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Forsmark site investigations

Difference flow logging in boreholes KFM25, KFM26 and KFM27

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Abstract

This report presents the main principles of the methods as well as the results of measurements carried out in boreholes KFM25, KFM26, and KFM27 at Forsmark, Sweden, in October and November 2019.

The Posiva Flow Log, Difference Flow Method (PFL DIFF) uses a flowmeter that incorporates a flow guide and can be used for relatively quick determinations of transmissivity and the hydraulic head of the fractures/fracture zones intersecting the boreholes.

The first flow logging measurement was carried out with a 5 m long test section by moving the measurement tool in 0.5 m long increments covering the entire measurable length of a borehole while borehole remained at undisturbed conditions. An additional flow logging during undisturbed conditions with a 1 m long test section and in 0.1 m long increments was conducted, where more detailed information on fracture-specific flows was needed. In KFM26 and KFM27 entire measurable length was measured with 1 m long test section while in KFM25 the measurement was not conducted. The flow logging measurement setup with a 5 m long test section and 0.5 m long increments was repeated while water level in the measured borehole was lowered by pumping water out of the borehole. The flow logging measurement in pumped conditions was conducted also using 1 m test section, with 0.1 m steps.

A high-resolution absolute pressure sensor was used to measure the absolute total pressure along the borehole. These measurements were carried out in parallel with the flow measurements.

The flow along the borehole was measured below the casing shoe during undisturbed conditions to detect possible leaks between the casing and the bedrock.

Measurements of electrical conductivity (EC) and temperature of borehole water were also conducted. The EC measurements were used to study the occurrence of saline water in the borehole in un-pumped as well as in pumped conditions.

High flow rates were measured in all of the boreholes. Drawdown of 5 m was achieved only in KFM25 while in KFM26 and KFM27 maximum achievable drawdowns with available pumping equipment was 1 m and 2.8 m respectively. Large number of flowing fractures were found in all the boreholes. 44 fractures were found (0.49 fractures/m) in KFM25, 49 fractures (0.54 fractures/m) in KFM26 and 70 fractures (0.80 fractures/m) in KFM27. In KFM25 and KFM26 all measured flows were clearly below upper limit of flow measurement range but in KFM27 one measured fracture (fracture 86.8 m) flow was near the upper limit while drawdown was 2.8 m. In this case moving the probe to the depth of fracture changed the pressure conditions at the measurement location. This affects the measurement but should not deteriorate the measurement results.

Sammanfattning

Denna rapport presenterar huvudprinciperna för metoden och resultat av mätningar utförda i borrhål KFM25, KFM26 och KFM27 i Forsmark, Sverige, i oktober och november 2019.

Posiva Flow Log, Differensflödesloggning (*PFL DIFF*) är en snabb metod för bestämning av transmissiviteten och hydraulisk tryckhöjd i borrhålssektioner och sprickor/sprickzoner i kärnborrhål.

Flödet till eller från en 5 m lång testsektion (*som successivt förflyttades med 0,5 m*) mättes i borrhålet under såväl naturliga förhållanden som vid pumpning. En ytterligare flödesloggning under ostörda förhållanden, med 1 m testsektion och 0,1 m mätningsmellanrum utfördes, om mer detaljerad information behövdes om sprickspecifika flöden i ett borrhål. Flödesmätningarna upprepades under pumpning med en 1 m lång testsektion som successivt förflyttades i steg om 0,1 m.

En högupplösande absoluttryckgivare användes för att mäta det absoluta totala trycket längs borrhålet. Dessa mätningar utfördes tillsammans med flödesmätningarna.

Mätning av flödet längs borrhålet gjordes nedanför foderröret under naturliga betingelser för att detektera läckage av foderröret.

Elektrisk konduktivitet (*EC*) och temperatur på borrhålsvattnet mättes också. EC-mätningarna användes för att studera förekomsten av saltvatten i borrhålet under såväl naturliga som pumpade förhållanden.

I alla borrhålen mättes höga flödeshastigheter. Endast i KFM25 uppnåddes en neddragning på 5 m, medan i KFM26 och KFM27 var de maximala möjliga neddragningarna med en tillgänglig pumputrustning 1 m respektive 2,8 m. I alla borrhålen hittades ett stort antal flödesfrakturer. 44 sprickor hittades (0,49 sprickor/m) i KFM25, 49 sprickor (0,54 sprickor/m) i KFM26 och 70 sprickor (0,80 sprickor/m) i KFM27. I KFM25 och KFM26 var alla mätta flöden tydligt under den övre gränsen av flödesmätningsavståndet. I KFM27 mättes en spricka (spricka 86,8 m), flödet nära den övre gränsen medan neddragningen var 2,8 m. När sonden i detta fall fördes till sprickdjupet, förändrades tryckförhållanden i borrhålet. Detta påverkar mätningen, men borde inte försämra mätningsresultaten.

Contents

1 Introduction

The core drilled boreholes KFM25, KFM26 and KFM27 at Forsmark, Sweden were measured using the Posiva Flow Log, Difference Flow Method (PFL DIFF) which provides a swift, multifaceted characterization of a borehole. The measurement campaign was conducted between October 22 and November 9, 2019.

The three boreholes KFM25, KFM26 and KFM27 are relatively shallow with quite short casing tubes. Lengths of boreholes were ca 100 m. Boreholes were equipped with casing tubes which were 76.3 mm in inner diameter. Boreholes were 75.6 mm in inner diameter. Casing tube lengths had been adjusted to penetrate the soil cover above bedrock, longest casing tube being 9.03 m long. Technical data of boreholes is presented in Table 1-1.

Table 1-1. Technical data of the measured boreholes (RH 2000 coordinate system).

Borehole ID	Length (m)	Inclination (degrees)	Z coordinate of top of the casing (m a.s.l.)	Length of casing tube (m)
KFM25	100.72	−84.27	2.66	6.08
KFM26	100.74	−84.88	3.00	6.15
KFM27	100.64	−74.97	2.54	9.03

The locations of measured boreholes at Forsmark are illustrated in Figure 1-1. Borehole number 1 is KFM27, borehole number 2 is KFM26, and borehole number 3 is KFM25.

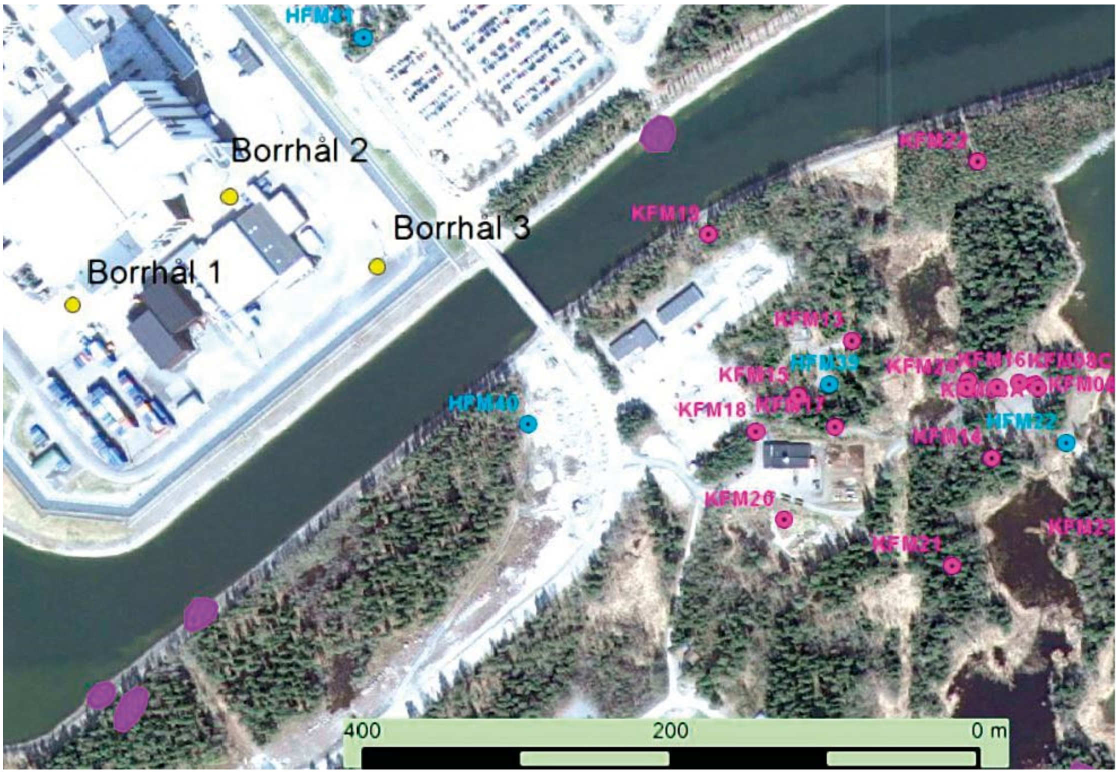

Figure 1-1. *Locations of the boreholes in Forsmark (from AP SFK-19-022).*

The PFL DIFF measurements were coordinated and led by Posiva Solutions Oy. AFRY Finland Oy acted as subcontractor in the assignment. PFL DIFF has previously been employed in Posiva's site characterisation programme in Finland as well as at the Äspö Hard Rock Laboratory at Simpevarp, Sweden. The assignment at the latter site included measurements in the 1 700 m long cored borehole KLX02 at Laxemar together with a methodology study (Ludvigson et al. 2002). PFL DIFF has also been employed in SKB's site characterisation programme at Laxemar and Forsmark.

This document reports the results acquired by the PFL DIFF method. The measurements were carried out to investigate the near-surface bedrock at Forsmark as instructed in SKB's internal controlling document AP SFK-19-022. The controlling documents for performing according to this Activity Plan are listed in Table 1-2. The list of the controlling documents excludes the assignment-specific quality plans. Both the Activity Plan and the Method Descriptions are SKB's internal controlling documents. The measurement data and the results were delivered to the SKB site characterization database SICADA and are traceable by the Activity Plan number.

Table 1-2. SKB's internal controlling documents for the activities concerning this report.

Activity Plan	Number	Version
PFL-mätningar KFM25, 26 och KFM27	AP SFK-19-022	1.0
Method Descriptions	**Number**	**Version**
Method Description for Difference Flow Logging	SKB MD 322.010e	2.0

2 Objectives and scope of work

The main objective of the PFL DIFF measurements in the boreholes was to identify water-conductive sections/fractures. Secondly, the measurements aimed at a hydro-geological characterisation, which includes the inspection of the prevailing water flow balance in the borehole and the hydraulic properties (*transmissivity and undisturbed hydraulic head*) of the tested sections. Based on the results of these investigations, a more detailed characterisation of flow anomalies along the borehole, e.g. an estimate of the conductive fracture frequency (*CFF*), may be obtained.

Besides difference flow logging, the measurement programme also included supporting measurements, performed in order to gain a better understanding of the overall hydro-geochemical conditions. These measurements included the electrical conductivity (*EC*) and the temperature of the borehole fluid as well as the single-point resistance of the borehole wall.

To measure the absolute pressure along the borehole, a high-resolution pressure sensor was used, and pressure measurement was carried out simultaneously with the flow measurements. The results are used for the calculation of the hydraulic head along the borehole.

The flow along the borehole was measured below the casing tube in undisturbed conditions (*without pumping*) to detect possible leaks from the casing.

3 Principles of measurement and interpretation

3.1 Measurements

Unlike conventional borehole flowmeters, which measure the total cumulative flow rate along a borehole, the PFL DIFF probe measures the flow rate into or out of defined borehole sections during both non-pumped ("undisturbed") and pumped conditions. The advantage that follows from measuring the flow rate in isolated sections is improved detection of incremental changes of flow along the borehole. As these flows are generally very small, they can easily be missed when using conventional flowmeters. Technical illustrations of the PFL DIFF probe are presented in Figure 3-1.

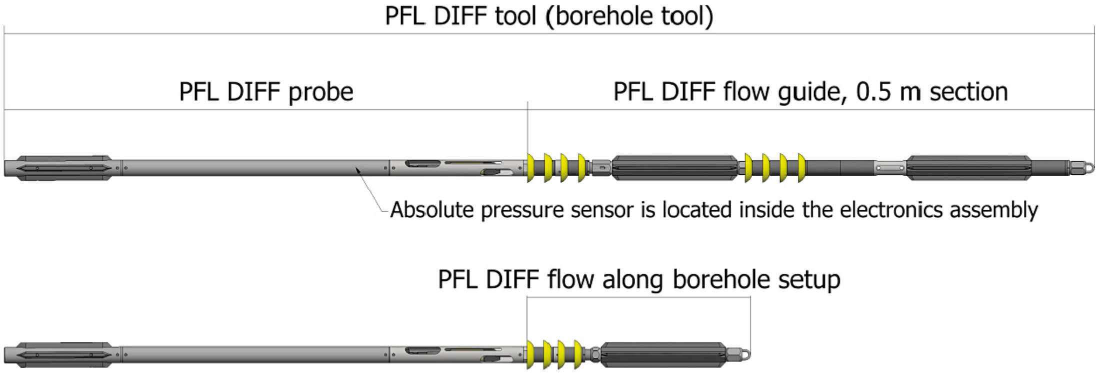

Figure 3-1. *Technical illustration of the PFL DIFF probe in different setups.*

Rubber sealing disks located at the top and bottom of the PFL DIFF probe are used to isolate the flow of water in the test section from the flow in the rest of the borehole, see Figure 3-2. Flow inside the test section is directed through the flow sensor. Flow along the borehole is directed around the test section by means of a bypass pipe and is discharged at either the upper or lower end of the probe. The entire structure is called the flow guide. A schematic illustration representing a cross-section of the PFL DIFF probe's structure is presented in Figure 3-3. It should be noted that, depending on pressure difference between a fracture and a borehole, the direction of the measured flow can be from the bedrock into the borehole as the magenta coloured arrows represent in Figure 3-2 and Figure 3-3, or from the borehole into the bedrock in which case the arrowheads in Figure 3-2 and Figure 3-3 would be inverted. The same applies to flow along the hole as well, as it can go either upwards or downwards depending on the prevailing conditions in a borehole at a certain length.

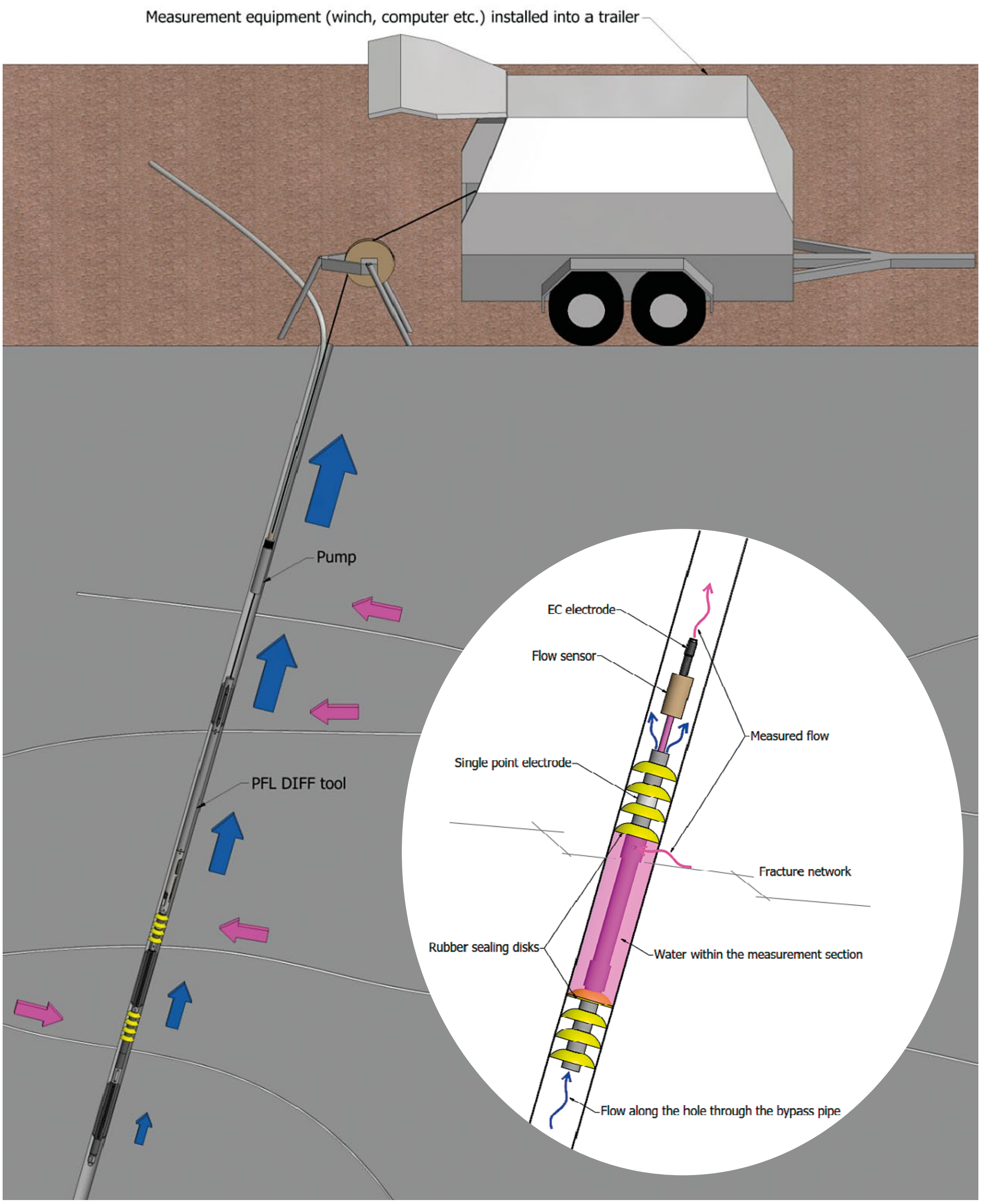

Figure 3-2. *Schematic illustration of the probe used in the PFL DIFF.*

Generally, two separate measurements with two different section lengths (*e.g. 5 m and 1 m*) are used. The 5 m setup is usually used first to obtain a general picture of the flow anomalies. It is also good for measuring larger (*less than 5 m in length*) fracture zones. The 1 m section setup can separate anomalies which are close to each other. Different section lengths can also confirm that a flow anomaly is real and not caused for instance by leakage of the rubber discs.

In addition to incremental changes in flow, the PFL DIFF probe can also be used to measure the electrical conductivity (*EC*) of both borehole water and fracture-specific water. The electrode used in EC measurements is located at the top of the flow sensor (*Figure 3-2*).

The single point resistance (*SPR*) of a borehole wall (*grounding resistance*). The SPR electrode is located between the uppermost rubber sealing discs (*Figure 3-2*), and is used for the high-resolution length determination of fractures and geological structures.

The ambient water pressure profile in a borehole. Located inside the watertight electronics assembly, the pressure sensor transducer is connected to the measurement section through a tube.

The temperature of the water in a borehole. The temperature sensor is part of the flow sensor (*Figure 3-2*).

The measurement range for flow rate is 30 mL/h – 300 000 mL/h in general. The PFL DIFF probes have been calibrated for flow range from 6 mL/h to 300 000 mL/h in laboratory but usually conditions at field raise the lower limit to around 30 mL/h. Therefore, in some cases flow rates below 30 mL/h can be measured. On the other hand, lower limit of 30 mL/h cannot be assured in all borehole conditions. Examples of possible sources for disturbances are drilling debris entrained in the borehole water, bubbles of gas in the water and very high flow rates along the borehole (*some 30 L/min, i.e., 1 800 000 mL/h or more*). In case of significant disturbances, the practical measurement limits are calculated separately for each set of data. Measurement range of 30–300 000 mL/h has been determined based on experience and it is valid in most of cases, but exceptions exist.

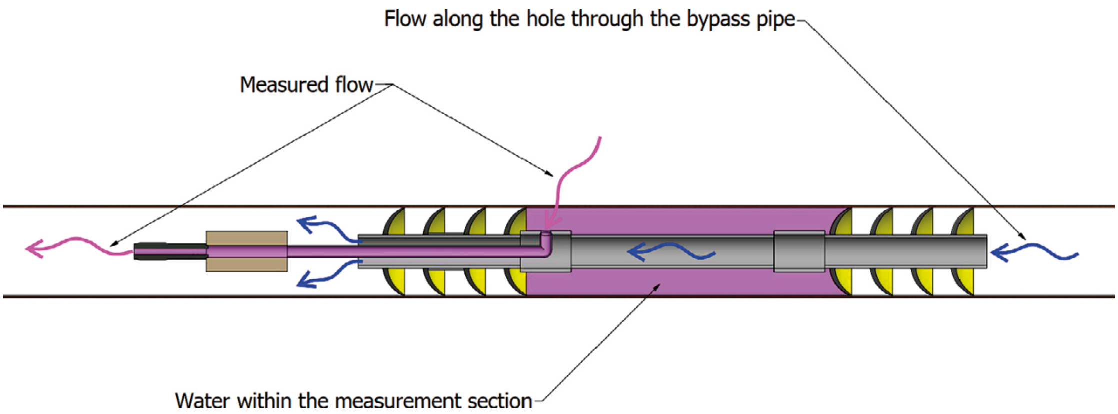

Figure 3-3. *The absolute pressure sensor is located inside the electronics assembly and connected to the section through a tube.*

3.2 Interpretation

The interpretation of data is based on Thiem's formula, which describes a steady-state and two-dimensional radial flow into the borehole (de Marsily 1986):

$$h_s - h = \frac{Q}{T \cdot a} \quad (3\text{-}1)$$

where

h is the hydraulic head in the borehole (at borehole radius r_0),

h_S is the hydraulic head at the radius of influence (R),

Q is the flow rate into the borehole,

T is the transmissivity of the test section.

The constant *a* depends on the assumed flow geometry. For cylindrical flow, the constant *a* is:

$$a = \frac{2\pi}{\ln(R/r_0)} \quad (3\text{-}2)$$

where

r_0 is the radius of the borehole and

R is the radius of influence, i.e. distance to a constant head boundary.

If measurements of flow rate are carried out using two levels of hydraulic head in a borehole, i.e. undisturbed and pump-induced heads, then the computational value of head when section flow is zero (h_s) and the transmissivity of the borehole sections tested can be calculated. Equation 3-1 can be reformulated in the following two ways:

$$Q_{s0} = T_s \cdot a \cdot (h_s - h_0) \quad (3\text{-}3)$$

$$Q_{s1} = T_s \cdot a \cdot (h_s - h_1), \quad (3\text{-}4)$$

where

h_0 and h_1 are the hydraulic heads in the borehole at the test levels,

Q_{s0} and Q_{s1} are the measured flow rates in the test section,

T_s is the transmissivity of the test section and

h_s is the undisturbed hydraulic head of the section, i.e. head when the section flow is zero.

In general, since very little is known about the flow geometry, cylindrical flow without skin effect is assumed. The measurements are conducted in steady state conditions and therefore no skin effect can be assumed, and the calculated transmissivity is determined based on the smallest conductivity in the fracture network where the water flow is coming from or going to. Basically, in case of positive skin the calculated transmissivity represents only the transmissivity close to the borehole and transmissivity of the fracture or fracture network further away from the borehole wall cannot be estimated. Cylindrical flow geometry is justified because the borehole is at a constant head, and no strong pressure gradients along the borehole exist except at its ends.

The radial distance *R* to the undisturbed hydraulic head h_s is not known and must therefore be assumed. In this case, a value of 500 for the quotient R/r_0 is selected. This corresponds a radius of influence of 19 m when the diameter of the borehole is 76 mm. Assuming a value of 500 implies that $a \approx 1$.

The hydraulic head h_s and the PFL transmissivity $T_{PFL,s}$ in the test section can be deduced from Equation 3-5 and 3-6:

$$h_s = \frac{h_0 - bh_1}{1-b} \quad (3\text{-}5)$$

$$T_{PFL,s} = \frac{1}{a}\frac{Q_{s0} - Q_{s1}}{h_1 - h_0}, \quad (3\text{-}6)$$

where

$b = Q_{s0}/Q_{s1}$

The PFL fracture transmissivity ($T_{PFL,f}$) and fracture hydraulic head (h_f) of individual fractures can be calculated provided that the flow rates at the individual fractures are known. Similar assumptions to those employed above must be used (*a steady-state cylindrical flow regime without skin zones*).

$$h_{\mathrm{f}} = \frac{h_0 - b h_1}{1 - b} \tag{3-7}$$

$$T_{\mathrm{PFL,f}} = \frac{1}{a} \frac{Q_{\mathrm{f0}} - Q_{\mathrm{f1}}}{h_1 - h_0}, \tag{3-8}$$

where

Q_{f0} and Q_{f1} are the flow rates at a fracture and h_f and T_f are the hydraulic head (*head when fracture flow is zero*) and PFL fracture transmissivity of a fracture, respectively.

Since the actual flow geometry and any skin effects cannot be determined for steady-state flow, transmissivity values should only be considered as an indication of the prevailing orders of magnitude. As the calculated hydraulic heads do not depend on geometrical properties but only on the ratio of the flows measured at different heads in the borehole, they should be less sensitive to unknown fracture geometry. However, it is important to recognise that the measured fracture heads are a result of that the open boreholes connect fractures that may not be connected otherwise. A discussion of potential uncertainties in the calculation of transmissivity and hydraulic head can be found in Ludvigson et al. (2002).

The assumed constant radius of influence used in the formula of transmissivity, leads to uncertainty in determination of the transmissivity. The assumption of constant radius of influence (*R = 19 m*) leads to definition of PFL transmissivity which is practically ΔQ/Δh, i.e. the specific capacity ($T_{PFL} \approx \Delta Q/\Delta h$). Finally, elevated noise level may affect the flow measurements and decrease the resolution of the flow measurements. This may affect determination of the transmissivity values in low-conducting sections, in which the increased noise level could mask smaller flow anomalies. In this report transmissivity refers to transmissivity calculated by Thiem's formula with above mentioned assumptions unless otherwise stated.

Transmissivity of the entire borehole can be evaluated in several ways using data of the pumping phase. The assumption above (*cylindrical and steady state flow*) leads to Thiems's formula (de Marsily 1986):

$$T_T = \frac{Q}{s 2\pi} \ln\left(\frac{R}{r_0}\right) \tag{3-9}$$

where

s is drawdown and Q is the pumping rate at the end of the pumping phase.

In the Moye formula (Moye 1967) it is assumed that the steady-state flow is cylindrical near the borehole (*to distance r = L/2, where L is the section under test)* and spherical further away, see the discussion in Chapter 2 of Follin (1992):

$$T_M = \frac{Q}{s 2\pi} \left[1 + ln\left(\frac{L}{2 r_0}\right)\right] \tag{3-10}$$

where

L is length of the test section (*m*), in this case water filled uncased part of the borehole.

4 Equipment specification

With the PFL DIFF method, the flow of groundwater into or out of a borehole section is monitored using a flow guide which employs rubber sealing discs to isolate any such flow from the flow of water along the borehole. This flow guide defines the test section being measured without altering the hydraulic head. Groundwater flowing into or out of the test section is guided to the flow sensor, and flow is measured using the thermal pulse and thermal dilution methods. Measured values are transferred to a computer in digital form. The main instruments and features of the equipment are listed in Table 4-1.

Table 4-1. Equipment and features.

Type of instrument	PFL DIFF probe
Borehole diameters	56 mm, 66 mm and 76 mm (or larger)
Length of test section	The flow guide length can be varied
Method of flow measurement	Thermal pulse and thermal dilution
Range and accuracy of measurement	See Table 4-2
Additional measurements	Temperature, Single point resistance, Electrical conductivity of water, Water pressure, Air pressure
Winch	Mount Sopris Wna 10, 0.55 kW, conductors, Gearhart-Owen cable head
Length determination	Based on a digital distance counter at winch
Logging computer	PC (Windows 7)
Software	Based on MS Visual Basic
Total power consumption	1.5 – 2.5 kW depending on the type of pump employed
Calibration of flow probe	May 2019 (Probe FL12)

The range and accuracy of the sensors used is presented in Table 4-2.

Table 4-2. Range and accuracy of sensors.

Sensor	Range	Accuracy
Flow	30 – 300 000 mL/h	± 10 % curr. value
Temperature (central thermistor)	0 – 50 °C	0.1 °C
Temperature difference (between outer thermistors)	−2 – +2 °C	0.0001 °C
Electrical conductivity of water (EC)	0.02 – 11 S/m	± 5 % curr. value
Single point resistance (SPR)	5 – 500 000 Ω	± 10 % curr. value
Groundwater level sensor	0 – 0.1 MPa	± 1 % full-scale
Air pressure sensor	800 – 1 060 hPa	± 5 hPa
Absolute pressure sensor	0 – 20 MPa	± 0.01 % full-scale

5 Execution of measurements

5.1 General

The work was carried out according to Activity Plan AP SFK-19-022 following the SKB Method Description 322.010e, Version 2.0 (*Method description for Difference Flow Logging; Table 1-2).* Time was synchronized to Swedish normal time (*UTC + 1*). The activity schedules of the borehole-specific measurements are presented in Table 5-1, Table 5-2 and Table 5-3. The items and activities in the tables coincide to those presented in the Activity Plan. The planned measurement programme is described below.

The dummy logging (*Item 4*) of the borehole was conducted in order to minimize the risk of the measurement tools getting stuck in the borehole. The dummy probe also collects solid material from the borehole wall. The solid material collected by the dummy is used to evaluate whether it is safe to continue measurements in a borehole with other logging tools. Dummy logging does not completely eliminate the risk of equipment getting stuck but it obviously reduces the risk, as well as provides crucial information on the openness of a borehole.

The electrical conductivity (*EC*) and temperature of borehole water (*Item 5*) during undisturbed conditions were measured before flow logging.

The flow along the borehole (*Item 6*) was measured below the casing tube to observe possible leaks from the casing. Measurement was conducted during undisturbed conditions. Casing tubes in the measured boreholes were 76 mm in diameter, which enabled measurement of flow along a casing tube similarly as along a borehole. Flow along the lower part of the casing tube was also measured in all three boreholes.

The flow logging during undisturbed conditions (*Item 7*) was carried out in the borehole with a 5 m section length and in 0.5 m length increments (*step length*). An additional flow logging during undisturbed conditions with a 1 m section length and in 0.1 m length increments (*Item 7 extra 1*) was conducted, when more detailed information on fracture-specific flows in a borehole was needed, on the basis of the first measurement.

The pumping was started after flow logging in undisturbed conditions. After minimum of 12 hours of pumping, flow logging with pumping (*Item 8*) was conducted using the same section and step lengths as in Item 7.

The flow logging was continued with a 1 m section length and a 0.1 m step length (*Item 9*).

The EC of borehole water (*Item 10*) was logged while the measured borehole was still pumped.

The recovery measurement of the groundwater level after pumping the borehole was originally included in the Activity Plan, but was dismissed as unnecessary prior to execution of the measurements.

Additional measurements carried out during the measurement campaign are listed as extra activities in the tables.

Table 5-1. Flow logging and testing in KFM25. Activity schedule.

Item	Activity	Description	Date
4	Dummy logging	Borehole stability/risk evaluation.	2019-10-22
5	EC and temperature of borehole water	Logging without the lower rubber discs, no pumping.	2019-10-23
6	Flow along the borehole	Flow along the borehole below the casing tube (lengths 5.0 m, 7.0 m and 85.1 m) without the lower rubber discs, no pumping.	2019-10-24
7	Flow logging without pumping	Section length L_w = 5 m, step length dL = 0.5 m, no pumping.	2019-10-23
8	Flow logging with pumping	Section length L_w = 5 m, step length dL = 0.5 m, with pumping. Drawdown = 5 m.	2019-10-25
9	Flow logging with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 5 m.	2019-10-25 – 2019-10-26
10	EC and temperature of borehole water with pumping	Logging without the lower rubber discs, with pumping. Drawdown = 5 m.	2019-10-26

Table 5-2. Flow logging and testing in KFM26. Activity schedule.

Item	Activity	Description	Date
4	Dummy logging	Borehole stability/risk evaluation.	2019-10-27
5	EC and temperature of borehole water	Logging without the lower rubber discs, no pumping.	2019-10-27
6	Flow along the borehole	Flow along the borehole below the casing tube (lengths 5.9 m, 9.4 m and 95.5 m) without the lower rubber discs, no pumping.	2019-10-30
7	Flow logging without pumping	Section length L_w = 5 m, step length dL = 0.5 m, no pumping.	2019-10-28
7 extra 1	Flow logging without pumping	Section length L_w = 1 m, step length dL = 0.1 m, no pumping.	2019-10-28 – 2019-10-29
8	Flow logging with pumping	Section length L_w = 5 m, step length dL = 0.5 m, with pumping. Drawdown = 1 m.	2019-10-31
8 extra 1	Flow logging with pumping	Water level measurement while waiting for steady state with pumping.	2019-10-30 – 2019-10-31
9	Flow logging with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 1 m.	2019-10-31 – 2019-11-01
10	EC and temperature of borehole water with pumping	Logging without the lower rubber discs, with pumping. Drawdown = 1 m.	2019-11-01

Table 5-3. Flow logging and testing in KFM27. Activity schedule.

Item	Activity	Description	Date
4	Dummy logging	Borehole stability/risk evaluation.	2019-11-04 – 2019-11-05
5	EC and temperature of borehole water	Logging without the lower rubber discs, no pumping.	2019-11-05
6	Flow along the borehole	Flow along the borehole below the casing tube (lengths 8.0 m and 9.8 m) without the lower rubber discs, no pumping.	2019-11-06 – 2019-11-07
6 extra 1	Flow along the borehole	Flow along the borehole at bottom of the borehole (lengths 92.1 m) without the lower rubber discs, with and without pumping.	2019-11-07
7	Flow logging without pumping	Section length L_w = 5 m, step length dL = 0.5 m, no pumping.	2019-11-05
7 extra 1	Flow logging without pumping	Section length L_w = 1 m, step length dL = 0.1 m, no pumping.	2019-11-05 – 2019-11-06
8	Flow logging with pumping	Section length L_w = 5 m, step length dL = 0.5 m, with pumping. Drawdown = 2.8 m.	2019-11-08
9	Flow logging with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 2.8 m. Measurement not reported and renewed later due to excessive noise in flow result.	2019-11-08 – 2019-11-09
9 extra 1	Flow logging with pumping	Section length L_w = 1 m, step length dL = 0.1 m, with pumping. Drawdown = 2.8 m.	2019-11-09 – 2019-11-10
10	EC and temperature of borehole water with pumping	Logging without the lower rubber discs, with pumping. Drawdown = 2.8 m.	2019-11-09

5.2 Nonconformities

The Activity plan specified a target drawdown of 5 m during pumping as drawdown of 5 m was considered sufficient from data processing point of view. Usually a 10 m drawdown is used, but in these cases when the casing pipes are short (between 6.08 and 9.03 m), a smaller drawdown can be used to extend the coverage of the measurements in the upper part of the borehole, as longer section of the borehole remains below water level. Reducing the drawdown from 10 m to 5 m affects the detection of fractures with small transmissivities. It is possible that some of the fractures that could have been detected with 10 m drawdown were not detected with 5 m drawdown. In general minimum PFL transmissivity with 5 m drawdown is around 1.5×10^{-9} m^2/s (8.33×10^{-9} $m^3/s/5$ m). This does not mean that it is impossible to detect fractures with smaller transmissivities but most likely fractures that have larger transmissivities have been detected. Although in these boreholes fracture frequency was so high that it is possible that some flowing fractures have not been detected because they locate so close to larger fracture or between larger fractures.

However, the target drawdown of 5 m was achieved only in borehole KFM25. Despite a high pumping rate, only 1 m drawdown was achieved in borehole KFM26 and 2.8 m drawdown in borehole KFM27. The inner diameter of casing pipes was 76.3 mm which constrains the physical size of a pump that can be used in a borehole. In this case a Grundfos MP1 submersible pump, which has a maximum pumping capacity of ca 30 L/min, was used. Obtained drawdowns and pumping rates at boreholes are presented in Section 6.6. At borehole KFM27, which was measured last, a drawdown of 2.8 m was achieved with a pumping rate of 34.5 L/min. High pumping rate was achieved by using two Grundfors MP1 submersible pumps in series.

Pumping of boreholes was planned in a way that unmeasurable part at top of borehole would be small. For this reason pumped drawdown was 5 m instead of 10 m. Even with the target drawdown of 5 m or less, it was not possible to continue flow logging all the way up to the casing tube while the pumping was on. Nevertheless, flow logging was continued after removing the pump from the borehole and the upper part of the hole was flow logged while the water level was recovering.

Interpretation of transmissivity and head assume steady-state conditions. Therefore, measurement results obtained during unstable pressure conditions, cannot be evaluated in a similar way as for steady-state conditions. The results obtained during the unstable pressure conditions, and interpretations based on those results, are presented with different colours than other measurements in plots and tables, and comments have been added accordingly.

High flow rates, requiring special attention, were observed at all boreholes. Usually the length intervals, in which flow rates are close to the upper measurement limit, are re-measured with a smaller drawdown to achieve flow rate clearly within measurement limits. In these measurements, with the drawdown already being smaller than usual, it was not seen applicable to further decrease the pumped drawdown since the pressure difference between measurements with and without pumping was already small.

The flow probe is calibrated up to 300 000 mL/h and it is an upper limit that cannot be exceeded. In KFM27, one section flow exceeded the upper measurement limit (*316 076 mL/h, see Section 4.6.1*). Fracture-specific flows at the same area were slightly below the upper measurement limit and therefore it was decided that the measurements with a smaller pumping rate were not necessary to carry out (see Section 4.6.2). Also, even smaller flows (*100 000–300 000 mL/h*) can cause flow friction in flow sensor, causing a slight pressure rise in the measurement section. Usually flow measurements have been repeated with a smaller drawdown even if upper limit has not been exceeded, as in these cases actual flow rate for those sections could probably be higher than the measured flow rates. In these measurements high fracture and section flows which caused friction loss in the PFL DIFF probe's flow guide, causing a slight pressure rise, were examined in more detail to make sure that correct head and flow values were used in interpretation (*see Appendices KFM##.10.1 – KFM##.10.n*).

Weights and a centralizer attached to the lower end of the PFL DIFF probe, together with other technical limitations, reduced the measurable section of the borehole at the bottom by ca 3.8 m. The weights and the centralizer take ca 3.7 m, while length required for flipping the sealing discs of the device is ca 0.1–0.2 m. It is also possible that there are fallen rocks and debris at the bottom of the borehole, limiting the measurable length.

Flow along a borehole was measured just below casing pipe in order to detect possible leakages between casing pipe and bedrock. This measurement is in the activity plan. In these boreholes inner diameter of casing pipe is 76.3 mm therefore the rubber disks also seal the casing pipe and flow along the casing pipe could be measured also. Therefore this additional measurement was conducted although it was not in the activity plan. If the casing pipe is larger the measurement cannot be done.

Nonconformities mentioned above concern all measured boreholes. Borehole-specific nonconformities are summarised below.

5.2.1 KFM25

An additional flow along the borehole measurement was conducted at the length of 5.0 m, at the casing tube as a complementary measurement to the initial flow along the borehole measurement. Another additional flow along the borehole measurement was conducted at the length of 85.1 m. The results from those additional time series measurement are presented in Appendix KFM25.2.6 and KFM25.2.8. The additional measurements are included in Item 6 presented in Table 5-1.

To extend the flow logging measurements under pumped conditions to the casing tube, the submersible pump was lifted out of the borehole and the flow logging was then continued further upwards during groundwater recovery (*i.e. groundwater level was in transition during the measurement*). Length interval of ca 4.9–9.9 m was measured using 5 m measurement section, and length interval of ca 4.4–9.7 m was measured using 1 m measurement section. Differences in measured length intervals result from different measurement steps used with different section lengths (*i.e. 0.1 m measurement step with 1 m measurement section and 0.5 m measurement step with 5 m measurement section*). Three flowing fractures (*fractures at 6.6 m, 8.3 m and 9.4 m*) were detected within the measured length interval (*see Appendix KFM25.2.1*). The measurements conducted during groundwater recovery are included in Item 8 (*5 m section length*) and Item 9 (*1 m section length*) presented in Table 5-1.

5.2.2 KFM26

An additional flow along the borehole measurement was conducted at the length of 5.9 m, at the casing tube as a complementary measurement to the initial flow along the borehole measurement. Another additional flow along the borehole measurement was conducted at the length of 95.5 m. The results from those additional time series measurement are presented in Appendix KFM26.2.6 and KFM26.2.8. The additional measurements are included in Item 6 presented in Table 5-2.

The entire length of the borehole KFM26 was measured with flow logging without pumping using 1 m measurement section and 0.1 m measurement interval. The measurement results are labelled as Extra 1 in graphs presented in the appendices. The measurement was conducted to distinguish individual fracture flows from the flow anomalies obtained in Flow 1 measurement (*5 m section length*) and to extend the measurement under natural conditions to cover the bottom of the borehole in more detail, as far as possible. The results from Extra 1 measurement replaced Flow 1 measurement results in fracture-specific interpretations. The measurement is presented as Item 7 extra 1 in Table 5-2.

To extend the flow logging measurements under pumped conditions to the casing tube, the submersible pump was lifted out of the borehole and the flow logging was then continued further upwards during groundwater recovery (*i.e. groundwater level was in transition during the measurement*). Therefore, length interval of ca 5.9–6.4 (*5 m and 1 m measurement section*) was measured during groundwater recovery. No additional flowing fractures were detected within the measured length interval (*see Appendix KFM26.2.1*). The measurements conducted during groundwater recovery are included in Item 8 (*5 m section length*) and Item 9 (*1 m section length*) presented in Table 5-2.

Drawdown had to be adjusted and depth of the submersible pump was changed prior to starting Flow 2 measurement and therefore flow logging was conducted as another measurement event. The measurement data containing water level measurement while waiting for steady state with pumping is presented in Appendix KFM26.9.2. The flow logging is presented as Item 8 extra 1 in Table 5-2.

5.2.3 KFM27

Additional flow along the borehole measurements were performed with and without pumping. Flow along the borehole without pumping was measured at the length of 8.0 m at the casing tube to detect any possible leaks at the casing tube. This measurement is included in Item 6 in Table 5-3. Another flow measurement along the borehole was conducted without pumping at the length of 92.1 m to obtain more information regarding the unmeasurable (*see above*) bottom part of the borehole. While the time series measurement was being performed, pumping was started for test purposes. However, the pumping period was not long enough that reliable steady-state pressure conditions in the borehole could be reached. Therefore, the vertical flow results measured in pumped conditions are not used in interpretations in any way and should be considered as indicative only. Both measurements (*with and without pumping at the length of 92.1 m*) are included in Item 6 extra 1 presented in Table 5-3.

The entire length of the borehole KFM27 was measured with flow logging without pumping using 1 m measurement section and 0.1 m measurement interval. The measurement results are labelled as Extra 1 in graphs presented in the appendices. The measurement was conducted to distinguish individual fracture flows from the flow anomalies obtained in Flow 1 measurement (*5 m section length*) and to extend the measurement under natural conditions to cover the bottom of the borehole in more detail as far as possible. The results from Extra 1 measurement have completely replaced Flow 1 measurement results in fracture-specific interpretations. The measurement is presented as Item 7 extra 1 in Table 5-3.

The initial flow logging measurement using 1 m measurement section and 0.1 m measurement interval in pumped conditions performed between 2019-11-08 and 2019-11-09 (*Item 9 in Table 5-1*) was dismissed due to excessive noise present in the flow results. The results from the measurement (*Item 9*) are not reported or used in any way in the interpretations. The entire length of the borehole was then re-measured between 2019-11-09 and 2019-11-10 with flow logging in pumped conditions using the same measurement parameters. Results from the re-measurement are labelled as Flow 3 in graphs presented in the appendices. The re-measurement is presented as Item 9 extra 1 in Table 5-3.

To extend the flow logging measurements under pumped conditions to the casing tube, the submersible pump was lifted out of the borehole and the measurement was then continued further upwards during groundwater recovery (*i.e. groundwater level was in transition during the measurement*). Length interval of ca 8.4–10.3 m was measured using 1 m measurement section. Two flowing fractures (*fractures at 9.1 m and 10.1 m*) were detected within the measured length interval (*see Appendix KFM27.2.1*). The measurement conducted during groundwater recovery is included in Item 9 extra 1 (*1 m section length*) presented in Table 5-3.

6 Results

Measurement results are presented in detail in three appendices, A–C. The table of contents of the appendices is the same for all boreholes and therefore the appendices are referenced by denoting as KFM##.m.n. in which ## denotes the borehole number and m and n are detailing numbers of appendices presenting certain measurement results. At the end of appendices there might be additional plots that are numbered similarly but are borehole-specific plots representing special cases.

6.1 Length calibration

An accurate length scale for the measurements is difficult to achieve in long boreholes. The main cause of inaccuracy is stretching of the logging cable. The stretching depends on the tension on the cable, the magnitude of which in turn depends, among other things, on the inclination of the borehole and the roughness (*friction properties*) of the borehole wall. The cable tension is larger when the borehole is measured upwards. The cables, especially new cables, may also stretch out permanently. Length marks at the cable have been set to tensioned (*ca 100 kg*) cable to simulate cable stretching during measurement. The boreholes KFM25, KFM26 and KFM27 are not very long so cable stretching is not a big issue in this case.

6.1.1 SPR measurement

All flow logging sequences can be length calibrated by synchronising the SPR results (*SPR is recorded during all flow logging measurements but not during the borehole EC measurements)* with other resistivity measurements. However, in this measurement campaign reference data for SPR was no available. Length determination is based on cable marks in the measurement cable. In practice the first flow logging was set as a reference measurement and subsequent measurements were length matched to it if needed.

6.1.2 Estimated error in location of detected fractures

Despite the length calibration described above, there can still be errors due to the following reasons.

Stretching of the cable is most likely different during measurement than while cable marks have been set (*calibration tension ca 100 kg*). Based on experience 1 000 m of measurement cable stretches about 3 m when tension is increased from 75 kg to 175 kg. Based on this estimated length error in positioning the PFL DIFF probe in 100 m long borehole while cable tension varies from 50 kg to 150 kg is ± 0.15 m at the most.

The point interval in the overlapping mode flow measurements is 0.1 m. This could cause an error of ± 0.05 m. This error is random.

The length of the test section is not exact. The specified section length denotes the distance between the nearest upper and lower rubber sealing discs. Effectively, the section length can be longer. At the upper end of the test section there are four rubber sealing discs. The distance between them is 5 cm. This will cause rounded flow anomalies: a flow may be detected already when a fracture is situated between the upper rubber sealing discs. These phenomena can cause an error of ± 0.05 m when the short measurement step length (*0.1 m*) is used.

In worst-case scenario, the errors from sources 1, 2 and 3 are summed and the total estimated error would be ± 0.25 m. Note, that error given above is an estimation based on experience and observations from earlier measurements and it is not guaranteed to hold in all conditions.

Knowing the location accurately is important when different measurements are compared, for instance flow logging and borehole TV. In that case, the situation may not be as severe as the case above, since some of the length errors are systematic and the error is nearly constant in fractures that are close to each other.

Fractures nearly parallel with the borehole may also be problematic. Fracture location may be difficult to define accurately in such cases.

6.2 Electrical conductivity and temperature

6.2.1 Electrical conductivity and temperature of borehole water

The EC of the borehole water is initially measured when the borehole is at rest, i.e., at undisturbed conditions. The measurement was repeated during pumping (*after a pumping period of three to five days*). Measurements were performed downwards in order to avoid mixing of the borehole water before the measurement. Electrical conductivity measurement results have been presented in Appendices KFM##.1.1 in linear EC scale and in Appendices KFM##1.2 in logarithmic EC scale.

The temperature of the borehole water was measured simultaneously with the EC measurements. The EC values are temperature corrected to 25 °C to make them more comparable with other EC measurements (Heikkonen et al. 2002). The temperature results are presented in Appendices KFM##.1.3.

The length calibration of the borehole EC measurements is not as accurate as in other measurements, because SPR is not registered. The length correction is linear and based on the nearest tape marks on the cable at start and end length.

6.3 Pressure measurements

Absolute pressure was registered along with the other measurements in Items 6–9. The pressure sensor measures the sum of hydrostatic pressure in the borehole and air pressure. Air pressure was also registered separately (*Appendices KFM##.9.2*). The hydraulic head along the borehole at undisturbed and pumped conditions is determined in the following way. First, the monitored air pressure at the site is subtracted from the measured absolute pressure. The hydraulic head (h) at a certain elevation (*z*) is calculated according to the following expression (Nordqvist 2001):

$$h = (p_{abs} - p_b)/(\rho_{fw} \cdot g) + z \qquad (6\text{-}1)$$

where

h is the hydraulic head in metre above sea level (masl) according to the RH 2000 reference system,

p_{abs} is the absolute pressure (Pa),

p_b is the barometric (air) pressure (Pa),

ρ_{fw} is the unit density, 1 000 kg/m^3

g is the standard gravity, 9.80665 m/s^2 and

z is the elevation of measurement (masl) according to the RH 2000 reference system.

The calculated head distributions are presented in Appendices KFM##.9.1. Exact z-coordinates are important in hydraulic head calculation as an error in the z-coordinate leads to an equal error in the calculated head.

6.4 Flow logging

6.4.1 General comments on results

The measuring programme contained several flow logging sequences, which are numbered as Flow 1 (*flow flogging without pumping with a 5 m section length, Q_0 in tables*), Flow 2 (*flow logging with pumping with a 5 m section length, Q_1 in section flow table*) and Flow 3 (*flow logging with pumping with a 1 m section length, Q_1 in fracture flow table*). They are presented in the same diagram with the SPR (*right hand side; Appendices KFM##.2.1 – KFM##.2.n*). The SPR usually has a lower value over fractures where flow is detected. Many other resistance anomalies result from other fractures and geological features. As the electrode of the SPR tool is located within the upper rubber sealing discs of the probe, the locations of resistance anomalies associated with leaking fractures coincide with the lower end of the flow anomalies. The exact position of the SPR electrode is 5 cm higher than upper end of the measurement section (*the lowest rubber disc at upper end on section*). The reference length for both SPR and flow measurement is distance between borehole 0 m length and upper end of measurement section. This has been considered when processing the data.

The flow logging was first performed with a 5 m section length and with 0.5 m length increments. The method (*overlapping flow logging*) gives the position of conductive zones along a borehole with a length resolution of 0.5 m.

Under undisturbed conditions (or if the borehole is not pumped using a sufficient drawdown) the flow direction may be into the borehole or out from it. The direction of small flows (*< 100 mL/h*) cannot be detected in the normal overlapping mode (*thermal dilution method*). Therefore, the measurement time was longer (*so that the thermal pulse method could be used*) at every 5 m interval in both (*under undisturbed and pumped conditions*) 5 m section measurements.

The length of the test section and the length of the increments determine the presence of a flow anomaly of a single fracture. If the distance between flow yielding fractures is less than section length, the flow anomalies will overlap, resulting in a stepwise flow data plot. The overlapping flow logging was repeated using a 1 m long test section and 0.1 m length increments.

