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SKB P-23-15

ISSN 1651-4416
ID 2024072
October 2023

Groundwater flow measurements in permanently installed boreholes

Test campaign no. 16, 2022

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Keywords: Groundwater flow, dilution test, tracer test, AP SFK-22-030

Abstract/Summary

This report describes the performance and evaluation of groundwater flow measurements in 24 borehole sections in permanently installed boreholes within the Forsmark site investigation area. The objective was to determine groundwater flow rates in some of the, at the time available, borehole sections instrumented for this purpose. This is the sixteenth test campaign performed within the monitoring program and the third campaign using online measuring equipment. Measurements are planned to be repeated once every year, which some varying number of sections each year.

The groundwater flow rates were determined through dilution measurements during natural conditions. Measured flow rates ranged from 0.03 to 32 ml/min with calculated Darcy velocities from $1.6 \cdot 10^{-10}$ to $1.9 \cdot 10^{-7}$ m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.0001 and 1.9 m/m.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i 24 borrhålssektioner i permanent installerade borrhål inom Forsmarks platsundersökningsområde. Syftet var att bestämma grundvattenflödet i ett antal av de vid denna tidpunkt och för detta ändamål instrumenterade sektioner. Detta är den sextonde mätkampanjen som genomförts i övervakningsprogrammet och den tredje som genomförts med utrustning för mätning online. Mätningarna är planerade att återupprepas en gång per år, med varierande antal sektioner från år till år.

Grundvattenflödet mättes med utspädningsmetoden under naturliga förhållanden i utvalda borrhålssektioner. Uppmätta grundvattenflöden låg i intervallet 0,03 – 32 ml/min med beräknade Darcy hastigheter mellan $1{,}6 \cdot 10^{-10}$ och $1{,}9 \cdot 10^{-7}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,0001 och 1,9 m/m.

Contents

1 Introduction

Knowledge of groundwater flow under natural conditions is an important part of the overall understanding of hydrogeological and hydrochemical conditions at Forsmark, and for the function of the engineered barriers (SKB 2001, 2003). Measurements during the construction phase may also be used for verification of the hydrostructural model of the site.

As a part of the programme for monitoring of geoscientific parameters and biological objects within the Forsmark site investigation area (SKB 2007) groundwater flow measurements have been carried out in permanently installed boreholes on a yearly basis since 2005. Measurements performed until 2012 were done during a short time period, generally one week, in the late autumn every year. However, the measured groundwater flow rates showed large variations between the years in many sections. Therefore, during 2013 – 2017 measurements were made over a longer period (3–10 months) to study the variability of groundwater flow and try to evaluate possible reasons for the variations. The compiled analysis (Andersson et al. 2018) included factors such as precipitation, groundwater levels, hydraulic transmissivity distribution, hydraulic gradients and measurement methodology. According to the results, the most contributing factors were evaporation in sampling tubes and the measuring time. Another factor that affected the quality of the measurements was the fact that the equipment was quite worn after 14 years. This applies especially to the sampling equipment.

The first attempts with online measurements, a new measuring methodology that would eliminate problems with evaporation and troublesome sampling equipment, were made in 2019. In November to December 2019 measurements were performed in three borehole sections using the customary sampling equipment and the new online equipment simultaneously. The comparison between the two methods gave consistent results, but with increased control and time resolution using the online equipment (Andersson and Wass 2020). Altogether, this supported a change of method to online measurements which also would remove the need of sample handling and sample analyses.

In 2020 the measurements were performed in 19 sections with the new online methodology only, i.e. no measurements were made with the previously used sampling equipment (Föhlinger and Wass 2021). The measurements performed in 2021 (Wass and Larsson 2023) and in 2022 in 22 and 24 borehole sections, respectively, were made in the same way.

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 16, autumn 2022. The work was carried out in accordance with activity plan AP SFK-22-030 and the field work was conducted from the beginning of October 2022 to the middle of November 2022. In Table 1-1 the controlling documents for performing the activity are listed. The activity plan and the method description are SKB's internal controlling documents.

A map of the site investigation area at Forsmark including borehole locations is presented in Figure 1-1.

The original results are stored in the primary data base Sicada and are traceable by the activity plan number.

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Övervakning av grundvattenflöde i Forsmark 2022. (In Swedish.)	1988984 – AP SFK-22-030	1.0
Method description	**Number**	**Version**
Metodbeskrivning för grundvattenflödesmätningar. (In Swedish.)	1189502 – SKB MD 350.001	3.0

Figure 1-1. *Overview over the Forsmark site investigation area, showing locations of boreholes included in this activity.*

In Table 1-2 a summary of all 33 sections used for groundwater flow monitoring in Forsmark is shown. The geological structures are given by the site descriptive model, SDM-Site (Follin et al. 2007).

Table 1-2. Summary of borehole sections used for groundwater flow monitoring in Forsmark 2005–2022.

Borehole	Section no	Secup (mbl)[1)]	Seclow (mbl)	SecMid (mbl)	Elevation SecMid (m RH2000)	Geologic Character[2)]	Measured 2022 (Yes/No)
KFM01A	5	109	130	119.5	-115.60	Multiple fractures,	Y
KFM01D	2	429	438	433.5	-342.84	Single fracture, FFM01	Y
	4	311	321	316	-252.34	Single fracture, FFM01	Y
KFM02A	3	490	518	504	-494.78	Zone ZFMF1	Y
	5	411	442	426.5	-417.61	Zone ZFMA2	Y
KFM02B	2	491	506	498.5	-483.64	Zone ZFMF1	N
	4	410	431	420.5	-406.87	Zone ZFMA2	N
KFM03A	4	633.5	650	641.75	-630.94	Zone ZFMB1	N
KFM04A	4	230	245	237.5	-199.65	Zone ZFMA2	Y
KFM05A	4	254	272	263	-221.22	Single fracture, FFM01	Y
KFM06A	3	738	748	743	-622.59	Zone ZFMNNE0725	Y
	5	341	362	351.5	-298.35	Zone ZFMENE0060A	Y
KFM06C	3	647	666	656.5	-526.86	Possible DZ5	Y
	5	531	540	535.5	-434.66	Zone ZFMWNW044	Y
KFM08A	2	684	694	689	-550.37	Possible DZ4 (S-WNW)	Y
	6	265	280	272.5	-227.61	Zone ZFMENE1061A	Y
KFM08D	2	825	835	830	-662.36	Zone ZFMENE0168	N
	4	660	680	670	-537.88	Zone ZFMNNE2308	N
KFM10A	2	430	440	435	-299.65	Zone ZFMA2	N
KFM11A	2	690	710	700	-593.57	ZFMWNW0001	Y
	4	446	456	451	-389.44	ZFMWNW3259	Y
KFM12A	3	270	280	275	-226.55	ZFMWNW0004	N
HFM01	2	33.5	45.5	39.5	-36.83	Zone ZFMA2	Y
HFM02	2	38	48	43	-39.72	Zone ZFM1203	Y
HFM04	2	58	66	62	-57.74	Zone ZFM866	Y
HFM13	1	159	173	166	-138.44	Zone ZFMENE0401A	Y
HFM15	1	85	95	90	-60.45	Zone ZFMA2	Y
HFM16	2	54	67	60.5	-57.00	Zone ZFMA8	N
HFM19	1	168	185.2	176.6	-137.17	Zone ZFMA2	N
HFM21	3	22	32	27	-18.63	Single fracture, FFM02	Y
HFM27	2	46	58	52	-45.42	Zone ZFM1203	Y
HFM32	3	26	31	28.5	-27.24	Single fracture, FFM03	Y
HFM33	2	121	137.5	129.5	-102.02	Single fracture	Y

1) Metre borehole length

2) Deformation zones according to Forsmark modelling stage 2.2 (Follin et al. 2007)

2 Objective and scope

The objective of this activity was to determine the groundwater flow in permanently installed borehole sections at Forsmark. In total 24 selected borehole sections, instrumented for this purpose, were measured, cf. Table 1-2. This was the 16th test campaign performed within the monitoring program and measurements are planned to be repeated every year. The measurements will serve as a basis to studying undisturbed groundwater flow as well as to monitor changes caused by future activities in the area, such as underground construction and drilling.

The groundwater flow in the selected borehole sections was determined through tracer dilution measurements. There are some other activities going on in the area during the test campaign but the impact on the flow measurements is estimated to be insignificant and the measurements may, on the whole, be regarded as performed during natural, i.e. undisturbed, hydraulic conditions, see Chapter 5.

3 Equipment and methodology

3.1 The dilution method – general principles

In the dilution method, a tracer solution is introduced and homogeneously distributed within an isolated borehole section. The tracer is subsequently diluted by the in-situ groundwater flow through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section and the groundwater flow rate is calculated as a function of the decreasing tracer concentration with time, Figure 3-1.

The method description used was "Metodbeskrivning för grundvattenflödesmätningar" (SKB MD 350.001), cf. Table 1-1.

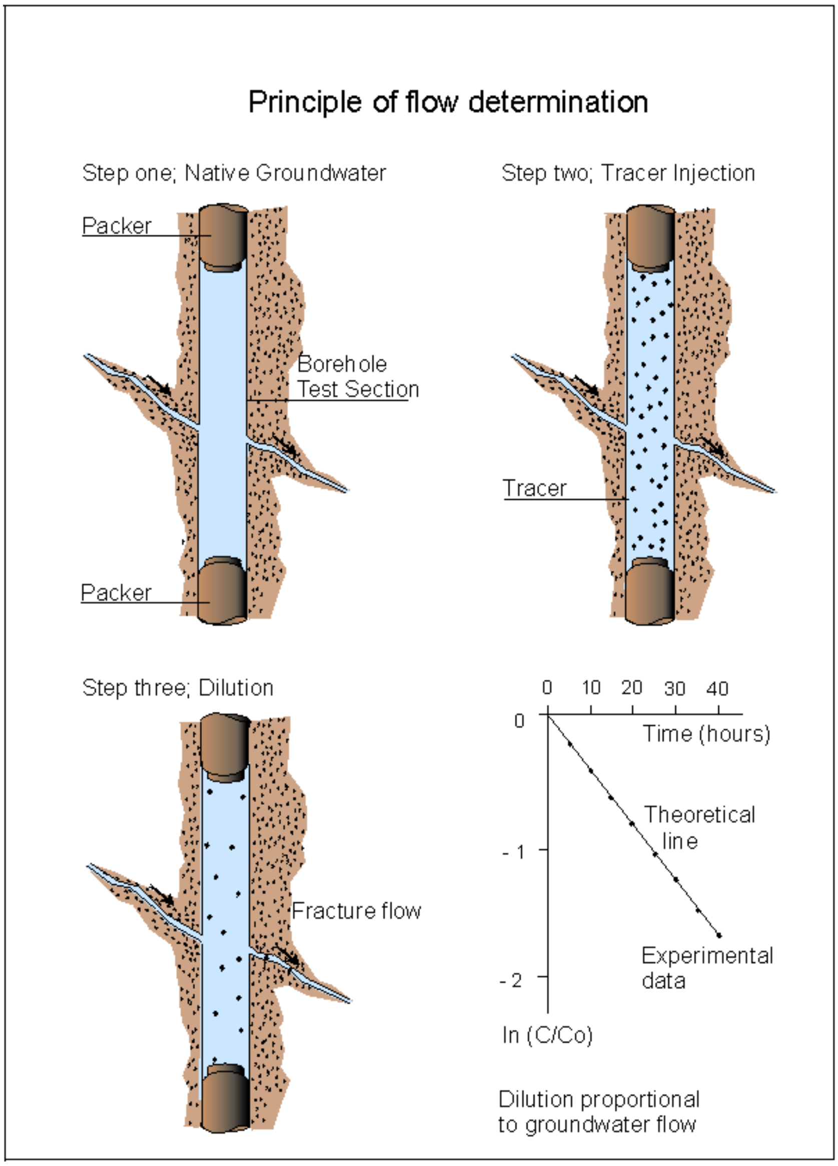

Figure 3-1. *General principles of dilution and flow determination (SKB MD 350.001).*

3.2 Borehole equipment

Each borehole used for groundwater flow measurements is instrumented with 1–9 inflatable packers isolating 2–10 borehole sections. Drawings of the instrumentation in core and percussion boreholes are presented in Figure 3-2.

Sections used for groundwater flow measurements and water sampling are also equipped with volume-reducing "dummies" made of Polyethylene. Furthermore, each section intended for groundwater flow measurements is equipped with three polyamide tubes connecting the borehole section with the ground surface. Two of the tubes are used for injection, sampling and circulation in the borehole section and one is used for pressure monitoring. All isolated borehole sections are connected to the Hydro Monitoring System (HMS) for pressure monitoring.

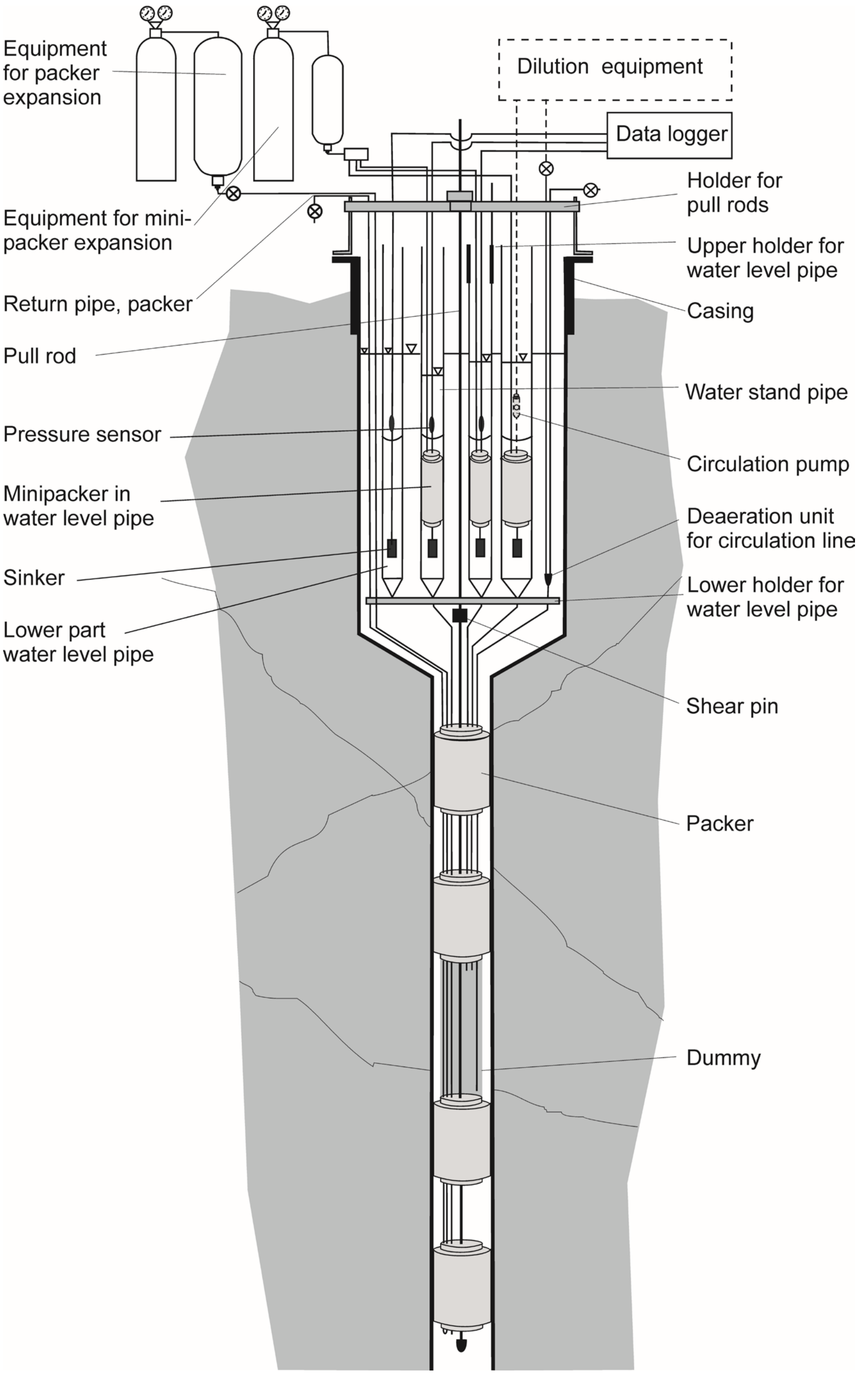

Figure 3-2. Example of permanent instrumentation in core and percussion boreholes with circulation sections.

3.3 Dilution test equipment and methodology

The tracer dilution tests were performed using six identical equipment set-ups, allowing six borehole sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-3. The basic idea is to create an internal circulation in the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to measure the tracer concentration outside the borehole in order to monitor the dilution of the tracer with time.

