Report
P-19-05
August 2019

Pumping tests, flow logging and water sampling in boreholes HFM42–HFM46

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SVENSK KÄRNBRÄNSLEHANTERING

ISSN 1651-4416
SKB P-19-05
ID 1673371
August 2019

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

Abstract

SKB conducts bedrock investigations as a preparation for the planned spent fuel repository in Forsmark. The repository plant consists of an underground and an above-ground part and is designed for the disposal of 6000 canisters of spent nuclear fuel from our Swedish nuclear power plants. The major part of the above-ground facility is located in an operating area south of the power plants. The underground parts consist of a central area and a repository area, connections to the main part through hoist and ventilation shafts, and a ramp for vehicle transport.

The purpose of the construction preparatory investigations is to provide a basis for decisions on location, and to determine conditions for foundation of the operating area's buildings and infrastructure, shafts and ramp.

In this area five boreholes were percussion drilled, HFM42 to HFM46, with a length of 200 m each. HFM43 to HFM46 were drilled in purpose to conduct hydraulic tests to examine the hydraulic properties in Singö deformation zone and zone ZFMENE0159A. The fifth borehole, HFM42, is mainly planned to be used for seismic investigations.

The main purpose of the pumping test with flow logging and water sampling was to target the dominating fractures in each borehole to be used in the subsequent interference tests. The pumping conducted prior to the flow logging also gave the hydraulic transmissivity for each borehole and were evaluated both stationary and transient. During the pumping, water samples were collected for analysis of the water chemistry characteristics of the boreholes.

In HFM42 the total transmissivity of the borehole was estimated to 9.3×10^{-4} m^2/s (stationary) and 6.8×10^{-4} m^2/s (transient). Two dominating fractures were found, one at about a length of 90 m and one at about 158 m.

In HFM43 the total transmissivity of the borehole was estimated to 1.5×10^{-3} m^2/s (stationary) and 8.7×10^{-4} m^2/s (transient). One largely dominating fracture was found at about a length of 106 m.

In HFM44 the total transmissivity of the borehole was estimated to 4.2×10^{-4} m^2/s (stationary). Three dominating fractures were found, one at about a length of 50 m, the largest one at about 72 m and one at about 123 m.

In HFM45 the total transmissivity of the borehole was estimated to 2.0×10^{-4} m^2/s (stationary) and 2.9×10^{-5} m^2/s (transient). Two dominating fractures were found, one at about a length of 73 m, one at 184 m and one at about 158 m. A part of the inflow is entering below the deepest measuring level, which was 195 m, and about 2 L/min of the total 38 L/min is entering the borehole above a length of 18 m.

In HFM46 the total transmissivity of the borehole was estimated to 1.8×10^{-4} m^2/s (stationary) and 8.5×10^{-5} m^2/s (transient). One dominating fracture was found at about length of 122 m. A part of the inflow is entering below the deepest measuring level, which was 186 m, and about 5 L/min of the total 46 L/min is entering the borehole above a length of 15.5 m.

Sammanfattning

SKB genomför förberedande undersökningar inför det planerade kärnbränsleförvaret i Forsmark. Förvaret kommer att bestå av en undermarksdel och en ovanmarksdel och dimensionerat fördeponering av 6 000 kapslar använt kärnbränsle från våra svenska kärnkraftverk. Huvuddelarna av ovanmarksdelen är samlat i ett driftsområde. Undermarksdelen består av ett centralområde och ett förvarsområde, förbindelser till ovanmarksdelen i form av schakt för hissar och ventilation, och en ramp för fordonstransporter.

Syftet med de byggförberedande undersökningarna är att ge underlag för beslut om placering av, samt grundläggningsförutsättningar för driftområdets byggnader och infrastruktur, schakt och ramp.

I detta område har SKB borrat fem hål, HFM42 till HFM46, med ett djup av ungefär 200 m vardera. HFM43 till HFM46 borras med syfte att genomföra hydrauliska prov för att undersöka de hydrauliska egenskaperna i Singö-zonen och zonen ZFMENE0159A. Det femte borrhålet, HFM42, är huvudsakligen planerat att användas för seismiska undersökningar.

Huvudsyftet med dessa hydrauliska tester var att lokalisera de dominerande hydrauliska strukturerna i varje borrhål, vilka sedan ska användas för att användas för utförande av interferenstester. Pumpningen som utfördes vid flödesloggningen gav också den hydrauliska transmissiviteten för varje borrhål, vilken utvärderades både stationärt och transient med hjälp av mjukvaran AQTESOLV. Under pumpningen togs även vattenprover för analys av de vattenkemiska egenskaperna i borrhålen.

I HFM42 beräknades borrhålets totala transmissivitet till $9{,}3 \times 10^{-4}$ m^2/s (stationärt) och 6.8×10^{-4} m^2/s (transient). Två dominerande sprickor hittades, en på ca 90 m djup och en på ca 158 m.

I HFM43 beräknades den totala transmissiviteten i borrhålet till $1{,}5 \times 10^{-3}$ m^2/s (stationärt) och 8.7×10^{-4} m^2/s (transient). En stor dominerande spricka hittades på ca 106 m djup.

I HFM44 beräknades den totala stationära transmissiviteten hos borrhålet till $4{,}2 \times 10^{-4}$ m^2/s under pumpning. Tre dominerande sprickor hittades i hålet, den största på ca 72 m djup, och två mindre på ca 50 m och ca 123 m.

I HFM45 beräknades borrhålets totala transmissivitet till $2{,}0 \times 10^{-4}$ m^2/s (stationärt) och 2.9×10^{-5} m^2/s (transient). Tre dominerande sprickor hittades, en på ca 73 m, en vid 184 m djup och en vid ca 158 m. En del av inflödet kommer under den djupast loggade nivån som var 195 m och ca 2 liter / min av det totala flödet på 38 L/min kommer in i borrhålet ovanför 18 m djup.

I HFM46 beräknades den totala transmissiviteten hos borrhålet till omkring $1{,}8 \times 10^{-4}$ m^2/s (stationärt) och 8.5×10^{-5} m^2/s (transient). En dominerande spricka hittades på ca 122 meter djup. En del av inflödet kommer in i hålet under den djupaste mätnivån som var 186 m, och ca 5 L/min av den totala 46 L/min kommer in i borrhålet över 15,5 m djup.

Contents

1 Introduction

SKB conducts bedrock investigations in Forsmark in the area were the spent fuel repository is planned to be located. It will consist of an underground part and an above-ground part and will be designed for the disposal of 6 000 canisters of spent nuclear fuel from our Swedish nuclear power plants.

The major part of the above-ground facility is located in an operating area south of the power plants next to Söderviken (see Figure 1-1). The underground part consists of a central area and a repository area, connections to the main part through hoist and ventilation shafts, and a ramp for vehicle transport.

The purpose of the construction preparatory investigations, which these investigations are a part of, is to provide a basis for decisions on location, and to determine conditions for foundation of the operating area's buildings and infrastructure, shafts and ramp.

This document reports the results of the hydraulic testing of the percussion-drilled boreholes HFM42, HFM43, HFM44, HFM45 and HFM46. Their locations can be seen in Figure 1-1 and these boreholes were drilled during spring 2018 (Nilsson 2018). The tests were carried out as a pumping test combined with flow logging using a spinner equipment. As a complement, a pumping test above a packer placed at the highest test position for the spinner, was also conducted in order to detect all major inflows in the boreholes. Water sampling was made three times in conjunction to the pumping of each borehole to get data of the water chemistry. No other hydraulic tests had been carried out in the actual boreholes before this campaign.

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

Figure 1-1. *The investigated boreholes in red. Upper picture is from Söderviken and the lower is over the SFR area.*

The work was carried out in accordance to SKB internal controlling documents; see Table 1-1. Data and results were delivered to the SKB site characterization database SICADA, where they are traceable by the Activity Plan number.

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

Activity Plan	Number	Version
Hydrotester och vattenprovtagning i hammarborrhål HFM42–HFM46	AP SFK-18-013	1.0
Method documents	**Number**	**Version**
Metodbeskrivning för hydrauliska enhålspumptester	SKB MD 321.003	1.0
Metodbeskrivning för flödesloggning	SKB MD 322.009	1.0
Metodbeskrivning för hydrauliska injektionstester	SKB MD 323.001	
Instruktion för analys av injektions- och enhålspumptester	SKB MD 320.004	1.0
Mätsystembeskrivning för HydroTestutrustning för HammarBorrhål. HTHB	SKB MD 326.001	3.0

2 Objective

The objective of the pumping tests, water sampling and flow logging in boreholes HFM42 to HFM46 was to investigate the hydraulic properties of the aquifer, and to identify the position and hydraulic character of major inflows. These data will then be the basis for the design of interference tests performed in boreholes HFM43 to HFM46 to examine the hydraulic properties of the Singö-deformation zone and zone ZFMENE0159A. Borehole HFM42 will be used for seismic investigations and prior to that measured to get hydraulic data before other installations.

Furthermore, another aim was to collect water samples to investigate the hydrochemical properties of the groundwater.

3 Scope

3.1 Boreholes tested

Technical data of the boreholes tested are displayed in Table 3-1. The reference point in the boreholes is always top of casing (ToC). The Swedish National coordinate system (RT90 2.5 gon W) is used in the x-y-plane together with RHB70 in the z-direction. Northing and Easting refer to the top of the boreholes at top of casing. The borehole diameter in Table 3-1, measured as the diameter of the drill bit, refers to the initial diameter just below the casing. The borehole diameter decreases along the borehole due to wearing of the drill bit.

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

Borehole								Casing		Drilling finished
ID	Elevation of top of casing (ToC) (m.a.s.l.)	Borehole length from ToC (m)	Bh-diam. (below casing) (m)	Inclin. -top of bh (from horizontal plane) (°)	Dip-Direction -top of bh (°)	Northing (m)	Easting (m)	Length (m)	Inner diam. (m)	Date (YYYY-MM-DD)
HFM42	4.21	195.30	0.1407	−89.12	173.28	6700137	1631076	6.03	0.1583	2018-04-11
HFM43	4.33	200.00	0.1407	−85.21	301.88	6700256	1631043	6.03	0.1603	2018-04-23
HFM44	2.94	199.6	0.1405	−85.60	250	6699322	161395	9.03	0.1603	2018-04-26
HFM45	3.86	200.00	0.1405	−85.5	285	6699603	161117	6.28	0.1603	2018-05-04
HFM46	1.70	200.00	0.1408	−85.8	90	6699951	161325	6.03	0.1603	2018-04-08

3.2 Tests performed

The tests in the boreholes were all conducted in open borehole with a submersible pump spinner logger. The depths from which the borehole was flow logged, as well as the test periods, pumped flow and drawdown are presented in Table 3-2. In all but one borehole the upper part of the borehole, which was not flow logged with the spinner, was pumped above a packer to locate any inflow above that point. Results from these pumping's are given in Table 3-2.

Table 3-2. Borehole tests performed.

Bh ID	Test section flow logged (m)	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)	Pumped flow (L/min)	Drawdown (m)	Pumped flow above packer (L/min)
HFM42	14–195.3	2018-05-03 08:45	2018-05-03 15:30	45	1.1	0
HFM43	11.5–200	2018-05-03 15:57	2018-05-04 15:56	140	2.1	-
HFM44	18–199.6	2018-05-22 12:35	2018-05-22 19:03	102.5	5.4	0
HFM45	18–200	2018-05-25 10:11	2018-05-25 19:27	38	4.2	2
HFM46	15.5–200	2018-05-23 13:00	2018-05-24 17:25	46	5.6	5

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

Data for the boreholes HFM42 to HFM46 is seen in Appendix 1.

During the pumping in the boreholes water samples were collected and submitted for analysis.

3.3 Equipment check

Prior to the tests, an equipment check was performed to establish the operating status of sensors and other equipment. A control of the calibration of the sensor for electric conductivity (EC) was made at the workshop using calibration standard and calibration constants were implemented. To check the function of the pressure sensor P1 (cf. Figure 4-1), the air pressure was recorded and found to be as expected. While lowering the pressure sensor into the borehole, measured pressure coincided well with the total head of water ($p/\rho g$). The temperature sensor displayed expected values in both air and water.

The equipment did malfunction during two tests, in HFM42 and HFM43 and no data for EC are available from these tests. Otherwise the EC displayed a zero value in air and expected values in borehole water. Temperature sensor did break during the test in HFM46 and was replaced before flow logging the borehole during pumping.

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

4 Description of equipment

4.1 Overview

Flow logging means identifying locations where water flows into or out of the borehole when pumping or injecting water. In these tests a submersible pump has been used to generate an upward flow in the boreholes. The drawdown and flow during pumping as well as position of the probe, spinner revolutions, temperature and electrical conductivity was measured and logged by a CR5000 logger.

Flow logging is performed as a relative measurement where pulses are generated by a spinning rotor (rotating propeller, Figure 4-1) placed in a test probe (measuring tube) which is designed to measure as much of the passing water volume as possible while being lowered. The probe is lowered in the borehole (applicable to pumping), in the opposite direction to the flow along the borehole, at an even speed of 3 m/min using an electric motor (see Figure 4-2). The rotational speed of the spinner is determined by the flow through the test probe. When passing a transmissive fracture with a flow of 0.5 L/min or more the rotation speed of the spinner decreases. Tests performed in laboratory shows that the linearity between the number of pulses per unit of time and the flow in different test tubes (corresponding to different diameter boreholes) is very good.

Temperature and electrical conductivity can vary in-between different fractures and these parameters can be of good help for determine the position of the fracture of interest. A description of the sensors used in the equipment can be found in Table 4-1.

Results in the form of flow and hydraulic transmissivity for individual anomalies are calculated, by weight, from total pump flow measured on the surface and estimated hydraulic transmissivity for the entire borehole. The pumping period has been evaluated as a single-hole pumping test with both stationary and transient method. The transient evaluation has been made with the AQTESOLV (2007) software, developed for various types of hydraulic tests.

The packer used is normally expanded by nitrogen gas or compressed air.

Figure 4–1. *The spinner used for logging of the flow (left) and probe with plastic guides (right). A rubber disk at the end of the probe can be changed for different diameters of the borehole (left in the box).*

Figure 4–2. Set-up, cable drum with electrical motor for lowering the probe and a measuring wheel for positioning the probe (left).

4.2 Measurement sensors

Technical data of the sensors used together with estimated data specifications of the test system for pumping tests and flow logging are given in Table 4-2.

Table 4-2. Technical data for sensors used during flow logging and pumping.

	Type	Range	Resolution	Inaccuracy
Pressure transducer	Druck PTX 161/D sg	1 000 kPa	0.04 kPa	± 0.25 % full scale (BSL)
Flow meter (surface)	Krohne Aquaflux 010K, DN40	0.75–750 L/min	-	± 0.225 % o. r. Q > 75 L/min*
Spinner (flow in borehole)	SEBA M1	-	0.2–0.5 L/min (76 mm bh-diam)	± 0.5 L/min**
Temperature	INOR	0–50 °C	0.002 °C	± 0.5 °C
Electrical conductivity	Aqua Troll 100	0–1 800 mS/m	0.03 mS/m	± 5 % o.r.
Position (depth)	Leine & Linde (pulsa signal)	-	3 mm	± 0.3 m, L < 100 m ± 0.5 m, L > 100 m

* Increasing to about 2.5 % o.r. at 7.5 L/min.
** Flow through spinner sond, not the flow out of borehole.