The position (*borehole length*) of the detected fractures is shown on the middle scale in Appendices *KFM##.2.1 – KFM##.2.n* . They are interpreted based on the flow curves and therefore represent flowing fractures. A long line represents the location of a flowing fracture; a short line denotes that the existence of a leaking fracture is uncertain. The short line is used when the flow rate is less than 30 mL/h or if determination of flow rate is uncertain due to overlapping flow anomalies or because of noise (*Section 6.4.4).*

The coloured triangles show the magnitude and direction (*from borehole into bedrock or from bedrock into borehole*) of the measured flows. The triangles have the same colour as the corresponding curves.

The glossary of terms used in the tables in Appendices KFM##.4 and KFM##.6 are given in Appendices KFM##.3.

KFM25

Results from the vertical flow along the borehole measurements conducted without pumping, alongside with concurrent air pressure and water level measurement results, are presented in Appendices KFM25.2.6 – KFM25.2.8. Three time series measurements were conducted in KFM25, at the borehole lengths of 5.0 m (*in the casing tube*), 7.0 m (*below the percussion drilled part of the borehole where the casing tube is installed*) and at 85.1 m.

Vertical flows measured at the lengths of 5.0 m and 7.0 m fluctuated notably. The reason for the fluctuation is not fully clear. If the highest spike values would be left disregarded, the averaged flow rate for both measurements would be in the range of ca 250 mL/h. However, also the direction of flow varied to some extent during the both measurements rendering the results ultimately inconclusive. Despite the uncertainty over the interpretation of the results, it still can be concluded that the casing tube or the junction of the bedrock and the casing tube did not leak notably in un-pumped conditions.

Vertical flow measured at 85.1 m was made to detect possible flowing fractures present in the unmeasurable lower part of the borehole. The measured vertical flow stabilized to ca 2 000 mL/h (*average of 10 last flow measurements*), towards the bottom of the borehole. The result coincides with the one obtained from the flow logging without pumping measurement (*Flow 1*) as the sum of measured fracture flows below the length of 85.1 m was 2 292 mL/h into the bedrock. However, it should be taken into account that groundwater level was in slight transition during the vertical flow measurement and did not reach the same level as during Flow 1 measurement (*the measurement had to be finished due to limitations in measurement timetable*), difference being ca 15 cm below the water level measured during Flow 1 measurement (*see Appendix KFM25.9.2*). As even the slightest change in groundwater level can impact fracture flows considerably, there remains a possibility that somewhat higher fracture flows into the bedrock in the bottom part of the borehole could exist.

KFM26

Results from the vertical flow along the borehole measurements conducted without pumping, alongside with concurrent air pressure and water level measurement results, are presented in Appendices KFM26.2.6 – KFM26.2.8. Three time series measurements were conducted in KFM26 at the borehole lengths of 5.9 m (*in the casing tube*), 9.4 m (*just below the percussion drilled part of the borehole where the casing tube is installed*) and at 95.5 m.

Vertical flow measured at the length of 5.9 m (*Appendix KFM26.2.6*) had some fluctuation in the flow result. The reason for the fluctuation is not fully clear. However, if the highest spike values are disregarded, the averaged flow rate would be in the range of ca 200 mL/h. In general, it could be concluded that the casing tube did not have notable leaks in un-pumped conditions.

Vertical flow measured at the length of 9.4 m (*Appendix KFM26.2.7*) stabilised to ca 3 600 mL/h on average. Direction of the measured flow was upwards, towards surface of the borehole. The result coincides with the one obtained from flow logging without pumping measurement (Item *7 Extra 1 measurement*) as the sum of fracture flows above 9.4 m was 3 038 mL/h. Difference of groundwater level in the borehole between the two measurements was ca 5 cm, which could explain the difference in flow rates between these two measurements.

Vertical flow measured at 95.5 m (*Appendix KFM26.2.8*) was made to detect possible flowing fractures present in the unmeasurable lower part of the borehole. The measured vertical flow stabilized to ca 34 300 mL/h. Direction of the measured flow was upwards, towards surface of the borehole. Only one low-yielding fracture had previously been detected below the length of 95.5 m (*Item 7 Extra 1 measurement, fracture at 95.9 m*). The obtained vertical flow result therefore indicates a presence of a significant inflow between 97.0 m (*bottommost flow logging measurement data available*) and the bottom of the borehole. Note that groundwater level during the measurement was not exactly the same compared to the measurements conducted at and under the casing tube (*see Appendices KFM26.2.6 – KFM26.2.8 and KFM26.9.2*), but was ca 18 cm lower.

KFM27

Results from the vertical flow along the borehole measurements conducted without pumping, alongside with concurrent air pressure and water level measurement results, are presented in Appendices KFM27.2.6 – KFM27.2.8. Three time series measurements were conducted in KFM27 at the lengths of 8.0 m (*in the casing tube*), 9.8 m (*below the percussion drilled part of the borehole where the casing tube is installed*) and at 92.1 m.

Vertical flow measured at the length of 8.0 m had some fluctuation in the flow result. The reason for the fluctuation is not fully clear. However, if the highest spike values are disregarded, the averaged flow rate for the measurement would be in the range of ca 130 mL/h, directed downwards. Based on the result, it could be possible that the casing tube could have had a minor leak somewhere above the length of 8.0 m in un-pumped conditions.

Vertical flow measured at the length of 9.8 m stabilised to ca 44 000 mL/h on average, if the coincident spikes in the measured flow rate are disregarded. Direction of the measured flow was upwards. The result coincides with the ones obtained from flow logging without pumping measurement as the outflow measured above 9.8 m was 43 600 mL/h (*Extra 1 measurement, see Appendices KFM27.2.1 and KFM27.6.1*).

Vertical flow measured at 92.1 m was made to detect possible flowing fractures present in the unmeasurable lower part of the borehole. The measured vertical flow stabilized to ca 18 500 mL/h. Direction of the measured flow was upwards. Three relatively small inflowing fractures had previously been detected below the length of 92.1 m (*fractures at 93.5 m, 94.5 m and 95.4 m*). When those fracture flows are subtracted from the measured vertical flow, the result indicates a presence of a notable inflow of ca 18 000 mL/h between the length of 97.0 m (the bottommost flow logging measurement data available) and the bottom of the borehole.

6.4.2 Transmissivity and hydraulic head of borehole sections

The borehole was flow logged with a 5 m section length and with 0.5 m length increments in both, undisturbed conditions and during pumping.

The results of the measurements with 5 m section length are presented in tables (*Appendices KFM##.4*). All flowing borehole sections are shown in Appendices KFM##.2. Secup and Seclow in Appendices KFM##.4 are the distances along the borehole from the reference level (*top of the casing tube*) to the upper end of the test section and to the lower end of the test section, respectively. The Secup and Seclow values for the two sequences (*measurements in undisturbed conditions and during pumping*) are not exactly identical, due to a minor difference in the cable stretching. The difference between these two sequences was small. Secup and Seclow given in Appendices KFM##.4.n are calculated as the average of these two values.

The total conductive fracture frequency (*CFF*) is presented graphically (*Appendices KFM##.5.4*).

Pressure was measured and hydraulic head calculated as described in Section 6.3. h_{0FW} and h_{1FW} in Appendices KFM##.4 represent heads determined without and with pumping, respectively. The head in the borehole and calculated heads of borehole sections are given in RH 2000 scale.

The flow results in Appendices KFM##.4 (*Q_0 and Q_1*), representing the flow rates derived from measurements during undisturbed conditions and under pumping, are presented side by side to make comparison easier. Flow rates are positive if the flow direction is from the bedrock into the borehole and vice versa.

It is also possible to detect the existence of flow anomalies below the lower measurement limit (*30 mL/h = 8.33×10^{-9} m^3/s*), even though the exact numerical values below the limit are uncertain.

The flow data is presented as a plot (*Appendix KFM##.5.1*). The left-hand plot in each diagram represents flow from the borehole into the bedrock for the respective test sections, while the right-hand plot represents flow from the bedrock into the borehole. If flow could not be detected (*zero flow*), no corresponding point will be visible on the logarithmic plots in the appendices.

The lower and upper measurement limits of the flow are also presented in the plot (*Appendix KFM##.5.1*) and in the tables (*Appendices KFM##.4*). There are theoretical and practical lower limits of flow (*Section 6.4.4*).

The hydraulic head and transmissivity (T_{PFL}) of borehole sections can be calculated from the flow data using the method described in Chapter 3. The results are illustrated in Appendices KFM##.5.2. The hydraulic head of sections is presented in the plots if none of the two flow values at the same length is equal to zero. Transmissivity is presented if none or just one of the flows is equal to zero.

The measurement limits of transmissivity are also shown in Appendices KFM##.5.2 and in Appendices KFM##.4. All the measurement limit values of transmissivity are based on the actual pressure difference in the borehole (*h_{0FW} and h_{1FW} in Appendices KFM##.4*).

KFM25

The sum of all the detected flows in un-pumped conditions (Q_0) was 7.84×10^{-7} m^3/s (*2 821 mL/h*). More flows into the borehole than into the bedrock were detected. This sum should normally be zero if the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures remain at steady-state pressure. In this case the measured inflows and outflows were not balanced, the sum of the absolute flow rates was 4.28×10^{-6} m^3/s, leaving the unbalance between inflows and outflows considerably higher than the given ± 10 % accuracy of the flow measurement. The reason for the off-balance might be that there are more flows into the bedrock in the unmeasured bottom part of the borehole. Water level of the borehole was steady during the flow logging, indicating that the measurements were conducted in stable conditions.

The sum of measured section flows in pumped conditions (Q_1) was 1.18×10^{-4} m^3/s (*425 537 mL/h*). Pumping rate during the measurement with 5 m drawdown was ca 8.43 L/min (*505 800 mL/h*) on average.

The pumping rate was notably higher than the sum of measured section flows (Q_1). However, in KFM25 the sum of section flows, as such, cannot be compared directly to the pumping rate because upper part of the borehole could not be measured in pumped conditions, as the pump had to be lifted out of the borehole to reach the uppermost lengths of the hole with the PFL DIFF probe. It should also be noted that the measured flow rates from sections at 63.46 m (*Secup*) and 73.46 m (*Secup*) were enough to cause friction loss in the PFL DIFF probe's flow guide causing a slight pressure rise in the measurement section while pumping was on. Pressure increase of ca 1.3 kPa at the section at 63.46 m (*Secup*) and pressure increase of ca 1.6 kPa at the section at 73.46 m (*Secup*) was measured. Therefore, actual flow rate for those sections could probably be higher than the measured flow rates. These section lengths were examined in more detail to make sure that correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendices KFM25.10.1 – KFM25.10.2*). The occurrences described above could partly explain the off-balance between the sum of section flows and the measured pumping rate. Also, there could be more flows into the hole in the unmeasured bottom part of the borehole.

Note that the given length for the uppermost section measured during groundwater recovery (*4.95 m, Secup*) is 3.5 m (*see Appendix KFM25.4*). The physical length of the measurement section was 5 m, but the interpreted section length is based on the actual measurement points within the last interpreted section which resulted in shorter reported section length.

Another 3.5 m section was added to the bottom of the borehole to give additional information over the lower parts of the hole (*see Appendix KFM25.4*). Value for the section flow without pumping (Q_0) is based on the fracture flow interpretation of Flow 1 measurement and the corresponding section head (h_{0FW}) is the bottommost measured value available from Flow 1 measurement (*from the length of 92.01 m*). Respectively, values for for the corresponding section flow (Q_1) and head (h_{1FW}) at 93.51 m (*Secup*) with pumping are from Flow 3 measurement.

KFM26

The sum of all the detected flows in un-pumped conditions (Q_0) was -1.95×10^{-5} m^3/s *(−70 252 mL/h)*. If the detected inflow from the bottom of the borehole (*vertical flow measured at ca 95.5 m, see Section 6.4.1*), is considered, the sum would be -9.99×10^{-6} m^3/s (*−35 952 mL/h*). More flows into the bedrock than into the borehole were detected. This sum should normally be zero if the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures remain at steady-state pressure. In this case the measured inflows and outflows were not balanced, the sum of the absolute flow rates was 3.09×10^{-5} m^3/s, leaving the unbalance between inflows and outflows significantly higher than the given ± 10 % accuracy of the flow measurement. However, even a small change in a borehole water level can have a considerable impact on fracture-specific flows if there are highly transmissive fractures present in a borehole. In KFM26 this is the case at fractures at 35.2 m, 70.1 m, 80.8 m, 85.9 m and 94.5 m (*see Appendices KFM26.6.1 – KFM26.6.2*) and therefore the small variation in groundwater level (*ca 3 cm*) noticed during Flow 1 measurement (*see Appendix KFM26.9.2*) could, at least partly, explain the off-balance.

The sum of measured section flows in pumped conditions (Q_1) was 8.18×10^{-5} m^3/s (*294 383 mL/h*). Pumping rate during the measurement with 1 m drawdown was ca 19.2 L/min (*1 152 000 mL/h*) on average (*ca 19.3 L/min at the start and ca 18.7 L/min in the end of the measurement*).

The pumping rate was notably higher than the sum of measured section flows (Q_1). However, in KFM26 the sum of section flows, as such, cannot be compared directly to the pumping rate because upper part of the borehole could not be measured in pumped conditions, as the pump had to be lifted out of the borehole to reach the uppermost lengths of the hole with the PFL DIFF probe. It should also be noted that the measured flow rates from sections at 69.88 m (*Secup*) and 89.90 m (*Secup*) were enough to cause friction loss in the PFL DIFF probe's flow guide causing a slight pressure rise in the measurement section while pumping was on. Pressure increase of ca 0.7 kPa at the section at 69.88 m (Secup) and pressure increase of ca 1.5 kPa at the section at 89.90 m (*Secup*) was measured. Therefore, actual flow rate for those sections could probably be higher than the measured flow rates. These section lengths were examined in more detail to make sure that correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendices KFM26.10.1 – KFM26.10.2*). The occurrences described above could partly explain the off-balance. However, the most important contributing factor to the difference between the sum of measured section flows and the measured pumping rate is that there probably remains a significant conductivity in the unmeasurable bottom part of the borehole. This assumption is based on the vertical flow measurement result conducted in un-pumped conditions at the borehole length of 95.5 m (*see Section 6.4.1*).

Flow anomalies applicable to section 9.84 m (*Secup*) from Flow 2 measurement were unclear and inconsistent compared to the result from Flow 3 measurement from the corresponding length interval (*see Appendix KFM26.2.1*). Therefore reliable section flow rate for section 9.84 m (*Secup*) in pumped conditions could not be defined.

Note that the given length for the uppermost section measured during groundwater recovery (*5.84 m, Secup*) is 4 m (*see Appendix KFM26.4*). The physical length of the measurement section was 5 m, but the interpreted section length is based on the actual measurement points within the last interpreted section which resulted in shorter reported section length.

Another nonconforming section, with a length of 2 m, was added to the bottom of the borehole (*94.9 m, Secup*) to give additional information over the lower parts of the borehole (*see Appendix KFM26.4*). Values for the section flow without pumping (Q_0) and the corresponding section head (h_{0FW}) are based on the fracture flow interpretation of Item 7 Extra 1 measurement. Respectively, values for the corresponding section flow (Q_1) and head (h_{1FW}) at with pumping are interpreted from Flow 3 measurement.

KFM27

The sum of all the detected flows in un-pumped conditions (Q_0) was -1.20×10^{-5} m^3/s (*−43 350 mL/h*). If the inflow from the unmeasurable bottom part of the borehole (*See Section 6.4.1*) is taken into account, the sum of flows would be -7.04×10^{-6} m^3/s (*−25 350 mL/h*). More flows into the bedrock than into the borehole were detected. This sum should normally be zero if the flows in the borehole are not disturbed by noise or other external factors, the borehole is not pumped, the water level is constant, the salinity distribution in the borehole is stabilized and the fractures are at steady state pressure. In this case the measured inflows and outflows were balanced, the sum of the absolute flow rates was 1.26×10^{-4} m^3/s (*or 1.31×10^{-4} m^3/s when adding the inflow from the bottom part*), thus the unbalance between inflows and outflows was well within the given ± 10 % accuracy of the flow measurement.

High flow rates in un-pumped conditions were measured at sections 14.85 m and 84.89 m (*Secup*). High outflow at section 14.85 m (*Secup*) caused a pressure drop of ca 7.4 kPa and high inflow at section 84.89 m (*Secup*) caused a pressure rise of ca 1.3 kPa. These measured flow rates were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the two sections would probably be higher than the measured flow rates. These section lengths were examined in more detail to make sure correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to visualise the effect of pressure increase (*Appendices KFM27.10.1 and KFM27.10.5*).

The sum of measured section flows in pumped conditions (Q_1) was 1.50×10^{-4} m^3/s (*539 119 mL/h*). Pumping rate during the measurement with 2.8 m drawdown was ca 31.5 L/min (*1 890 000 mL/h*) on average (*ca 36.5 L/min at the very start and ca 31.6 L/min in the end of the measurement*). Note that the drawdown of 2.8 m was not enough to turn the direction of all section inflows. Flow directions of sections at 8.35 m, 10.35 m, 14.85 m, 19.86 m and 24.88 m (*Secup*) remained into the bedrock.

The pumping rate was significantly higher than the sum of measured section flows (Q_1). However in KFM27 the sum of section flows, as such, cannot be compared directly to the pumping rate because upper part of the borehole could not be measured in pumped conditions, as the pump had to be lifted out of the borehole in order to reach the uppermost lengths with the PFL DIFF probe. More importantly, the measured flow rate of ca 316 076 mL/h from the section at 84.89 m (*Secup*) exceeded the upper measurement limit of the PFL DIFF probe causing a considerable pressure rise of ca 14.0 kPa in the measurement section while pumping was on. Pressure increase was noticed also at sections 64.88 m and 69.88 m (*Secup*). Pressure increase of ca 3.5 kPa at the section 64.88 m and ca 3.8 kPa at the section 69.88 m was measured. Additionally, high outflow at section 14.85 m (*Secup*) caused a pressure drop of ca 2.4 kPa. All these measured flow rates were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the four sections would probably be higher than the measured flow rates. These section lengths were examined in more detail to make sure that correct head and flow values were used in interpretation.

Flow rate and borehole head were plotted together to visualise the effect of pressure increase (see Appendices KFM27.10.2, KFM27.10.4 and KFM27.10.6). It should also be taken into consideration that as the flow logging measurement passes the flowing borehole section relatively quickly; perfect steady-state conditions cannot be reached during normal measurement if a section has significant influence on a borehole flow system. A clear example of the described conditions can be seen at the section 84.89 m (*Secup*) as the measured pumping rate drops dramatically from ca 36 L/min to ca 12 L/min (*see Appendix KFM27.10.6*) when the PFL DIFF probe remained on the high yielding fractured zone (*within the section were fractures at 85.9 m, 86.8 m, 87.9 m and 88.4 m*). As soon as the PFL DIFF probe had passed the high yielding fractured zone, pumping rate normalised to ca 33 L/min. Therefore it can be assumed that the actual transmissivity value for the section at 84.89 m (*Secup*) would most probably be higher than the one reported here. The occurrences described above could partly explain the off-balance between the sum of section flows and the measured pumping rate. Finally, there could probably be a notable inflow from the unmeasurable bottom part of the borehole, estimated on the basis of vertical flow result measured at 92.1 m in un-pumped conditions (*see Section 6.4.1*).

Note that the given length for the uppermost section measured during groundwater recovery (*Secup at 8.35 m*) is 2 m (*see Appendices KFM27.2.1 and KFM27.4*). The physical length of the measurement section was 1 m, but the interpreted section length was chosen to cover the interval measured during groundwater recovery as a whole for the purpose of more convenient presentation. Flow (Q_0) and head (h_{0FW}) in un-pumped conditions for the section are from Extra 1 measurement. The results from Extra 1 measurement were selected due to more straightforward interpretation of measurement results conducted using a shorter test section (*1 m*) compared to Flow 1 measurement (*5 m test section*) from the corresponding borehole lengths.

Interpretation of the section 10.35 m (*Secup*) is based on Extra 1 and Flow 3 measurements. Given length for the section is nonconforming 4.5 m even though the actual test section was physically 1 m in length. Again, the interpreted section length was chosen to cover the measured interval as a whole for the purpose of more convenient presentation. Extra 1 and Flow 3 measurements were chosen for interpretation because of their more representative results from that particular borehole length interval compared to Flow 1 and Flow 2 measurement results. Also, the fracture-specific results would have had to been used even if Flow 1 and Flow 2 results would have been selected as a base for the interpretation.

Yet another nonconforming section, with a length of 2 m, was added to the bottom of the borehole (*94.89 m, Secup*) to give additional information over the lower parts of the borehole (*see Appendices KFM27.2.5 and KFM27.4*). Values for the section flow without pumping (Q_0) and the corresponding section head (h_{0FW}) are based on the fracture flow interpretation of Extra 1 measurement. Respectively, values for the corresponding section flow (Q_1) and head (h_{1FW}) at with pumping are interpreted from Flow 3 measurement.

6.4.3 Transmissivity and hydraulic head of fractures

An attempt was made to evaluate the magnitude of fracture-specific flow rates. The first step in this procedure is to identify the locations of individual flowing fractures and then evaluate their flow rates. This is done based on flow logging with 1 m section length in pumped conditions. In cases where the fracture distance is less than one metre, it may be difficult to evaluate the flow rate. In these cases, a stepwise increase or decrease in the flow data plot equals the flow rate of a specific fracture (*filled triangles in the appendices KFM##.2).*

The measurement program included flow logging with 5 m section length in undisturbed conditions and flow loggings with 1 m and 5 m section lengths in pumped conditions. In pumped conditions fracture flows were interpreted based on results from flow logging with 1 m section length. In unpumped conditions determining flows of individual fractures can be more difficult as measurement section is longer and possible cover multiple fractures at the same time. This was taken into account during the measurement and if the fracture flows were difficult to interpret based on the measurement an extra measurement was conducted with 1 m section length. These results were used together to interpret flows in unpumped conditions. If the flow for a specific fracture cannot be determined conclusively in unpumped conditions, the flow rate is marked with "-" and the value 0 is used in the transmissivity calculation (*Appendices KFM##.6*). The flow direction is evaluated as well. The results of the evaluation are plotted in Appendices KFM##.2, blue filled triangle.

Fracture-specific transmissivities were compared with transmissivities of sections in Appendices KFM##.8. All fracture-specific transmissivities within each 5 m interval were first summed together to make them comparable with measurements with a 5 m section length. The results are fairly consistent between the two types of measurements. The decrease of flow as a function of pumping time can sometimes be seen in some fractures (*storage effect*). The 1 m section measurements were carried out after the 5 m section measurements and therefore flow rate and transmissivity can be smaller in the 1 m section measurement results.

KFM25

The total amount of detected fractures was 44, of which 18 were detected also without pumping. Measured length was 90 m so there were 0.49 fractures per meter on average. Three of the fractures were detected during groundwater recovery. The sum of fracture flows during pumping of the borehole (*including the fractures measured during groundwater recovery*) was 1.20×10^{-4} m^3/s (*430 649 mL/h*). Pumping rate during the measurement with 5 m drawdown was ca 8.5 L/min (*510 000 mL/h*) on average (*ca 9.2 L/min at the start and ca 8.2 L/min in the end of the measurement*). The pumping rate was notably higher than the sum of measured fracture flows (Q_f) and clearly exceeded the given ± 10 % accuracy of the flow measurement.

However, to reach the uppermost lengths of the borehole with the PFL DIFF probe, submersible pump had to be lifted out of the borehole and flow measurement was then continued during groundwater recovery. Therefore, the sum of fracture-specific flows in KFM25, as such, cannot be directly compared to the pumping rate because the upper part of the borehole could not be measured in the similar steady-state pumped conditions as the rest of the borehole. Instead, fracture-specific flows (Q_f) and fracture heads (h_{fFW}) at the lengths of 6.6 m, 8.3 m and 9.4 m were measured during groundwater recovery while water level in the borehole was in transition. It should also be noted that the direction of measured flow was into the bedrock in fractures at 8.3 m and 9.4 m. Additionally, flows at fractures at 66.5 m and 73.9 m caused a slight pressure rise in the measurement section while pumping was on. Measured flow rates at these lengths were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the two fractures could probably be higher than the measured flow rates. The magnitude of pressure increase was ca 1.5 kPa at the most. These lengths were examined in more detail to make sure correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendices KFM25.10.1 – KFM25.10.2*). The occurrences described above could partly explain the off-balance between the sum of fracture flows and the measured pumping rate.

KFM26

The total amount of detected fractures was 49, of which 39 were detected also without pumping. Measured length was 90 m so there were 0.54 fractures per meter on average. Five of the fractures (*fractures at 7.1 m, 7.9 m, 9.1 m, 11.1 m and 13.1 m*) were not detected (*or flow could not be defined due to uncertain flow anomalies*) under pumped conditions. The sum of fracture flows during pumping of the borehole was 9.28×10^{-5} m^3/s (*334 049 mL/h*). Pumping rate during the measurement with 1 m drawdown was ca 20.4 L/min (*1 344 000 mL/h*) on average (*ca 22.9 L/min at the start and ca 19.0 L/min in the end of the measurement*). The pumping rate was significantly higher than the sum of measured fracture flows (Q_l) and the given ± 10 % accuracy of the flow measurement was clearly exceeded.

Flows at fractures at 70.1 m and 94.5 caused a slight pressure rise in the measurement section while pumping was on. Measured flow rates at these lengths were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the two fractures could probably be higher than the measured flow rates. The magnitude of pressure increase was ca 1.7 kPa at the most. These lengths were examined in more detail to make sure correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to see the effect of pressure increase (*Appendices KFM26.10.1 – KFM26.10.2*). The occurrences described above could partly explain the off-balance. However, the most important contributing factor to the difference between the sum of measured fracture flows and the measured pumping rate is that there probably remains a significant conductivity in the unmeasurable bottom part of the borehole. This assumption is based on the vertical flow measurement result conducted in un-pumped conditions at the borehole length of 95.5 m (*see Section 6.4.1*).

The fracture-specific interpretation for fracture at 23.3 m is based on Flow 2 measurement result. Values for the fracture flow with pumping (Q_l) and the hydraulic head (h_{lFW}) are based on the of Flow 2 measurement from the corresponding borehole length. Flow 2 measurement result is more representative due to inconsistent fracture flow anomaly observed in Flow 3 measurement (*see Appendix KFM26.2.2*).

KFM27

The total amount of detected fractures was 70, of which 59 were detected also without pumping. Measured length was 87 m so there were 0.8 fractures per meter on average. Two of the fractures were detected during groundwater recovery. Note that a leak detected at the joint of casing tube and borehole is presented as a fracture at the length of 9.1 m (*see Appendices KFM27.2.1 and KFM27.6.1*). The sum of fracture flows during pumping of the borehole was 2.31×10^{-4} m^3/s (*831 598 mL/h*). Pumping rate during the measurement with 2.8 m drawdown was ca 35.3 L/min (*2 118 000 mL/h*) on average (*ca 40.2 L/min at the start and ca 34.6 L/min in the end of the measurement*). The pumping rate was significantly higher than the sum of measured section flows (Q_l) and the given ± 10 % accuracy of the flow measurement was exceeded. With 2.8 m drawdown, the directions of measured fracture-specific flows remained into the bedrock at all fractures between the length interval of 9.1–28.8 m.

High flows in un-pumped conditions were measured at fractures at 16.8 m, 19.6 m, 67.0 m and 86.8 m. Outflow at fractures at 16.8 m and 19.6 m caused a pressure drop of ca 1.9 kPa and 2.1 kPa and inflow at fractures at 67.0 m and 86.8 m caused a slight pressure rise of ca 0.5 kPa and ca 1.0 kPa, respectively. These measured flow rates were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the three fractures would probably be higher than the measured flow rates. These borehole lengths were examined in more detail to make sure correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to visualise the effect of pressure increase (*see Appendices KFM27.10.1, KFM27.10.3 and KFM27.10.5*).

In order to reach the uppermost lengths of the borehole with the PFL DIFF probe, submersible pump had to be lifted out of the borehole and flow measurement was then continued during groundwater recovery. Therefore the sum of fracture-specific flows in KFM27, as such, cannot be directly compared to the pumping rate because the upper part of the borehole could not be measured in the similar steady-state pumped conditions as the rest of the borehole. Instead, fracture-specific flows (Q_l) and fracture heads (h_{lFW}) at the lengths of 9.1 m and 10.1 m were measured during groundwater recovery while water level in the borehole was in transition.

A very high inflow of 273 000 mL/h at fracture at 86.8 m measured in pumped conditions was very near the upper measurement limit of the PFL DIFF probe and caused a significant pressure rise of ca 13.5 kPa in the measurement section. The measured flows at fractures at 67.0 m, 73.3 m and 88.4 m caused also a considerable pressure rise in the measurement section. Pressure increase of ca 3.0 kPa at fracture at 67.0 m, ca 3.3 kPa at fracture at 73.3 m and ca 4.8 kPa at fracture at 88.4 m was measured. Measured flow rates at the listed fractures were high enough to cause friction loss in the PFL DIFF probe's flow guide and therefore actual flow rates for the four fractures could probably be notably higher than the measured flow rates. These lengths were examined in more detail to make sure correct head and flow values were used in interpretation. Flow rate and borehole head were plotted together to visualise the effect of pressure increase (*Appendices KFM27.10.2, KFM27.10.4 and KFM27.10.6*). The occurrences described above could explain most of the off-balance. It should also be taken into consideration that as the flow logging measurement passes the flowing fracture relatively quickly; perfect steady-state conditions cannot be reached during normal measurement if a fracture has significant influence on a borehole flow system. A clear example of the described conditions can be seen at fracture at 86.8 m as the measured pumping rate drops dramatically from ca 38 L/min to ca 19 L/min (*see Appendix KFM27.10.6*) when the PFL DIFF probe remained on the fracture. As soon as the PFL DIFF probe had passed the high yielding fracture, pumping rate normalised to ca 39 L/min. Therefore, it can be assumed that the actual transmissivity value for the fracture at 86.8 m would most probably be higher than the one reported here. Another important contributing factor to the difference between the sum of measured fracture flows and the measured pumping rate is that there probably remains a significant inflow in the unmeasurable bottom part of the borehole. This assumption is based on the vertical flow measurement result conducted in un-pumped conditions at the borehole length of 92.1 m (*see Section 6.4.1*).

6.4.4 Theoretical and practical measurement limits of flow and transmissivity

The theoretical minimum for measurable flow rate in overlapping measurements is 30 mL/h. In laboratory conditions as low as 6 mL/h flow rates can be measured but in general 30 mL/h has been considered as minimum measurable flow rate in borehole conditions. In result figures and tables flow rates below 30 mL/h have been presented but these are considered to be less certain than flow rates above 30 mL/h. The upper limit of flow measurement is 300 000 mL/h. Even higher flow rates could be measured by the device but due to small dimensions in flow sensor flow friction through the sensor begins to affect while flow rate through the sensor is high. Therefore, technically measurement results can be correct but the result if affected by the measurement and doesn't represent what it should.

In practice, the minimum measurable flow rate may be much higher. Borehole conditions may have an influence on the flow base level (*i.e. noise level*). Noise levels can be evaluated in intervals along the borehole where no flowing fractures or other complicating structures are lacking and may vary along a borehole.

There are several known reasons for increased noise in the flow.

- Roughness of the borehole wall.
- Solid particles such as clay or drilling debris in the water.
- Gas bubbles entrained in the water.
- High flow rate along the borehole.
- Mixing of waters with different salinity within the test section.

Roughness in the borehole wall always results in high levels of noise, not only in the flow results, but also in the SPR results. The flow curve and SPR curves are typically spiky when the borehole wall is rough.

Drilling debris usually increase noise levels. This kind of noise is typical for both undisturbed conditions and under pumping.

Pumping results in lower water pressure in the borehole and in fractures located near the borehole. This may lead to the release of dissolved gas and increase the quantity of gas bubbles entrained in the water. Some fractures may produce more gas than others. Sometimes, when the borehole is being measured upwards, increased noise levels are observed just above certain fractures. One of the reasons for this is assumed to be gas bubbles.

The effect of a high flow rate along the borehole can often be seen above fractures with a high flow and while borehole wall is assumed to be rough. The rubber sealing discs hold the pressure that high flow causes well but if there are leakages between rubber discs and borehole wall high flows along borehole cause increased noise level.

Another reason for increased noise level could be that when the PFL DIFF probe passes a fracture, there still might be less saline water within the test section from other parts of the borehole. When waters with different salinity mix, it might cause high noise level to the flow rate results.

The practical minimum for measurable flow rate is presented in Appendices KFM*##.5.1* using dark grey dashed line (*Lower limit of flow rate*). The practical minimum level of the measurable flow is always evaluated in pumped conditions since this measurement is the most important for transmissivity calculations. The limit is an approximation. It is evaluated to obtain a limit below which there may be fractures or structures that remain undetected.

The noise level in these measurements was 30 mL/h. In many cases even smaller flows were successfully detected. The noise line (*grey dashed line*) was never drawn below 30 mL/h, because the values of flow rate measured below 30 mL/h are uncertain.

There were some cases when flow rate was close to upper measurement limit and high flow rate caused pressure elevation in the measurement section. In these cases flows were measured with decreased drawdown in order to obtain more representative flow rate value.

The practical minimum for measurable flow rate is also presented in Appendices KFM##.4 (*Q-lower limit P*) and is obtained from the plots in Appendices KFM *KFM##.2.1 – KFM##.2.n* (*Lower limit of flow rate. Flow rate under 6 mL/h is not plotted*). The practical minimum of transmissivity can be evaluated using Q-lower limit and the actual head difference at each measurement location (*Appendices KFM##.4* T_D*-measl*$_{LP}$). The theoretical minimum for transmissivity (T_D*-measl*$_{LT}$) is evaluated using a Q value of 30 mL/h. The upper limit for transmissivity can be evaluated using the maximum flow rate (*300 000 mL/h*) and the actual head difference as above (*Appendices KFM##.4* T_D*-measl*$_U$). In cases when upper limit of measured flow rate has been passed flow measurement is repeated with a smaller drawdown to obtain flow rate within the limits therefore upper limit for transmissivity is never exceeded.

All three flow limits are plotted with the measured flow rates (*Appendices KFM##.5.1*).

The three transmissivity limits are also presented graphically (*Appendices KFM##.5.2*).

Similar flow and transmissivity limits are not provided for the fracture-specific results as the limits for these are harder to define. The situation is similar for the upper flow limit. If several high-flowing fractures are positioned closer to one another than a distance of 1 m, the upper flow limit will depend on the sum of these flows, and this must be below 300 000 mL/h.

6.4.5 Sensitivity of transmissivity and the hydraulic head to the errors in flow and pressure measurements

Transmissivity and hydraulic head results have been presented in tables and plots without assuming any errors related to measured values. Nevertheless, possible errors in flow and pressure measurement affects the transmissivity and hydraulic head. Possible error in flow measurement is ± 10 % of the measured value and ± 2 kPa in pressure measurement. Errors in transmissivity and hydraulic head have been evaluated assuming largest possible error that can occur within these errors in flow and pressure measurements. The error limits for transmissivity and hydraulic head have been plotted in Appendices KFM##.5.3. and KFM##.7.2.

6.5 Transmissivity of the entire borehole

The transmissivity of the entire borehole was evaluated based on pumping rate and drawdown caused by the pumping during the flow logging. This is done with two steady-state methods described in Chapter 3. The results of analysis is presented in Table 6-1.

Table 6-1. Evaluated transmissivities for entire boreholes; T_M see (3-10), T_T see (3-9).

Borehole ID	Pumping rate (L/min)	Drawdown (m)	Borehole length (m)	T_M (m^2/s)	T_T (m^2/s)
KFM25	8.5	5	94.64	3.66×10^{-5}	2.80×10^{-5}
KFM26	19.1	1	94.59	4.12×10^{-4}	3.15×10^{-4}
KFM27	34.5	2.8	91.61	2.65×10^{-4}	2.03×10^{-4}

In Thiems formula (Equation 3-9), R/r_0 is assumed to be 500, Q is pumping rate and s is drawdown by the end of the flow period (*Appendices KFM##.9.2*). In the Moye formula (*Equation 3-10*) the borehole length means water filled, uncased part of the borehole.

6.6 Groundwater level and pumping rate

The level of the groundwater table in the boreholes during the measurement sequences is presented in Appendices KFM##.9.2. The borehole KFM25 was pumped between October 24 and October 26 with a drawdown approximately 5 m. The borehole KFM26 was pumped between October 30 and November 1 with a drawdown approximately 1 m. Pumping period of borehole KFM27 was between November 7 and November 10 with a drawdown approximately 2.8 m.

7 Summary

In this study, the Posiva Flow Log, Difference Flow Method has been used to determine the location and flow rate of flowing fractures or structures in boreholes KFM25, KFM26 and KFM27 at Forsmark, Sweden. Measurements were carried out both when the water level in the borehole was at rest and during pumping. A 5 m long section length with 0.5 m long increments was used initially. The borehole was also measured with a 1 m long section and 0.1 m long increments.

The distribution of saline water along the borehole was logged by electrical conductivity and temperature measurements of the borehole water. Based on the results water salinity or changes in salinity did not affect the quality of measurement results.

Possible casing tube leakages were checked by measuring flow along the boreholes just below the casing tube in undisturbed conditions. In KFM27 leakage was found. The diameter of the casing pipes was 76.3 mm allowing the measurement of flow along the casing pipe.

The conductive fracture frequency was quite high and in some cases it was difficult to distinguish individual fractures especially in natural conditions. On average there were 0.49 fractures per meter in KFM25, 0.54 fractures per meter in KFM26 and 0.8 fractures per meter in KFM27. In boreholes KFM26 and KFM27 flows were measured both with 5 m section length and 1 m section length in natural conditions to obtain more detailed fracture-specific flow values. High flow values were also detected. Usually high flows are re-measured with a smaller drawdown to obtain more representative flow value. In these measurements, with the drawdown already being smaller than usual, it was not seen useful to further decrease the pumped drawdown since the complete pressure differences with and without pumping were already small. High fracture and section flows can cause rise to friction loss in the PFL DIFF probe's flow guide, causing a slight pressure rise inside the measurement section. These cases were examined in more detail to make sure that correct head and flow values were used in interpretation. In general noise level in flow measurements was low *(< 30 mL/h*) therefore all flows higher than 30 mL/h were most likely detected.

Highly transmissive fractures caused also high pumping rates. Drawdown of 5 m was reached only in one of the three measured boreholes (*KFM25*) due to the limited capacity of submersible pump that could fit into the boreholes. The smallest drawdown was obtained in borehole KFM26, in which drawdown of 1.0 m was obtained with a pumping rate of ca 19.1 L/min. In this case, results obtained even with the 1.0 m drawdown were considered adequately reliable. Drawdown of 2.8 m was obtained in borehole KFM27 with a pumping rate of 34.5 L/min by adding a second submersible pump in to the borehole. The addition of second pump was tested and done only at this last measured borehole to obtain larger drawdown. In borehole KFM27 high flow rate was detected at the joint of casing pipe and the borehole. Most probably this is not a bedrock fracture, but it has been considered in fracture- and section-specific tables and with added remarks on the results denoting that the flow is from the joint of casing pipe and borehole.

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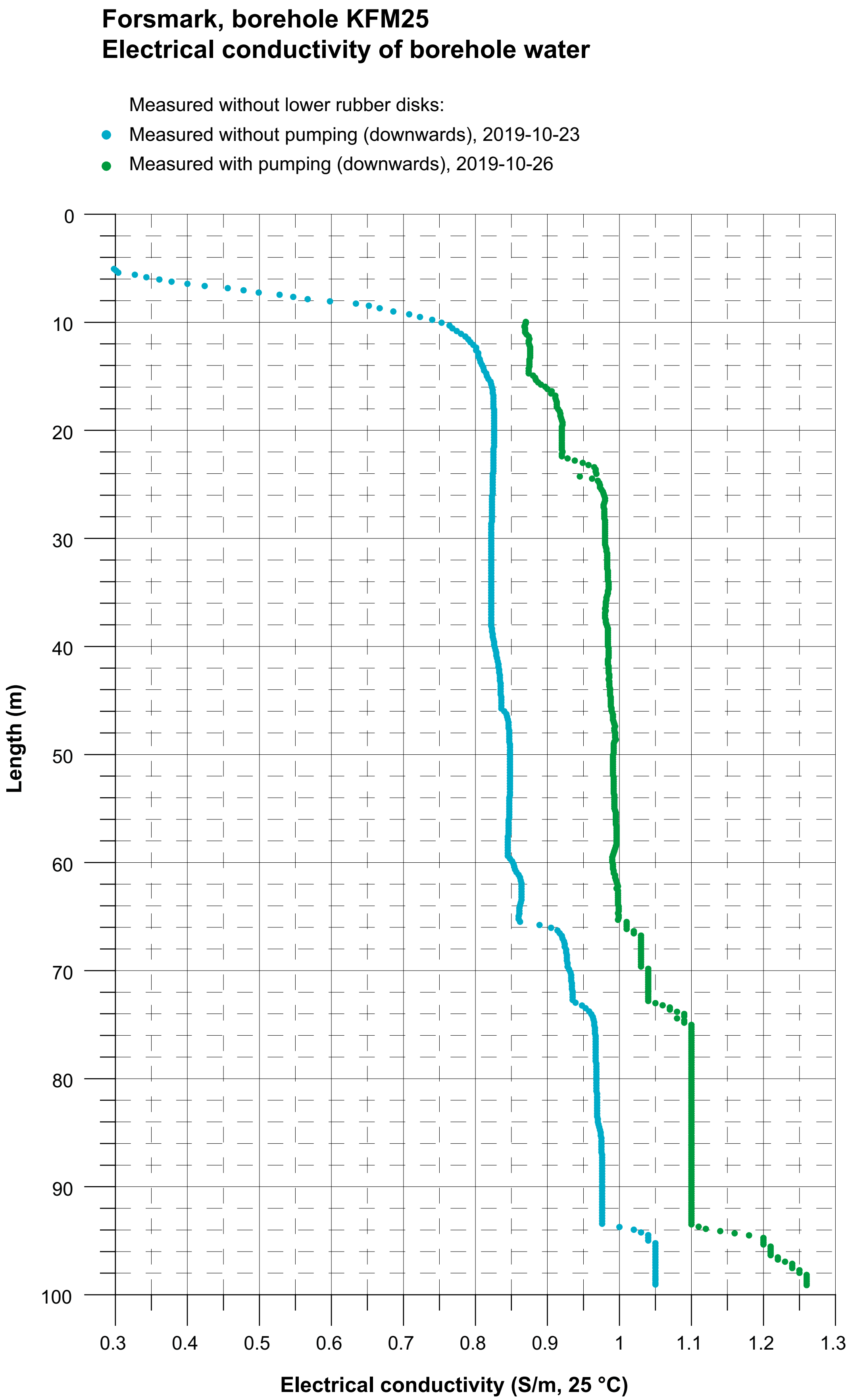
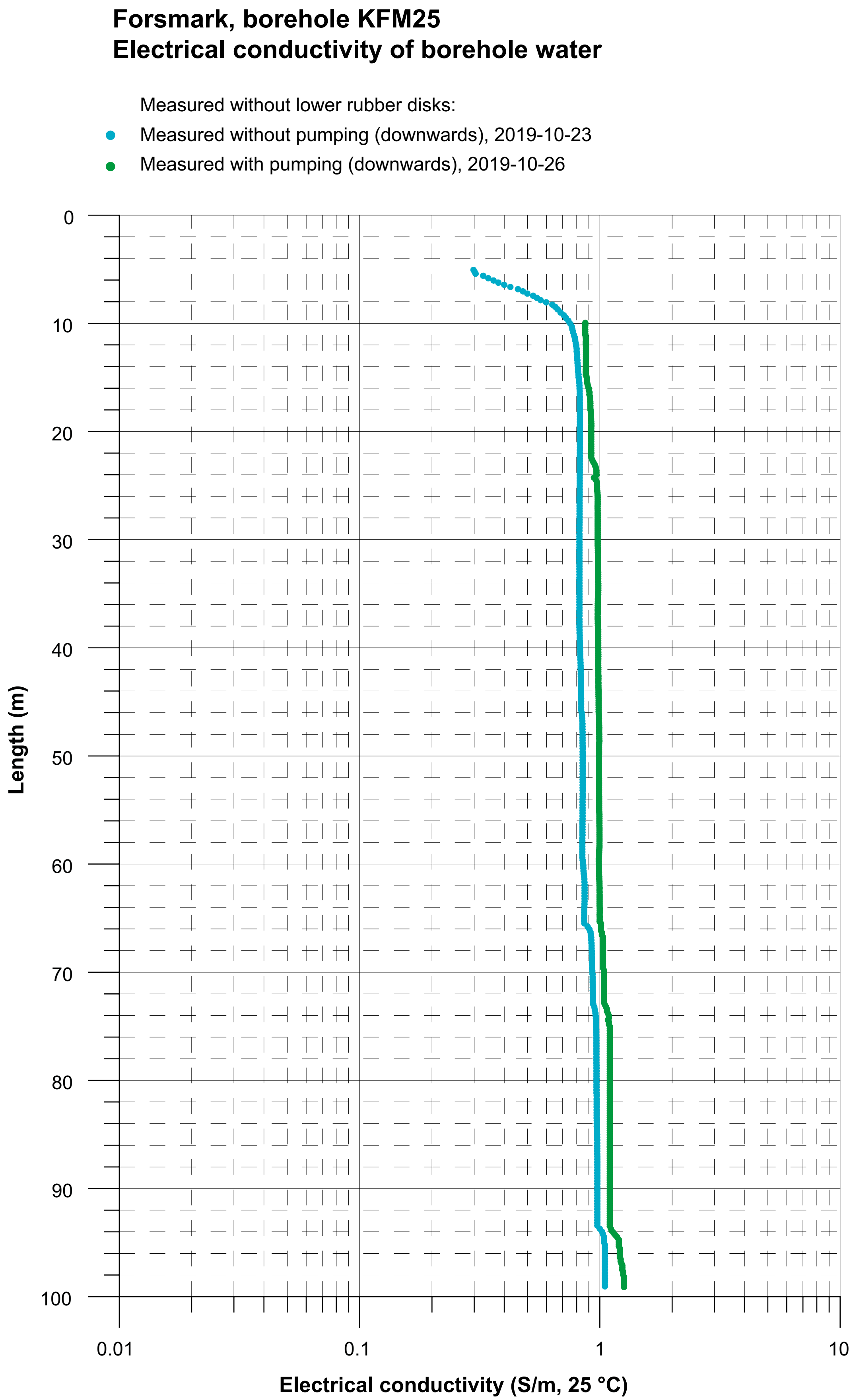
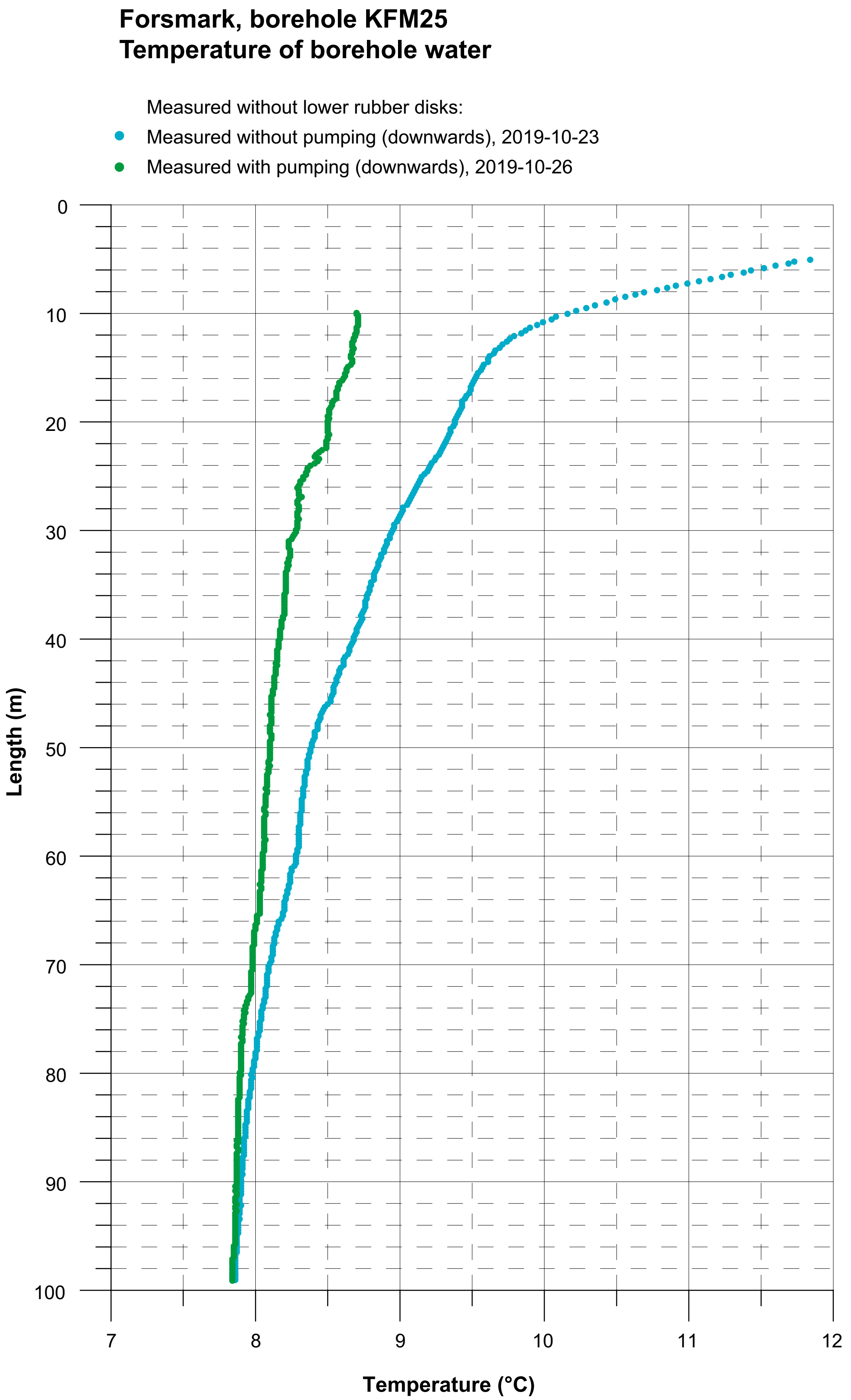
Appendix A