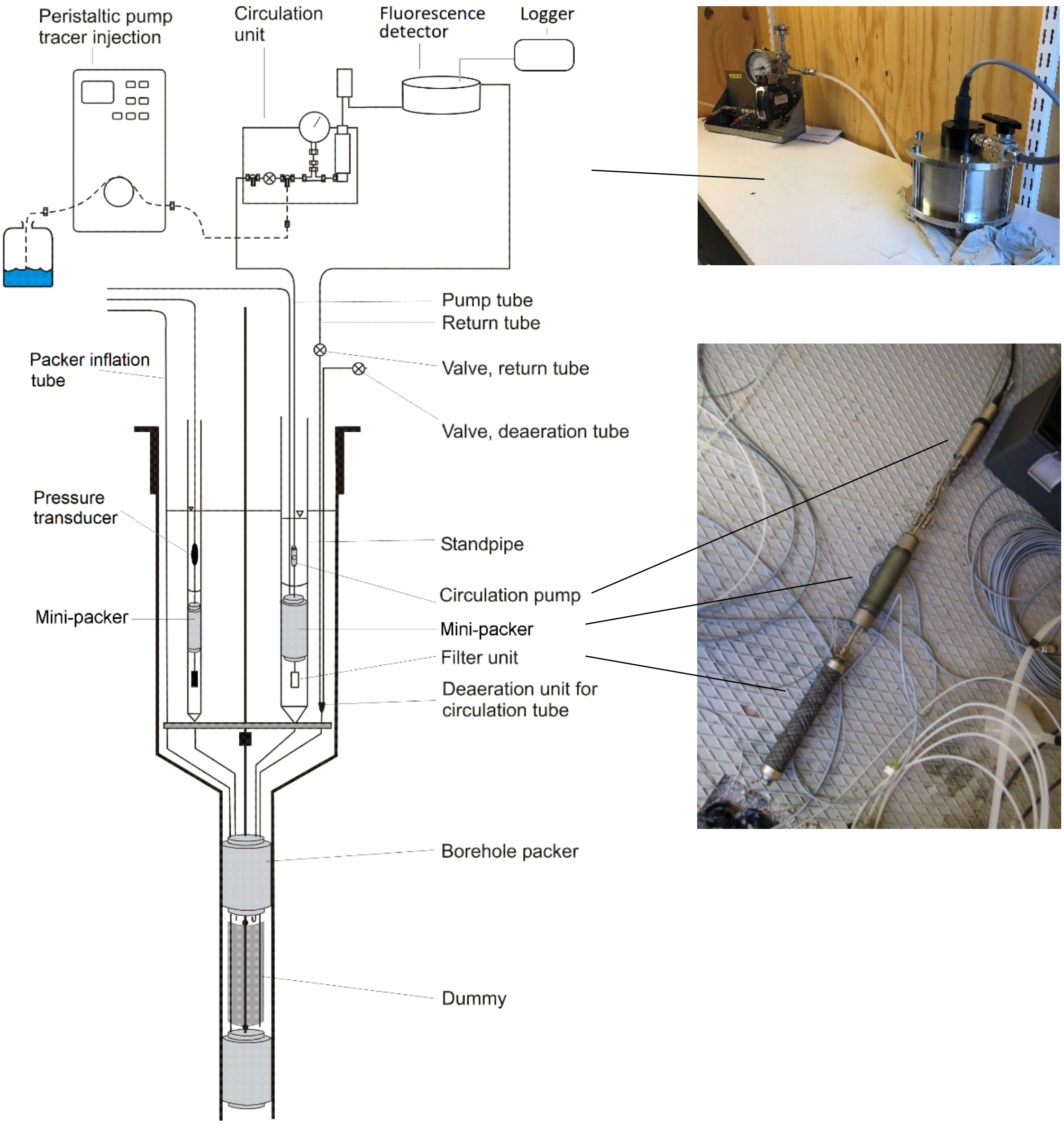

Figure 3-3. Schematic drawing of the equipment used in tracer dilution measurements.

Circulation is controlled via a down-hole pump with adjustable speed and measured by a flow meter. Tracer injections are performed with a peristaltic pump by injecting a concentrated tracer solution during a time period equivalent to the time needed to circulate one section volume, see Figure 3-4. This procedure helps to quickly achieve a constant concentration of tracer throughout the entire borehole volume. The concentration of the solution is chosen so that a concentration of the tracer in the section is in the order of 0.5–1 ppm, which is assumed to avoid density effects.

The tracer concentration is measured by continuously circulating the water through the online fluorescence detector. The measurements are performed in a closed circuit and no water is extracted for sampling. The fluorescence detector is of type GGUN-FL30 and it is possible to measure up to three different tracer solutions, turbidity and temperature at the same time, see Figure 3-5. Technical data are given in Andersson and Wass (2020). The detector is connected to a data logger that could store data to a microSD-card every 2–900 second, see Figure 3-6. By connecting a computer to the logger, it is possible to follow the measurements in real time in the software FLUO. The program is also used to download data and to convert the output signal (mV) to concentration (ppb) via a calibration file, see Section 4.1.

The tracer used is the fluorescent dye Amino-G Acid (360/450 nm) from Aldrich (techn. Quality). The tracer has been frequently used in tracer tests at various sites in crystalline rocks in Sweden since early 1980´s and have been found to be conservative, i.e. non-sorbing in this environment. Sodium Fluorescein was used in the first campaigns in Forsmark but later replaced as this tracer also is used as a marker of drilling fluid. The advantage of using fluorescent dyes is that they are detectable in very low concentrations and easy to analyze and measure online. The drawback is that they are easily degraded in sunlight. Samples should therefore be kept dark. The start concentration of 0.5–1 ppm allows a dilution of about 100 times for Amino-G before being affected by background fluorescence. The error in the online measurement is estimated to be within ± 10 % (SKB MD 350.001).

The equipment used and test procedure principles are described in detail in SKB MD 350.001, see Table 1-1.

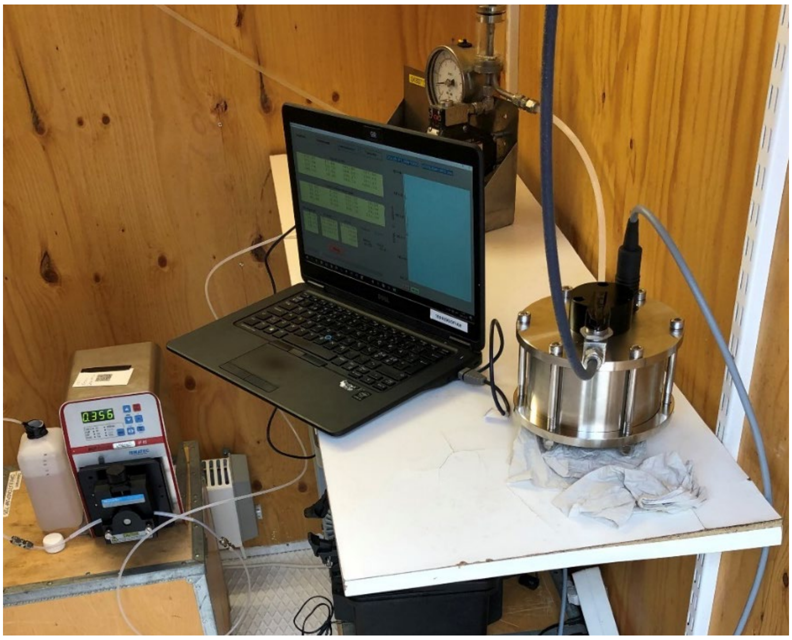

Figure 3-4. *All equipment during injection. Pump for tracer injection to the left, circulation unit in the back, fluorescence detector in the front connected to the logger under the bench. The logger is during injection connected to the computer, which makes it possible to follow the concentration in real time.*

Figure 3-5. *Fluorescence detector GGUN- FL30 connected for online measurement.*

Figure 3-6. *Data logger with transportation box and computer with on-measurements in the FLUO program.*

3.4 Analyses and interpretations

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural, unlabelled (no tracer present), groundwater (Gustafsson 2002). The so-called "dilution curves" were plotted as the natural logarithm of concentration versus time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (c/c_0) and time, t (s):

$$\ln\left(\frac{c}{c_0}\right) = -\left(\frac{Q_{bh}}{V}\right) \cdot t \qquad \text{Equation 3-1}$$

where Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V (m^3) is the volume of the borehole section. By plotting ln (c/c_0) or ln c versus t, Q_{bh} may then be obtained from the straight-line slope multiplied with the borehole section volume V. An example of a typical tracer dilution curve is shown in Figure 3-7.

The flow, Q_{bh}, may be translated into a Darcy velocity by taking into account the distortion of the flow caused by the borehole and the angle between the borehole and flow direction. In practice, a 90º angle between the borehole axis and the flow direction is assumed and the relation between the flow in the rock, the Darcy velocity, v (m/s), and the measured flow through the borehole section, Q_{bh}, can be expressed as:

$$Q_{bh} = v \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha \qquad \text{Equation 3-2}$$

where L_{bh} is the length of the borehole section (m), r_{bh} is the borehole radius (m) and α is the factor accounting for the distortion of flow caused by the borehole. For further information about the factor α see Andersson et al. (2018).

Hydraulic gradients are roughly estimated from Darcy´s law where the gradient, I, is calculated as the function of the Darcy velocity, v, with the hydraulic conductivity, K (m/s):

$$I = \frac{v}{K} = \frac{Q_{bh} \cdot L_{bh}}{\alpha \cdot A \cdot T_{bh}} = \frac{Q_{bh} \cdot L_{bh}}{2 \cdot d_{bh} \cdot L_{bh} \cdot T_{bh}} \qquad \text{Equation 3-3}$$

where T_{bh} (m^2/s) is the transmissivity of the section, obtained from hydraulic measurements, A the cross-section area between the packers, and d_{bh} (m) the borehole diameter.

The factor α is commonly given the value 2 in the calculations, which is the theoretical value for a homogeneous porous medium. Since the rock is mostly heterogeneous, and because the angles between the borehole axis and the flow direction in the sections are not always 90º, the calculation of the hydraulic gradient is a rough estimation.

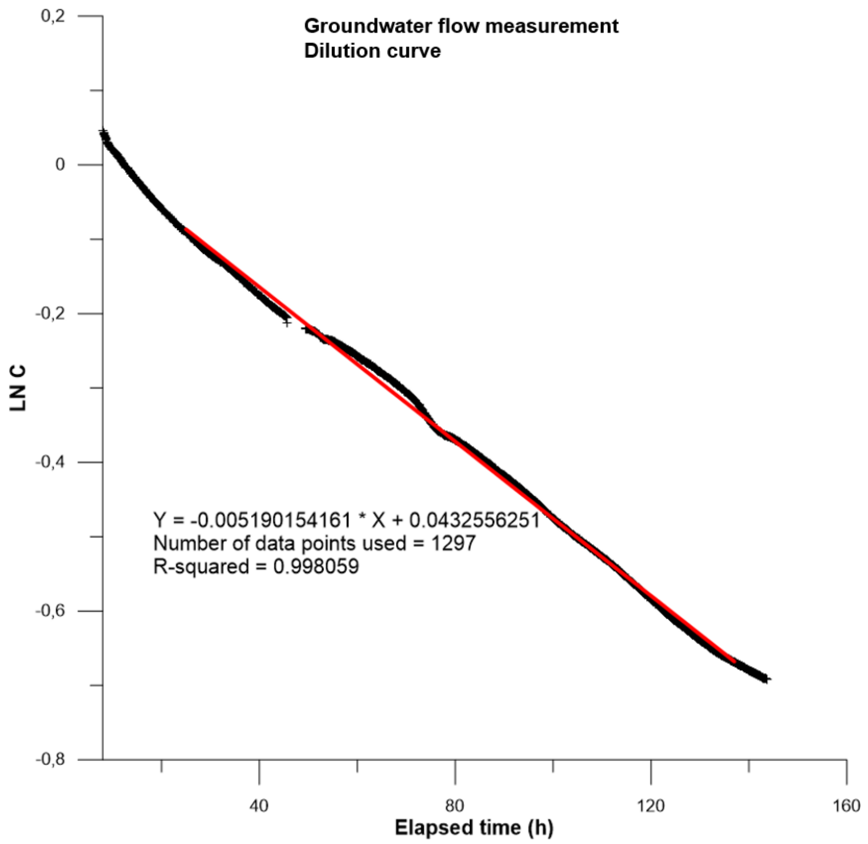

Figure 3-7. *Example of a tracer dilution graph (logarithm of concentration versus time), including straight-line fit. The used interval is chosen by eye assessment as the injection and start-up effects varies from section to section (Andersson et al. 2018).*

4 Execution

4.1 Preparations and calibration

The preparations included function checks of the equipment and printing of field protocols. It also included mixing of a tracer stock solution, which was used both for the calibration solutions and for the tracer injections in field.

All four GGUN-FL 30 detectors were calibrated at the Rejlers laboratory using a two-point calibration with the tracer Amino-G Acid (7-amino-1,3-naphtalene-disulfonic acid, Aldrich Chemie) in the concentrations 100 ppb and 1000 ppb (Table 4-1). These calibration values are then stored in the data file used to transform measured output in mV to concentrations in ppb when downloading the data from the loggers. The calibrations were performed with room temperature tracer solutions (about 22℃), which differs from the section water in field that often has a temperature around 10 ℃ (a parameter also measured by the online detector). The fluorescence for Amino-G Acid is however relative insensitive to changes in temperature (Smart and Laidlaw 1977). The difference of about 12 ℃ between the laboratory and the field temperatures corresponds to a reduction of the fluorescence with about 2 %, which could be considered as negligible relative other sources of errors.

Table 4-1. Data signal (mv) at calibration before field campaign, with Amino-G acid solutions of 100 and 1000 ppb

Detector (number)	Data signal (mv) at calibration	
	100 ppb	1000 ppb
1943	22.61	213.69
1955	34.37	323.54
1956	33.17	309.94
1957	29.88	283.19
1984	41.42	386.09
1985	52.74	490.69
1986	34.58	286.41

Validation of the calibration curves were performed in the laboratory with an Amino-G Acid solution of 500 ppb. All detectors gave good results with deviations varying between 494 and 505 ppb, which must be considered as acceptable (Table 4-2).

After the field measurements, the validation with 500 ppb solution was repeated for all detectors. The measured value with 500 ppb solution differed maximum 15 ppb, about 3 %, between the validation before and after field measurements for all detectors.

Table 4-2. Concentrations obtained at validation with 500 ppb solutions in September 2022, before field campaign, and November 2022, after field campaign.

Detector (number)	Concentration (ppb) at validation	
	September 2022 Solution 500 ppb	November 2022 Solution 500 ppb
1943	501	507
1955	505	516
1956	502	517
1957	499	508
1984	503	515
1985	494	506
1986	502	514

4.2 Execution of field work

The borehole sections included in the monitoring program during the test campaign 2022 are listed in Table 4-3. Measuring was performed with equipment described in Section 3.3 and six sections were measured simultaneously.

Before injection background concentrations in each section was measured during approximately 15–20 minutes of circulation at a logging interval of 10 seconds. This approach for measuring of background concentrations was first used in the test campaign 2021, see Section 4.3.2 for more information.

The tests were made by injecting a finite volume of tracer solution (Amino-G Acid, 1 000 mg/l) into the selected borehole sections and allowing the natural groundwater flow to dilute the tracer. The tracer was injected during a time period equivalent to the time needed to circulate one section volume. The injection/circulation flow ratio was set to 1/1 000, implying that the initial concentration in the borehole section should be about 1 mg/l for Amino-G Acid. The injection phase was monitored in real time with the online detection system, making it possible to adjust the injection flow rate to ensure that desired tracer concentrations are reached in the system. During injection data was detected with a logging interval of 10 seconds.

After injection, data was monitored with an interval of 5 minutes. The online detector also makes it possible to follow and monitor the mixture of tracer in the section after the injection, as shown in Figure 4-1. If the test period for a section was two weeks or more, the equipment was inspected after one week and at the same time data was downloaded. After completion of each test, at least three section volumes were pumped from the measured section in order to remove the remaining tracer.

Table 4-3. Borehole sections included in the monitoring program, test campaign 2022.

Borehole: section	Depth (m)	T (m^2/s) [1)]	Geologic character[2)]	Test period (yymmdd)			(No. weeks)
KFM01A:5	109 – 130	1.0 E-7	Multiple fractures, FFM02	221006	–	221020	2
KFM01D:2	429 – 438	6.2 E-8	Single fracture, FFM01	221020	–	221102	2
KFM01D:4	311 – 321	1.8 E-7	Single fracture, FFM01	221102	–	221110	1
KFM02A:3	490 – 518	4.0 E-6	Zone ZFMF1	221006	–	221026	3
KFM02A:5	411 – 442	2.9 E-6	Zone ZFMA2	221026	–	221102	1
KFM04A:4	230 – 245	4.6 E-5	Zone ZFMA2	221102	–	221117	2
KFM05A:4	254 – 272	1.9 E-8	Single fracture, FFM01	221005	–	221018	2
KFM06A:3	738 – 748	3.1 E-7	Zone ZFMNNE0725	221020	–	221101	2
KFM06A:5	341 – 362	9.2 E-7	Zone ZFMENE0060A	221011	–	221018	1
KFM06C:3	647 – 666	9.0 E-8	Possible DZ5	221018	–	221101	2
KFM06C:5	531 – 540	1.2 E-6	Zone ZFMWNW044	221101	–	221117	2
KFM08A:2	684 – 694	1.4 E-6	Possible DZ4 (S-WNW)	221006	–	221019	2
KFM08A:6	265 – 280	1.3 E-6	Zone ZFMENE1061A	221019	–	221103	2
KFM11A:2	690 – 710	1.0 E-6	ZFMWNW0001	221101	–	221108	1
KFM11A:4	446 – 456	3.1 E-8	ZFMWNW3259	221109	–	221116	1
HFM01:2	33.5 – 45.5	4.5 E-5	Zone ZFMA2	221109	–	221116	1
HFM02:2	38 – 48	5.9 E-4	Zone ZFM1203	221103	–	221109	1
HFM04:2	58 – 66	7.9 E-5	Zone ZFM866	221005	–	221012	1
HFM13:1	159 – 173	2.9 E-4	Zone ZFMENE0401A	221019	–	221025	1
HFM15:1	85 – 95	1.0 E-4	Zone ZFMA2	221025	–	221101	1
HFM21:3	22 – 32	1.0 E-4	Single fracture, FFM02	221108	–	221117	1
HFM27:2	46 – 58	4.0 E-5	Zone ZFM1203	221020	–	221110	3
HFM32:3	26 – 31	2.3 E-4	Single fracture, FFM03	221012	–	221020	1
HFM33:2	121 – 137.5	4.7E-04	Single fracture	221110	–	221116	1

[1)] Transmissivity for core drilled holes (KFM) from hydraulic injection tests (PSS) or PFL (Posiva Flow Log) measurements, for percussion drilled holes (HFM) transmissivity is from spinner measurements (HTHB).
[2)] Deformation zones according to Forsmark modelling stage 2.2 (Follin et al. 2007)

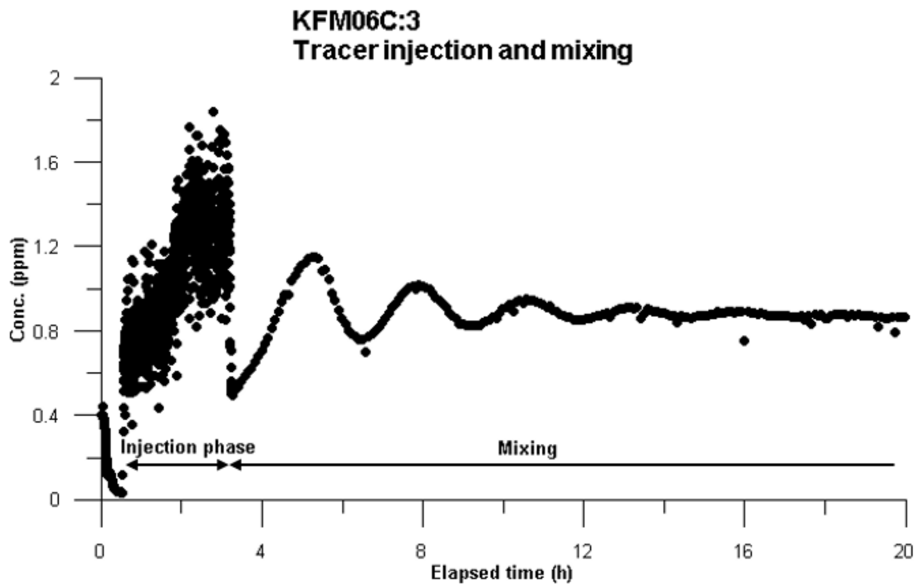

Figure 4-1. *Injection phase and mixing in KFM06C:3.*

4.2.1 Nonconformities

- In KFM01A:5 the circulation pump stopped 2022-10-11, about five days after tracer injection. The pump was restarted about 4 hours later the same day, and thereafter the pump was running to the intended stop of the measurement 2022-10-20.
- In KFM05A:4 the pump stopped when pumping out the remaining tracer after the measurement, which means that less than the intended three section volumes were removed. The low transmissivity makes it difficult to pump the section without the pump stopping when the inflow of water to the section is too low.
- In KFM06A:3 the circulation pump first stopped about three days after tracer injection, which was not discovered until the following week when attendance was made. The pump was then restarted but stopped again the next day and this was repeated once more. At the fourth attempt the pump flow rate was slightly lowered and this time the pump ran until the intended manual stop when the measurement was finished. Despite the initial pump problems, it has been possible to obtain sufficient data for a credible evaluation.
- In KFM06C:3 a small leakage between the pump tube and the circulation unit was discovered after eight days of pumping. The leak was fixed and does not appear to have affected the evaluated flow rate.
- In HFM27:2 a small leakage was discovered at the valve to the return tube 14 days after the measurement started. The leak was fixed and does not appear to have affected the evaluated flow rate.
- The circulation pumps in KFM11A:4 and HFM33:2 stopped during some hours 2022-11-12 when a power loss occurred. The pumps started again when the power returned. This has not affected the evaluated flow rates in these sections.