4.3 Evaluation

The tests were evaluated both stationary and transient and the transient evaluation was made using the software AQTESOLV. It is a software that offers a number of hydraulic models to simulate different types of aquifers and hydraulic situations.

In this case, a solution developed by Dougherty-Babu (Dougherty and Babu 1984) for pseudo-radial converging flow has been used in all cases. The solution takes into account wellbore storage and skin effects.

The stationary evaluation has been made with Moye's formula according to the following equations:

$$T_M = \frac{Q_p}{dh_p} \cdot C_M = \frac{Q_p}{s} \cdot C_M$$

$$C_M = \frac{1 + ln\left(\frac{L_W}{2r_W}\right)}{2\pi}$$

Q_p = flow rate by the end of the flow period (m^3/s)
C_M = geometrical shape factor (-)
r_w = borehole radius (m)
L_w = section length (m)
s = maximum drawdown ($dh_p = h_i - h_p$) (m)

For all boreholes except one, a transient evaluation was possible, and the results gives a lower value (Tt) of hydraulic transmissivity than the value (T_M) calculated with Moye's formula. This can be explained by the fact that the skin factor usually is negative in the transient evaluation, something that Moye's formula does not take into account. A negative skin factor means that the drawdown in the borehole is less than equivalent to the hydraulic transmissivity of the aquifer. In addition, Moye's formula assumes formal stationary conditions, which most often has not been reached when pumping is completed. Even the latter contributes to a high value with Moye's formula.

4.4 Test procedure

Before flow logging, a short pump test is normally conducted to determine how much flow to be used during pumping. The target is to get a sufficient drawdown to activate as much fractures as possible and this flow should ideally create about 10 meters of drawdown. A larger drawdown could activate more fractures but also result in a shorter part of the borehole getting flow logged.

The borehole is then normally flow logged during undisturbed condition to get a background value of the flow registered by the spinner during lowering. This background spin is then subtracted from the logging made during pumping. In this project three of the boreholes, HFM44–HFM46, were logged in full length before pumping. The other two were, due to lack of time, only logged for about 20 m to get a general background spin in the water column.

The spinner probe is then lifted and positioned. A submersible pump together with the pressure transducer is lowered to position above the spinner and then started. The pumping runs continuously until a relatively stationary drawdown is achieved, normally about 1.5–2 hours, before the borehole is flow logged during pumping.

When the flow logging is finished, the spinner is lifted out of the borehole together with the pump and a packer is mounted in the same upper position as the flow logging started. The pump is then lowered again and started. The target is then to get the same drawdown in this short section to see if there are any water inflow not logged by the spinner. The pump and flow meter are not able to work with flows below 0.75 L/min and smaller inflows will not be registered in this part of the borehole.

No recovery period was logged and analyzed.

4.5 Water sampling and analysis

A series of water samples was collected in the percusssion drilled boreholes during pumping, one in the beginning of the pumping, a second in the middle and a third one just before end of pumping in each borehole. The samples were collected in order to contribute to area coverage of the hydro-chemical data from shallow part of bedrock.

The sampling and analysis were preformed according to the SKB class IIb, cc h procedure with an addition of TOC (total organic carbon) and DOC (dissolved organic carbon) analysis.

Three nonconformities from the planned sampling and analysis programme occurred, listed below.

- No field temperature was measured for samples collected in HFM42.
- The first sample in borehole HFM42 has a non-acceptable charge balance error, 11 %.
- The second and third sample in borehole HFM45 has only field measurements of pH and electric conductivity and has no analysis for alkalinity. They were sampled late on a Friday and the laboratory was closed.

The analytical data is compiled in Table 4-3 to 4-6.

Table 4-3. Compilation of isotope data from water sampling conducted during pumping test in five percussion boreholes.

Idcode	Start date (yyyy-mm-dd hh:mm)	Stop date (yyyy-mm-dd hh:mm)	Section (m)	Sample no	dD (devSMOW)	Tr TU	$d^{18}O$ (devSMOW)
HFM42	2018-05-03 11:10	2018-05-03 11:30	6.03–195.30	31301	−75.8	2.4	−10.05
HFM42	2018-05-03 12:51	2018-05-03 13:01	6.03–195.30	31302	−71.7	2.3	−9.64
HFM42	2018-05-03 14:27	2018-05-03 14:47	6.03–195.30	31303	−71.4	1.8	−9.73
HFM43	2018-05-04 09:48	2018-05-04 10:08	6.03–200.00	31298	−75.7	4.3	−10.06
HFM43	2018-05-04 11:50	2018-05-04 12:10	6.03–200.00	31299	−74.7	1.8	−9.80
HFM43	2018-05-04 13:30	2018-05-04 13:50	6.03–200.00	31300	−74.5	1.8	−9.74
HFM44	2018-05-22 14:40	2018-05-22 15:00	9.03–199.60	31304	−68.1	3.5	−8.87
HFM44	2018-05-22 16:35	2018-05-22 16:55	9.03–199.60	31305	−66.5	4.1	−8.85
HFM44	2018-05-22 18:08	2018-05-22 18:28	9.03–199.60	31306	−66.6	5.1	−8.88
HFM45	2018-05-25 14:20	2018-05-25 14:40	6.28–200.30	31310	−67.2	6.1	−8.87
HFM45	2018-05-25 16:00	2018-05-25 16:20	6.28–200.30	31311	−73.9	4.0	−9.71
HFM45	2018-05-25 17:30	2018-05-25 17:50	6.28–200.30	31312	−73.9	3.3	−9.87
HFM46	2018-05-24 11:25	2018-05-24 11:45	6.03–200.00	31307	−73.3	1.7	−9.86
HFM46	2018-05-24 13:20	2018-05-24 13:40	6.03–200.00	31308	−71.5	1.3	−9.66
HFM46	2018-05-24 14:20	2018-05-24 14:40	6.03–200.00	31309	−70.9	1.9	−9.30

Table 4-4. Compilation of analysis of trace elements from water sampling conducted during pumpingtest in five percussion boreholes.

Idcode	Start date (yyyy-mm-dd hh:mm)	Stop date (yyyy-mm-dd hh:mm)	Sektion (m)	Sample no	Al (µg/L)	Ba (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Co (µg/L)	Hg (µg/L)	Mo (µg/L)	Ni (µg/L)	Pb (µg/L)	V (µg/L)	Zn (µg/L)
HFM42	2018-05-03 11:10	2018-05-03 11:30	6.03-195.30	31301	427	62.0	0.0897	1.11	18.4	0.315	< 0.002	9.70	1.11	3.07	1.50	44.6
HFM42	2018-05-03 12:51	2018-05-03 13:01	6.03-195.30	31302	19.2	41.7	0.0699	0.237	2.11	0.0693	< 0.002	8.08	0.521	0.315	0.358	11.1
HFM42	2018-05-03 14:27	2018-05-03 14:47	6.03-195.30	31303	40.5	39.5	< 0.02	0.248	2.09	0.0446	< 0.002	7.67	0.218	0.571	0.522	5.15
HFM43	2018-05-04 09:48	2018-05-04 10:08	6.03-200.00	31298	28.0	50.9	0.377	0.593	0.842	0.116	< 0.002	9.85	0.878	0.835	0.550	8.47
HFM43	2018-05-04 11:50	2018-05-04 12:10	6.03-200.00	31299	3.57	42.3	< 0.02	0.193	< 0.2	0.0519	< 0.002	9.84	0.273	0.366	0.605	1.92
HFM43	2018-05-04 13:30	2018-05-04 13:50	6.03-200.00	31300	12.8	42.3	< 0.02	0.356	0.560	0.0722	< 0.002	9.14	< 0.2	0.430	0.487	2.21
HFM44	2018-05-22 14:40	2018-05-22 15:00	9.03-199.60	31304	3.15	57.6	0.0350	0.193	< 0.2	0.147	< 0.002	44.0	0.413	0.217	0.391	4.28
HFM44	2018-05-22 16:35	2018-05-22 16:55	9.03-199.60	31305	2.88	52.4	0.0238	0.168	< 0.2	0.107	< 0.002	29.2	0.331	0.169	0.308	2.88
HFM44	2018-05-22 18:08	2018-05-22 18:28	9.03-199.60	31306	2.48	53.1	< 0.02	0.177	0.206	0.110	< 0.002	23.6	0.209	0.150	0.315	2.46
HFM45	2018-05-25 14:20	2018-05-25 14:40	6.28-200.30	31310	3.43	79.5	0.394	0.0967	6.47	0.551	0.004	4.23	0.846	6.21	0.292	24.1
HFM45	2018-05-25 16:00	2018-05-25 16:20	6.28-200.30	31311	2.19	59.5	0.131	0.0848	0.513	0.295	< 0.002	5.47	0.251	0.280	0.194	11.8
HFM45	2018-05-25 17:30	2018-05-25 17:50	6.28-200.30	31312	1.58	64.9	0.0917	0.0863	0.654	0.346	< 0.002	6.86	0.396	0.526	0.173	8.74
HFM46	2018-05-24 11:25	2018-05-24 11:45	6.03-200.00	31307	2.63	69.6	0.285	0.224	0.621	0.188	< 0.002	6.02	1.67	0.204	0.651	36.0
HFM46	2018-05-24 13:20	2018-05-24 13:40	6.03-200.00	31308	3.35	52.2	0.230	0.110	1.05	0.0653	< 0.002	4.97	0.667	0.175	0.632	9.39
HFM46	2018-05-24 14:20	2018-05-24 14:40	6.03-200.00	31309	2.90	51.8	0.162	0.115	0.889	< 0.02	< 0.002	4.79	0.338	0.178	0.592	7.90

Table 4-5. Compilation of water analysis of major elements and components from water sampling conducted during pumping test in five percussion boreholes.

Idcode	Start date (yyyy-mm-dd hh:mm)	Stop date (yyyy-mm-dd hh:mm)	Sektion (m)	Sample no	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Alk. (mg/L)	Cl (mg/L)	SO_4 (mg/L)	SO4_S (mg/L)	Br (mg/L)
HFM42	2018-05-03 11:10	2018-05-03 11:30	6.03–195.30	31301	1 040	24.9	364	82.1	369.2	1 569	244.9	98.3	5.57
HFM42	2018-05-03 12:51	2018-05-03 13:01	6.03–195.30	31302	1 420	28.2	545	118	248.9	2 913	336.8	118	10.5
HFM42	2018-05-03 14:27	2018-05-03 14:47	6.03–195.30	31303	1 410	27.9	537	116	247.8	2 883	338.1	118	10.5
HFM43	2018-05-04 09:48	2018-05-04 10:08	6.03–200.00	31298	1 090	26.8	372	88.4	304.9	2 174	256.0	94.2	8.02
HFM43	2018-05-04 11:50	2018-05-04 12:10	6.03–200.00	31299	1 080	25.9	354	83.7	308.7	2 034	257.3	93.9	7.42
HFM43	2018-05-04 13:30	2018-05-04 13:50	6.03–200.00	31300	1 080	25.9	361	84.7	308.8	2 029	261.8	95.0	7.49
HFM44	2018-05-22 14:40	2018-05-22 15:00	9.03–199.60	31304	1 710	30.1	497	152	140.7	3 419	357.6	122	11.9
HFM44	2018-05-22 16:35	2018-05-22 16:55	9.03–199.60	31305	1 580	29.8	473	146	142.9	3 331	353.8	123	11.6
HFM44	2018-05-22 18:08	2018-05-22 18:28	9.03–199.60	31306	1 560	29.9	470	146	143.2	3 314	356.3	122	11.4
HFM45	2018-05-25 14:20	2018-05-25 14:40	6.28–200.30	31310	1 300	44.1	113	131	156.5	2 237	300.3	102	7.62
HFM45	2018-05-25 16:00	2018-05-25 16:20	6.28–200.30	31311	1 410	25.3	545	138	x	3 122	344.7	116	11.0
HFM45	2018-05-25 17:30	2018-05-25 17:50	6.28–200.30	31312	1 360	23.8	541	133	x	3 153	330.6	112	10.7
HFM46	2018-05-24 11:25	2018-05-24 11:45	6.03–200.00	31307	1 570	15.6	947	180	105.8	4 352	391.5	134	14.3
HFM46	2018-05-24 13:20	2018-05-24 13:40	6.03–200.00	31308	1 690	16.2	1 040	191	92.4	4 420	408.6	144	15.3
HFM46	2018-05-24 14:20	2018-05-24 14:40	6.03–200.00	31309	1 720	16.3	1 030	191	94.2	4 679	414.9	145	15.4

X: No result due to closed laboratory.
XX: Not analysed.

Table 4-5. Continued.

Idcode	Start date (yyyy-mm-dd hh:mm)	Stop date (yyyy-mm-dd hh:mm)	Sektion (m)	Sample no	I (mg/L)	Si (mg/L)	Fe (mg/L)	Mn (mg/L)	Li (mg/L)	Sr (mg/L)	P (mg/L)
HFM42	2018-05-03 11:10	2018-05-03 11:30	6.03–195.30	31301	1.74	7.23	2.53	0.535	0.0378	2.69	0.0192
HFM42	2018-05-03 12:51	2018-05-03 13:01	6.03–195.30	31302	1.53	6.38	1.61	0.755	0.0451	4.34	0.0104
HFM42	2018-05-03 14:27	2018-05-03 14:47	6.03–195.30	31303	1.56	6.42	1.85	0.745	0.0440	4.27	0.0076
HFM43	2018-05-04 09:48	2018-05-04 10:08	6.03–200.00	31298	1.33	6.49	1.14	0.568	0.0398	2.70	0.0142
HFM43	2018-05-04 11:50	2018-05-04 12:10	6.03–200.00	31299	1.52	6.63	1.13	0.544	0.0385	2.57	0.0078
HFM43	2018-05-04 13:30	2018-05-04 13:50	6.03–200.00	31300	1.50	6.61	1.25	0.554	0.0391	2.63	0.00897
HFM44	2018-05-22 14:40	2018-05-22 15:00	9.03–199.60	31304	1.11	6.39	1.38	0.924	0.0348	5.08	< 0.005
HFM44	2018-05-22 16:35	2018-05-22 16:55	9.03–199.60	31305	1.02	6.52	1.48	0.915	0.0375	4.60	0.00561
HFM44	2018-05-22 18:08	2018-05-22 18:28	9.03–199.60	31306	1.13	6.52	1.49	0.912	0.0367	4.59	0.00694
HFM45	2018-05-25 14:20	2018-05-25 14:40	6.28–200.30	31310	0.60	3.78	0.0287	0.284	0.0211	1.27	0.0924
HFM45	2018-05-25 16:00	2018-05-25 16:20	6.28–200.30	31311	0.94	4.30	1.18	1.49	0.0415	6.90	< 0.005
HFM45	2018-05-25 17:30	2018-05-25 17:50	6.28–200.30	31312	1.06	4.24	1.10	1.49	0.0398	6.94	< 0.005
HFM46	2018-05-24 11:25	2018-05-24 11:45	6.03–200.00	31307	0.90	4.99	0.191	1.47	0.0437	10.0	< 0.005
HFM46	2018-05-24 13:20	2018-05-24 13:40	6.03–200.00	31308	1.00	5.80	0.779	1.58	0.0456	10.8	< 0.005
HFM46	2018-05-24 14:20	2018-05-24 14:40	6.03–200.00	31309	0.90	6.00	0.945	1.61	0.0454	10.8	< 0.005

X: No result due to closed laboratory.
XX: Not analysed.