KFM25.1.1 – KFM25.1.2	Electrical conductivity of borehole water
KFM25.1.3	Temperature of borehole water
KFM25.2.1 – KFM25.2.5	Flow rate and single point resistance
KFM25.2.6	Vertical flow along the borehole at 5.0 m
KFM25.2.7	Vertical flow along the borehole at 7.0 m
KFM25.2.8	Vertical flow along the borehole at 85.1 m
KFM25.3	Glossary of terms used in the tables in Appendices
KFM25.4	Results of section flows
KFM25.5.1	Plotted flow rates of 5 m sections
KFM25.5.2	Plotted transmissivity and head of 5 m sections
KFM25.5.3	Transmissivity and head of 5 m sections with calculated error limits
KFM25.5.4	Conductive fracture frequency
KFM25.6.1 – KFM25.6.2	Inferred fracture flow anomalies from flow logging
KFM25.7.1	Plotted transmissivity and head of detected fractures
KFM25.7.2	Transmissivity and head of detected fractures with calculated error limits.
KFM25.8	Comparison between section transmissivity and fracture transmissivity
KFM25.9.1	Head in the borehole during flow logging
KFM25.9.2	Air pressure, water level in the borehole and pumping rate during flow logging
KFM25.10.1 – KFM25.10.2	Flow rate, single point resistance and head in the borehole during flow logging

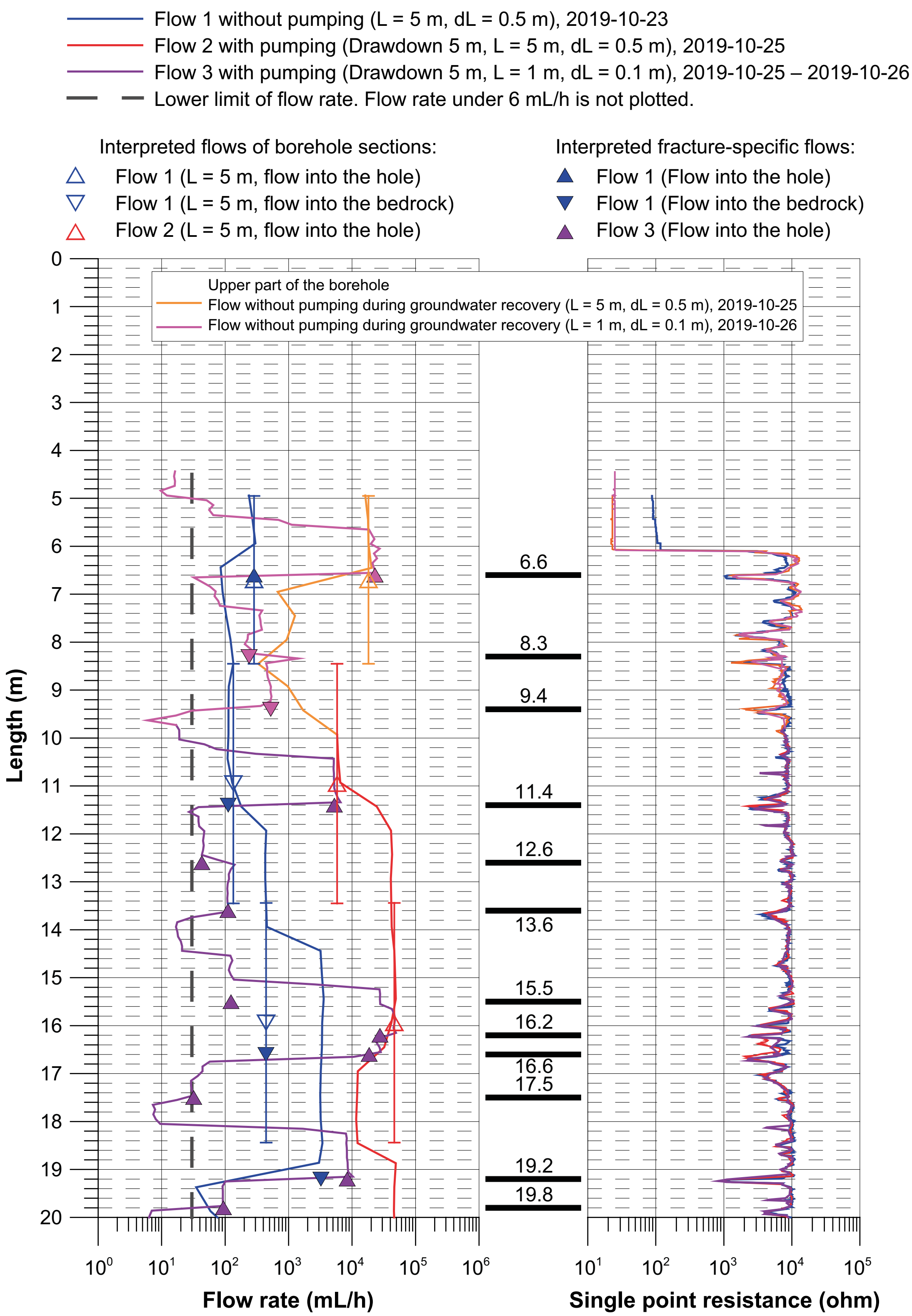

Forsmark, borehole KFM25
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-23
Measured with pumping (downwards), 2019-10-26
0
10
20
30
40
50
60
70
80
90
100
Length (m)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
Electrical conductivity (S/m, 25 °C)

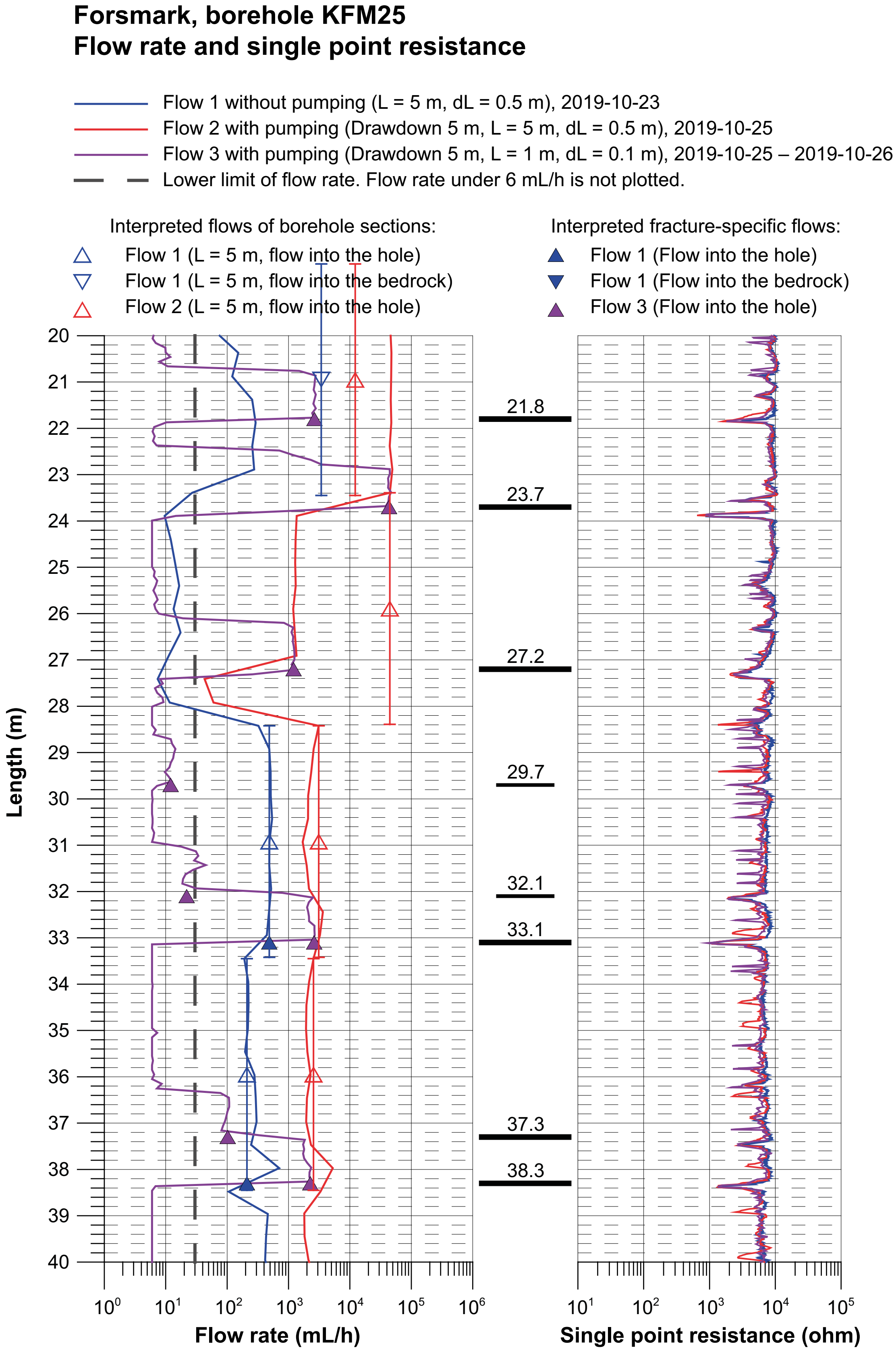


Forsmark, borehole KFM25
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-23
Measured with pumping (downwards), 2019-10-26
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0.01
0.1
1
10
Electrical conductivity (S/m, 25 °C)


Forsmark, borehole KFM25
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-23
Measured with pumping (downwards), 2019-10-26
0
10
20
30
40
50
60
70
80
90
100
Length (m)
7
8
9
10
11
12
Temperature (°C)

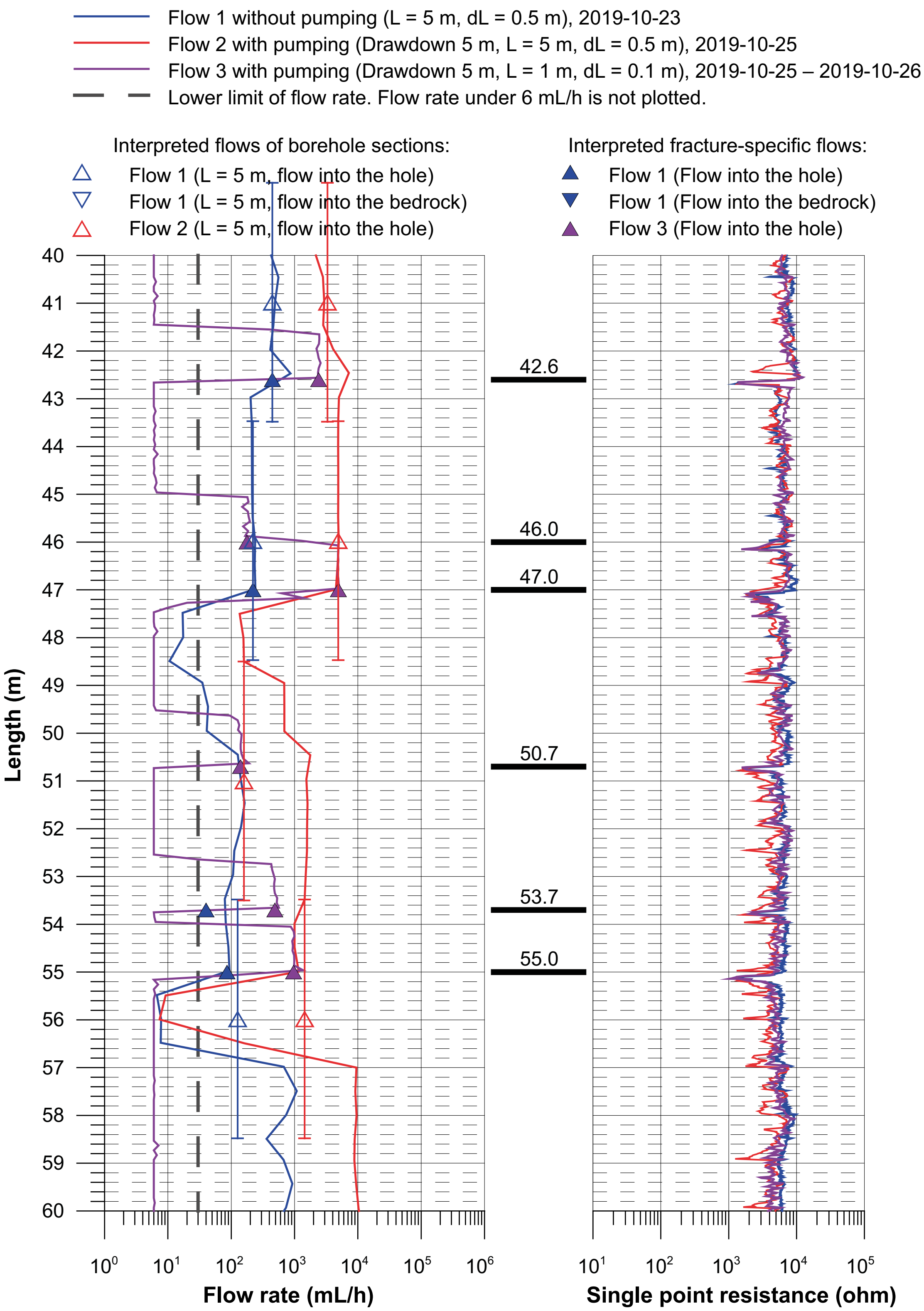
Forsmark, borehole KFM25
Flow rate and single point resistance



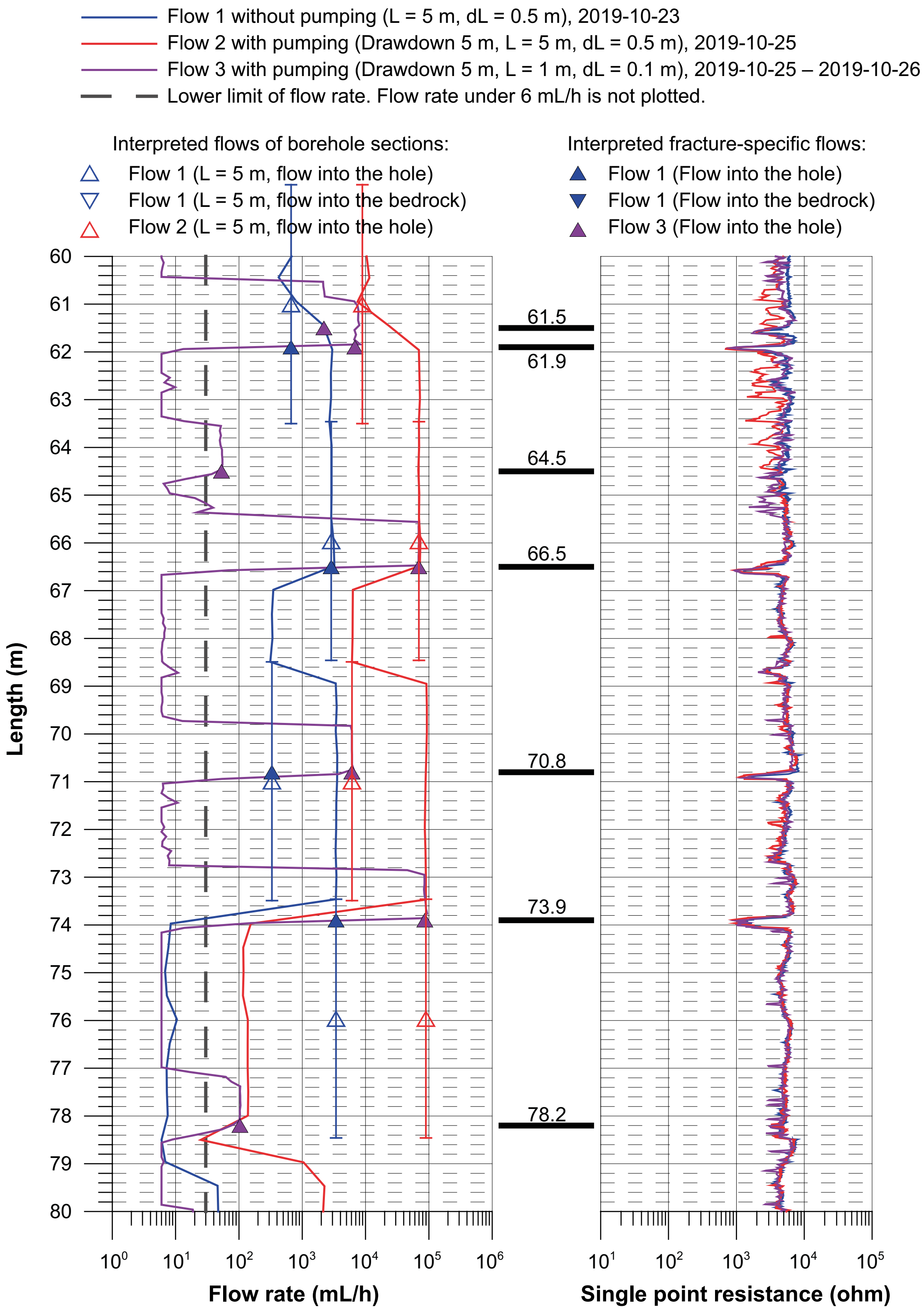


Forsmark, borehole KFM25
Flow rate and single point resistance
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2019-10-23
Flow 2 with pumping (Drawdown 5 m, L = 5 m, dL = 0.5 m), 2019-10-25
Flow 3 with pumping (Drawdown 5 m, L = 1 m, dL = 0.1 m), 2019-10-25 – 2019-10-26
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.
Interpreted flows of borehole sections:
Flow 1 (L = 5 m, flow into the hole)
Flow 1 (L = 5 m, flow into the bedrock)
Flow 2 (L = 5 m, flow into the hole)
Interpreted fracture-specific flows:
Flow 1 (Flow into the hole)
Flow 1 (Flow into the bedrock)
Flow 3 (Flow into the hole)
Length (m)
21.8
23.7
27.2
29.7
32.1
33.1
37.3
38.3
Flow rate (mL/h)
Single point resistance (ohm)

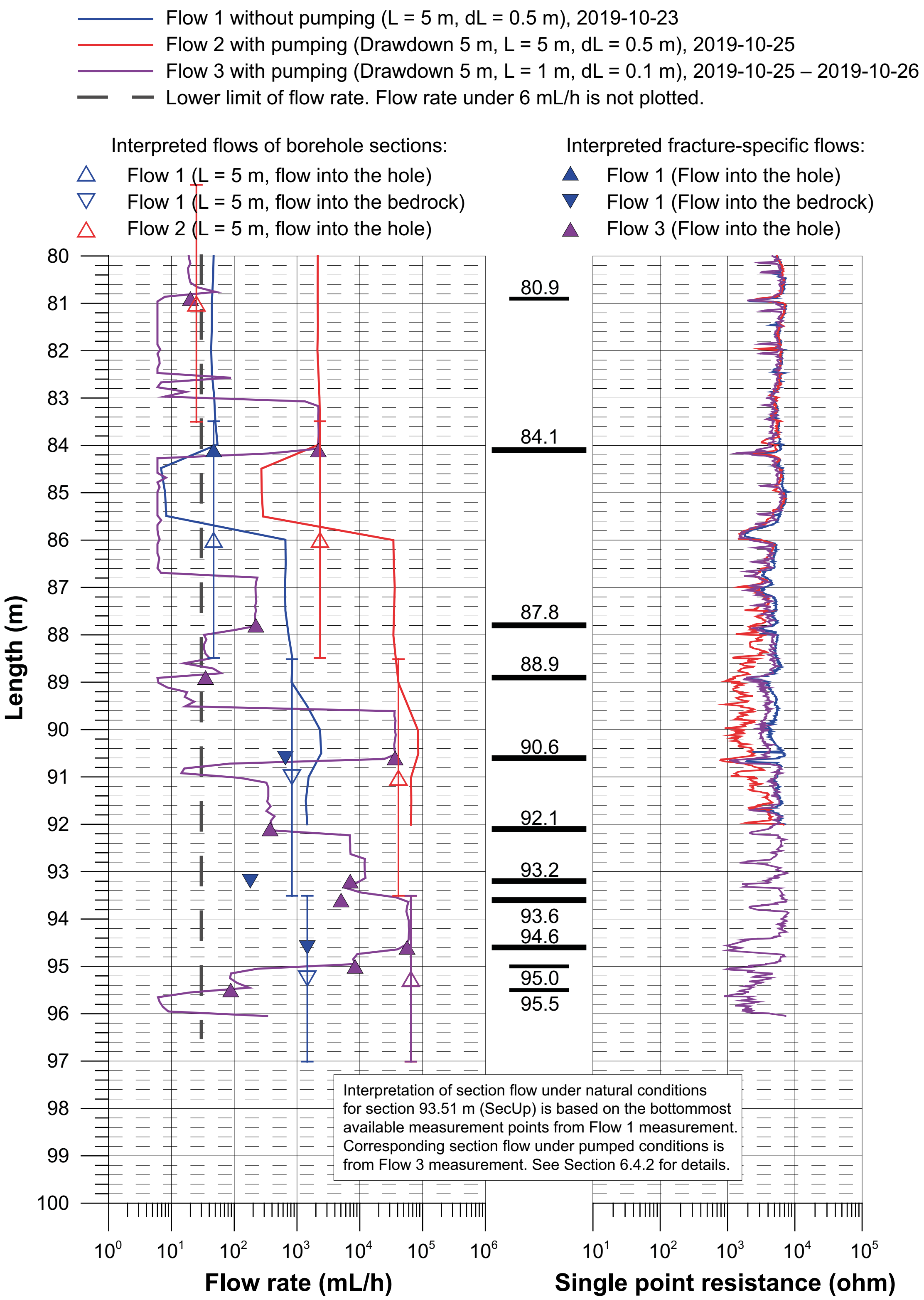
Forsmark, borehole KFM25
Flow rate and single point resistance

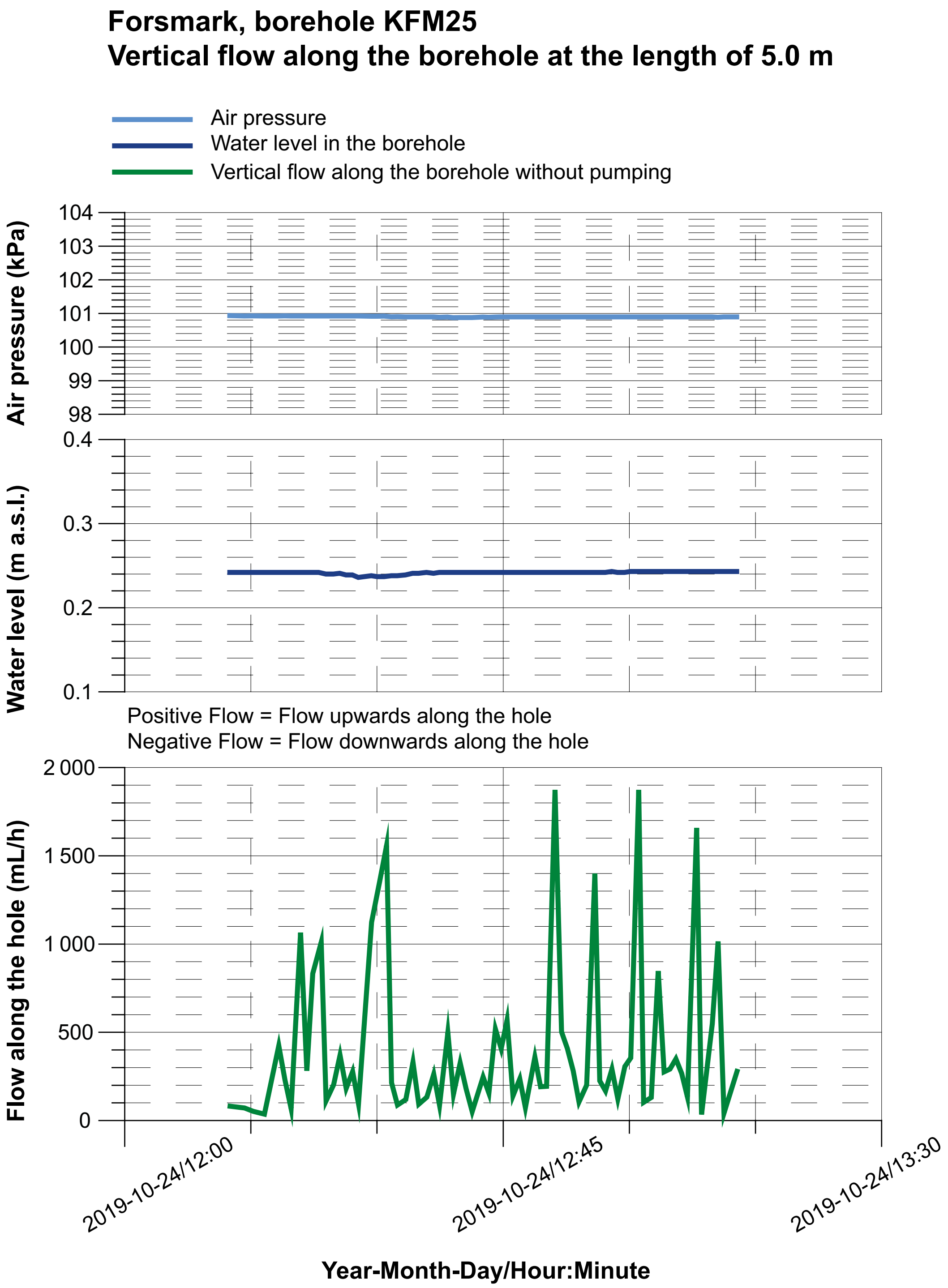


Forsmark, borehole KFM25
Flow rate and single point resistance

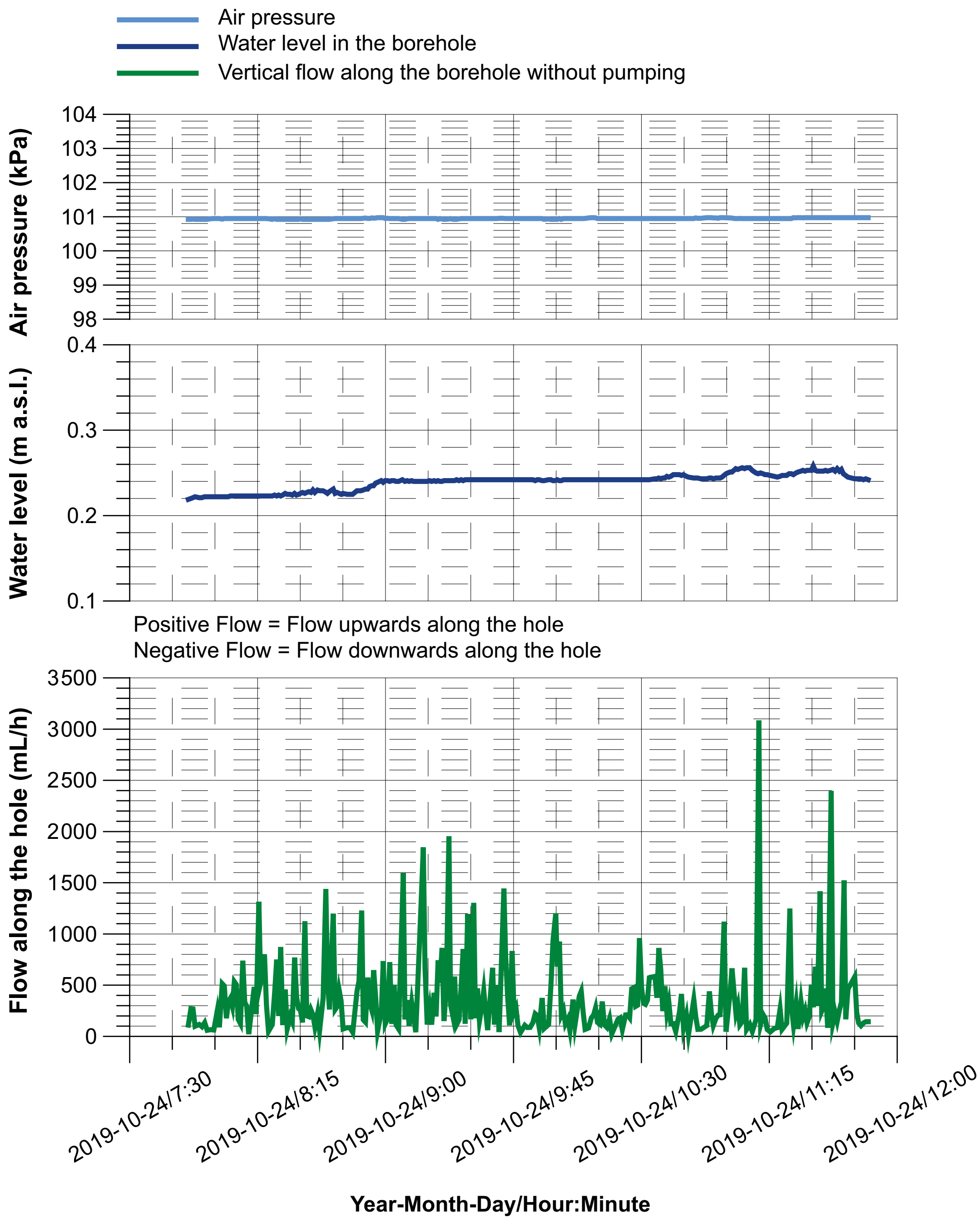


Forsmark, borehole KFM25
Flow rate and single point resistance

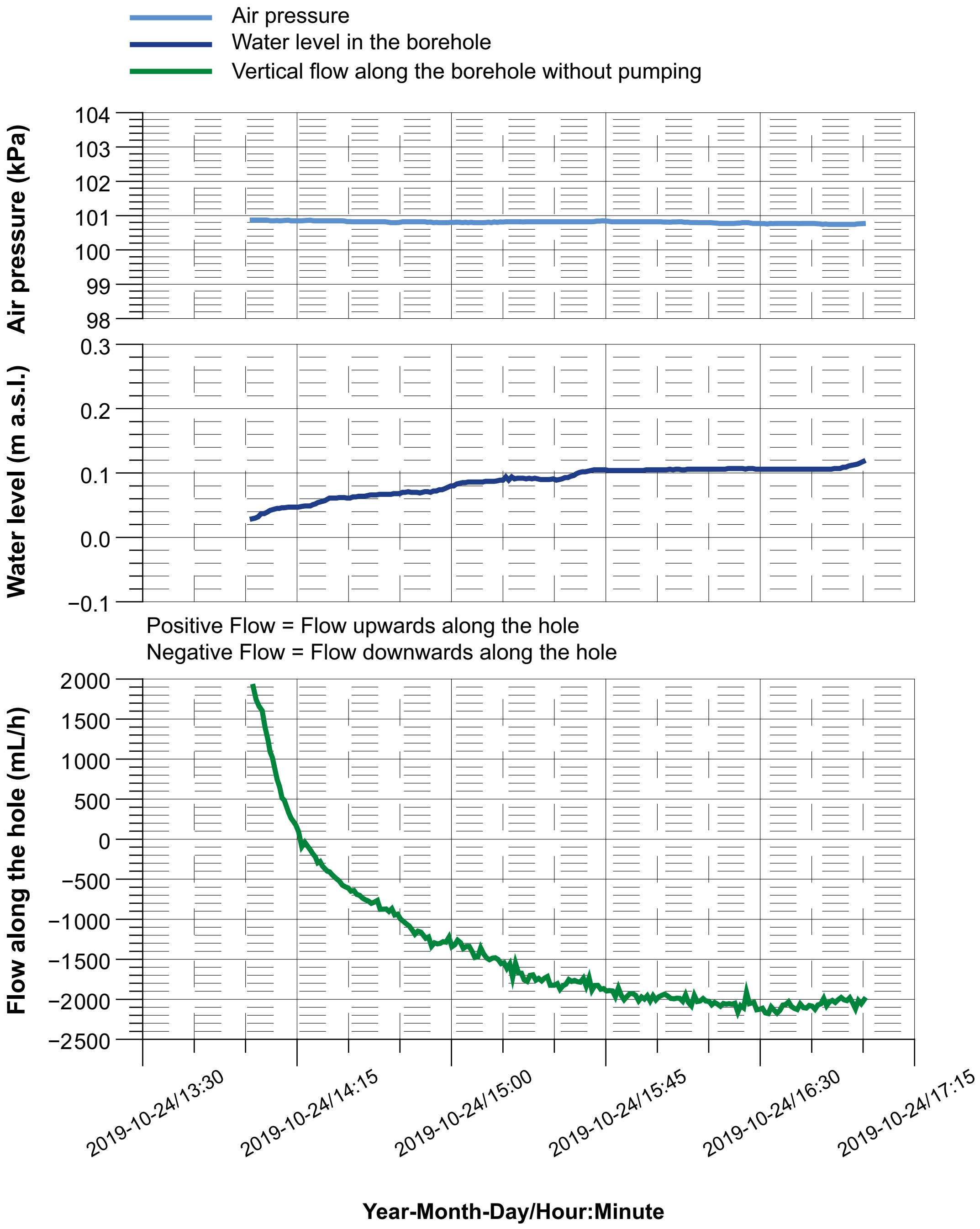



Forsmark, borehole KFM25
Vertical flow along the borehole at the length of 5.0 m
Air pressure
Water level in the borehole
Vertical flow along the borehole without pumping
Air pressure (kPa)
104
103
102
101
100
99
98
Water level (m a.s.l.)
0.4
0.3
0.2
0.1
Positive Flow = Flow upwards along the hole
Negative Flow = Flow downwards along the hole
Flow along the hole (mL/h)
2 000
1 500
1 000
500
0
2019-10-24/12:00
2019-10-24/12:45
2019-10-24/13:30
Year-Month-Day/Hour:Minute

Forsmark, borehole KFM25
Vertical flow along the borehole at the length of 7.0 m



Forsmark, borehole KFM25
Vertical flow along the borehole at the length of 85.1 m



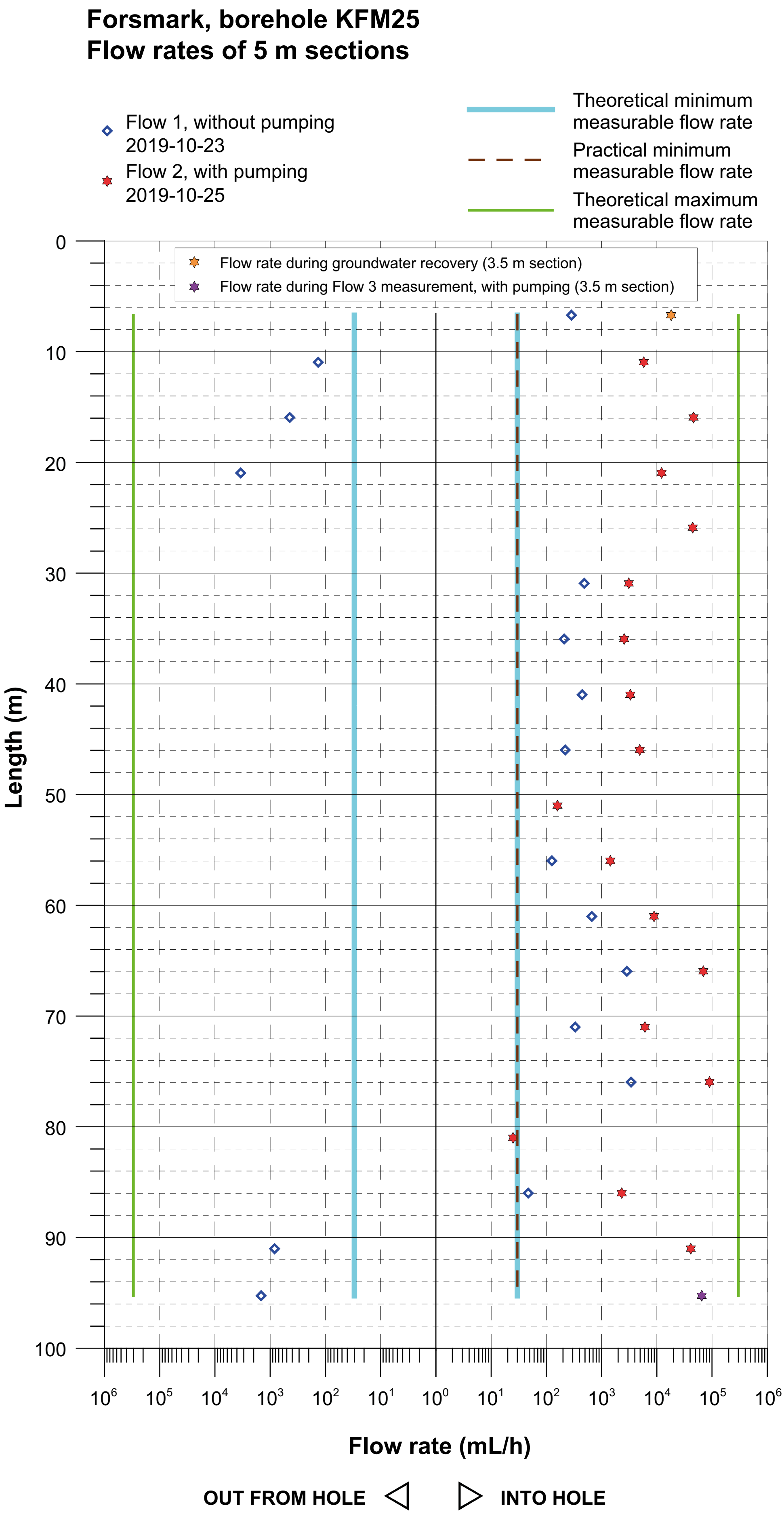
Glossary of terms used in the tables in Appendices.

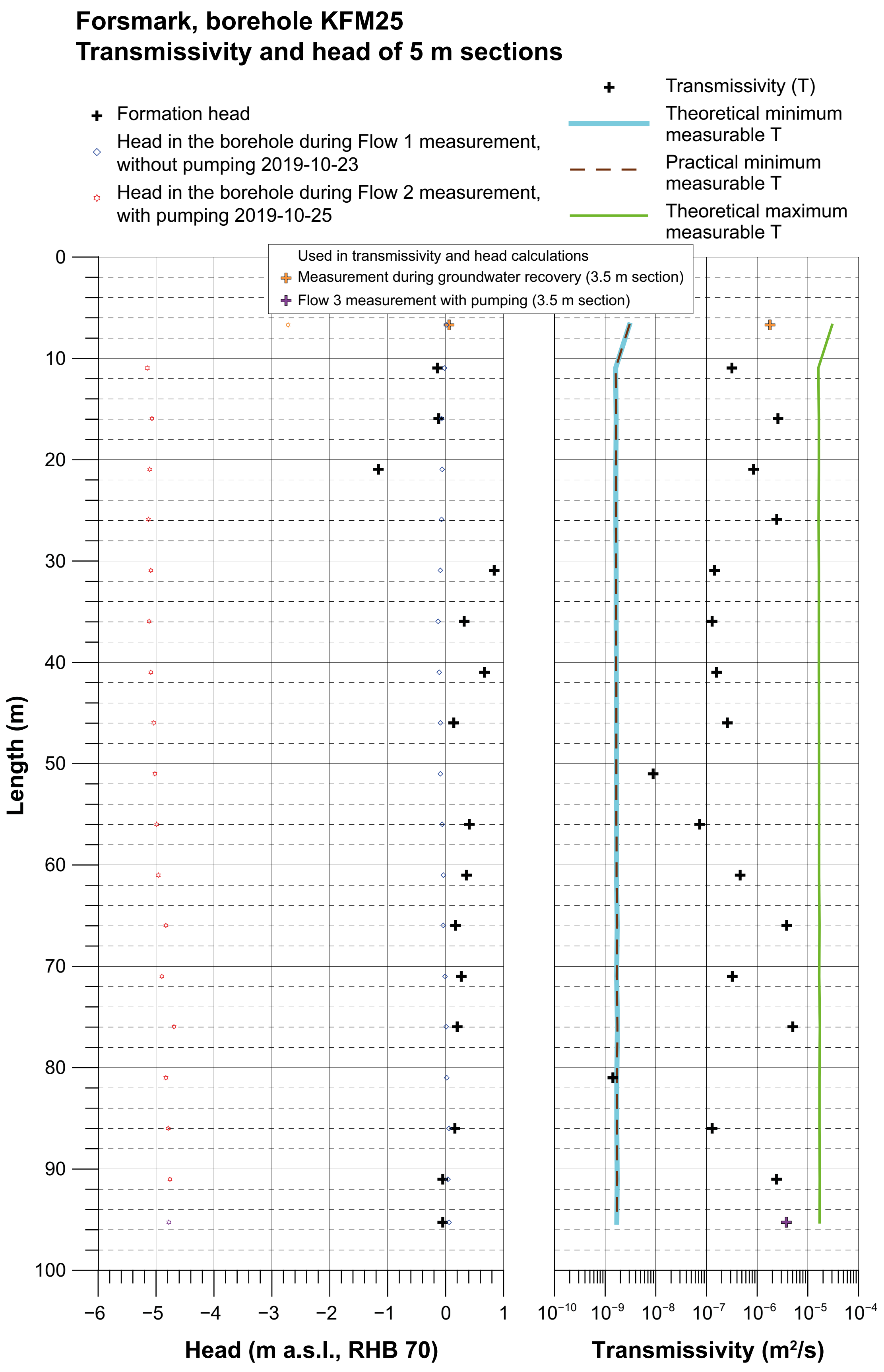
Header	Unit	Definition
Borehole ID		**ID for borehole**
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging
L_w	m	Section length used in the difference flow logging.
dL	m	Step length (increment) used in the difference flow logging.
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h=h0 in the open borehole.
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period.
h_{0FW}	m a.s.l.	Corrected initial hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid before pumping.
h_{1FW}	m a.s.l.	Corrected hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL DIFF.
Q-lower limit P	mL/h	Practical lower measurement limit for flow rate.
T-$measl_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$measl_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-$meas_{lU}$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	m a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions).

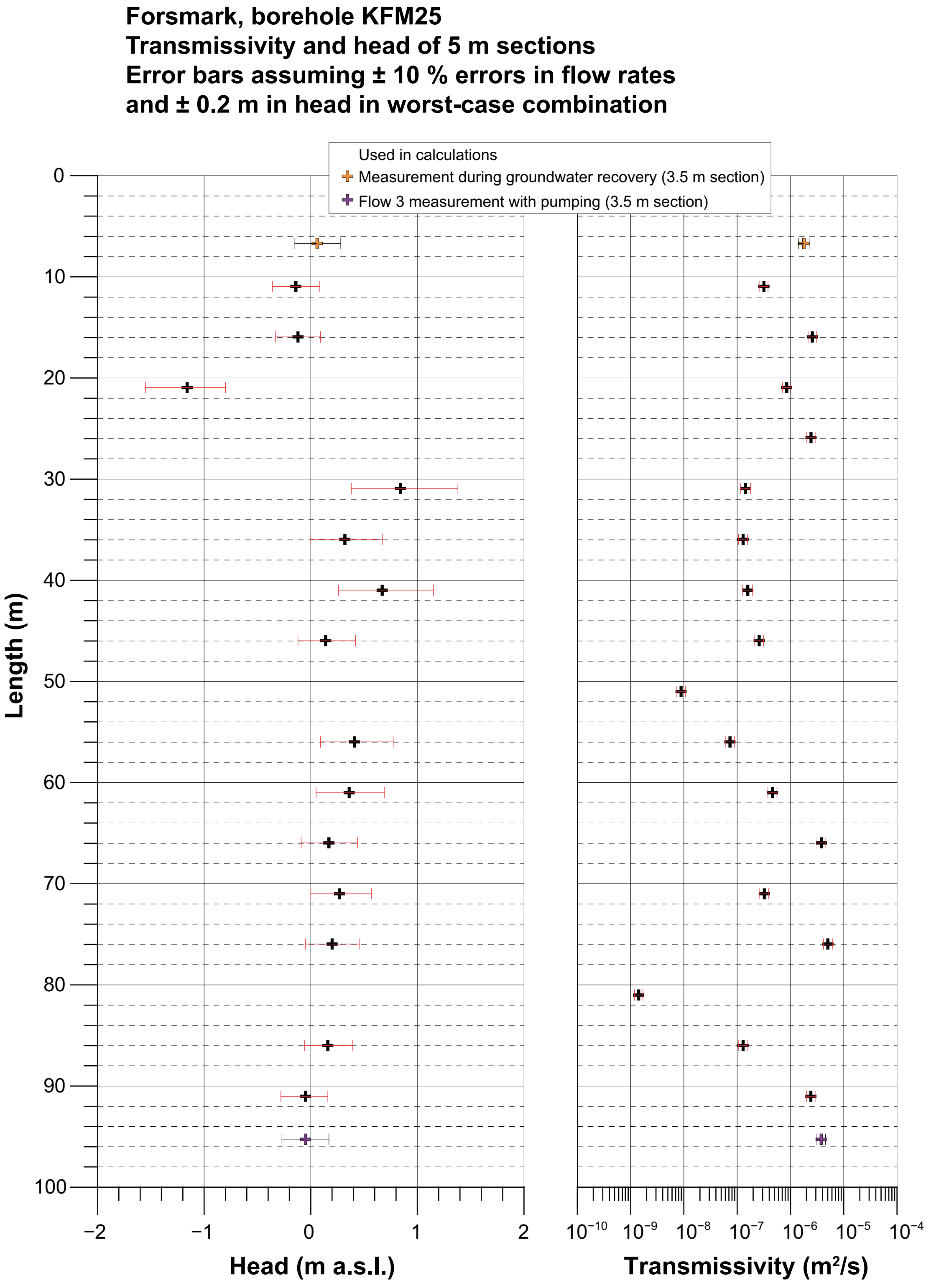
Results of section flows.

Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFM25	4.95	8.45	3.5	7.92E−08	0.02	5.04E−06	−2.72	1.8E−06	0.1	30	3.0E−09	3.0E−09	3.0E−05	*
KFM25	8.45	13.45	5	−3.75E−08	−0.02	1.61E−06	−5.15	3.2E−07	−0.1	30	1.6E−09	1.6E−09	1.6E−05	
KFM25	13.44	18.44	5	−1.23E−07	−0.07	1.28E−05	−5.07	2.6E−06	−0.1	30	1.6E−09	1.6E−09	1.7E−05	
KFM25	18.45	23.45	5	−9.49E−07	−0.06	3.39E−06	−5.11	8.5E−07	−1.2	30	1.6E−09	1.6E−09	1.7E−05	
KFM25	23.39	28.39	5	-	−0.07	1.24E−05	−5.13	2.4E−06	-	30	1.6E−09	1.6E−09	1.6E−05	
KFM25	28.42	33.42	5	1.35E−07	−0.09	8.64E−07	−5.09	1.4E−07	0.8	30	1.6E−09	1.6E−09	1.6E−05	
KFM25	33.45	38.45	5	5.83E−08	−0.13	7.11E−07	−5.12	1.3E−07	0.3	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	38.48	43.48	5	1.24E−07	−0.11	9.19E−07	−5.09	1.6E−07	0.7	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	43.47	48.47	5	6.11E−08	−0.09	1.36E−06	−5.04	2.6E−07	0.1	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	48.50	53.50	5	-	−0.09	4.42E−08	−5.02	8.9E−09	-	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	53.48	58.48	5	3.50E−08	−0.06	4.00E−07	−4.99	7.3E−08	0.4	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	58.50	63.50	5	1.85E−07	−0.04	2.48E−06	−4.96	4.6E−07	0.4	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	63.46	68.46	5	7.97E−07	−0.04	1.93E−05	−4.83	3.8E−06	0.2	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	68.49	73.49	5	9.25E−08	−0.01	1.69E−06	−4.90	3.2E−07	0.3	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	73.46	78.46	5	9.50E−07	0.01	2.49E−05	−4.69	5.0E−06	0.2	30	1.8E−09	1.8E−09	1.7E−05	
KFM25	78.50	83.50	5	-	0.02	6.94E−09	−4.83	1.4E−09	-	30	1.7E−09	1.7E−09	1.7E−05	**
KFM25	83.49	88.49	5	1.31E−08	0.06	6.44E−07	−4.79	1.3E−07	0.2	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	88.51	93.51	5	−2.31E−07	0.04	1.15E−05	−4.76	2.4E−06	−0.1	30	1.7E−09	1.7E−09	1.7E−05	
KFM25	93.51	97.01	3.5	−4.06E−07	0.06	1.81E−05	−4.78	3.8E−06	−0.1	30	1.7E−09	1.7E−09	1.7E−05	***

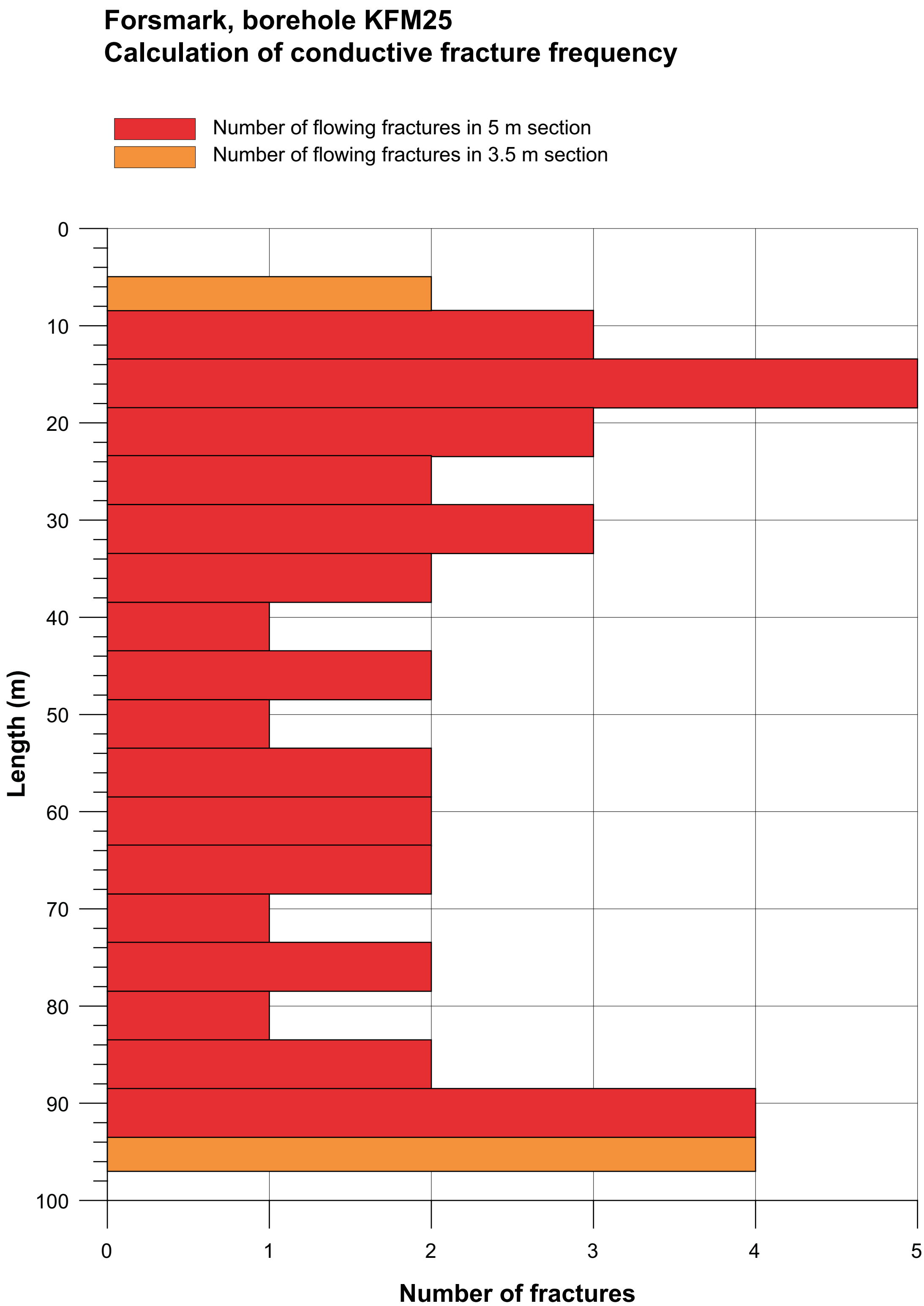
* Values for Flow (Q_1) and Head (h_{1FW}) are from the measurement made without pumping, during groundwater recovery. The upper part of the borehole could not be measured while pumping the borehole (while the pump remained in the borehole).
** Uncertain = The measured flow rate (Q_1) is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
*** Values for Flow (Q_1) and Head (h_{1FW}) are from Flow 3 measurement.


