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Forsmark site investigation

Hydraulic interference tests

Boreholes HFM01, HFM02 and HFM03

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May 2003

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Keywords: Forsmark, hydrogeology, hydraulic tests, pumping tests, interference tests, cross-hole tests, water sampling, hydraulic parameters, transmissivity, storativity.

Abstract

Two hydraulic interference tests were performed by pumping in HFM01 and HFM02, respectively and monitoring the pressure responses in percussion boreholes drilled in hard rock and in groundwater monitoring wells in the Quaternary deposits at drillsite 1 at Forsmark. The main objective of the interference tests was to confirm previous indications of a sub-horizontal fracture zone between HFM01 and HFM02 and to preliminary assess the hydraulic properties of such a zone. The quality of the interference tests are evaluated by checking the reciprocity principle between the two boreholes.

During the interference tests, the pressure responses were monitored in the percussion boreholes HFM01–HFM03 and the groundwater monitoring wells in the Quaternary deposits SFM0001–SFM0003. Manual registration was also performed in the percussion-drilled part of KFM01A (0–100) and in the new water prospecting boreholes for the power plant at Forsmark.

The results obtained in the pumping boreholes HFM01 and HFM02 are consistent with those from the previous single-hole tests with the HTHB-system in conjunction with the flow logging in these boreholes.

The results from the interference tests confirm the anticipated hydraulic connection between HFM01 and HFM02 via a potential sub-horizontal zone. The transmissivity of the potential zone is assumed to increase towards HFM02. Near HFM01 the estimated transmissivity of the zone is c $5 \cdot 10^{-5}$ m^2/s and towards HFM02 c $5 \cdot 10^{-4}$ m^2/s. The storativity of the zone was estimated to c $5 \cdot 10^{-5}$ m^2/s. The distance between the holes is c 220 m along the potential zone. The pressure response time lag between HFM01 and HFM02 was c 4–5 minutes in both tests.

When HFM01 was pumped, the pressure responses in HFM02 and the nearby HFM03 were similar although the latter response was slightly more delayed at the beginning of the flow period. The responses then approached each other and coincided almost by the end of the flow period. The pressure response time lag in HFM03 was c 10 minutes. The distance between HFM01-HFM03 is also c 220 m. The response in HFM03 may have propagated via the assumed zone between HFM01 and HFM02 and then indirectly through the rock mass to HFM03, possibly via sub-vertical fractures. Alternatively, the response in HFM03 may be direct via another parallel zone extending between HFM01 and HFM03.

When HFM02 was pumped, a rather delayed pressure response (c 4–5 min) was observed in HFM03, despite the very short distance between these holes, indicating an indirect hydraulic connection in the rock mass between them, possibly via sub-vertical fractures.

In the observation boreholes HFM01 and HFM02 consistent (almost reciprocal) responses in relation to the flow rates in the holes were obtained, which supports the reciprocity principle in this case.

Sammanfattning

Två hydrauliska interferenstester utfördes genom att pumpa i HFM01 respektive HFM02 och mäta de erhållna responserna i hammarborrhål och jordrör på Borrplats 1 i Forsmark. Huvudsyftena med interferenstesterna var att bekräfta tidigare indikationer av en subhorisontell zon mellan HFM01 och HFM02 och att preliminärt skatta de hydrauliska egenskaperna av en sådan zon. Kvaliteten på interferenstesterna utvärderas genom att kontrollera reciprocitetsprincipen mellan de två borrhålen.

Under interferenstesterna registrerades tryckresponserna i hammarborrhålen HFM01–HFM03 och i jordrören SFM001–SFM003. Manuell registrering utfördes också i den hammarborrade delen av KFM01A (0–100 m) och i de nya vattenprospekterings-borrhålen för Forsmarksanläggningen.

Resultaten som erhölls i pumphålen HFM01 och HFM02 överensstämde med resultaten från de tidigare enhålstesterna med HTHB-systemet i samband med flödesloggning av dessa borrhål.

Resultaten från interferenstesterna bekräftar den antagna hydrauliska konnektionen mellan HFM01 och HFM02 via en förmodad subhorisontell zon. Transmissiviteten hos denna förmodade zon antas öka mot HFM02. Nära HFM01 är den skattade transmissiviteten av zonen ca $5 \cdot 10^{-5}$ m^2/s and mot HFM02 ca $5 \cdot 10^{-4}$ m^2/s. Zonens storativitet skattades till ca $5 \cdot 10^{-5}$. Avståndet mellan borrhålen är ca 220 m längs den förmodade zonen. Responstiden mellan HFM01 och HFM02 var ca 4–5 min vid båda testerna.

När HFM01 pumpades var tryckresponserna i HFM02 och HFM03 likartade. Dock var den senare responsen något mer fördröjd i början av flödesperioden. Responserna närmade sig sedan och sammanföll nästan vid slutet av flödesperioden. Responstiden i HFM03 var ca 10 min. Även avståndet mellan HFM01 och HFM03 är ca 220 m. Responsen i HFM03 kan ha fortplantat sig via den förmodade zonen från HFM01 till HFM02 och därifrån indirekt via bergmassan till HFM03, eventuellt via subvertikala sprickor. Alternativt kan responsen i HFM03 ha fortplantats direkt via en annan parallell zon mellan HFM01 och HFM03.

När HFM02 pumpades observerades en ganska fördröjd tryckrespons (ca 4–5 min) i HFM03, trots det mycket korta avståndet mellan dessa borrhål, vilket kan tyda på ett indirekt hydrauliskt samband i bergmassan mellan dessa borrhål, möjligen via subvertikala sprickor.

I observationshålen HFM01 och HFM02 erhölls konsistenta (nästan reciproka) responser i relation till pumpflödena, vilket stöder reciprocitetsprincipen för detta fall.

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1 Introduction

Percussion borehole HFM01 was drilled with the main objective to serve as a supply well for flushing water needed for drilling the cored boreholes KFM01A and 1B, see Figure 1-1. HFM01 is c 200 m long with a capacity of c 3000 L/h. According to the flow meter survey /1/, the main inflow was located to c 42 m but a minor additional inflow also occurred at c 60 m along the borehole. Two other percussion boreholes (HFM02 and HFM03) were drilled as potential supply wells for flushing water and/or monitoring wells. HFM02 is c100 m long with a very large inflow of c 60 000 L/h (1000 L/min) at c 43 m below ground surface. HFM03 was drilled as a shallow monitoring well close to HFM02 with a length of c 26 m. The main inflow (c 6000 L/h) was concentrated to a short interval at c 21 m below surface.

At the time of the interference tests, the upper part (0–100 m) of the cored borehole KFM01A was drilled and cased along the entire interval. Grouting had been performed between the outer casing and the rock. Finally, three groundwater monitoring wells had been drilled in the Quaternary deposits at the drillsite.

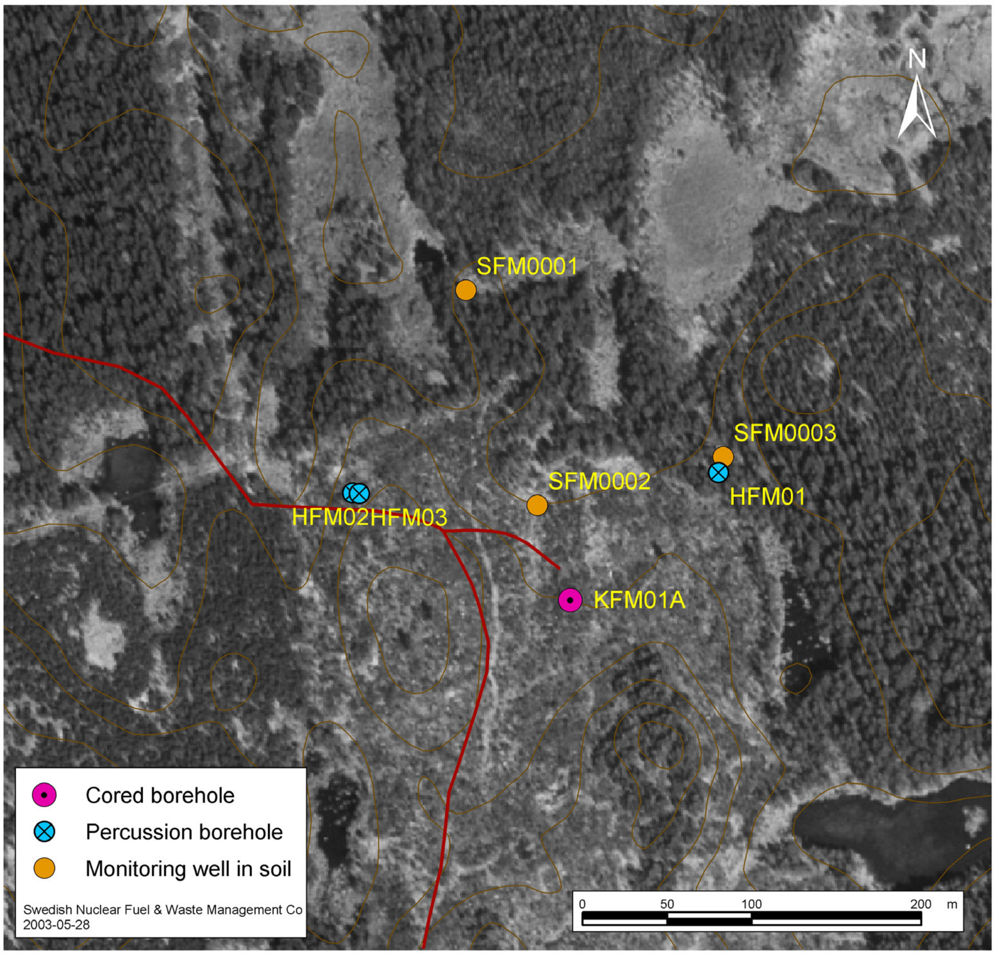


Figure 1-1. *Map showing the location of boreholes, monitoring wells and reflectors at drillsite 1 at Forsmark.*

2 Objectives

Two hydraulic interference tests were performed by pumping in HFM01 and HFM02, respectively. The main objective of the interference test was to confirm previous indications of a sub-horizontal fracture zone between HFM01 and HFM02 and to achieve a preliminary assessment of the hydraulic properties of this zone. The quality of the interference tests are evaluated by checking the reciprocity principle between the two boreholes.

3 Scope

3.1 Boreholes

Technical data of the boreholes involved in the interference tests are shown in Table 3-1. HFM01 and HFM02 were used as pumping boreholes whereas the other boreholes were used as observation/monitoring wells. The upper part (0–100 m) of KFM01A was drilled with a larger diameter and was cased off at the time of the interference tests.

The reference point in the boreholes is always top of casing (ToC). The Swedish National coordinate system (RT90 2.5 g W) is used in the x-y-plane together with RHB70 in the z-direction. Northing and Easting refer to the top of the boreholes at top of casing.

Table 3-1. Technical data of the boreholes involved in the interference tests (from SICADA). H=percussion boreholes, K=cored boreholes, S=groundwater monitoring wells in the Quaternary deposits (soil).

Borehole								**Casing**		**Drilling finished**
ID	**Elevation** of top of casing (ToC) (m.a.s.l.)	**Borehole length** from ToC (m)	**Bh-diam.** (below casing) (m)	**Inclin.** -top of bh (from horizontal plane) (°)	**Bearing** -top of bh (from local N) (°)	**Northing**	**Easting**	**Length** (m)	**Inner diam.** (m)	**Date** (YYYY-MM-DD)
HFM01	1.73	200.20	0.140	-77.51	34.06	6699605	1631485	31.93	0.160	2002-05-03
HFM02	3.05	100.00	0.137	-87.79	6.52	6699593	1631269	25.40	0.160	2002-05-21
HFM03	3.15	26.00	0.136	-87.28	264.53	6699593	1631272	13.10	5.5	2002-05-28
KFM01A	3.125	[1)] 100.57	[2)] 0.164	-84.73	318.35	6699530	1631397	29.40	5.7	2002-06-10
KFM01A								[3)] 100.43	11.0	
SFM001	1.104	5.5	0.168	-90	0	6699713	1631335	4.5	0.050	2002-05-23
SFM002	2.022	5.7	0.168	-90	0	6699586	1631378	4.7	0.050	2002-05-30
SFM003	1.944	11.0	0.168	-90	0	6699615	1631487	10.0	0.050	2002-05-30

1) Borehole length of the percussion-drilled interval
2) Borehole diameter of the percussion-drilled interval at the time of the test. The borehole was subsequently reamed to 0.254 m in this interval
3) Final borehole casing

3.2 Interference tests performed

The interference tests were mainly performed according to Activity Plan AP PF 400-02-23 (SKB internal controlling document) following the methodology description for interference tests (SKB MD 330.003). The so called HTHB system for pumping tests in percussion boreholes was not available for the interference tests and a simpler, temporary equipment system had to be used instead. Pertinent data for the interference tests are listed in Table 3-2. The tests in the pumping boreholes constitute the second test campaign in these boreholes, cf Table 3-2 (Test no). The first test campaign consisted of single-hole tests with the HTHB system /1/.

During the interference tests, water samples were taken in the pumping boreholes and submitted for analysis. The results of the analyses are presented in /2/.

Table 3-2. Pertinent data for the hydraulic interference tests performed.

Pumping Bh ID	Pumped section (open hole) (m)	Test type[1]	Test no	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
HFM01	31.93-200.20	2	2	2002-06-25 10:25	2002-06-26 00:30
HFM02	25.40-100.00	2	2	2002-06-26 10:40	2002-06-27 06:00

1) 2: Interference test

During the interference tests, the pressure responses in the other boreholes listed in Table 3-1 were monitored. The distances between the percussion boreholes are shown in Table 3-3. The distances are calculated from the hydraulic point of application in each borehole listed below in Table 3-3 (length from ToC). This point is assumed to correspond to the main inflow zone as identified from the flow logging /1/. The distances to the monitoring wells are calculated from the point of application in the pumping borehole to the bottom of each monitoring well.

In addition, manual groundwater level measurements were made in the new water prospecting boreholes BH1–BH5 for potential water supply to the power plant at Forsmark. Of these boreholes, BH1–3 are described in /3/ whereas BH4–5 were drilled later. The approximate distances to these boreholes (along the surface) from the pumping boreholes are listed in Table 3-3. Approximate technical data together with estimated yield and transmissivity for BH1–5 are presented in Table 3-4.

Table 3-3. Calculated distances to the boreholes involved in the two interference tests. The distances to BH1–5 are only approximate.

Pumping Bh ID	Distance to observation boreholes (m)										
	HFM01*	HFM02*	HFM03*	SFM001	SFM002	SFM003	BH1	BH2	BH3	BH4	BH5
HFM01	-	221	220	189	123	51	1260	1260	1340	1310	1370
HFM02	221	-	22	143	119	225	1040	1040	1130	1100	1170

* Hydraulic point of application in HFM01=42.5 m, in HFM02=43 m and in HFM03=21 m

Table 3-4. Approximate technical data together with estimated yield and transmissivity of boreholes BH1–5. From /3/.

Pumping Bh ID	Total length (m)	Inclination	Bearing (from N)	Vertical depth (m)	Estimated T (m^2/s)	Estimated inflow during drilling (L/h)
BH1	52	60	105	45	$2.0 \cdot 10^{-4}$	10 000
BH2	40	50	100	31	$2.2 \cdot 10^{-4}$	10 000
BH3	61	60	45	53	$5.7 \cdot 10^{-5}$	7 200
BH4	80	60	50-55	69	-	800
BH5	40	60	50-55	35	-	10 000

3.3 Equipment check

An equipment check was performed at the site as a simple and fast test to establish the operating status of sensors and other equipment. In addition, calibration constants were implemented and checked.

To check the function of the pressure sensors, the pressure in air was recorded and found to be as expected. Submerged in water, the pressure coincided well, while lowering, to the total head of water.

4 Equipment

4.1 Description of equipment

The temporary test system used for the interference tests is described in Activity Plan AP PF 400-02-09 (SKB internal controlling document). The equipment in the pumping boreholes consisted of the following parts:

- submersible pump with submarine contact and hose to the ground surface,
- wire to anchor the pump,
- pressure transducer in the borehole,
- flow meter at the surface,
- data logger to sample data from the flow meter and the pressure transducer,
- flow rate control valve at the surface,
- PC to visualize the data.

All observation boreholes and pipes used for pressure monitoring were open without packers. The monitoring of pressure/water level in the boreholes/pipes was carried out in three different ways, cf Table 5-1:

- by pressure transducer in the borehole connected the data logger,
- combined down-hole pressure transducer and data logger,
- manual measurements of the water level in the boreholes/pipes.

In conjunction with the sampling of water level data from un-instrumented boreholes, manual levelling was also made in boreholes with pressure transducers for checking and calibration purposes.

4.2 Sensors

Technical specifications of the equipment system used for the interference tests are listed in Table 4-1.

The accuracy of measured relative pressure changes (calculated drawdown/recovery) from the combined down-hole pressure transducer and data logger used in the observation boreholes should not exceed the accuracy of the transducer/logger itself. The accuracy of the pressure- and flow measurements in the pumping boreholes could to some degree be affected by the data logger, but the accuracy should be of the same order as the sensors themselves.

Table 4-1. Technical specification of the equipment system used for the interference tests for different measurement parameters.

Technical specification				
Parameter	**Name**	**Unit**	**Value/range**	**Comments**
Pressure (pumping borehole)	Output signal Meas. range Resolution Accuracy	mV kPa kPa kPa	0 – 100 0 – 1000 0.05 1	Absolute pressure.
Pressure (observation borehole)	Output signal Meas. range Resolution Accuracy	digital kPa kPa kPa	– 0 – 400 0.01 1	Absolute pressure. Pressure sensor integrated with data logger.
Flow (at surface)	Output signal Meas. range Resolution Accuracy	mA l/min l/min % o.r.	4 – 20 5* – 500* 0.1 +/– 1	*The specifications of the submersible borehole pump determine the actual measurement range.

Table 4-2 illustrates the position of sensors for each test. For the interference tests, only the positions of sensors for pressure (P) together with the (lower) level of the submersible pump (Pump) are relevant. Positions are given in metres from top of casing (ToC). Equipment affecting wellbore storage is given in terms of diameter of submerged item. Position is given as "in section" or "above section". The volume of the submerged pump (~ 4 dm^3) is in most cases of minor importance.

Table 4-2. Position (from ToC) of sensors and equipment affecting wellbore storage in the pumping boreholes HFM01 and HFM02 during the interference tests.

Borehole information			Sensors		Equipment affecting wellbore storage (WBS)		
ID	**Test section (m)**	**Test no**	**Type**	**Position (m b. ToC)**	**Position***	**Function**	**Outer diameter (mm)**
HFM01	31.93-200.20	1	Pump (lower) P (P1)	49.5 48	In Section	Pump string (hose) Signal cable Pump cable	33 8 15
HFM02	25.40-100.00	2	Pump (lower) P (P1)	16 14.5	In Section	Pump string (hose) Signal cable Pump cable	33 8 15

* Position of equipment that can affect wellbore storage. Position given as "In Section" or "Above Test section".

5 Performance

5.1 Preparations

The pressure sensors were calibrated at GEOSIGMAs engineering workshop in Librobäck, Uppsala. The combined pressure transducer and data loggers uses factory calibration but were checked against manual levelling during the test. The flow meter was calibrated at the GEOSIGMA workshop approximately one year before the tests.

Functionality checks of the equipment were performed before prior to test start (cf Section 3.3). No errors were detected during these checks.

5.2 Performance of tests

5.2.1 Test principle

The interference tests were carried out as constant flow rate tests followed by a pressure recovery period. The type of pressure- or water level registration in the observation boreholes together with the standard sampling frequency for pressure transducers during the interference tests are listed in Table 5-1.

Table 5-1. Type of pressure registration and monitoring of the water level in the different boreholes during the interference tests in HFM01 and HFM02.

Borehole	Type av registration	Sampling frequency	Comments
HFM01	Pressure transducer + data logger at surface*	Standard (minimum=1 s)	
HFM02 and HFM03	Combined downhole pressure transducer and data logger + manual	1 min + manual	Manual registration during the first c 10 min of pumping
KFM01A (cased 0-100 m)	Manual	1-2 times/h	For checking of the grouting in KFM01A
SFM0001	Manual	1-2 times/h	
SFM0002	Manual	1-2 times/h	
SFM0003	Pressure transducer + data logger at surface*	Standard (minimum =1 s)	The scan interval was successively increased

* The pressure transducers were connected to the same data logger

This configuration of pressure registration and water level monitoring was maintained during the interference test in HFM02. Unfortunately, the combined transducer and logger used in HFM02 and HFM03 was not functioning satisfactorily during this test as discussed above. Manual registrations of the water level were therefore carried out in these boreholes.

5.2.2 Test procedure

Before the tests, function checks and cleaning of equipment together with time synchronisation of clocks and data loggers were performed according to the Activity Plan. A short flow capacity test was carried out to choose an appropriate flow rate for the test. In both cases the extracted water was discharged on the ground, into the nearby marchland.

The flow period of the interference test in HFM01 was c 7.5 h, followed by a recovery period of c 8 hours. The flow period of the test in HFM02 was c 6 h succeeded by a recovery period of c 15 hours. In general, the sampling frequency of pressure in the pumping borehole was according to Table 5-2. In the observation boreholes with the combined pressure transducer and logger, the sampling frequency was 1 minute over the whole test period.

