	m**3/s	Corrected q1Tc for estimated borehole radius (rwa)
corr_com_flow_q2tcr	FLOAT	m**3/s	Corrected q2Tc for estimated borehole radius (rwa)
transmissitivy_hole_t	FLOAT	m**2/s	T: Transmissivity of the entire hole, see table description
value_type_t	CHAR		0:true value,–1:T<lower meas.limit,1:T>upper meas.limit
bc_t	CHAR		Best choice code: 1 means T is best transm. choice, else 0
cum_transmissivity_tf	FLOAT	m**2	T_F: Cumulative transmissivity, see table description
value_type_tf	CHAR		0:true value,–1:TF<lower meas.limit,1:TF>upper meas.limit
bc_tf	CHAR		Best choice code: 1 means TF is best transm. choice, else 0
l_measl_tf	FLOAT	m**2/s	Lower measurement limit of T_F,see table description
cum_transmissivity_tft	FLOAT	m**2	T_FT: Cumulative transmissivity, see table description
value_type_tft	CHAR		0:true value,–1:TFT<lower meas.limit,1:TFT>upper meas.limit
bc_tft	CHAR		Best choice code: 1 means TFT is best transm. choice,else 0
u_measl_tf	FLOAT	m**2/s	Upper measurement limit of T_F, see table description
reference	CHAR		SKB number for reports describing data and results
comments	CHAR		Short comment to evaluated data (optional)
error_flag	CHAR		If error_flag = "*" then an error occured and an error
in_use	CHAR		If in_use = "*" then the activity has been selected as
Sign	CHAR		Activity QA signature

Plu_impeller_anomaly

idcode	start_date	stop_date	secup (m)	seclow (m)	section_no	l_a_upper (m)	l_a_lower (m)	fluid_temp_tea (oC)	fluid_elcond_eca (mS/m)	fluid_salinity_tdsa (mg/l)	dq1 (m**3/s)	dq2 (m**3/s)
HFR101	080523 09:27:10	080526 10:46:14	8.0	207.3		107.3	108.0				3.4E-04	
HFR101	080523 09:27:10	080526 10:46:14	8.0	207.3		196.0	197.0				3.3E-05	
HFR105	080425 07:46:53	080428 11:43:57	21.1	190.0		55.6	55.8				6.3E-05	
HFR105	080425 07:46:53	080428 11:43:57	21.1	190.0		89.1	89.5				6.7E-05	
HFR105	080425 07:46:53	080428 11:43:57	21.1	190.0		119.4	120.0				1.2E-04	

cont.

r_wa (m)	dq1_corrected (m**3/s)	dq2_corrected (m**3/s)	spec_cap_dq1c_s1 (m**2/s)	spec_cap_dq2c_s2 (m**2/s)	value_type_dq1_s1	value_type_dq2_s2	ba (m)	transmissivity_tfa (m**2/s)	value_type_tfa	bc_tfa	l_measl_tfa (m**2/s)	u_measl_tfa (m**2/s)	comments
0.069			1.5E-05		0		0.7	2.6E-06	0	1	1.67E-06	8.30E-05	
0.070			1.5E-06		0		1.0	2.5E-07	0	1	1.67E-06	8.30E-05	
0.071			1.6E-05		0		0.2	5.7E-06	0	1	1.67E-06	8.30E-05	
0.070			1.6E-05		0		0.4	6.0E-06	0	1	1.67E-06	8.30E-05	
0.070			2.9E-05		0		0.6	1.1E-05	0	1	1.67E-06	8.30E-05	