Forsmark, borehole KFM25
Flow rates of 5 m sections
Flow 1, without pumping 2019-10-23
Flow 2, with pumping 2019-10-25
Theoretical minimum measurable flow rate
Practical minimum measurable flow rate
Theoretical maximum measurable flow rate
Flow rate during groundwater recovery (3.5 m section)
Flow rate during Flow 3 measurement, with pumping (3.5 m section)
Length (m)
Flow rate (mL/h)
OUT FROM HOLE
INTO HOLE


Forsmark, borehole KFM25
Transmissivity and head of 5 m sections
Formation head
Head in the borehole during Flow 1 measurement, without pumping 2019-10-23
Head in the borehole during Flow 2 measurement, with pumping 2019-10-25
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Used in transmissivity and head calculations
Measurement during groundwater recovery (3.5 m section)
Flow 3 measurement with pumping (3.5 m section)
Length (m)
Head (m a.s.l., RHB 70)
Transmissivity (m²/s)



Forsmark, borehole KFM25
Transmissivity and head of 5 m sections
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination
Used in calculations
Measurement during groundwater recovery (3.5 m section)
Flow 3 measurement with pumping (3.5 m section)
Length (m)
0
10
20
30
40
50
60
70
80
90
100
−2
−1
0
1
2
Head (m a.s.l.)
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}
Transmissivity (m²/s)


Forsmark, borehole KFM25
Calculation of conductive fracture frequency
Number of flowing fractures in 5 m section
Number of flowing fractures in 3.5 m section
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Number of fractures

Inferred fracture flow anomalies from flow logging.

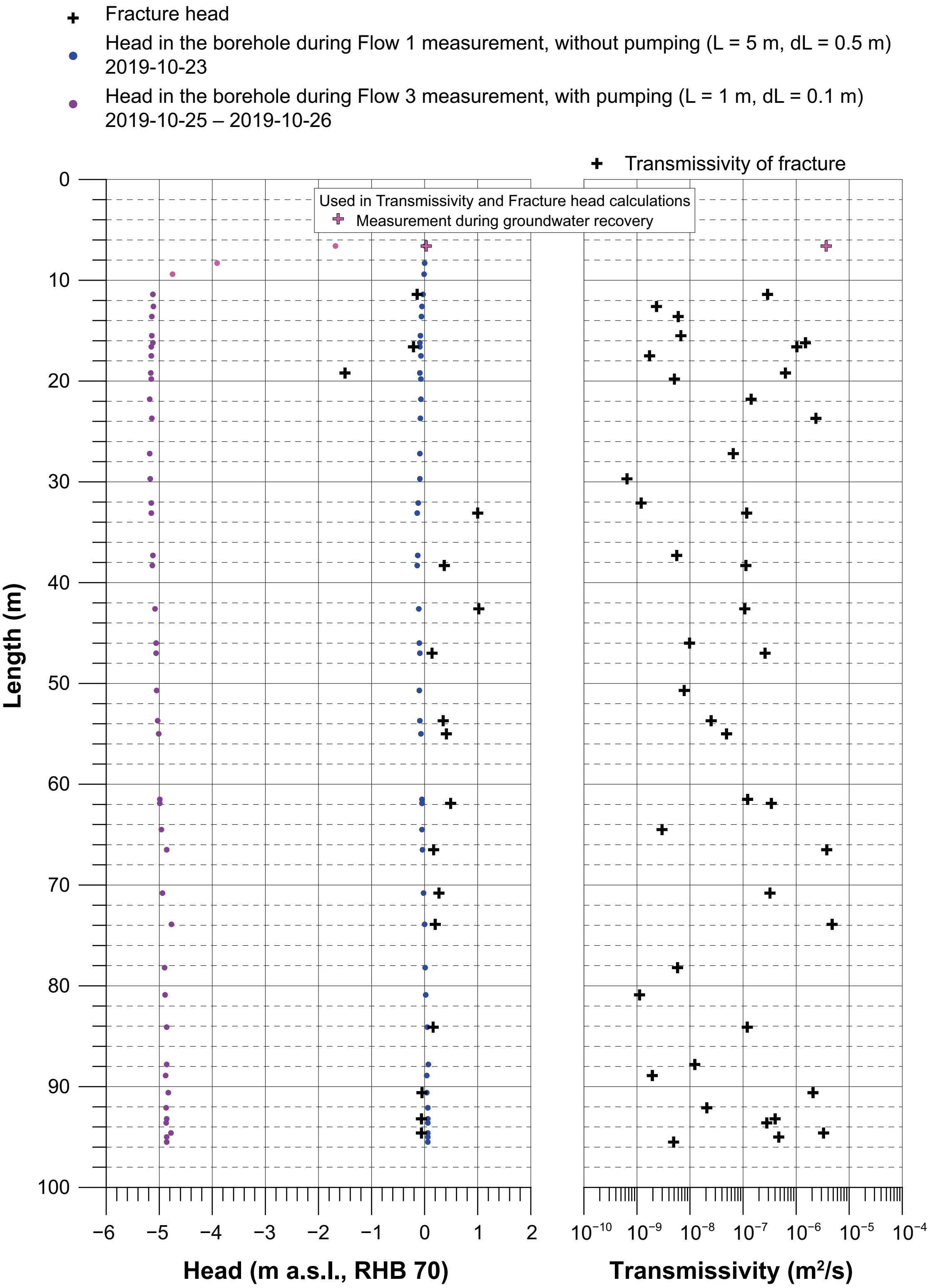
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0 (m^3/s)	h_{0FW} (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Comments
KFM25	6.6	1	0.1	7.92E−08	0.01	6.36E−06	−1.68	3.7E−06	0.0	**
KFM25	8.3	1	0.1	-	0.00	−6.64E−08	−3.91	-	-	**,***
KFM25	9.4	1	0.1	-	−0.01	−1.46E−07	−4.75	-	-	**,***
KFM25	11.4	1	0.1	−3.11E−08	−0.03	1.46E−06	−5.12	2.9E−07	−0.1	
KFM25	12.6	1	0.1	-	−0.05	1.19E−08	−5.11	2.3E−09	-	
KFM25	13.6	1	0.1	-	−0.06	3.08E−08	−5.14	6.0E−09	-	
KFM25	15.5	1	0.1	-	−0.08	3.44E−08	−5.14	6.7E−09	-	
KFM25	16.2	1	0.1	-	−0.09	7.64E−06	−5.12	1.5E−06	-	
KFM25	16.6	1	0.1	−1.22E−07	−0.09	5.17E−06	−5.15	1.0E−06	−0.2	
KFM25	17.5	1	0.1	-	−0.07	8.89E−09	−5.15	1.7E−09	-	
KFM25	19.2	1	0.1	−8.97E−07	−0.09	2.32E−06	−5.16	6.3E−07	−1.5	
KFM25	19.8	1	0.1	-	−0.07	2.61E−08	−5.15	5.1E−09	-	
KFM25	21.8	1	0.1	-	−0.07	7.33E−07	−5.18	1.4E−07	-	
KFM25	23.7	1	0.1	-	−0.08	1.21E−05	−5.14	2.4E−06	-	
KFM25	27.2	1	0.1	-	−0.09	3.36E−07	−5.18	6.5E−08	-	
KFM25	29.7	1	0.1	-	−0.09	3.33E−09	−5.17	6.5E−10	-	*
KFM25	32.1	1	0.1	-	−0.12	6.11E−09	−5.15	1.2E−09	-	*
KFM25	33.1	1	0.1	1.35E−07	−0.14	7.28E−07	−5.15	1.2E−07	1.0	
KFM25	37.3	1	0.1	-	−0.13	2.83E−08	−5.12	5.6E−09	-	
KFM25	38.3	1	0.1	5.83E−08	−0.14	6.28E−07	−5.13	1.1E−07	0.4	
KFM25	42.6	1	0.1	1.24E−07	−0.11	6.67E−07	−5.08	1.1E−07	1.0	
KFM25	46.0	1	0.1	-	−0.10	4.92E−08	−5.06	9.8E−09	-	
KFM25	47.0	1	0.1	6.11E−08	−0.09	1.37E−06	−5.06	2.6E−07	0.1	
KFM25	50.7	1	0.1	-	−0.10	3.89E−08	−5.05	7.8E−09	-	
KFM25	53.7	1	0.1	1.11E−08	−0.09	1.36E−07	−5.03	2.5E−08	0.4	
KFM25	55.0	1	0.1	2.39E−08	−0.07	2.68E−07	−5.01	4.9E−08	0.4	
KFM25	61.5	1	0.1	-	−0.05	6.11E−07	−4.99	1.2E−07	-	
KFM25	61.9	1	0.1	1.85E−07	−0.05	1.89E−06	−4.99	3.4E−07	0.5	
KFM25	64.5	1	0.1	-	−0.05	1.47E−08	−4.96	3.0E−09	-	
KFM25	66.5	1	0.1	7.97E−07	−0.04	1.92E−05	−4.86	3.8E−06	0.2	
KFM25	70.8	1	0.1	9.25E−08	−0.02	1.69E−06	−4.94	3.2E−07	0.3	
KFM25	73.9	1	0.1	9.50E−07	0.00	2.40E−05	−4.77	4.8E−06	0.2	
KFM25	78.2	1	0.1	-	0.01	2.89E−08	−4.90	5.8E−09	-	
KFM25	80.9	1	0.1	-	0.02	5.56E−09	−4.89	1.1E−09	-	*
KFM25	84.1	1	0.1	1.31E−08	0.05	6.08E−07	−4.86	1.2E−07	0.2	
KFM25	87.8	1	0.1	-	0.07	6.14E−08	−4.86	1.2E−08	-	
KFM25	88.9	1	0.1	-	0.04	9.72E−09	−4.88	2.0E−09	-	
KFM25	90.6	1	0.1	−1.81E−07	0.04	1.01E−05	−4.83	2.1E−06	−0.1	
KFM25	92.1	1	0.1	-	0.06	1.03E−07	−4.87	2.1E−08	-	
KFM25	93.2	1	0.1	−5.00E−08	0.06	1.95E−06	−4.86	4.0E−07	−0.1	
KFM25	93.6	1	0.1	-	0.06	1.39E−06	−4.87	2.8E−07	-	
KFM25	94.6	1	0.1	−4.06E−07	0.06	1.57E−05	−4.78	3.3E−06	−0.1	
KFM25	95.0	1	0.1	-	0.06	2.34E−06	−4.86	4.7E−07	-	*
KFM25	95.5	1	0.1	-	0.06	2.44E−08	−4.86	4.9E−09	-	*

* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.

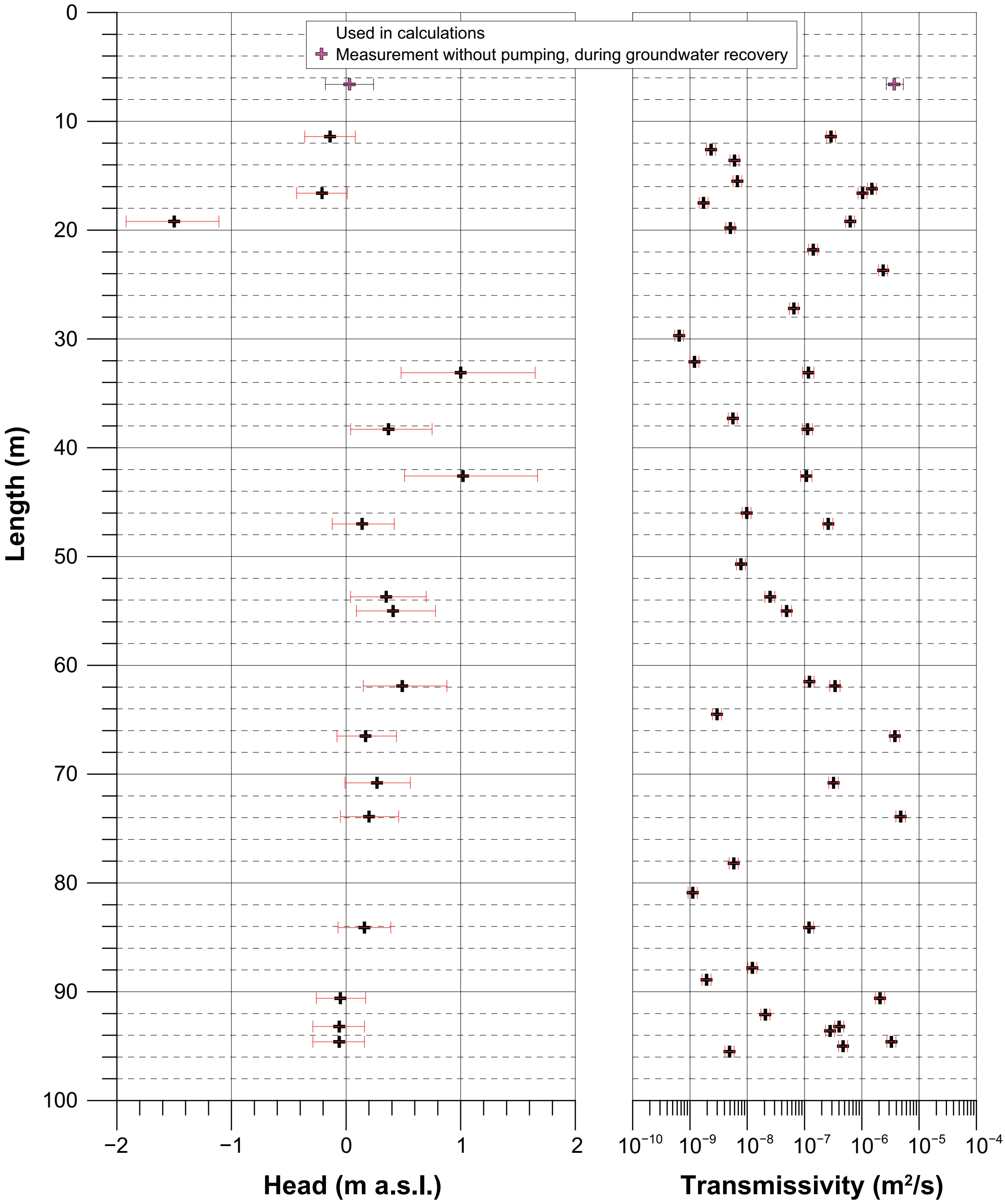
** Values for Flow (Q_1) and Head (h_{1FW}) are from the measurement made without pumping, during groundwater recovery. The upper part of the borehole could not be measured while pumping the borehole (while the pump remained in the borehole).

*** Calculation for T_D would result in unrealistic figure. Therefore T_D is not presented.

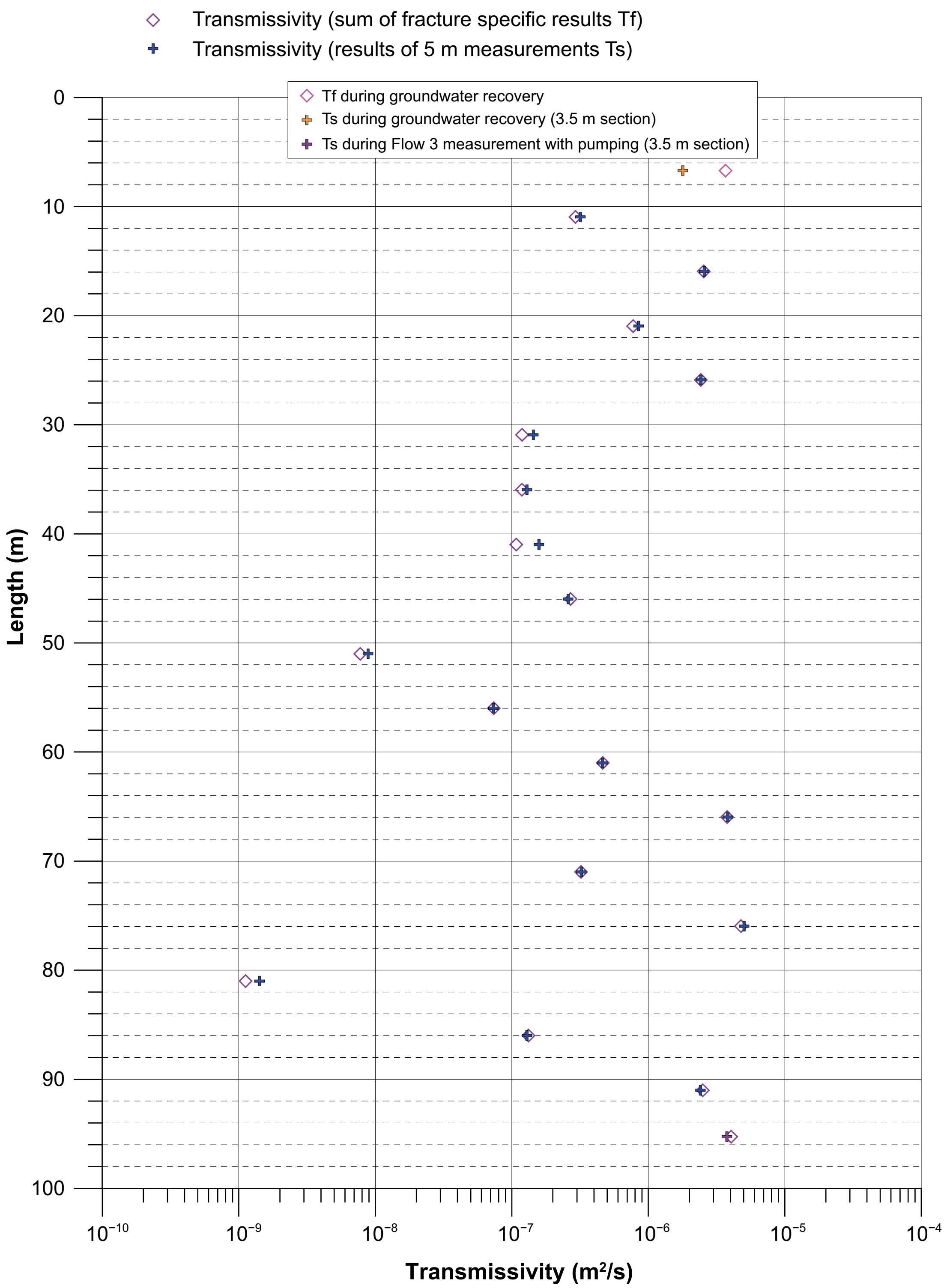
Forsmark, borehole KFM25
Transmissivity and head of detected fractures



Forsmark, borehole KFM25
Transmissivity and head of fractures
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination

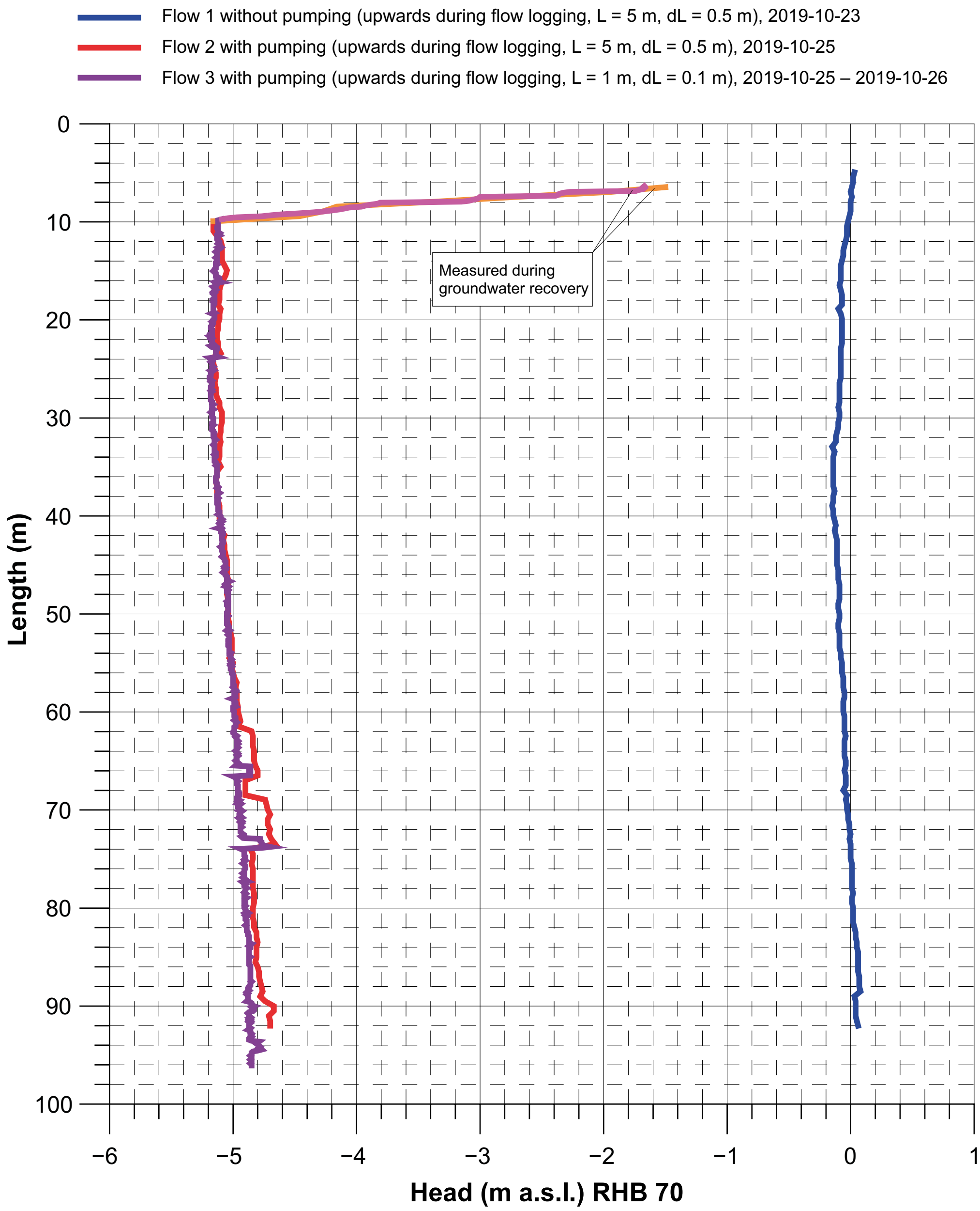


Forsmark, borehole KFM25
Comparison between section transmissivity and fracture transmissivity

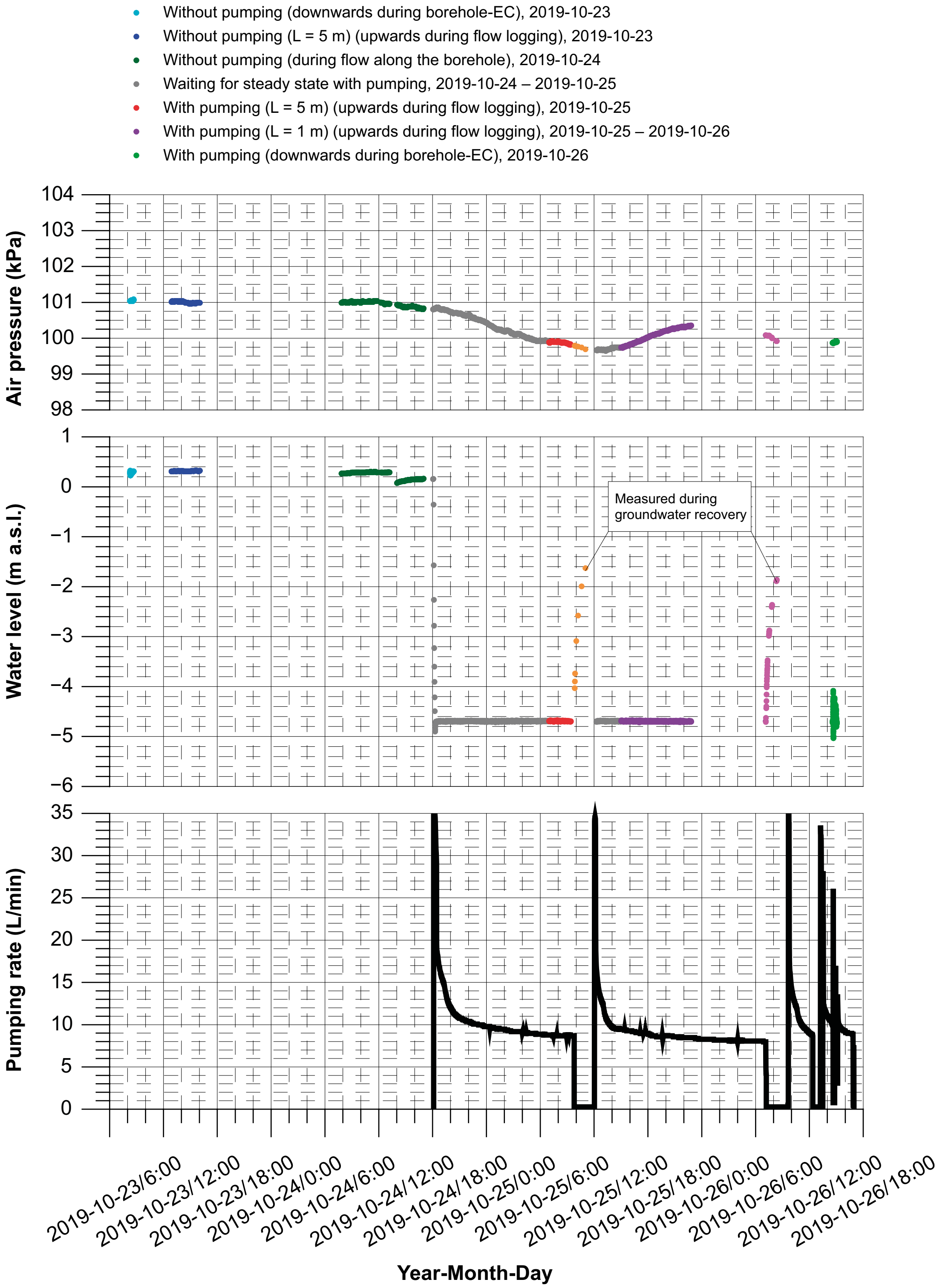


Forsmark, borehole KFM25
Head in the borehole during flow logging

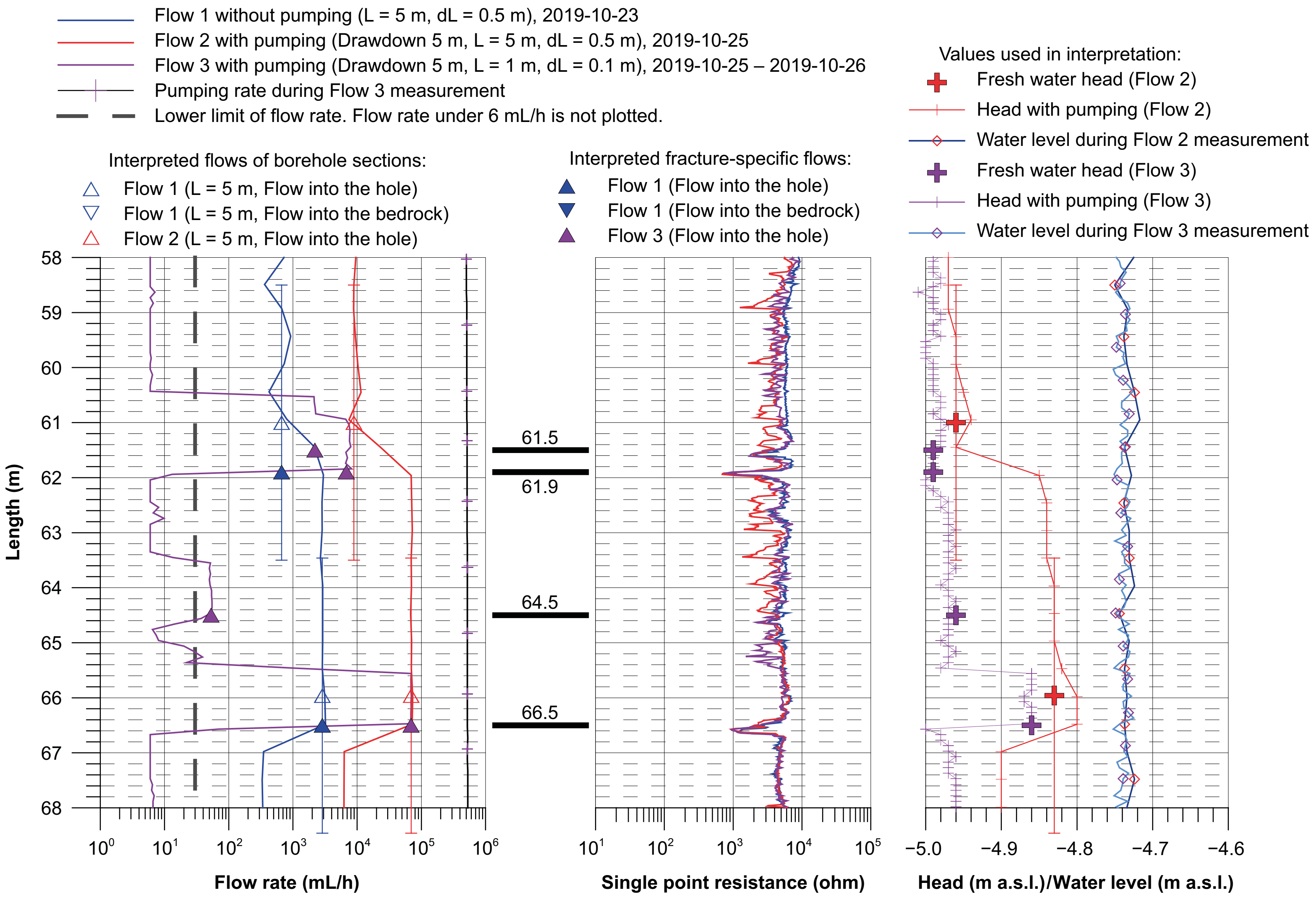
Head (m a.s.l.) = (Absolute pressure (Pa) − Airpressure (Pa) + Offset)/(1000 kg/m³ × 9.80665 m/s²) + Elevation (m)
Offset = Correction for absolute pressure sensor



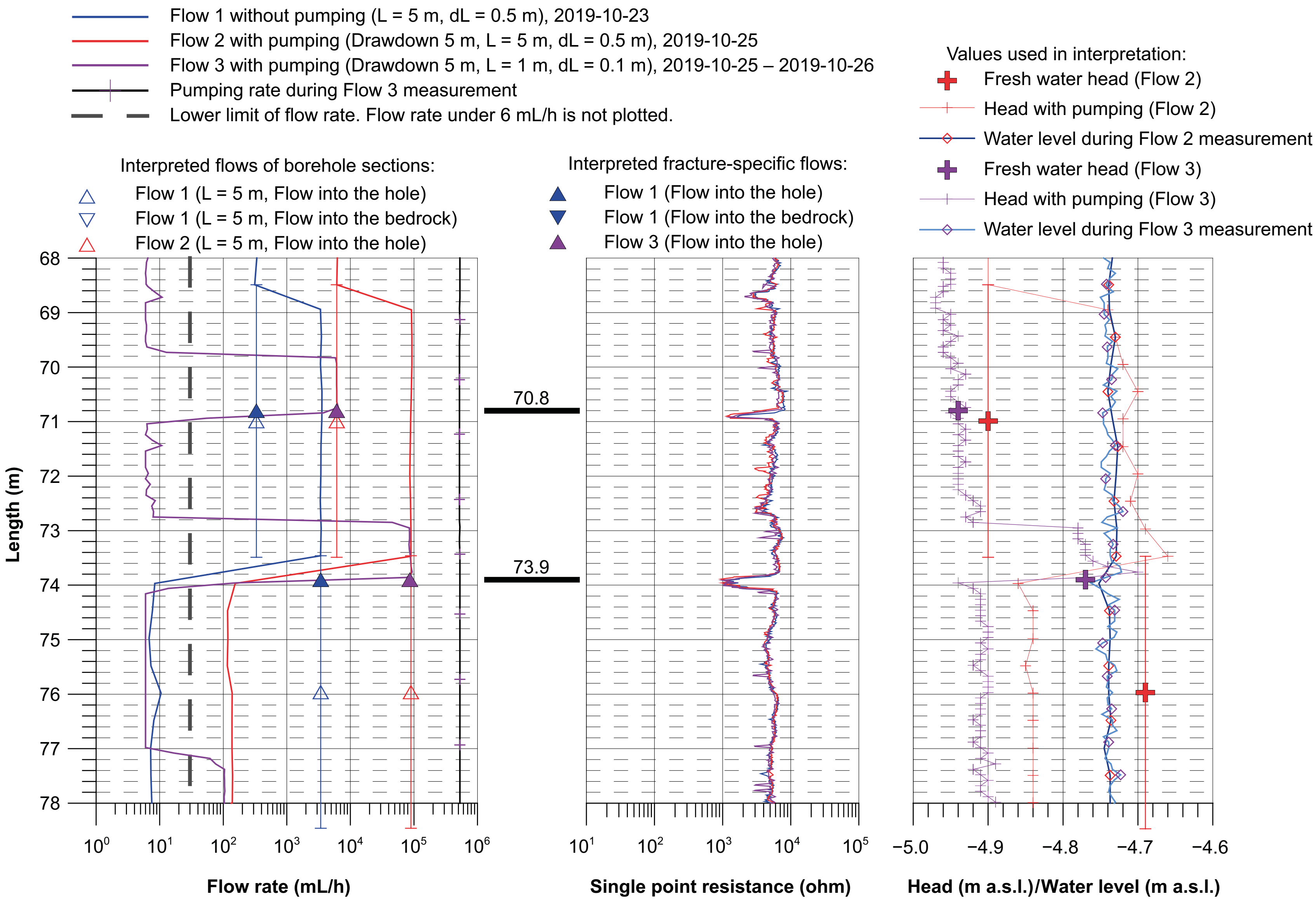
Forsmark, borehole KFM25
Air pressure, water level in the borehole and pumping rate during flow logging



Forsmark, borehole KFM25
Flow rate, single point resistance and head in the borehole during flow logging

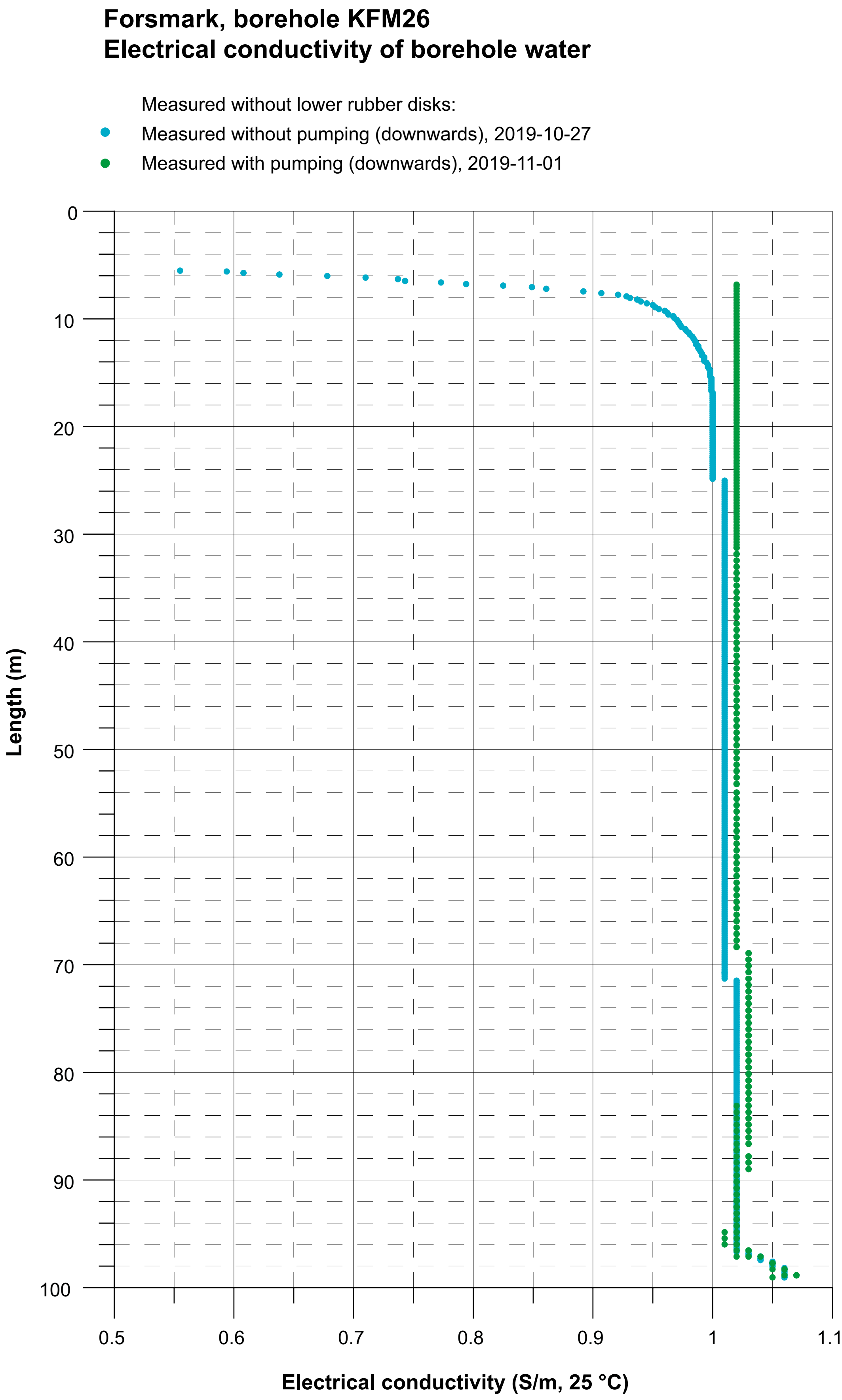


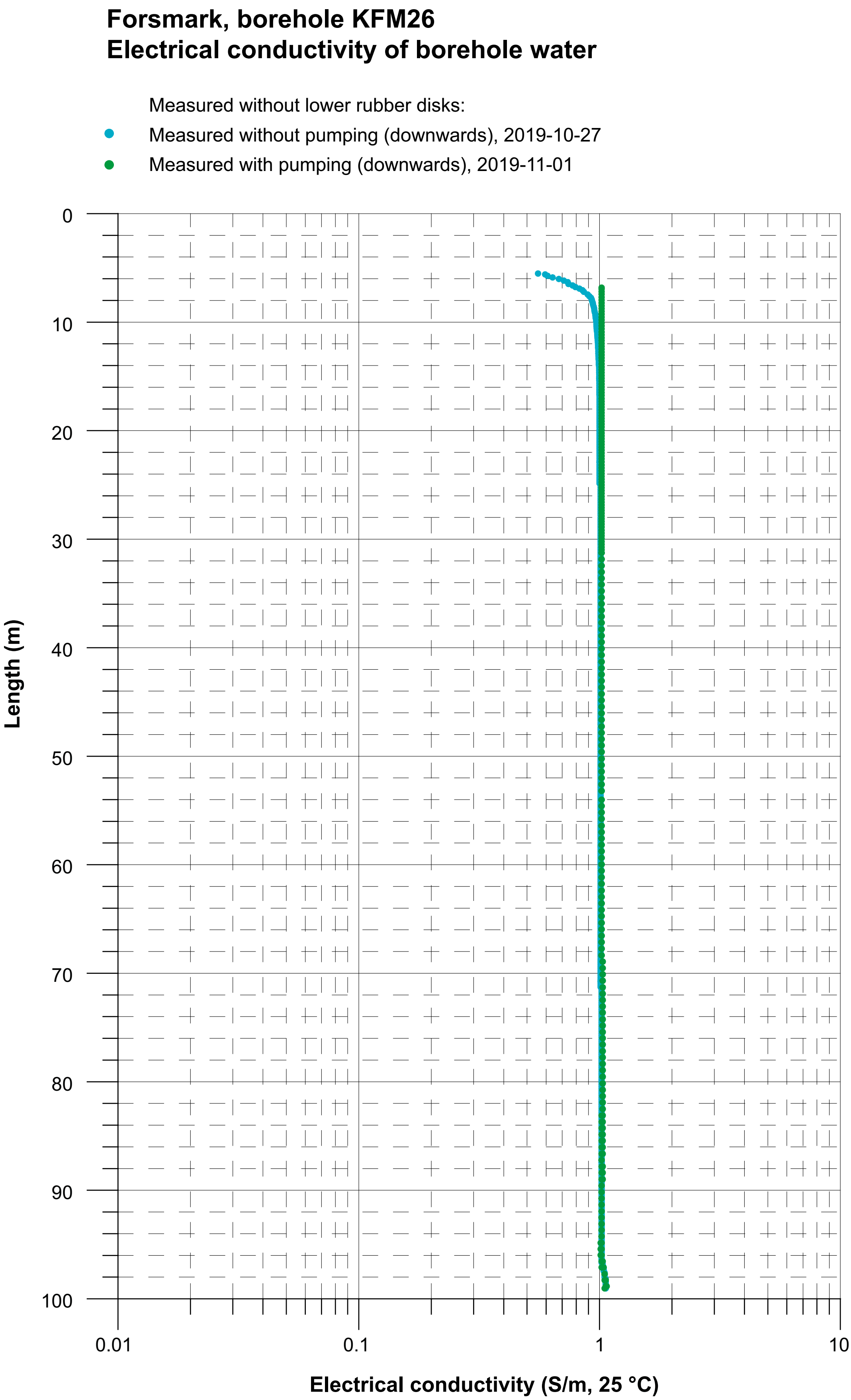
Forsmark, borehole KFM25
Flow rate, single point resistance and head in the borehole during flow logging

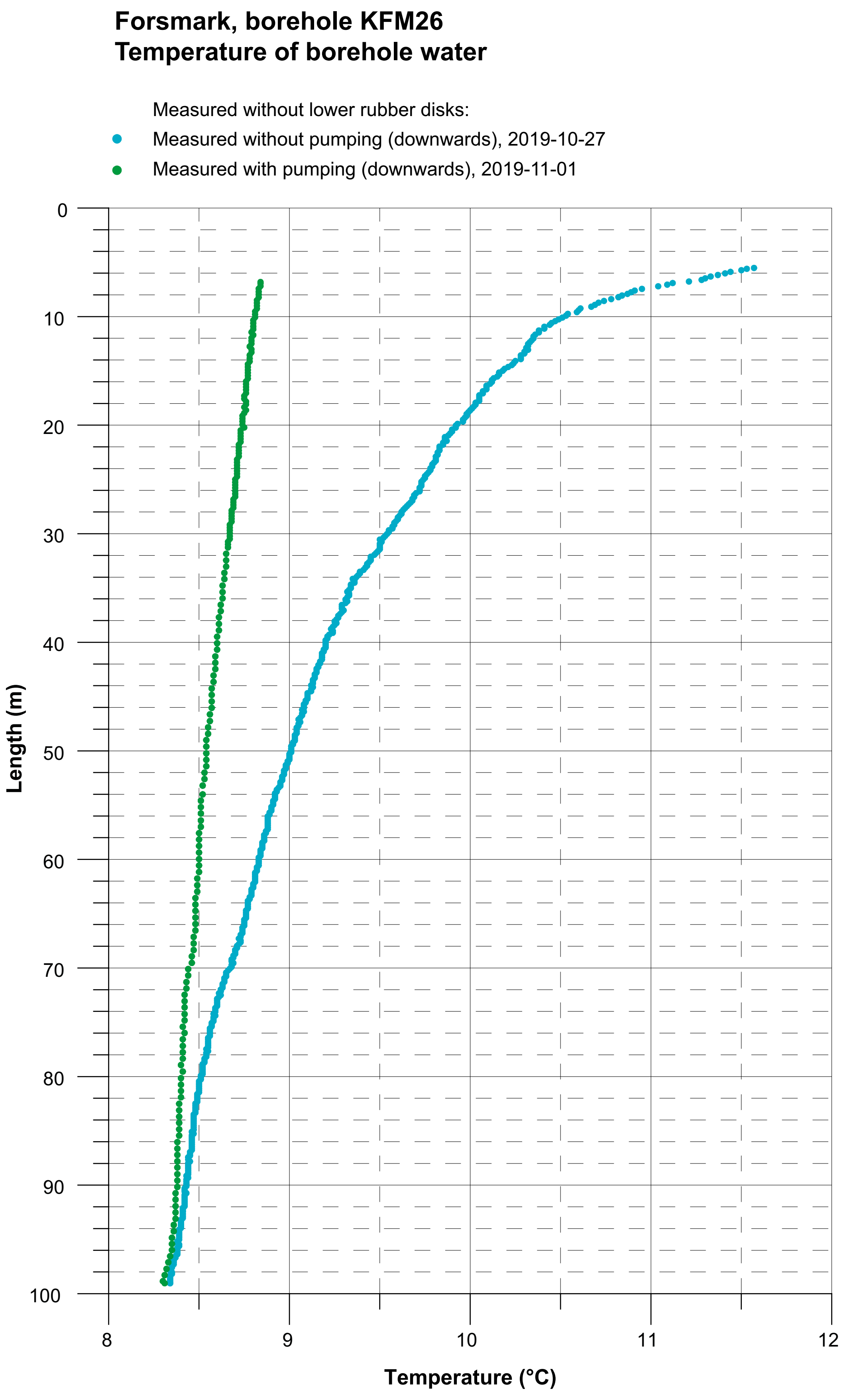


Appendix B

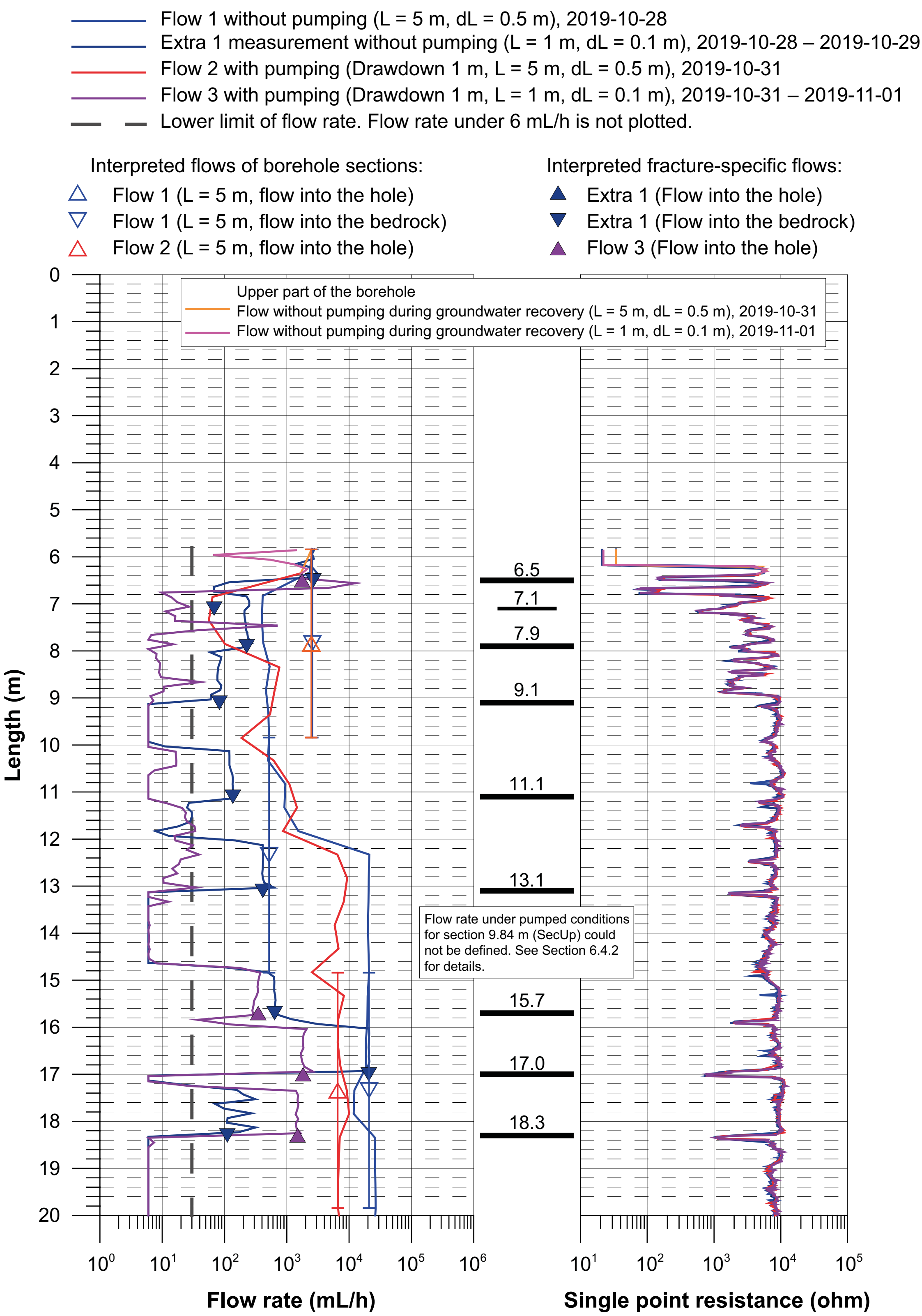
KFM26.1.1 – KFM26.1.2	Electrical conductivity of borehole water
KFM26.1.3	Temperature of borehole water
KFM26.2.1 – KFM26.2.5	Flow rate and single point resistance
KFM26.2.6	Vertical flow along the borehole at 5.9 m
KFM26.2.7	Vertical flow along the borehole at 9.4 m
KFM26.2.8	Vertical flow along the borehole at 95.5 m
KFM26.3	Glossary of terms used in the tables in Appendices
KFM26.4	Results of section flows
KFM26.5.1	Plotted flow rates of 5 m sections
KFM26.5.2	Plotted transmissivity and head of 5 m sections
KFM26.5.3	Transmissivity and head of 5 m sections with calculated error limits
KFM26.5.4	Conductive fracture frequency
KFM26.6.1 – KFM26.6.2	Inferred fracture flow anomalies from flow logging
KFM26.7.1	Plotted transmissivity and head of detected fractures
KFM26.7.2	Transmissivity and head of detected fractures with calculated error limits.
KFM26.8	Comparison between section transmissivity and fracture transmissivity
KFM26.9.1	Head in the borehole during flow logging
KFM26.9.2	Air pressure, water level in the borehole and pumping rate during flow logging
KFM26.10.1 – KFM26.10.2	Flow rate, single point resistance and head in the borehole during flow logging