Table 5-2. Standard sampling frequency for pressure in the pumping borehole during the interference tests.

Time interval (s) from start or stop of pumping	Sampling frequency (s)
1-1200	1
>1200	60

5.3 Data handling

A list of the data files from the data loggers is shown in Appendix 1. Files in mio-format, to be further processed by the program PUMPKONV, was created through macro-editing the original logger files in the text editor UltraEdit.

These files (*.mio-files) with pressure- versus time data were converted to drawdown- and recovery files by the code PUMPKONV and plotted in different diagrams by the code SKB-plot in accordance with the Instruction SKB MD 320.004 (Instruktion för analys av injektions- och enhålspumptester).

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

5.4 Analyses and interpretation

As discussed in Section 5.2.1 the interference tests were performed as constant flow rate tests although some variations of the flow rate occurred. A period with pseudo-radial flow could in most cases be identified during the tests. Consequently, methods for constant-flow rate tests in an equivalent porous medium were used by the analyses and interpretation of the tests.

Firstly, a qualitative evaluation of the actual flow regimes (pseudo-linear, pseudo-radial and pseudo-spherical flow) and possible external boundary conditions during the tests was performed. The qualitative analyses were made from log-log diagrams of drawdown and/or recovery data together with its corresponding derivatives versus time.

The quantitative, transient interpretation of the hydraulic parameters (transmissivity, storativity from the observation boreholes together with the skin factor and wellbore storage coefficient from the pumping boreholes) was primarily based on the identified pseudo-radial flow regime during the tests in log-log and lin-log data diagrams. For tests indicating a fractured- or borehole storage dominated response, respectively, corresponding type curves were used in the analyses.

If possible, transient analyses were applied both on the drawdown- and recovery phase of the tests. The recovery data were plotted versus equivalent time. The analysis of the drawdown- and recovery data was generally made both according to Theis-Walton's and Cooper-Jacob's methods, cf standard textbooks. In addition, a preliminary steady-state analysis (e.g. Moye's formula) was made for the pumping boreholes for comparison.

The transient analysis of responses in the pumping boreholes dominated by wellbore storage was made according to the single-hole methods described in /4/. The estimation of the borehole storage coefficient, in appropriate pumping tests, was based on the early borehole response with 1:1 slope.

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the interference tests are according to SKB MD 320.004 (Instruction for analysis of single-hole injection- and pumping tests) and the methodology description for interference tests (SKB MD 330.003). Additional symbols used are explained in the text.

6.2 Water sampling

Water samples were collected in the pumping boreholes during the interference test in HFM01 and submitted for analysis, see Table 6-1. The analyses are presented in /2/.

Table 6-1. Data of water samples collected during the interference test in HFM01 and submitted for analysis.

Bh ID	Date and time of sample	Pumped section (m)	Sample type	Sample ID no	Remarks
HFM01	2002-06-25 16:00	31.93-200.20	WC080	4172	Open-hole test

6.3 Interference test in HFM01

6.3.1 Pumping borehole HFM01

General test data from the pumping borehole HFM01 are presented in Table 6-2.

Table 6-2. General test data from the pumping borehole HFM01.

Supporting test parameter	General test data		
Pumping borehole	HFM01 (31.93-200.20 m)		
Testtype[1]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	2		
Field crew	S. Jönsson, J. Levén (GEOSIGMA AB)		
Test equipment system	Temporary		
General comment	Interference test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	M	200.20
Casing length	L_c	M	31.93
Test section- secup	Secup	M	31.93
Test section- seclow	Seclow	M	200.20
Test section length	L_w	M	168.27
Test section diameter	$2 \cdot r_w$	Mm	140
Test start (start of pressure registration)		yymmdd hh:mm	020625 10:00
Packer expanded		yymmdd hh:mm:ss	-
Start of flow period		yymmdd hh:mm:ss	020625 10:25:01
Stop of flow period		yymmdd hh:mm:ss	020625 16:31:02
Test stop (stop of pressure registration)		yymmdd hh:mm	020626 01:00
Total flow time	t_p	Min	366
Total recovery time	t_F	Min	509

1: Constant Head injection and recovery or Constant Rate withdrawal and recovery

Pressure and water level data

Water level data in pumping borehole HFM01	Nomen-clature	Unit	Value	GW level (m a s l)
Pressure in borehole before start of flow period	h_i	m	43.96	0.77*
Pressure in borehole before stop of flow period	h_p	m	12.121	-31.07
Pressure in borehole at stop of recovery period	h_F	m	42.524	-0.67
Maximal drawdown in borehole during flow period	s_p	m	31.839	

* based on manual water level measurements

Manual water level measurements in pumping borehole HFM01				
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**GW level (m b. ToC)**	**GW level (m a s l)**
2002-06-25	10:10:00		0.98	0.77
2002-06-25	11:08:00		26.94	-24.57
2002-06-25	12:08:00		30.27	-27.82
2002-06-25	12:59:00		30.92	-28.46
2002-06-25	14:44:30		32.29	-29.80
2002-06-25	16:22:00		33.02	-30.51

Flow data

Flow data in pumping borehole HFM01	**Nomen-clature**	**Unit**	**Value**
Flow rate from test section just before stop of flowing	Q_p	m^3/s	$1.25 \cdot 10^{-3}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	
Total volume discharged during flow period	V_p	m^3	

Comments to the test

The flow rate in HFM01 decreased from c 100 L/min at the beginning of the flow period to c 75 L/min by the end of the period, due to the decreasing hydraulic head in the hole during pumping. Furthermore, a distortion of the pressure occurred in HFM01 during the recovery phase, manifested by the apparently incomplete recovery of the groundwater level to the natural level prior to the test, cf the table above. It is not clear if this disturbance is related to the equipment used or due to external effects.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-1–5 in Appendix 2. As expected, clear effects of wellbore storage (WBS) dominated the early response in the (open) pumping borehole HFM01 during the flow period as well as the recovery period. After c 80 min of pumping, a rather well defined pseudo-radial flow regime lasted to c 400 min (end of the flow period). This flow regime is assumed to represent the local hydraulic properties of a possible fracture zone intersecting the pumping borehole. The flow logging indicated that the most conductive part of the assumed fracture zone intersected HFM01 at c 43 m.

The response during the recovery phase confirms the WBS-dominated early flow regime, but no pseudo-radial flow regime occurred during the recovery period, possibly due to the disturbance described above.

Interpreted parameters

Quantitative analysis was only made on the flow period in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4.

The transient, quantitative interpretation of the flow period of the test is indicated in Figures A2-2 – A2-3 in Appendix 2. The results are shown in Table 6-13 and 6-14 and in the Test Summary Sheets below.

6.3.2 Observation borehole HFM02

General test data from the observation borehole HFM02 are presented in Table 6-3.

Table 6-3. General test data from the observation borehole HFM02.

Pressure and water level data

Water level data in observation borehole HFM02	Nomen-clature	Unit	Value	GW level (m a s l)
Pressure in borehole before start of flow period	h_i	m	28.692	0.87 *
Pressure in borehole before stop of flow period	h_p	m	28.241	0.42
Pressure in borehole at stop of recovery period	h_F	m	28.523	0.70
Maximal drawdown in borehole during flow period	s_p	m	0.451	

* based on manual water level measurements

Manual water level measurements in observation borehole HFM02				
Date YYYY-MM-DD	Time tt:mm:ss	Time (min)	GW level (m b. ToC)	GW level (m a s l)
2002-06-25	10:25:00	0	2.18	0.87
2002-06-25	11:01:00	36	2.26	0.79
2002-06-25	13:13:00	168	2.47	0.58
2002-06-25	14:54:00	269	2.51	0.54
2002-06-25	15:28:00	303	2.53	0.52
2002-06-25	16:50:00	19 *	2.58	0.47

* from stop of pumping

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-6–10 in Appendix 2. Both the drawdown- and recovery curves for HFM02 (including the pressure derivative) indicate an apparent no-flow hydraulic boundary by the end of the test phases or, alternatively, a dual-permeability formation. The first part of the curves indicates a slightly higher transmissivity and lower storativity than the later part.

After c 150 min of pumping, a rather well defined pseudo-radial flow regime lasted to c 400 min (end of the flow period). This flow regime may represent the hydraulic properties of an assumed fracture zone intersecting HFM02 at c 42 m (according to the flow logging) with increased hydraulic conductivity. The relatively short response time (c 2 min) in HFM02 indicates a good hydraulic connection between HFM01 and HFM02, possibly via a fracture zone.

The apparent hydraulic boundary effects (or dual-permeability) indicate that the assumed fracture zone may have different hydraulic properties along its extension. The zone may be more extended and with higher transmissivity towards HFM02 than at HFM01, cf the table of results below.

During the recovery phase, the corresponding pseudo-radial flow regime occurred during c 120–200 min of equivalent time (end of test). The recovery response was similar to that of the flow period with the hydraulic boundary effects more pronounced at the end of the test.

Interpreted parameters

Quantitative analysis was made on both the flow- and recovery period in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4.

The transient, quantitative interpretation of the flow- and recovery period of the test is shown in Figures A2-7 – A2-10 in Appendix 2. The interpretation is based on the assumed flow regimes discussed above. The results, which are similar for the flow- and recovery period. The results are shown in a Table 6-13 and 6-14 and in the Test Summary Sheets below.

6.3.3 Observation borehole HFM03

General test data from the observation borehole HFM03 are presented in Table 6-4.

Table 6-4. General test data from the observation borehole HFM03.

Pressure and water level data

Water level data in observation borehole HFM03	Nomen-clature	Unit	Value	GW level (m a s l)
Pressure in borehole before start of flow period	h_i	m	23.497	0.95 *
Pressure in borehole before stop of flow period	h_p	m	23.081	0.53
Pressure in borehole at stop of recovery period	h_F	m	23.332	0.785
Maximal drawdown in borehole during flow period	s_p	m	0.416	

* based on manual water level measurements

Manual water level measurements in observation borehole HFM03				
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**GW level (m b. ToC)**	**GW level (m a s l)**
2002-06-25	10:25:00	0	2.20	0.95
2002-06-25	11:02:00	37	2.27	0.88
2002-06-25	13:14:00	169	2.45	0.70
2002-06-25	14:54:00	269	2.49	0.66
2002-06-25	15:28:00	303	2.52	0.63
2002-06-25	16:50:00	19 *	2.57	0.58

* from stop of pumping

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-11–15 in Appendix 2. Both the drawdown- and recovery curves from HFM03 were similar to the corresponding curves from HFM02, but the response time was longer in HFM03 (c 10 min). This fact may indicate a good hydraulic connection between HFM01 and HFM03, either directly or alternatively, via HFM02. According to the flow logging, a zone with high transmissivity may intersect HFM03 at c 21 m. This zone may have good hydraulic connection with the zone assumed to intersect HFM02, possibly via sub-vertical fractures.

After c 150 min of pumping, a rather well defined (late) pseudo-radial flow regime lasted to c 400 min (end of the flow period). This flow regime may either represent a zone between HFM01 and HFM03, or interconnected zones assumed to intersect HFM02 and HFM03. During the recovery phase the corresponding pseudo-radial flow regime prevailed during c 150–200 min of equivalent time.

Interpreted parameters

Quantitative analysis was made on both the flow- and recovery period in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4. The transient, quantitative interpretation of the flow- and recovery period of the tests is shown in Figures A2-12 – A2-15 in Appendix 2. The interpretation is based on the assumed flow regimes discussed above. The results are shown in Table 6-13 and 6-14 and in the Test Summary Sheets below.

The calculated (apparent?) storativity value from the recovery phase may not be representative and may reflect decreased (indirect) hydraulic communication between HFM01 and HFM03, possibly via HFM02.

6.4 Interference test in HFM02

6.4.1 Pumping borehole HFM02

General test data from the pumping borehole HFM02 are presented in Table 6-5.

Table 6-5. General test data from the pumping borehole HFM02.

Supporting test parameter	**General test data**		
Pumping borehole	HFM02		
Testtype[1]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	2		
Field crew	(S. Jönsson, J. Levén) GEOSIGMA AB		
Test equipment system	Temporary		
General comment	Interference test		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	M	100.00
Casing length	L_c	M	25.40
Test section- secup	Secup	M	25.40
Test section- seclow	Seclow	M	100.00
Test section length	L_w	M	74.60
Test section diameter	$2 \cdot r_w$	Mm	137
Test start (start of pressure registration)		yymmdd hh:mm	020626 10:00
Packer expanded		yymmdd hh:mm:ss	-
Start of flow period		yymmdd hh:mm:ss	020626 10:40:00
Stop of flow period		yymmdd hh:mm:ss	020626 16:50:00
Test stop (stop of pressure registration)		yymmdd hh:mm	020627 06:00
Total flow time	t_p	Min	370
Total recovery time	t_F	Min	790

1: Constant Head injection and recovery or Constant Rate withdrawal and recovery

Pressure and water level data

Water level data in pumping borehole HFM02	Nomen-clature	Unit	Value	GW level (m a s l)
Pressure in pumping borehole before start of flow period	h_i	m	-2.22	0.83 *
Pressure in pumping borehole before stop of flow period	h_p	m	-3.12	-0.07
Pressure in pumping borehole at stop of recovery period	h_F	m	-	-
Maximal drawdown in pumping borehole during flow period	s_p	m	0.9	

* based on manual water level measurements

Manual water level measurements in pumping borehole HFM02				
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**GW level (m b. ToC)**	**GW level (m a s l)**
2002-06-26	10:28:00	-12	2.22	0.83
2002-06-26	10:46:00	6	2.41	0.64
2002-06-26	11:09:00	29	2.56	0.49
2002-06-26	11:20:00	40	2.61	0.44
2002-06-26	11:54:00	74	2.72	0.33
2002-06-26	12:16:00	96	2.79	0.26
2002-06-26	12:49:00	129	2.85	0.20
2002-06-26	13:55:00	195	2.95	0.10
2002-06-26	14:44:00	244	3.015	0.04
2002-06-26	15:34:00	295	3.07	-0.02
2002-06-26	16:42:00	362	3.12	-0.07
2002-06-27	07:32:00	878 *	2.30	0.75

* from stop of pumping

Flow data

Flow data in pumping borehole HFM02	Nomen-clature	Unit	Value
Flow rate from test section just before stop of flowing	Q_p	m^3/s	$1.78 \cdot 10^{-3}$
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	
Total volume discharged during flow period	V_p	m^3	

Manual measurements or readings on display			Flow rate
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**(L/min)**
2002-06-26	10:46:00	6	109 *
2002-06-26	11:20:00	40	108 *
2002-06-26	12:16:00	96	107 *

* flow readings on the display

Comments to the test

The flow rate in HFM02 was rather constant at c 107 L/min during almost the entire test.

Since net electricity was not available at this borehole, the submersible pump was run by a mobile electric generator and the data logger by batteries. As a consequence, the sensitive PDCR-pressure transducers located in HFM02 and HFM03 did not work satisfactorily. For this reason, manual measurements of the water level were performed during the flow period. During the recovery period registration was omitted. The water level in HFM01 did not recover to the initial level. The reason to this fact is unclear.

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-16 – A2-18 in Appendix 2. Due to the failure of the pressure transducers in HFM02 and HFM03, both the qualitative and quantitative analyses in these boreholes are uncertain. No recovery period was registered in these boreholes during this test.

A fracture-dominated response with an initial linear flow regime (slope 1:2 in log-log) is indicated in HFM02 during the flow period. No effects of hydraulic boundaries or dual-permeability effects were seen. After c 200 min of pumping, pseudo-radial flow prevailed to c 400 min (end of the flow period). This flow regime is assumed to represent the assumed zone intersecting HFM02 at c 42 m, see above.

Interpreted parameters

Quantitative analysis was made on the flow period in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4. The transient, quantitative interpretation of the flow period of the test is indicated in Figures A2-17 – A2-18 in Appendix 2. The interpretation is based on the assumed flow regimes discussed above. The results are shown in Table 6-13 and 6-14 and in the Test Summary Sheets below.

6.4.2 Observation borehole HFM01

General test data from the observation borehole HFM01 are presented in Table 6-6.

Table 6-6. General test data from the observation borehole HFM01.

Pressure and water level data

Water level data in observation borehole HFM01	Nomen-clature	Unit	Value	GW level (m a s l)
Level in borehole before start of flow period	h_i	m	19.304	0.72 *
Level in borehole before stop of flow period	h_p	m	18.734	0.15
Level in borehole at stop of recovery period	h_F	m	19.181	0.60
Maximal drawdown in borehole during flow period	s_p	m	0.57	

* based on manual water level measurements

Manual water level measurements in observation borehole HFM01				
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**GW level (m b. ToC)**	**GW level (m a s l)**
2002-06-26	10:40:00	0	1.03	0.72
2002-06-26	10:45:00	5	1.04	0.71
2002-06-26	10:48:00	8	1.05	0.70
2002-06-26	10:50:00	10	1.06	0.695
2002-06-26	10:52:00	12	1.07	0.685
2002-06-26	10:55:00	15	1.08	0.68
2002-06-26	11:48:00	18	1.21	0.55
2002-06-26	12:38:00	118	1.325	0.44
2002-06-26	14:22:00	222	1.47	0.29
2002-06-26	15:34:00	295	1.53	0.24
2002-06-26	16:07:00	327	1.56	0.21
2002-06-27	07:05:00	851 *	1.11	0.65

* from stop of pumping

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-19 – A2-23 in Appendix 2. The drawdown- and recovery curves in HFM01 are very similar to the corresponding responses in HFM02 during pumping of HFM01, cf the reciprocity principle. Accordingly, the same interpretation of flow regimes was made as for observation borehole HFM02.

After c 150 min of pumping, a rather well defined (late) pseudo-radial flow regime lasted to c 400 min (end of the flow period). This flow regime probably represents the assumed, more transmissive zone intersecting HFM02. During the recovery phase, the corresponding pseudo-radial flow regime occurred during c 150–200 min of equivalent time.

Interpreted parameters

Quantitative analysis was made on both the flow- and recovery periods in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4. The transient, quantitative interpretation of the flow- and recovery period of the tests is shown in Figures A2-20 – A2-23 in Appendix 2. The interpretation is based on the assumed flow regimes discussed above. The results are shown in Table 6-13 and 6-14 and in the Test Summary Sheets below.

6.4.3 Observation borehole HFM03

General test data from the observation borehole HFM03 are presented in Table 6-7.

Table 6-7. General test data from the observation borehole HFM01.

Pressure and water level data

Water level data in observation borehole HFM03	Nomen-clature	Unit	Value	
Level in borehole before start of flow period	h_i	m	-2.23	0.92 *
Level in borehole before stop of flow period	h_p	m	-2.99	0.16
Level in borehole at stop of recovery period	h_F	m	-	-
Maximal drawdown in borehole during flow period	s_p	m	0.76	

* based on manual water level measurements

Manual water level measurements in observation borehole HFM03				
Date YYYY-MM-DD	**Time tt:mm:ss**	**Time (min)**	**GW level (m b. ToC)**	**GW level (m a s l)**
2002-06-26	10:28:00	-12	2.23	0.92
2002-06-26	10:48:00	8	2.27	0.88
2002-06-26	11:21:00	41	2.45	0.70
2002-06-26	11:53:00	73	2.56	0.59
2002-06-26	12:22:00	102	2.64	0.51
2002-06-26	13:55:00	195	2.81	0.34
2002-06-26	15:36:00	297	2.935	0.22
2002-06-26	16:41:00	361	2.99	0.16
2002-06-27	07:33:00	879 *	2.31	0.84

* from stop of pumping

Interpreted flow regimes

Selected test diagrams are presented in Figures A2-24–26 in Appendix 2. Due to the failure of the pressure transducers in HFM02 and HFM03, both the qualitative and quantitative analyses in these boreholes are uncertain. No recovery period was registered in these boreholes during the test.

A similar drawdown was obtained in HFM03 as in the pumping borehole HFM02 (c 0.8–0.9 m, respectively) by the end of the flow period. However, the response time was rather long (c 7–8 min) at the relatively short distance between HFM02 and HFM03. This fact may indicate a decreased (indirect) hydraulic connection between two rather high-transmissive zones, possibly via sub-vertical fractures.

After c 150 min of pumping, a pseudo-radial flow regime lasting to c 400 min (end of the flow period) is indicated.

Interpreted parameters

Quantitative analysis was made on the flow period in semi-logarithmic- and log-log diagrams according to the methods described in Section 5-4. The transient, quantitative interpretation of the flow period of the test is shown in Figures A2-25 – A2-26 in Appendix 2. The interpretation is based on the assumed flow regimes discussed above. The results are shown in Table 6-13 and 6-14 and in the Test Summary Sheets below.

The calculated (apparent) storativity value from the flow period is probably not representative and may reflect a decreased (indirect) hydraulic connection between HFM02 and HFM03.

6.5 Monitoring wells and other observation boreholes

6.5.1 Monitoring wells

The manual measurements of the groundwater level in the monitoring wells penetrating the soil layers during the interference tests in HFM01 and HFM02 are presented in Table 6-8 and Figure 6-1. The flow periods of the interference tests are shown in the figure. The distances to the monitoring wells from the pumping boreholes are shown in Table 3-3. Figure 6-1 indicates a naturally decreasing trend of the groundwater level in the soil layers before and during the interference tests. A slight response occurred in SFM0001 during the pumping of HFM02, but the interference is uncertain.