4.3 Evaluation of data

4.3.1 Filtering of data due to gas bubbles

A disadvantage with the used online GGUN instrument is its sensitivity to gas bubbles in the water flow. Gas bubbles occur when pressurized water from depth is pumped to the surface. If the sampling occurs when a gas bubble passes through the sensor it generates a disturbance in data, the detected signal becomes much smaller generating a lower concentration for this sampling point. The consequence will be fluctuation in data which affects the evaluation. To achieve a good and correct fit for calculating ground water flow in the section, the data must be filtered before evaluation.

Data filtering is performed by comparing each measured value to a floating mean value of ten data points. If the difference between the measured value and the floating mean value is larger than 5 ppb, the point is excluded from the further analysis. Only values with lower concentrations than the floating mean are excluded, see Figure 4-2.

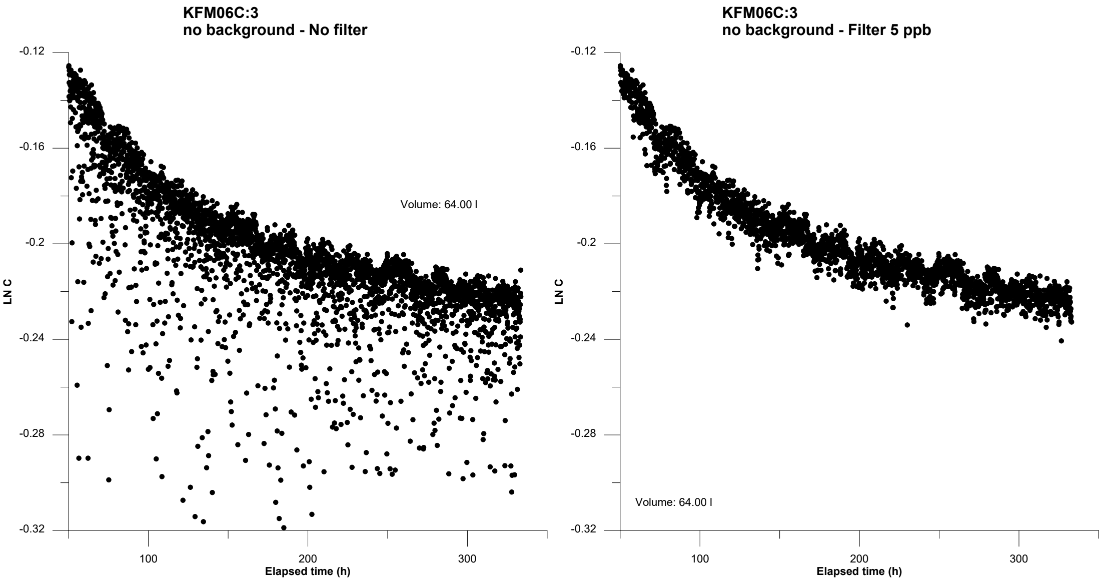

Figure 4-2. *Unfiltered and filtered data. Fluctuations are due to gas bubbles.*

4.3.2 Used background concentrations

The used initial background concentration affects the evaluated results. In previous years, before the use of online measurements, background concentrations were obtained by a single sample before injection start. In campaign no 14 2020, the first one with online measurements, background concentrations were measured with 5 minutes scan during 24 hours before tracer injection. The background measurements in campaign no 14 showed that the most representing part occurs during the first hours of pumping and the procedure of background measurement was suggested to be shortened (Föhlinger and Wass 2021). In the report it was proposed that the injection of tracer could start after pumping a volume corresponding to three tube volumes of the pump hose. Hence, starting with campaign no 15 2021, the background concentration is measured during approximately 15–20 minutes of circulation at a logging interval of 10 seconds while the logging is monitored in real time at a computer. The background measurements are considered complete when the real time monitored data show stable values.

4.3.3 Evaluation of dilution graphs

Data is evaluated, as described in Section 3.4, by a straight-line fit to logarithmic tracer concentration data versus elapsed time during the dilution phase. Evaluation is mainly performed on the later part of data to reduce effects from the injection and start of circulating the section water. The used interval is chosen by eye assessment as the injection and start-up effects varies from section to section (Andersson et al. 2018). The chosen evaluation period should consist of a linear period of data as long as possible. After choosing evaluation interval a sensitivity analysis is made to estimate the impact on the results depending on chosen limits for the evaluation period. See also discussion in Section 5.3.

5 Results

5.1 General

Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP SFK-22-030). Only data in databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. However, such revision of the database will not necessarily result in a revision of this report, although the normal procedure is that major data revisions entail a revision also of the report.

5.2 Test campaign no. 16, 2022

Tracer dilution graphs for each borehole section are presented in Appendix 1. The flow rate is calculated from the slope of the straight-line fit. The results show that the groundwater flow during natural conditions varies from 0.03 to 32 ml/min in the measured sections with Darcy velocities ranging from $1.6 \cdot 10^{-10}$ to $1.9 \cdot 10^{-7}$ m/s.

A summary of the results obtained is presented in Table 5-1 including measured groundwater flow rates, Darcy velocities and hydraulic gradients together with transmissivities and volumes of the borehole sections.

Table 5-1. Results from groundwater flow measurements, test campaigns no. 16, 2022.

Borehole/ section	Depth (m)	Trans- missivity (m^2/s)[1)]	Vol. (l)	Time Interval (h) From	To	Back- ground (ppb)	Measured flow, *Q* (ml/min)	Darcy velocity, *v* (m/s)*10^{-9}	Hydraulic gradient, *I* (m/m)
KFM01A :5	109 – 130	1.0E-07	33.21	135	310	71	0.03	0.2	0.03
KFM01D:2	429 – 438	6.2 E-8	38.33	30	310	25	0.04	0.5	0.08
KFM01D:4	311 – 321	1.8 E-7	31.27	40	190	34	0.09	1.0	0.06
KFM02A:3	490 – 518	4.0 E-6	66.33	150	370	26	0.6	2.3	0.02
KFM02A:5	411 – 442	2.9 E-6	60.78	90	168	47	0.6	2.0	0.02
KFM04A:4	230 – 245	4.6 E-5	35.00	90	355	30	1.4	9.8	0.003
KFM05A:4	254 – 272	1.9 E-8	40.62	100	310	128	0.04	0.2	0.2
KFM06A:3	738 – 748	3.1 E-7	58.25	390	670	27	0.1	1.4	0.05
KFM06A:5	341 – 362	9.2 E-7	46.64	70	160	31	0.8	4.3	0.1
KFM06C:3	647 – 666	9.0 E-8	64.00	160	340	25	0.07	0.4	0.08
KFM06C:5	531 – 540	1.2 E-6	43.61	110	375	51	0.7	8.5	0.06
KFM08A:2	684 – 694	1.4 E-6	55.15	100	310	15	0.2	1.7	0.01
KFM08A:6	265 – 280	1.3 E-6	34.67	75	356	18	0.05	0.4	0.004
KFM11A:2	690 – 710	1.0 E-6	68.48	55	167	3	0.4	2.4	0.05
KFM11A:4	446 – 456	3.1 E-8	40.50	80	167	3	0.6	6.0	1.9
HFM01:2	33.5 – 45.5	4.5 E-5	39.83	45	165	246	3.6	18	0.005
HFM02:2	38 – 48	5.9 E-4	28.53	28	38.5	174	32	194	0.003
HFM04:2	58 – 66	7.9 E-5	27.52	55	142	156	1.3	9.6	0.001
HFM13:1	159 – 173	2.9 E-4	39.28	12	42	147	32	139	0.007
HFM15:1	85 – 95	1.0 E-4	35.74	40	167	144	1.8	11	0.001
HFM21:3	22 – 32	1.0 E-4	31.39	15	215	151	1.0	6.0	0.0006
HFM27:2	46 – 58	4.0 E-5	40.29	200	499	113	0.2	1.2	0.0004
HFM32:3	26 – 31	2.3 E-4	20.06	95	170	64	0.4	4.4	0.0001
HFM33:2	121 – 137.5	4.7E-04	54.10	25	137	34	4.7	17	0.0006

[1)] Transmissivity for core drilled holes (KFM) from hydraulic injection tests (PSS) or PFL (Posiva Flow Log) measurements, for percussion drilled holes (HFM) transmissivity is from spinner measurements (HTHB).

In Appendix 2 the groundwater levels in the selected boreholes during the test period are presented together with the local precipitation, see also Table 4-3 for actual measurement periods for each section. The groundwater levels were generally very stable during the measurement period and no obvious effects of rain were seen any of the borehole sections.

Other activities performed in the Forsmark area during the test period were borehole packer releases in HFM05 and HFM38 and packer removal in HFM05, cf. Table 5-2. However, these are not believed to have affected the ongoing groundwater flow measurements. The power loss that occurred 2022-11-12 disturbed the ongoing measurements in KFM11A:4 and HFM33:2 as the circulation pumps stopped. When the power returned after some hours the pumps started again and the relatively short circulation break has not affected the evaluation of flow rates in any of the sections.

Table 5-2. Activities performed in the Forsmark area during test campaign no. 16, 2022.

Start date	Stop date	Borehole	Activity
2022-10-05		HFM05	Borehole packer release
2022-11-09		HFM38	Borehole packer release
2022-11-10	2022-11-10	HFM05	Instrumentation - packer removal
2022-11-12	2022-11-12	AFR	Power loss (from 08:16 to 11:45)

Hydraulic gradients are calculated according to the Darcy concept and are within the expected range (< 10 %) in most of the measured sections. It should be noted that the Darcy concept is built on assumptions of a homogeneous porous medium and values for a fractured medium should therefore be treated with great care. For KFM05A:4, KFM06A:5 and KFM11A:4 the hydraulic gradient is very large. This indicates that the flow rates measured during these periods are higher than expected. The large gradients may be due to rough estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture.

KFM05A:4 represents a single fracture (cf. Table 4-3), where the Darcy concept may be questioned. The same applies to both sections in KFM01D, HFM21:3, HFM32:3 and HFM33:2 even though the results are not deviant in these sections.

In borehole sections HFM02:2 and HFM13:1 the dilution of tracer was quite fast. In HFM02:2 higher injection concentration should be considered for the next test campaign.

5.3 Flow rate comparison

For comparison reasons flow rates obtained from previously performed test campaigns are compiled in Table 5-3 and Figure 5-1. Activites in the Forsmark area during the campaigns in 2005–2022 are found in Appendix 3.

The comparison shows that the flow rates measured 2022 are within the range of the values measured in previous campaigns in most borehole sections. However, due to start-up effects the measured flow in several sections can vary over the measurement period with higher flow in the beginning (first 100–200 hours), compared to the flow towards the end of the measurement period. During the last years of long-term measurements and evaluations (2013–2017) it became increasingly clear that the latter part of the curve should be used to obtain an evaluated value as reliable as possible (Andersson et al. 2018). In earlier test campaigns (2005–2012) the measurement duration has only been about 200 hours at the longest, why the flow rates presented for these years in Table 5-3 probably are overestimated for some sections.

In addition, the previous method (used before 2020) included a sampling procedure with a constant flow rate which also contributed to the dilution of tracer. Hence, the flow rates obtained had to be adjusted for the sampling flow rate of approximately 0.06 – 0.1 ml/min. For several sections this is a substantial part of the total measured flow and introduces uncertainties as the sampling flow rate was calculated from the measured sample volume in the tubes. The sampling flow rate was probably somewhat underestimated due to evaporation from the test tubes and sometimes also malfunctioning samplers.

Given the background mentioned above, the most accurate comparison for the flow rates in 2022 would be to the results from 2020 and 2021, as the new online detectors were used all three years. In general, the measured flow in 2022 is in good agreement with the results from the previous two years for most sections. For some sections, the results from 2022 show that it is rather the flow measured in 2020 or 2021 that deviates, as for KFM01D:2, KFM08A:6 and HFM21:3. For KFM01D:2 and KFM08A:6 the deviating higher flow rates in 2020 and 2021, respectively, are probably due to too short measurement periods as discussed in Wass and Larsson (2023).

In KFM11A:2 the flow measured in 2022 is four to five times smaller than the flow measured in 2020. No measurement was performed in 2021 as the borehole equipment in KFM11A was removed. Hence, the result from 2022 is after re-installation of the equipment in the borehole. However, compared to the measurements from 2005–2017, it is rather the result from 2020 that stands out and the flow from 2022 is not particularly deviant.

Table 5-3. Results from groundwater flow measurements in 2005–2022. Only sections measured during 2022 are shown in the table. For detailed data from each year see Andersson et al. (2018), Föhlinger and Wass (2021) and Wass and Larsson (2023).

Borehole: section	T[1] (m^2/s)	2005–2012 (ml/min)	2013–2017 (ml/min)	Sep–Nov 2020 (ml/min)	Oct–Nov 2021 (ml/min)	Oct–Nov 2022 (ml/min)
KFM01A:5	1.0 E-7	0.05 – 0.2	0.02 – 0.7	0.05	0.06	0.03
KFM01D:2	6.2 E-8	0.04 – 0.3	0.06	1.0	0.05	0.04
KFM01D:4	1.8 E-7	0.1 – 0.7	0.1 – 0.3	0.07	0.09	0.09
KFM02A:3	4.0 E-6	0.8 – 2.1	0.1 – 1.3	-	0.7	0.6
KFM02A:5	2.9 E-6	0.1 – 1.0	0.2 – 0.4	-	0.5	0.6
KFM04A:4	4.6 E-5	2.5 – 16	1.1 – 4.0	-	1.4	1.4
KFM05A:4	1.9 E-8	0.02 – 2.3	0.03 – 0.2	-	0.02	0.04
KFM06A:3	3.1 E-7	0.05 – 0.6	0.01 – 0.3	0.2	0.2	0.1
KFM06A:5	9.2 E-7	0.2 – 5.7	0.01 – 0.4	1.5	0.8	0.8
KFM06C:3	9.0 E-8	0.03 – 0.4	0.01 – 0.23	0.2	0.08	0.07
KFM06C:5	1.2 E-6	0.2 – 0.8	0.02 – 0.5	0.8	0.7	0.7
KFM08A:2	1.4 E-6	0.7 – 3.1	0.02 – 0.5	0.2	0.1	0.2
KFM08A:6	1.3 E-6	0.06 – 0.2	0.02 – 0.3	0.05	0.3	0.05
KFM11A:2	1.0 E-6	0.2 – 0.9	0.2 – 0.8	1.8	-	0.4
KFM11A:4	3.1 E-8	0.01 – 0.3	0.01 – 0.07	0.7	-	0.6
HFM01:2	4.5 E-5	3.4 – 7.8	1.5 – 11	4.3	3.2	3.6
HFM02:2	5.9 E-4	5.2 – 38	6.5 – 81	12	17	32
HFM04:2	7.9 E-5	0.8 – 10	0.7 – 1.3	-	1.4	1.3
HFM13:1	2.9 E-4	3.3 – 24	22 – 31	-	21	32
HFM15:1	1.0 E-4	0.6 – 8.5	0.8 – 2.9	-	1.7	1.8
HFM21:3	1.0 E-4	0.9 – 2.1	0.2 – 0.6	0.2	1.0	1.0
HFM27:2	4.0 E-5	0.3 – 0.8	0.02 – 0.2	0.08	0.2	0.2
HFM32:3	2.3 E-4	0.5 – 1.2	0.3 – 1.0	-	0.4	0.4
HFM33:2	4.7 E-4	-	-	6.5	3.9	4.7

[1)] Transmissivity for core drilled holes (KFM) from hydraulic injection tests (PSS) or PFL (Posiva Flow Log) measurements. for percussion drilled holes (HFM) transmissivity is from spinner measurements (HTHB).