Forsmark, borehole KFM26
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-27
Measured with pumping (downwards), 2019-11-01
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0.5
0.6
0.7
0.8
0.9
1
1.1
Electrical conductivity (S/m, 25 °C)

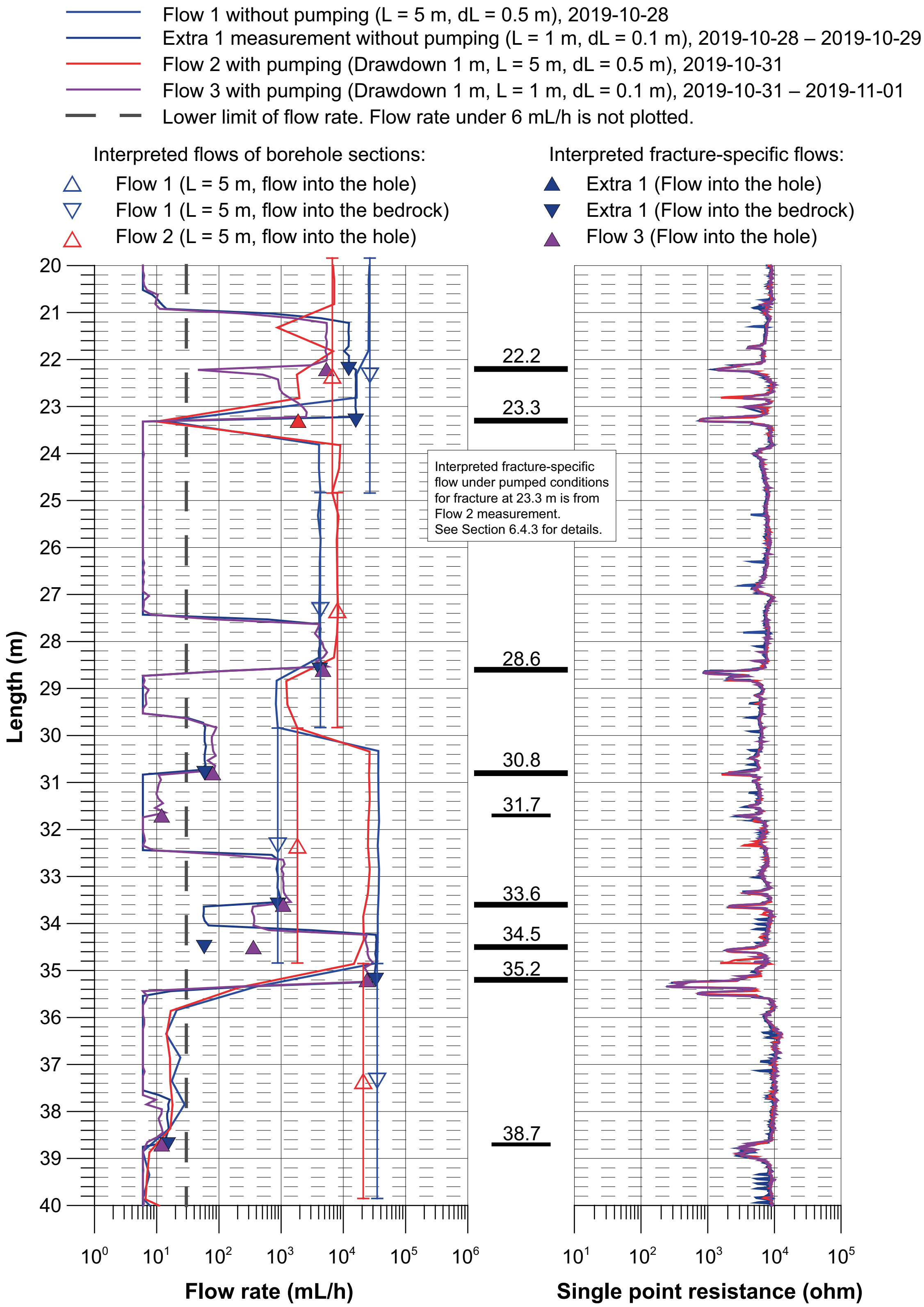

Forsmark, borehole KFM26
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-27
Measured with pumping (downwards), 2019-11-01
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0.01
0.1
1
10
Electrical conductivity (S/m, 25 °C)


Forsmark, borehole KFM26
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-10-27
Measured with pumping (downwards), 2019-11-01
Length (m)
Temperature (°C)
0
10
20
30
40
50
60
70
80
90
100
8
9
10
11
12

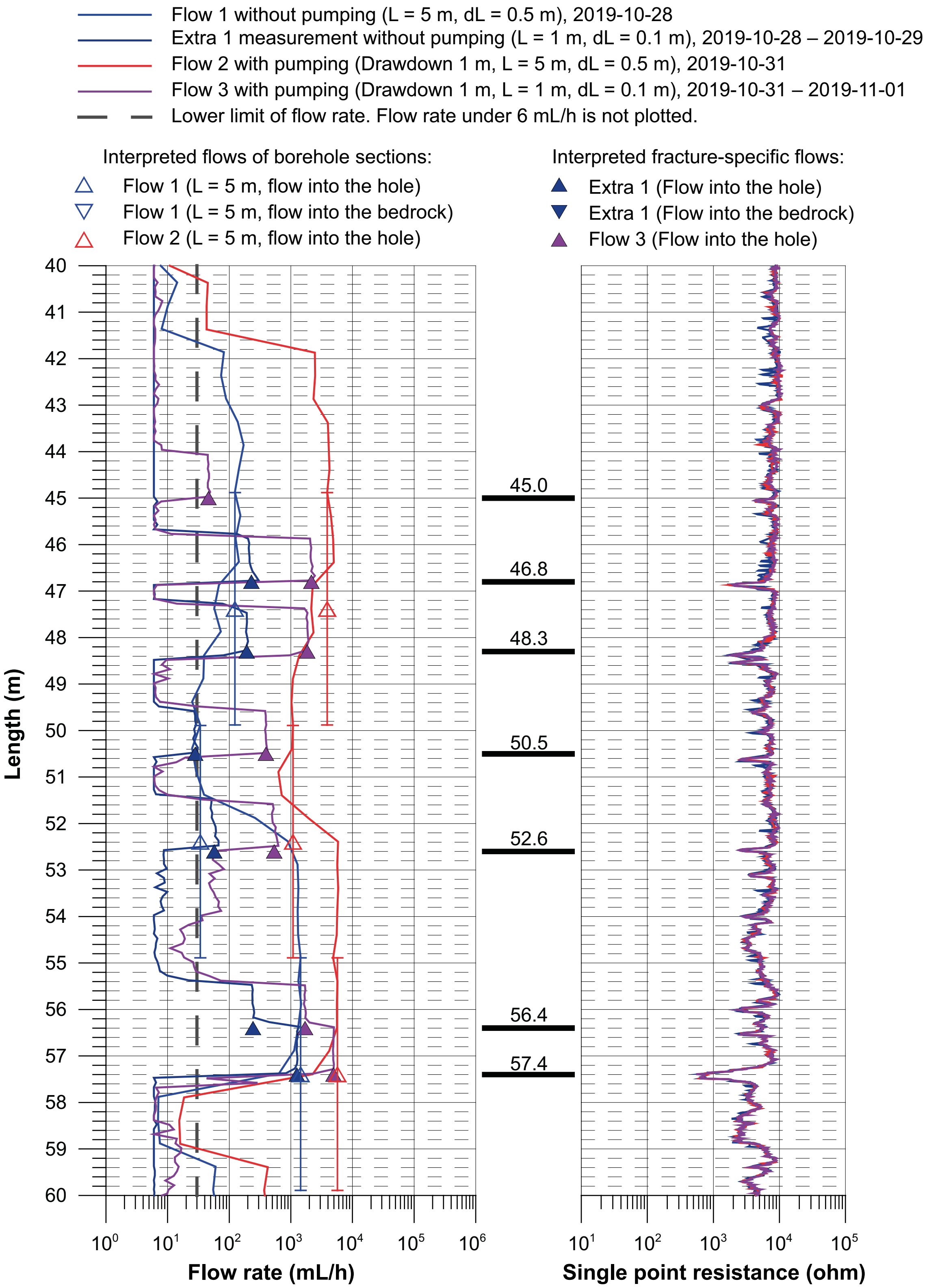
Forsmark, borehole KFM26
Flow rate and single point resistance



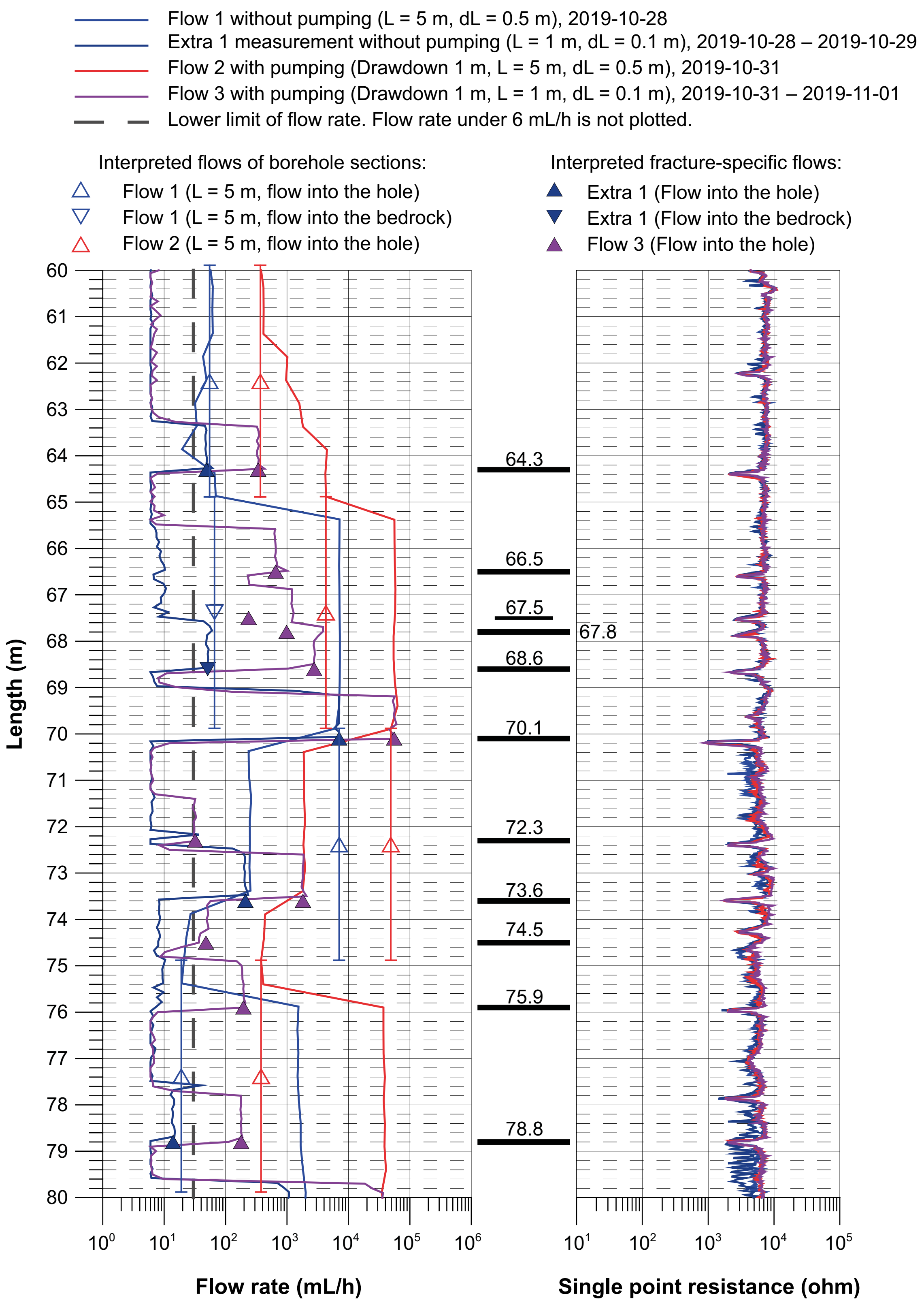
Forsmark, borehole KFM26
Flow rate and single point resistance



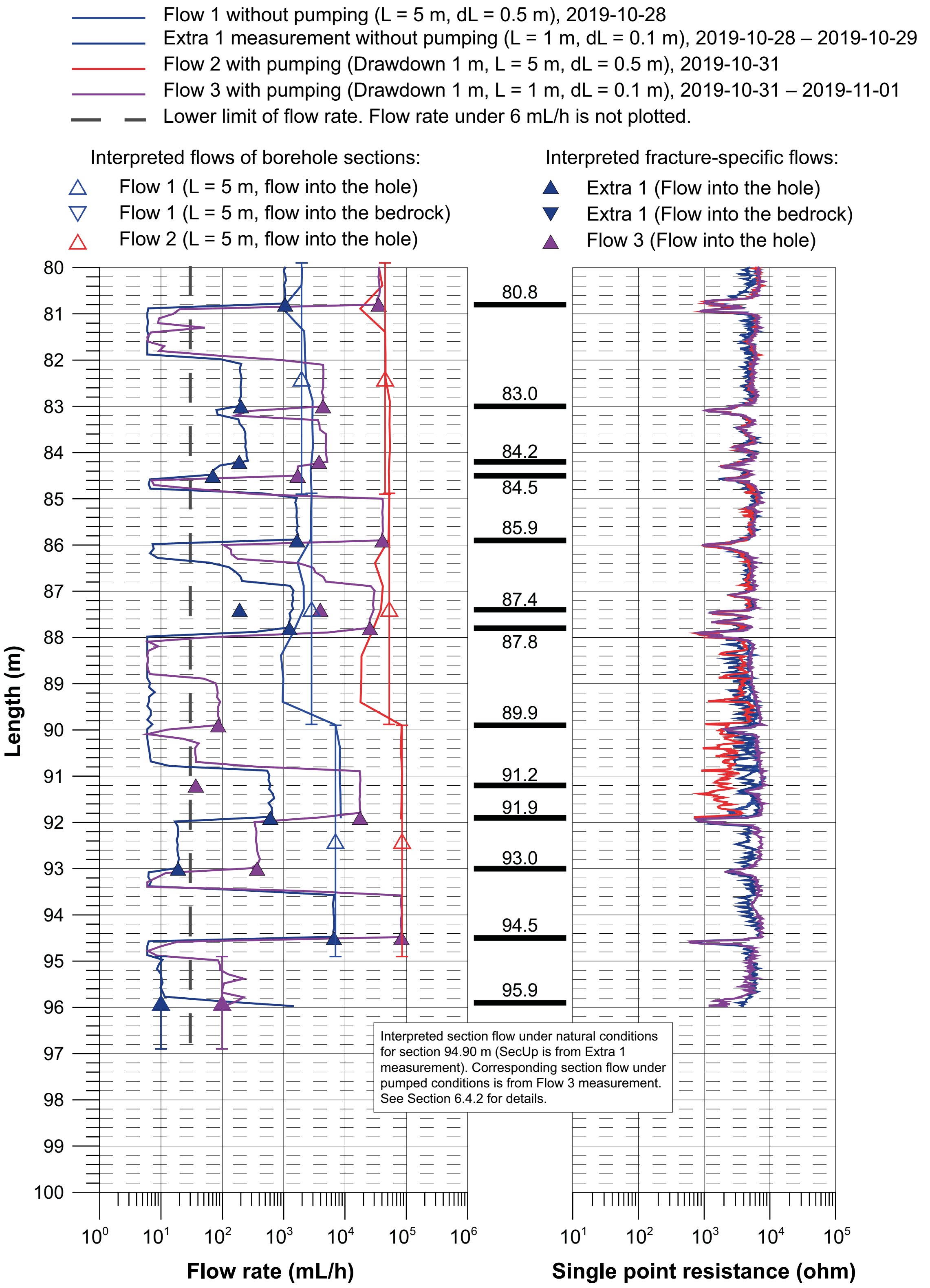
Forsmark, borehole KFM26
Flow rate and single point resistance



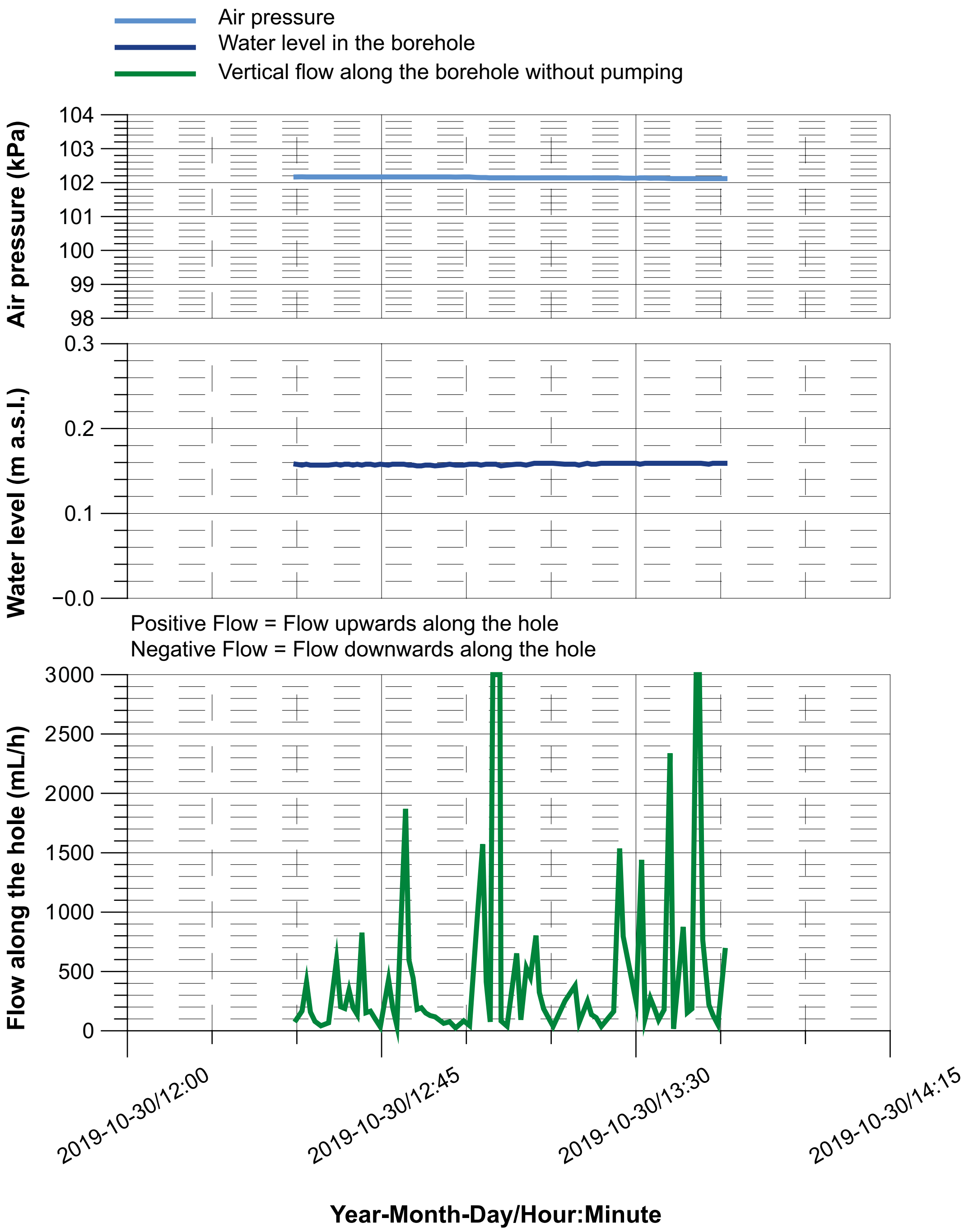
Forsmark, borehole KFM26
Flow rate and single point resistance



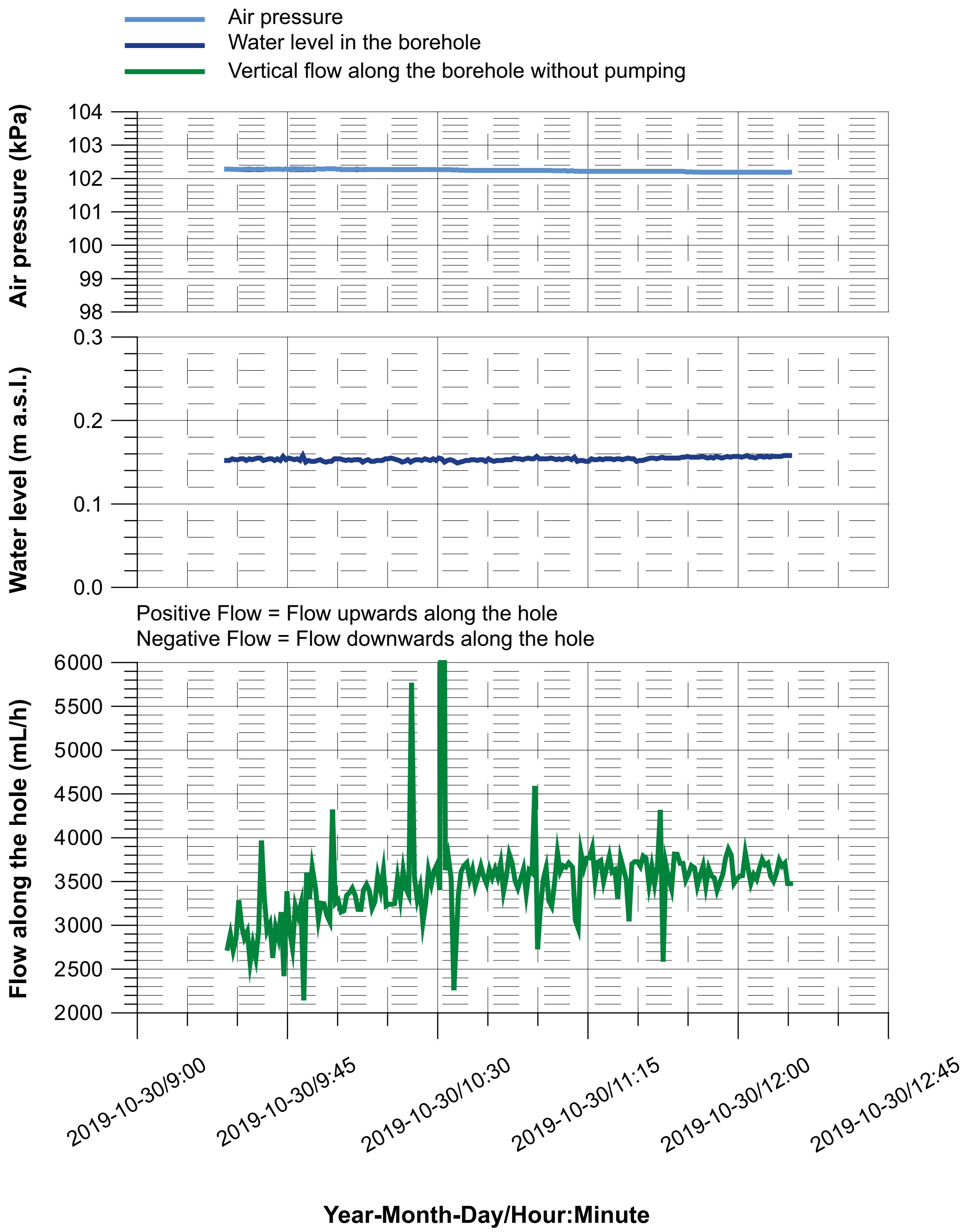
Forsmark, borehole KFM26
Flow rate and single point resistance

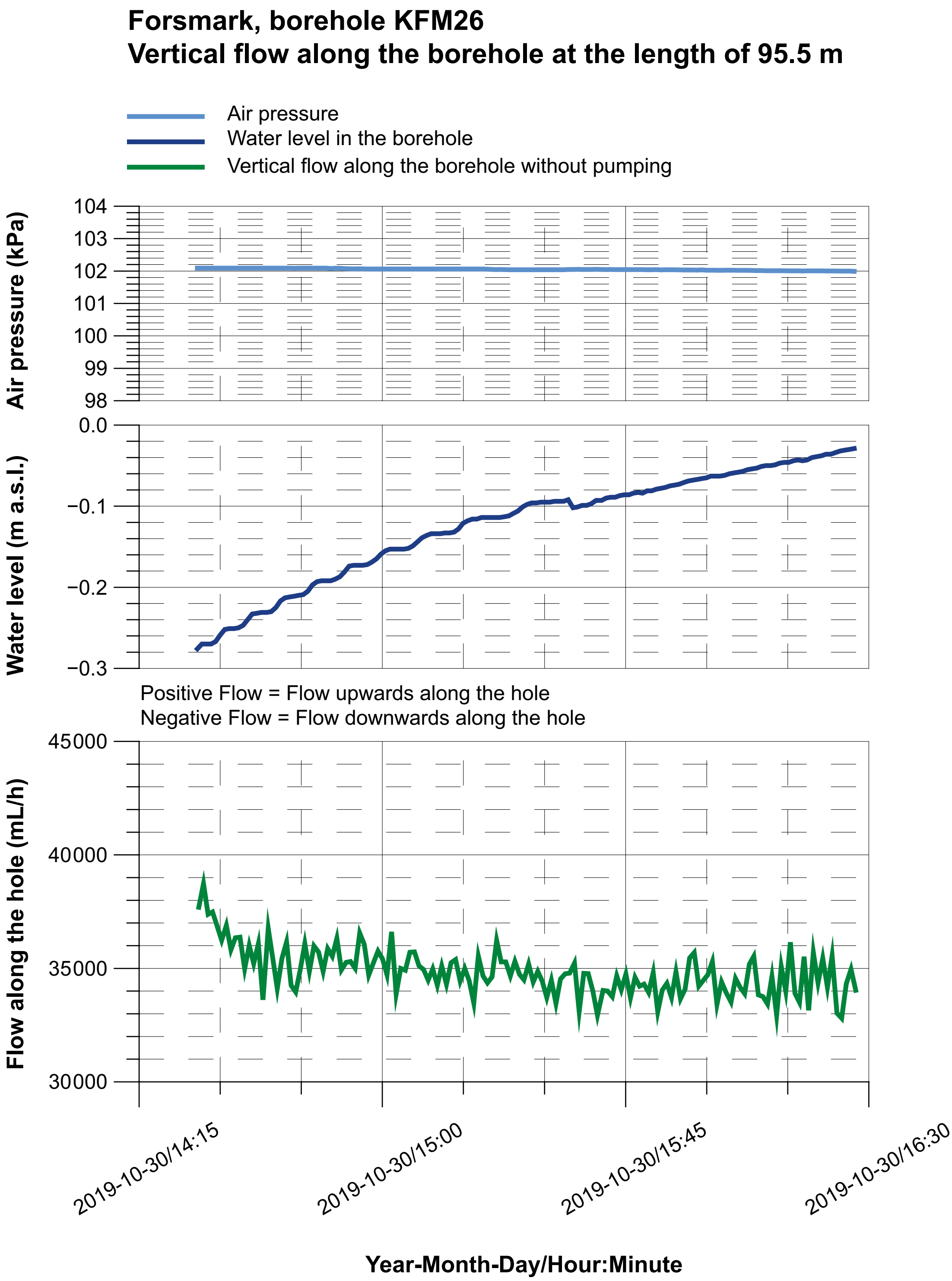


Forsmark, borehole KFM26
Vertical flow along the borehole at the length of 5.9 m



Forsmark, borehole KFM26
Vertical flow along the borehole at the length of 9.4 m




Forsmark, borehole KFM26
Vertical flow along the borehole at the length of 95.5 m
Air pressure
Water level in the borehole
Vertical flow along the borehole without pumping
Air pressure (kPa)
104
103
102
101
100
99
98
Water level (m a.s.l.)
0.0
−0.1
−0.2
−0.3
Positive Flow = Flow upwards along the hole
Negative Flow = Flow downwards along the hole
Flow along the hole (mL/h)
45000
40000
35000
30000
2019-10-30/14:15
2019-10-30/15:00
2019-10-30/15:45
2019-10-30/16:30
Year-Month-Day/Hour:Minute

Glossary of terms used in the tables in Appendices.

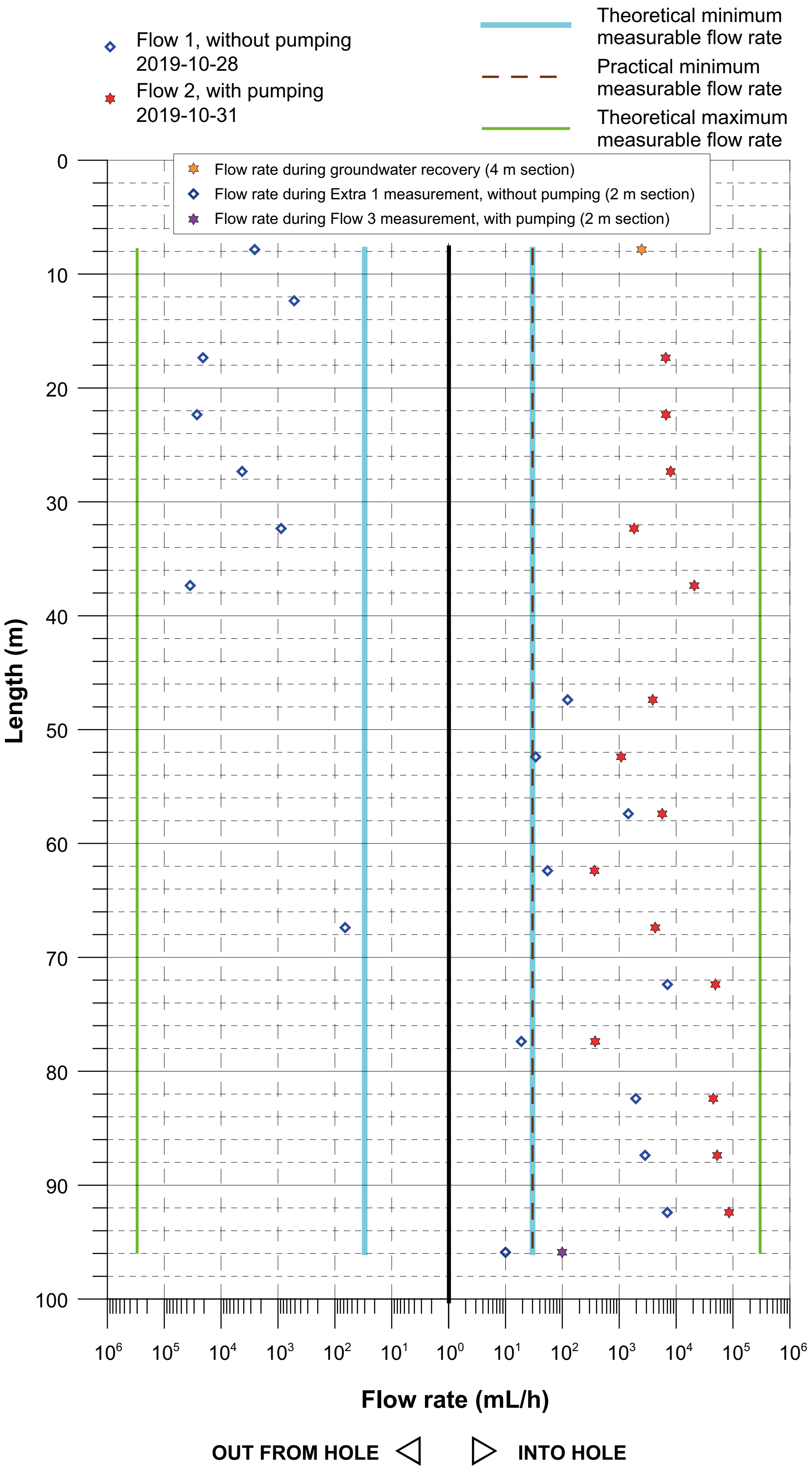
Header	Unit	Definition
Borehole ID		**ID for borehole**
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging.
L_w	m	Section length used in the difference flow logging.
dL	m	Step length (increment) used in the difference flow logging.
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h=h0 in the open borehole.
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period.
h_{0FW}	m a.s.l.	Corrected initial hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid before pumping.
h_{1FW}	m a.s.l.	Corrected hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL DIFF.
Q-lower limit P	mL/h	Practical lower measurement limit for flow rate.
T-measl$_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-measl$_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-measl$_U$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	m a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions).

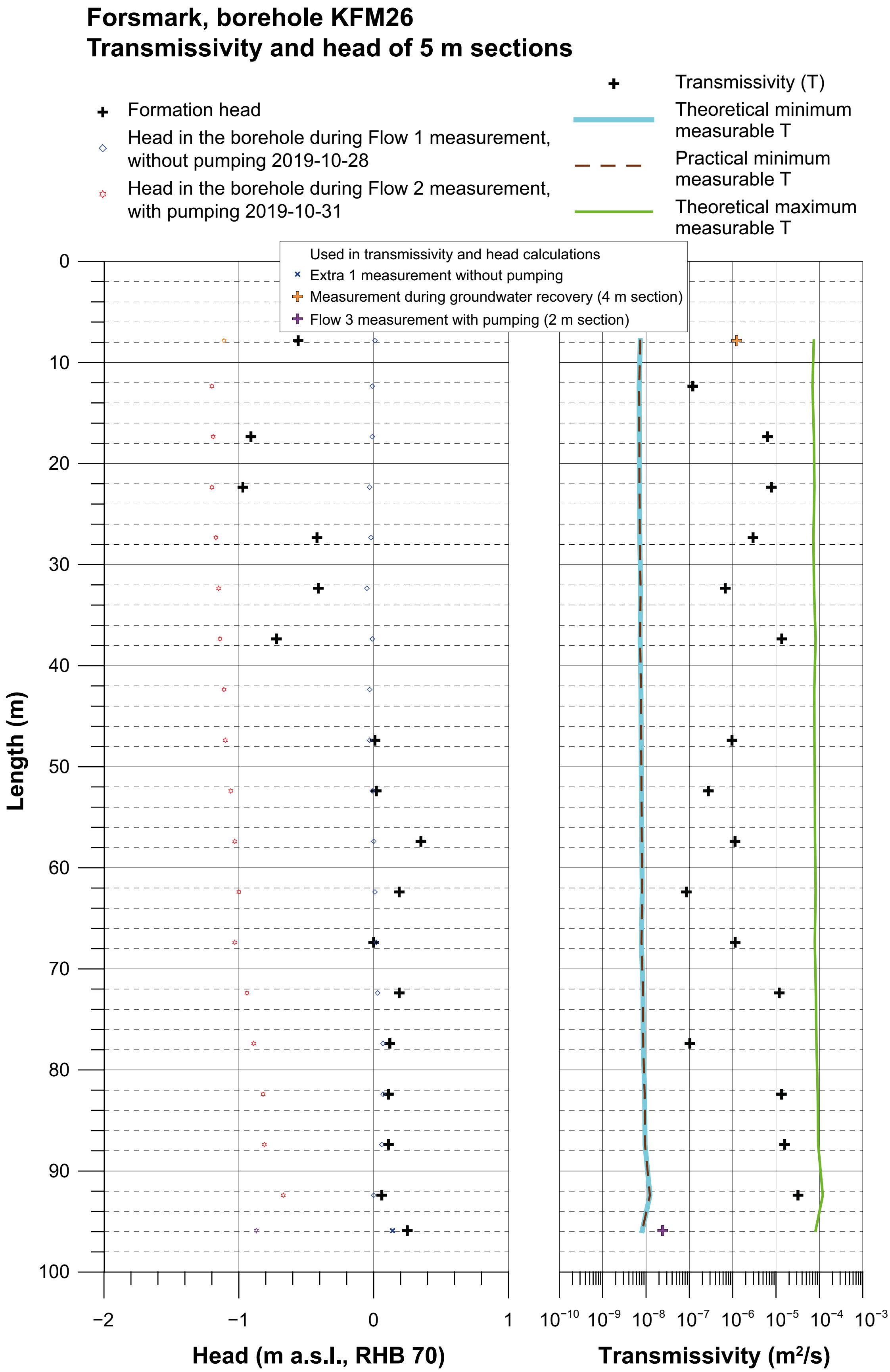
Results of section flows.

Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFM26	5.84	9.84	4	−7.14E−07	0.01	6.86E−07	−1.11	1.2E−06	−0.6	30	7.4E−09	7.4E−09	7.4E−05	*
KFM26	9.84	14.84	5	−1.44E−07	−0.01	-	−1.20	1.2E−07	-	30	6.9E−09	6.9E−09	6.9E−05	
KFM26	14.84	19.84	5	−5.79E−06	−0.01	1.82E−06	−1.19	6.4E−06	−0.9	30	7.0E−09	7.0E−09	7.5E−05	
KFM26	19.84	24.84	5	−7.39E−06	−0.03	1.85E−06	−1.20	7.8E−06	−1.0	30	7.0E−09	7.0E−09	7.7E−05	
KFM26	24.83	29.83	5	−1.19E−06	−0.02	2.23E−06	−1.17	2.9E−06	−0.4	30	7.2E−09	7.2E−09	7.3E−05	
KFM26	29.84	34.84	5	−2.45E−07	−0.05	5.06E−07	−1.15	6.8E−07	−0.4	30	7.5E−09	7.5E−09	7.5E−05	
KFM26	34.85	39.85	5	−9.73E−06	−0.01	5.81E−06	−1.14	1.4E−05	−0.7	30	7.3E−09	7.3E−09	8.1E−05	
KFM26	39.86	44.86	5	-	−0.03	-	−1.11	-	-	30	7.6E−09	7.6E−09	7.6E−05	
KFM26	44.88	49.88	5	3.44E−08	−0.03	1.08E−06	−1.10	9.6E−07	0.0	30	7.7E−09	7.7E−09	7.7E−05	
KFM26	49.89	54.89	5	9.44E−09	−0.01	3.01E−07	−1.06	2.7E−07	0.0	30	7.9E−09	7.9E−09	7.8E−05	
KFM26	54.89	59.89	5	4.02E−07	0.00	1.58E−06	−1.03	1.1E−06	0.4	30	8.0E−09	8.0E−09	8.0E−05	
KFM26	59.89	64.89	5	1.53E−08	0.01	1.02E−07	−1.00	8.5E−08	0.2	30	8.2E−09	8.2E−09	8.2E−05	
KFM26	64.88	69.88	5	−1.83E−08	0.02	1.19E−06	−1.03	1.1E−06	-	30	7.9E−09	7.9E−09	7.9E−05	
KFM26	69.88	74.88	5	1.96E−06	0.03	1.36E−05	−0.94	1.2E−05	0.2	30	8.5E−09	8.5E−09	8.3E−05	
KFM26	74.88	79.88	5	5.28E−09	0.07	1.05E−07	−0.89	1.0E−07	0.1	30	8.6E−09	8.6E−09	8.6E−05	**
KFM26	79.90	84.90	5	5.44E−07	0.07	1.25E−05	−0.82	1.3E−05	0.1	30	9.3E−09	9.3E−09	9.2E−05	
KFM26	84.88	89.88	5	7.90E−07	0.06	1.47E−05	−0.81	1.6E−05	0.1	30	9.5E−09	9.5E−09	9.4E−05	
KFM26	89.90	94.90	5	1.95E−06	0.00	2.37E−05	−0.67	3.2E−05	0.1	30	1.2E−08	1.2E−08	1.2E−04	
KFM26	94.90	96.90	2	2.78E−09	0.14	2.75E−08	−0.87	2.4E−08	0.3	30	8.2E−09	8.2E−09	8.2E−05	**,***

* Values for Flow (Q_1) and Head (h_{1FW}) are from the measurement made without pumping, during groundwater recovery. The upper part of the borehole could not be measured while pumping the borehole (while the pump remained in the borehole).
** Uncertain = The measured flow rate (Q_0) is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
*** Values for Flow (Q_0) and Head (h_{0FW}) are from the Extra 1 measurement. Values for Flow (Q_1) and Head (h_{1FW}) are from the Flow 3 measurement.

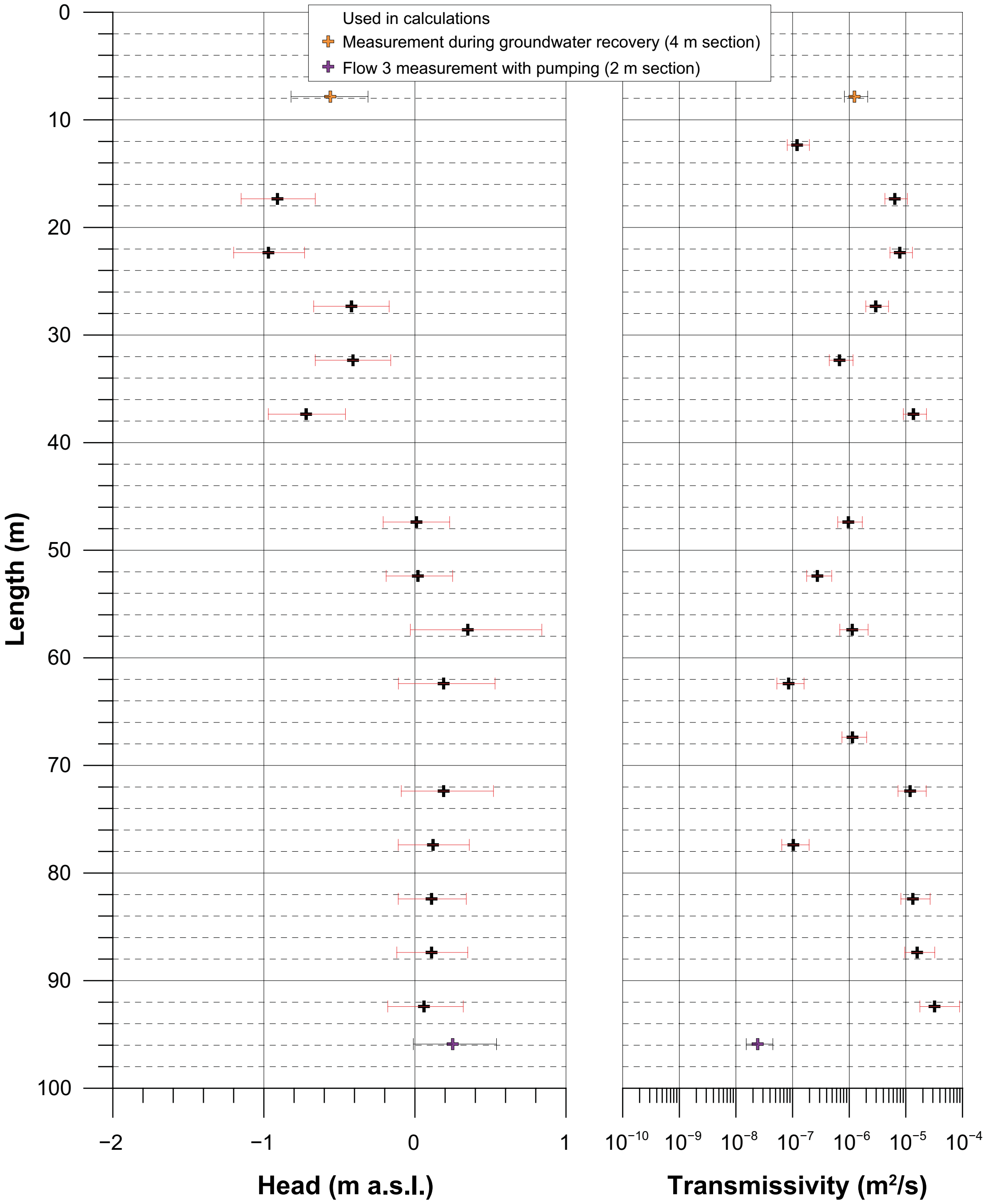
Forsmark, borehole KFM26
Flow rates of 5 m sections

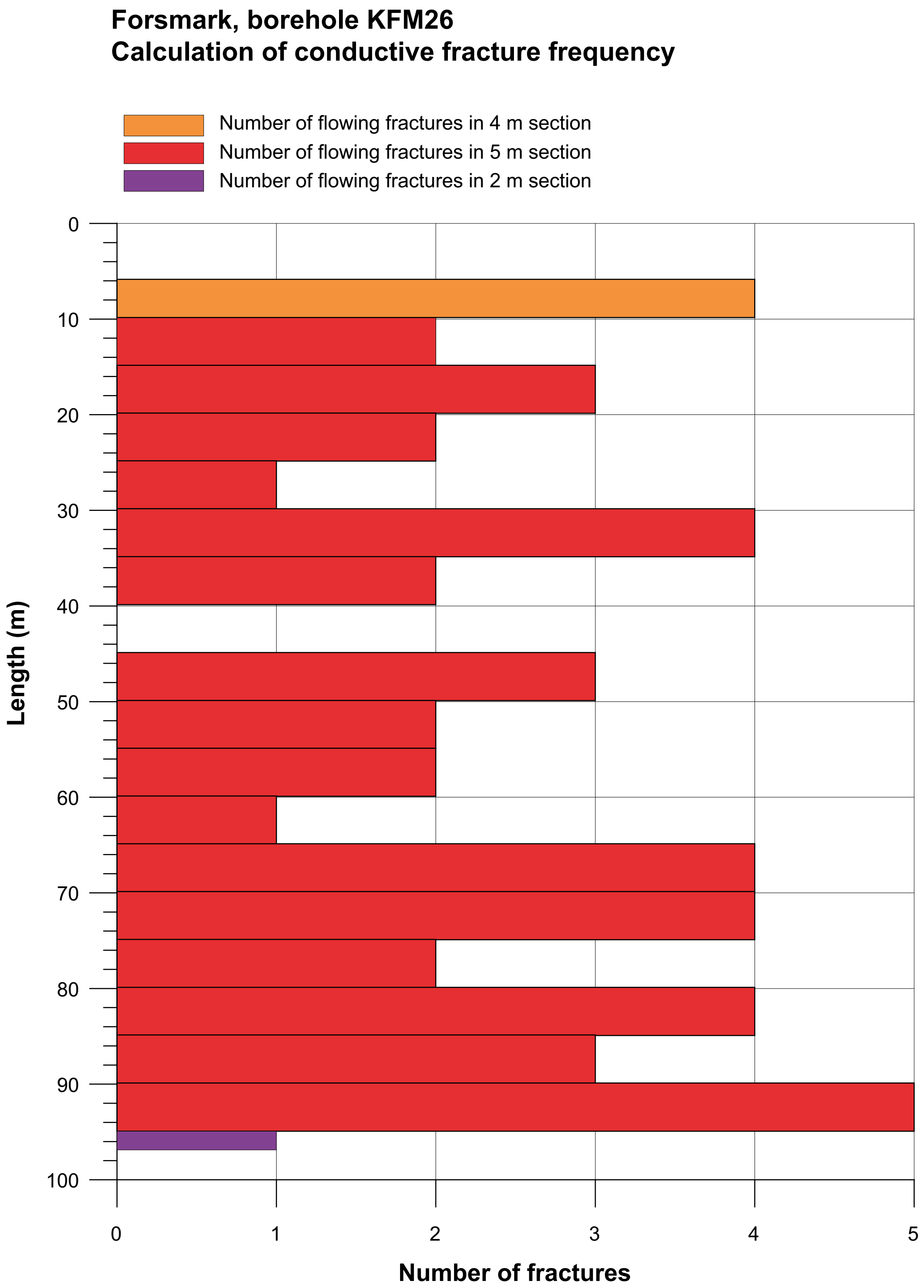




Forsmark, borehole KFM26
Transmissivity and head of 5 m sections
Formation head
Head in the borehole during Flow 1 measurement, without pumping 2019-10-28
Head in the borehole during Flow 2 measurement, with pumping 2019-10-31
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Used in transmissivity and head calculations
Extra 1 measurement without pumping
Measurement during groundwater recovery (4 m section)
Flow 3 measurement with pumping (2 m section)
Length (m)
Head (m a.s.l., RHB 70)
Transmissivity (m²/s)

Forsmark, borehole KFM26
Transmissivity and head of 5 m sections
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination



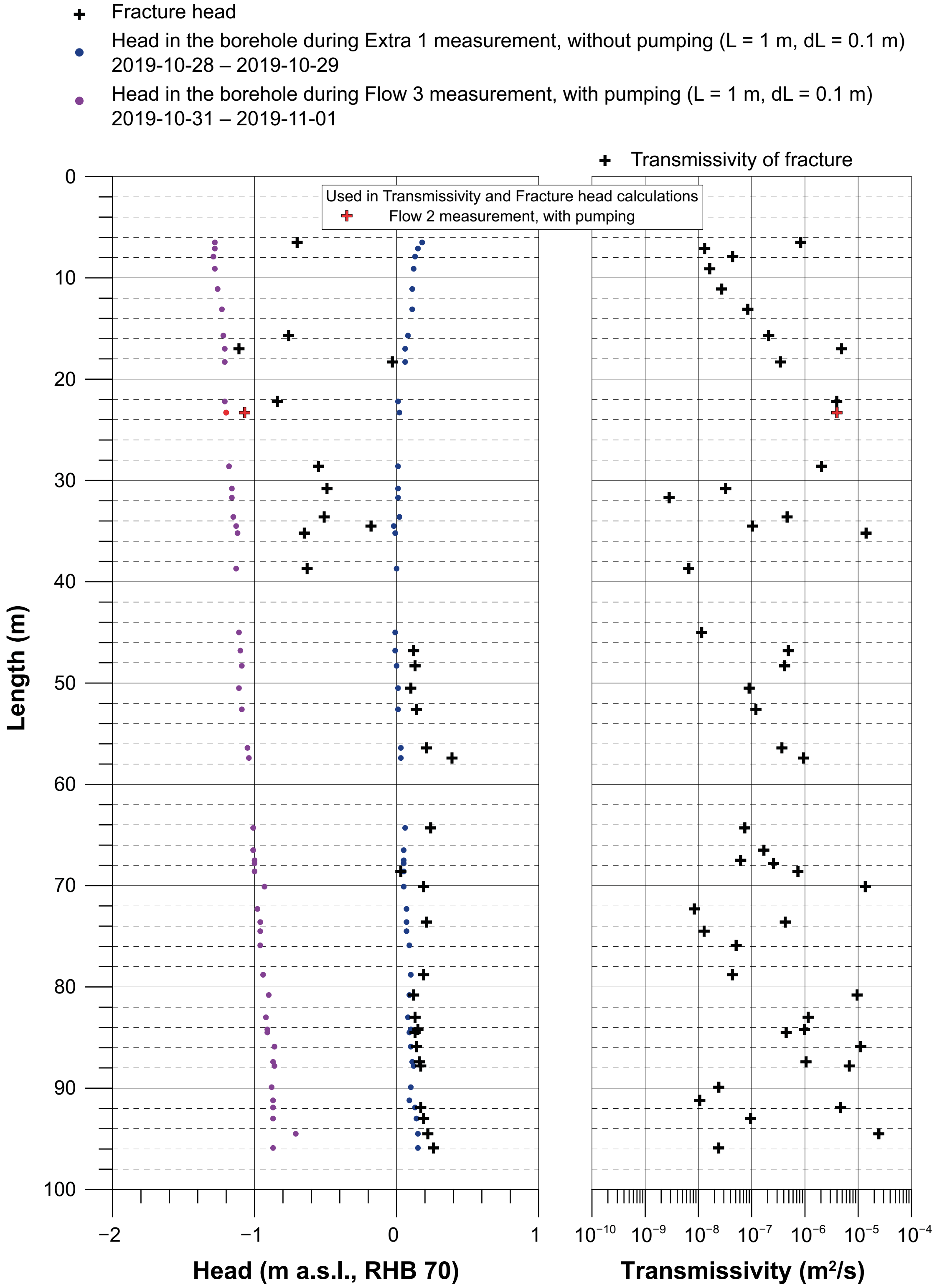

Forsmark, borehole KFM26
Calculation of conductive fracture frequency
Number of flowing fractures in 4 m section
Number of flowing fractures in 5 m section
Number of flowing fractures in 2 m section
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Number of fractures

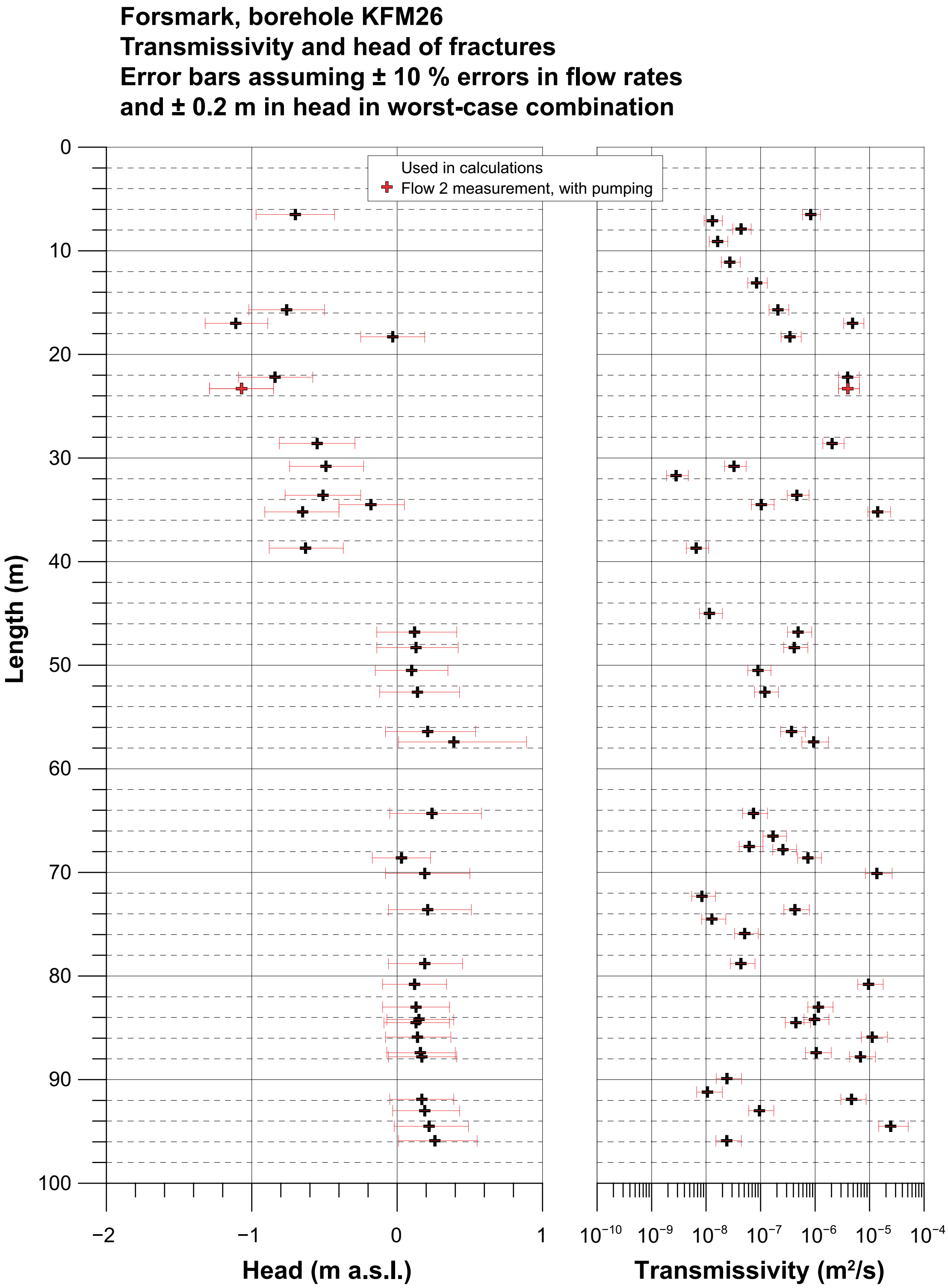
Inferred fracture flow anomalies from flow logging.