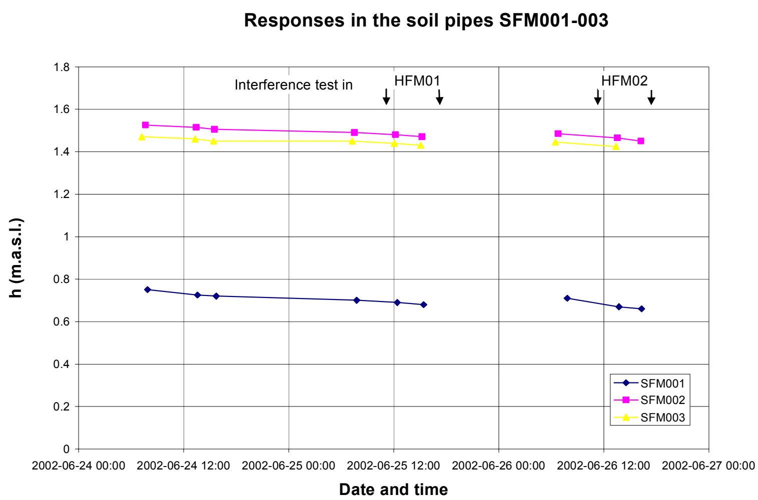


Figure 6-1. *Groundwater level in the monitoring wells SFM0001–SFM0003 during the interference tests in HFM01 and HFM02 at drillsite 1 in the Forsmark area.*

Table 6-8. Manual measurements of the groundwater level in the monitoring wells SFM0001–0003 during the interference tests at HFM01 and HFM02.

Manual water level measurements in monitoring wells SFM0001-SFM0003				
Monitoring well	**Date YYYY-MM-DD**	**Time tt:mm**	**GW level (m b. top)**	**GW level (m a s l)**
SFM0001	2002-06-24	07:52	0.35	0.75
	2002-06-24	13:35	0.375	0.725
	2002-06-24	15:43	0.38	0.72
	2002-06-25	07:46	0.40	0.70
	2002-06-25	12:24	0.41	0.69
	2002-06-25	15:25	0.42	0.68
	2002-06-26	07:50	0.39	0.71
	2002-06-26	13:44	0.43	0.67
	2002-06-26	16:19	0.44	0.66
SFM0002	2002-06-24	15:32	0.515	1.505
	2002-06-25	07:32	0.53	1.49
	2002-06-25	12:12	0.54	1.48
	2002-06-25	15:14	0.55	1.47
	2002-06-26	06:48	0.535	1.485
	2002-06-26	13:33	0.555	1.465
	2002-06-26	16:15	0.57	1.45
SFM0003	2002-06-24	07:12	0.47	1.47
	2002-06-24	13:19	0.48	1.46
	2002-06-24	15:24	0.49	1.45
	2002-06-25	07:15	0.49	1.45
	2002-06-25	12:04	0.50	1.44
	2002-06-25	15:05	0.51	1.43
	2002-06-26	06:28	0.495	1.445
	2002-06-26	13:24	0.515	1.425
	2002-06-26	16:11	0.54	1.40

6.5.2 Other observation boreholes

Some manual measurements of the groundwater level were made during the interference tests in five nearby water prospecting boreholes. The boreholes in question are owned by the power plant at Forsmark and denoted by BH1–5, see Table 6-9. The distances to these boreholes from the pumping boreholes are listed in Table 3-3. The levelling of the top of casing of the five boreholes is made by a handheld GPS. Table 6-9 indicates that these boreholes were unaffected by the interference tests.

Table 6-9. Manual measurements of the groundwater level in the new water prospecting boreholes BH1–5 during the interference tests at HFM01 and HFM02.

Manual water level measurements in the new water prospecting boreholes for the power plant			
Borehole	**Date** YYYY-MM-DD	**Time** tt:mm	**GW level** (m b. ToC)
BH1	2002-06-25	09:38	1.53
	2002-06-25	13:54	1.53
	2002-06-25	16:10	1.52
	2002-06-26	10:13	1.51
	2002-06-26	13:42	1.51
	2002-06-26	16:26	1.51
BH2	2002-06-25	09:36	2.65
	2002-06-25	13:50	2.65
	2002-06-25	16:11	2.66
	2002-06-26	10:11	2.64
	2002-06-26	13:41	2.65
	2002-06-26	16:21	2.65
BH3	2002-06-24	13:22	4.10
	2002-06-24	15:05	4.10
	2002-06-24	16:37	4.10
	2002-06-25	09:26	4.10
	2002-06-25	11:42	4.11
	2002-06-25	13:59	4.105
	2002-06-25	15:56	4.11
	2002-06-26	10:02	4.10
	2002-06-26	13:30	4.10
	2002-06-26	16:10	4.10
BH4	2002-06-24	13:24	5.73
	2002-06-24	15:08	5.75
	2002-06-24	16:38	5.75
	2002-06-25	09:28	5.74
	2002-06-25	11:44	5.74
	2002-06-25	14:01	5.74
	2002-06-25	15:57	5.74
	2002-06-26	10:04	5.72
	2002-06-26	13:32	5.72
	2002-06-26	16:12	5.72
BH5	2002-06-24	13:19	4.18
	2002-06-24	15:01	4.18
	2002-06-24	16:34	4.18
	2002-06-25	09:24	4.19
	2002-06-25	11:38	4.19
	2002-06-25	13:57	4.19
	2002-06-25	15:55	4.19
	2002-06-26	10:01	4.18
	2002-06-26	13:29	4.18
	2002-06-26	16:08	4.18

6.6 Response analysis in the percussion boreholes

A simplified response analysis according to the methodology description for interference tests (SKB MD 330.003) was made in this case due to the few observation boreholes. The response time lags (dt_L) in the percussion boreholes during the interference tests in HFM01 and HFM02 are shown in Table 6-10a. The time lags were in this case derived from the drawdown curves in the percussion boreholes at an actual drawdown of 0.01 m.

The normalised response time with respect to the distance to the pumping borehole (Index 1) was calculated. The normalised response time is inversely related to the hydraulic diffusivity (T/S) of the formation. The distances between the boreholes are shown in Table 3-3. In addition, the normalized drawdown with respect to the flow rate (Index 2) was calculated in Table 6-10b.

$dt_{L[s=0.01\ m]} / r_s^2$ = normalised response time with respect to the distance r_s:

$dt_{L[s=0.01\ m]}$ = time after start of pumping (s) at a drawdown s=0.01 m in the observation section

r_s = 3D-distance between the hydraulic point of application (hydr. p.a.) in the pumping borehole and observation borehole (m)

s_p/Q_p = normalized drawdown with respect to the flow rate

s_p = drawdown at stop of pumping in the actual observation borehole (m)

Q_p = flow rate by the end of the flow period (m^3/s)

Table 6-10a. Calculated response time lags and normalized response times for the percussion boreholes during the interference tests in HFM01 and HFM02.

Pumping borehole	Observation borehole	Section (m)	hydr. p.a. (m)	$dt_{L[s=0.01\ m]}$ (min)	r_s (m)	$dt_{L[s=0.01\ m]}/r_s^2$ (s/m^2)
HFM01	HFM02	25.40-100.00	43	6	221	$7.37 \cdot 10^{-3}$
	HFM03	13.10-26.00	21	12	220	$1.49 \cdot 10^{-2}$
HFM02	HFM01	31.93-200.20	42.5	5	221	$6.14 \cdot 10^{-3}$
	HFM03	13.10-26.00	21	6.7	22	$8.26 \cdot 10^{-1}$

Table 6-10b. Drawdown and normalized drawdown for the percussion boreholes during the interference tests in HFM01 and HFM02.

Pumping borehole	Q_p (m^3/s)	Observation borehole	Section (m)	r_s (m)	s_p (m)	s_p/Q_p (s/m^2)
HFM01	$1.25 \cdot 10^{-3}$	HFM02	25.40-100.00	221	0.45	360
		HFM03	13.10-26.00	220	0.42	336
HFM02	$1.78 \cdot 10^{-3}$	HFM01	31.93-200.20	221	0.57	320
		HFM03	13.10-26.00	22	0.76	427

Table 6-10a shows that the normalised response time is short and similar between HFM01 and HFM02 in both directions. It may be assumed that this response propagated via a potential sub-horizontal zone between the boreholes. Between HFM01-HFM03 the response time was only slightly higher but almost two orders of magnitude higher between HFM02-HFM03. This fact may indicate that the latter case represents a more indirect hydraulic connection between the boreholes (in the rock mass rather than via a fracture zone) whereas the hydraulic connection between HFM01-HFM02 is more direct.

Table 6-10b shows that the normalised drawdowns are similar in all observation boreholes except in HFM03 with only a slightly higher drawdown despite the much shorter distance to the pumping borehole HFM02. This fact also supports the assumption that the hydraulic connection between HFM01-HFM02 is dominated by flow along a potential sub-horizontal fracture zone whereas the connection between HFM02-HFM03 is more indirect, possibly by sub-vertical fractures.

6.7 Reciprocity between HFM01 and HFM02

One of the purposes of the interference tests was to investigate the quality of the tests by checking the reciprocity principle between HFM01 and HFM02. This principle can in this case be expressed as (see e.g. /5/):

$$s_{HFM02}/Q_{HFM01} = s_{HFM01}/Q_{HFM02} \qquad (6\text{-}1)$$

s_{HFM01} and s_{HFM02} are the drawdowns in the observation boreholes HFM01 and HFM02, respectively at a certain time and Q_{HFM01} and Q_{HFM02} the corresponding flow rates in the pumping boreholes HFM01 and HFM02, respectively.

The results of the actual interference tests are shown in Table 6-11. The flow period of both tests was c 6 h. The table shows that the results are similar for the interference tests in HFM01 and HFM02 which fact thus supports the reciprocity principle in this case.

Table 6-11. Check of the reciprocity principle for the interference tests in HFM01 and HFM02. Q_p is the flow rate in the pumping boreholes and s_p is the drawdown in the observation boreholes HFM01 and HFM02 at the end of the flow period.

Pumping borehole	Q_p (m^3/s)	Observation Borehole	Distance (m)	s_p (m)	s_{HFM01}/Q_{HFM02} (s/m^2)	s_{HFM02}/Q_{HFM01} (s/m^2)
HFM01	$1.25 \cdot 10^{-3}$	HFM02	221	0.45		360
HFM02	$1.78 \cdot 10^{-3}$	HFM01	221	0.57	320	

6.8 Summary of interference tests

A compilation of measured test data from the interference tests in HFM01 and HFM02, respectively is shown in Table 6-12. In Table 6-13 and 6-14, calculated hydraulic parameters of the formation and borehole, respectively, are shown.

The lower and upper practical measurement limits for the actual test system, expressed in terms of specific flow (Q/s), are assumed to be the same as for the HTHB system /1/, i.e. Q/s–L=$2\cdot10^{-6}$ m^2/s and Q/s–U=$2\cdot10^{-3}$ m^2/s for pumping tests.

Table 6-12. Summary of test data for the interference tests performed in percussion boreholes HFM01 and HFM02 at drillsite 1 in the Forsmark area. Only data from percussion boreholes are included in the table.

Pumping borehole	Borehole ID	Section (m)	Test type[1)]	h_i (m)	h_p (m)	h_F (m)	Q_p (m^3/s)
HFM01	HFM01	31.93-200.20	1B	43.96	12.121	42.524	$1.25\cdot10^{-3}$
	HFM02	25.40-100.00	2	28.692	28.241	28.523	-
	HFM03	13.10-26.00	2	23.497	23.081	23.332	-
HFM02	HFM02	25.40-100.00	1B	-2.22	-3.12	-3.12	$1.78\cdot10^{-3}$
	HFM01	31.93-200.20	2	19.304	18.734	19.181	-
	HFM03	13.10-26.00	2	-2.23	-2.99	-2.99	-

1) 1B: Pumping test-submersible pump, 2: Interference test

Table 6-13. Summary of calculated hydraulic parameters of the formation from the interference tests in HFM01 and HFM02at drillsite 1 in the Forsmark area.

Pumping borehole ID	Borehole ID	Section (m)	Test type	Q/s (m^2/s)	T (m^2/s)	S (-)	S* (-)	Comments
HFM01	HFM01	31.93-200.20	1B	$4.54\cdot10^{-5}$	$5.08\cdot10^{-5}$	-	$5\cdot10^{-5}$	
	HFM02	25.40-100.00	2		$5.26\cdot10^{-4}$	$5.10\cdot10^{-5}$		
	HFM03	13.10-26.00	2		$5.26\cdot10^{-4}$	$5.89\cdot10^{-5}$		
HFM02	HFM01	31.93-200.20	2		$5.31\cdot10^{-5}$	$6.33\cdot10^{-5}$		
	HFM02	25.40-100.00	1B	$2.09\cdot10^{-3}$	$5.10\cdot10^{-4}$	-	$5\cdot10^{-5}$	
	HFM03	13.10-26.00	2		$4.87\cdot10^{-4}$	-		Indirect response?

Q/s = specific flow for the pumping borehole
T = transmissivity from transient evaluation
S = storativity from transient evaluation
S* = assumed value of the storativity by the estimation of the skin factor

Table 6-14. Summary of calculated hydraulic parameters of the pumping boreholes from the interference tests in HFM01 and HFM02 in the Forsmark area.

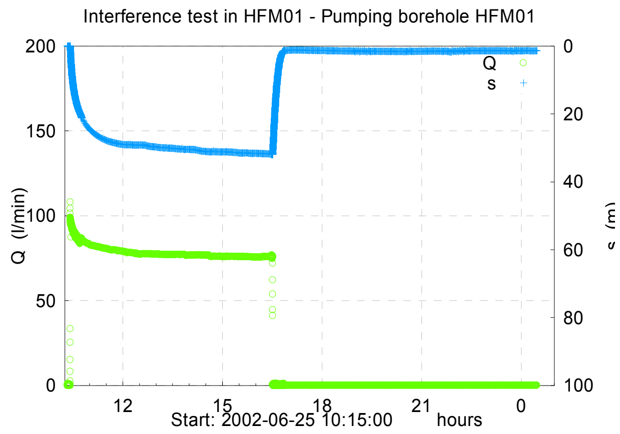
Borehole ID	Section (m)	Test type	C (m^3/Pa)	ζ (-)
HFM01	31.93-200.20	1B	$2.0 \cdot 10^{-6}$	-0.08
HFM02	25.40-100.00	1B	-	-7.18

C = wellbore storage coefficient
ζ = skin factor

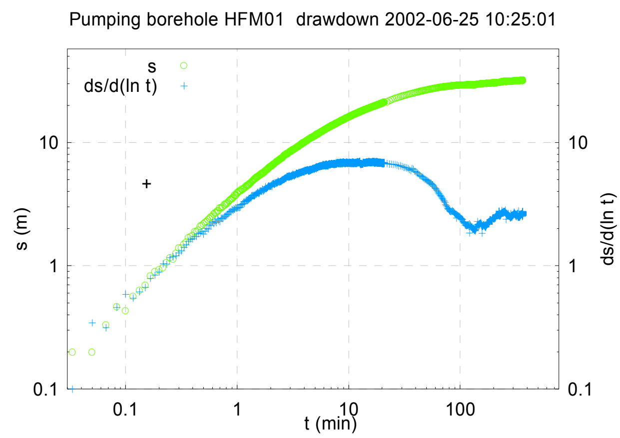
Test Summary Sheet – Pumping borehole HFM01

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	2
Borehole ID:	HFM01	Test start:	2002-06-25 10:25
Test section (m):	31.93-200.20	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Section diameter, $2\cdot r_w$ (m):	0.140	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

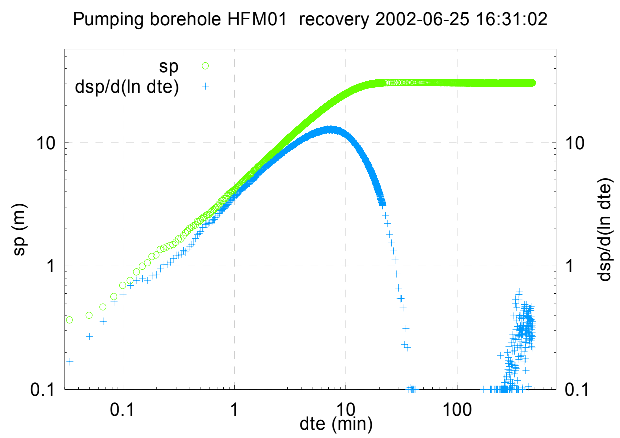
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
h_0 (m)	43.96		
h_i (m)	43.96		
h_p (m)	12.121	h_F (kPa)	280.069
Q_p (m^3/s)	$1.25\cdot10^{-3}$		
tp (min)	366	t_F (min)	509
S	$7\cdot10^{-5}$	S	$7\cdot10^{-5}$
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	$4.54\cdot10^{-5}$		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	80	dt_{e1} (min)	-
t_2 (min)	400	dt_{e2} (min)	-
T_w (m^2/s)	$5.08\cdot10^{-5}$	T_w (m^2/s)	-
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	$2.0\cdot10^{-6}$	C (m^3/Pa)	$1.87\cdot10^{-6}$
C_D (-)		C_D (-)	
ξ (-)	-0.08	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

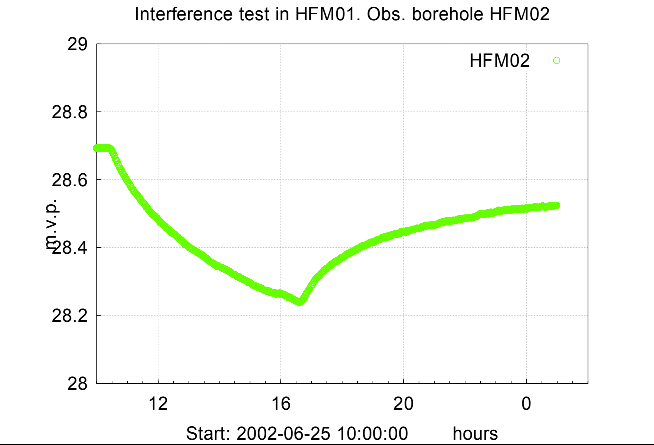
Flow regime:	PRF	C (m^3/Pa)	$2.0\cdot10^{-6}$
t_1 (min)	80	C_D (-)	
t_2 (min)	400	ξ (-)	-0.08
T_T (m^2/s)	$5.08\cdot10^{-5}$		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Wellbore storage dominated flow transiting to pseudo-radial flow (PRF).

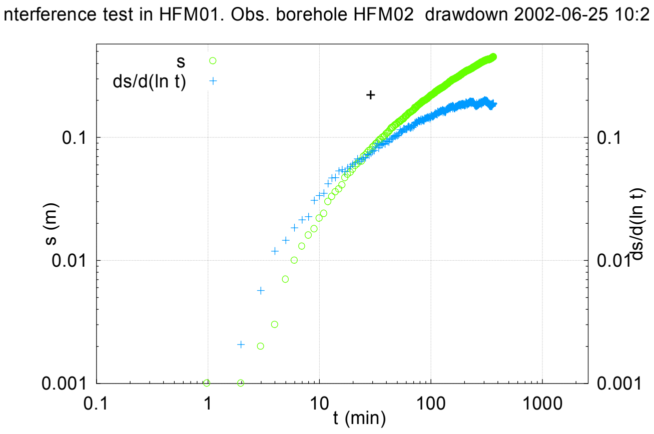
Test Summary Sheet – Observation borehole HFM02

Project:	PLU	Test type:	2
Area:	Forsmark	Test no:	1
Borehole ID:	HFM02	Test start:	2002-06-25 10:25
Test section (m):	25.40-100.00	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Pumping borehole ID:	HFM01		
Observation borehole diameter, $2 \cdot r_w$ (m):	0.137	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

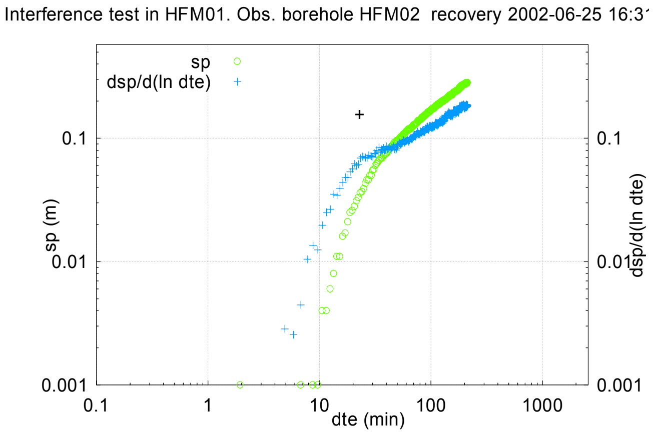
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
h_0 (m)	28.69		
h_i (m)	28.69		
h_p (m)	28.24	h_F (m)	28.52
Q_p (m^3/s)	-		
tp (min)	366	t_F (min)	509
S	-	S	-
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	-		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	150	dt_{e1} (min)	120
t_2 (min)	400	dt_{e2} (min)	200
T_w (m^2/s)	$5.26 \cdot 10^{-4}$	T_w (m^2/s)	$6.34 \cdot 10^{-4}$
S_w (-)	$5.10 \cdot 10^{-5}$	S_w (-)	$6.33 \cdot 10^{-5}$
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	-	C (m^3/Pa)	-
C_D (-)	-	C_D (-)	-
ξ (-)	-	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

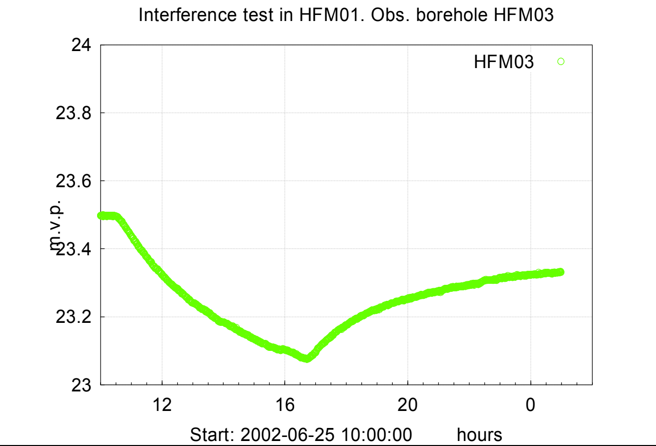
Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	150	C_D (-)	-
t_2 (min)	400	ξ (-)	-
T_T (m^2/s)	$5.26 \cdot 10^{-4}$		
S (-)	$5.10 \cdot 10^{-5}$		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Pseudo-radial flow (PRF) by the end of the flow period. Slight effects of a hydraulic no-flow boundary or dual-permeability formation.