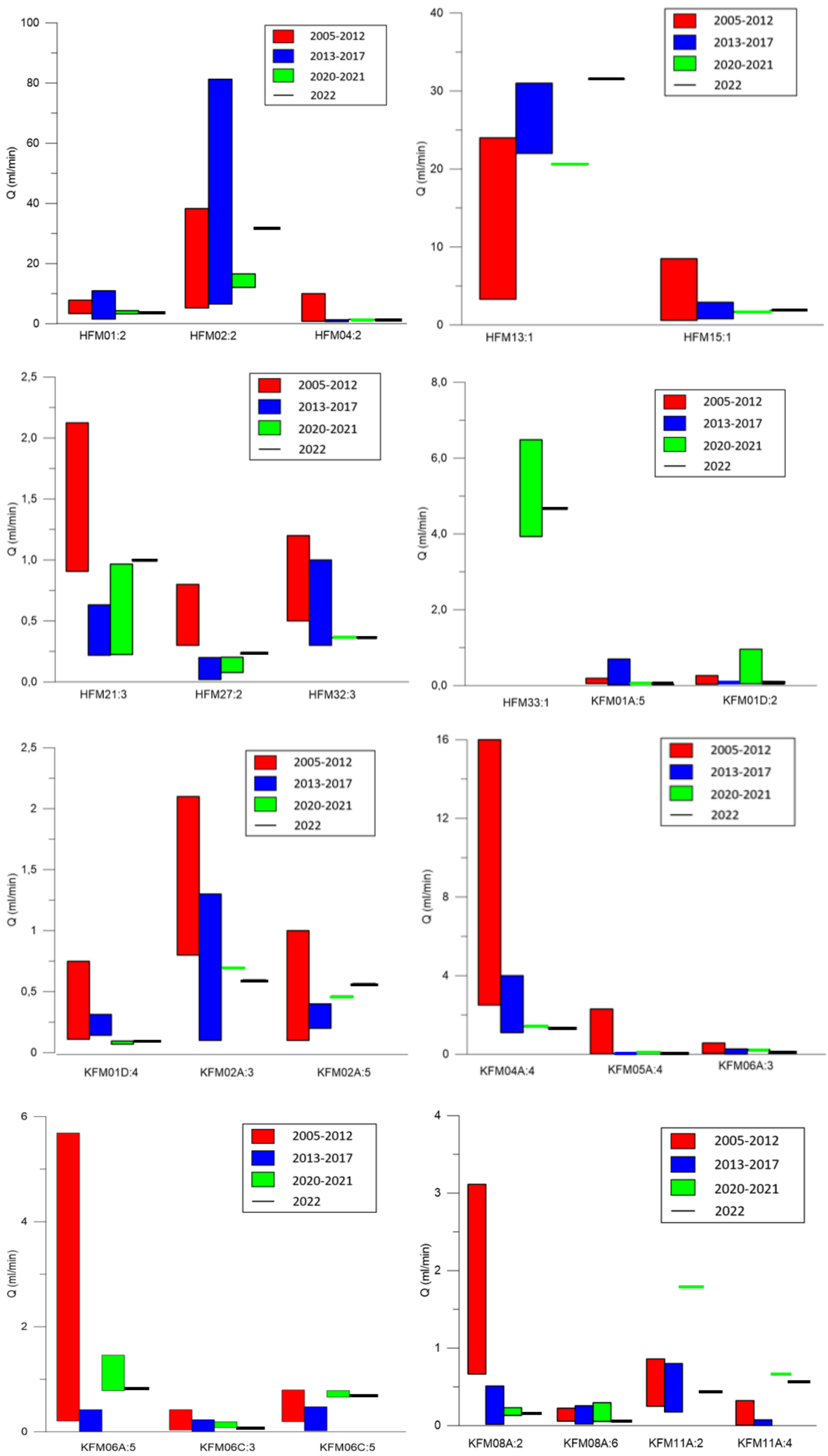

***Figure 5-1**. Summarized results from groundwater flow measurements 2005–2022. Only sections measured during 2022 are shown in the figure.*

6 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications. SKBdoc documents will be submitted upon request to document@skb.se.

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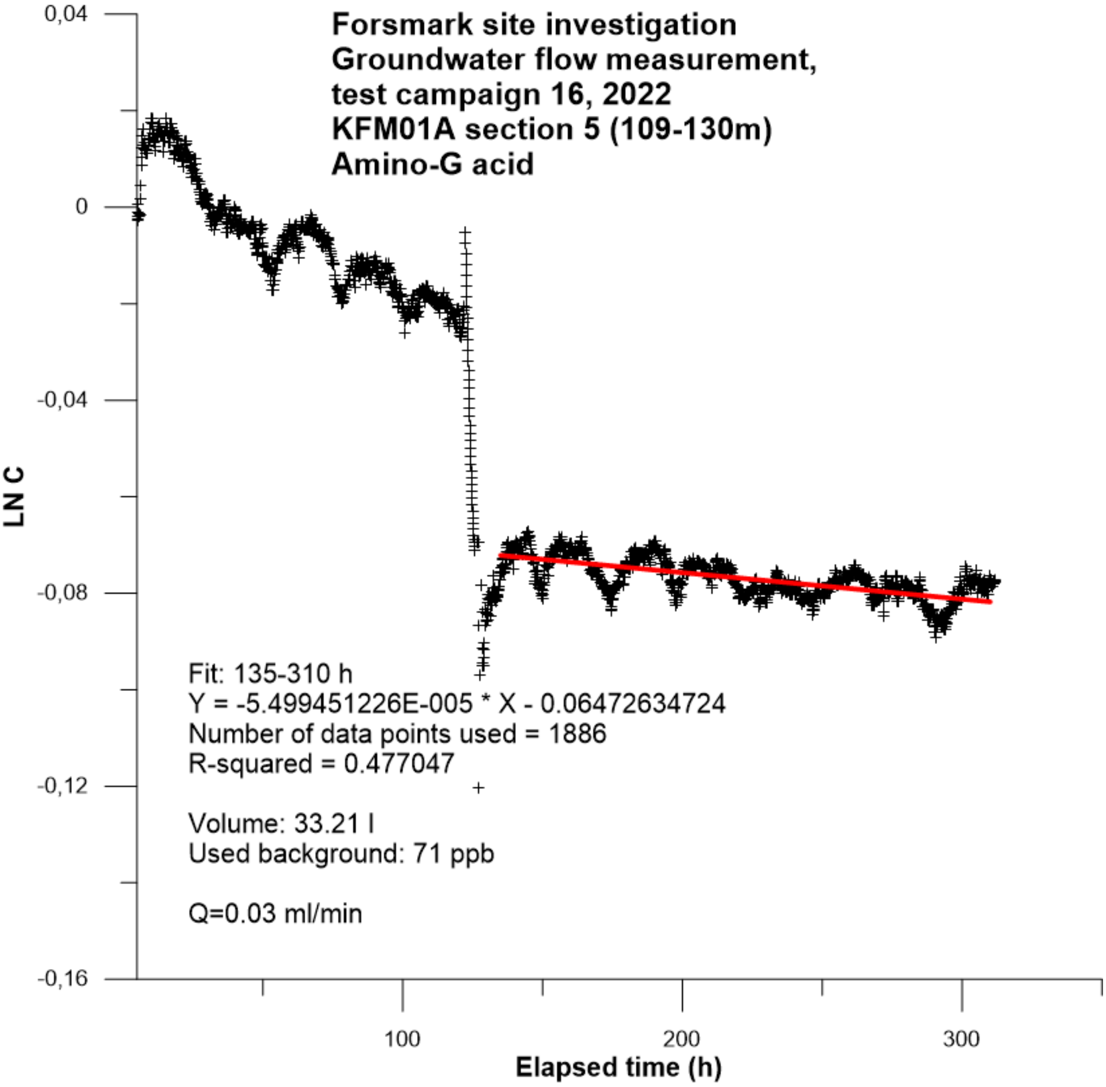
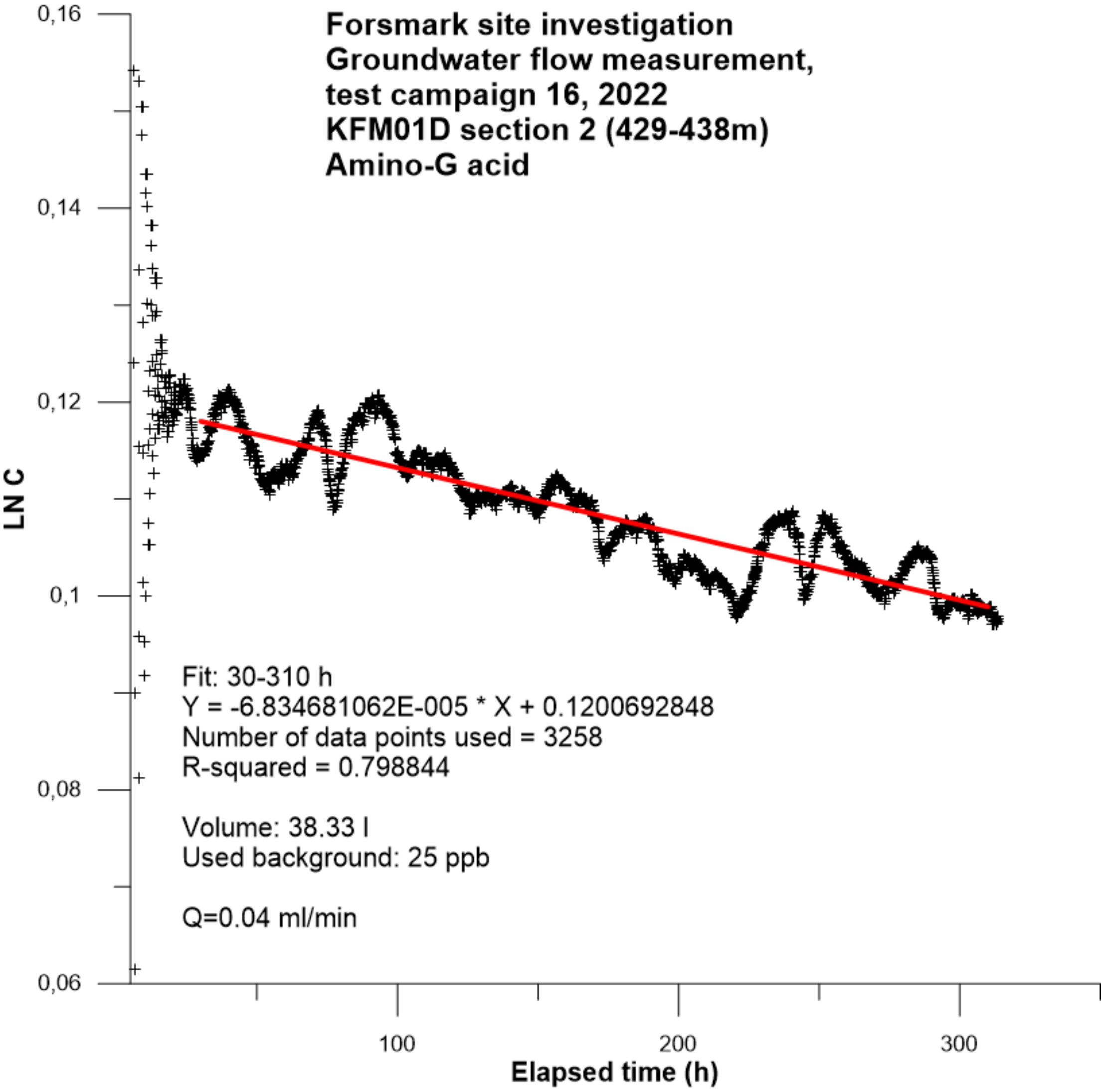
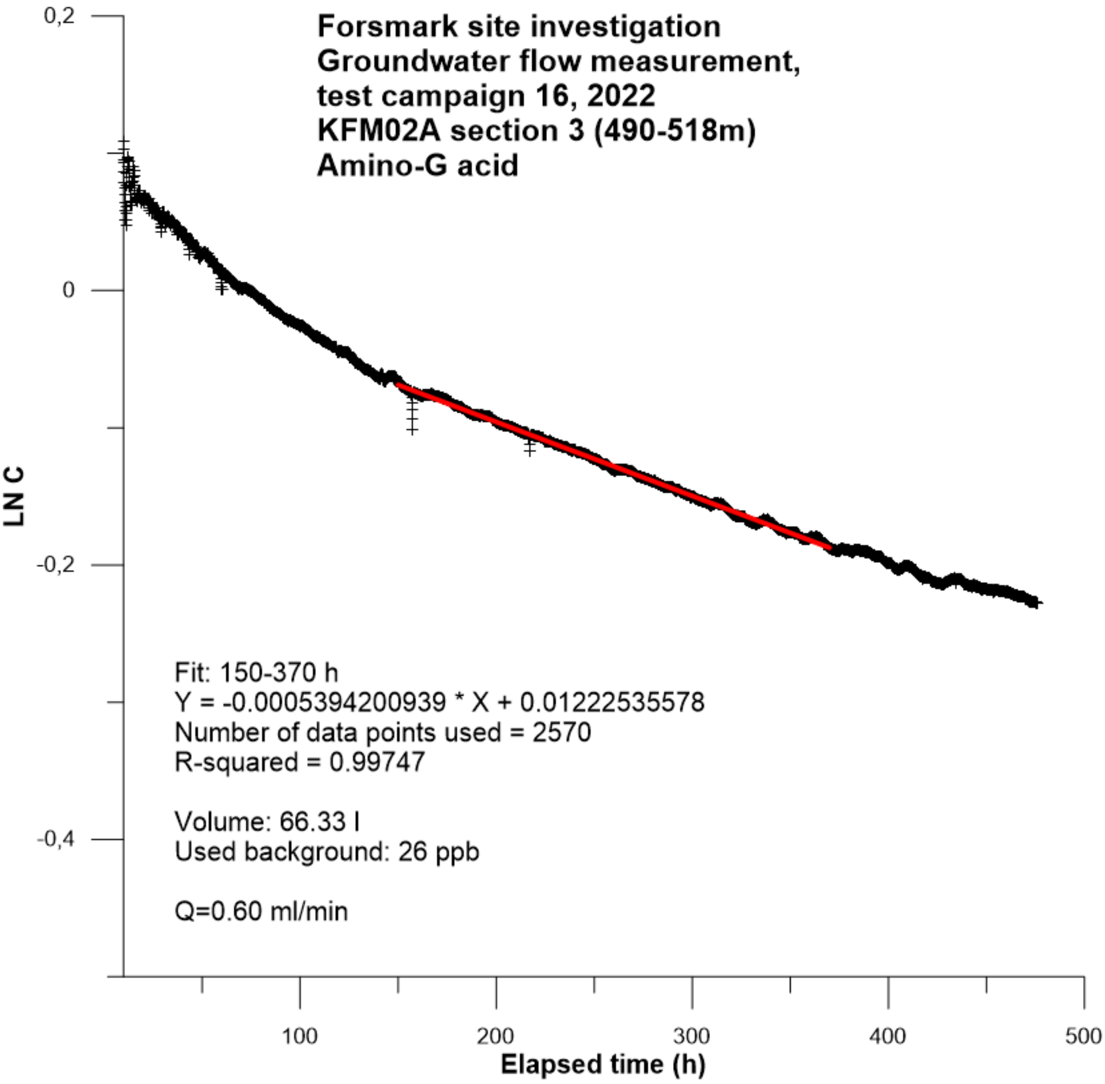
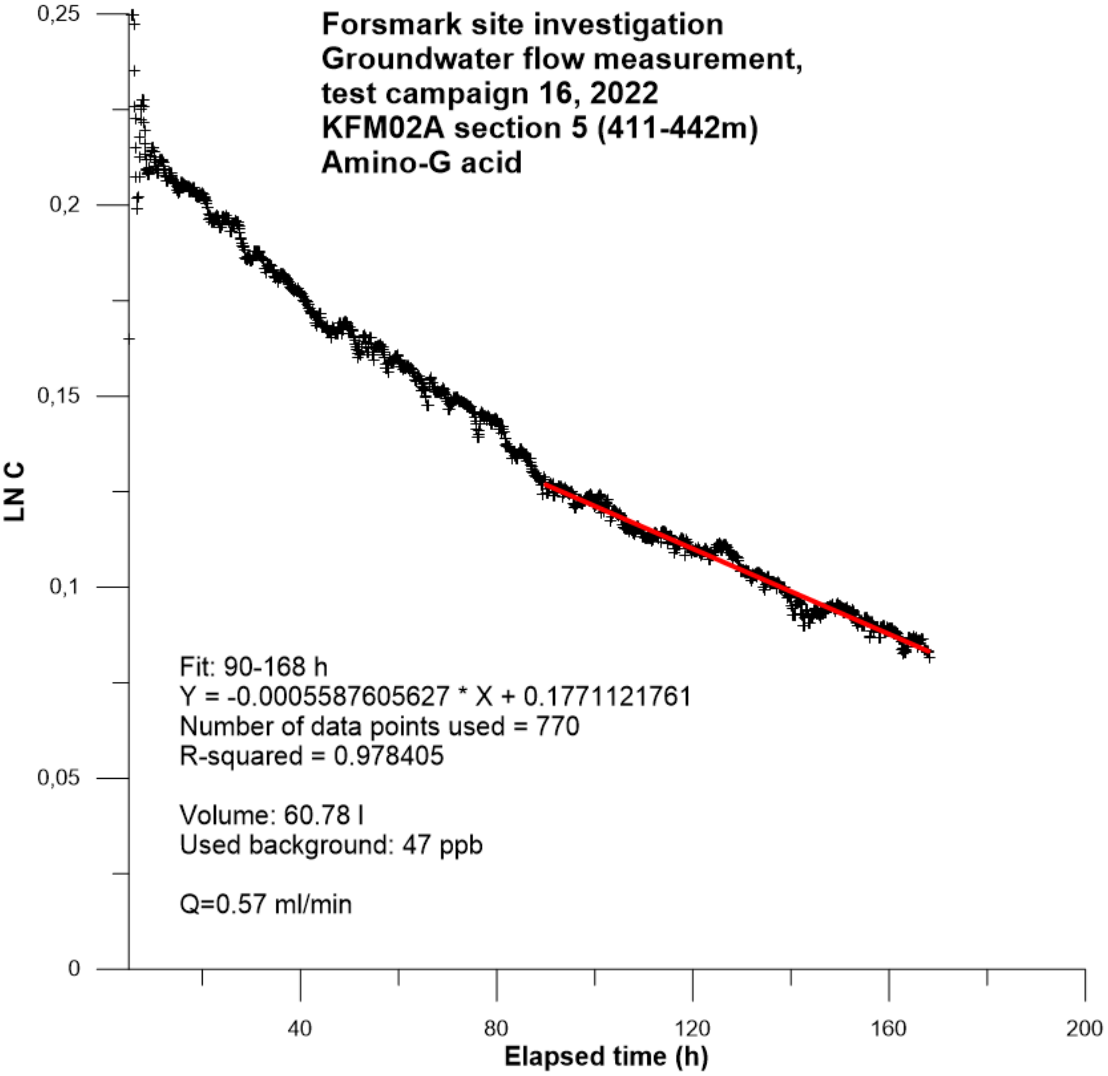
Appendix 1