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0** (m^3/s)	h_{0FW} (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Comments
KFM26	6.5	1	0.1	−7.39E−07	0.18	4.89E−07	−1.28	8.3E−07	−0.7	
KFM26	7.1	1	0.1	−1.89E−08	0.15	-	−1.28	1.3E−08	-	*
KFM26	7.9	1	0.1	−6.31E−08	0.13	-	−1.29	4.4E−08	-	
KFM26	9.1	1	0.1	−2.31E−08	0.12	-	−1.28	1.6E−08	-	
KFM26	11.1	1	0.1	−3.78E−08	0.11	-	−1.26	2.7E−08	-	
KFM26	13.1	1	0.1	−1.14E−07	0.11	-	−1.23	8.5E−08	-	
KFM26	15.7	1	0.1	−1.77E−07	0.08	9.64E−08	−1.22	2.1E−07	−0.8	
KFM26	17.0	1	0.1	−5.75E−06	0.06	5.08E−07	−1.21	4.9E−06	−1.1	
KFM26	18.3	1	0.1	−3.08E−08	0.06	4.14E−07	−1.21	3.5E−07	0	
KFM26	22.2	1	0.1	−3.39E−06	0.01	1.49E−06	−1.21	4.0E−06	−0.8	
KFM26	23.3	1	0.1	−4.39E−06	0.02	5.19E−07	−1.20	4.0E−06	−1.1	***
KFM26	28.6	1	0.1	−1.16E−06	0.01	1.31E−06	−1.18	2.1E−06	−0.6	
KFM26	30.8	1	0.1	−1.64E−08	0.01	2.22E−08	−1.16	3.3E−08	−0.5	
KFM26	31.7	1	0.1	-	0.01	3.33E−09	−1.16	2.8E−09	-	*
KFM26	33.6	1	0.1	−2.47E−07	0.02	3.00E−07	−1.15	4.6E−07	−0.5	
KFM26	34.5	1	0.1	−1.61E−08	−0.02	9.92E−08	−1.13	1.0E−07	−0.2	
KFM26	35.2	1	0.1	−9.17E−06	−0.01	6.61E−06	−1.12	1.4E−05	−0.7	
KFM26	38.7	1	0.1	−4.17E−09	0	3.33E−09	−1.13	6.6E−09	−0.6	*
KFM26	45.0	1	0.1	-	−0.01	1.28E−08	−1.11	1.2E−08	-	
KFM26	46.8	1	0.1	6.36E−08	−0.01	6.00E−07	−1.10	4.9E−07	0.1	
KFM26	48.3	1	0.1	5.33E−08	0	5.11E−07	−1.09	4.2E−07	0.1	
KFM26	50.5	1	0.1	7.78E−09	0.01	1.09E−07	−1.11	9.0E−08	0.1	
KFM26	52.6	1	0.1	1.58E−08	0.01	1.49E−07	−1.09	1.2E−07	0.1	
KFM26	56.4	1	0.1	6.78E−08	0.03	4.72E−07	−1.05	3.7E−07	0.2	
KFM26	57.4	1	0.1	3.47E−07	0.03	1.37E−06	−1.04	9.4E−07	0.4	
KFM26	64.3	1	0.1	1.36E−08	0.06	9.39E−08	−1.01	7.4E−08	0.2	
KFM26	66.5	1	0.1	-	0.05	1.81E−07	−1.01	1.7E−07	-	
KFM26	67.5	1	0.1	-	0.05	6.58E−08	−1.00	6.2E−08	-	*
KFM26	67.8	1	0.1	-	0.05	2.73E−07	−1.00	2.6E−07	-	
KFM26	68.6	1	0.1	−1.42E−08	0.05	7.69E−07	−1.00	7.4E−07	0	
KFM26	70.1	1	0.1	1.96E−06	0.05	1.54E−05	−0.93	1.4E−05	0.2	
KFM26	72.3	1	0.1	-	0.07	8.89E−09	−0.98	8.4E−09	-	
KFM26	73.6	1	0.1	5.86E−08	0.07	5.03E−07	−0.96	4.3E−07	0.2	
KFM26	74.5	1	0.1	-	0.07	1.33E−08	−0.96	1.3E−08	-	
KFM26	75.9	1	0.1	-	0.09	5.42E−08	−0.96	5.1E−08	-	
KFM26	78.8	1	0.1	3.89E−09	0.10	4.97E−08	−0.94	4.4E−08	0.2	
KFM26	80.8	1	0.1	2.94E−07	0.09	9.86E−06	−0.90	9.6E−06	0.1	
KFM26	83.0	1	0.1	5.58E−08	0.08	1.22E−06	−0.92	1.2E−06	0.1	
KFM26	84.2	1	0.1	5.22E−08	0.10	1.05E−06	−0.91	9.8E−07	0.2	
KFM26	84.5	1	0.1	1.94E−08	0.09	4.69E−07	−0.91	4.5E−07	0.1	
KFM26	85.9	1	0.1	4.58E−07	0.10	1.14E−05	−0.86	1.1E−05	0.1	
KFM26	87.4	1	0.1	5.31E−08	0.11	1.10E−06	−0.87	1.1E−06	0.2	
KFM26	87.8	1	0.1	3.44E−07	0.12	7.08E−06	−0.86	6.8E−06	0.2	
KFM26	89.9	1	0.1	-	0.10	2.39E−08	−0.88	2.4E−08	-	
KFM26	91.2	1	0.1	-	0.09	1.03E−08	−0.87	1.1E−08	-	
KFM26	91.9	1	0.1	1.69E−07	0.13	4.89E−06	−0.87	4.7E−06	0.2	
KFM26	93.0	1	0.1	5.28E−09	0.14	1.03E−07	−0.87	9.5E−08	0.2	
KFM26	94.5	1	0.1	1.83E−06	0.15	2.31E−05	−0.71	2.4E−05	0.2	
KFM26	95.9	1	0.1	2.78E−09	0.15	2.75E−08	−0.87	2.4E−08	0.3	

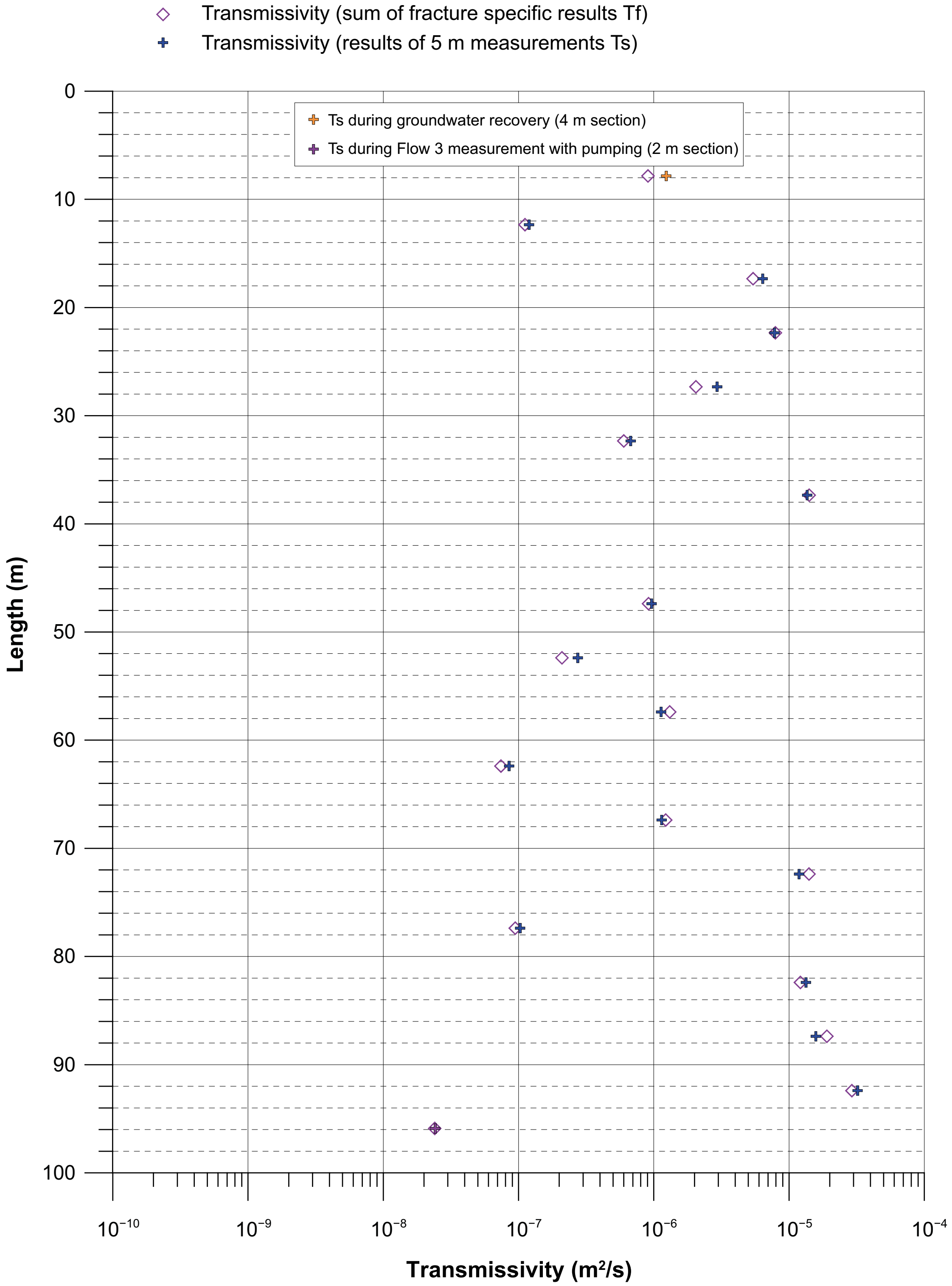
* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
** All values for Flow (Q_0) and Head (h_{0FW}) are from Extra 1 measurement.
*** Values for Flow (Q_1) and Head (h_{1FW}) are from Flow 2 measurement.

Forsmark, borehole KFM26
Transmissivity and head of detected fractures



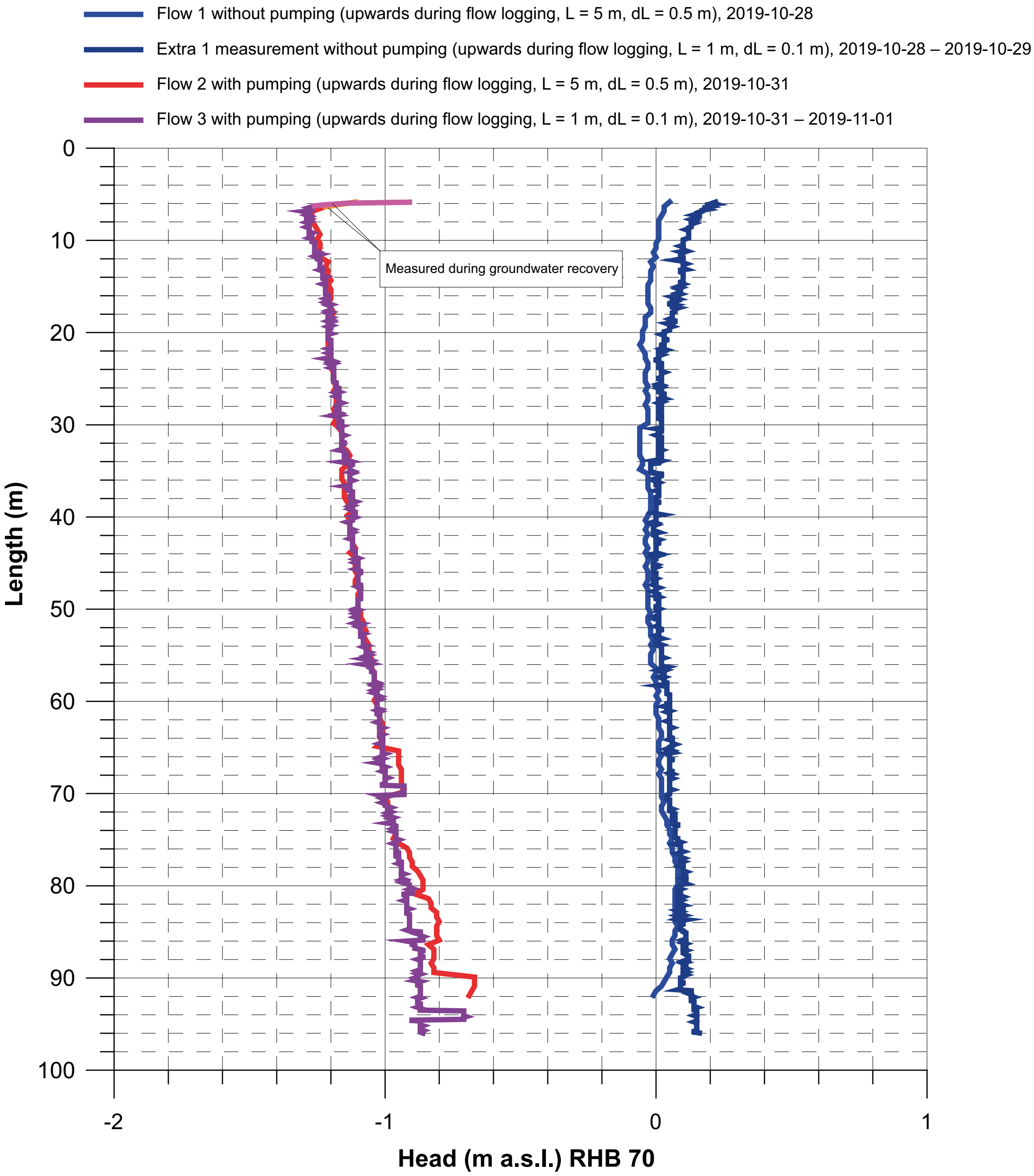

Forsmark, borehole KFM26
Transmissivity and head of fractures
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination
Used in calculations
Flow 2 measurement, with pumping
Length (m)
Head (m a.s.l.)
Transmissivity (m²/s)

Forsmark, borehole KFM26
Comparison between section transmissivity and fracture transmissivity

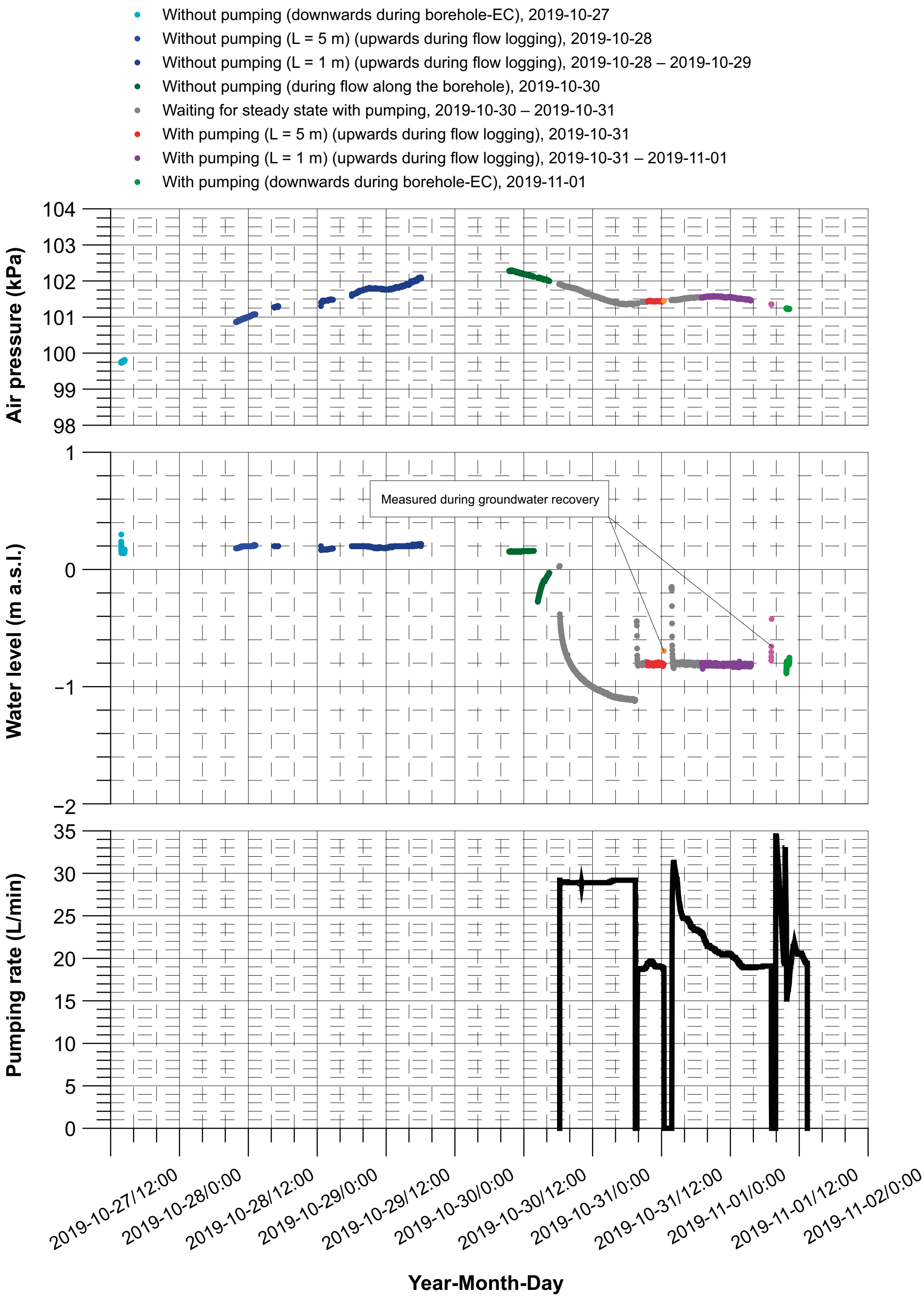


Forsmark, borehole KFM26
Head in the borehole during flow logging

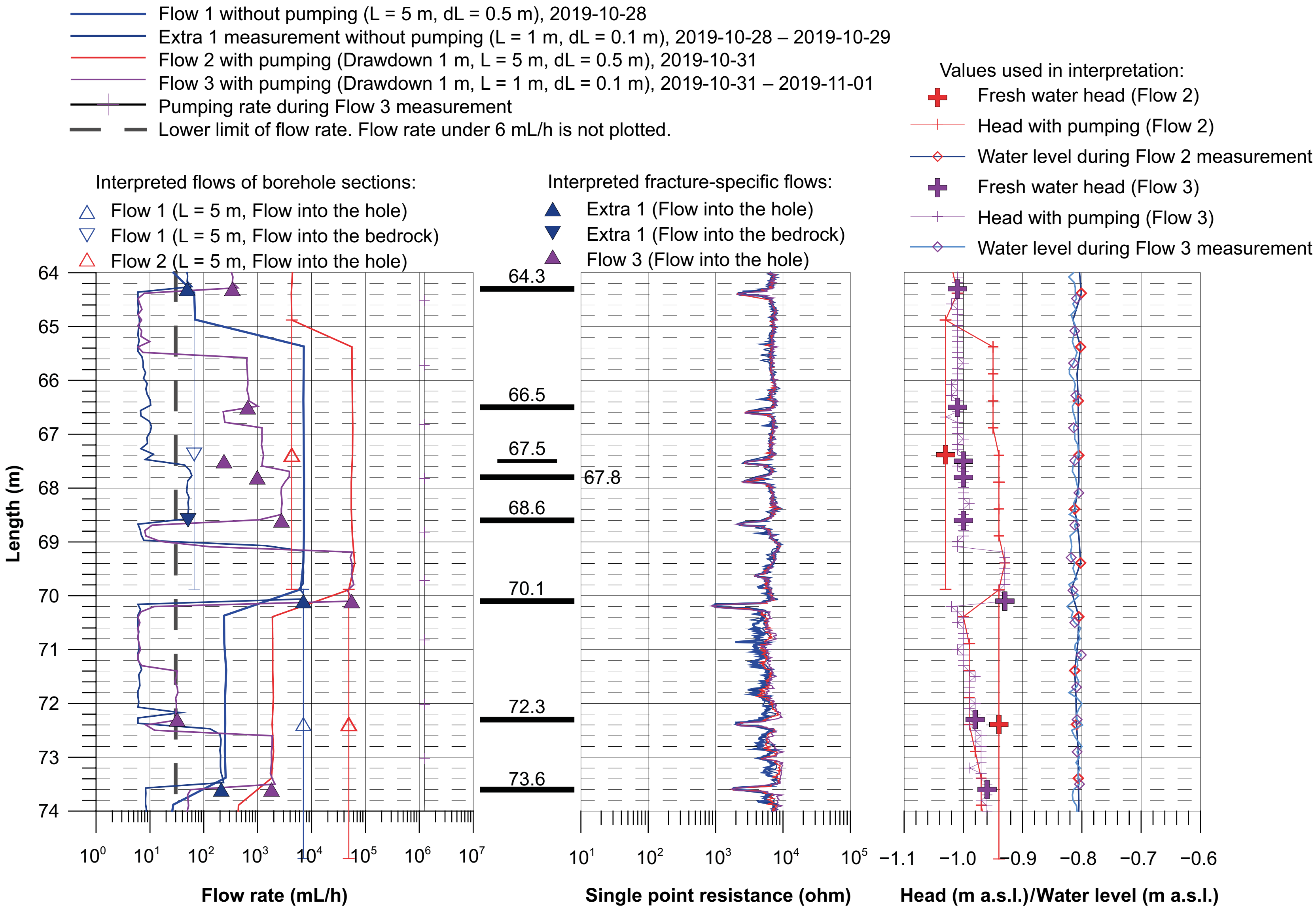
Head (m a.s.l.) = (Absolute pressure (Pa) − Airpressure (Pa) + Offset)/(1000 kg/m³ × 9.80665 m/s²) + Elevation (m)
Offset = Correction for absolute pressure sensor



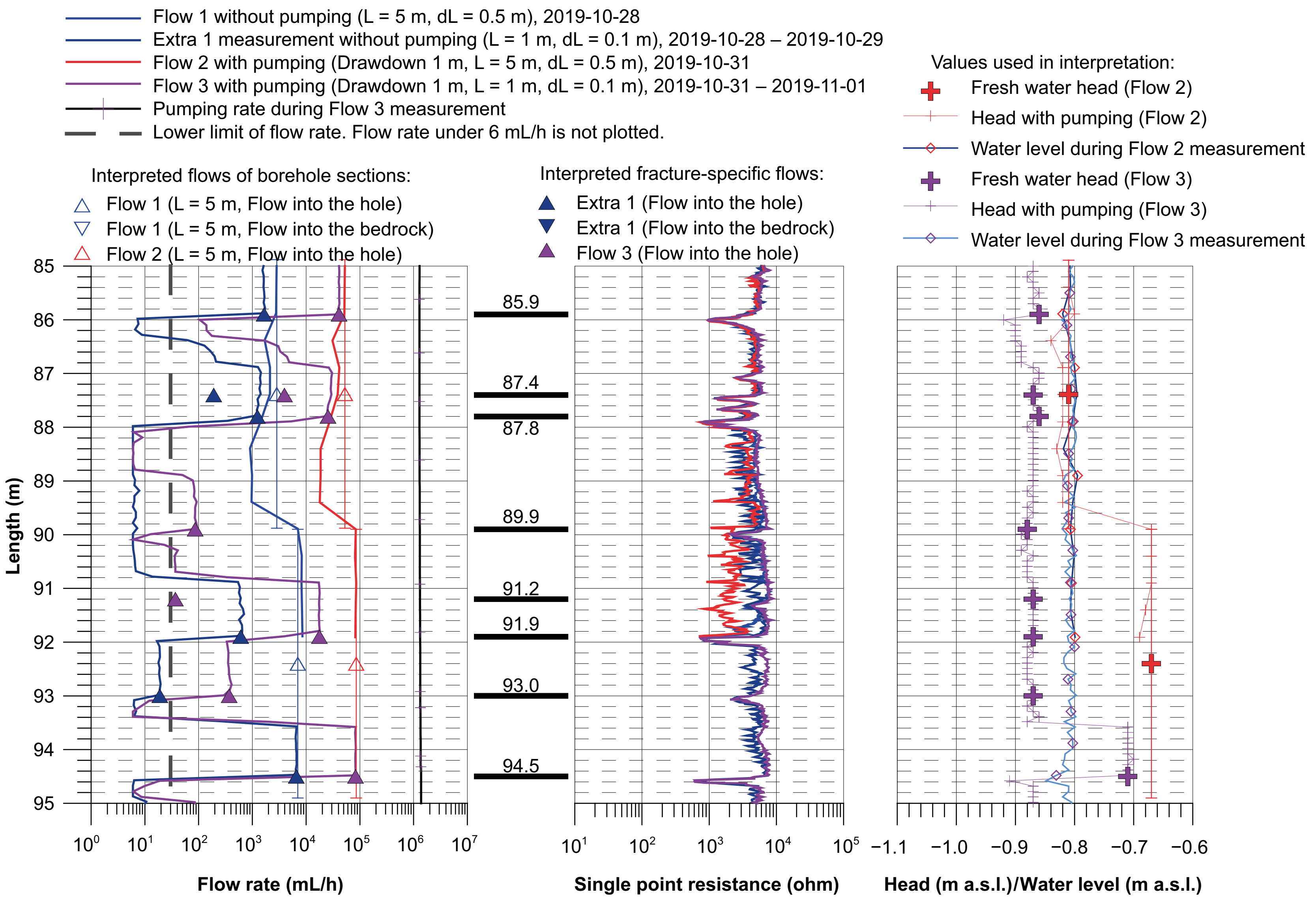
Forsmark, borehole KFM26
Air pressure, water level in the borehole and pumping rate during flow logging



Forsmark, borehole KFM26
Flow rate, single point resistance and head in the borehole during flow logging

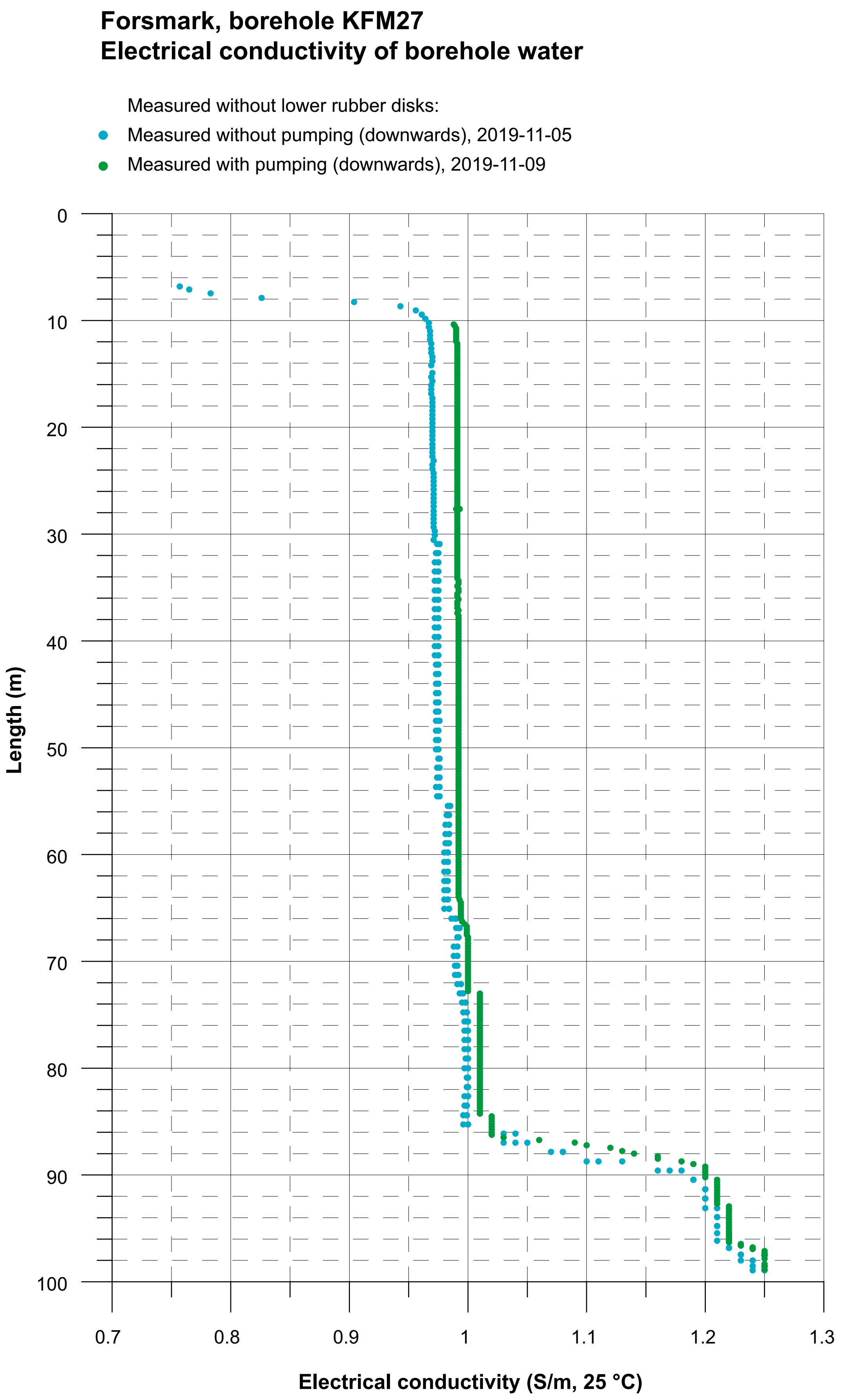


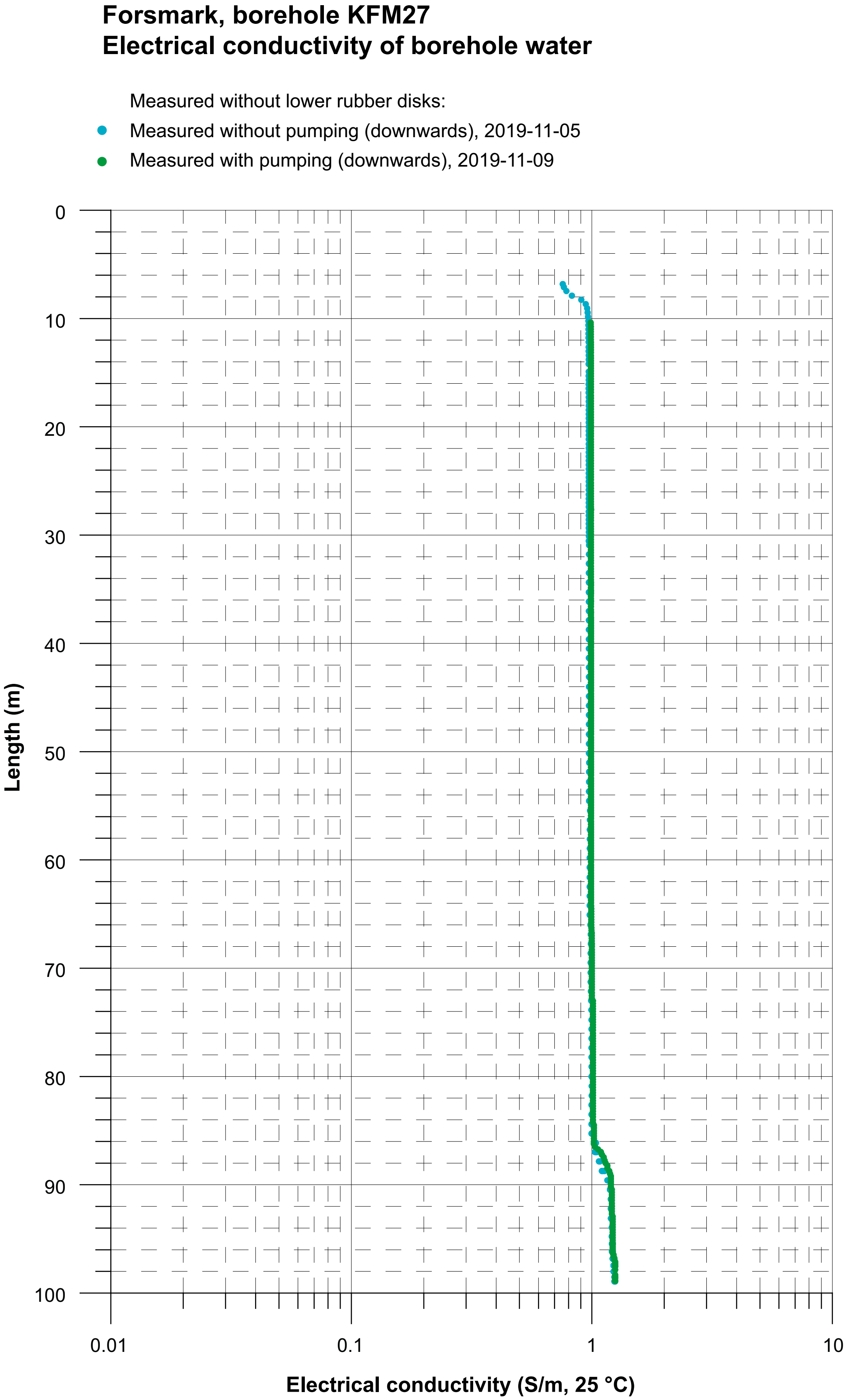
Forsmark, borehole KFM26
Flow rate, single point resistance and head in the borehole during flow logging

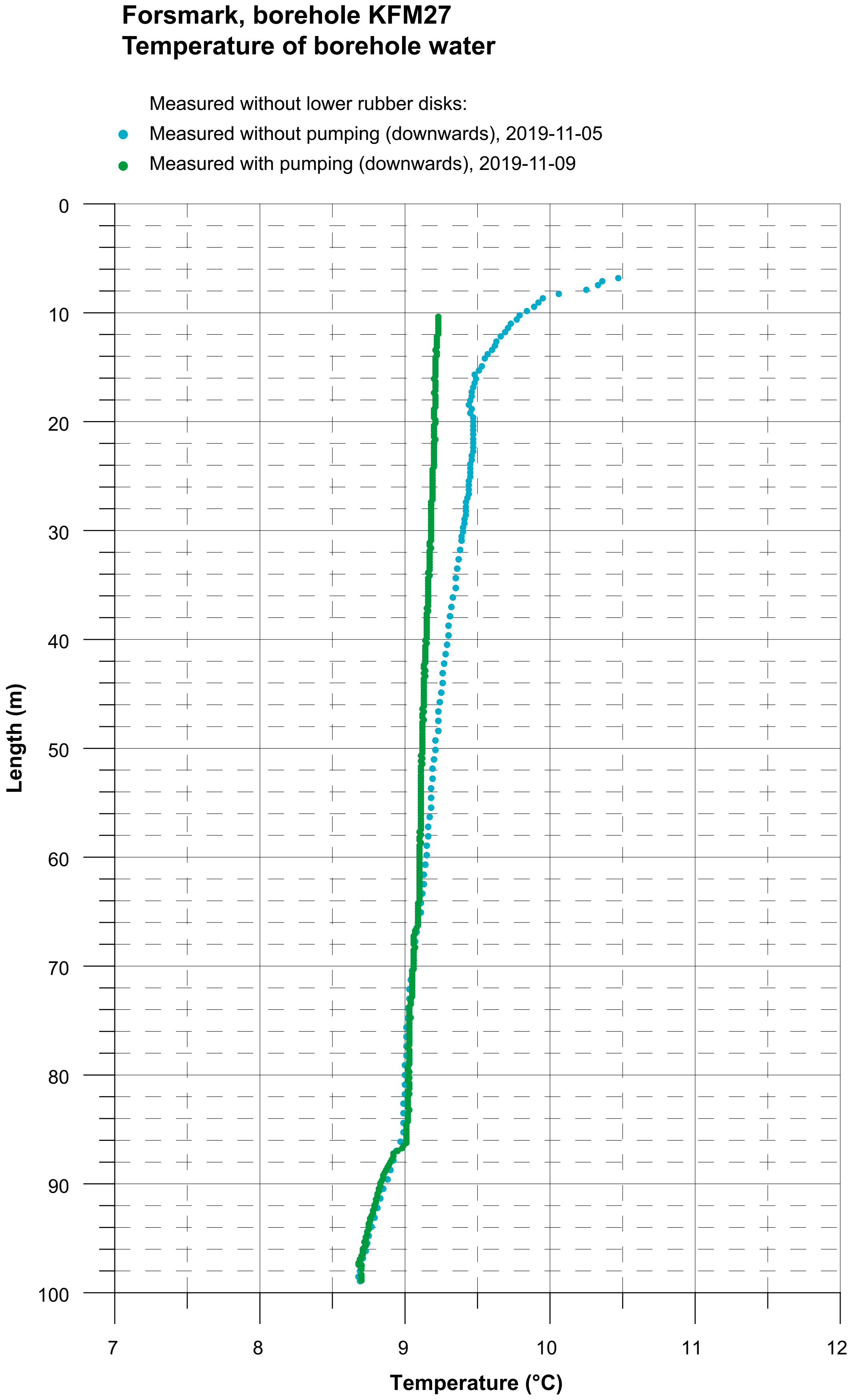


Appendix C

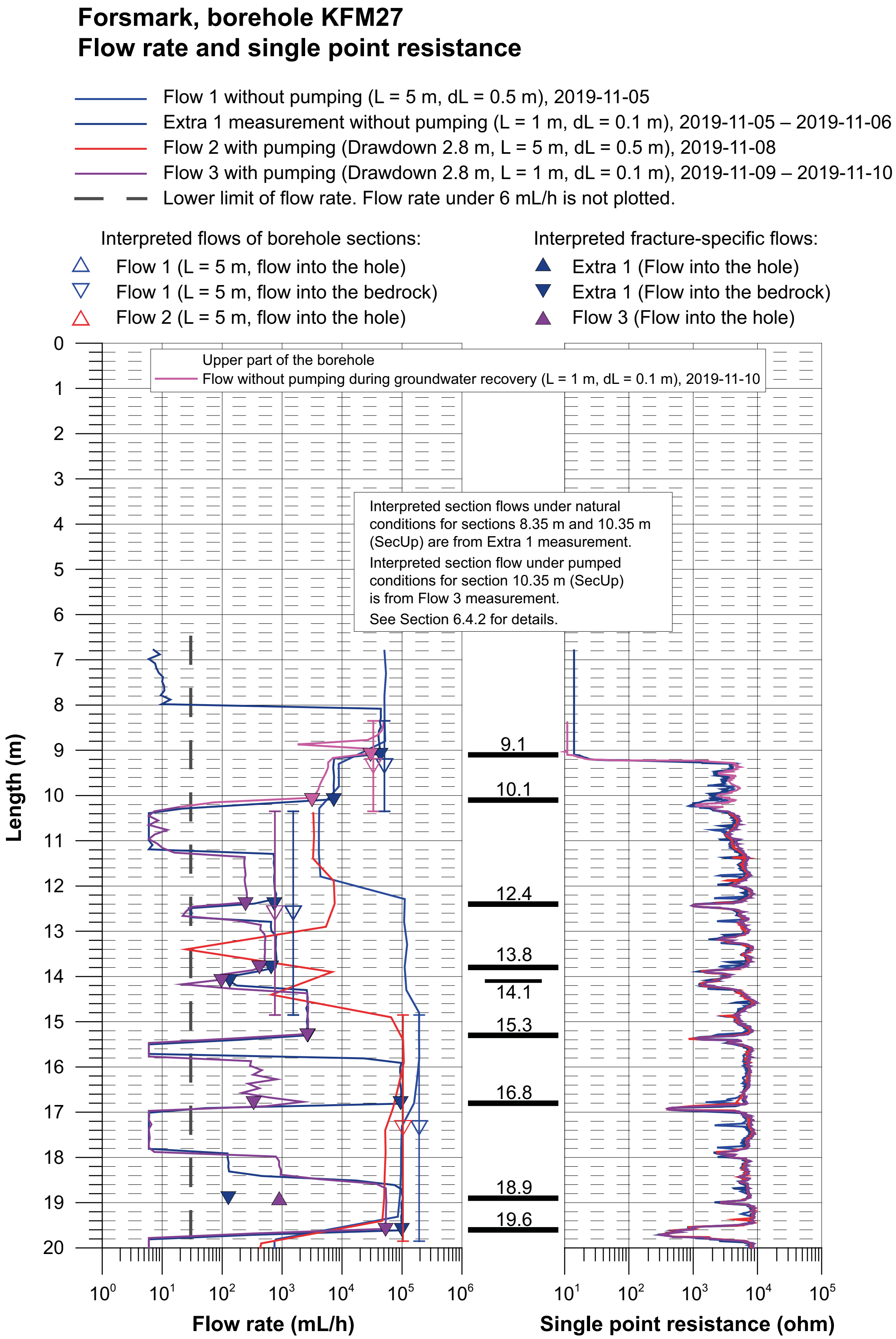
KFM27.1.1 – KFM27.1.2	Electrical conductivity of borehole water
KFM27.1.3	Temperature of borehole water
KFM27.2.1 – KFM27.2.5	Flow rate and single point resistance
KFM27.2.6	Vertical flow along the borehole at 8.0 m
KFM27.2.7	Vertical flow along the borehole at 9.8 m
KFM27.2.8	Vertical flow along the borehole at 92.1 m
KFM27.3	Glossary of terms used in the tables in Appendices
KFM27.4	Results of section flows
KFM27.5.1	Plotted flow rates of 5 m sections
KFM27.5.2	Plotted transmissivity and head of 5 m sections
KFM27.5.3	Transmissivity and head of 5 m sections with calculated error limits
KFM27.5.4	Conductive fracture frequency
KFM27.6.1 – KFM27.6.2	Inferred fracture flow anomalies from flow logging
KFM27.7.1	Plotted transmissivity and head of detected fractures
KFM27.7.2	Transmissivity and head of detected fractures with calculated error limits.
KFM27.8	Comparison between section transmissivity and fracture transmissivity
KFM27.9.1	Head in the borehole during flow logging
KFM27.9.2	Air pressure, water level in the borehole and pumping rate during flow logging
KFM27.10.1 – KFM27.10.6	Flow rate, single point resistance and head in the borehole during flow logging


Forsmark, borehole KFM27
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-11-05
Measured with pumping (downwards), 2019-11-09
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0.7
0.8
0.9
1
1.1
1.2
1.3
Electrical conductivity (S/m, 25 °C)

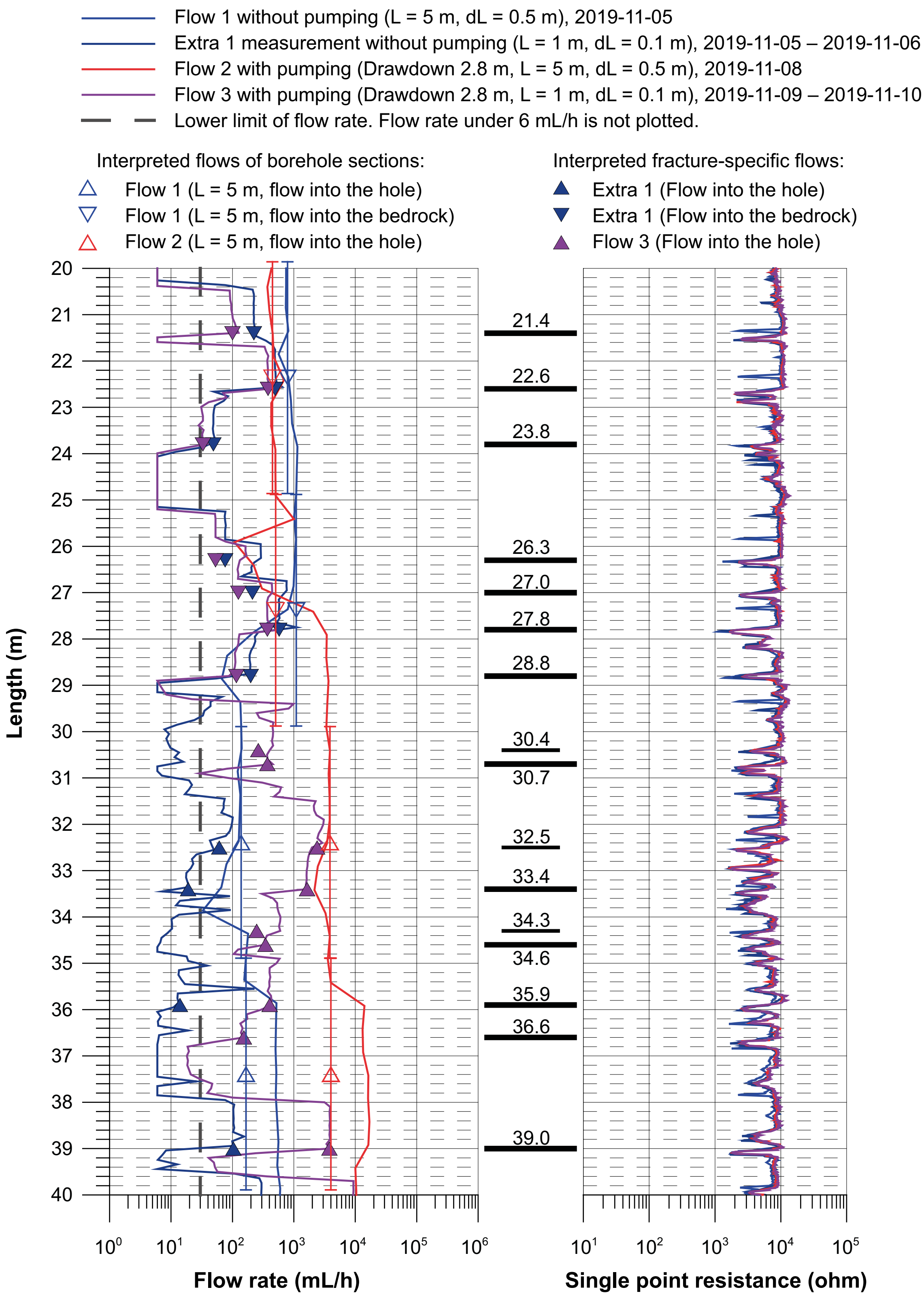

Forsmark, borehole KFM27
Electrical conductivity of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-11-05
Measured with pumping (downwards), 2019-11-09
0
10
20
30
40
50
60
70
80
90
100
Length (m)
0.01
0.1
1
10
Electrical conductivity (S/m, 25 °C)