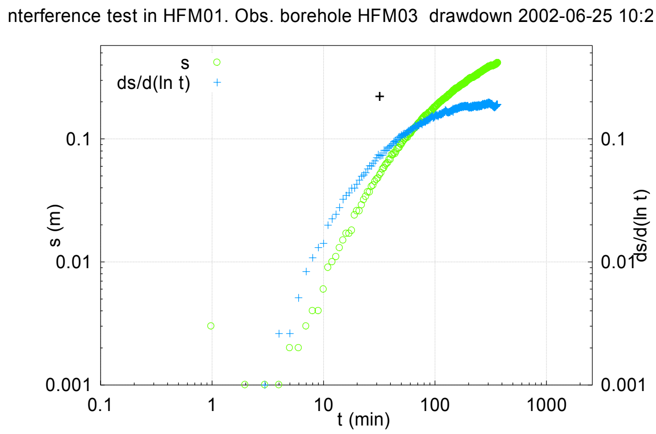
Test Summary Sheet – Observation borehole HFM03

Project:	PLU	Test type:	2
Area:	Forsmark	Test no:	1
Borehole ID:	HFM03	Test start:	2002-06-25 10:25
Test section (m):	13.10-26.00	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Pumping borehole ID:	HFM01		
Observation borehole diameter, $2 \cdot r_w$ (m):	0.136	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

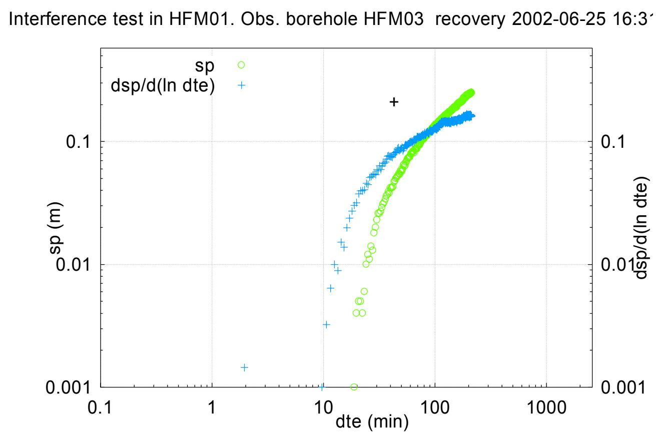
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
h_0 (m)	23.50		
h_i (m)	23.50		
h_p (m)	23.08	h_F (m)	23.33
Q_p (m^3/s)	-		
tp (min)	366	t_F (min)	509
S	-	S	-
EC_w (mS/m)	-		
Te_w(gr C)	-		
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	-		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	150	dt_{e1} (min)	150
t_2 (min)	400	dt_{e2} (min)	200
T_w (m^2/s)	$5.26 \cdot 10^{-4}$	T_w (m^2/s)	$5.45 \cdot 10^{-4}$
S_w (-)	$5.89 \cdot 10^{-5}$	S_w (-)	($1.44 \cdot 10^{-4}$)
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)	-	C (m^3/Pa)	-
C_D (-)	-	C_D (-)	-
ξ (-)	-	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

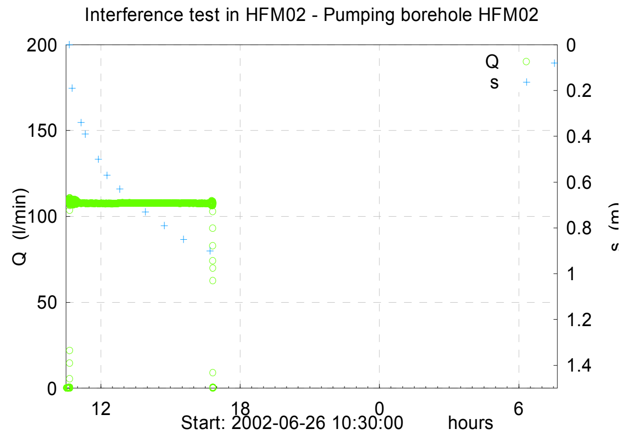
Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	150	C_D (-)	-
t_2 (min)	400	ξ (-)	-
T_T (m^2/s)	$5.26 \cdot 10^{-4}$		
S (-)	$5.89 \cdot 10^{-5}$		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Pseudo-radial flow (PRF) by the end of the flow period.

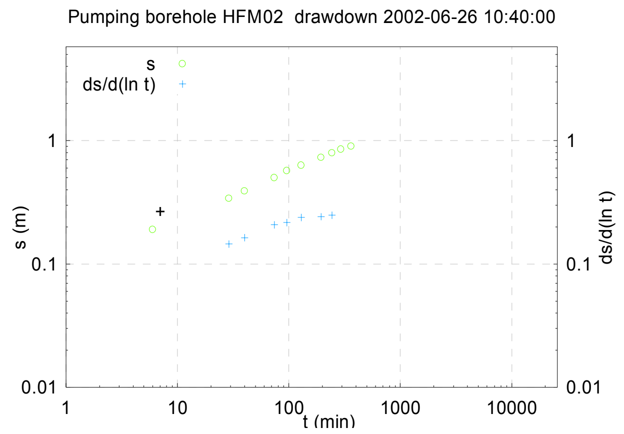
Test Summary Sheet - Pumping borehole HFM02

Project:	PLU	Test type:	1B
Area:	Forsmark	Test no:	2
Borehole ID:	HFM02	Test start:	2002-06-26 10:00
Test section (m):	25.40-100.00	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Section diameter, $2 \cdot r_w$ (m):	0.137	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period

*the pressure recovery was not registered in HFM02 and HFM03 due to a failure of the pressure transducer during the interference test in HFM02

Flow period		**Recovery period***	
Indata		**Indata**	
h_0 (m)	-2.22		
h_i (m)	-2.22		
h_p(m)	-3.12	h_F (m)	*
Q_p (m^3/s)	$1.78 \cdot 10^{-3}$		-
tp (min)	370	t_F (min)	790*
S*	$5 \cdot 10^{-5}$	S	-
EC_w (mS/m)			-
Te_w(gr C)			-
Derivative fact.	0.3	Derivative fact.	-
Results		**Results**	
Q/s (m^2/s)	$2.09 \cdot 10^{-3}$		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	-
t_1 (min)	200	dt_{e1} (min)	-
t_2 (min)	400	dt_{e2} (min)	-
T_w (m^2/s)	$5.10 \cdot 10^{-4}$	T_w (m^2/s)	-
S_w (-)	-	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)		C (m^3/Pa)	-
C_D (-)		C_D (-)	-
ξ (-)	-7.18	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

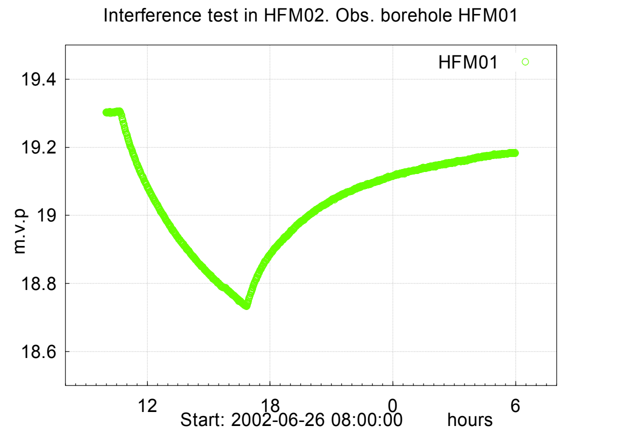
Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	200	C_D (-)	-
t_2 (min)	400	ξ (-)	-7.18
T_T (m^2/s)	$5.10 \cdot 10^{-4}$		
S (-)	-		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Initial linear fracture-dominated flow (1:2 slope in log-log diagram) transiting to pseudo-radial flow.

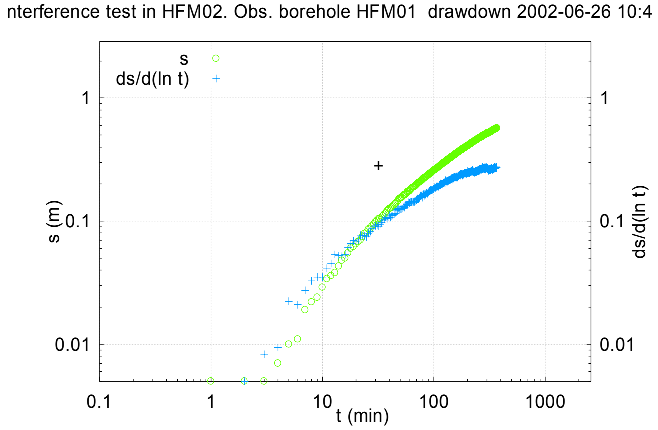
Test Summary Sheet - Observation borehole HFM01

Project:	PLU	Test type:	2
Area:	Forsmark	Test no:	1
Borehole ID:	HFM02	Test start:	2002-06-26 10:00
Test section (m):	31.93-200.20	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Pumping borehole ID:	HFM02		
Observation borehole diameter, $2 \cdot r_w$ (m):	0.140	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

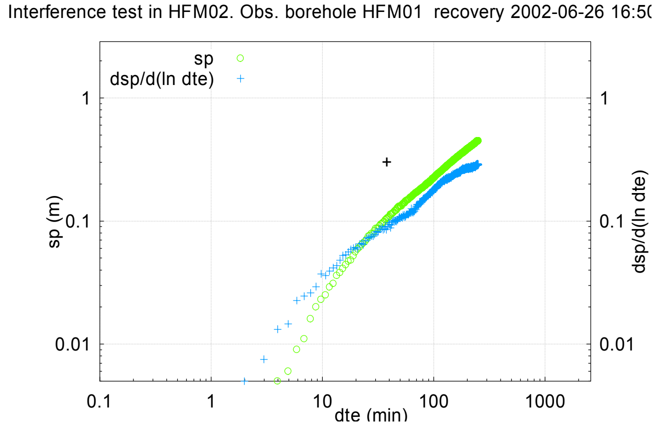
Linear plot Q and p



Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period



Flow period		**Recovery period***	
Indata		**Indata**	
h_0 (m)	19.30		
h_i (m)	19.30		
h_p(m)	18.73	h_F (m)	*
Q_p (m^3/s)	-		-
tp (min)	370	t_F (min)	790*
S	-	S	-
EC_w (mS/m)			-
Te_w(gr C)			-
Derivative fact.	0.3	Derivative fact.	0.3
Results		**Results**	
Q/s (m^2/s)	-		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	PRF
t_1 (min)	150	dt_{e1} (min)	150
t_2 (min)	400	dt_{e2} (min)	200
T_w (m^2/s)	$5.31 \cdot 10^{-4}$	T_w (m^2/s)	$5.10 \cdot 10^{-4}$
S_w (-)	$6.33 \cdot 10^{-5}$	S_w (-)	$7.35 \cdot 10^{-5}$
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)		C (m^3/Pa)	-
C_D (-)		C_D (-)	-
ξ (-)	-	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Interpreted formation and well parameters.

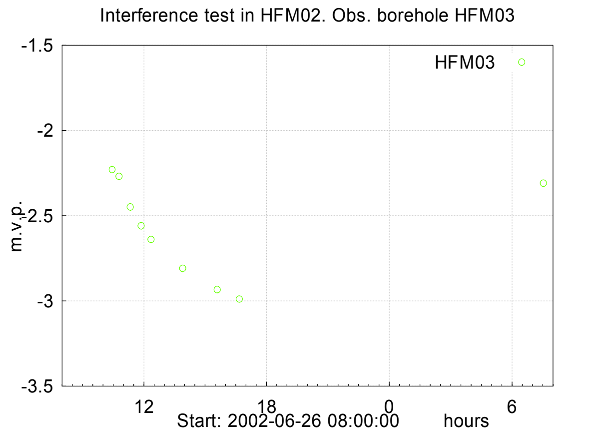
Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	150	C_D (-)	-
t_2 (min)	400	ξ (-)	-
T_T (m^2/s)	$5.31 \cdot 10^{-4}$		
S (-)	$6.33 \cdot 10^{-5}$		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Pseudo-radial flow (PRF) by the end of the flow period. Slight effects of a hydraulic no-flow boundary or dual-permeability formation.

Test Summary Sheet - Observation borehole HFM03

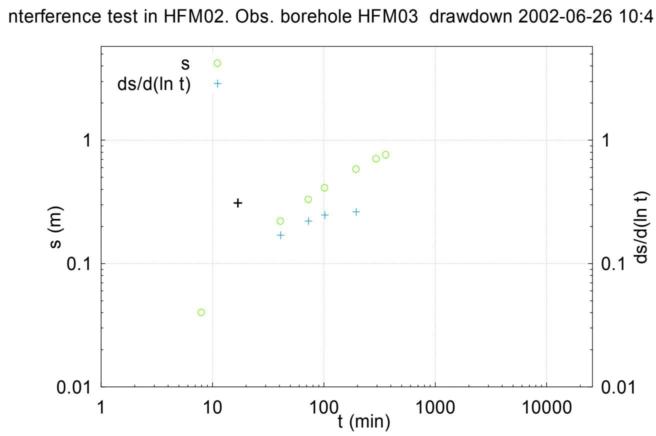
Project:	PLU	Test type:	2
Area:	Forsmark	Test no:	1
Borehole ID:	HFM02	Test start:	2002-06-26 10:00
Test section (m):	13.10-26.00	Responsible for test performance:	GEOSIGMA AB S. Jönsson / J. Levén
Section diameter, $2\cdot r_w$ (m):	0.136	Responsible for test evaluation:	GEOSIGMA AB J-E Ludvigson

Linear plot Q and p



Flow period		Recovery period*	
Indata		**Indata**	
h_0 (m)	-2.23		
h_i (m)	-2.23		
h_p(m)	-2.99	h_F (m)	*
Q_p (m^3/s)	-		-
tp (min)	370	t_F (min)	790*
S	-	S	-
EC_w (mS/m)			-
Te_w(gr C)			-
Derivative fact.	0.3	Derivative fact.	-
Results		**Results**	
Q/s (m^2/s)	-		
T_{Moye}(m^2/s)	-		
Flow regime:	PRF	Flow regime:	-
t_1 (min)	150	dt_{e1} (min)	-
t_2 (min)	400	dt_{e2} (min)	-
T_w (m^2/s)	$4.87\cdot10^{-4}$	T_w (m^2/s)	-
S_w (-)	$3.57\cdot10^{-3}$	S_w (-)	-
K_{sw} (m/s)	-	K_{sw} (m/s)	-
S_{sw} (1/m)	-	S_{sw} (1/m)	-
C (m^3/Pa)		C (m^3/Pa)	-
C_D (-)		C_D (-)	-
ξ (-)	-	ξ (-)	-
T_{GRF}(m^2/s)		T_{GRF}(m^2/s)	
S_{GRF}(-)		S_{GRF}(-)	
D_{GRF} (-)		D_{GRF} (-)	

Log-Log plot incl. derivate- flow period



Log-Log plot incl. derivative- recovery period

*the pressure recovery was not registered in HFM02 and HFM03 due to a failure of the pressure transducer during the interference test in HFM02

Interpreted formation and well parameters.

Flow regime:	PRF	C (m^3/Pa)	-
t_1 (min)	150	C_D (-)	-
t_2 (min)	400	ξ (-)	-
T_T (m^2/s)	$4.87\cdot10^{-4}$		
S (-)	$3.57\cdot10^{-3}$		
K_s (m/s)	-		
S_s (1/m)	-		

Comments: Rather delayed response in relation to the distance to the pumping borehole HFM02. Calculated storativity value probably non-representative due to assumed indirect hydraulic connection to this borehole section.

7 References

/1/ **Ludvigson J-E, Jönsson S, Levén J, 2003.** Pumping tests and flow logging. Boreholes KFM01A(0–100 m), HFM01, HFM02 and HFM03. SKB P-03-33, Svensk Kärnbränslehantering AB.

/2/ **Nilsson A-C, 2003.** Sampling and analyses of groundwater in percussion drilled boreholes in hard rock and monitoring wells in soil at drillsite DS1. Results from the percussion boreholes HFM01, HFM02, HFM03, KFM01A (borehole section 0–100 m) and the monitoring wells SFM0001, SFM0002 and SFM0003. SKB P-03-47, Svensk Kärnbränslehantering AB.

/3/ **Ludvigson J-E, 2002.** Bunnsinventering i Forsmark. SKB R-02-17, Svensk Kärnbränslehantering AB

/4/ **Almén K-E, Andersson J-E, Carlsson L, Hansson K, Larsson N-Å, 1986.** Hydraulic testing in crystalline rock. A comparative study of single-hole test methods. Technical Report 86-27, Svensk Kärnbränslehantering AB.

/5/ **Gustafson G, 1986.** Geohydrologiska förundersökningar i berg. Hydrogeological preinvestigations in rock. Theoretical basis and applications. Swedish Rock Engineering Research Foundation. BeFo 84:1/86.

Appendix 1

List of test data files

Files are named ”*bhnamn_secup_yymmdd_XX*”, where *yymmdd* is the date for 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 alternative; *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	Parameters[2]	Comments
HFM01	0 - 200.2	1B	2002-06-25 10:25:00	2002-06-26 00:02:48	2002-06-25 10:20:00	2002-06-26 00:02:48	HFM01.TXT	P, Q	Data incorrect after 2002-06-26 00:02:48, probably due to condensation in the data logger.
HFM02	0 - 100	2	2002-06-25 10:25:00	2002-06-26 07:23:00	2002-06-25 09:56:00	2002-06-26 07:23:00	HFM02_20020626.csv	P	
HFM03	0 - 26	2	2002-06-25 10:25:00	2002-06-26 07:20:00	2002-06-25 10:00:01	2002-06-26 07:20:00	HFM03_20020626.csv	P	
HFM02	0 - 100	1B	2002-06-26 10:40:00	2002-06-27 09:31:00	2002-06-26 10:20:00	2002-06-27 09:31:00	HFM02.TXT	P, Q	Pressure data incorrect depending on instable voltage from the diesel-driven generator.
HFM01	0 - 200.2	2	2002-06-26 10:40:00	2002-06-27 07:15:00	2002-06-26 08:30:00	2002-06-27 07:15:00	HFM01_20020627.csv	P	

1: 1A: Pumping test-wire-line equipment., 1B: Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF_sequential, 5B: Difference flow logging-PFL-DIFF_overlapping, 6: Flow logging-Impeller, Logging-EC: L-EC, Logging temperature: L-T, Logging single point resistance: L-SPR

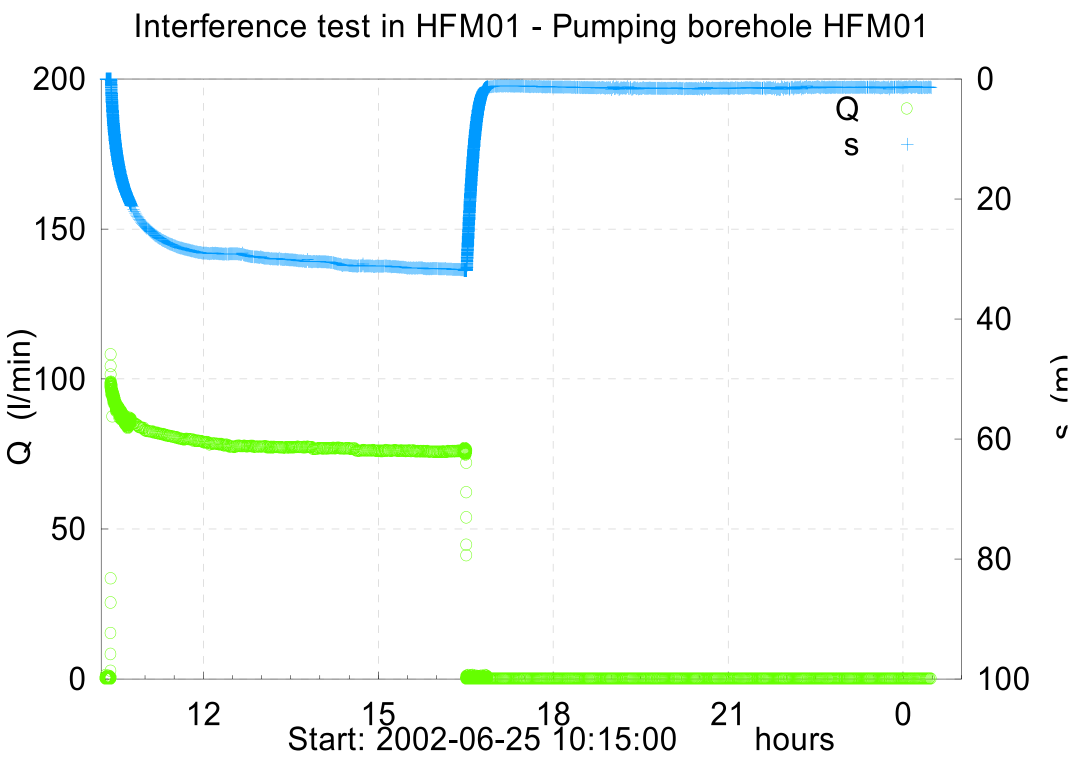
2: P =Pressure, Q =Flow, Te =Temperature, EC =El. conductivity. SPR =Single Point Resistance, C =Calibration file, R =Reference file, Sp= Spinner rotations.