Column	Datatype	Unit	Column Description
Site	CHAR		Investigation site name
Activity_type	CHAR		Activity type code
start_date	DATE		Date (yymmdd hh:mm:ss)
stop_date	DATE		Date (yymmdd hh:mm:ss)
Project	CHAR		project code
Idcode	CHAR		Object or borehole identification code
Secup	FLOAT	m	Upper section limit (m)
Seclow	FLOAT	m	Lower section limit (m)
Section_no	INTEGER	number	Section number
L	FLOAT	m	Corrected borehole length
cum_flow_q0	FLOAT	m**3/s	Undisturbed cumulative flow rate, see table description
cum_flow_q1	FLOAT	m**3/s	Cumulative flow rate at pumping flow Q1/head h1,see descr.
cum_flow_q2	FLOAT	m**3/s	Cumulative flow rate at pumping flow Q2/head h2, see descr.
cum_flow_q1t	FLOAT	m**3/s	Cumulative flow at the top of measured interval,pump flow Q1
cum_flow_q2t	FLOAT	m**3/s	Cumulative flow at the top of measured interval,pump flow Q2
corr_cum_flow_q1c	FLOAT	m**3/s	Corrected cumulative flow q1 at pump flow Q1,see tabledescr.
corr_cum_flow_q2c	FLOAT	m**3/s	Corrected cumulative flow q2 at pump flow Q2,see tabledescr.
corr_cum_flow_q1tc	FLOAT	m**3/s	Corrected cumulative flow q1T at pump flow Q1,see...
corr_cum_flow_q2tc	FLOAT	m**3/s	Corrected cumulative flow q2T at pump flow Q2,see...
corr_com_flow_q1tcr	FLOAT	m**3/s	Corrected q1Tc for estimated borehole radius (rwa)
corr_com_flow_q2tcr	FLOAT	m**3/s	Corrected q2Tc for estimated borehole radius (rwa)
transmissitivy_hole_t	FLOAT	m**2/s	T: Transmissivity of the entire hole, see table description
value_type_t	CHAR		0:true value,–1:T<lower meas.limit,1:T>upper meas.limit
bc_t	CHAR		Best choice code: 1 means T is best transm. choice, else 0
cum_transmissivity_tf	FLOAT	m**2	T_F: Cumulative transmissivity, see table description
value_type_tf	CHAR		0:true value,–1:TF<lower meas.limit,1:TF>upper meas.limit
bc_tf	CHAR		Best choice code: 1 means TF is best transm. choice, else 0
l_measl_tf	FLOAT	m**2/s	Lower measurement limit of T_F,see table description
cum_transmissivity_tft	FLOAT	m**2	T_FT: Cumulative transmissivity, see table description
value_type_tft	CHAR		0:true value,–1:TFT<lower meas.limit,1:TFT>upper meas.limit
bc_tft	CHAR		Best choice code: 1 means TFT is best transm. choice,else 0
u_measl_tf	FLOAT	m**2/s	Upper measurement limit of T_F, see table description
reference	CHAR		SKB number for reports describing data and results
comments	CHAR		Short comment to evaluated data (optional)
error_flag	CHAR		If error_flag = "*" then an error occured and an error
in_use	CHAR		If in_use = "*" then the activity has been selected as
Sign	CHAR		Activity QA signature

Results from chemical analyses

Appendix 4

Table A4-1. Hydrogeochemical data for groundwater in percussion boreholes HFR101 and HFR105.

Idcode	Sampling date	Secup (m)	Seclow (m)	Sample No.	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	SO_4 (mg/l)	SO_4-S (mg/l)	Br (mg/l)	F (mg/l)	Si (mg/l)
HFR101	2008-05-22 16:30:00	0,00	209,00	16020	1240	8,99	714	110	112	3360	322	119	12,9	0,90	5,79
HFR101	2008-05-22 17:50:00	0,00	209,00	16021	1260	9,24	699	111	113	3370	336	117	12.9	1,20	5,71
HFR101	2008-05-22 18:30:00	0,00	209,00	16022	1240	9,17	708	111	113	3470	332	115	12.7	1,22	5,65
HFR105	2008-04-25 09:00:00	0,00	200,00	16017	1460	21,4	520	141	127	3410	417	142	13,3	0,90	5,22
HFR105	2008-04-25 13:05:00	0,00	200,00	16018	1440	14,7	561	135	138	3480	441	150	14,3	1,02	5,88
HFR105	2008-04-25 17:50:00	0,00	200,00	16019	1450	14,0	551	135	141	3430	429	151	13,8	1,03	5,95

Idcode	Sampling date	Secup (m)	Seclow (m)	Sample No.	Li (mg/l)	Sr (mg/l)	RCB (%)	pH-L pH unit	EC-L (mS/m)	TOC (mg/l)	$^{10}B/^{11}B$ (no unit)	^3H (TU)	δ^2H (SMOW)	$\delta^{18}O$ (SMOW)
HFR101	2008-05-22 16:30:00	0,00	209,00	16020	0,050	9,55	-2,45	7,35	1030	1,6	0,2394			
HFR101	2008-05-22 17:50:00	0,00	209,00	16021	0,048	9,46	-2,43	7,35	1030	1,8	0,2395			
HFR101	2008-05-22 18:30:00	0,00	209,00	16022	0,049	9,37	-3,99	7,33	1040	1,7	0,2394	4,20	-80,6	-10,6
HFR105	2008-04-25 09:00:00	0,00	200,00	16017	0,044	5,30	-2,59	7,15	1070	2,5	0,2163			
HFR105	2008-04-25 13:05:00	0,00	200,00	16018	0,044	6,29	-3,55	7,27	1090	2,0	0,2400			
HFR105	2008-04-25 17:50:00	0,00	200,00	16019	0,044	6,09	-3,00	7,28	1090	2,2	0,2394	5,40	-68,2	-8,7

RCB = Relative Charge Balance
pH-L = pH from batch measurements in laboratory
EC-L = Electrical Conductivity from batch measurements in laboratory
TOC = Total Organic Carbon