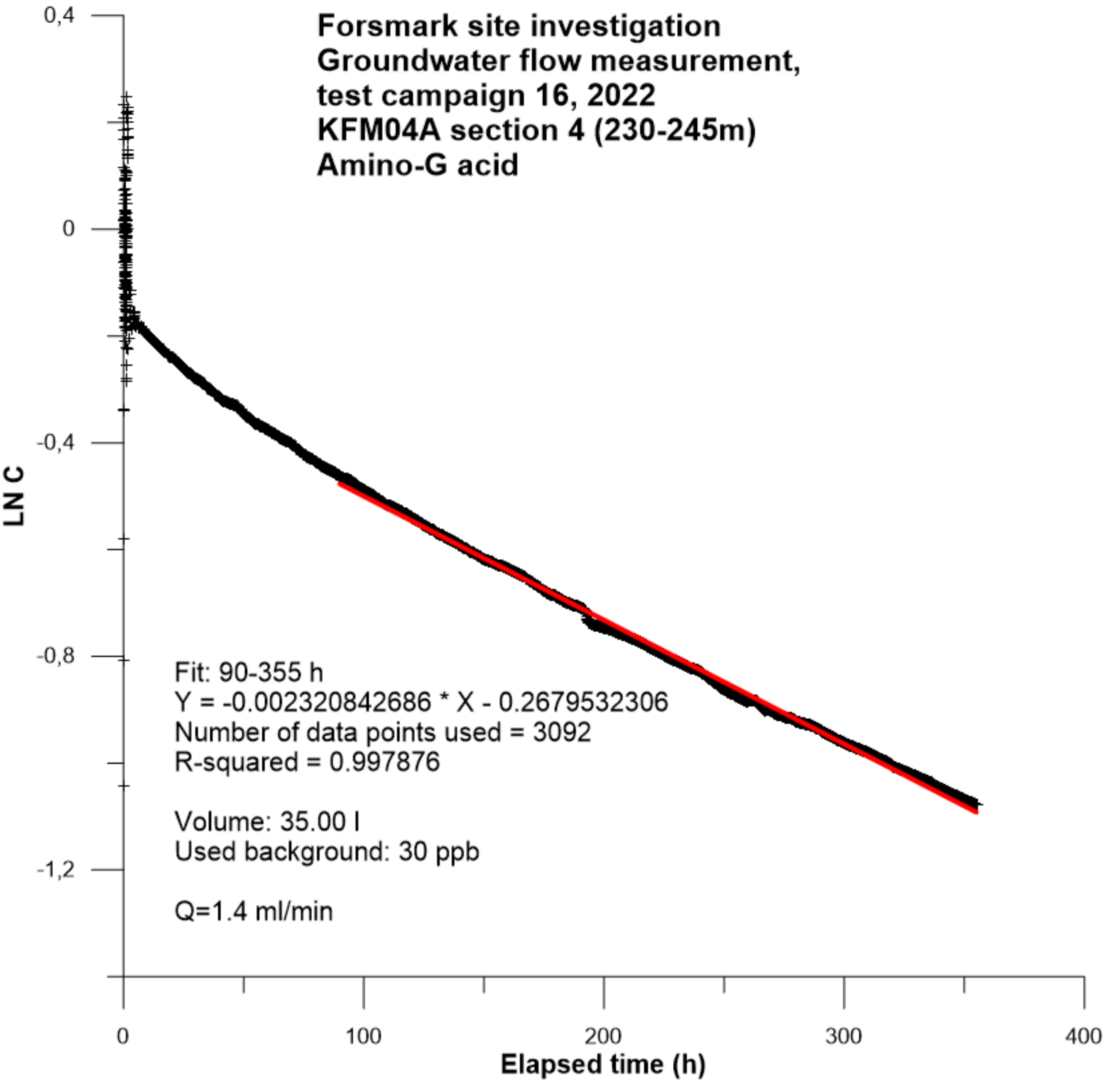
Tracer dilution graphs



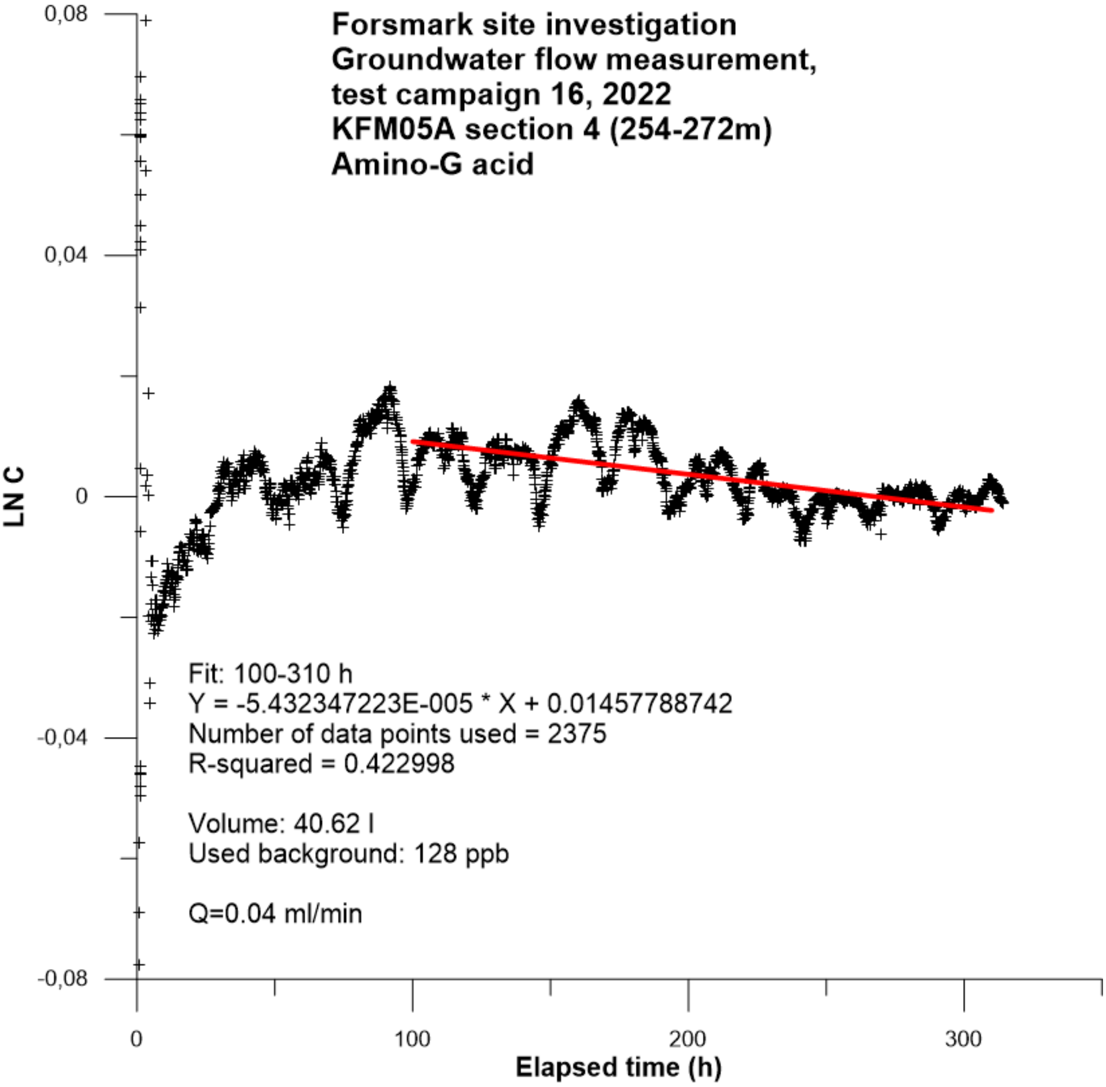

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM01D section 2 (429-438m)
Amino-G acid
Fit: 30-310 h
Y = -6.834681062E-005 * X + 0.1200692848
Number of data points used = 3258
R-squared = 0.798844
Volume: 38.33 l
Used background: 25 ppb
Q=0.04 ml/min
LN C
Elapsed time (h)
0,16
0,14
0,12
0,1
0,08
0,06
100
200
300

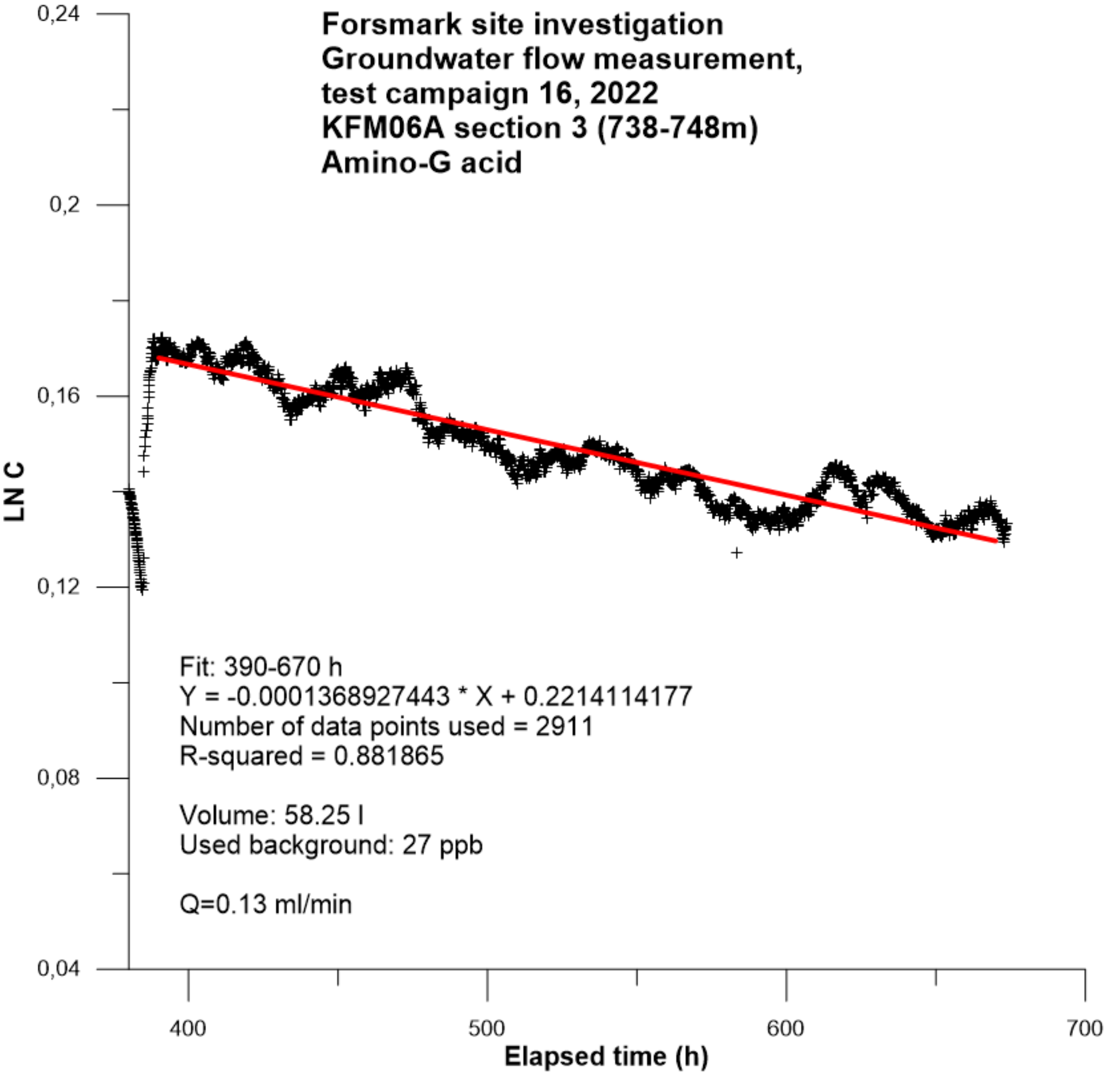

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM02A section 3 (490-518m)
Amino-G acid
Fit: 150-370 h
Y = -0.0005394200939 * X + 0.01222535578
Number of data points used = 2570
R-squared = 0.99747
Volume: 66.33 l
Used background: 26 ppb
Q=0.60 ml/min
0,2
0
-0,2
-0,4
LN C
100
200
300
400
500
Elapsed time (h)

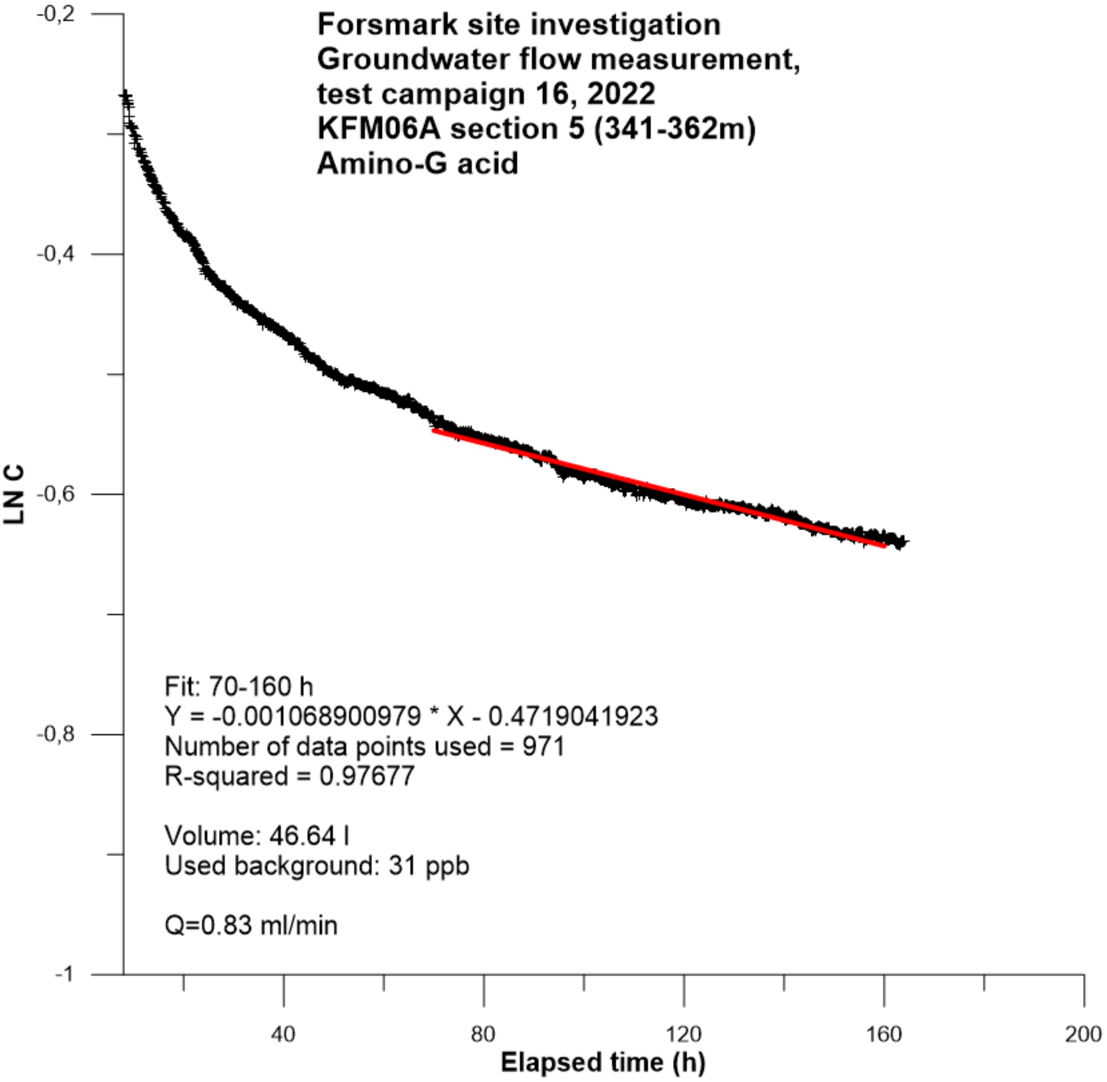

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM02A section 5 (411-442m)
Amino-G acid
Fit: 90-168 h
Y = -0.0005587605627 * X + 0.1771121761
Number of data points used = 770
R-squared = 0.978405
Volume: 60.78 l
Used background: 47 ppb
Q=0.57 ml/min
LN C
0,25
0,2
0,15
0,1
0,05
0
40
80
120
160
200
Elapsed time (h)