Appendix 2

Test diagrams

1. Interference test in HFM01
   – pumping borehole HFM01
   – observation borehole HFM02
   – observation borehole HFM03

2. Interference test in HFM02
   – pumping borehole HFM02
   – observation borehole HFM01
   – observation borehole HFM03



Figurre A2-1. *Linear plot of flow rate (Q) and drawdown (s) versus time in the pumping borehole HFM01.*

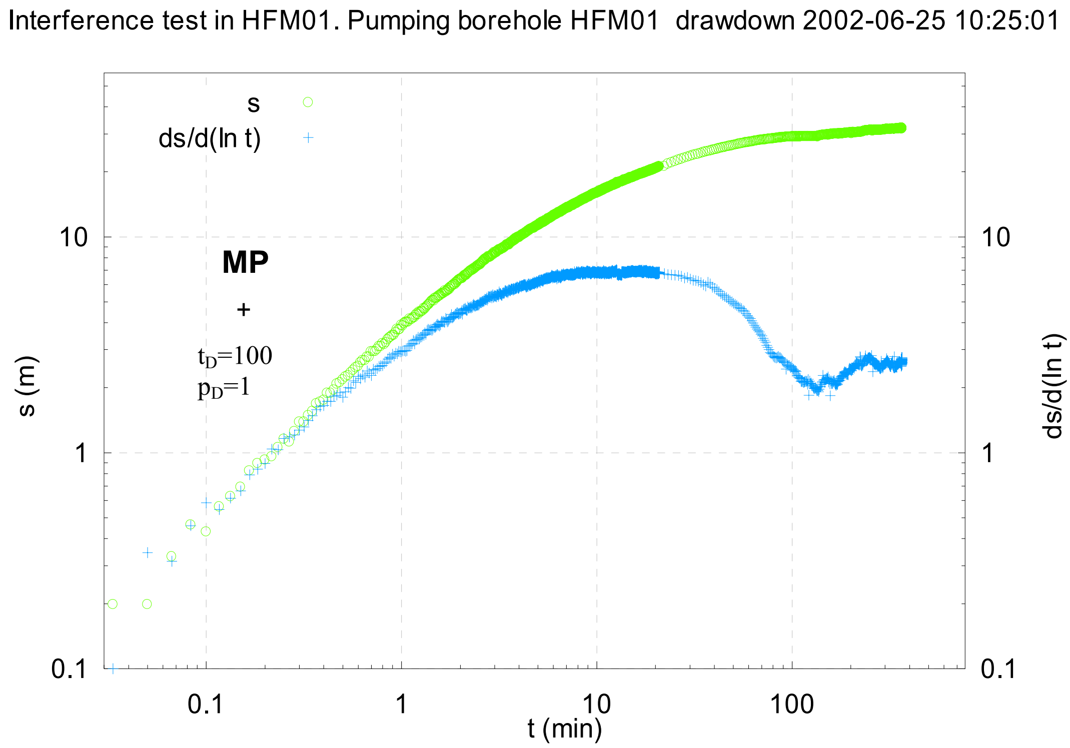


Figure A2-2. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) in the pumping borehole HFM01.*

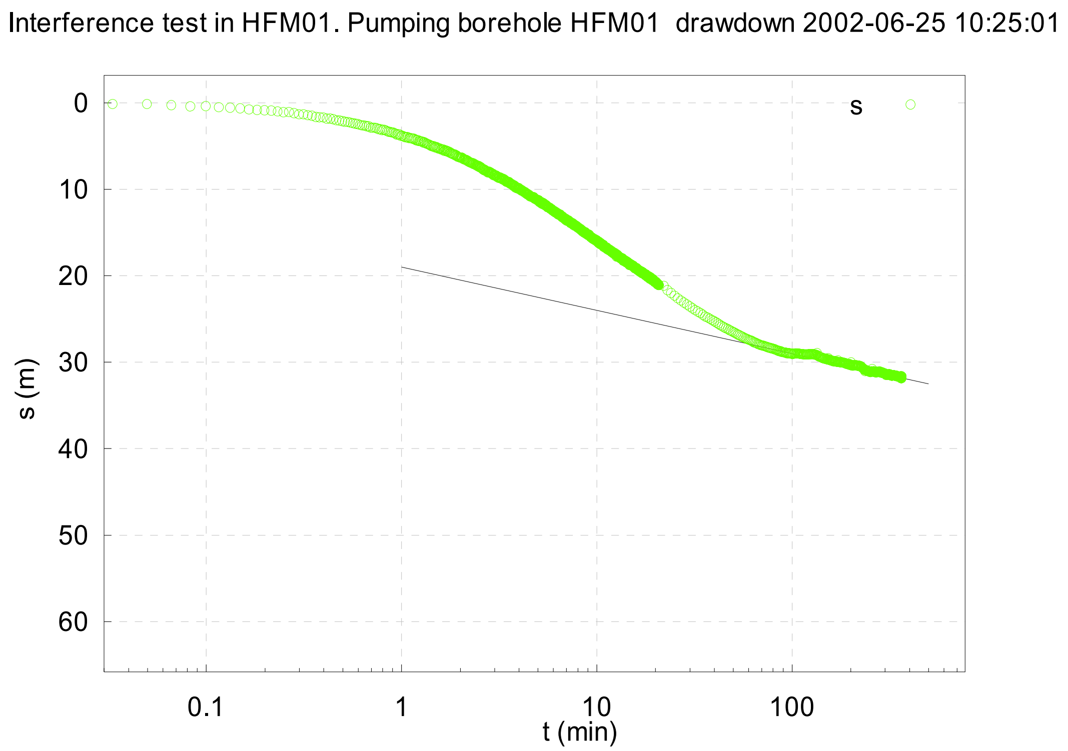


Figure A2-3. *Semi-logarithmic plot of drawdown (s) versus time (t) in the pumping borehole HFM01.*

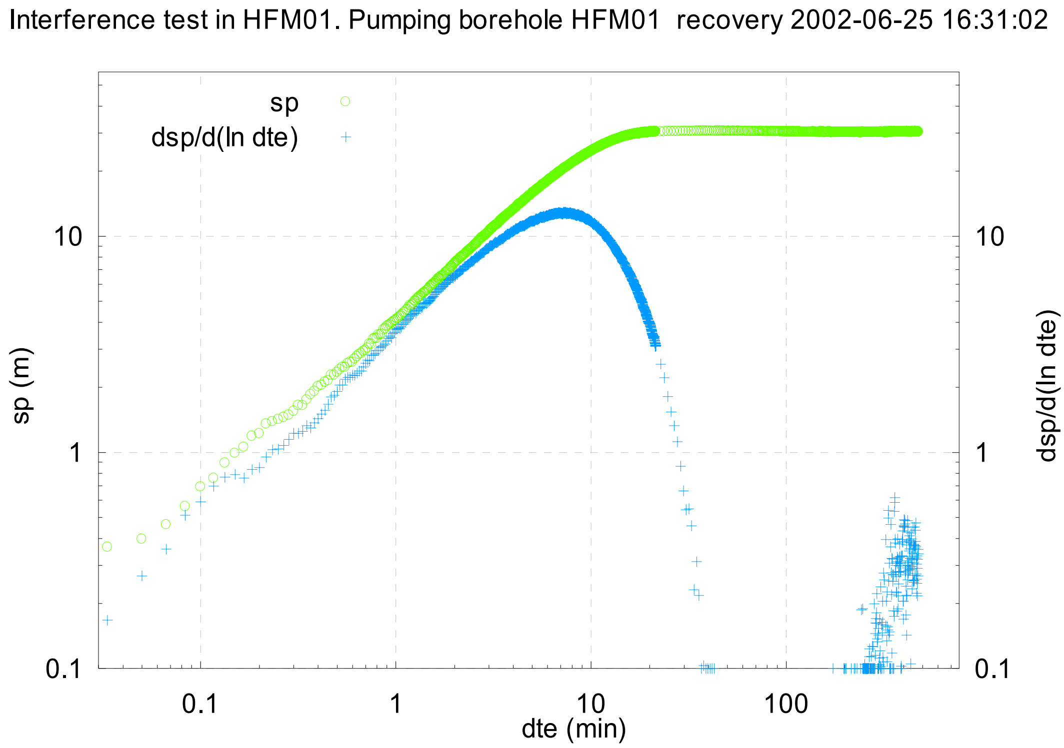


Figure A2-4. Logarithmic plot of pressure recovery (sp) and - derivative, dsp/d(ln dte), versus equivalent time (dte) in the pumping borehole HFM01.

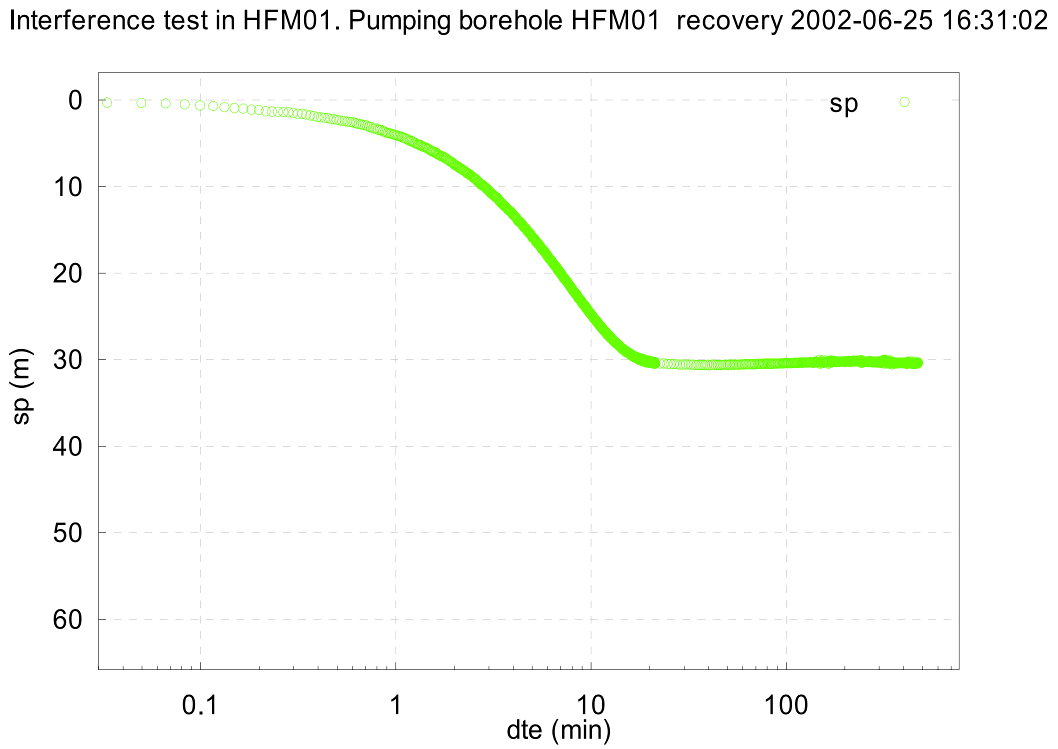


Figure A2-5. Semi-logarithmic plot of pressure recovery (sp) versus equivalent time (dte) in the pumping borehole HFM01.

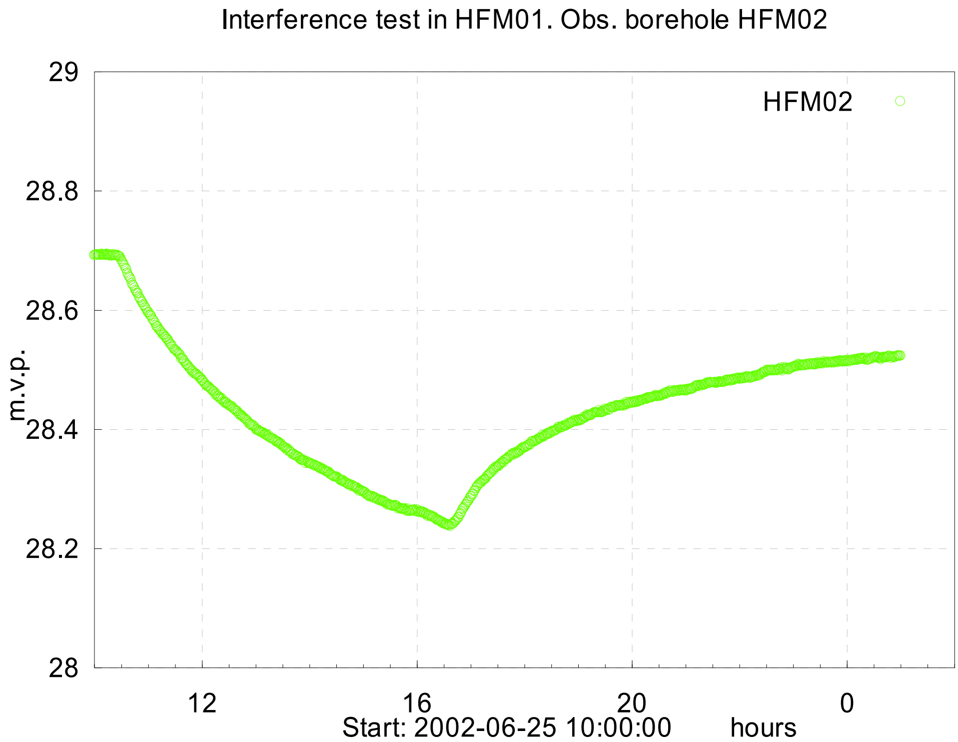


Figure A2-6. *Linear plot of flow rate (Q) and drawdown (s) versus time in the observation borehole HFM02.*

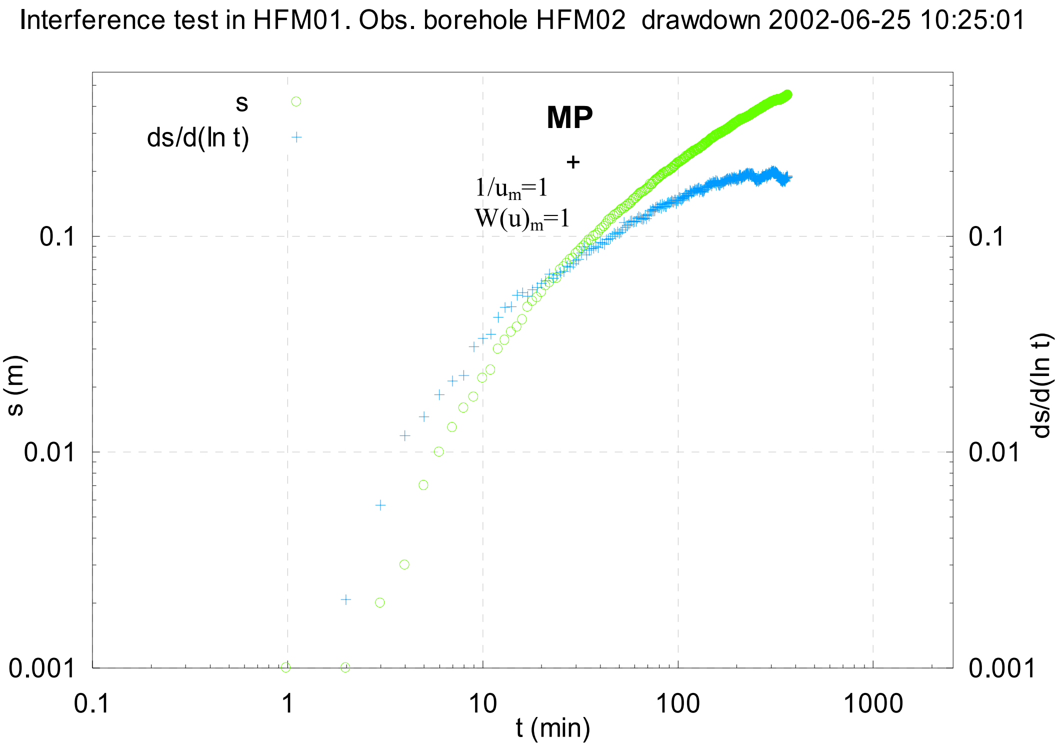


Figure A2-7. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) time in the observation borehole HFM02.*

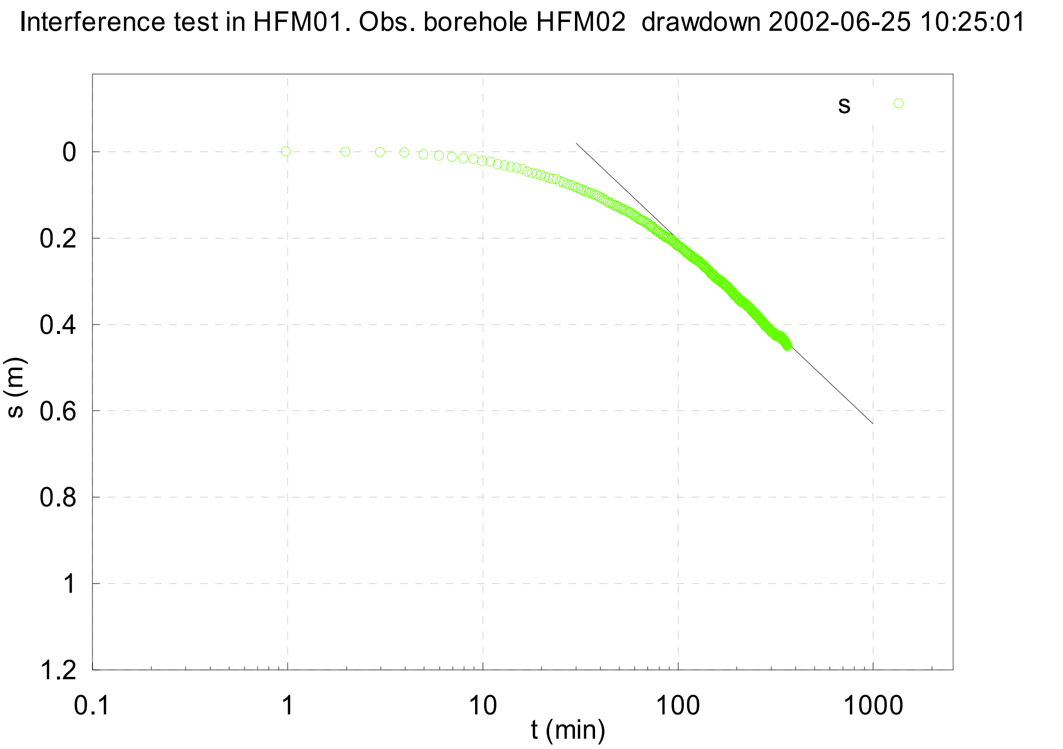


Figure A2-8. *Semi-logarithmic plot of drawdown (s) versus time (t) time in the observation borehole HFM02.*

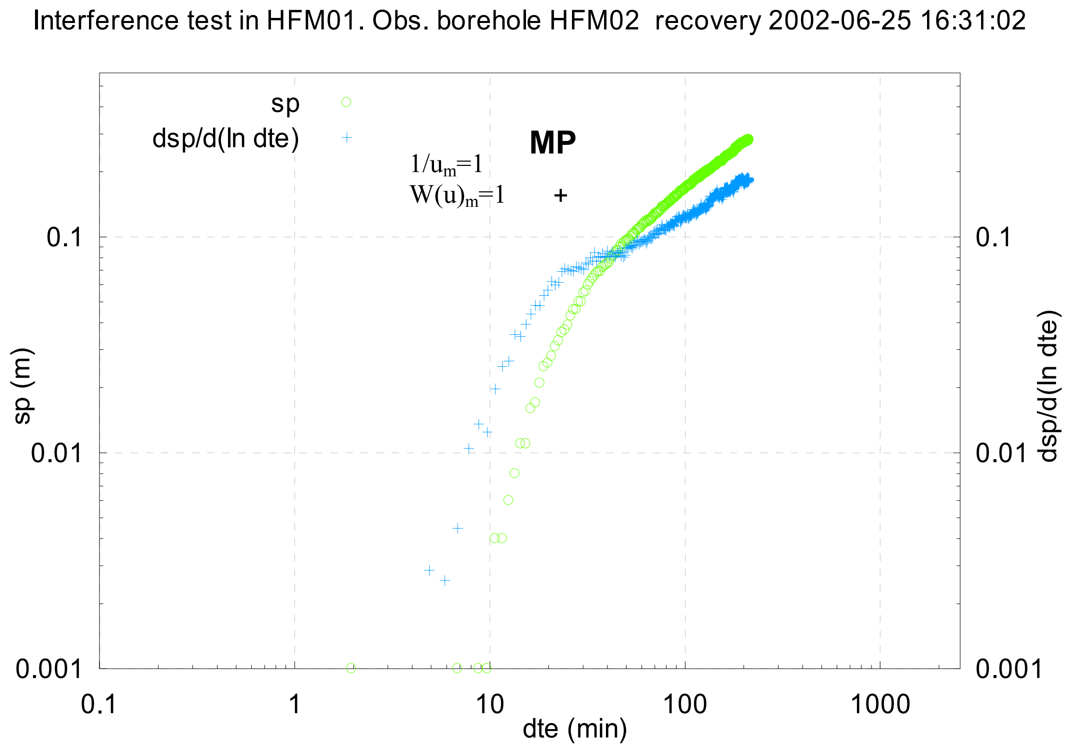


Figure A2-9. *Logarithmic plot of pressure recovery (sp) and – derivative, dsp/d(ln dte), versus equivalent time (dte) time in the observation borehole HFM02.*