Table 4-5. Continued.

Idcode	Start date (yyyy-mm-dd hh:mm)	Stop date (yyyy-mm-dd hh:mm)	Section (m)	Sample no	pH_lab	pH_field	EC_lab (mS/m)	EC_field (mS/m)	Temp. (°C)	Uranine (µg/L)	TOC (mg/L)	DOC (mg/L)
HFM42	2018-05-03 11:10	2018-05-03 11:30	6.03–195.30	31301	7.51	7.18	469.0	232	xx	2.00	7.6	7.6
HFM42	2018-05-03 12:51	2018-05-03 13:01	6.03–195.30	31302	7.41	7.16	930.0	920	xx	2.80	4.6	4.7
HFM42	2018-05-03 14:27	2018-05-03 14:47	6.03–195.30	31303	7.40	7.37	927.0	911	xx	2.70	5.0	5.0
HFM43	2018-05-04 09:48	2018-05-04 10:08	6.03–200.00	31298	7.31	6.97	690.0	104	9.6	2.30	6.2	5.8
HFM43	2018-05-04 11:50	2018-05-04 12:10	6.03–200.00	31299	7.43	7.44	678.0	668	9.3	2.40	6.0	6.1
HFM43	2018-05-04 13:30	2018-05-04 13:50	6.03–200.00	31300	7.44	7.15	685.0	656	11.6	2.30	6.1	6.0
HFM44	2018-05-22 14:40	2018-05-22 15:00	9.03–199.60	31304	7.37	7.64	1 029.0	1 024	8.5	0.40	2.1	2.2
HFM44	2018-05-22 16:35	2018-05-22 16:55	9.03–199.60	31305	7.35	7.42	1 014.0	1 002	8.8	0.40	2.2	2.2
HFM44	2018-05-22 18:08	2018-05-22 18:28	9.03–199.60	31306	7.37	7.32	1 029.0	1 003	8.5	0.40	2.3	2.3
HFM45	2018-05-25 14:20	2018-05-25 14:40	6.28–200.30	31310	7.98	7.52	724.0	724	10.7	0.80	3.0	3.0
HFM45	2018-05-25 16:00	2018-05-25 16:20	6.28–200.30	31311	x	7.77	x	933	11.3	0.40	2.3	2.2
HFM45	2018-05-25 17:30	2018-05-25 17:50	6.28–200.30	31312	x	7.39	x	935	13.6	0.50	2.2	2.2
HFM46	2018-05-24 11:25	2018-05-24 11:45	6.03–200.00	31307	7.46	6.69	1 150.0	1 217	9.8	0.80	4.1	3.2
HFM46	2018-05-24 13:20	2018-05-24 13:40	6.03–200.00	31308	7.37	7.07	1 303.0	1 258	10.8	0.60	2.5	2.9
HFM46	2018-05-24 14:20	2018-05-24 14:40	6.03–200.00	31309	7.39	7.11	1 313.0	1 272	10.9	0.50	2.6	3.1

X: No result due to closed laboratory
XX: Not analysed

5 Results

5.1 Borehole HFM42

Borehole HFM42 was flow logged from 14 m depth from top of casing (TOC) and down to 191 m during pumping. The pump was positioned 3 m above the start of flow logging, at 11 m TOC. A plot of flow (spins logged) and temperature is presented in Figure 5-1. The probe for electrical conductivity was malfunctioning during this test, hence no data is available. After flow logging the part above 14 m was sealed off with a packer and then pumped to the same drawdown as in the open borehole, but no inflow was found between 6 and 14 m.

The total transmissivity in HFM42 was evaluated using data from the pumping test and both a stationary value according to Moye (T_M) as well as a transient value (Tt) result from the pumping test was estimated. The value for T_M was 9.3E−04 m^2/s and Tt was estimated to 6.8E−04 m^2/s according to the model Dougherty-Babu using AQTESOLV and the transient value was chosen as most representative for the borehole. A plot of pumped flow, pressure as well as the transient evaluation and estimated parameters in AQTESOLV is presented in Appendix 2, Figure A2-1 to A2-3.

The plot of the flow and temperature in Figure 5-1 gives a weighted distribution of the total flow and transmissivity to the detected anomalies and is presented in Table 5-1. The dominating fracture in HFM42 is located around 90–91 m below TOC and contributes to about 50 % of the total inflow which is supported by the temperature log. About 25 % of the flow occurs at around 157 m TOC and 25 % in the bottom below the lowest logged depth of the borehole.

Table 5-1. Results of the flow logging in borehole HFM42. Each interpreted fracture contribution to the total flow and transmissivity, both transient (Tt) and stationary (T_M) evaluated values.

Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m^2/s)	T_M (m^2/s)
1	190–195	10.0	1.5E−04	2.0E−04
2	157–158	11.0	1.6E−04	2.3E−04
3	90–91	24.7	3.7E−04	5.0E−04
∑Bh	0–195	45.7	**6.8E−04**	9.3E−04

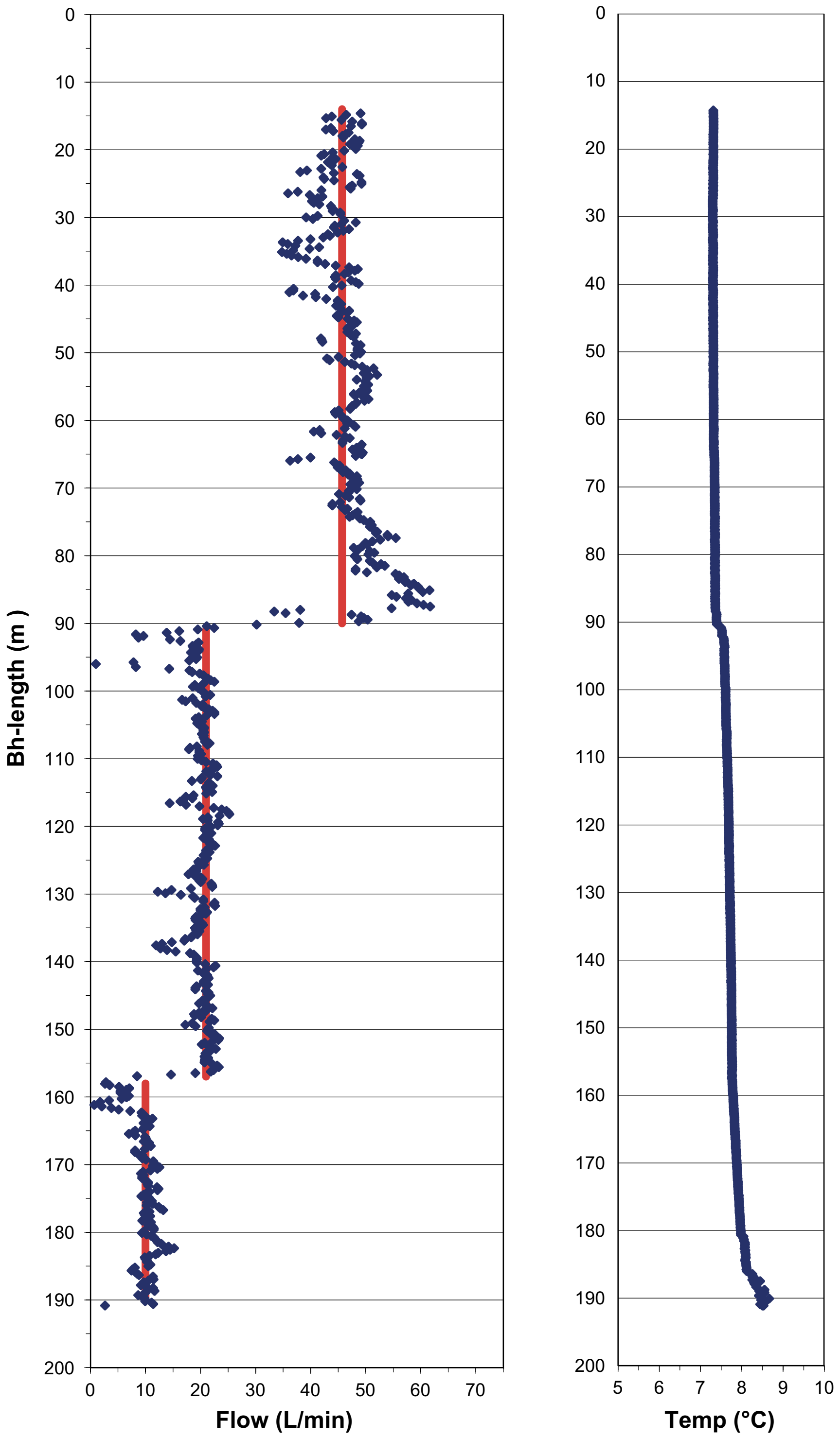


Figure 5-1. *Flow and temperature plotted against depth during logging of HFM42.*

5.2 Borehole HFM43

Borehole HFM43 was flow logged from 11.5 m depth from top of casing (TOC) and down to 195 m during pumping. The pump was positioned 2.5 m above the start position of flow logging, at 11.5 m TOC. A plot of flow (spins logged) and temperature is presented in Figure 5-2. The probe for electrical conductivity was malfunctioning during this test, hence no data is available. No pumping above upper flow logging position was conducted.

The total transmissivity in HFM43 was evaluated using data from the pumping test and both a stationary value according to Moye (T_M) as well as a transient value (Tt) result from the pumping test was estimated. The transient evaluation was somewhat complicated due to a decreasing flow during the test indicating different flow regimes in the vicinity of the borehole. The transient evaluation did however converge using multirate function in AQTESOLVE. The value for T_M was 1.5E−03 m^2/s and Tt was estimated to 8.7E−04 m^2/s according to the model Dougherty-Babu using AQTESOLV and the transient value was chosen as most representative for the borehole. A plot of pumped flow, pressure as well as the transient evaluation and estimated parameters in AQTESOLV is presented in Appendix 2, Figure A2-4 to A2-6.

The plot of the flow and temperature in Figure 5-2 gives a weighted distribution of the total flow and transmissivity to the detected anomalies and is presented in Table 5-2. The dominating fracture in HFM43 is located around 106–106.5 m below TOC and contributes to about 60 % of the total inflow. About 15 % of the total inflow appears to enter the borehole in the bottom part, 195–200 m TOC.

Table 5-2. Results of the flow logging in borehole HFM43. Each interpreted fracture contribution to the total flow and transmissivity, both transient (Tt) and stationary (T_M) evaluated values.

Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m^2/s)	T_M (m^2/s)
1	195–200	20.0	1.2E−04	2.1E−04
2	106–106.5	85.0	5.3E−04	9.0E−04
3	95–95.5	13.0	8.1E−05	1.4E-04
4	90–90.5	22.0	1.4E−04	2.3E−04
∑Bh	0–200	140.0	**8.7E−04**	1.5E−03

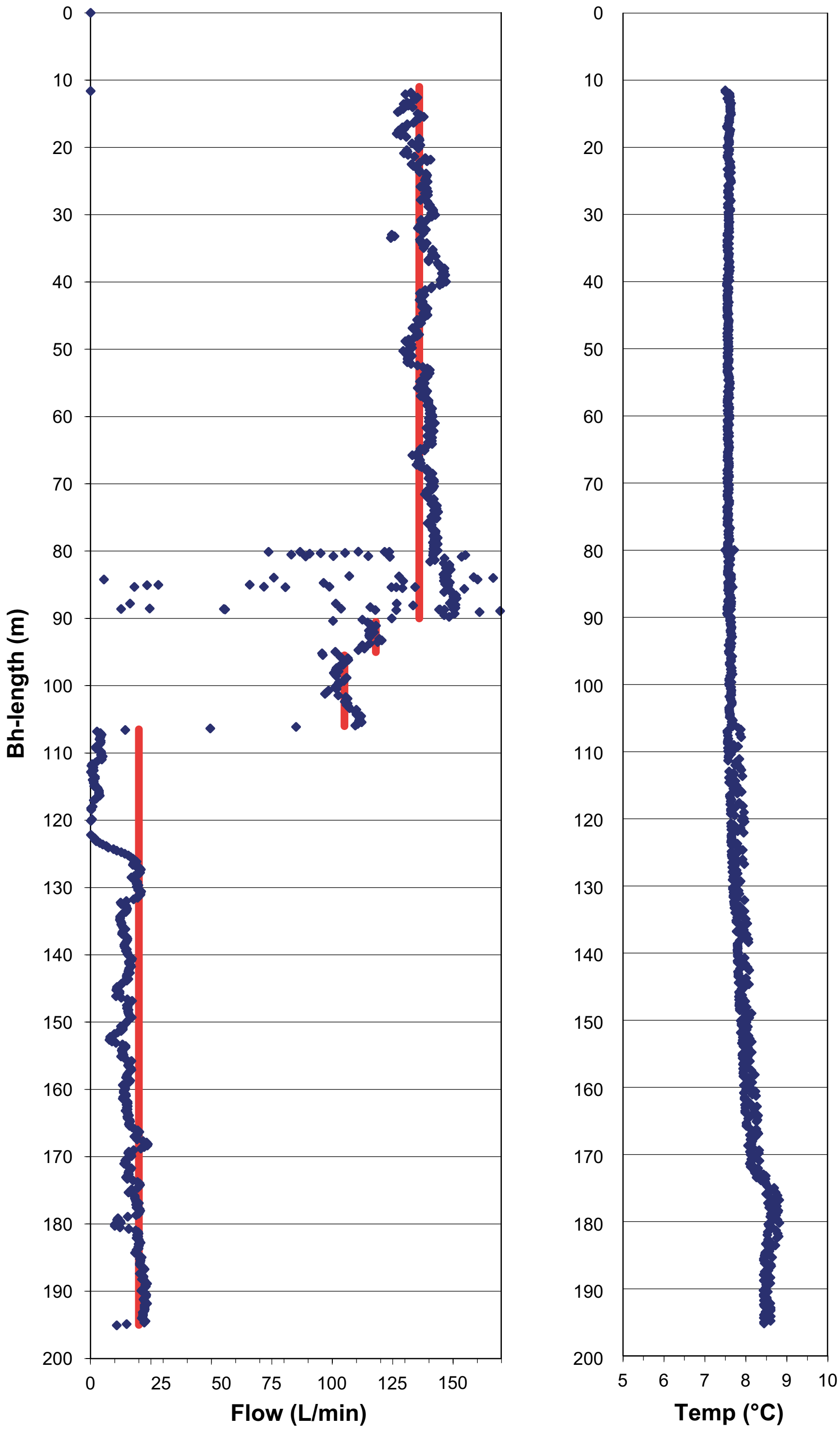


Figure 5-2. *Flow and temperature plotted against depth during logging of HFM43.*

5.3 Borehole HFM44

Borehole HFM44 was flow logged from 18 m depth from top of casing (TOC) and down to 195.1 m during pumping. The pump was positioned 4.5 m above the start position of flow logging, at 13.5 m TOC. A plot of flow (spins logged), electrical conductivity and temperature is presented in Figure 5-3. After flow logging, the part above 18 m was sealed off with a packer and then pumped to the same drawdown as in the open borehole, but no detectable inflow was found between 6 and 18 m. The pump test preceding the flow logging started at 245 L/min with a normal drawdown curve but after about 35 minutes the pressure dropped faster, and the flow had to be lowered in steps down to about 100 L/min indicating effects of a negative hydraulic boundary.