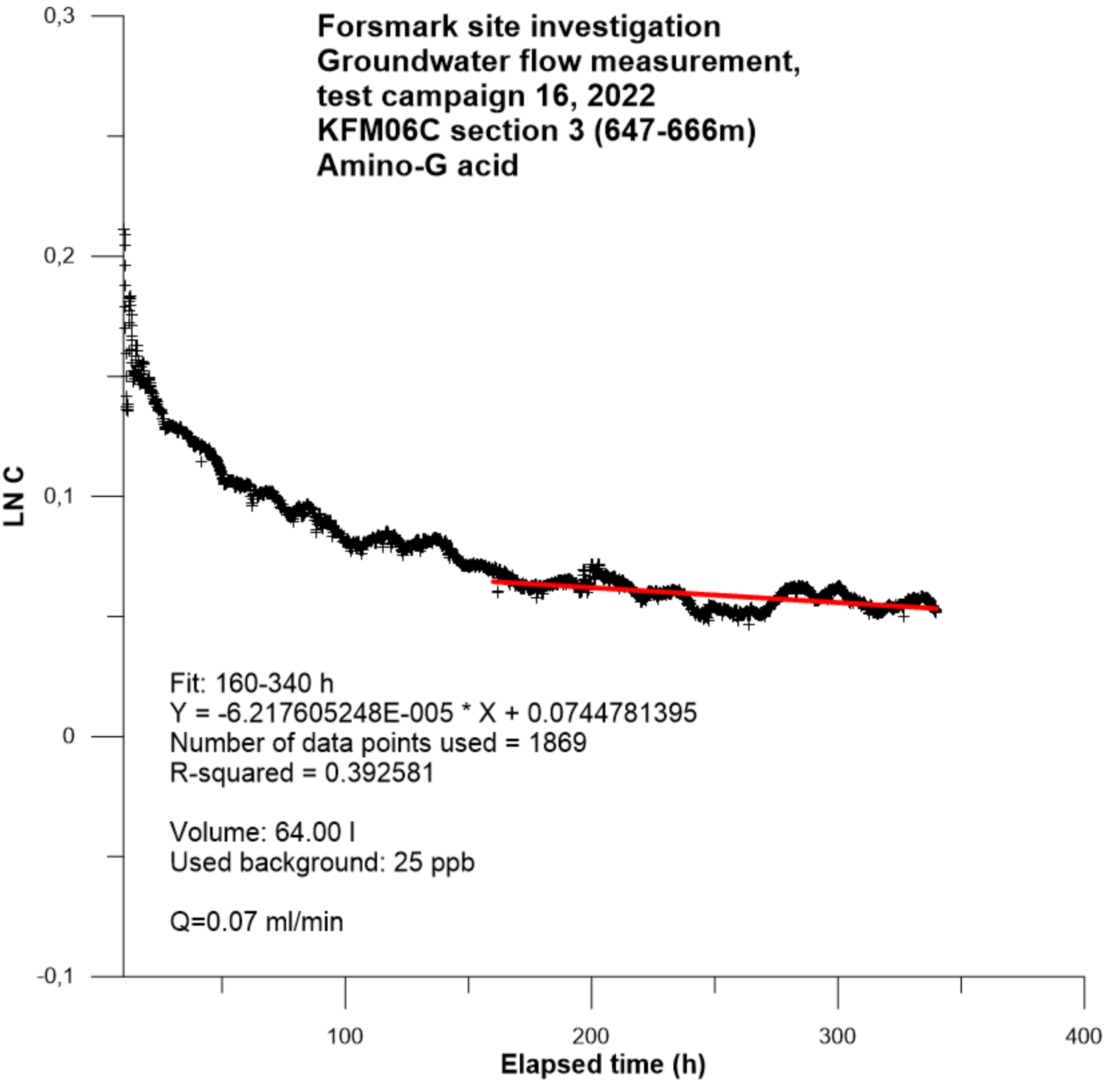


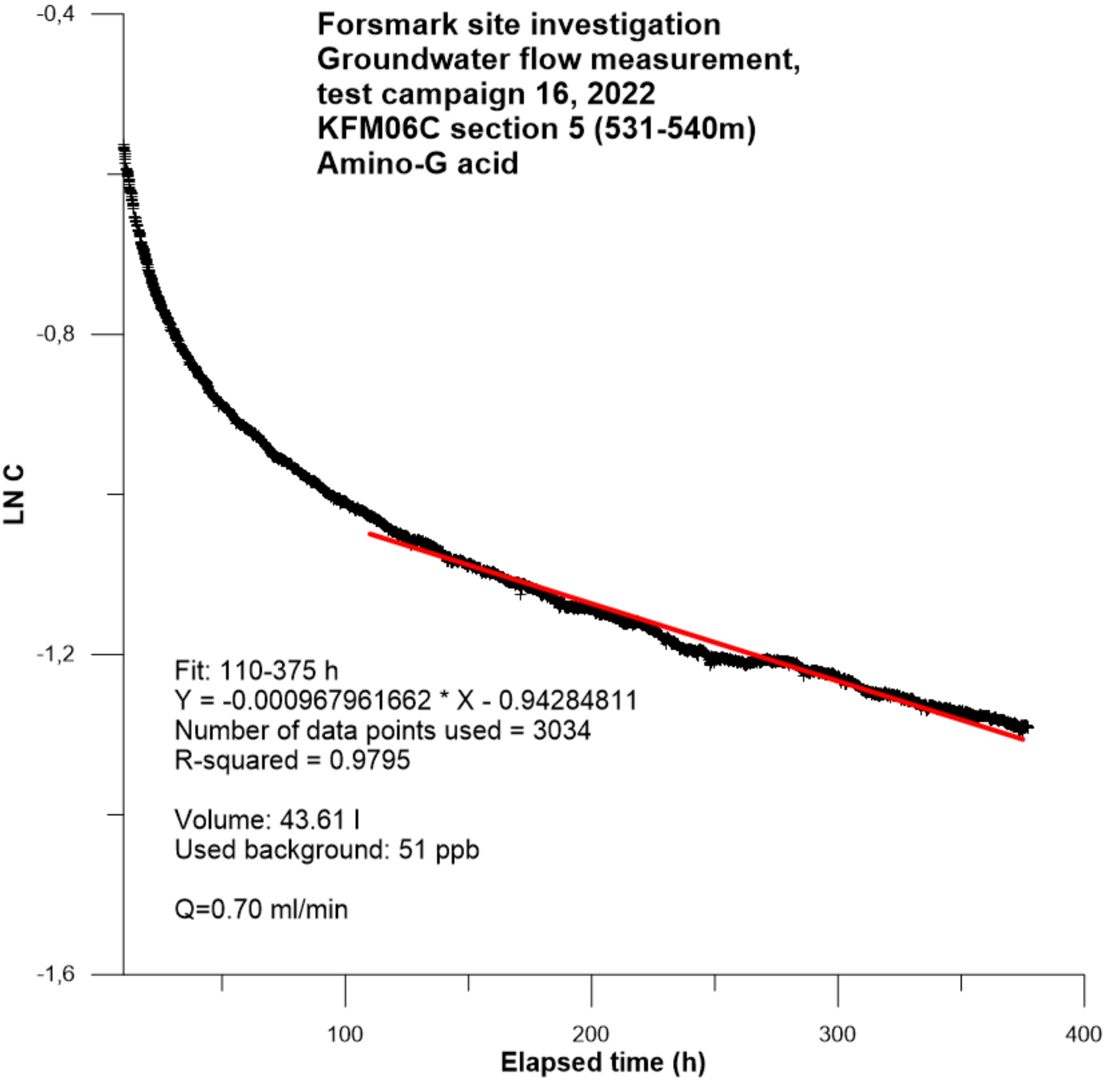
Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM04A section 4 (230-245m)
Amino-G acid
0,4
0
-0,4
-0,8
-1,2
LN C
Fit: 90-355 h
Y = -0.002320842686 * X - 0.2679532306
Number of data points used = 3092
R-squared = 0.997876
Volume: 35.00 l
Used background: 30 ppb
Q=1.4 ml/min
0
100
200
300
400
Elapsed time (h)

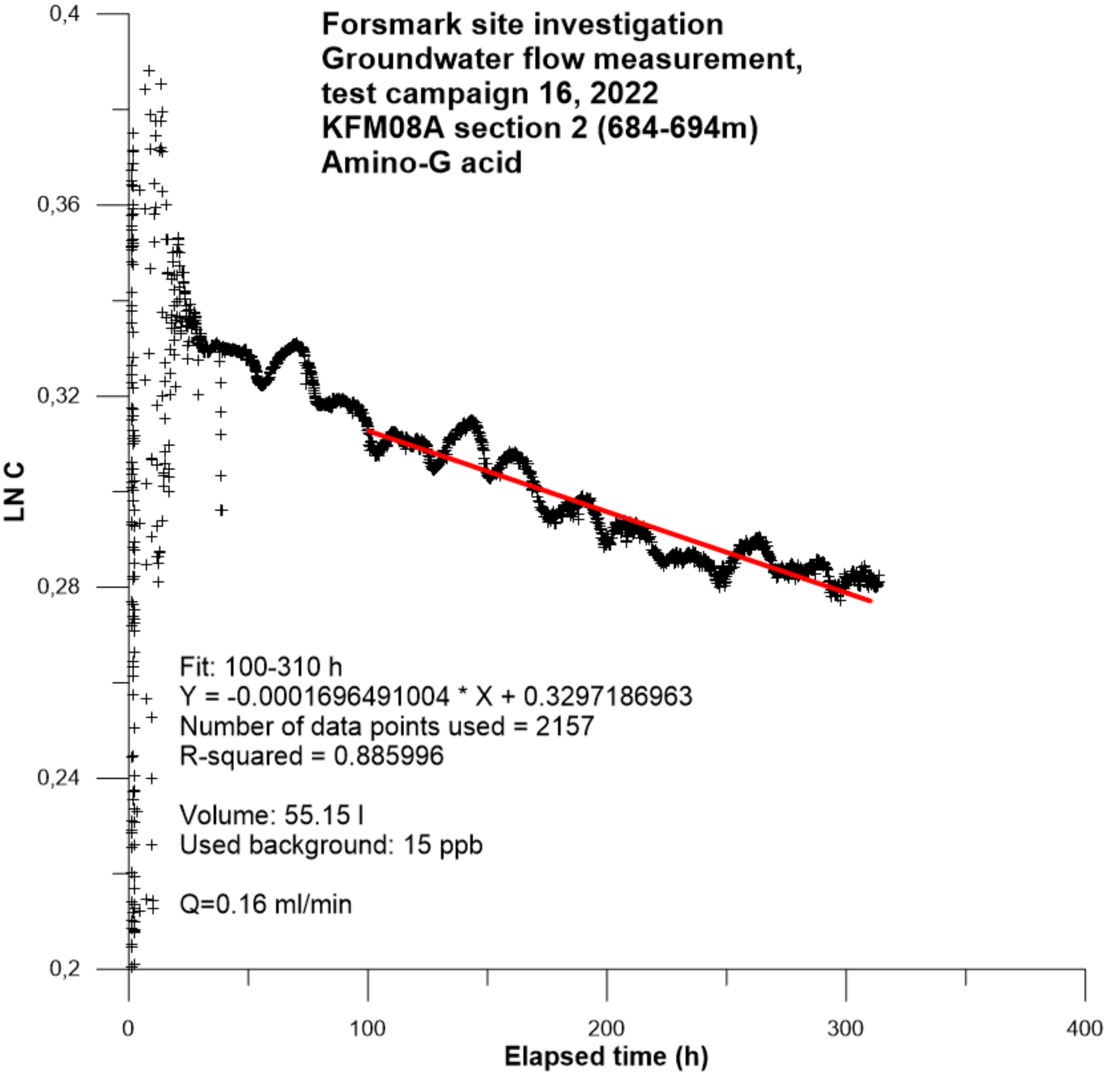

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM05A section 4 (254-272m)
Amino-G acid
0,08
0,04
0
-0,04
-0,08
LN C
Fit: 100-310 h
Y = -5.432347223E-005 * X + 0.01457788742
Number of data points used = 2375
R-squared = 0.422998
Volume: 40.62 l
Used background: 128 ppb
Q=0.04 ml/min
0
100
200
300
Elapsed time (h)

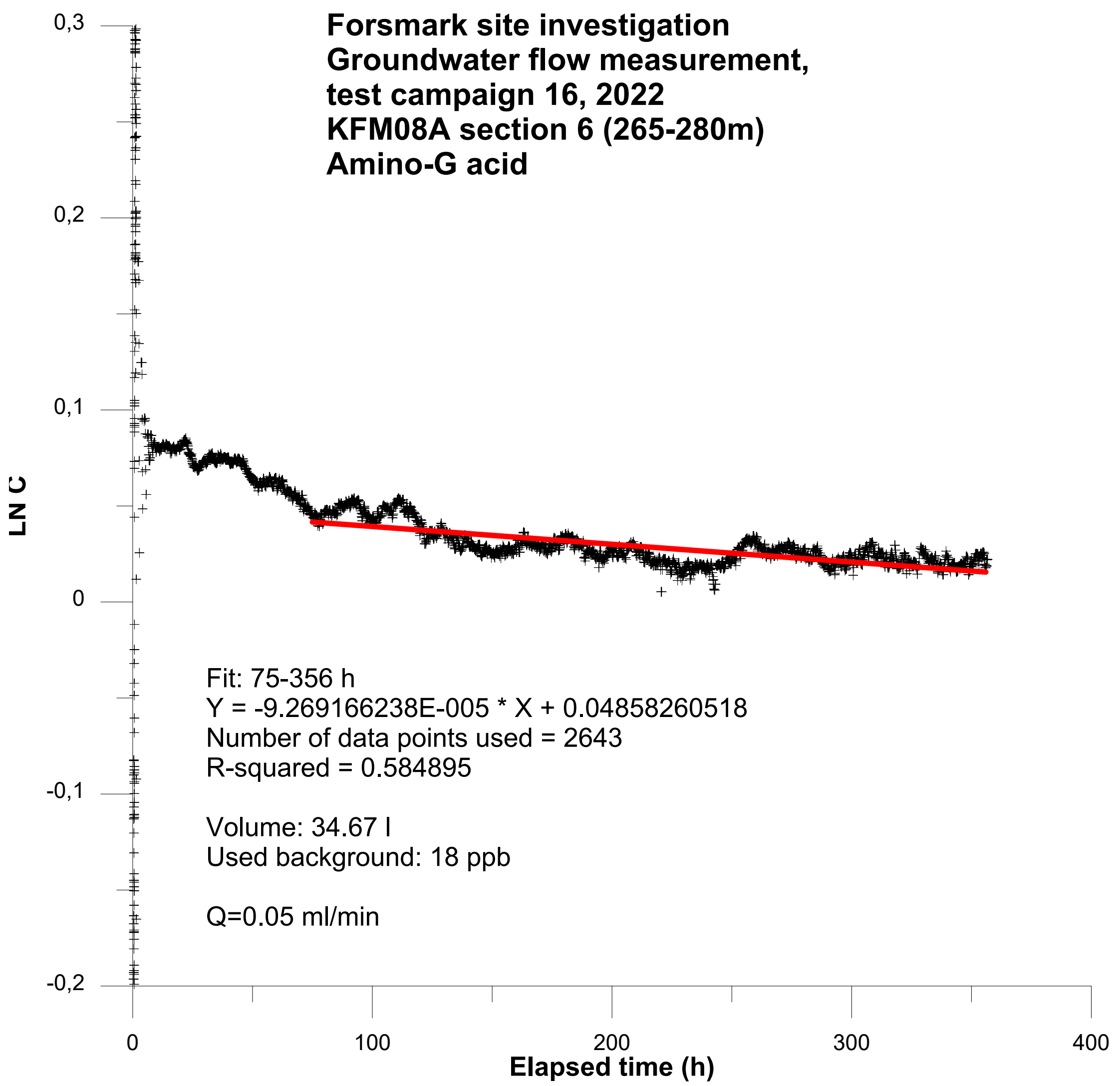

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM06A section 3 (738-748m)
Amino-G acid
Fit: 390-670 h
Y = -0.0001368927443 * X + 0.2214114177
Number of data points used = 2911
R-squared = 0.881865
Volume: 58.25 l
Used background: 27 ppb
Q=0.13 ml/min
LN C
0,24
0,2
0,16
0,12
0,08
0,04
400
500
600
700
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM06A section 5 (341-362m)
Amino-G acid
Fit: 70-160 h
Y = -0.001068900979 * X - 0.4719041923
Number of data points used = 971
R-squared = 0.97677
Volume: 46.64 l
Used background: 31 ppb
Q=0.83 ml/min
LN C
-0,2
-0,4
-0,6
-0,8
-1
40
80
120
160
200
Elapsed time (h)

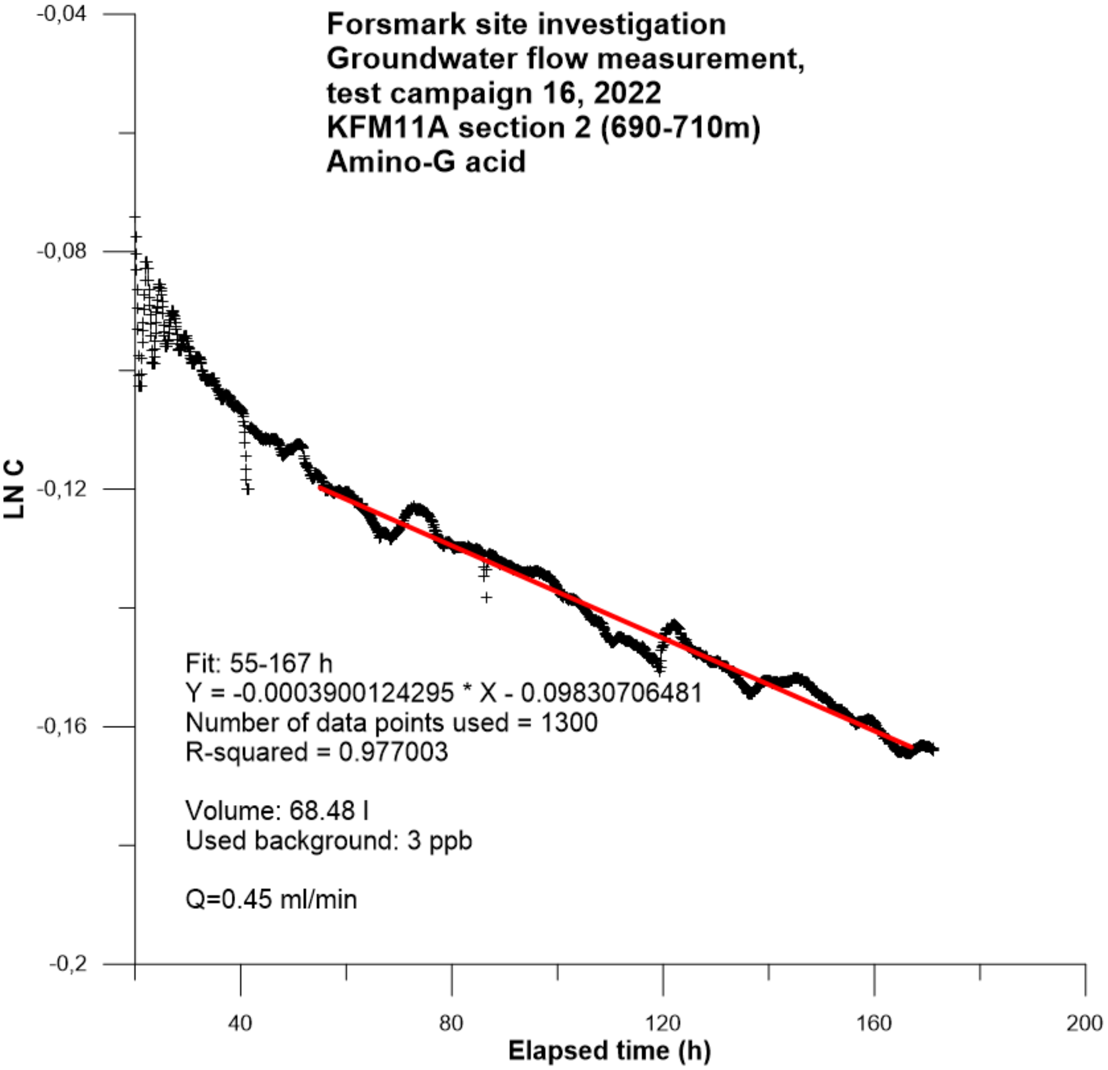

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM06C section 3 (647-666m)
Amino-G acid
Fit: 160-340 h
Y = -6.217605248E-005 * X + 0.0744781395
Number of data points used = 1869
R-squared = 0.392581
Volume: 64.00 l
Used background: 25 ppb
Q=0.07 ml/min
LN C
Elapsed time (h)
0,3
0,2
0,1
0
-0,1
100
200
300
400