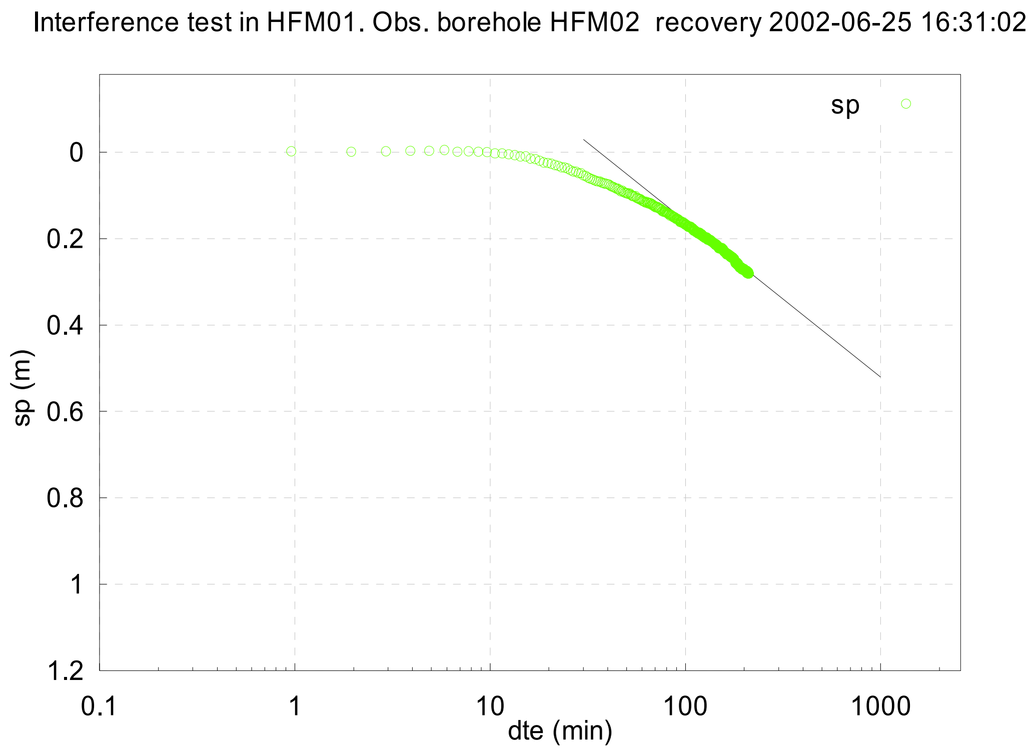


Figure A2-10. *Semi-logarithmic plot of pressure recovery (sp) versus equivalent time (dte) in the observation borehole HFM02.*

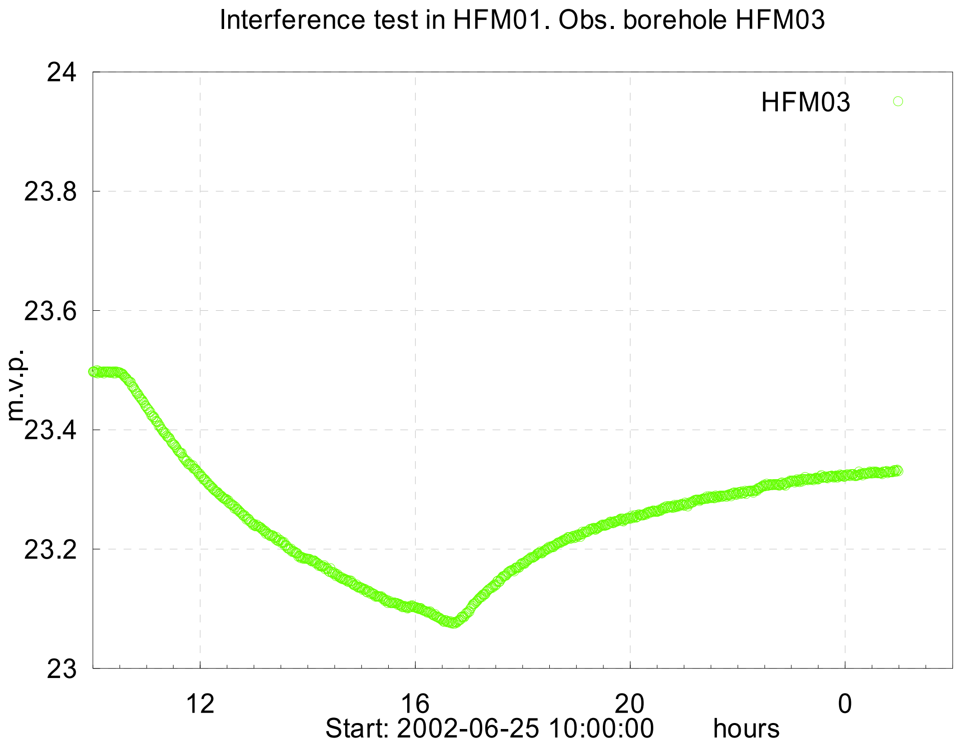


Figure A2-11. *Linear plot of flow rate (Q) and drawdown (s) versus time in the observation borehole HFM03.*

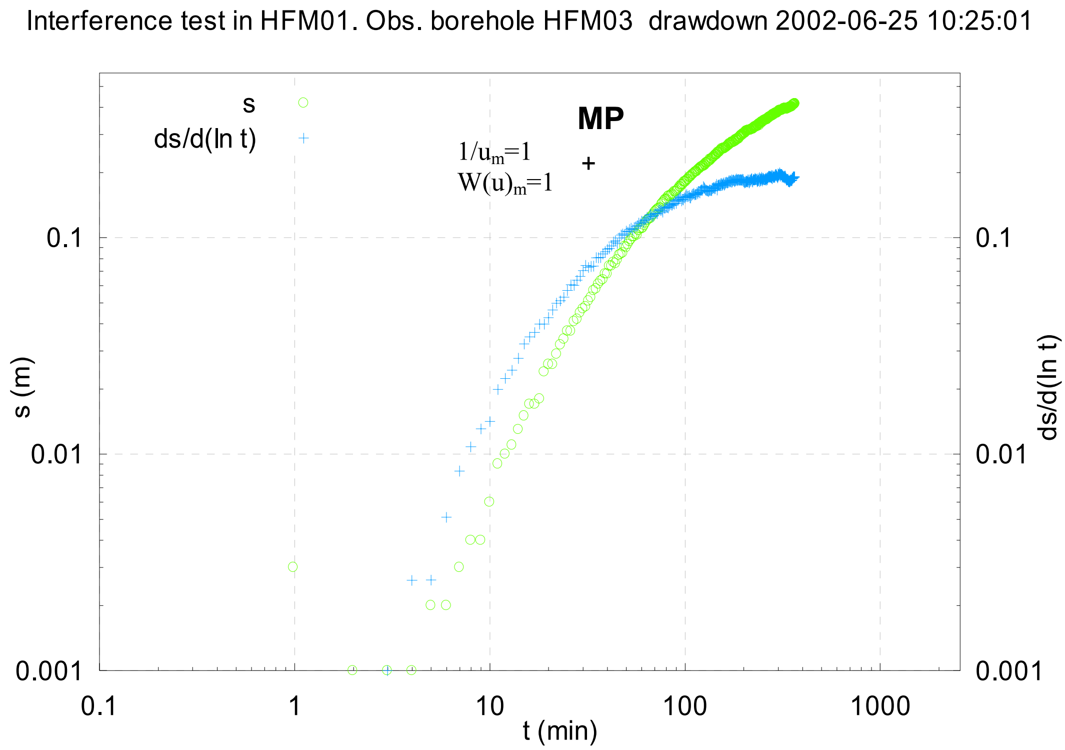


Figure A2-12. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) time in the observation borehole HFM03.*

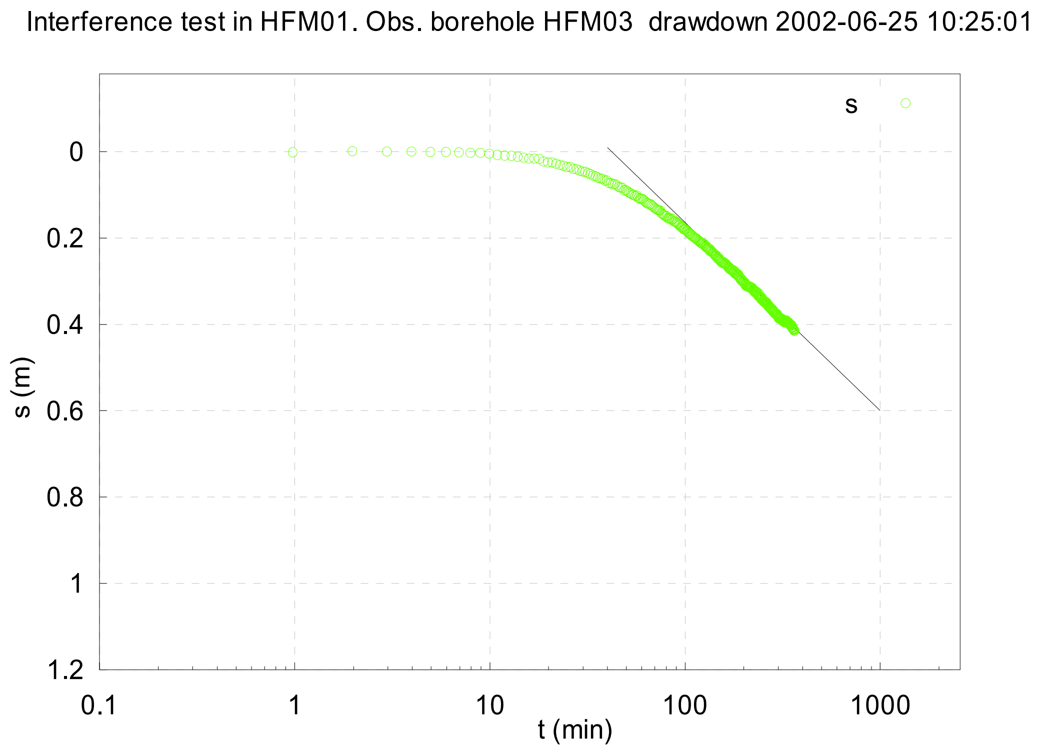


Figure A2-13. *Semi-logarithmic plot of drawdown (s) versus time (t) in the observation borehole HFM03.*

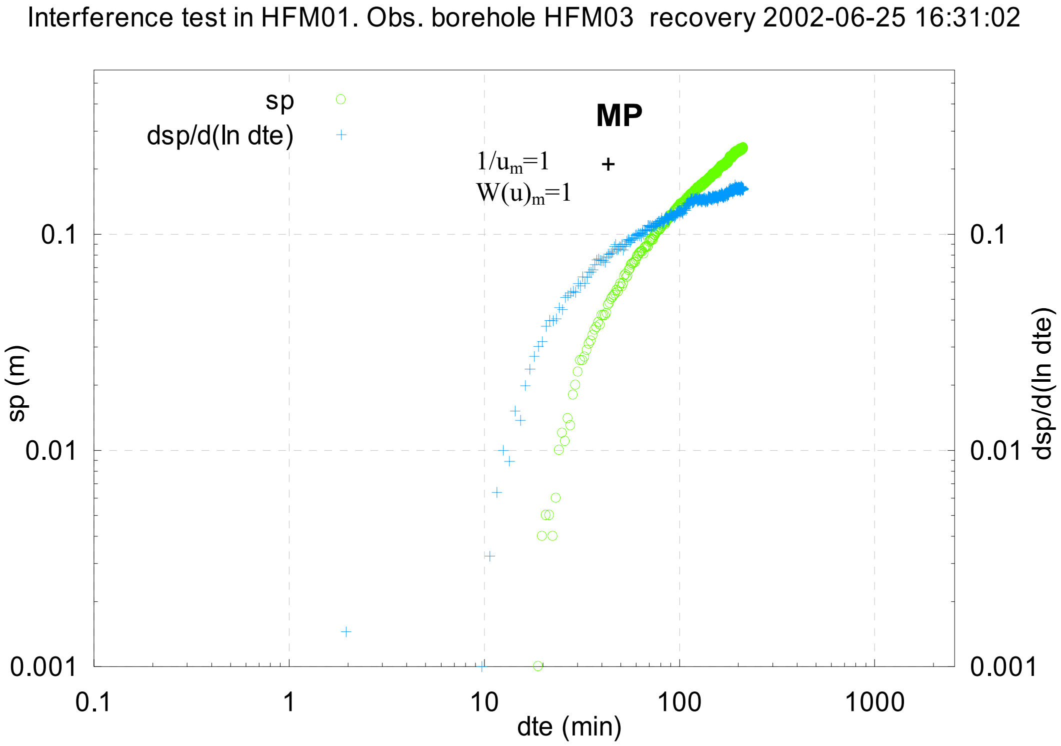


Figure A2-14. *Logarithmic plot of pressure recovery (sp) and – derivative, dsp/d(ln dte), versus equivalent time (dte) in the observation borehole HFM03.*

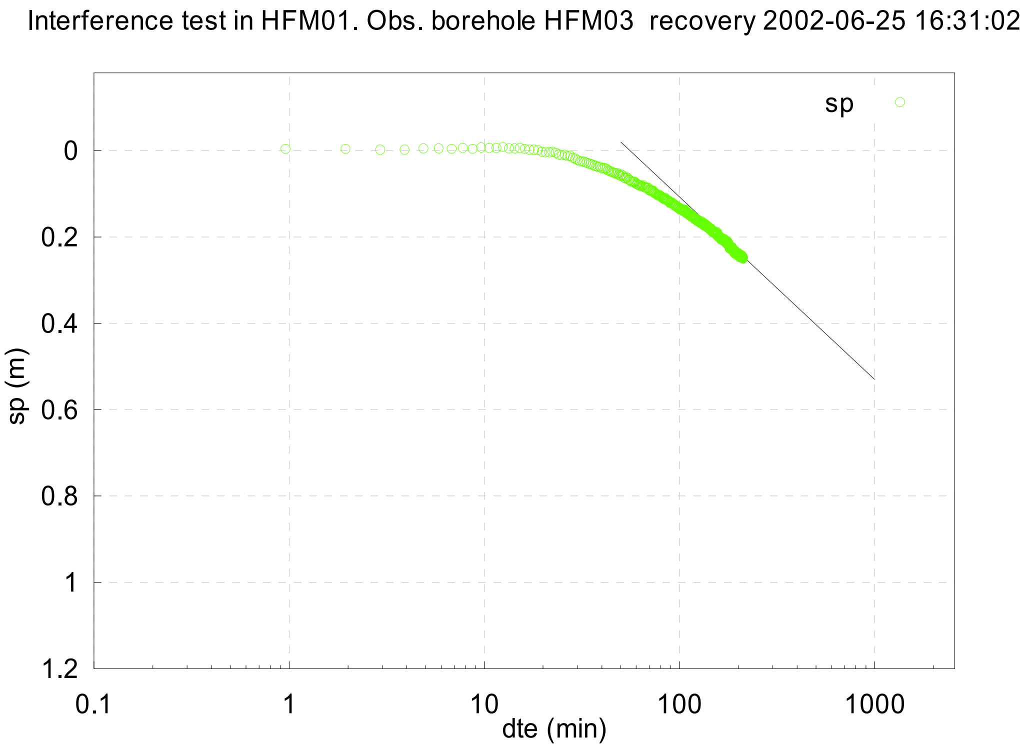


Figure A2-15. *Semi-logarithmic plot of pressure recovery (sp) versus equivalent time (dte) in the observation borehole HFM03.*

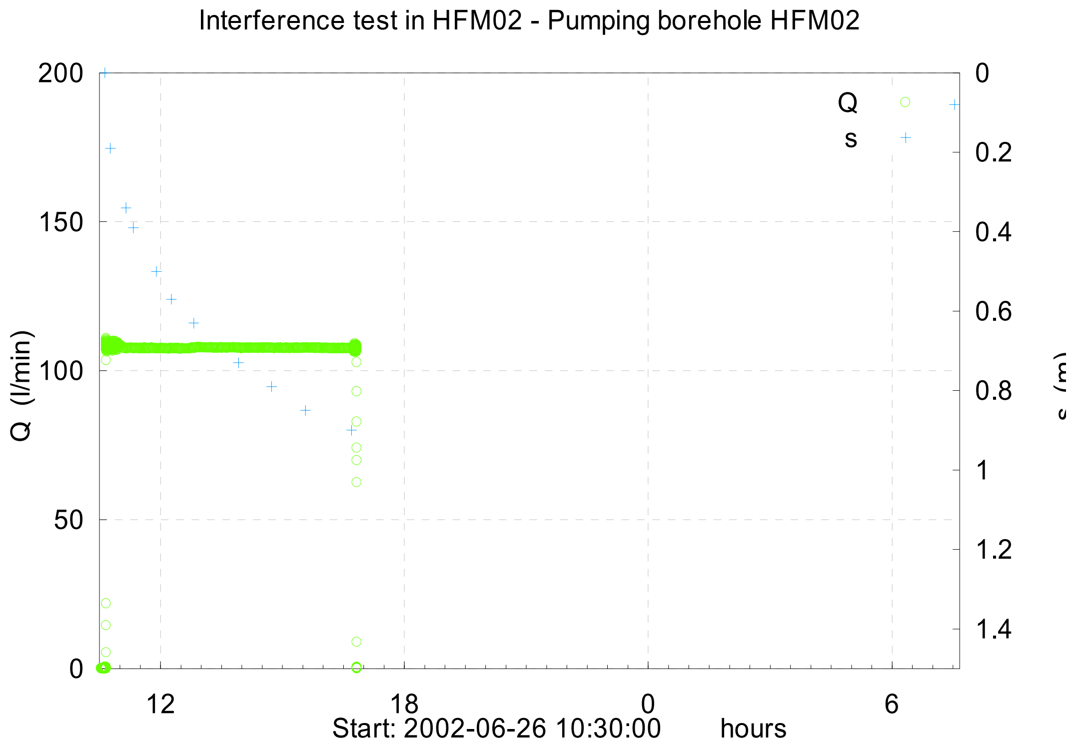


Figure A2-16. *Linear plot of flow rate (Q) and drawdown (s) versus time in the pumping borehole HFM02.*

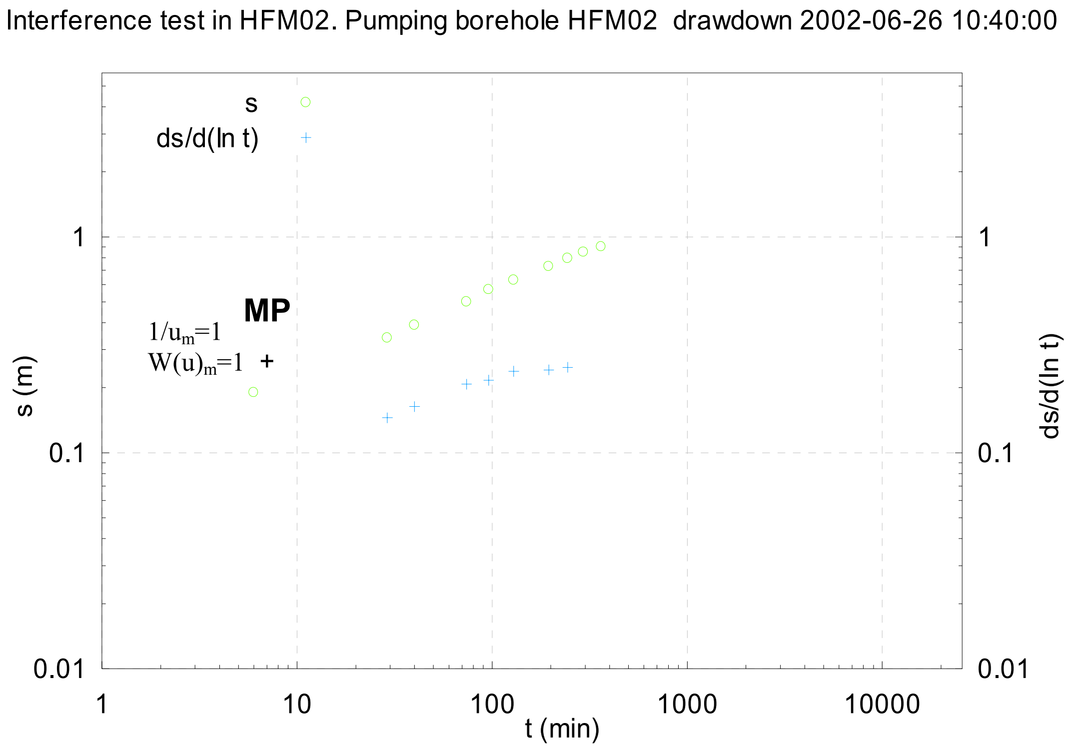


Figure A2-17. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) time in the pumping borehole HFM02.*