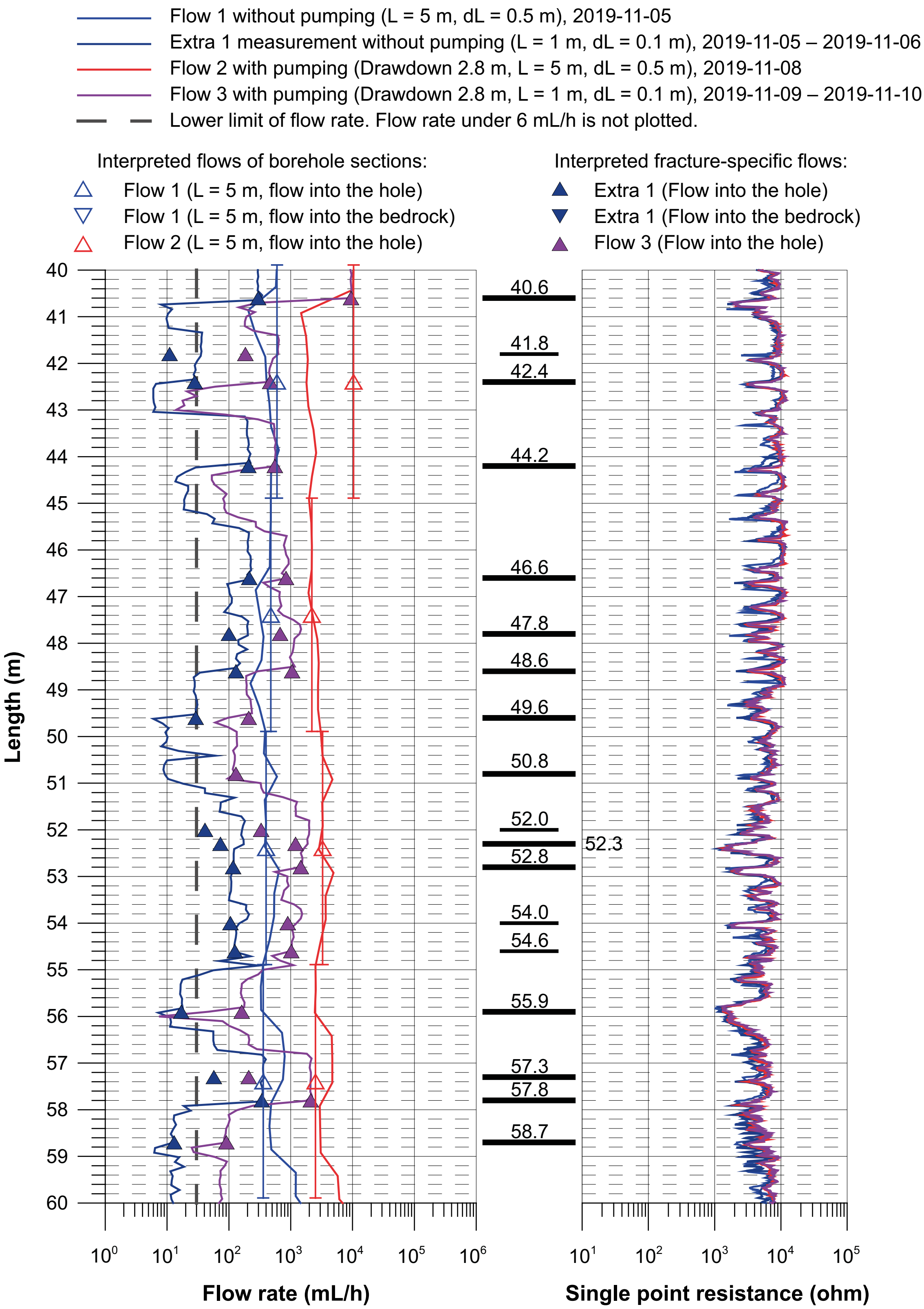
Forsmark, borehole KFM27
Temperature of borehole water
Measured without lower rubber disks:
Measured without pumping (downwards), 2019-11-05
Measured with pumping (downwards), 2019-11-09
0
10
20
30
40
50
60
70
80
90
100
Length (m)
7
8
9
10
11
12
Temperature (°C)


Forsmark, borehole KFM27
Flow rate and single point resistance
Flow 1 without pumping (L = 5 m, dL = 0.5 m), 2019-11-05
Extra 1 measurement without pumping (L = 1 m, dL = 0.1 m), 2019-11-05 – 2019-11-06
Flow 2 with pumping (Drawdown 2.8 m, L = 5 m, dL = 0.5 m), 2019-11-08
Flow 3 with pumping (Drawdown 2.8 m, L = 1 m, dL = 0.1 m), 2019-11-09 – 2019-11-10
Lower limit of flow rate. Flow rate under 6 mL/h is not plotted.
Interpreted flows of borehole sections:
Flow 1 (L = 5 m, flow into the hole)
Flow 1 (L = 5 m, flow into the bedrock)
Flow 2 (L = 5 m, flow into the hole)
Interpreted fracture-specific flows:
Extra 1 (Flow into the hole)
Extra 1 (Flow into the bedrock)
Flow 3 (Flow into the hole)
Upper part of the borehole
Flow without pumping during groundwater recovery (L = 1 m, dL = 0.1 m), 2019-11-10
Interpreted section flows under natural conditions for sections 8.35 m and 10.35 m (SecUp) are from Extra 1 measurement.
Interpreted section flow under pumped conditions for section 10.35 m (SecUp) is from Flow 3 measurement.
See Section 6.4.2 for details.
9.1
10.1
12.4
13.8
14.1
15.3
16.8
18.9
19.6
Length (m)
Flow rate (mL/h)
Single point resistance (ohm)

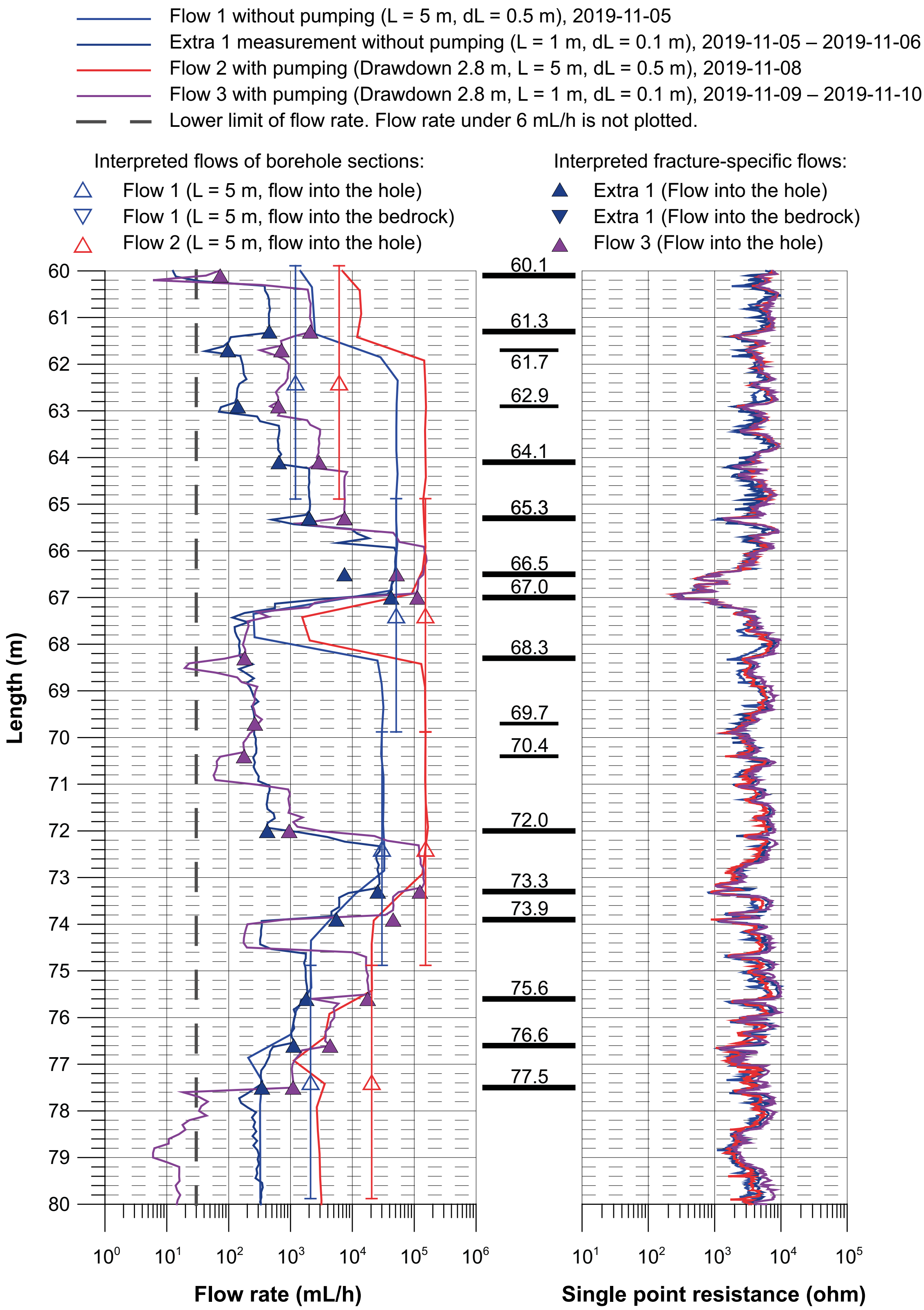
Forsmark, borehole KFM27
Flow rate and single point resistance



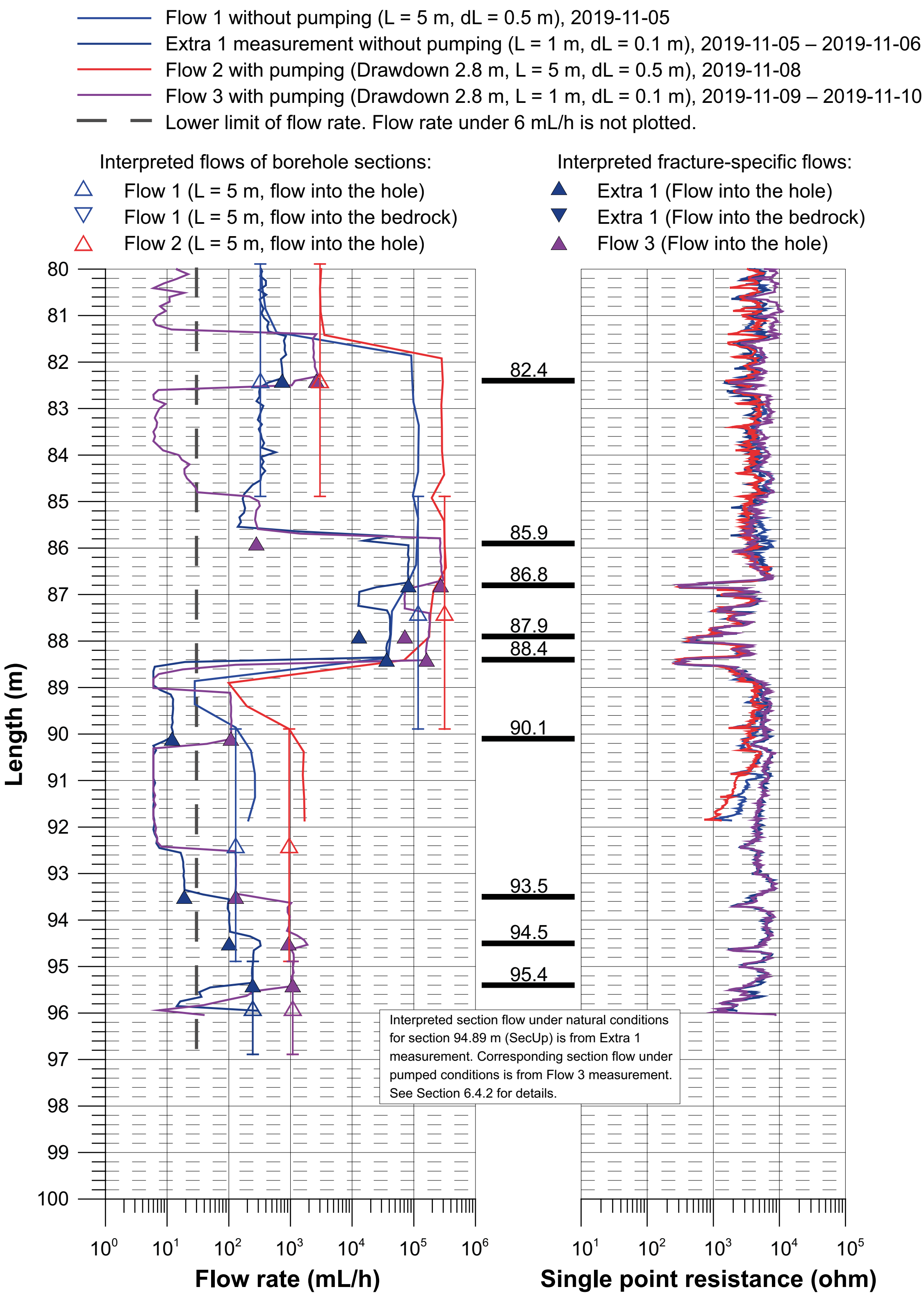
Forsmark, borehole KFM27
Flow rate and single point resistance

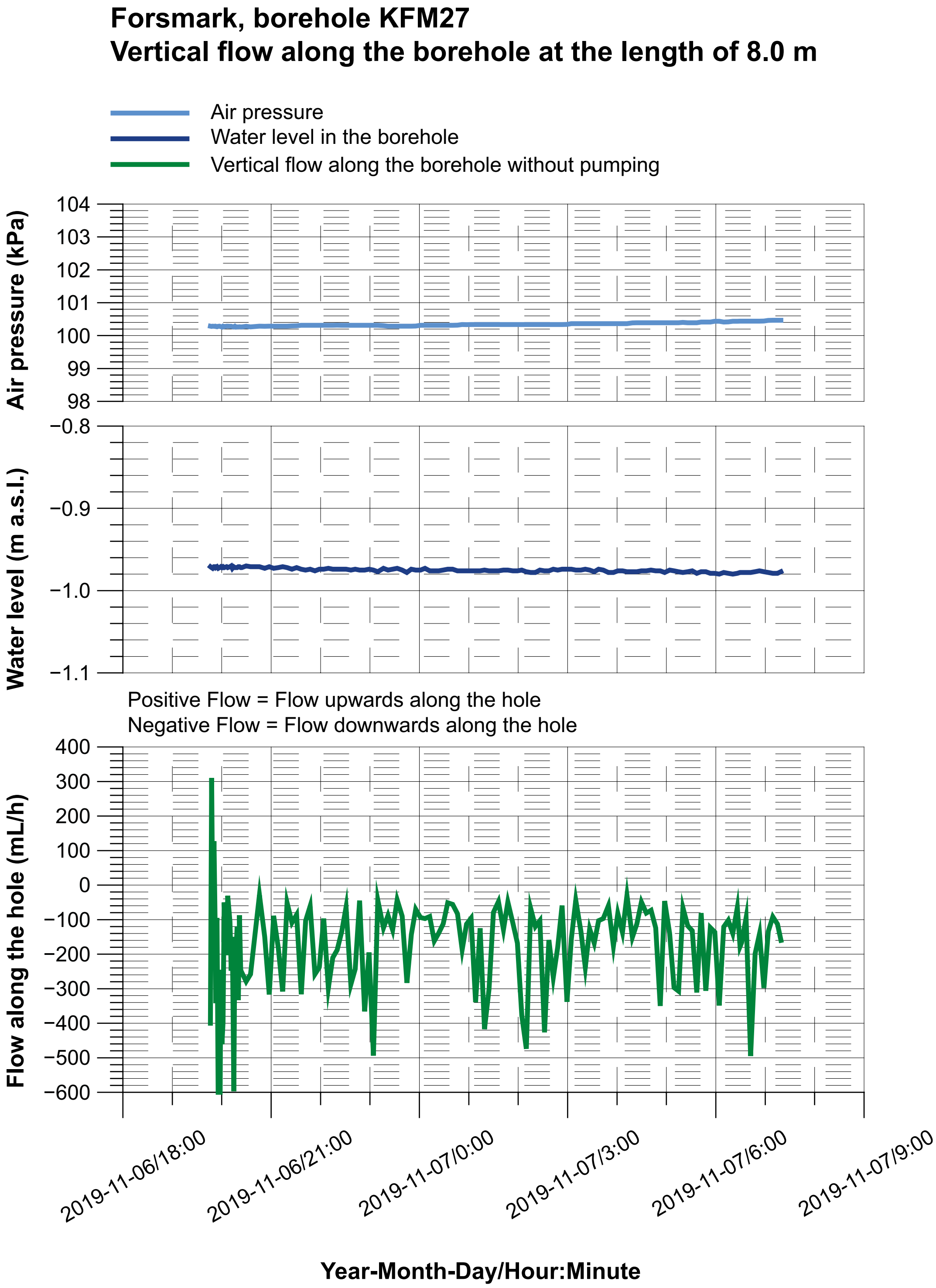


Forsmark, borehole KFM27
Flow rate and single point resistance



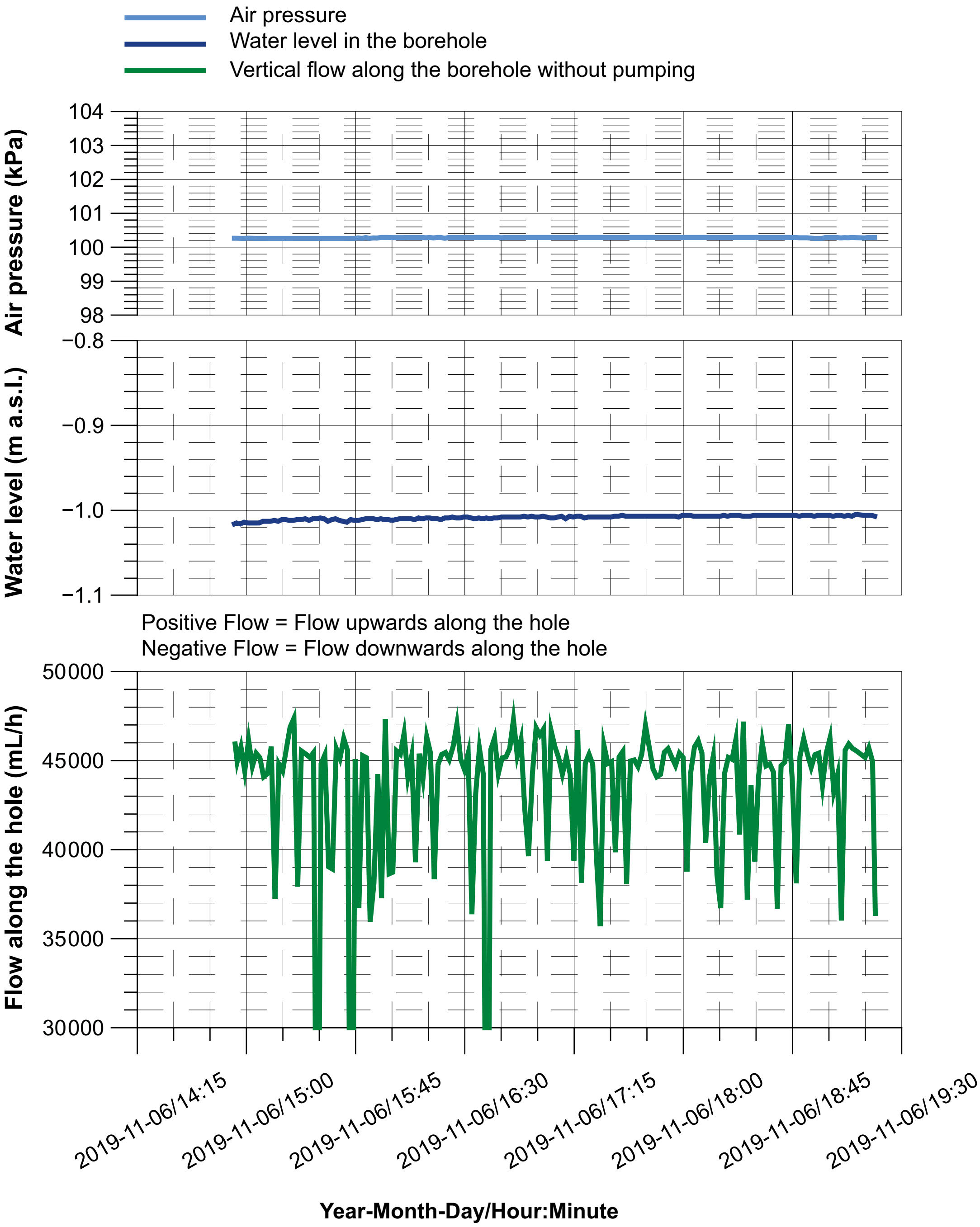
Forsmark, borehole KFM27
Flow rate and single point resistance



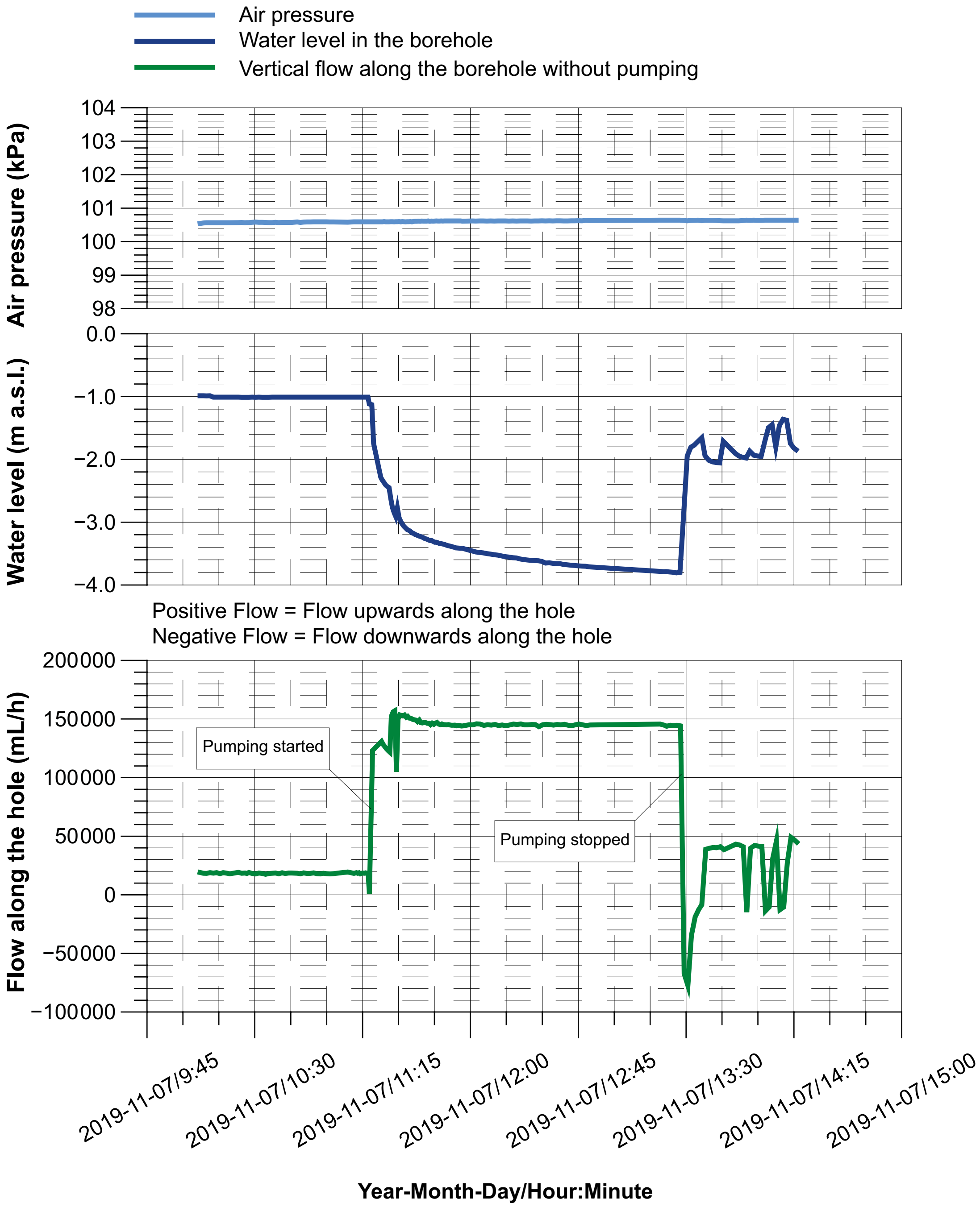


Forsmark, borehole KFM27
Vertical flow along the borehole at the length of 8.0 m
Air pressure
Water level in the borehole
Vertical flow along the borehole without pumping
Air pressure (kPa)
104
103
102
101
100
99
98
Water level (m a.s.l.)
−0.8
−0.9
−1.0
−1.1
Positive Flow = Flow upwards along the hole
Negative Flow = Flow downwards along the hole
Flow along the hole (mL/h)
400
300
200
100
0
−100
−200
−300
−400
−500
−600
2019-11-06/18:00
2019-11-06/21:00
2019-11-07/0:00
2019-11-07/3:00
2019-11-07/6:00
2019-11-07/9:00
Year-Month-Day/Hour:Minute

Forsmark, borehole KFM27
Vertical flow along the borehole at the length of 9.8 m



Forsmark, borehole KFM27
Vertical flow along the borehole at the length of 92.1 m



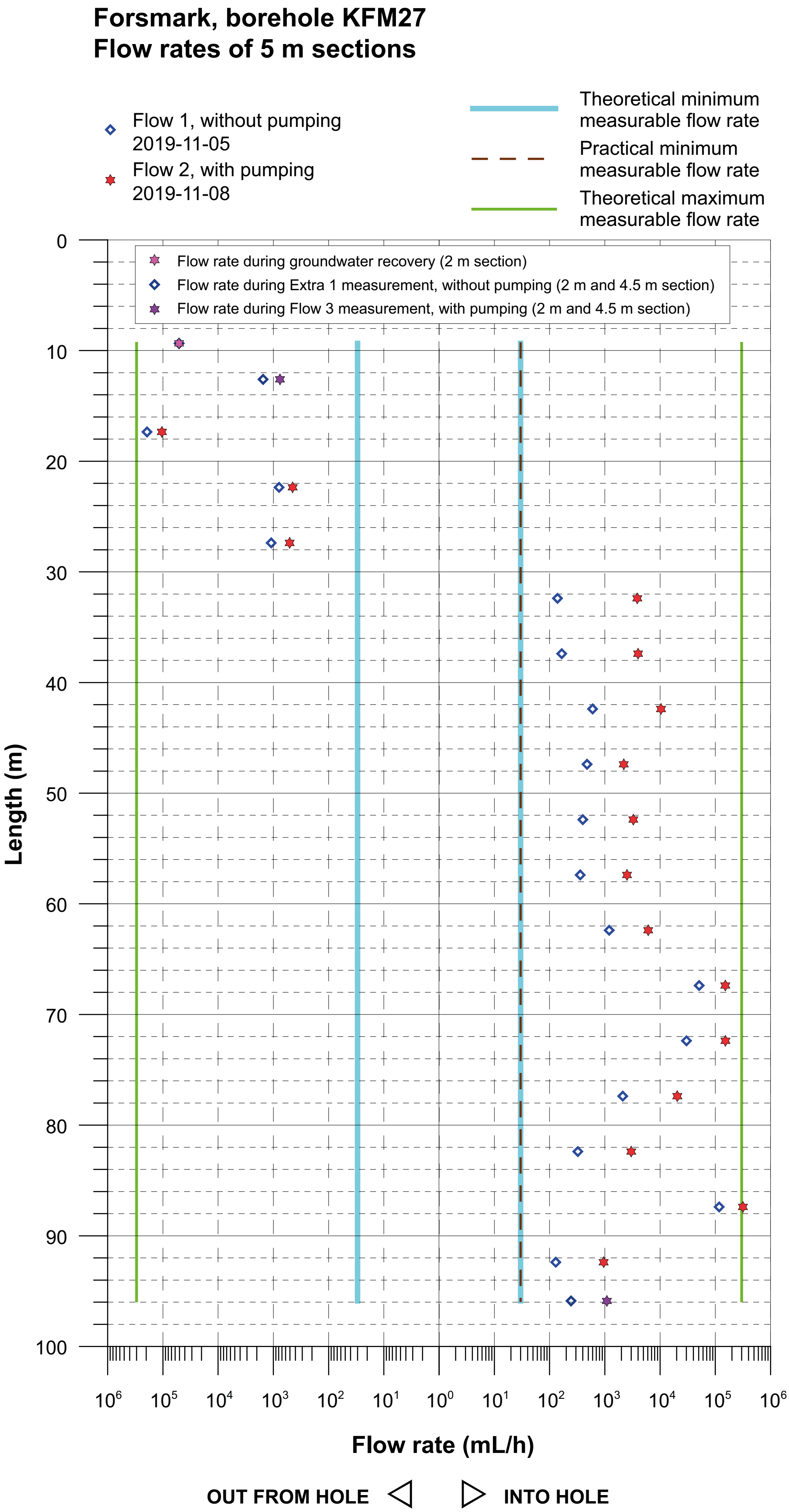
Glossary of terms used in the tables in Appendices.

Header	Unit	Definition
Borehole ID		**ID for borehole**
Secup	m	Length along the borehole for the upper limit of the test section (based on corrected length L).
Seclow	m	Length along the borehole for the lower limit of the test section (based on corrected length L).
Length to flow anom.	m	Length along the borehole to inferred flow anomaly during overlapping flow logging.
L_w	m	Section length used in the difference flow logging.
dL	m	Step length (increment) used in the difference flow logging.
Q_0	m^3/s	Measured flow rate through the test section or flow anomaly under natural conditions (no pumping) with h=h0 in the open borehole.
Q_1	m^3/s	Measured flow rate through the test section or flow anomaly during the first pumping period.
h_{0FW}	m a.s.l.	Corrected initial hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid before pumping.
h_{1FW}	m a.s.l.	Corrected hydraulic head along the borehole due to e.g. varying salinity conditions of the borehole fluid during the first pumping period.
T_D	m^2/s	Transmissivity of section or flow anomaly based on 2D model for evaluation of formation properties of the test section based on PFL DIFF.
Q-lower limit P	mL/h	Practical lower measurement limit for flow rate.
T-measl$_{LT}$	m^2/s	Estimated theoretical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-measl$_{LP}$	m^2/s	Estimated practical lower measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
T-measl$_{U}$	m^2/s	Estimated upper measurement limit for evaluated TD. If the estimated TD equals TD-measlim, the actual TD is considered to be equal or less than TD-measlim.
h_i	m a.s.l.	Calculated relative, natural freshwater head for test section or flow anomaly (undisturbed conditions).

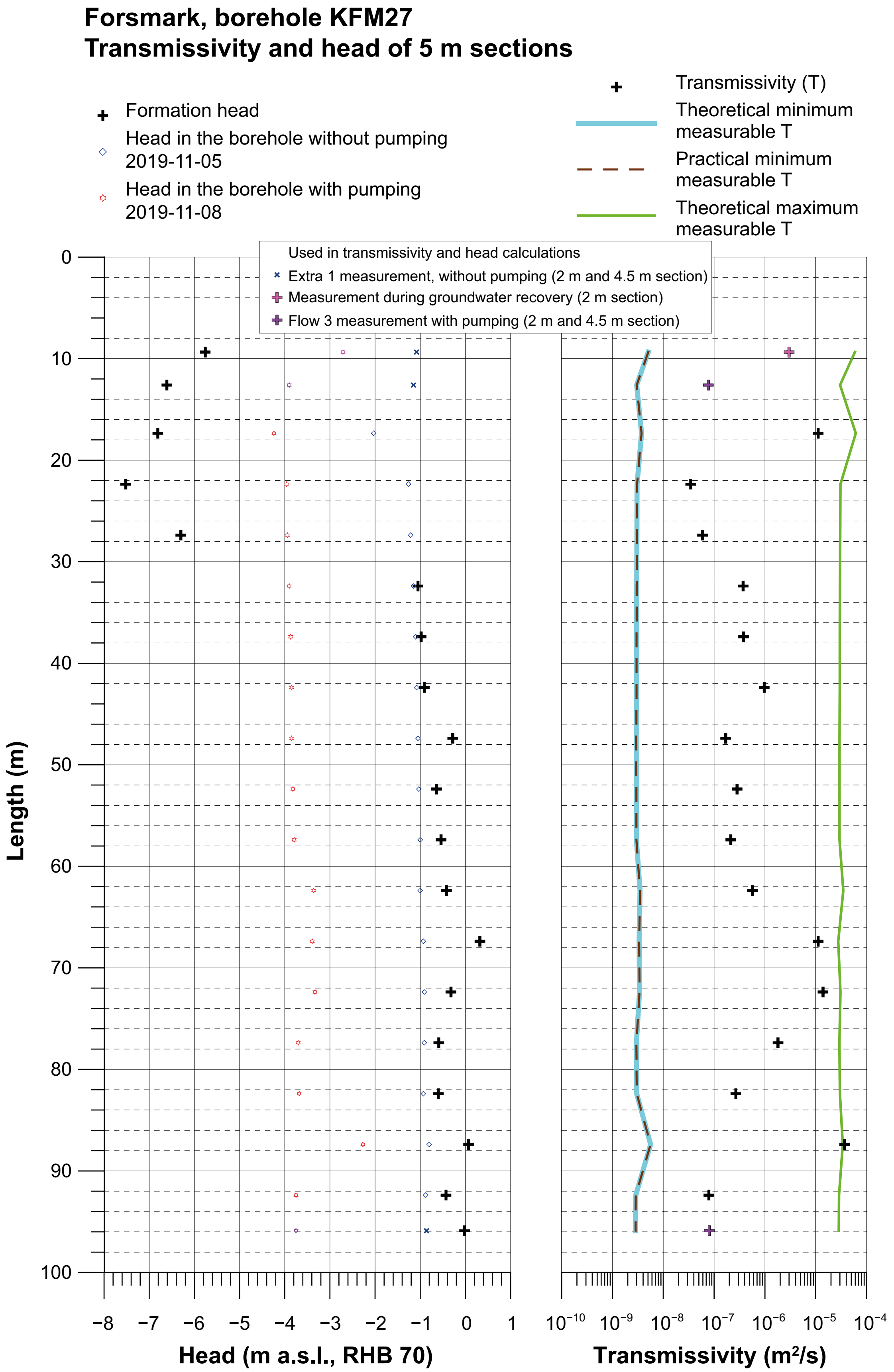
Results of section flows.

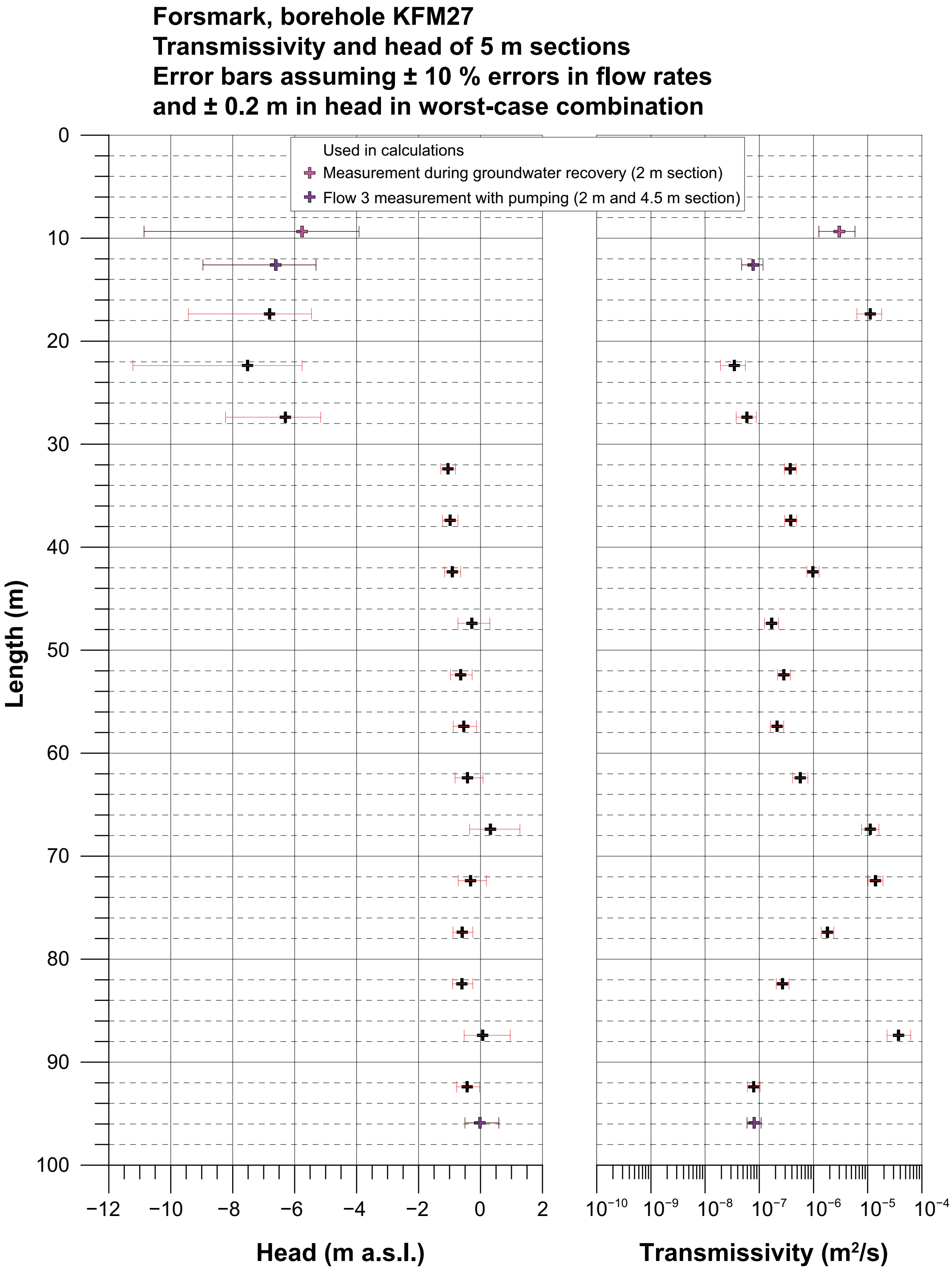
Borehole ID	Secup L(m)	Seclo L(m)	L_w (m)	Q_0 (m^3/s)	h_{0FW} (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Q-lower limit P (mL/h)	T_D-measl$_{LT}$ (m^2/s)	T_D - measl$_{LP}$ (m^2/s)	T_D - measl$_U$ (m^2/s)	Comments
KFM27	8.35	10.35	2	−1.41E−05	−1.08	−9.21E−06	−2.71	3.0E−06	−5.8	30	5.1E−09	5.1E−09	5.9E−05	*
KFM27	10.35	14.85	4.5	−4.26E-07	−1.15	−2.11E−07	−3.90	7.7E−08	−6.6	30	3.0E−09	3.0E−09	3.0E−05	**
KFM27	14.85	19.85	5	−5.38E-05	−2.03	−2.89E−05	−4.24	1.1E−05	−6.8	30	3.7E−09	3.7E−09	6.1E−05	
KFM27	19.86	24.86	5	−2.19E−07	−1.26	−1.24E−07	−3.96	3.5E−08	−7.5	30	3.1E−09	3.1E−09	3.1E−05	
KFM27	24.88	29.88	5	−3.04E−07	−1.21	−1.41E−07	−3.94	5.9E−08	−6.3	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	29.89	34.89	5	3.86E−08	−1.15	1.08E−06	−3.90	3.7E−07	−1.1	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	34.89	39.89	5	4.61E−08	−1.10	1.11E−06	−3.87	3.8E−07	−1.0	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	39.89	44.89	5	1.67E−07	−1.08	2.89E−06	−3.85	9.7E−07	−0.9	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	44.89	49.89	5	1.32E−07	−1.05	6.11E−07	−3.85	1.7E−07	−0.3	30	2.9E−09	2.9E−09	2.9E−05	
KFM27	49.89	54.89	5	1.11E−07	−1.03	9.12E−07	−3.82	2.8E−07	−0.6	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	54.89	59.89	5	9.97E−08	−1.00	6.99E−07	−3.79	2.1E−07	−0.5	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	59.89	64.89	5	3.34E−07	−1.00	1.69E−06	−3.36	5.7E−07	−0.4	30	3.5E−09	3.5E−09	3.5E−05	
KFM27	64.88	69.88	5	1.42E−05	−0.93	4.21E−05	−3.39	1.1E−05	0.3	30	3.4E−09	3.4E−09	2.8E−05	
KFM27	69.88	74.88	5	8.35E−06	−0.91	4.24E−05	−3.33	1.4E−05	−0.3	30	3.4E−09	3.4E−09	3.1E−05	
KFM27	74.88	79.88	5	5.86E−07	−0.91	5.69E−06	−3.70	1.8E−06	−0.6	30	3.0E−09	3.0E−09	2.9E−05	
KFM27	79.89	84.89	5	9.03E−08	−0.93	8.36E−07	−3.68	2.7E−07	−0.6	30	3.0E−09	3.0E−09	3.0E−05	
KFM27	84.89	89.89	5	3.26E−05	−0.80	8.78E−05	−2.27	3.7E−05	0.1	30	5.6E−09	5.6E−09	3.4E−05	
KFM27	89.89	94.89	5	3.58E−08	−0.88	2.65E−07	−3.75	7.9E−08	−0.4	30	2.9E−09	2.9E−09	2.9E−05	
KFM27	94.89	96.89	2	6.81E−08	−0.86	3.03E−07	−3.75	8.0E−08	0.0	30	2.9E−09	2.9E−09	2.9E−05	**

* Values for Flow (Q_1) and Head (h_{1FW}) are from the measurement made without pumping, during groundwater recovery. The upper part of the borehole could not be measured while pumping the borehole (while the pump remained in the borehole). Flow (Q_0 and Q_1) possibly from the joint of casing tube and borehole.
** Values for Flow (Q_0) and Head (h_{0FW}) are from the Extra 1 measurement. Values for Flow (Q_1) and Head (h_{1FW}) are from the Flow 3 measurement.

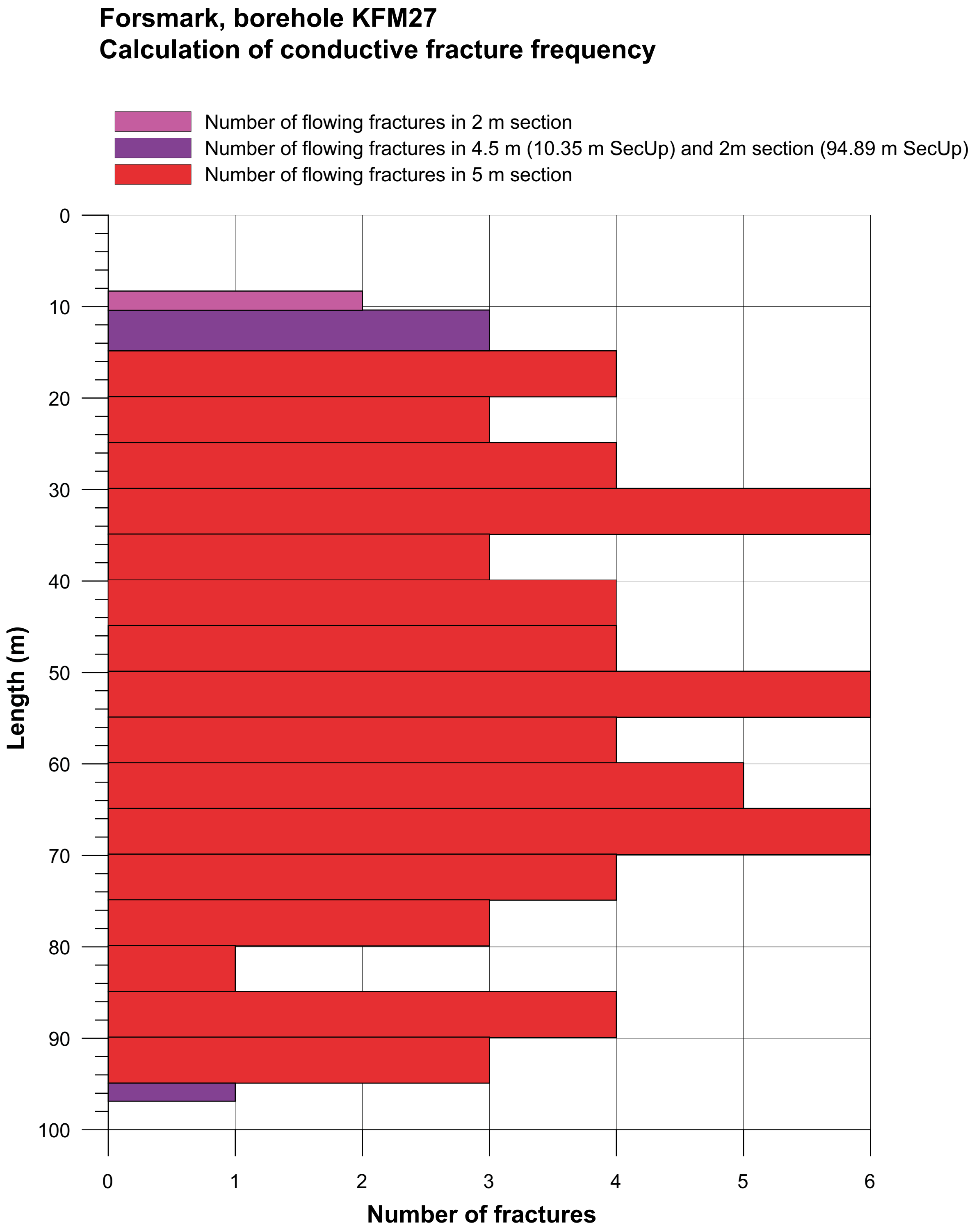


Forsmark, borehole KFM27
Flow rates of 5 m sections
Flow 1, without pumping 2019-11-05
Flow 2, with pumping 2019-11-08
Theoretical minimum measurable flow rate
Practical minimum measurable flow rate
Theoretical maximum measurable flow rate
Flow rate during groundwater recovery (2 m section)
Flow rate during Extra 1 measurement, without pumping (2 m and 4.5 m section)
Flow rate during Flow 3 measurement, with pumping (2 m and 4.5 m section)
Length (m)
0
10
20
30
40
50
60
70
80
90
100
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Flow rate (mL/h)
OUT FROM HOLE
INTO HOLE


Forsmark, borehole KFM27
Transmissivity and head of 5 m sections
Formation head
Head in the borehole without pumping 2019-11-05
Head in the borehole with pumping 2019-11-08
Transmissivity (T)
Theoretical minimum measurable T
Practical minimum measurable T
Theoretical maximum measurable T
Used in transmissivity and head calculations
Extra 1 measurement, without pumping (2 m and 4.5 m section)
Measurement during groundwater recovery (2 m section)
Flow 3 measurement with pumping (2 m and 4.5 m section)
Length (m)
Head (m a.s.l., RHB 70)
Transmissivity (m²/s)



Forsmark, borehole KFM27
Transmissivity and head of 5 m sections
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination
Used in calculations
Measurement during groundwater recovery (2 m section)
Flow 3 measurement with pumping (2 m and 4.5 m section)
Length (m)
0
10
20
30
40
50
60
70
80
90
100
−12
−10
−8
−6
−4
−2
0
2
Head (m a.s.l.)
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Transmissivity (m^2/s)


Forsmark, borehole KFM27
Calculation of conductive fracture frequency
Number of flowing fractures in 2 m section
Number of flowing fractures in 4.5 m (10.35 m SecUp) and 2m section (94.89 m SecUp)
Number of flowing fractures in 5 m section
Length (m)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
Number of fractures

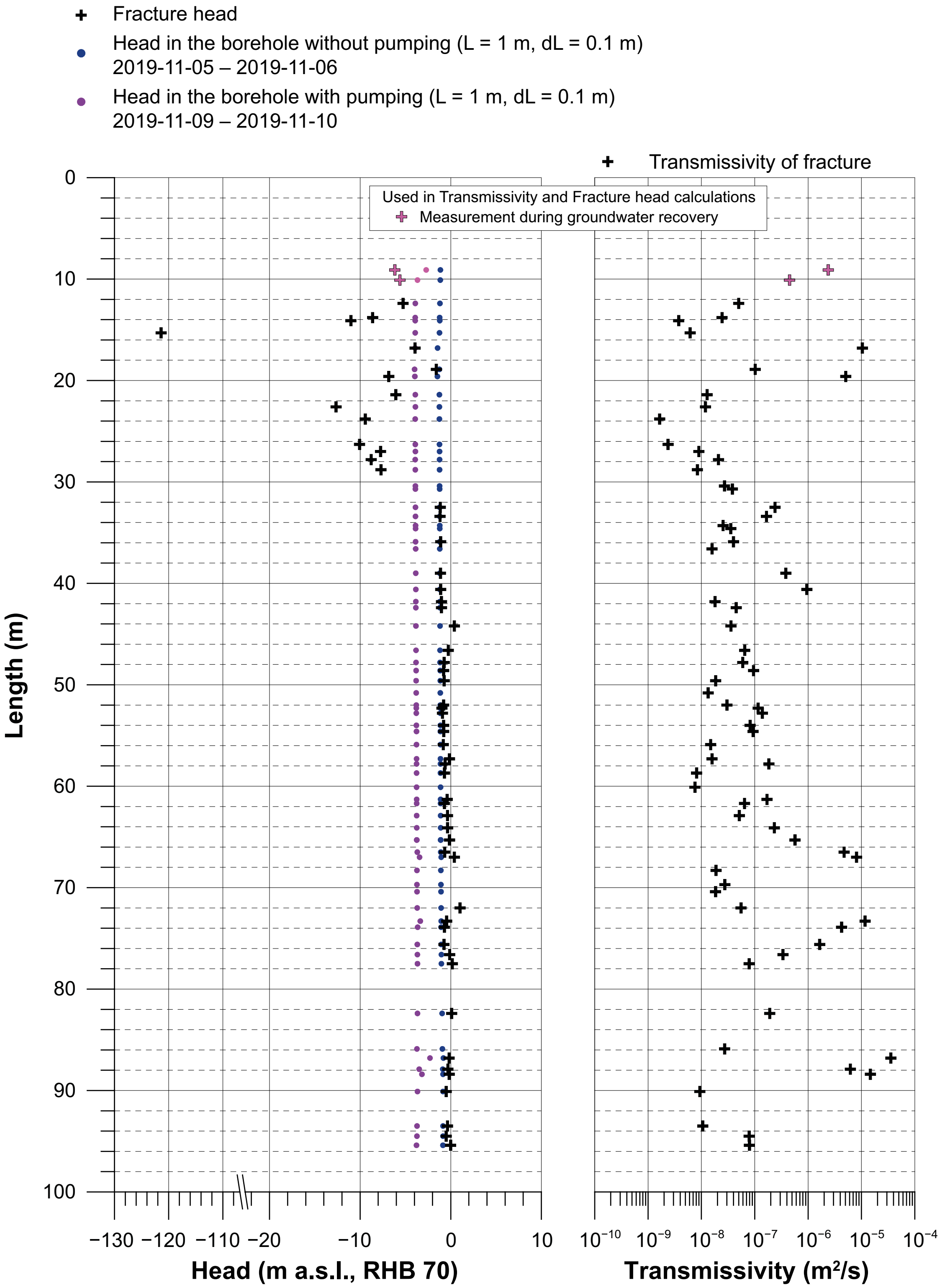
Inferred fracture flow anomalies from flow logging.