The total transmissivity in HFM44 was evaluated using data from the pumping test and both a stationary value according to Moye (T_M) as well as a transient value (Tt) result from the pumping test was estimated. The value for T_M was 4.2E−04 m^2/s and Tt was estimated to 8.7E−05 m^2/s according to the model Dougherty-Babu using AQTESOLV and the transient value was chosen as most representative for the borehole A plot of pumped flow, pressure as well as the transient evaluation and estimated parameters in AQTESOLV is presented in Appendix 2, Figure A2-7 to A2-9.

The plot of the flow and temperature in Figure 5-3 gives a weighted distribution of the total flow and transmissivity to the detected anomalies and is presented in Table 5-3. The dominating fracture in HFM44 is located around 73–73.5 m below TOC and contributes to about 70 % of the total inflow and one larger inflow was found at 50–50.5 m giving about 25 % of the total flow, the positions on these inflows are supported by the EC log. No detectable inflows were registered below 124 m as well as above 18 m TOC.

Table 5-3. Results of the flow logging in borehole HFM44. Each interpreted fracture contribution to the total flow and stationary transmissivity (T_M), no transient evaluation (Tt) was possible.

Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m^2/s)	T_M (m^2/s)
1	122.5–124	5.0	4.2E−06	2.0E−05
2	73-73.5	73.0	6.2E−05	3.0E−04
3	50–50.5	24.5	2.1E-05	9.9E−05
∑Bh	0–200	102.5	**8.7E−05**	4.2E−04

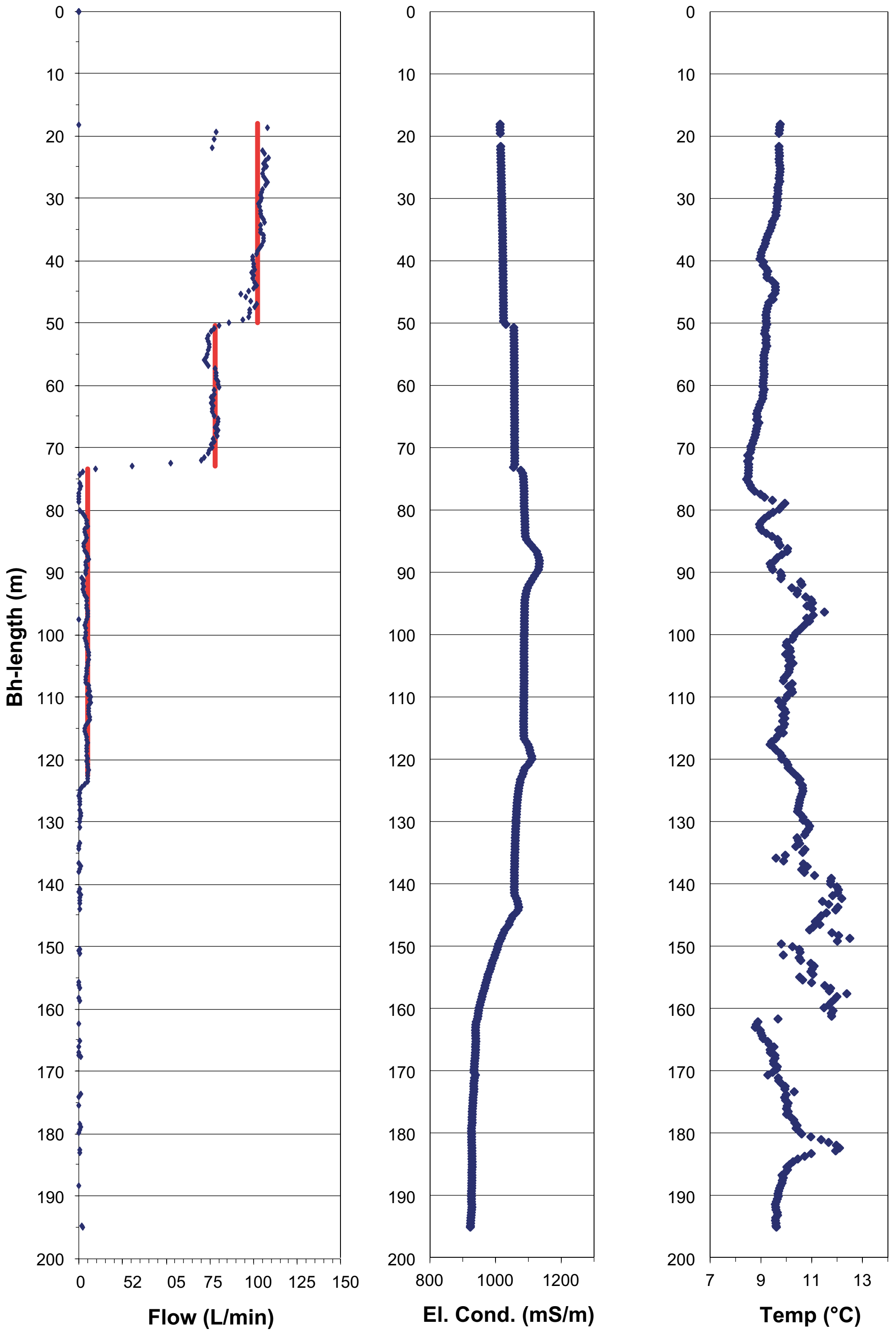


Figure 5-3. *Flow and temperature plotted against depth during logging of HFM44.*

5.4 Borehole HFM45

Borehole HFM45 was flow logged from 18 m depth from top of casing (TOC) and down to 195 m during pumping. The pump was positioned about 3.5 m above the start position of flow logging. A plot of flow (spins logged), electrical conductivity and temperature is presented in Figure 5-4. After flow logging, the part above 18 m was sealed off with a packer and then pumped to the same draw-down as in the open borehole and a total inflow of about 2 L/min was found between 6.3 and 18 m.

The total transmissivity in HFM45 was evaluated using data from the pumping test and both a stationary value according to Moye (T_M) as well as a transient value (Tt) result from the pumping test was estimated. The flow during pumping was increased several times during pumping making the transient evaluation a bit tricky, however the model converged. The value for T_M was 2.0E−04 m^2/s and Tt was estimated to 2.9E−05 m^2/s according to the model Dougherty-Babu using AQTESOLV and the transient value was chosen as most representative for the borehole... A plot of pumped flow, pressure as well as the transient evaluation and estimated parameters in AQTESOLV is presented in Appendix 2, Figure A2-10 to A2-12.

The plot of the flow and temperature in Figure 5-4 gives a weighted distribution of the total flow and transmissivity to the detected anomalies and is presented in Table 5-4. The dominating fracture in HFM45 appears to be in the bottom of the borehole between 195–200 m and this fracture contributes to about 65 % of the total flow. Three smaller fractures with a detectable flow was found at 183.5–184 m, 162.5–163 m and 73–74 m below TOC and between 6–18 m there is an inflow of about 2 L/min. The position of the inflows are supported by the EC log.

Tabell 5-4. Results of the flow logging in borehole HFM45. Each interpreted fracture contribution to the total flow and transmissivity, both transient (Tt) and stationary (T_M) evaluated values.

Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m^2/s)	T_M (m^2/s)
1	195–200	25.0	1.9E−05	1.3E−04
2	183.5–184	3.0	2.3E−06	1.6E-05
3	162.5–163	4.0	3.1E−06	2.1E−05
4	73–74	4.0	3.1E−06	2.1E−05
5	6–18	2.0	1.5E−06	1.0E−05
∑Bh	0–200	38.0	**2.9E−05**	2.0E−04

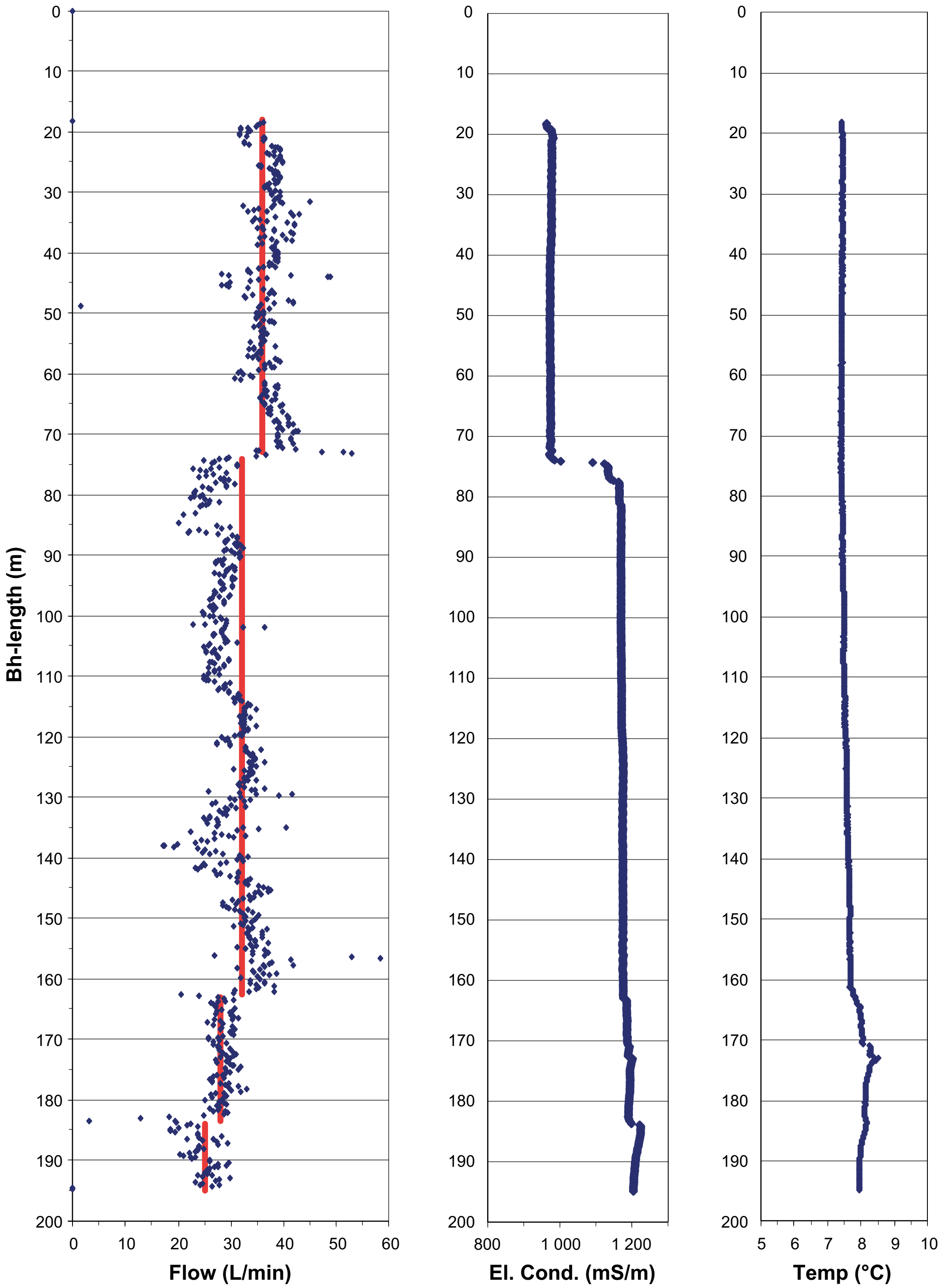


Figure 5-4. *Flow and temperature plotted against depth during logging of HFM45.*

5.5 Borehole HFM46

Borehole HFM46 was flow logged from 15.5 m depth from top of casing (TOC) and down to 185.5 m during pumping were the spinner got stuck and the logging was stopped. The pump was positioned 2.5 m above the start position of flow logging, at 13 m TOC. A plot of flow (spins logged), electrical conductivity and temperature is presented in Figure 5-5. After flow logging, the part above 15.5 m was sealed off with a packer and then pumped to the same drawdown as in the open borehole and a total inflow of about 5 L/min was found between 6 and 15.5 m.

The total transmissivity in HFM46 was evaluated using data from the pumping test and both a stationary value according to Moye (T_M) as well as a transient value (Tt) result from the pumping test was estimated. The value for T_M was 1.8E−04 m^2/s and Tt was estimated to 8.5E−05 m^2/s according to the model Dougherty-Babu using AQTESOLV. and the transient value was chosen as most representative for the borehole. A plot of pumped flow, pressure as well as the transient evaluation and estimated parameters in AQTESOLV is presented in Appendix 2, Figure A2-13 to A2-15.

The plot of the flow and temperature in Figure 5-5 gives a weighted distribution of the total flow and transmissivity to the detected anomalies and is presented in Table 5-5. The dominating fracture in HFM46 is located below 186 m and contributes with approximately 70 % of the total inflow. Since the spinner couldn't get any further down the positioning of this fracture is poor. One smaller anomaly was found at around 121–122 m and another inflow lies between the casing end at 6 m and 15.5 m TOC.

Tabell 5-5. Results of the flow logging in borehole HFM46. Each interpreted fracture contribution to the total flow and transmissivity, both transient (Tt) and stationary (T_M) evaluated values.

Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m^2/s)	T_M (m^2/s)
1	186–200	32.00	5.9E−05	1.3E−04
2	121–122	9.00	1.7E−05	3.5E−05
3	0–15.5	5.00	9.2E−06	2.0E−05
∑Bh	0–200	46.00	**8.5E−05**	1.8E−04

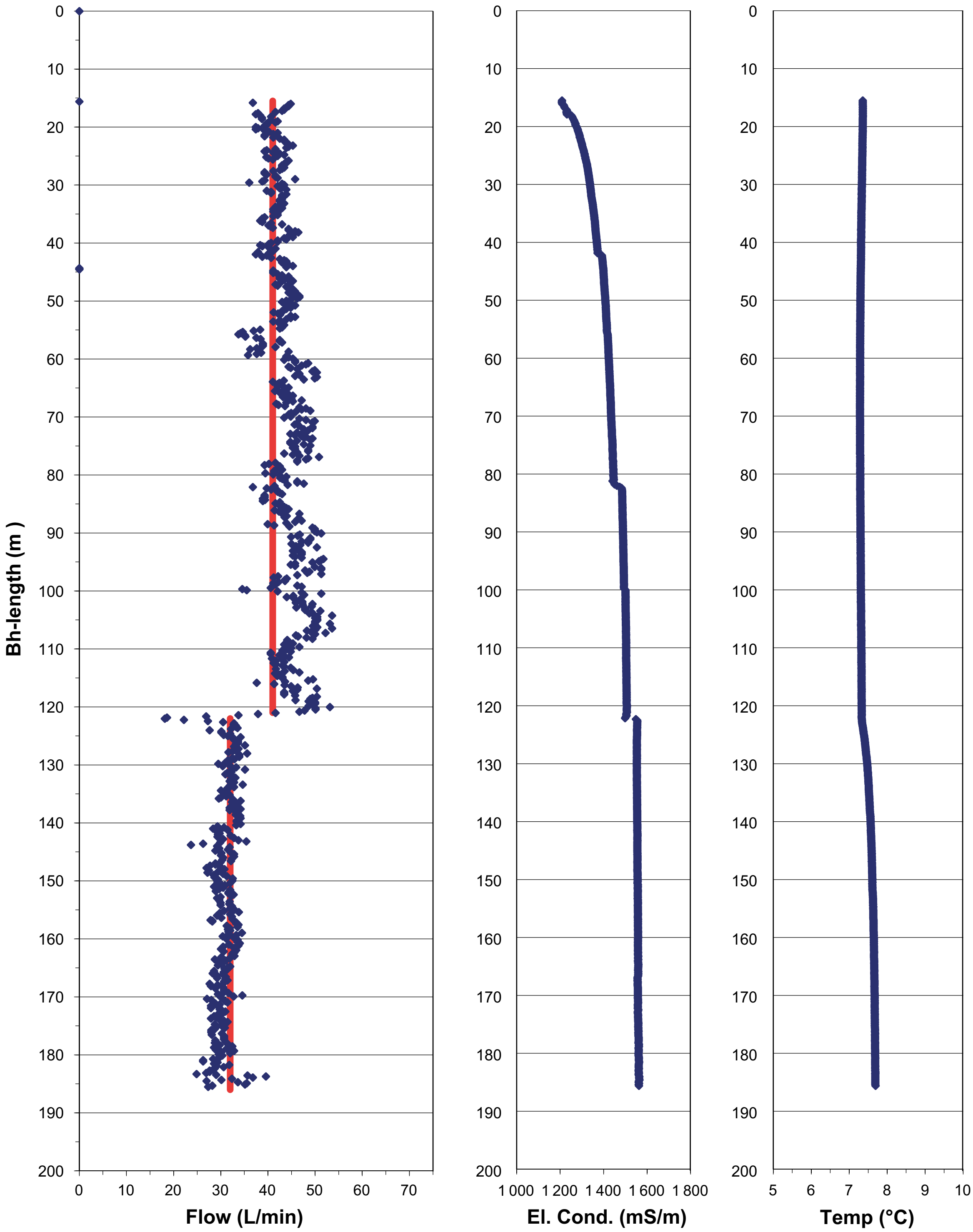


Figure 5-5. *Flow and temperature plotted against depth during logging of HFM46.*

5.6 Nonconformities

Over all the tests went rather well without any major problems. In the first two tests in HFM42 and HFM43 the probe measuring the electrical conductivity broke down and had to be replaced. Hence no data of EC is available for these boreholes during flow logging.