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM06C section 5 (531-540m)
Amino-G acid
Fit: 110-375 h
Y = -0.000967961662 * X - 0.94284811
Number of data points used = 3034
R-squared = 0.9795
Volume: 43.61 l
Used background: 51 ppb
Q=0.70 ml/min
LN C
-0,4
-0,8
-1,2
-1,6
100
200
300
400
Elapsed time (h)

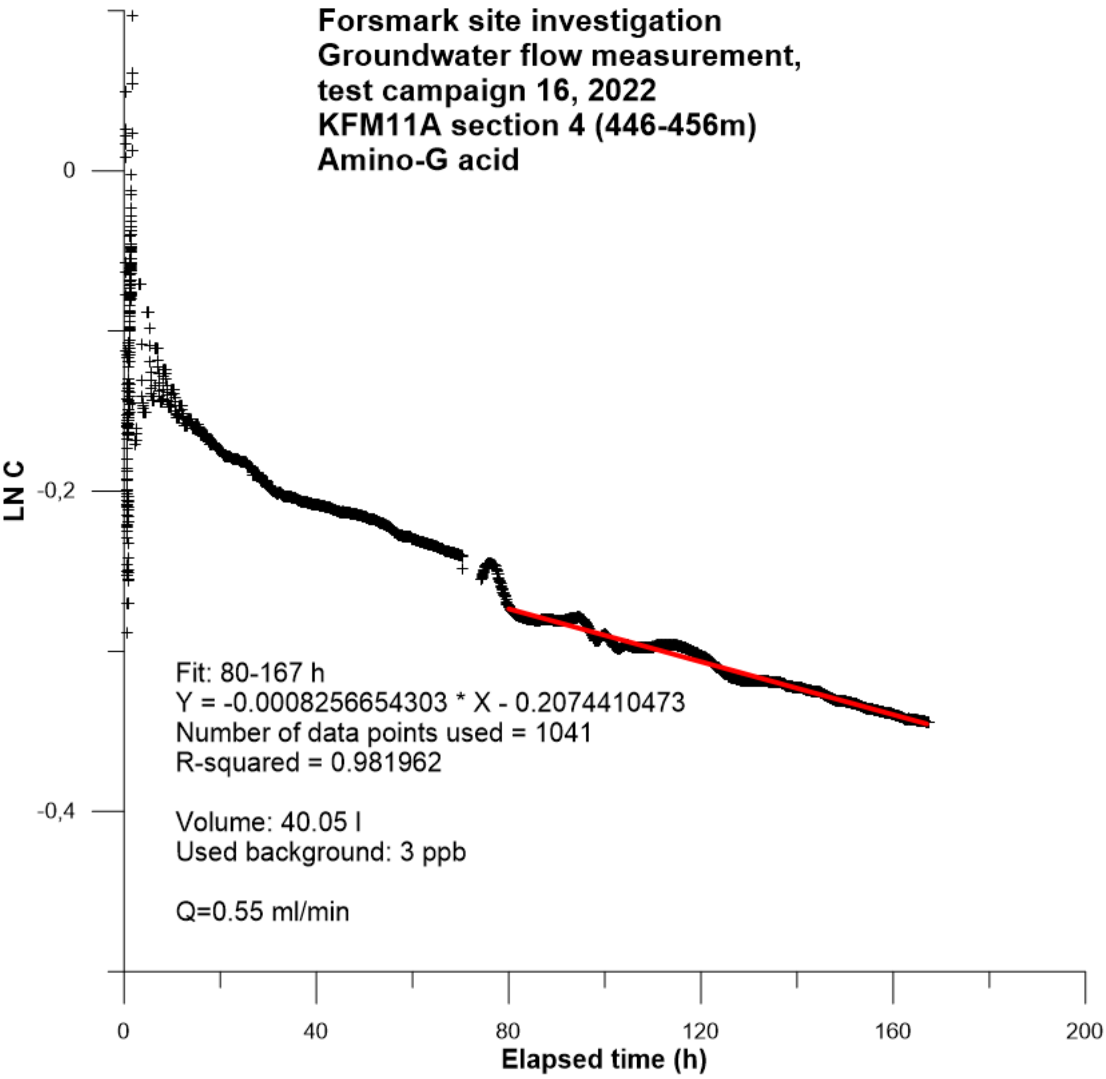

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM08A section 2 (684-694m)
Amino-G acid
Fit: 100-310 h
Y = -0.0001696491004 * X + 0.3297186963
Number of data points used = 2157
R-squared = 0.885996
Volume: 55.15 l
Used background: 15 ppb
Q=0.16 ml/min
LN C
0,4
0,36
0,32
0,28
0,24
0,2
0
100
200
300
400
Elapsed time (h)



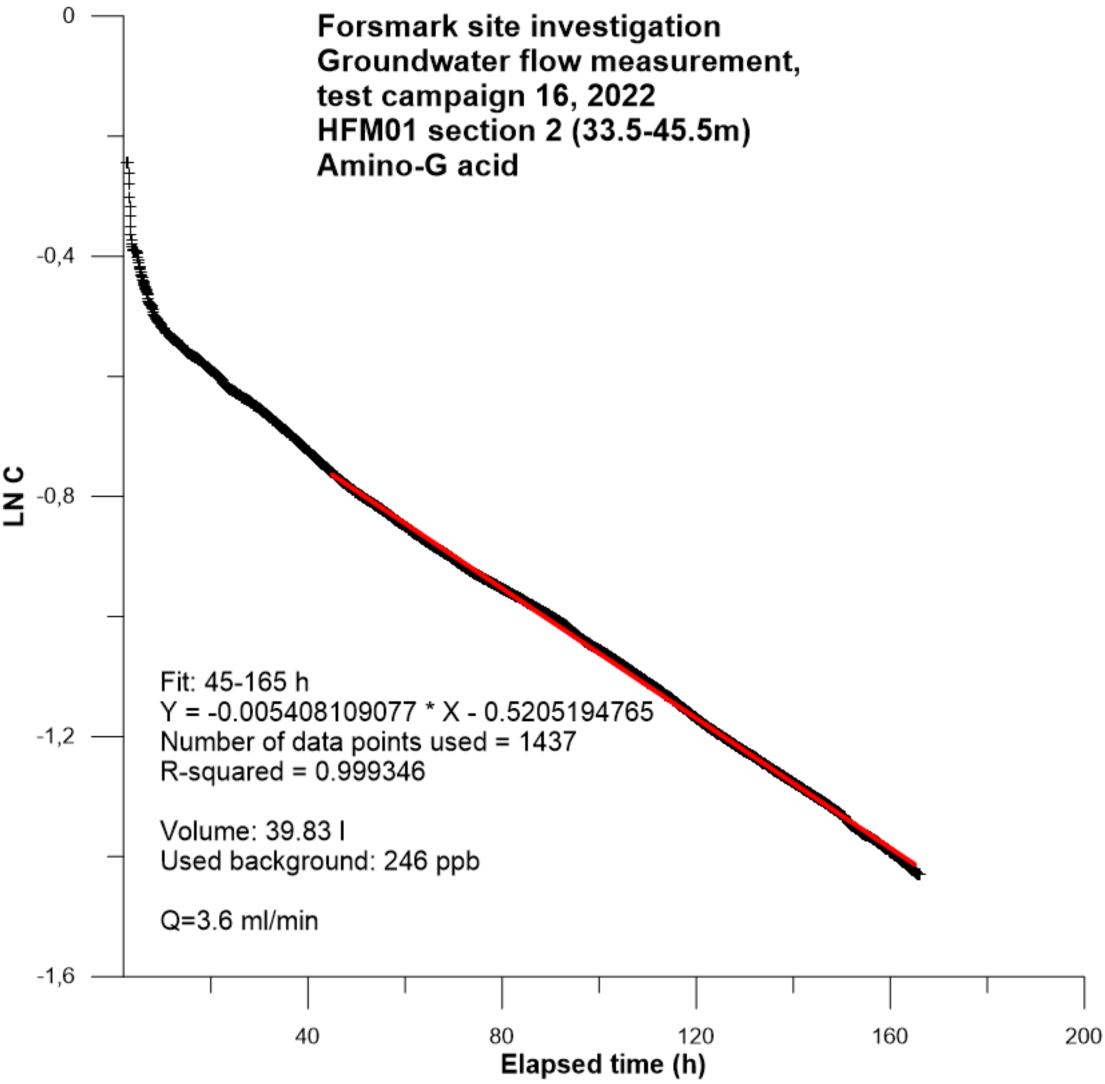
Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM08A section 6 (265-280m)
Amino-G acid
0,3
0,2
0,1
0
-0,1
-0,2
LN C
0
100
200
300
400
Elapsed time (h)
Fit: 75-356 h
Y = -9.269166238E-005 * X + 0.04858260518
Number of data points used = 2643
R-squared = 0.584895
Volume: 34.67 l
Used background: 18 ppb
Q=0.05 ml/min

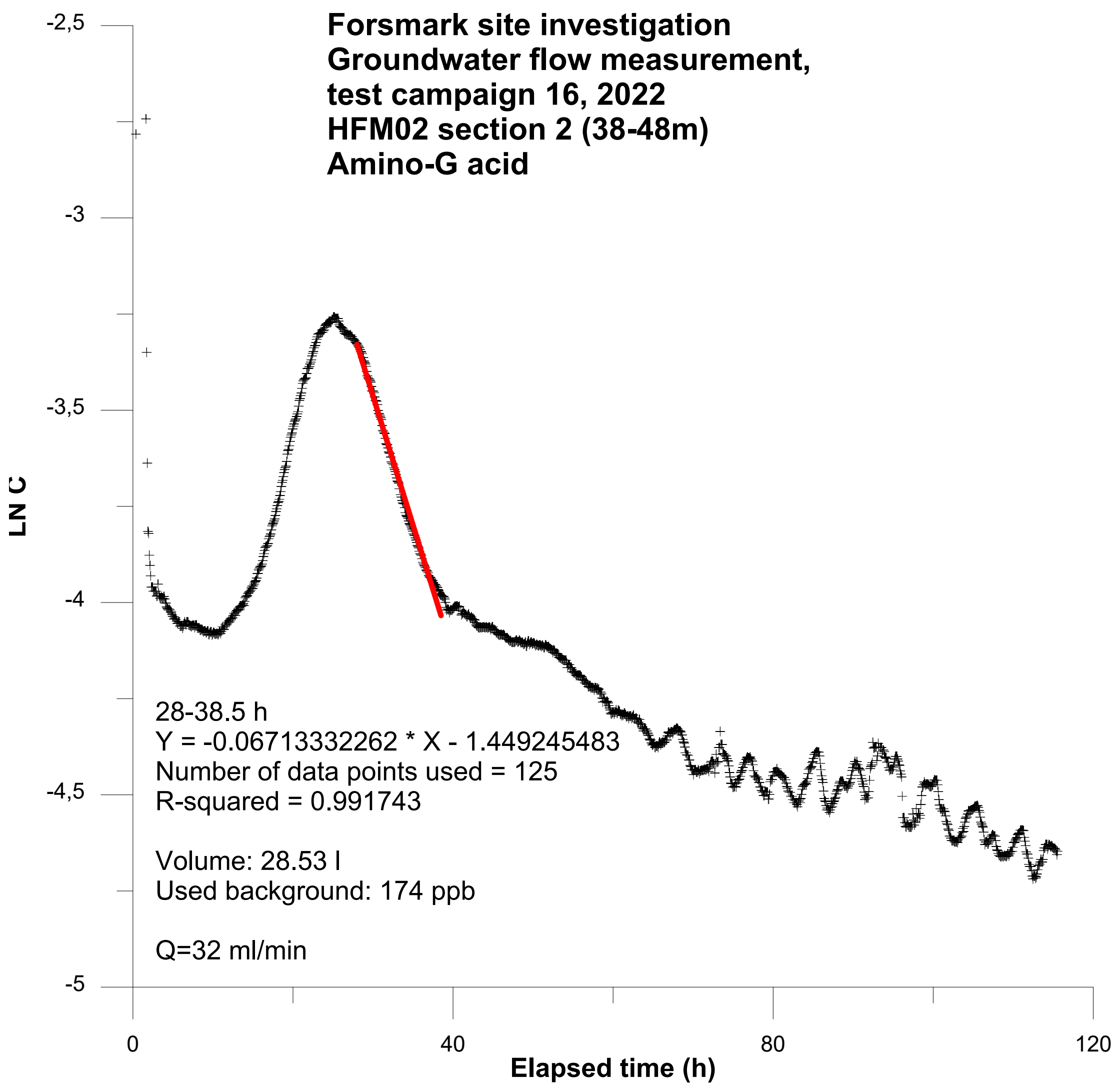


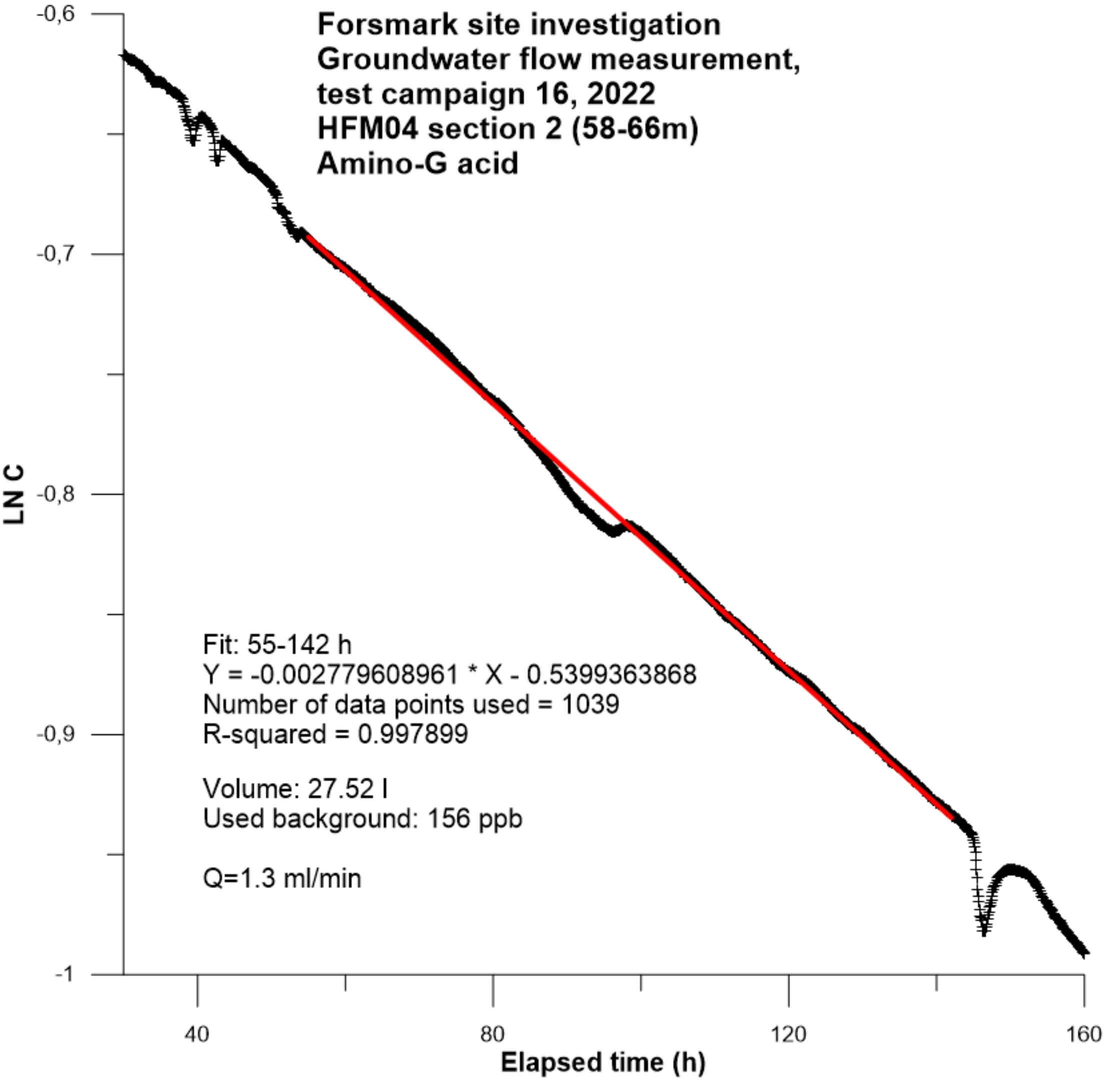
Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM11A section 2 (690-710m)
Amino-G acid
-0,04
-0,08
-0,12
-0,16
-0,2
LN C
Fit: 55-167 h
Y = -0.0003900124295 * X - 0.09830706481
Number of data points used = 1300
R-squared = 0.977003
Volume: 68.48 l
Used background: 3 ppb
Q=0.45 ml/min
40
80
120
160
200
Elapsed time (h)