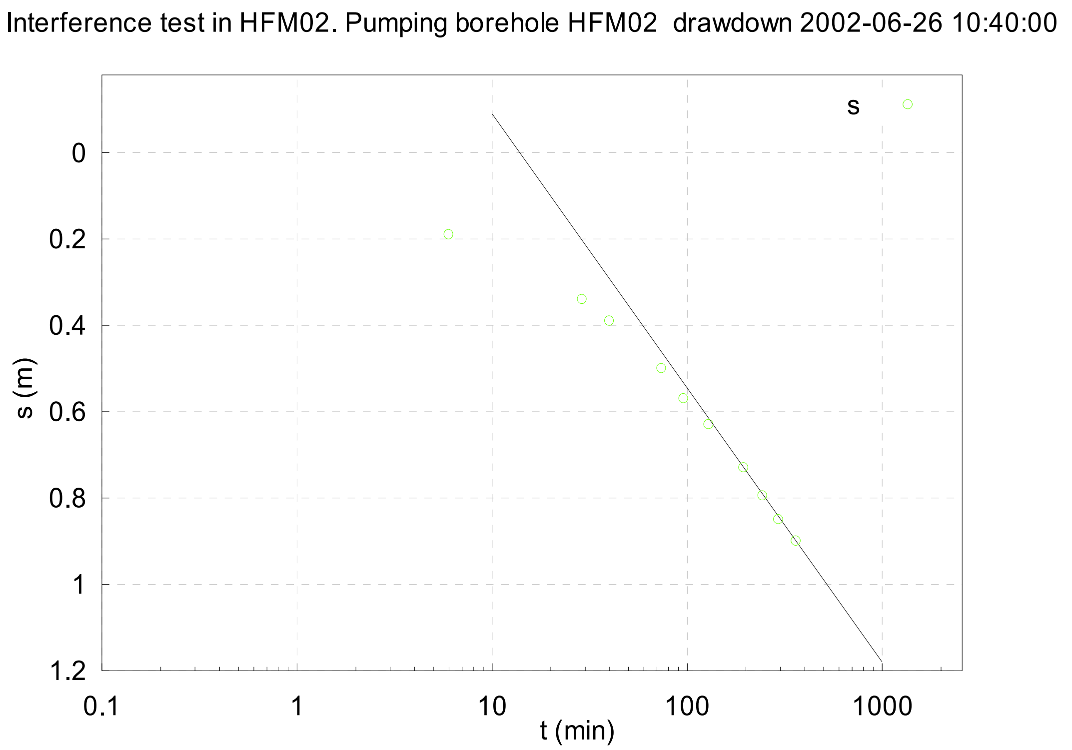


Figure A2-18. *Semi-logarithmic plot of drawdown (s) versus time (t) in the pumping borehole HFM02.*

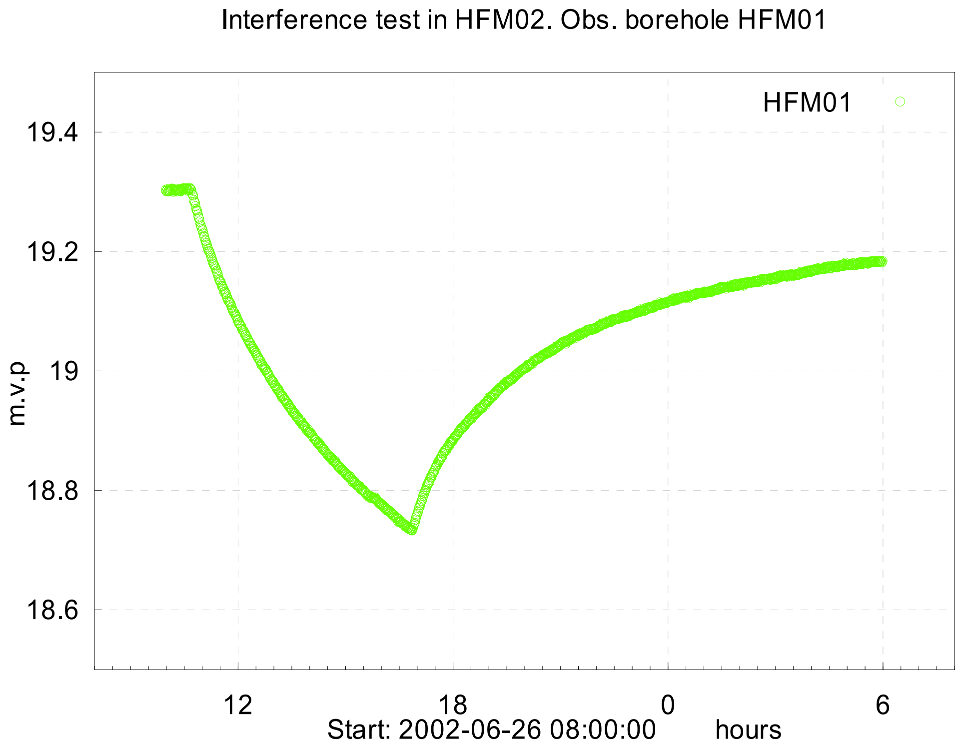


Figure A2-19. *Linear plot of flow rate (Q) and drawdown (s) versus time in the observation borehole HFM01.*

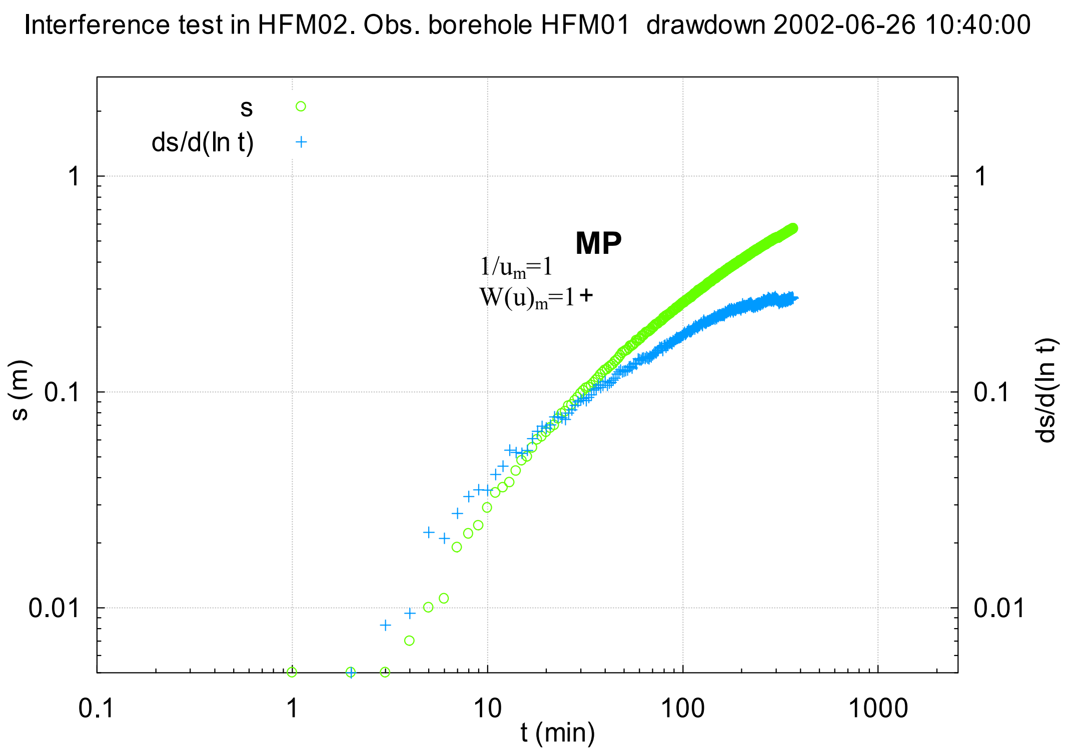


Figure A2-20. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) time in the observation borehole HFM01.*

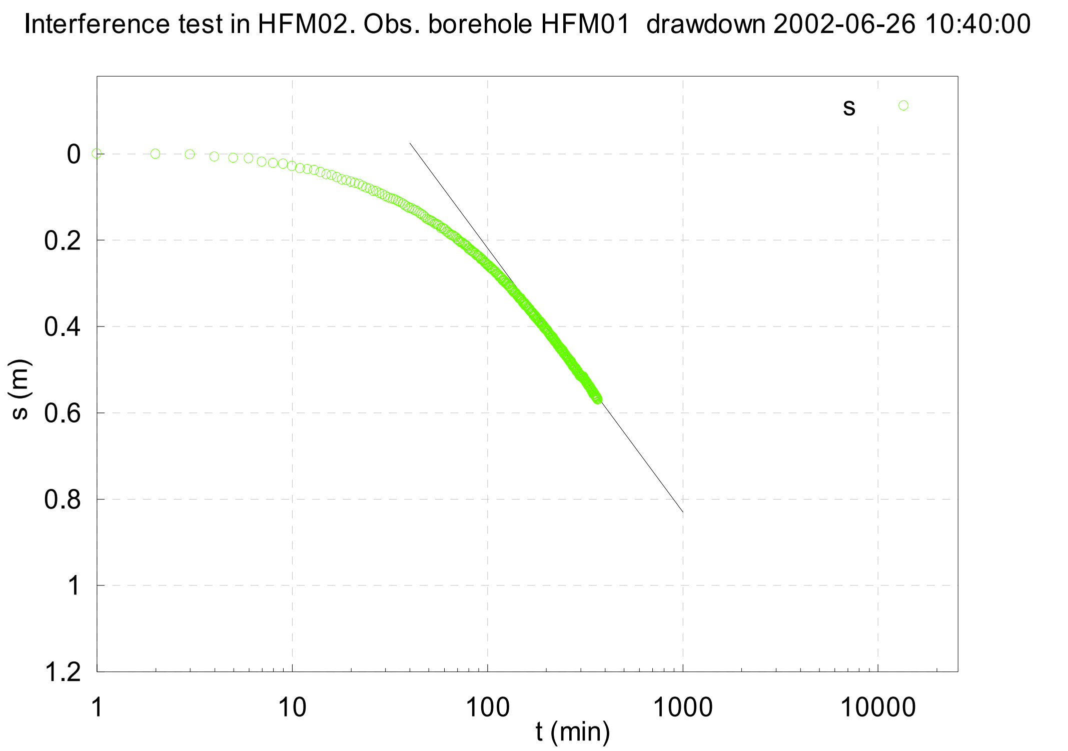


Figure A2-21. *Semi-logarithmic plot of drawdown (s) versus time (t) in the observation borehole HFM01.*

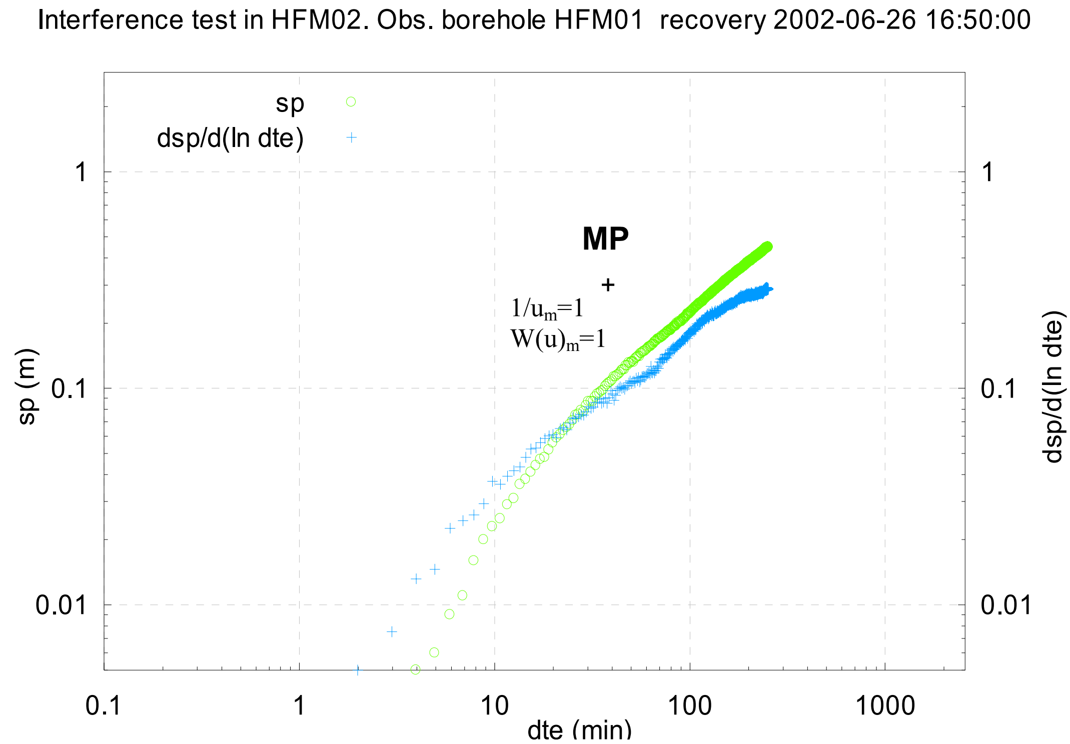


Figure A2-22. *Logarithmic plot of pressure recovery (sp) and – derivative, dsp/d(ln dte), versus equivalent time (dte) in the observation borehole HFM01.*

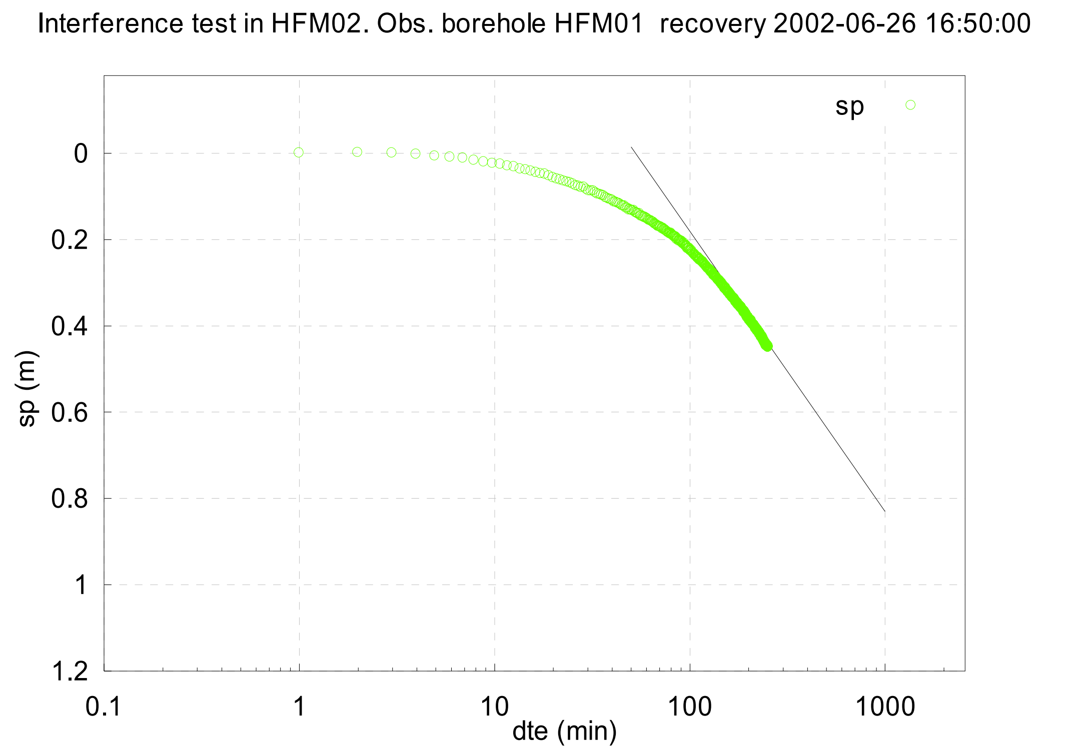


Figure A2-23. *Semi-logarithmic plot of pressure recovery (sp) versus equivalent time (dte) in the observation borehole HFM01.*

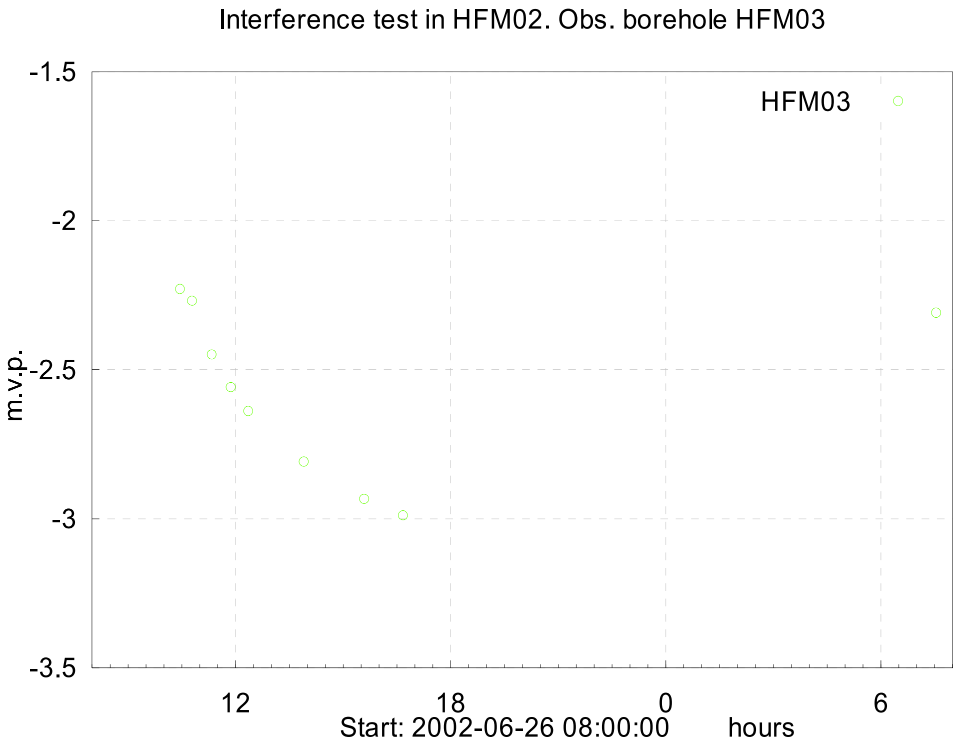


Figure A2-24. *Linear plot of flow rate (Q) and drawdown (s) versus time time in the observation borehole HFM03.*

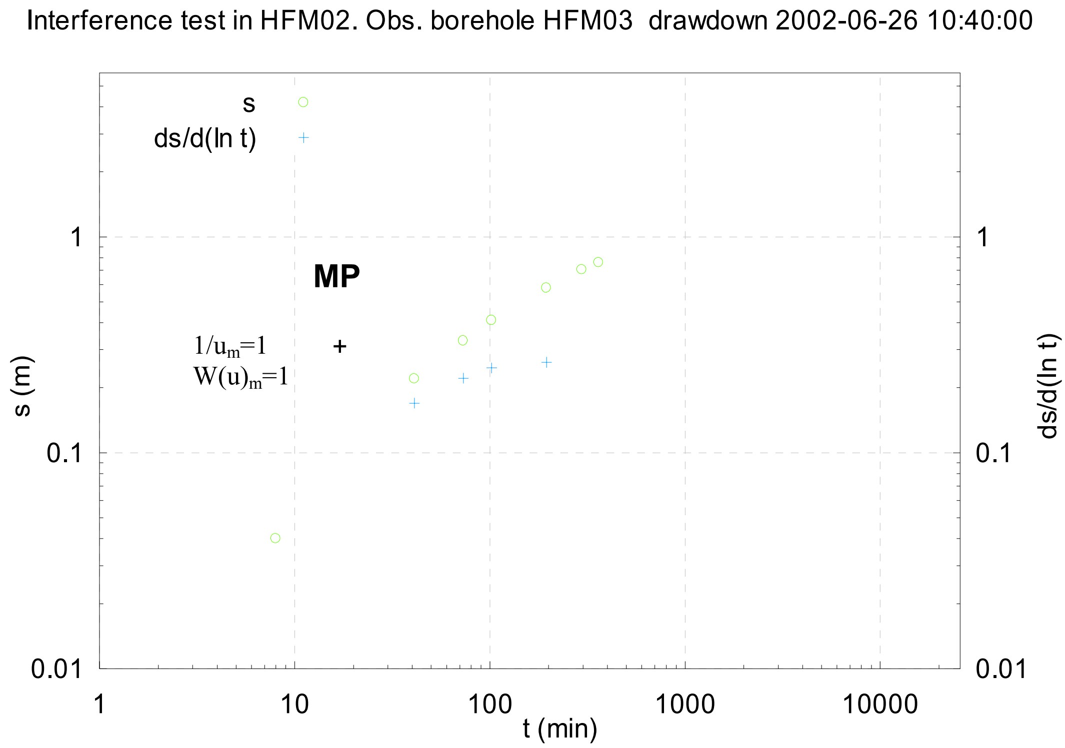


Figure A2-25. *Logarithmic plot of drawdown (s) and drawdown derivative, ds/d(ln t), versus time (t) time in the observation borehole HFM03.*