In the first two boreholes there was a shorter part of the borehole logged during undisturbed conditions in order to get a background number on the spinner revs for lowering through the water column.

In the other boreholes this logging in undisturbed conditions was extended to the entire borehole to be able to compensate the measurements for changing diameters, cavities etc. that affects the results of the flow logging in order to get a better resolution of the flow logging

During flow logging in HFM43 the spinner probe got stuck at about 127 m TOC. The probe had to be lifted and altered in diameter to be able to log the entire borehole. During this period the pump was stopped, and test data had to be corrected to the new diameter of the probe. This did however not affect the interpreted results of the flow logging.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

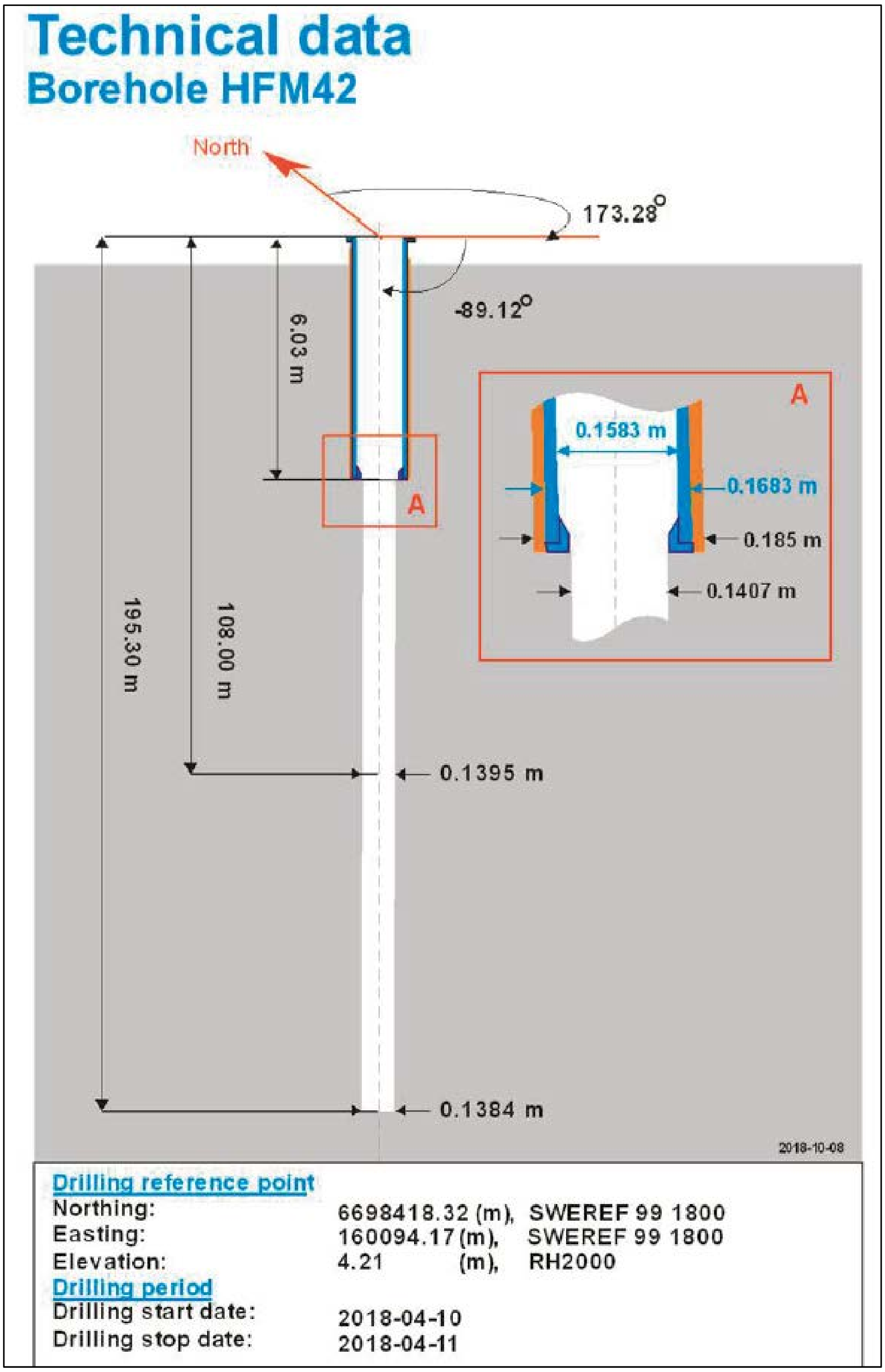
Nilsson G, 2018. Drilling of percussion boreholes HFM42–HFM46 in Forsmark to be used as monitoring wells. SKB P-18-09, Svensk Kärnbränslehantering AB.

Dougherty D E, Babu D K, 1984. Flow to a partially penetrating well in a double-porosity reservoir. Water Resources Research 20, 1116–1122.

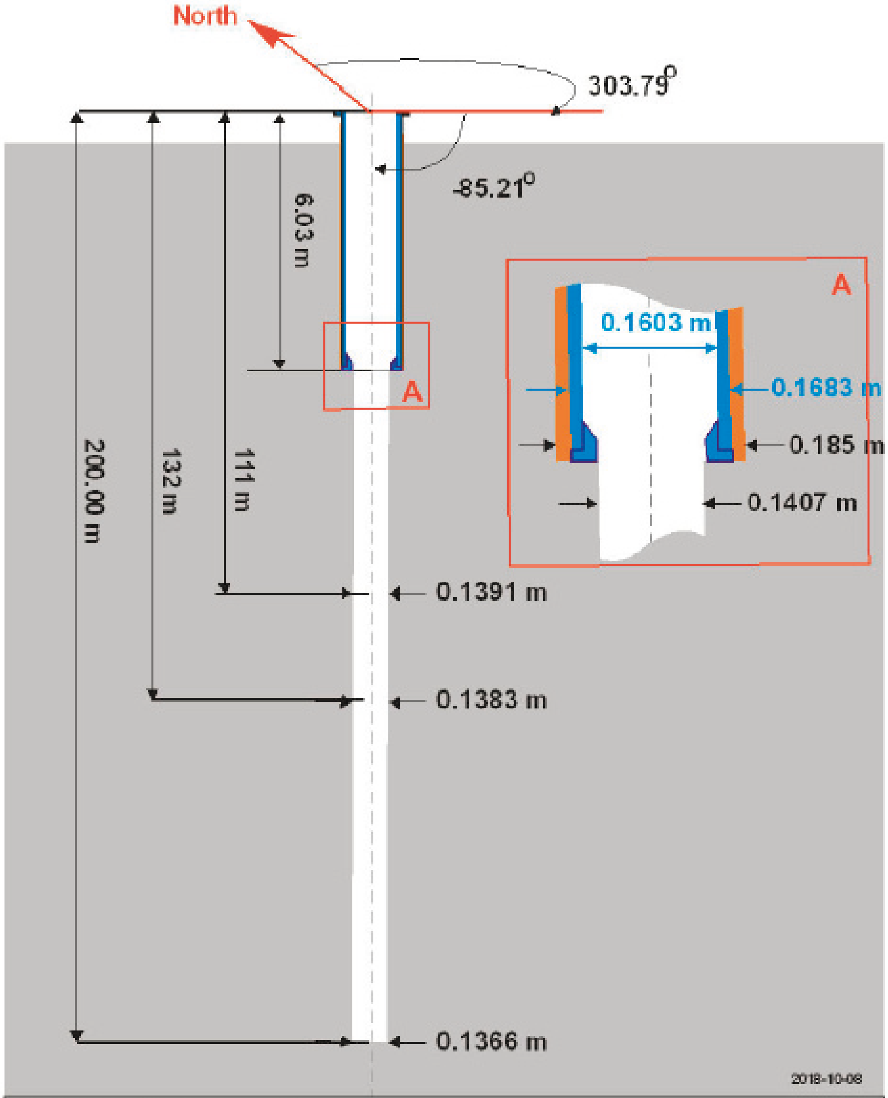
AQTESOLV, 2007. Windows Version 4.5. Software for aquifer tests. Available at: www.aqtesolv.com

Appendix 1

Technical data boreholes



Technical data
Borehole HFM43



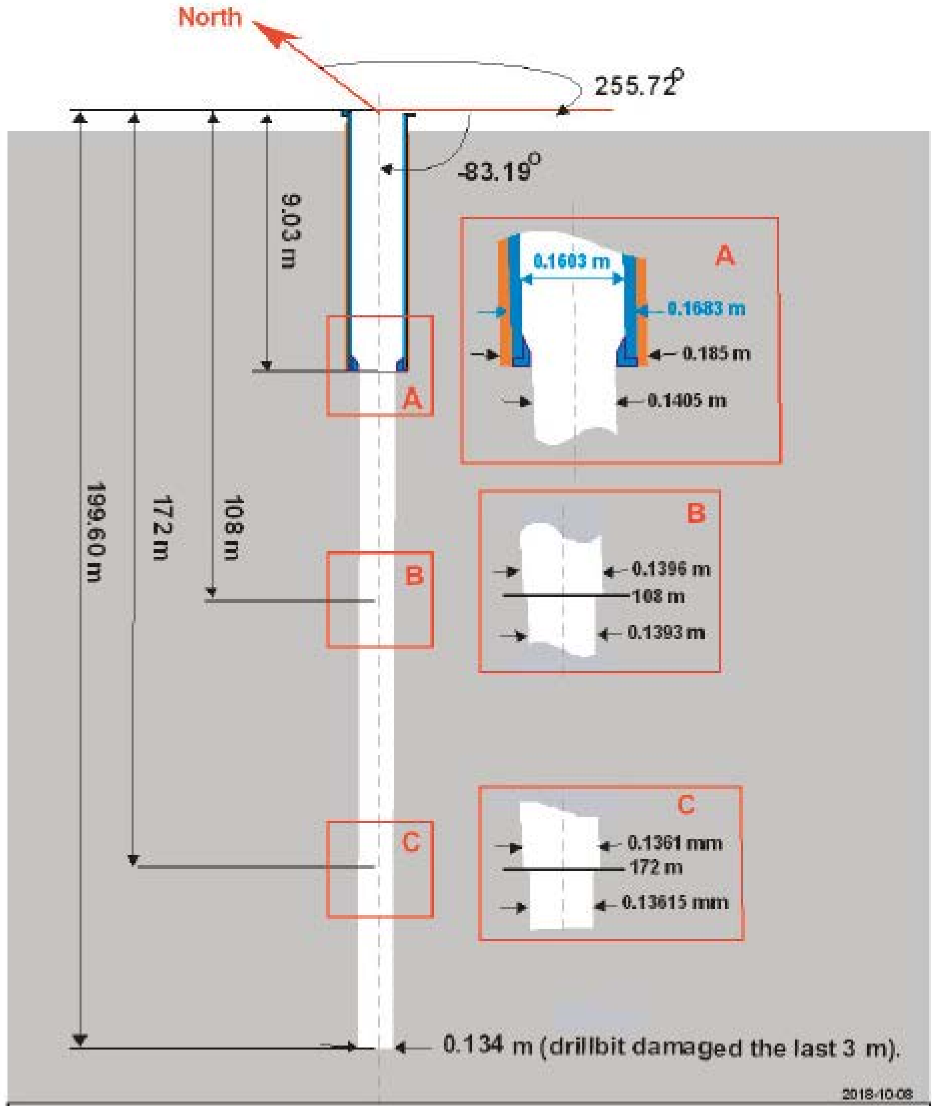
Drilling reference point

Northing:	6698537.92 (m), SWEREF 99 1800
Easting:	160064.53 (m), SWEREF 99 1800
Elevation:	4.33 (m), RH2000

Drilling period

Drilling start date:	2018-04-17
Drilling stop date:	2018-04-23

Technical data
Borehole HFM44



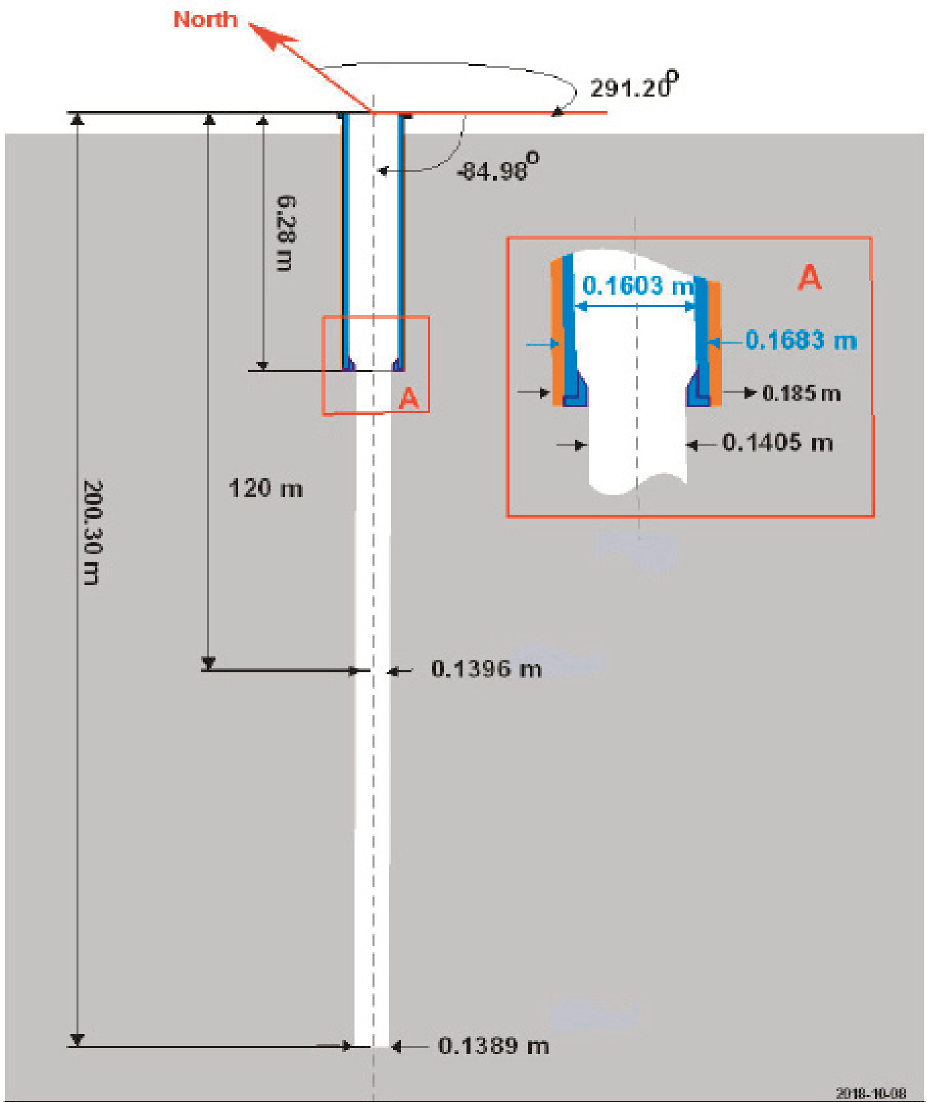
Drilling reference point

Northing:	6699322.21	(m),	SWEREF 99 1800
Easting:	161395.20	(m),	SWEREF 99 1800
Elevation:	2.94	(m),	RH2000