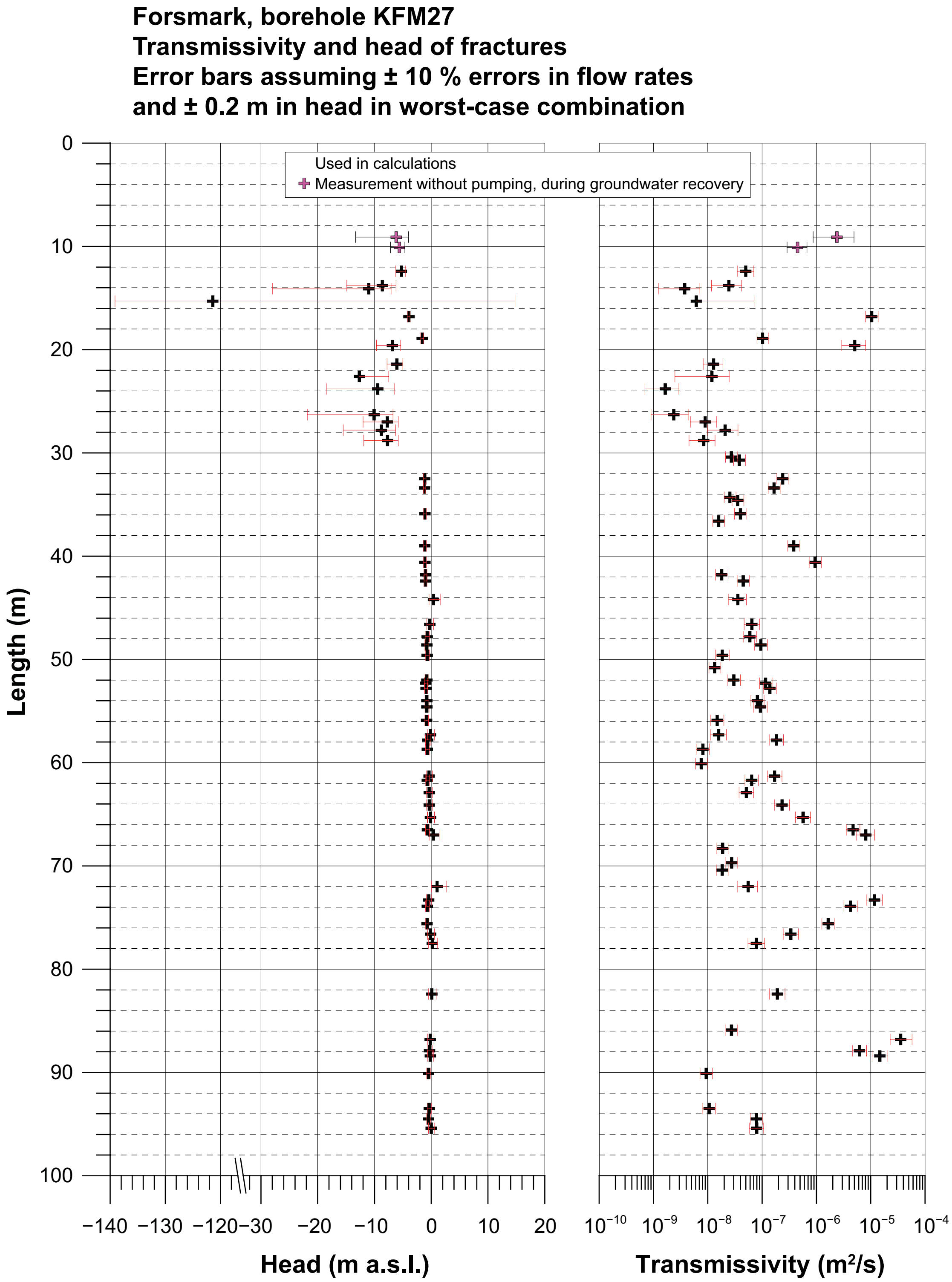
Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0** (m^3/s)	h_{0FW}** (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Comments
KFM27	9.1	1	0.1	−1.21E−05	−1.14	−8.33E−06	−2.71	2.4E−06	−6.2	***, ****
KFM27	10.1	1	0.1	−2.03E−06	−1.15	−8.81E−07	−3.67	4.5E−07	−5.6	***
KFM27	12.4	1	0.1	−2.06E−07	−1.19	−6.83E−08	−3.91	5.0E−08	−5.3	
KFM27	13.8	1	0.1	−1.83E−07	−1.22	−1.16E−07	−3.92	2.4E−08	−8.6	
KFM27	14.1	1	0.1	−3.72E−08	−1.21	−2.69E−08	−3.92	3.8E−09	−11.0	*
KFM27	15.3	1	0.1	−7.47E−07	−1.24	−7.31E−07	−3.92	6.2E−09	−121.4	*****
KFM27	16.8	1	0.1	−2.63E−05	−1.45	−9.33E−08	−3.93	1.0E−05	−3.9	
KFM27	18.9	1	0.1	−3.53E−08	−1.25	2.49E−07	−3.99	1.0E−07	−1.6	
KFM27	19.6	1	0.1	−2.76E−05	−1.47	−1.48E−05	−3.96	5.1E−06	−6.8	
KFM27	21.4	1	0.1	−6.22E−08	−1.25	−2.78E−08	−3.91	1.3E−08	−6.1	
KFM27	22.6	1	0.1	−1.38E−07	−1.25	−1.06E−07	−3.90	1.2E−08	−12.7	
KFM27	23.8	1	0.1	−1.36E−08	−1.25	−9.17E−09	−3.92	1.7E−09	−9.4	
KFM27	26.3	1	0.1	−2.11E−08	−1.24	−1.47E−08	−3.91	2.4E−09	−10.1	
KFM27	27.0	1	0.1	−5.89E−08	−1.23	−3.47E−08	−3.90	9.0E−09	−7.7	
KFM27	27.8	1	0.1	−1.60E−07	−1.23	−1.03E−07	−3.92	2.1E−08	−8.8	
KFM27	28.8	1	0.1	−5.50E−08	−1.23	−3.22E−08	−3.91	8.4E−09	−7.7	
KFM27	30.4	1	0.1	-	−1.23	7.31E−08	−3.90	2.7E−08	-	*
KFM27	30.7	1	0.1	-	−1.22	1.03E−07	−3.90	3.8E−08	-	
KFM27	32.5	1	0.1	1.69E−08	−1.22	6.64E−07	−3.89	2.4E−07	−1.2	*
KFM27	33.4	1	0.1	5.28E−09	−1.21	4.56E−07	−3.89	1.7E−07	−1.2	
KFM27	34.3	1	0.1	-	−1.21	6.89E−08	−3.88	2.6E−08	-	*
KFM27	34.6	1	0.1	-	−1.21	9.61E−08	−3.88	3.6E−08	-	
KFM27	35.9	1	0.1	3.89E−09	−1.21	1.12E−07	−3.88	4.0E−08	−1.1	
KFM27	36.6	1	0.1	-	−1.21	4.25E−08	−3.87	1.6E−08	-	
KFM27	39.0	1	0.1	2.89E−08	−1.20	1.06E−06	−3.86	3.8E−07	−1.1	
KFM27	40.6	1	0.1	8.25E−08	−1.20	2.62E−06	−3.85	9.5E−07	−1.1	
KFM27	41.8	1	0.1	3.06E-09	−1.19	5.14E−08	−3.85	1.8E−08	−1.0	*
KFM27	42.4	1	0.1	7.78E−09	−1.19	1.29E−07	−3.85	4.5E−08	−1.0	
KFM27	44.2	1	0.1	5.72E−08	−1.18	1.54E−07	−3.84	3.6E−08	0.4	
KFM27	46.6	1	0.1	5.94E−08	−1.18	2.33E−07	−3.83	6.5E−08	−0.3	
KFM27	47.8	1	0.1	2.78E−08	−1.18	1.88E−07	−3.83	6.0E−08	−0.7	
KFM27	48.6	1	0.1	3.61E−08	−1.16	2.92E−07	−3.82	9.5E−08	−0.8	
KFM27	49.6	1	0.1	8.06E−09	−1.15	5.81E−08	−3.82	1.9E−08	−0.7	
KFM27	50.8	1	0.1	-	−1.15	3.61E−08	−3.81	1.3E−08	-	
KFM27	52.0	1	0.1	1.14E−08	−1.15	9.19E−08	−3.80	3.0E−08	−0.8	*
KFM27	52.3	1	0.1	2.03E−08	−1.14	3.33E−07	−3.80	1.2E−07	−1.0	
KFM27	52.8	1	0.1	3.25E−08	−1.14	4.06E−07	−3.80	1.4E−07	−0.9	
KFM27	54.0	1	0.1	2.94E−08	−1.14	2.49E−07	−3.79	8.2E−08	−0.8	*
KFM27	54.6	1	0.1	3.47E−08	−1.14	2.83E−07	−3.78	9.3E−08	−0.8	*
KFM27	55.9	1	0.1	4.72E−09	−1.13	4.47E−08	−3.78	1.5E−08	−0.8	
KFM27	57.3	1	0.1	1.58E−08	−1.13	5.81E−08	−3.77	1.6E−08	−0.1	
KFM27	57.8	1	0.1	9.47E−08	−1.13	5.86E−07	−3.77	1.8E−07	−0.6	
KFM27	58.7	1	0.1	3.61E−09	−1.13	2.53E−08	−3.77	8.1E−09	−0.7	
KFM27	60.1	1	0.1	-	−1.12	2.03E−08	−3.77	7.6E−09	-	
KFM27	61.3	1	0.1	1.26E−07	−1.12	5.81E−07	−3.76	1.7E−07	−0.4	
KFM27	61.7	1	0.1	2.69E−08	−1.12	1.98E−07	−3.76	6.4E−08	−0.7	*
KFM27	62.9	1	0.1	3.89E−08	−1.11	1.77E−07	−3.76	5.1E−08	−0.4	*
KFM27	64.1	1	0.1	1.80E−07	−1.11	8.03E−07	−3.75	2.3E−07	−0.4	
KFM27	65.3	1	0.1	5.61E−07	−1.11	2.08E−06	−3.75	5.7E−07	−0.1	
KFM27	65.3	1	0.1	5.58E−07	−1.11	2.08E−06	−3.75	5.7E−07	−0.1	
KFM27	66.5	1	0.1	2.07E−06	−1.10	1.44E−05	−3.69	4.7E−06	−0.7	
KFM27	67.0	1	0.1	1.18E−05	−1.05	3.14E−05	−3.44	8.1E−06	0.4	
KFM27	68.3	1	0.1	-	−1.09	5.03E−08	−3.73	1.9E−08	-	
KFM27	69.7	1	0.1	-	−1.08	7.36E−08	−3.73	2.8E−08	-	*

Borehole ID	Length to flow anom. L (m)	L_w (m)	dL (m)	Q_0** (m^3/s)	h_{0FW}** (m a.s.l.)	Q_1 (m^3/s)	h_{1FW} (m a.s.l.)	T_D (m^2/s)	h_i (m a.s.l.)	Comments
KFM27	70.4	1	0.1	-	−1.07	4.92E−08	−3.72	1.8E−08	-	*
KFM27	72.0	1	0.1	1.17E−07	−1.06	2.64E−07	−3.70	5.5E−08	1.0	
KFM27	73.3	1	0.1	7.14E−06	−1.05	3.44E−05	−3.36	1.2E−05	−0.5	
KFM27	73.9	1	0.1	1.53E−06	−1.06	1.27E−05	−3.65	4.3E−06	−0.7	
KFM27	75.6	1	0.1	5.00E−07	−1.04	4.92E−06	−3.69	1.7E−06	−0.7	
KFM27	76.6	1	0.1	3.11E−07	−1.03	1.22E−06	−3.68	3.4E−07	−0.1	
KFM27	77.5	1	0.1	9.58E−08	−1.03	3.06E−07	−3.67	7.9E−08	0.2	
KFM27	82.4	1	0.1	2.03E−07	−0.95	7.28E−07	−3.67	1.9E−07	0.1	
KFM27	85.9	1	0.1	-	−0.92	7.75E−08	−3.73	2.7E−08	-	
KFM27	86.8	1	0.1	2.26E−05	−0.81	7.58E−05	−2.29	3.6E−05	−0.2	
KFM27	87.9	1	0.1	3.58E−06	−0.88	1.99E−05	−3.48	6.2E−06	−0.3	
KFM27	88.4	1	0.1	1.01E−05	−0.85	4.47E−05	−3.18	1.5E−05	−0.2	
KFM27	90.1	1	0.1	3.33E−09	−0.85	3.00E−08	−3.67	9.4E−09	−0.5	
KFM27	93.5	1	0.1	5.28E−09	−0.85	3.61E−08	−3.72	1.1E−08	−0.4	
KFM27	94.5	1	0.1	2.81E−08	−0.85	2.57E−07	−3.73	7.9E−08	−0.5	
KFM27	95.4	1	0.1	6.81E−08	−0.86	3.03E−07	−3.78	8.0E−08	0	

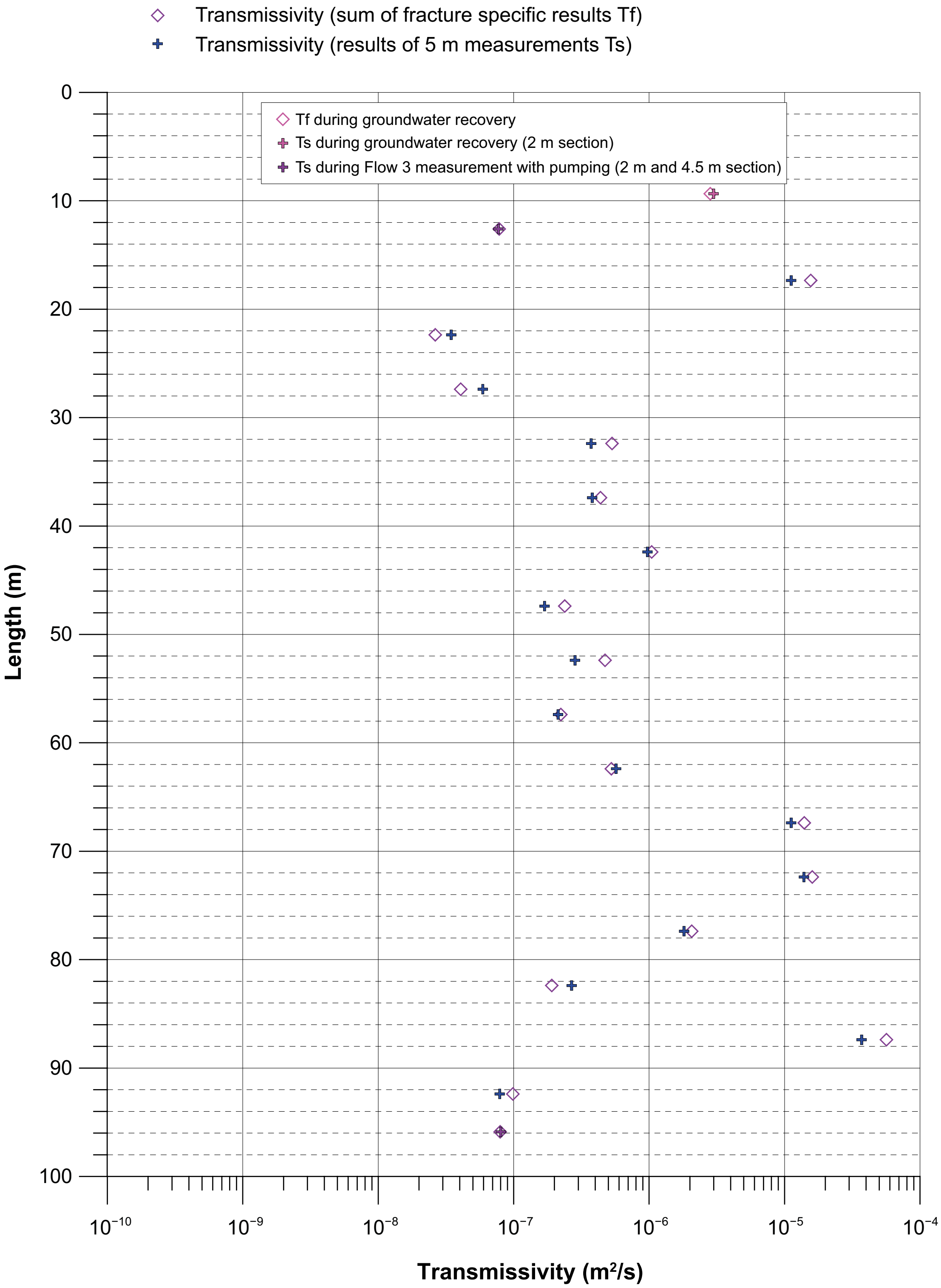
* Uncertain = The flow rate is less than 30 mL/h or the flow anomalies are overlapping or they are unclear because of noise.
** All values for Flow (Q_0) and Head (h_{0FW}) are from Extra 1 measurement.
*** Values for Flow (Q_1) and Head (h_{1FW}) are from the measurement made without pumping, during groundwater recovery. The upper part of the borehole could not be measured while pumping the borehole (while the pump remained in the borehole).
**** Flow (Q_0 and Q_1) possibly from the joint of casing tube and borehole.
***** Decreasing water level in borehole did not change fracture flow notably therefore T and Head values are unreliable. Reason for very small flow change is not clear.

Forsmark, borehole KFM27
Transmissivity and head of detected fractures



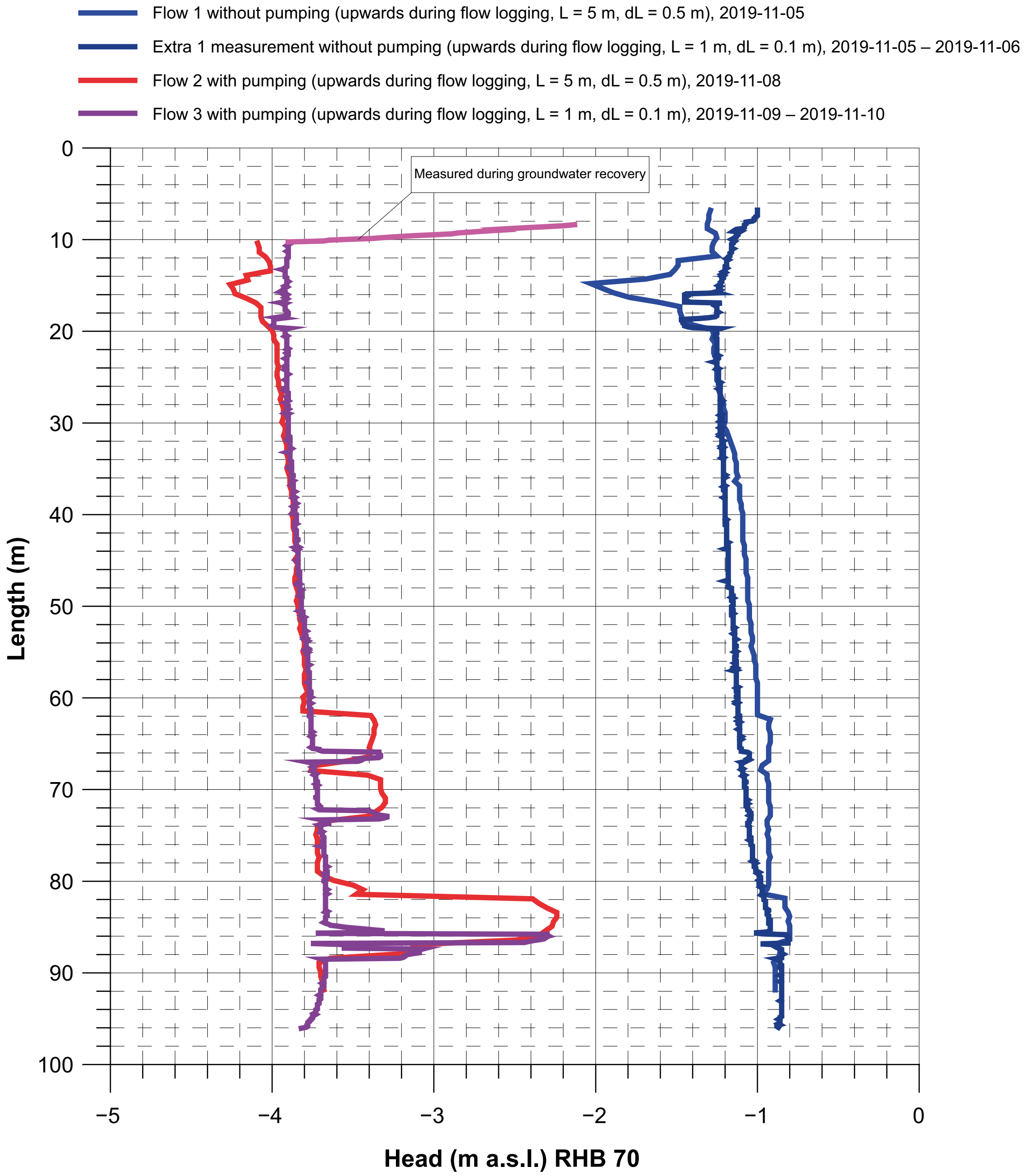

Forsmark, borehole KFM27
Transmissivity and head of fractures
Error bars assuming ± 10 % errors in flow rates
and ± 0.2 m in head in worst-case combination
Used in calculations
Measurement without pumping, during groundwater recovery
Length (m)
0
10
20
30
40
50
60
70
80
90
100
−140 −130 −120 −30 −20 −10 0 10 20
Head (m a.s.l.)
10⁻¹⁰ 10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴
Transmissivity (m²/s)

Forsmark, borehole KFM27
Comparison between section transmissivity and fracture transmissivity

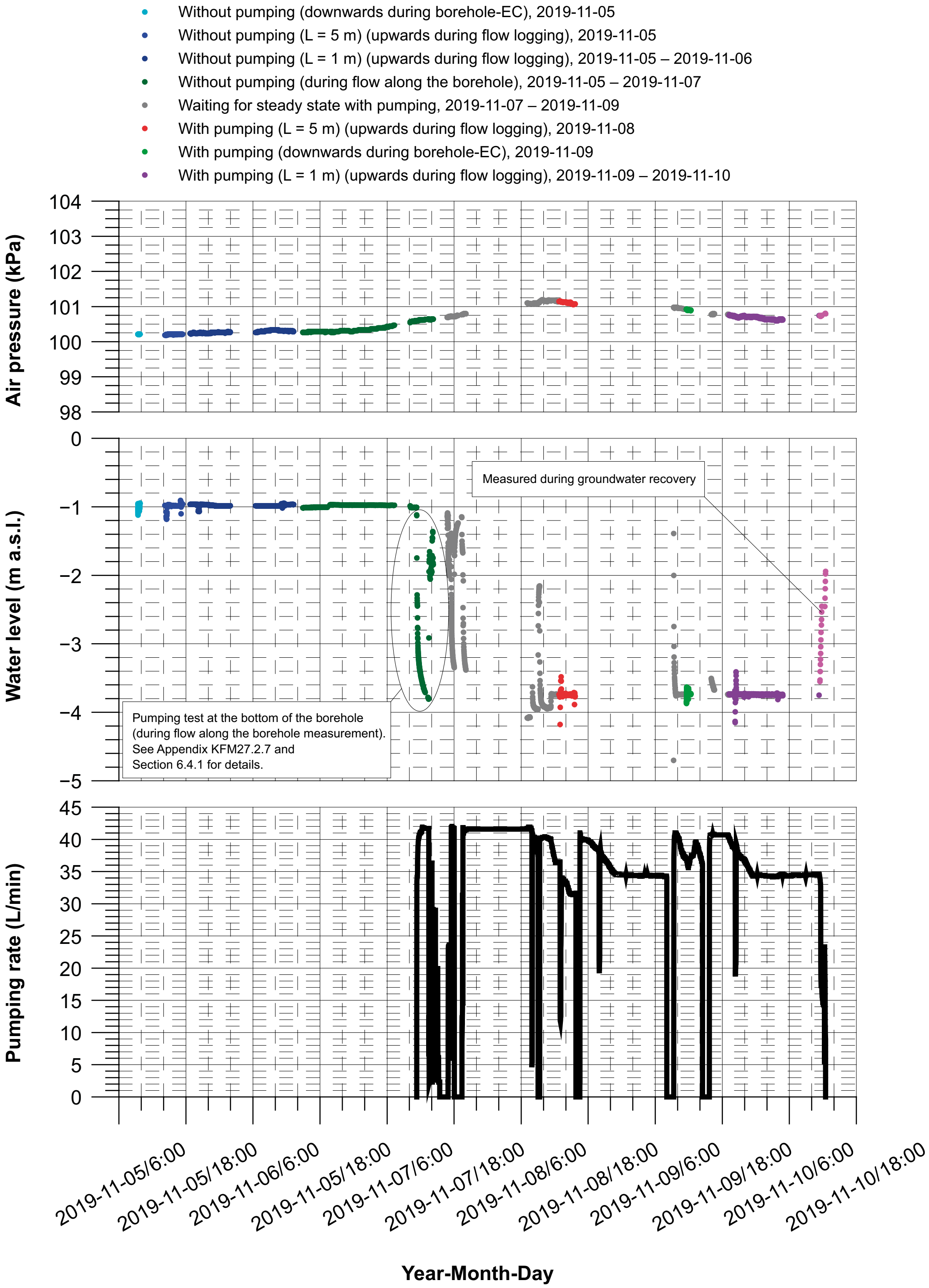


Forsmark, borehole KFM27
Head in the borehole during flow logging

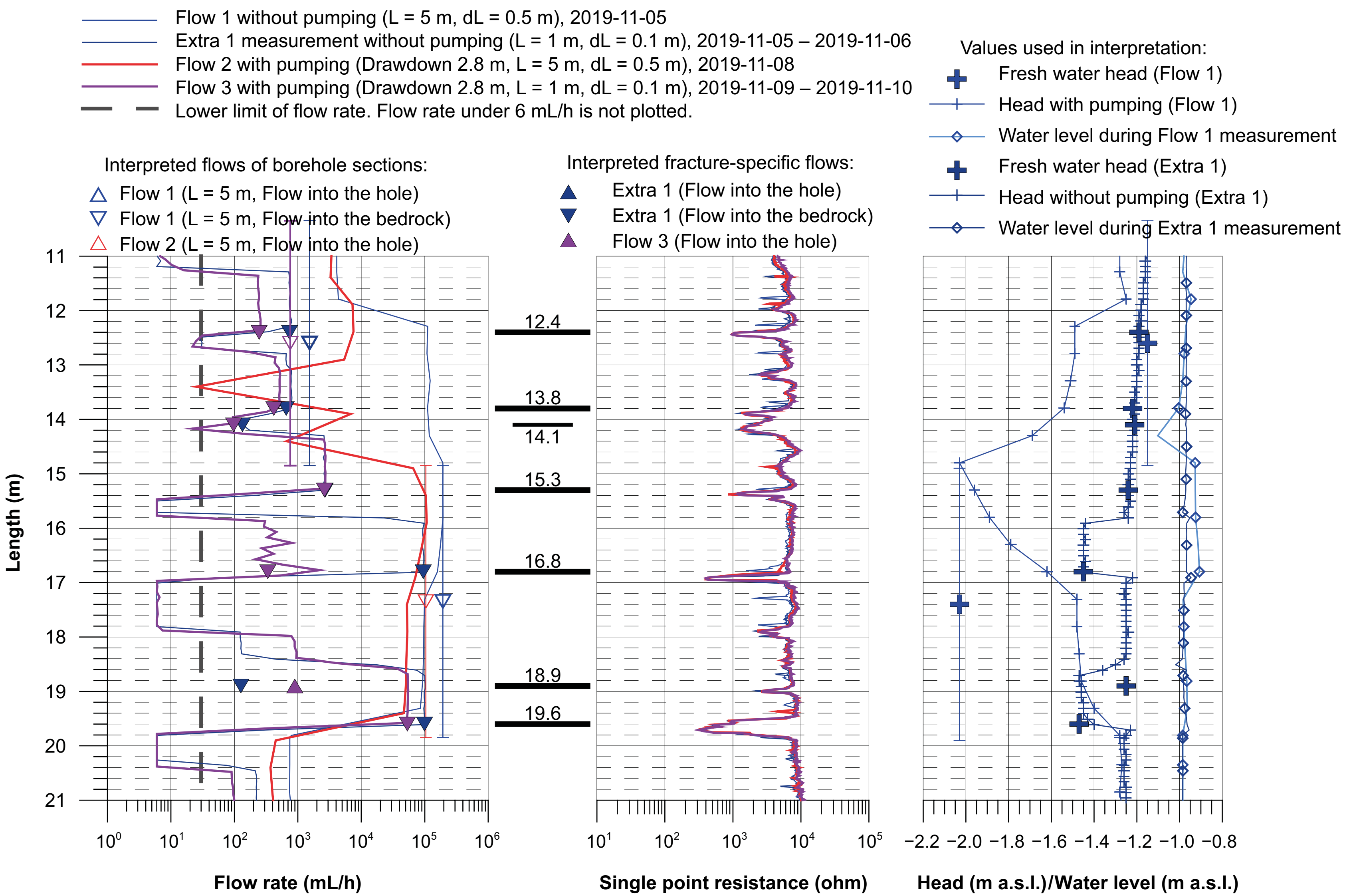
Head (m a.s.l.) = (Absolute pressure (Pa) − Airpressure (Pa) + Offset)/(1000 kg/m³ × 9.80665 m/s²) + Elevation (m)
Offset = Correction for absolute pressure sensor



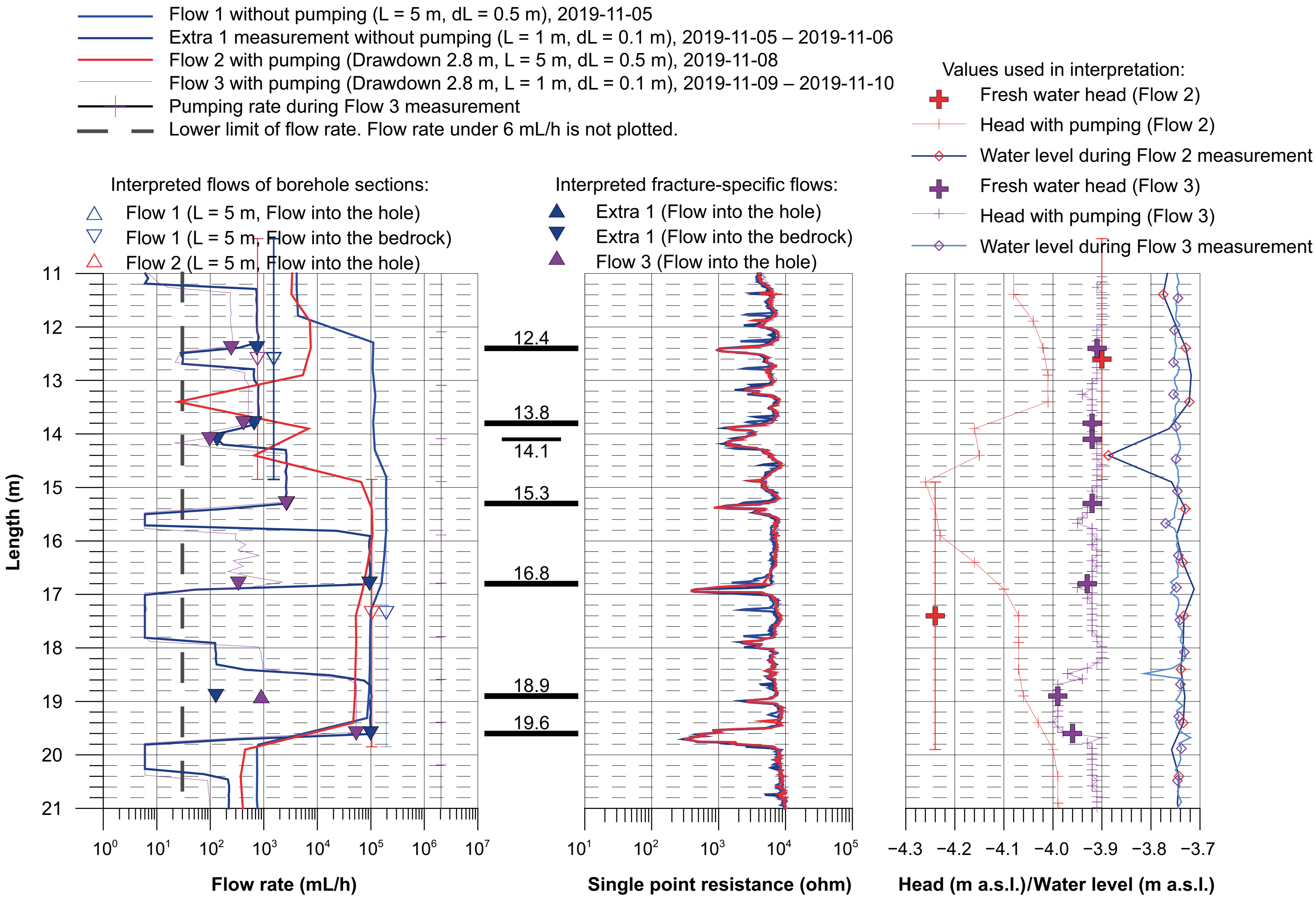
Forsmark, borehole KFM27
Air pressure, water level in the borehole and pumping rate during flow logging



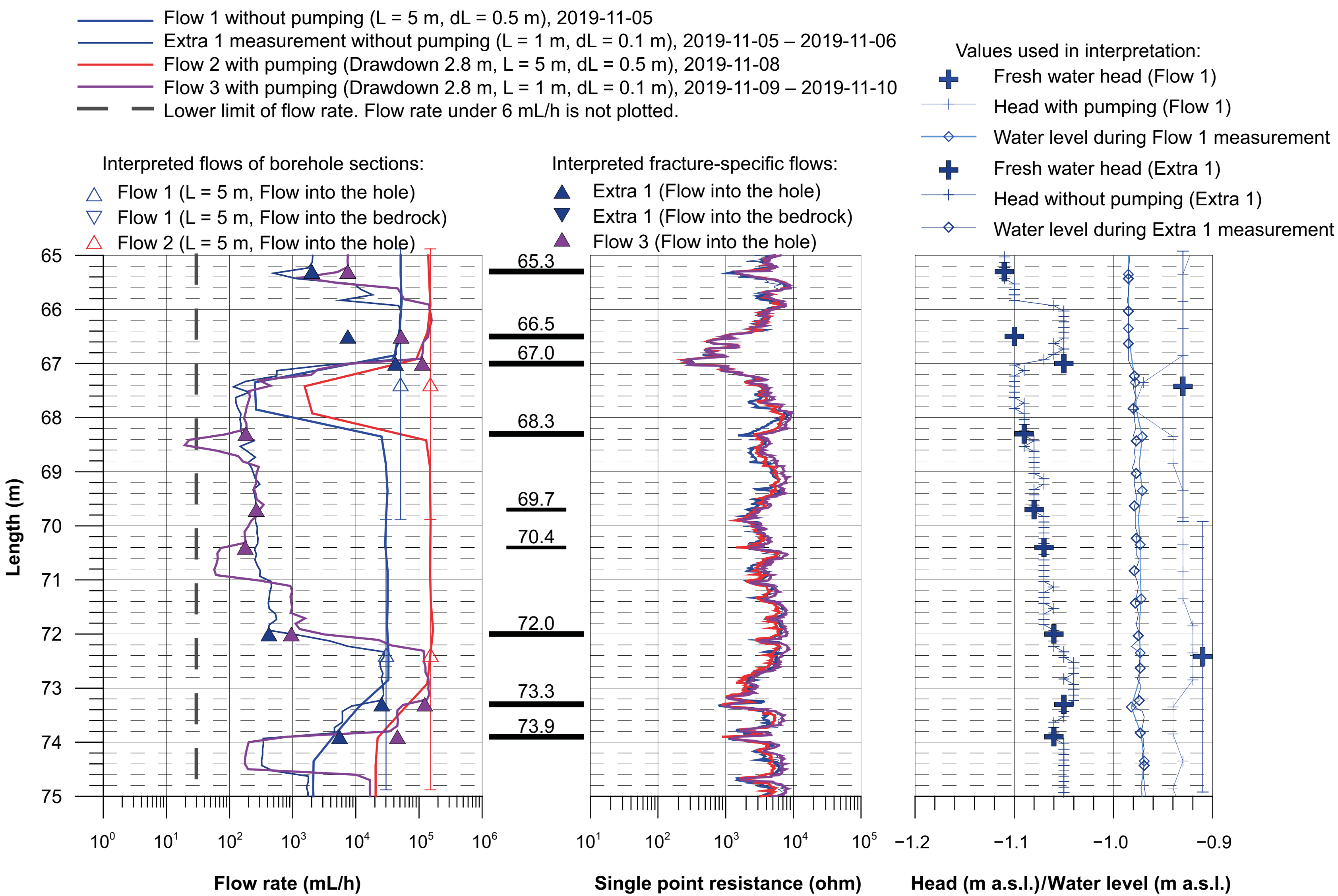
Forsmark, borehole KFM27
Flow rate, single point resistance and head in the borehole during flow logging



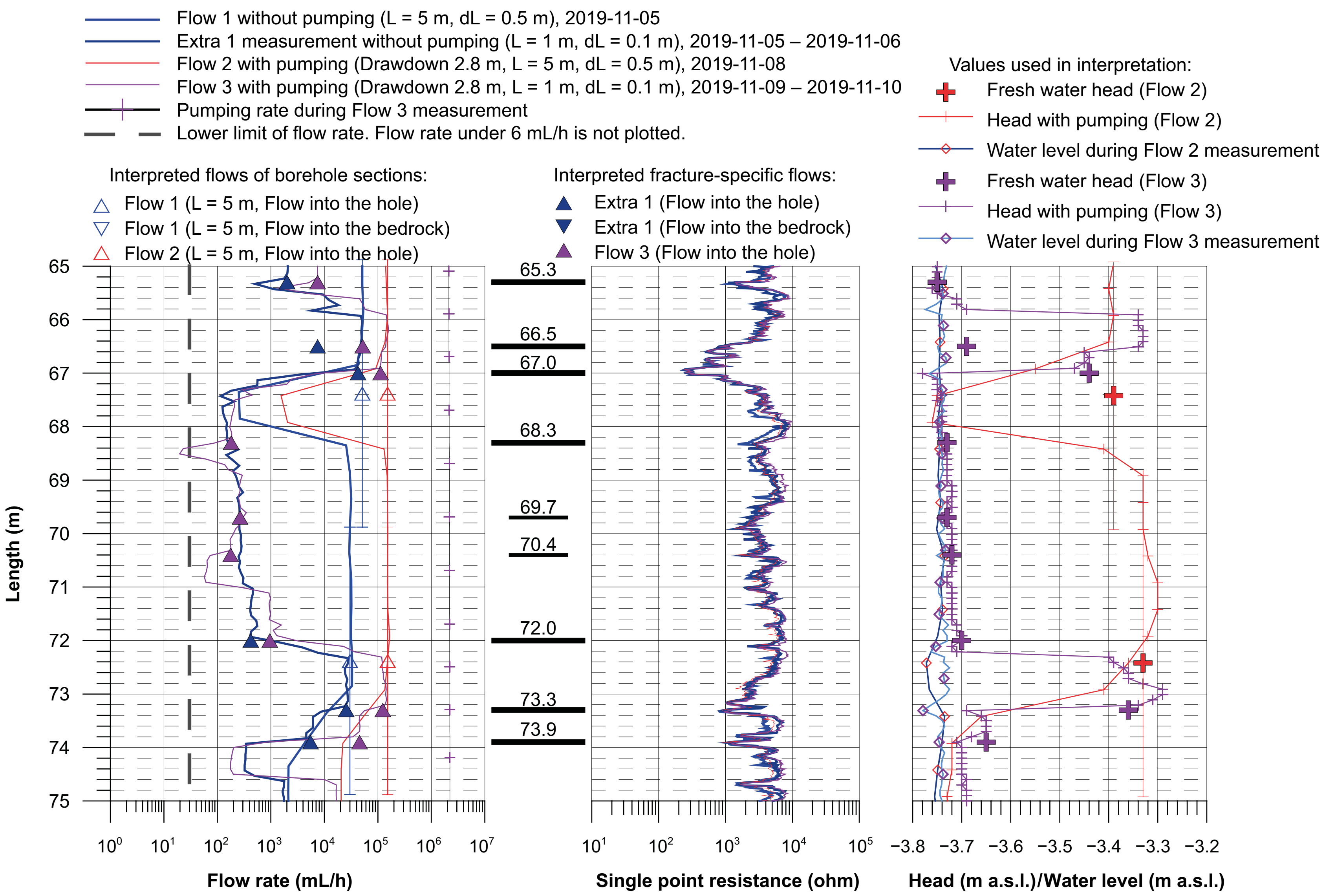
Forsmark, borehole KFM27
Flow rate, single point resistance and head in the borehole during flow logging



Forsmark, borehole KFM27
Flow rate, single point resistance and head in the borehole during flow logging

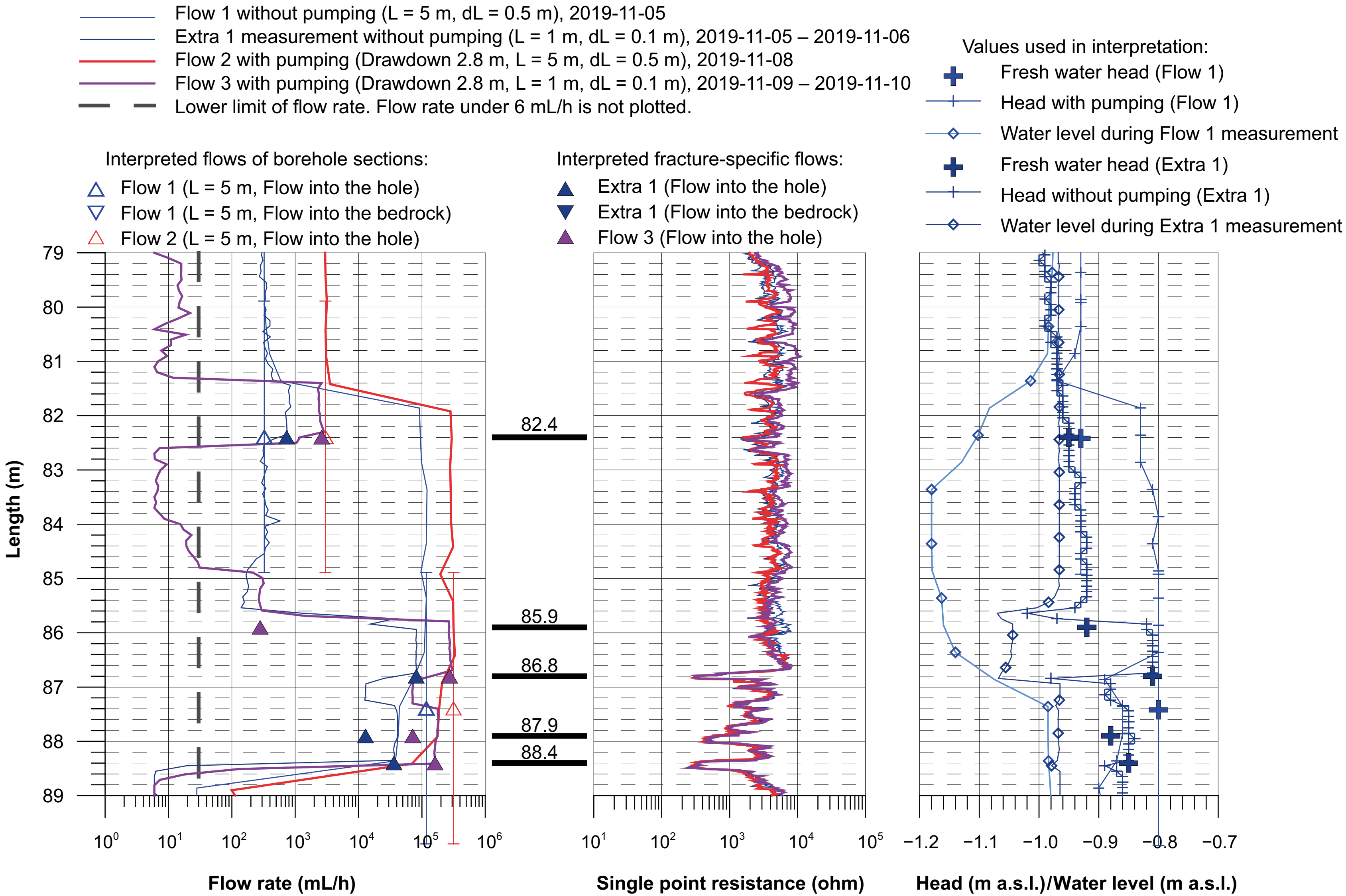


Forsmark, borehole KFM27
Flow rate, single point resistance and head in the borehole during flow logging

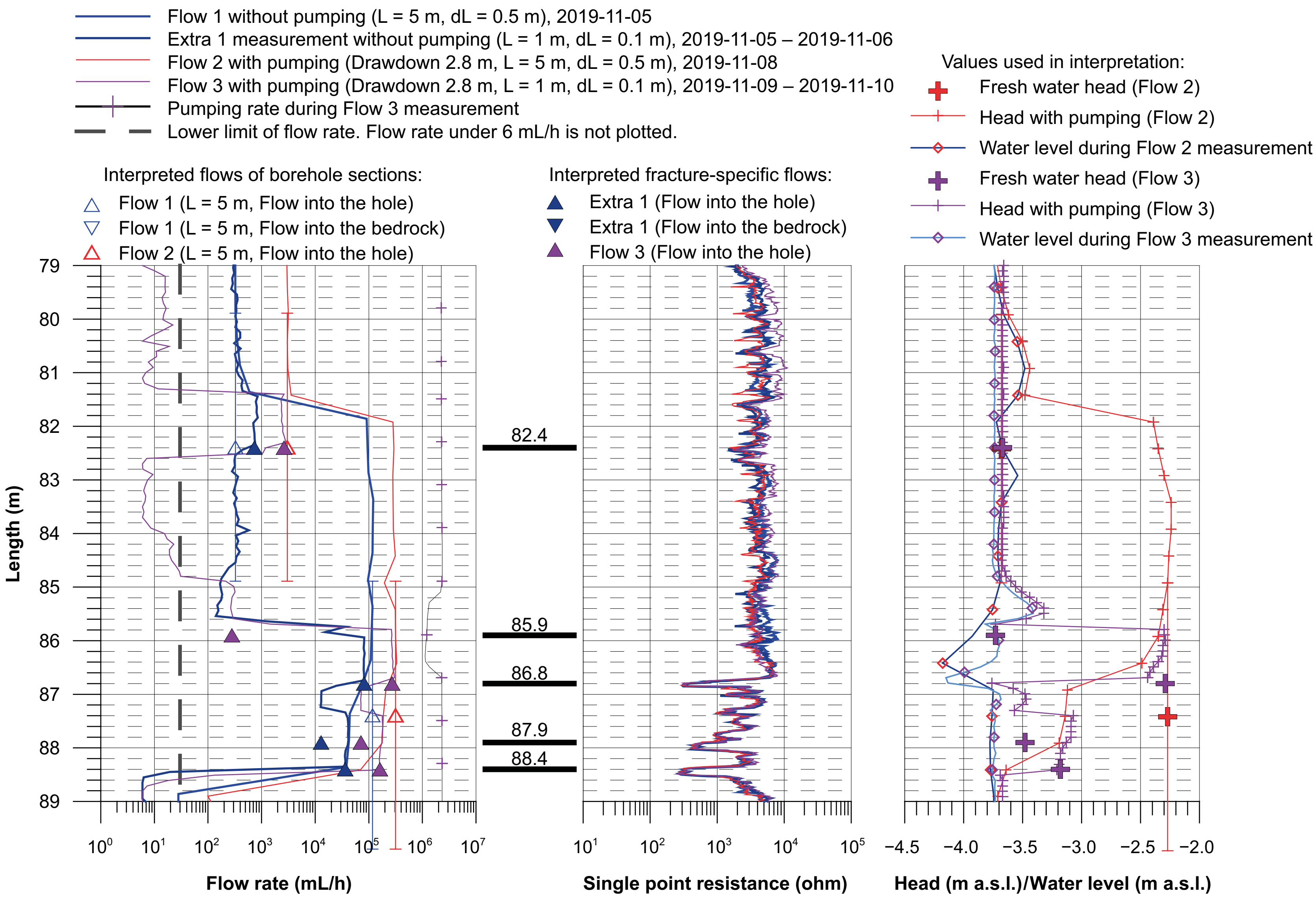


Forsmark, borehole KFM27

Flow rate, single point resistance and head in the borehole during flow logging



Forsmark, borehole KFM27
Flow rate, single point resistance and head in the borehole during flow logging



Arkitektkopia AB, Bromma, 2020

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