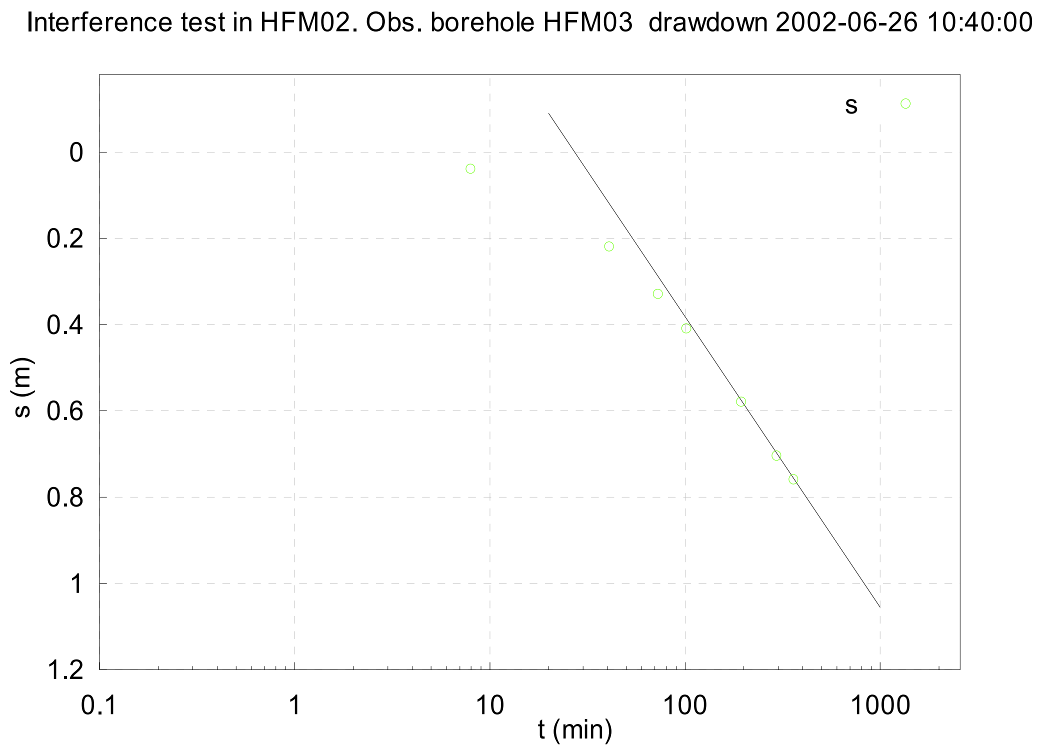


Figure A2-26. *Semi-logarithmic plot of drawdown (s) versus time (t) in the observation borehole HFM03.*

Appendix 3

Result tables to Sicada

Appendix 3:1. Result tables for Single-hole pumping and injection tests

Appendix 3:2. Result tables for Hydraulic interference tests

A. Result table for single-hole tests during the interference tests at Drillsite 1 at Forsmark site investigation for submission to the Sicada database

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_d; General information

Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-6)	Formation type (-)	Date and time for test, start YYYYMMDD hh:mm	Date and time for test, stop YYYYMMDD hh:mm	Date and time for flow, start YYYYMMDD hh:mm:ss	Date and time for flow, stop YYYYMMDD hh:mm:ss	Qp (m**3/s)	Value type	Q-measl-L (m**3)/s	Q-measl-U (m**3)/s	V_p (m**3)	Q_m (m**3/s)
HFM01	31.93	200.20	1B	1	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00	1.25E-03	0	8.33E-05	1.33E-03		
HFM02	25.40	100.00	1B	1	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00	1.78E-03	0	8.33E-05	1.33E-03		

cont.

tp (s)	t_F (s)	h_i (m a sl)	h_p (m a sl)	h_F (m a sl)	p_i (m)	p_p (m)	p_F (m)	Te_w (°C)	EC_w (mS/m)	TDS_w (mg/ L)	TDS_{wm} (mg/ L)	Reference	Comments (-)
21960	30540	0.77	-31.07	-0.67	43.96	12.12	42.52					P-03-35	
22200	47400	0.83	-0.07		-2.22	-3.12						P-03-35	

SINGLEHOLE TESTS, Pumping and injection, s_hole_test_ed1; Basic evaluation

Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YYYYMMDD hh:mm	Q/s (m^2/ s)	Value code	T_Q (m^2/ s)	T_M (m^2/ s)	b (m)	B (m)	TB (1D) (m^3/ s)	TB-measl-L (1D) (m^3/ s)	TB-measl-U (1D) (m^3/ s)	SB (1D) (m)	SB* (1D) (m)	L_f (1D) (m)	T_T (2D) (m^2/ s)	Q/s-measl-L (m^2/ s)	Q/s-measl-U (m^2/ s)	S (2D) (-)	S* (2D) (-)
HFM01	31.93	200.20	20020625 10:25	4.54E-05	0			168.27								5.08E-05	2.0E-06	2.0E-03		5.00E-05
HFM02	25.40	100.00	20020626 10:40	2.09E-03	0			74.6								5.10E-04	2.0E-06	2.0E-03		5.00E-05

cont.

K´/b´ (2D) (1/s)	K_S (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_S (3D) (1/m)	S_S* (3D) (1/m)	L_p (m)	C (m**3/Pa)	C_D (-)	ξ (2D) (-)	ω (-)	λ (-)	t_1 (s)	t_2 (s)	Comments (-)
						42.5	2.00E-06		-0.08			4800	24000	WBS
						43			-7.18			12000	24000	Fracture flow

Header	**Unit**	*Explanation*
Borehole		ID for borehole
Borehole secup	m	Length coordinate along the borehole for the upper limit of the test section
Borehole seclow	m	Length coordinate along the borehole for the lower limit of the test section
Test type (1- 7)	(-)	1A: Pumping test - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumpingtest-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-sequential, 5B: Difference flow logging-PFL-DIFF-overlapping, 6:Flow logging_Impeller,7:Grain size analysis
Date for test start		Date for the start of the pumping or injection test (YYYYMMDD hh:mm)
Start flow / injection		Date and time for the start of the pumping or injection period (YYMMDD hh:mm:ss)
Start flow / injection		Date and time for the end of the pumping or injection period (YYMMDD hh:mm:ss)
Q_m	m^3/s	Arithmetic mean flow rate of the pumping/injection period.
Q_p	m^3/s	Flow rate at the end of the pumping/injection period.
Value type	-	Code for Q_p-value; -1 means Q_p<lower measurement limit, 0 means measured value, 1 means Q_p> upper measurement value of flowrate
Q-measl_L	m^3/s	Estimated lower measurement limit for flow rate
Q-measl_U	m^3/s	Estimated upper measurement limit for flow rate
V_p	m^3	Total volume pumped (positive) or injected (negative) water during the flow period.
t_p	s	Time for the flowing phase of the test
t_F	s	Time for the recovery phase of the test
h_i	m	Initial formation hydraulic head. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_p	m	Final hydraulic head at the end of the pumping/injection period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
h_F	m	Final hydraulic head at the end of the recovery period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m.
p_i	kPa	Initial formation pressure.
p_p	kPa	Final pressure at the end of the pumping/injection period.
p_F	kPa	Final pressure at the end of the recovery period.
Te_w	gr C	Fluid temperature in the test section representative for the evaluated parameters
EC_w	mS/m	Electrical conductivity of the fluid in the test section representative for the evaluated parameters
TDS_w	mg/L	Total salinity of the fluid in formation at test section based on EC.
TDS_{wn}	mg/L	Total salinity of the fluid in formation at test section based on water sampling and chemical analysis.
Sec.type,	(-)	Test section (pumping or injection) is labeled 1 and all observation sections are labeled 2
Q/s	m2/s	Specific capacity, based on Qp and s=abs(pi-pp). Only given for test section (label 1) in interference test.
T_Q	m2/s	Transmissivity based on specific capacity and a a function for T=f(Q/s). The fuction used should be refered in "Comments"
T_M	m2/s	Transmissivity based on Moye (1967)
b	m	Interpreted formation thickness representative for evaluated T ot TB.
B	m	Interpreted witdth of a formation with evaluated TB
TB	m3/s	1D model for evaluation of formation properties. T=transmissivity, B=width of formation

TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or less than TB-measlim
TB-measl-L	m2/s	Estimated measurement limit for evaluated TB. If estimated TB equals TB-measlim in the table actual TB is considered to be equal or greater than TB-measlim
SB	m	1D model for evaluation of formation properties. S= Storativity, B=width of formation
SB*	m	1D model for evaluation of formation properties. Assumed SB. S= Storativity, B=width of formation
L_f	m	1D model for evaluation of Leakage factor
T_T	m2/s	2D model for evaluation of formation properties. T=transmissivity
T-measl-L	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or less than T-measlim
T-measl-U	m2/s	Estimated measurement limit for evaluated T (TT, TQ, TM). If estimated T equals T-measlim in the table actual T is considered to be equal or grater than T-measlim
S	(-)	2D model for evaluation of formation properties. S= Storativity
S*	(-)	2D model for evaluation of formation properties. Assumed S. S= Storativity
K´/b´	(1/s)	2D model for evaluation of leakage coefficient. K´= hydraulic conductivity in direction of leaking flow for the aquitard, b´= Saturated thickness of aquitard (leaking formation)
K_S	m/s	3D model for evaluation of formation properties. K=Hydraulic conductivity
K_S-measl-L	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or less than KS-measlim
K_S-measl-U	m/s	Estimated measurement limit for evaluated KS. If estimated KS equals KS-measlim in the table actual KS is considered to be equal or greater than KS-measlim
S_S	1/m	3D model for evaluation of formation properties. Ss=Specific Storage
S_S*	1/m	3D model for evaluation of formation properties. Assumed Ss. Ss=Specific Storage
L_p	m	Hydraulic point of appication, based on hydraulic conductivity distribution (if available) or the midpoint of the borehole test section
C	(m3/Pa)	Wellbore storage coefficient
C_D	(-)	Dimensionless wellbore storage coefficient
ξ	(-)	Skin factor
ω	(-)	Storativity ratio
λ	(-)	Interporosity flow coefficient
dt_1	s	Estimated start time after pump/injection start OR recovery start, for the period used for the evaluated parameter
dt_2	s	Estimated stop time after pump/injection start OR recovery start, for the period used for the evaluated parameter
Borehole secup	m	Length coordinate along the borehole for the upper limit of the observation section
Borehole seclow	m	Length coordinate along the borehole for the lower limit of the observation section
p_{ai}	kPa	Initial formation pressure of the observation section, which is located above the test section in the borehole
p_{ap}	kPa	Final pressure at the end of the pumping/injection period in the observation section, which is located above the test section in the borehole
p_{aF}	kPa	Final pressure at the end of the recovery period in the observation section, which is located above the test section in the borehole
p_{bi}	kPa	Initial formation pressure of the observation section, which is located below the test section in the borehole
p_{bp}	kPa	Final pressure at the end of the pumping/injection period in the observation section, which is located below the test section in the borehole
p_{bF}	kPa	Final pressure at the end of the recovery period in the observation section, which is located below the test section in the borehole
References		SKB report No for reports describing data and evaluation

B. Result table from the interference tests at Drillsite 1 at Forsmark site investigation for submission to the Sicada database

INTERFERENCE TESTS - OBSERVATION SECTIONS: plu_inf_test_obs_general data

ID Obs. Borehole	Borehole secup (m)	Borehole seclow (m)	Test type (1-7)	Formation type (-)	ID Pumped Borehole	Test secup	Test seclow	Date and time for test, start YY-MM-DD hh:mm	Date and time for test, stop YY-MM-DD hh:mm	Date and time for flow, start hh:mm:ss	Date and time for flow, stop hh:mm:ss	Lp (m)	r_s (m)	r_t (m)	dt_L (s)
HFM02	25.40	100.00	2	1	HFM01	31.93	200.20	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00	43	220.7		360
HFM03	13.10	26.00	2	1	HFM01	31.93	200.20	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00	21	219.6		720
SFM0001		5.50	2	2	HFM01	31.93	200.20	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00		189.3		
SFM0002		5.70	2	2	HFM01	31.93	200.20	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00		122.8		
SFM0003		11.00	2	2	HFM01	31.93	200.20	20020625 10:25	20020626 00:30	20020625 10:25:01	20020626 00:30:00		50.6		
HFM01	31.93	200.20	2	1	HFM02	25.40	100.00	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00	42.5	220.7		300
HFM03	13.10	26.00	2	1	HFM02	25.40	100.00	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00	21	22.3		400
SFM0001		5.50	2	2	HFM02	25.40	100.00	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00		143.1		
SFM0002		5.70	2	2	HFM02	25.40	100.00	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00		118.6		
SFM0003		11.00	2	2	HFM02	25.40	100.00	20020626 10:40	20020627 06:00	20020626 10:40:00	20020627 06:00:00		225.2		

cont.

h_i (m)	h_p (m)	h_F m)	p_i (kPa)	p_p (kPa)	p_F (kPa)	Te_o (°C)	EC_o (mS/m)	TDS_o (mg/ L)	TDS_{om} (mg/ L)	Reference	Comments (-)
0.87	0.42	0.70								P-03-35	
0.95	0.53	0.79								P-03-35	
0.70										P-03-35	
1.49										P-03-35	
1.45										P-03-35	
0.72	0.15	0.60								P-03-35	
0.92	0.16									P-03-35	
0.71	0.66									P-03-35	
1.49	1.45									P-03-35	
1.45	1.40									P-03-35	

INTERFERENCE TESTS - OBSERVATION SECTIONS: plu_inf_test_obs_evaluated data

ID Obs. Borehole	Borehole secup (m)	Borehole seclow (m)	Date and time for test, start YY-MM-DD hh:mm	Date and time for test, stop YY-MM-DD hh:mm	ID Pumped Borehole	Test secup	Test seclow	b (m)	B (m)	TB_o (1D) (m^3/s)	TB-measl-L (1D) (m^3/s)	TB-measl-U (1D) (m^3/s)	SB_o (1D) (m)	L_{f0} (1D) (m)	T_o (2D) (m^2/s)	T-measl-L (2D) (m^2/s)	T-measl-U (2D) (m^2/s)	S_o (2D) (-)
HFM02	25.40	100.00	20020625 10:25	20020626 00:30	HFM01	31.93	200.20	74.6							5.26E-04	2.00E-06	2.00E-03	5.10E-05
HFM03	13.10	26.00	20020625 10:25	20020626 00:30	HFM01	31.93	200.20	12.9							5.26E-04	2.00E-06	2.00E-03	5.89E-05
SFM0001		5.50	20020625 10:25	20020626 00:30	HFM01	31.93	200.20											
SFM0002		5.70	20020625 10:25	20020626 00:30	HFM01	31.93	200.20											
SFM0003		11.00	20020625 10:25	20020626 00:30	HFM01	31.93	200.20											
HFM01	31.93	200.20	20020626 10:40	20020627 06:00	HFM02	25.40	100.00	168.27							5.31E-04	2.00E-06	2.00E-03	6.33E-05
HFM03	13.10	26.00	20020626 10:40	20020627 06:00	HFM02	25.40	100.00	12.9							4.87E-04	2.00E-06	2.00E-03	
SFM0001		5.50	20020626 10:40	20020627 06:00	HFM02	25.40	100.00											
SFM0002		5.70	20020626 10:40	20020627 06:00	HFM02	25.40	100.00											
SFM0003		11.00	20020626 10:40	20020627 06:00	HFM02	25.40	100.00											

cont.

K'/b'_o (2D) (1/s)	K_{so} (3D) (m/s)	K_S-measl-L (3D) (m/s)	K_S-measl-U (3D) (m/s)	S_{so} (3D) (1/m)	t_1 or dt_1 (s)	t_2 or dt_2 (s)	Comments (-)
					9000	21960	
					9000	21960	
					9000	22200	
					9000	22200	

SICADA - description of plu_inf_test_obs

PLU interference tests, Observation section data

Header	Unit	Explanation
ID Obs Borehole	(-)	ID for observation borehole
Borehole secup	m	Length coordinate along the borehole for the upper limit of observation section
Borehole seclow	m	Length coordinate along the borehole for the lower limit of observation section
Test type (1- 7)	(-)	1A: Pumping test - wireline eq., 1B:Pumping test-submersible pump, 1C: Pumping test-airlift pumping, 2: Interference test, 3: Injection test, 4: Slug test, 5A: Difference flow logging-PFL-DIFF-sequential, 5B: Difference flow logging-PFL-DIFF-overlapping, 6: Flow logging Impeller, 7: Grain size analysis
Formation type	(-)	1: Rock, 2:Soil (superficial deposits)
ID Pumped Borehole	(-)	ID for pumped or injected borehole
Test secup	m	Length coordinate along the borehole for the upper limit of pumped or injected section
Test seclow	m	Length coordinate along the borehole for the lower limit of pumped or injected section
Date and time for test, start		Date and time for start of the pumping/injection test (YYYY-MM-DD hh:mm)
Date and time for test, stop		Date and time for stop of the pumping/injection test (YYYY-MM-DD hh:mm)
Date and time for flow, start		Date and time for start of the flow/injection period (YYYY-MM-DD hh:mm:ss)
Date and time for flow, stop		Date and time for stop of the flow/injection period (YYYY-MM-DD hh:mm:ss)
L_p	m	Hydraulic point of application. Based on the hydraulic conductivity distribution (if available) or the midpoint of the borehole section
r_s	m	Radial distance from point of application of T (or K)-distribution (or mid-point) of test section to point of applicationT(or K)-distribution (or mid-point) of observation section
r_t	m	Shortest distance from point of application of T (or K)-distribution (or mid-point) of test section to point of applicationT(or K)-distribution (or mid-point) of observation section via interptered major conductive features. In the "Comments" the Model version X.Y used should be reported
dt_L	s	Time lag for pressure response to reach observation well after start/stop of flow/injection
h_i	m	Initial formation hydraulic head. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m
h_p	m	Final hydraulic head at the end of the pumping/injection period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m
h_F	m	Final hydraulic head at the end of the recovery period. Measured as water level in open stand pipes from borehole section with reference level in the local coordinates system with z=0 m
p_i	kPa	Initial formation pressure
p_p	kPa	Final pressure at the end of the flow/injection period

p_F	kPa	Final pressure at the end of the recovery period
Te_o	gr C	Fluid temperature in formation at obsevation section
EC_o	mS/m	Electrical conductivity of the fluid in formation at observation section
TDS_o	mg/L	Total salinity of the fluid in formation at observation section based on EC
TDS_{om}	mg/L	Total salinity of the fluid in formation at observation section based on water sample and chemical analysis
b	m	Interpreted formation thickness or section length representative for evaluated T
B	m	Interpreted witdth of a formation for evaluated TB
TB_o	m^3/s	Based on 1D model for evaluation of formation properties. T=transmissivity, B=width of formation
TB-measl-L	m^2/s	Estimated lower measurement limit for evaluated TB. If estimated TB_0 equals TB-measlim-L in the table the actual TB_o is considered to be equal or less than TB-measlim-L
TB-measl-U	m^2/s	Estimated upper measurement limit for evaluated TB. If estimated TB_0 equals TB-measlim-U in the table the actual TB_o is considered to be equal or greater than TB-measlim-U
SB_o	m	Based on 1D model for evaluation of formation properties. S= Storativity, B=width of formation
L_{fo}	m	Leakage factor based on 1D model for evaluation of the leakage factor
T_o	m^2/s	Transmissivity based on 2D model for evaluation of formation properties. T_o denotes transmissivity evaluated from observation borehole
T-measl-L	m^2/s	Estimated lower measurement limit for evaluated T_o. If estimated T_o equals T-measlim-L in the table the actual T_o is considered to be equal or less than T-measlim-L
T-measl-U	m^2/s	Estimated upper measurement limit for evaluated T_o. If estimated T_o equals T-measlim-U in the table the actual T_o is considered to be equal or greater than T-measlim-U
S_o	(-)	Storativity based on 2D model for evaluation of formation properties. S_o denotes storativity evaluated from observation borehole
K'/b'_0	s^{-1}	Leakage coefficient based on 2D model. K´= hydraulic conductivity in direction of leaking flow for the aquitard, b´= saturated thickness of aquitard (leaky formation). K'/b'_0 denotes leakage coefficient evaluated from observation borehole
K_{S0}	m/s	Hydraulic conductivity based on 3D model for evaluation of formation properties
K_S-measl-L	m/s	Estimated lower measurement limit for evaluated K_S. If estimated K_S equals K_S-measlim-L in the table the actual K_S is considered to be equal or less than K_S-measlim-L
K_S-measl-U	m/s	Estimated upper measurement limit for evaluated K_S. If estimated K_S equals K_S-measlim-U in the table the actual K_S is considered to be equal or greater than K_S-measlim-U
S_{S0}	m^{-1}	Specific storage based on 3D model for evaluation of formation properties
dt_1	s	Estimated start time after start of flow/injection OR after start of recovery for the time interval used for the evaluated parameter by the analysis
dt_2	s	Estimated stop time after start of flow/injection OR after start of recovery for the time interval used for the evaluated parameter by the analysis
References		SKB report No for reports describing data and evaluation
Comments		Short comment to the evaluated parameters (Optional)

Index o — Observation borehole or observation section (o short for observation)