Drilling period

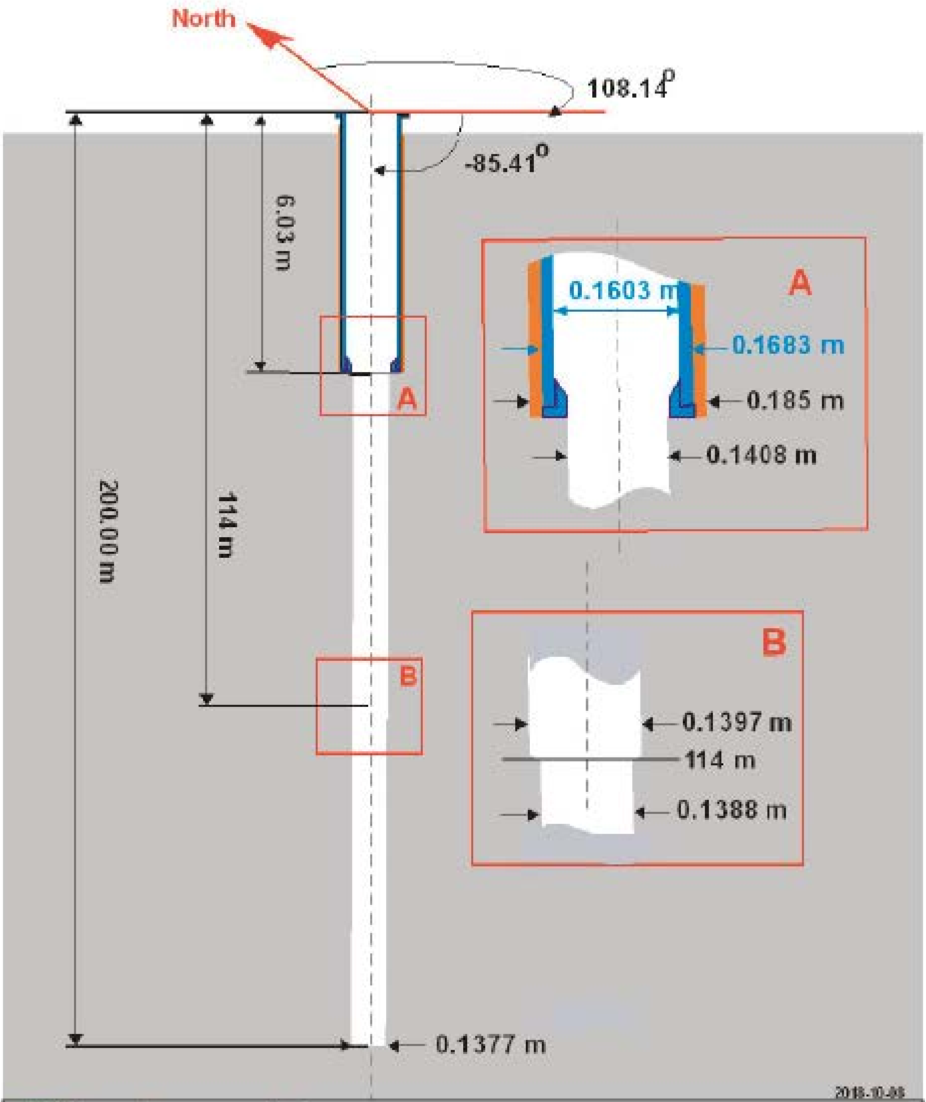
Drilling start date:	2018-04-24
Drilling stop date:	2018-04-26

Technical data
Borehole HFM45



Drilling reference point	
Northing:	6699603.14 (m). SWEREF 99 1800
Easting:	161117.22 (m). SWEREF 99 1800
Elevation:	3.86 (m). RH2000
Drilling period	
Drilling start date:	2018-05-02
Drilling stop date:	2018-05-04

Technical data
Borehole HFM46



Drilling reference point

Northing:	6699951.07	(m),	SWEREF 99 1800
Easting:	161324.55	(m),	SWEREF 99 1800
Elevation:	1.70	(m),	RH 2000

Drilling period

Drilling start date:	2018-05-06
Drilling stop date:	2018-05-08

Appendix 2

Plots of pressure and flow during pump test and evaluation of transient evaluations of pumping tests using AQTESOLV

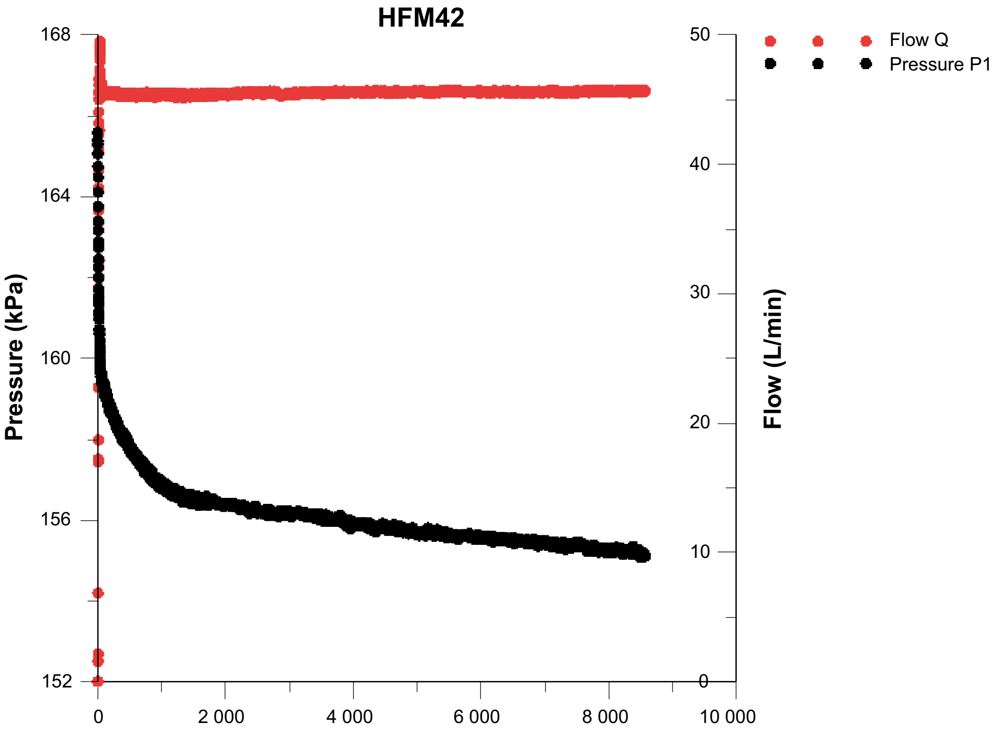


Figure A2-1. Flow (red) and pressure during pumping test in HFM42.

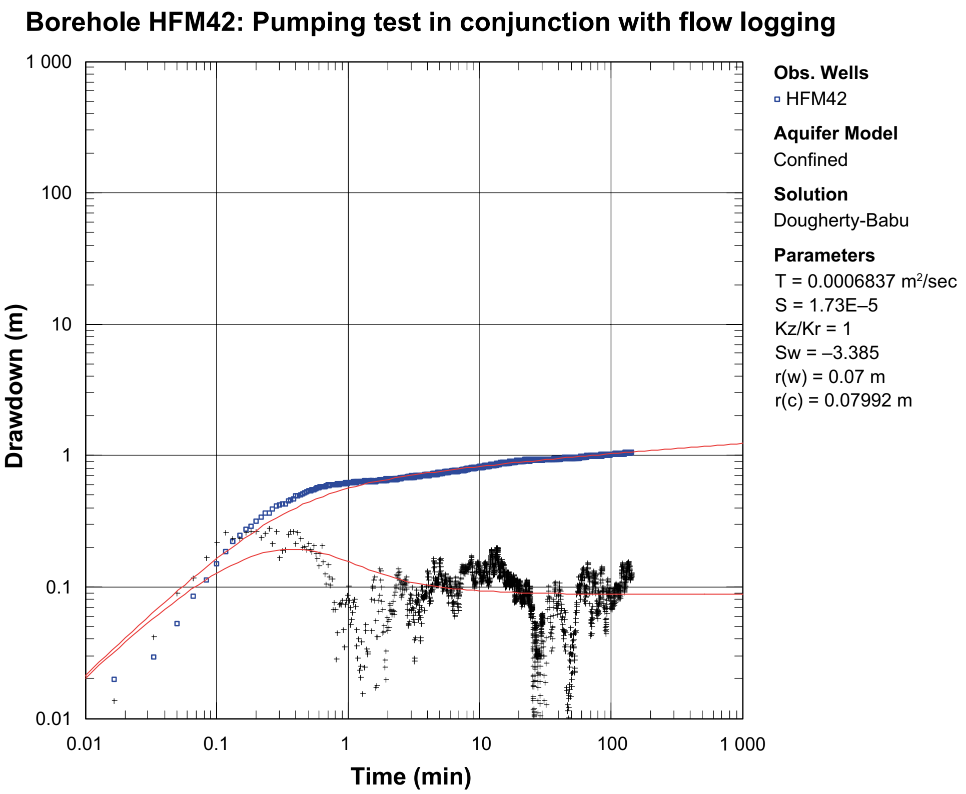


Figure A2-2. Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM42.

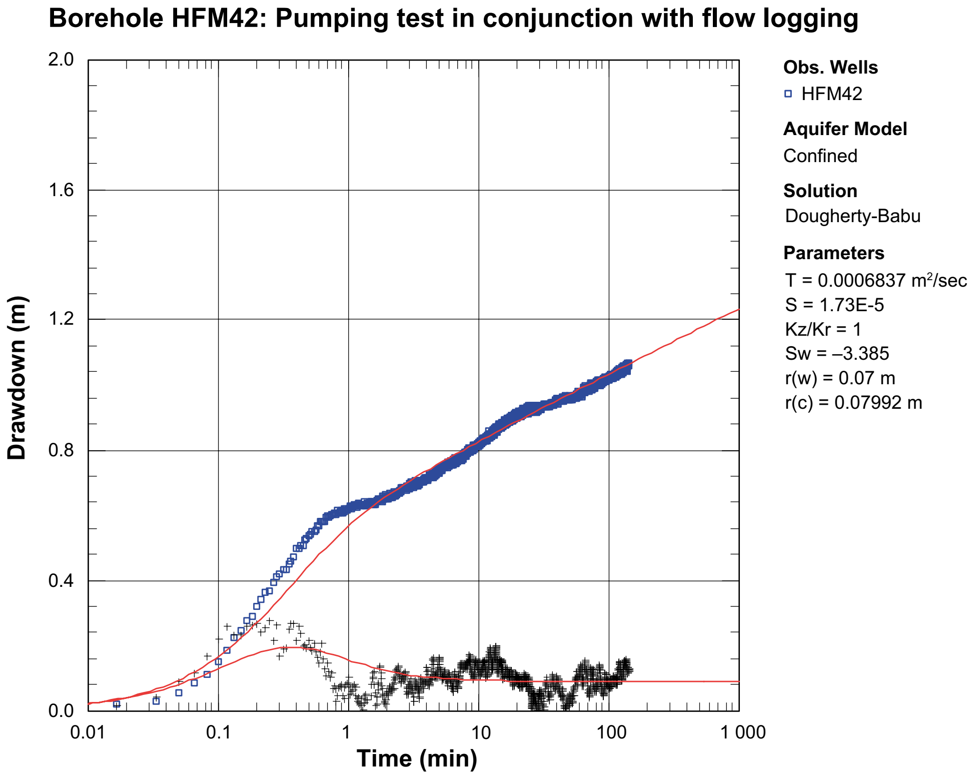


Figure A2-3. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM42.*

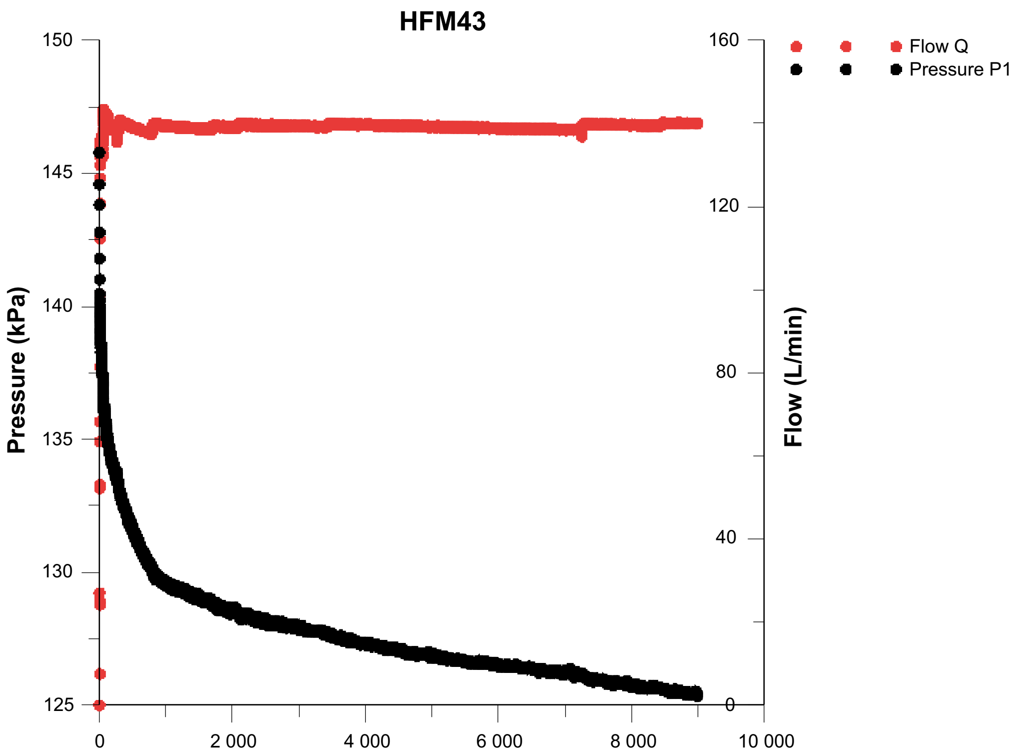


Figure A2-4. *Flow (red) and pressure during pumping test in HFM43.*

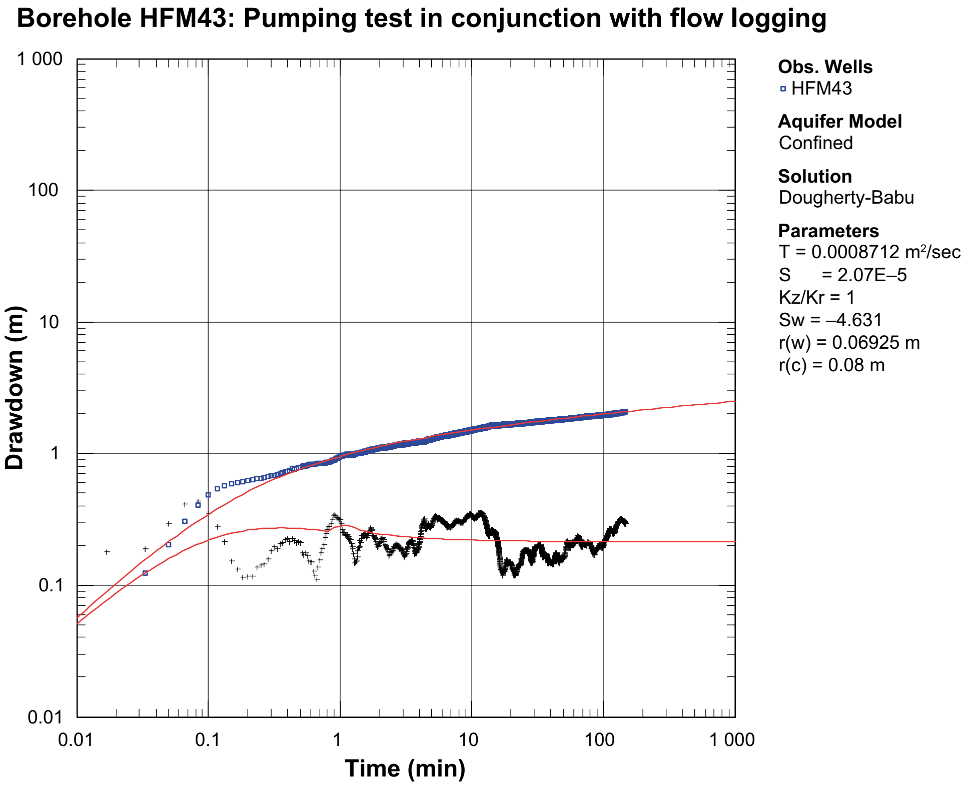


Figure A2-5. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM43.*

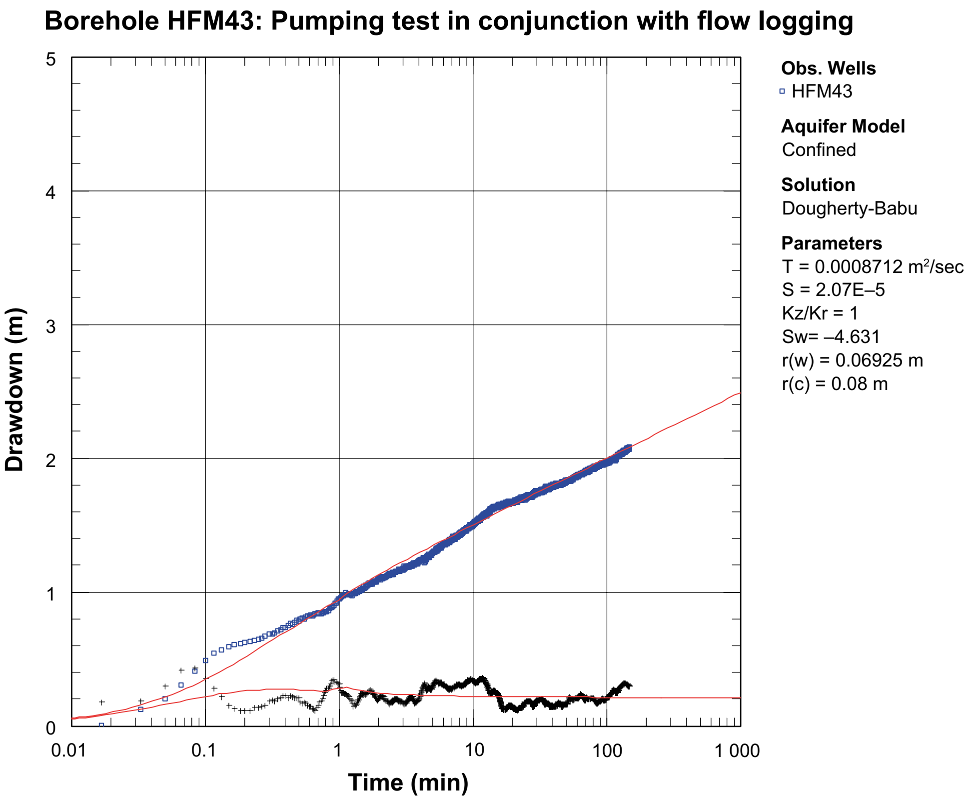


Figure A2-6. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM43.*

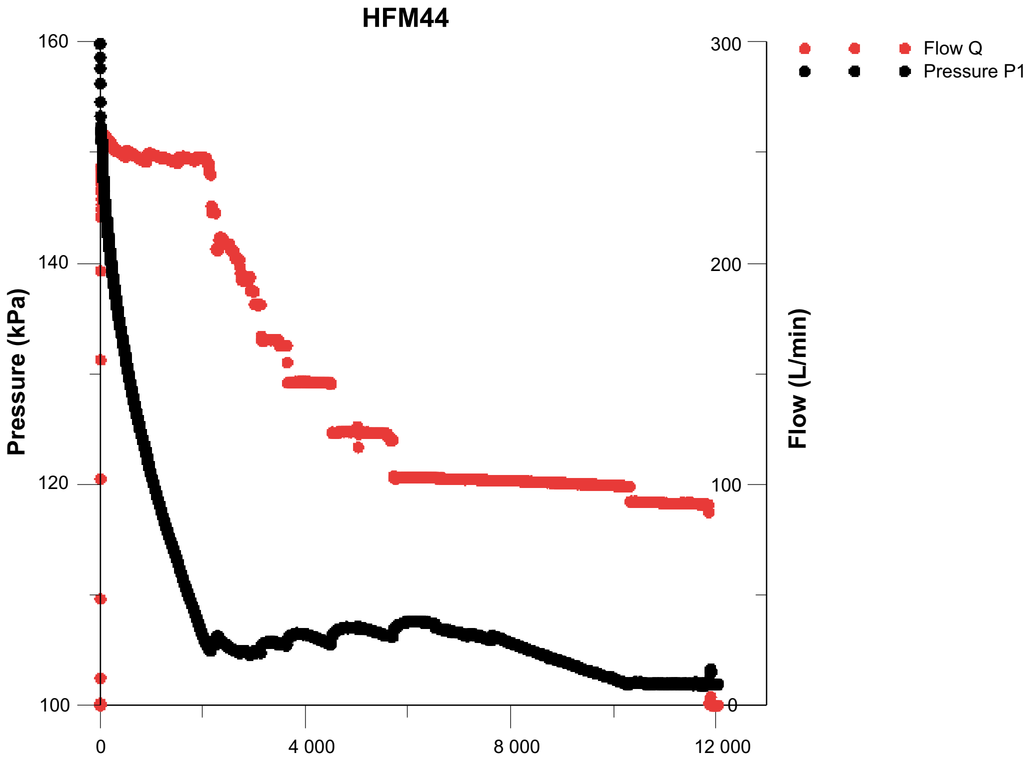


Figure A2-7. Flow (red) and pressure during pumping test in HFM44.

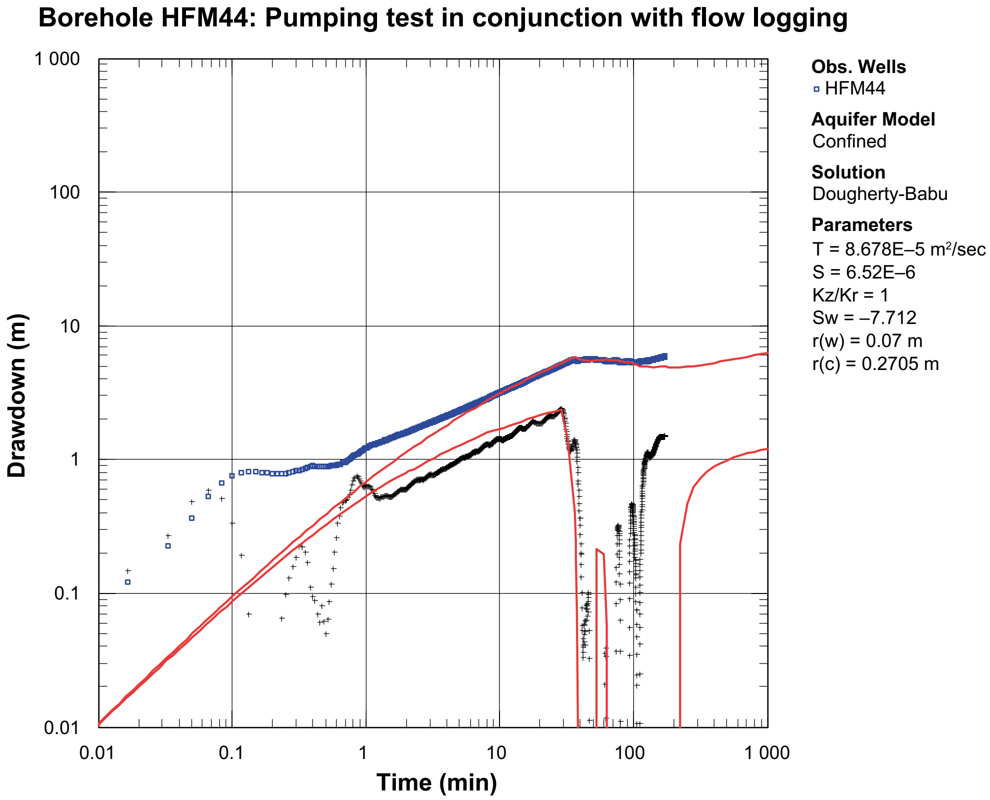


Figure A2-8. Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM44. No unambiguous solution was possible.

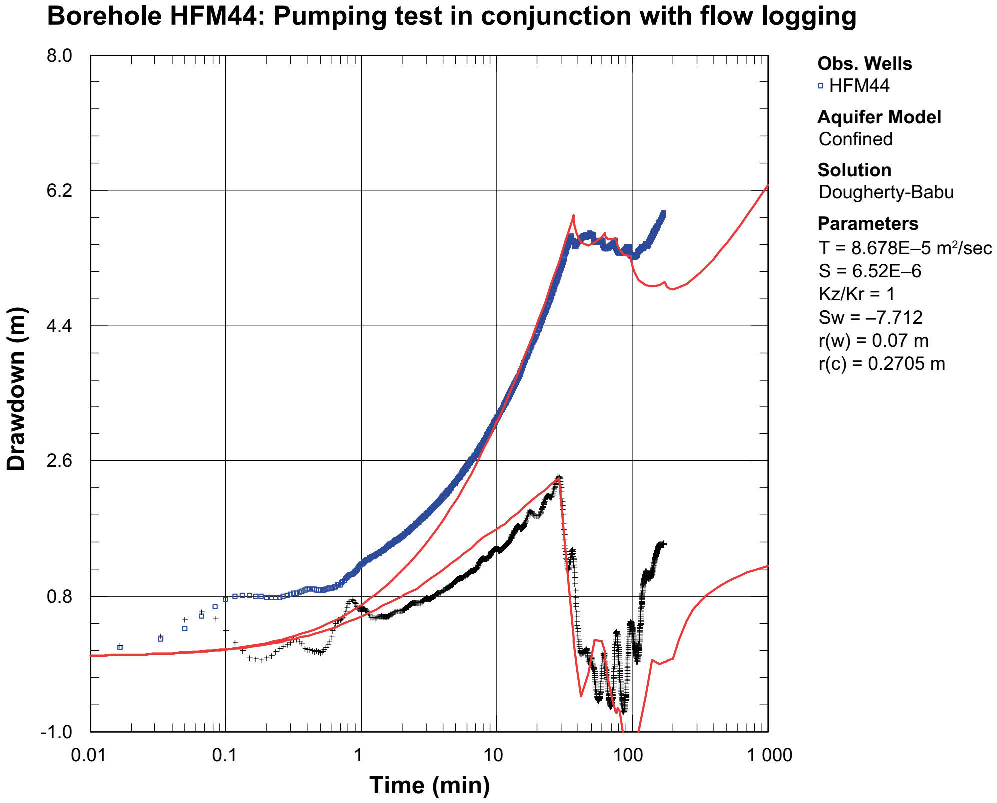


Figure A2-9. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM44.*

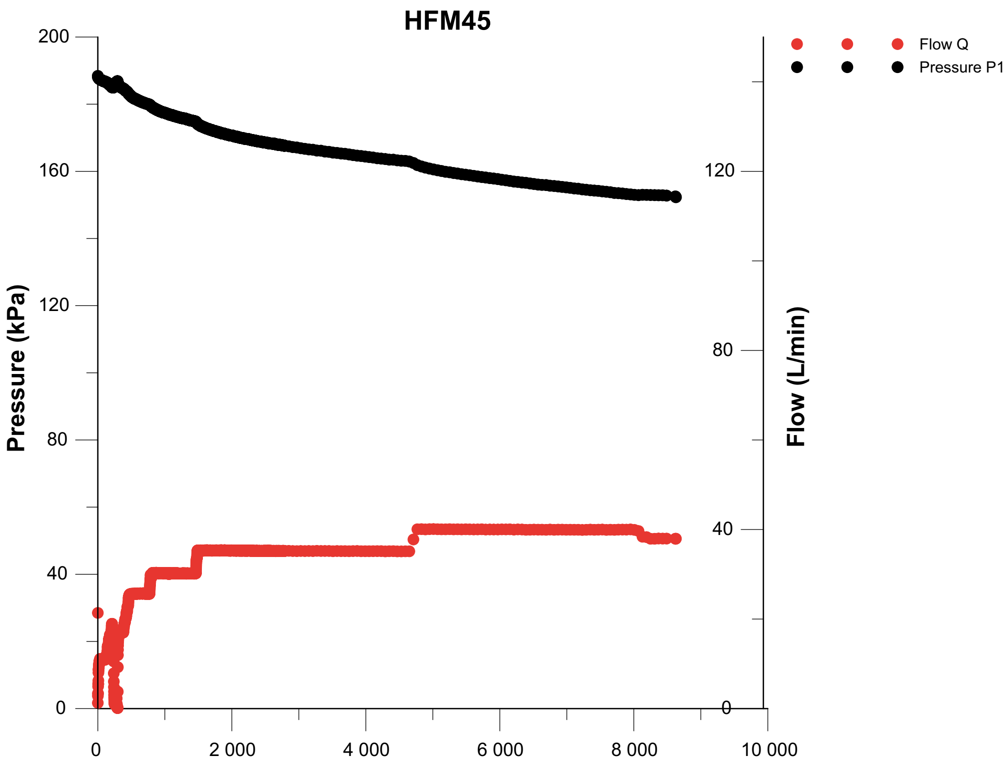


Figure A2-10. *Flow (red) and pressure during pumping test in HFM45.*

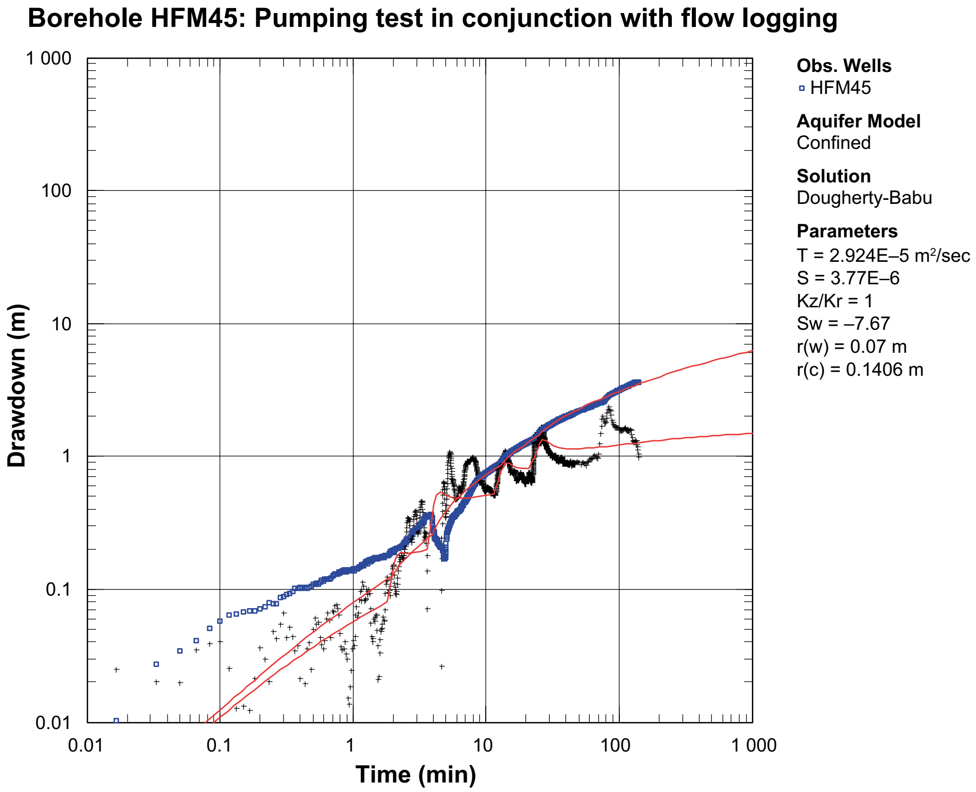


Figure A2-11. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM45.*

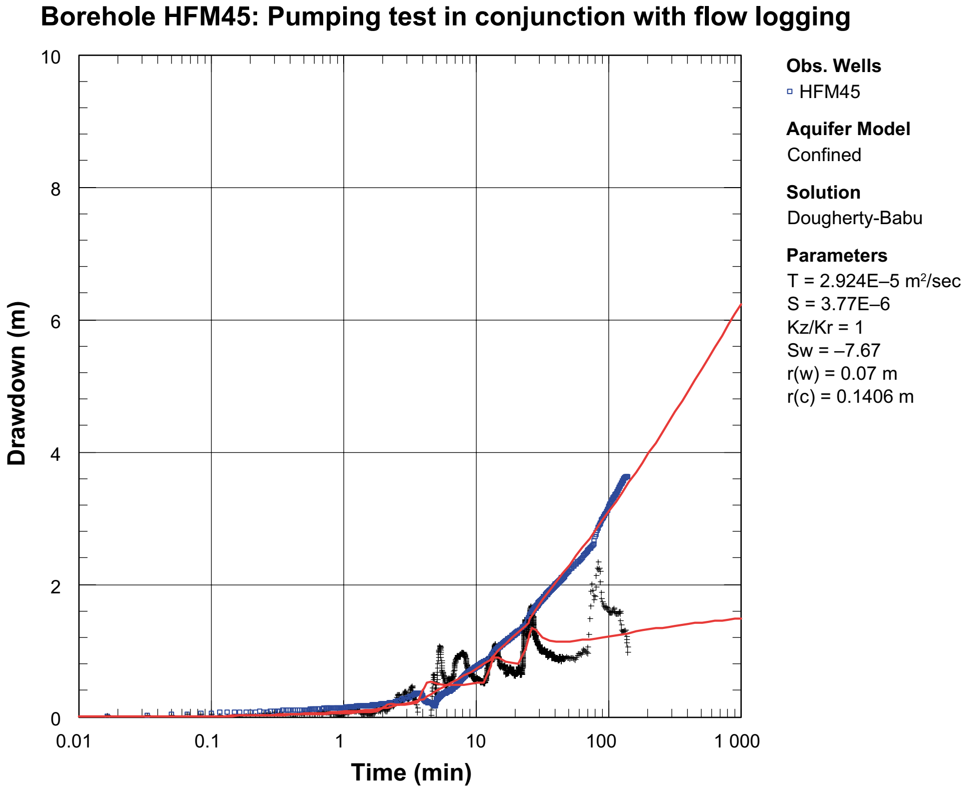


Figure A2-12. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM45.*

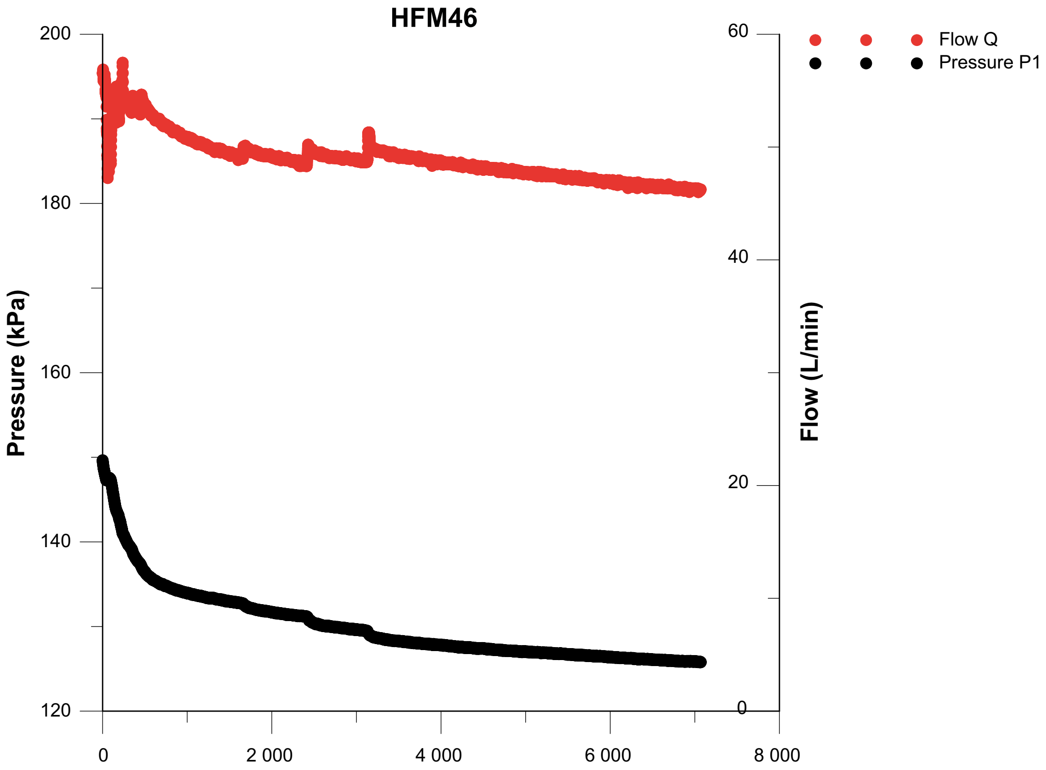


Figure A2-13. *Flow (red) and pressure during pumping test in HFM46.*

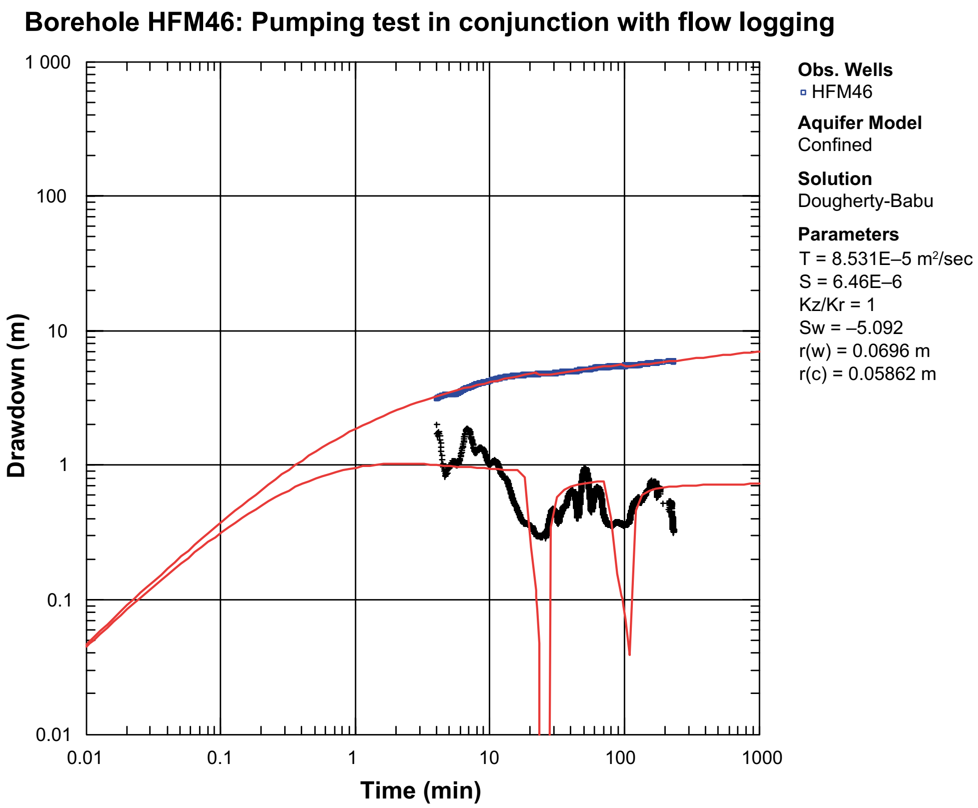


Figure A2-14. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM46.*

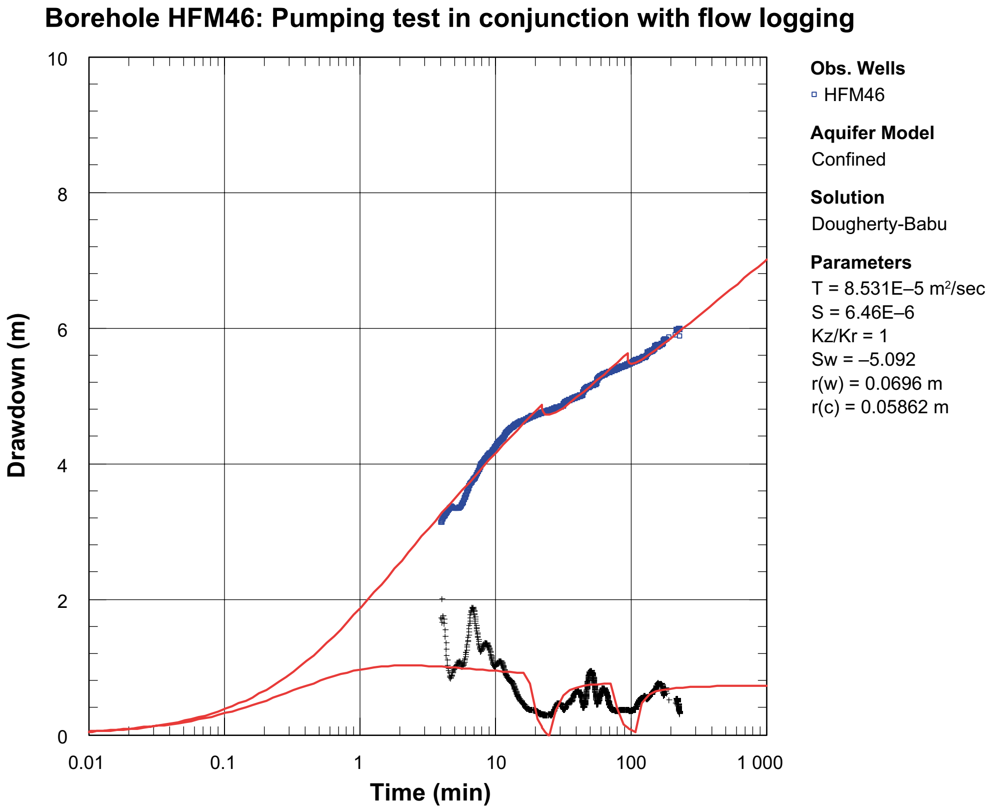


Figure A2-15. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time during the open-hole pumping test in HFM46.*

Table A-1. Compilation of the results. Static groundwater level presented in TOC before test start.

Borehole ID	Anomaly (#)	Bh-length (m)	Flow (L/min)	Tt (m²/s)	T_M (m²/s)	S (-)	Static groundwater level (m)
HFM42	1	190–195	10.0	1.5E–04	2.0E–04		
	2	157–158	11.0	1.6E–04	2.3E–04		
	3	90–91	24.7	3.7E–04	5.0E–04		
	∑Bh	0–195	45.7	**6.8E–04**	9.3E–04	1.73E–05	3.42
HFM43	1	195–200	20.0	1.2E–04	2.1E–04		
	2	106–106.5	85.0	5.3E–04	9.0E–04		
	3	95–95.5	13.0	8.1E–05	1.4E–04		
	4	90–90.5	22.0	1.4E–04	2.3E–04		
	∑Bh	0–200	140.0	**8.7E–04**	1.5E–03	2.07E–05	–
HFM44	1	122.5–124	5.0	4.2E–06	2.0E–05		
	2	73–73.5	73.0	6.2E–05	3.0E–04		
	3	50–50.5	24.5	2.1E–05	9.9E–05		
	∑Bh	0–200	102.5	**8.7E–05**	4.2E–04	6.52E–06	5.98
HFM45	1	195–200	25.0	1.9E–05	1.3E–04		
	2	183.5–184	3.0	2.3E–06	1.6E–05		
	3	162.5–163	4.0	3.1E–06	2.1E–05		
	4	73–74	4.0	3.1E–06	2.1E–05		
	5	6–18	2.0	1.5E–06	1.0E–05		
	∑Bh	0–200	38.0	**2.9E–05**	2.0E–04	3.77E–06	4.65
HFM46	1	186–200	32.00	5.9E–05	1.3E–04		
	2	121–122	9.00	1.7E–05	3.5E–05		
	3	0–15.5	5.00	9.2E–06	2.0E–05		
	∑Bh	0–200	46.00	**8.5E–05**	1.8E–04	6.46E–06	3.80

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