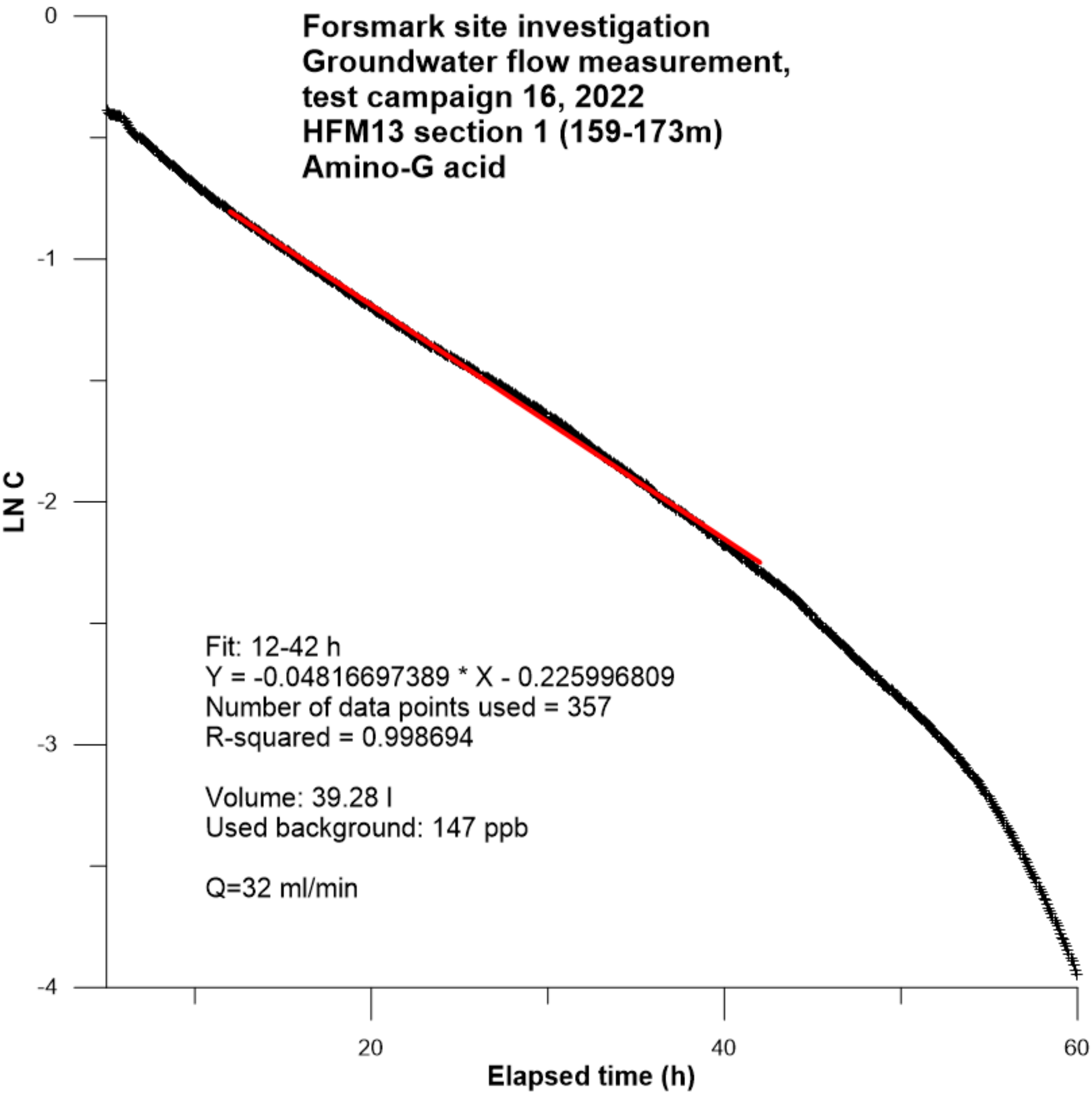


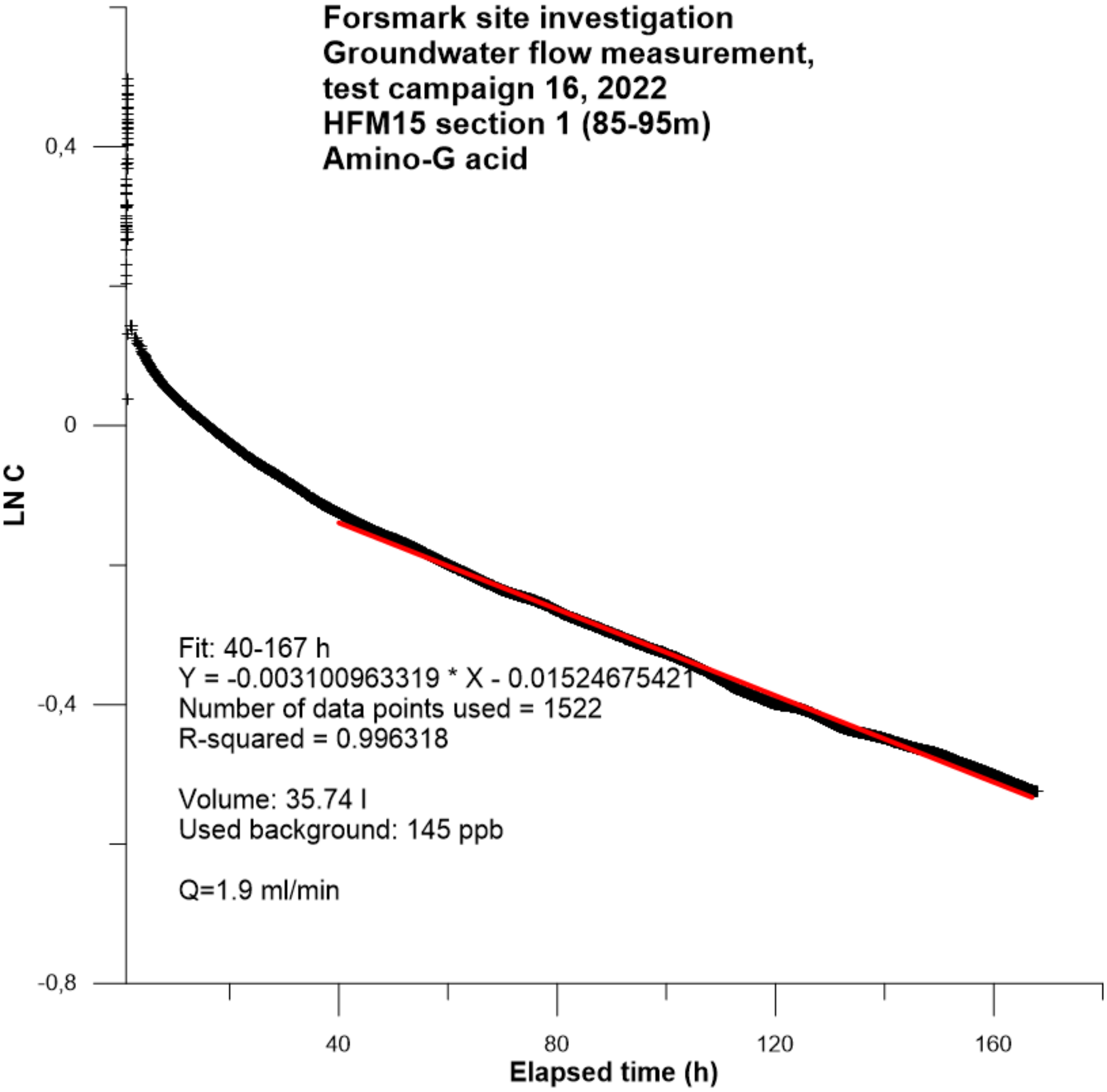
Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
KFM11A section 4 (446-456m)
Amino-G acid
LN C
0
-0,2
-0,4
Fit: 80-167 h
Y = -0.0008256654303 * X - 0.2074410473
Number of data points used = 1041
R-squared = 0.981962
Volume: 40.05 l
Used background: 3 ppb
Q=0.55 ml/min
0
40
80
120
160
200
Elapsed time (h)

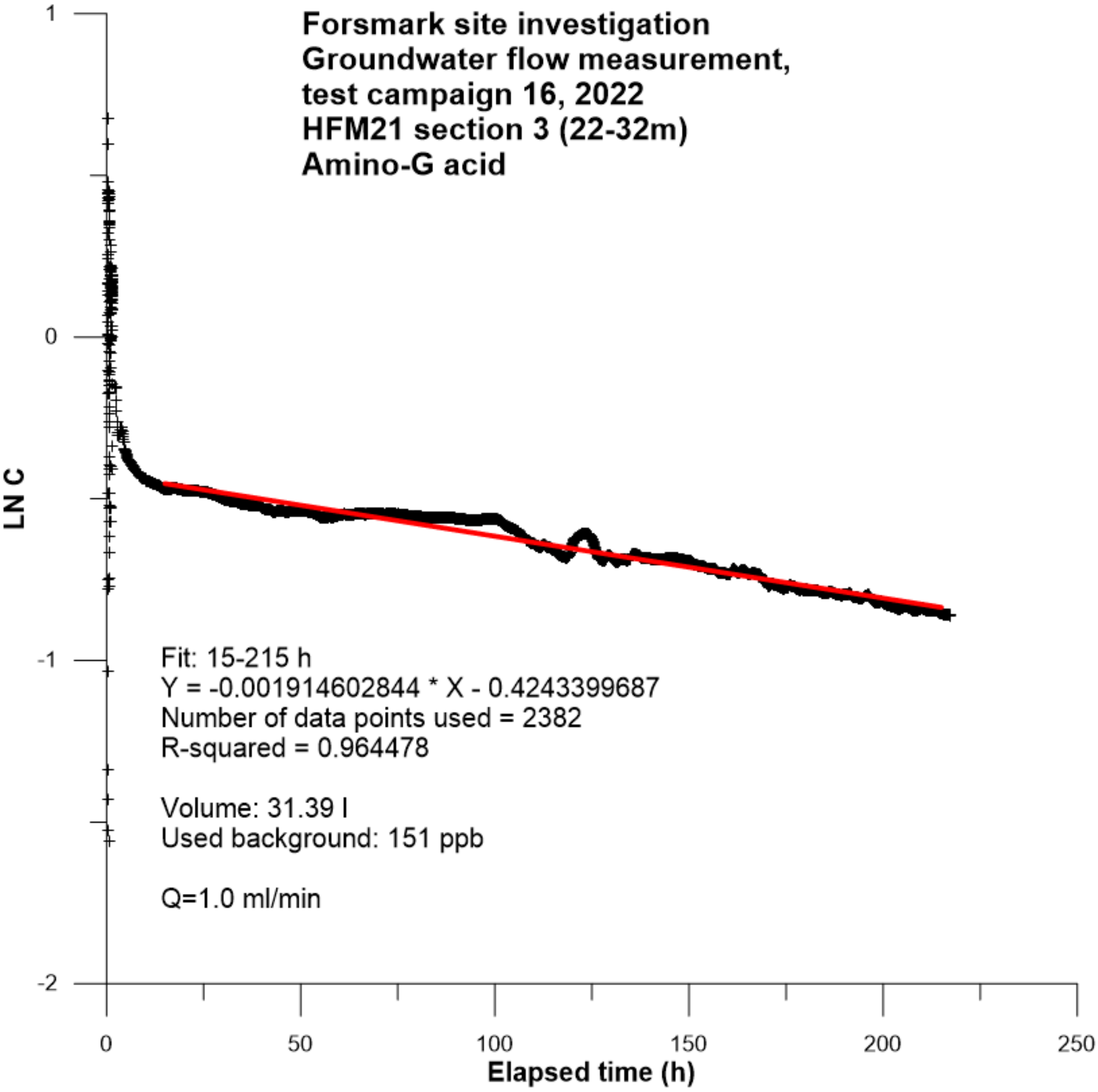

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM01 section 2 (33.5-45.5m)
Amino-G acid
Fit: 45-165 h
Y = -0.005408109077 * X - 0.5205194765
Number of data points used = 1437
R-squared = 0.999346
Volume: 39.83 l
Used background: 246 ppb
Q=3.6 ml/min
LN C
0
-0,4
-0,8
-1,2
-1,6
40
80
120
160
200
Elapsed time (h)

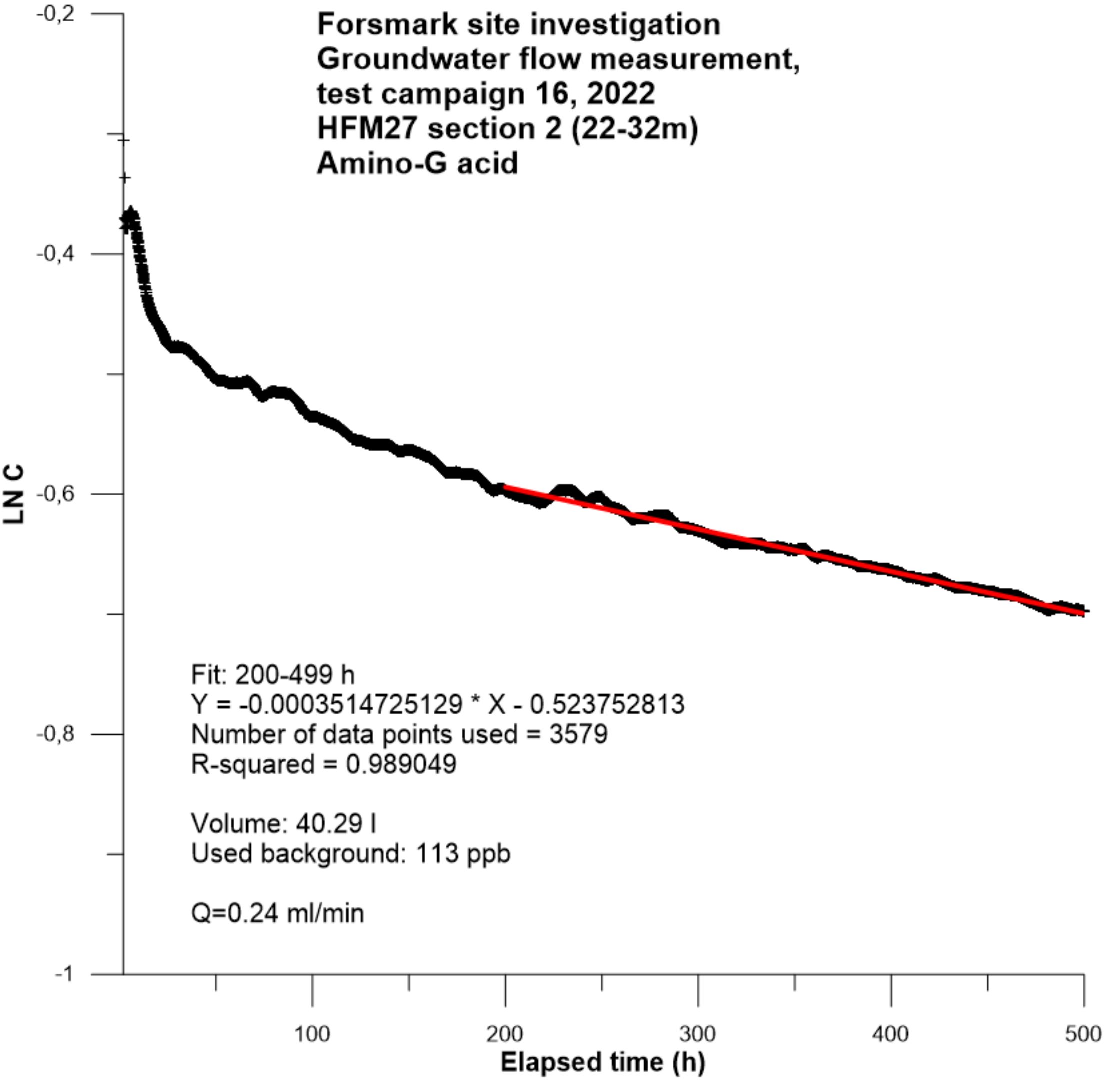

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM02 section 2 (38-48m)
Amino-G acid
-2,5
-3
-3,5
-4
-4,5
-5
LN C
28-38.5 h
Y = -0.06713332262 * X - 1.449245483
Number of data points used = 125
R-squared = 0.991743
Volume: 28.53 l
Used background: 174 ppb
Q=32 ml/min
0
40
80
120
Elapsed time (h)

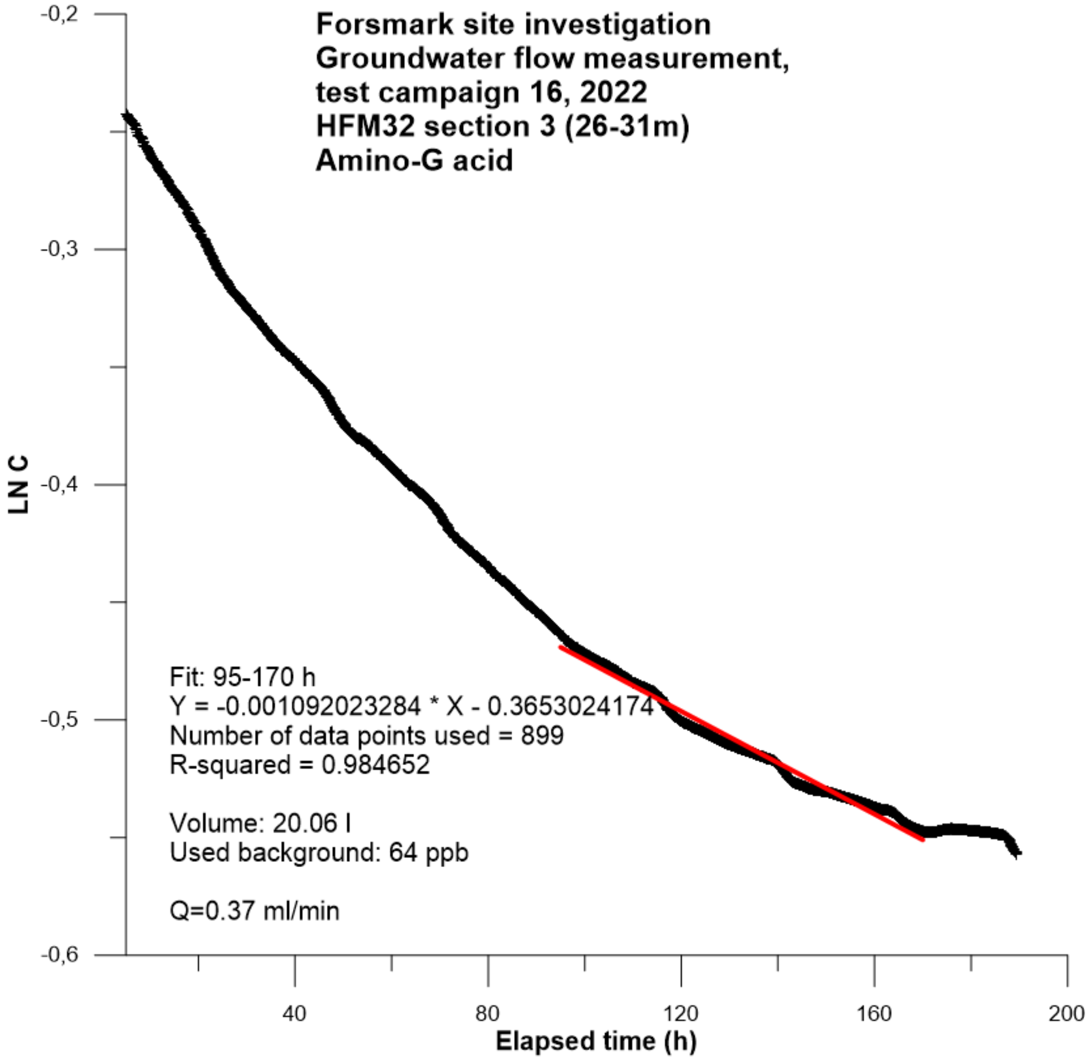

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM04 section 2 (58-66m)
Amino-G acid
Fit: 55-142 h
Y = -0.002779608961 * X - 0.5399363868
Number of data points used = 1039
R-squared = 0.997899
Volume: 27.52 l
Used background: 156 ppb
Q=1.3 ml/min
LN C
-0,6
-0,7
-0,8
-0,9
-1
40
80
120
160
Elapsed time (h)

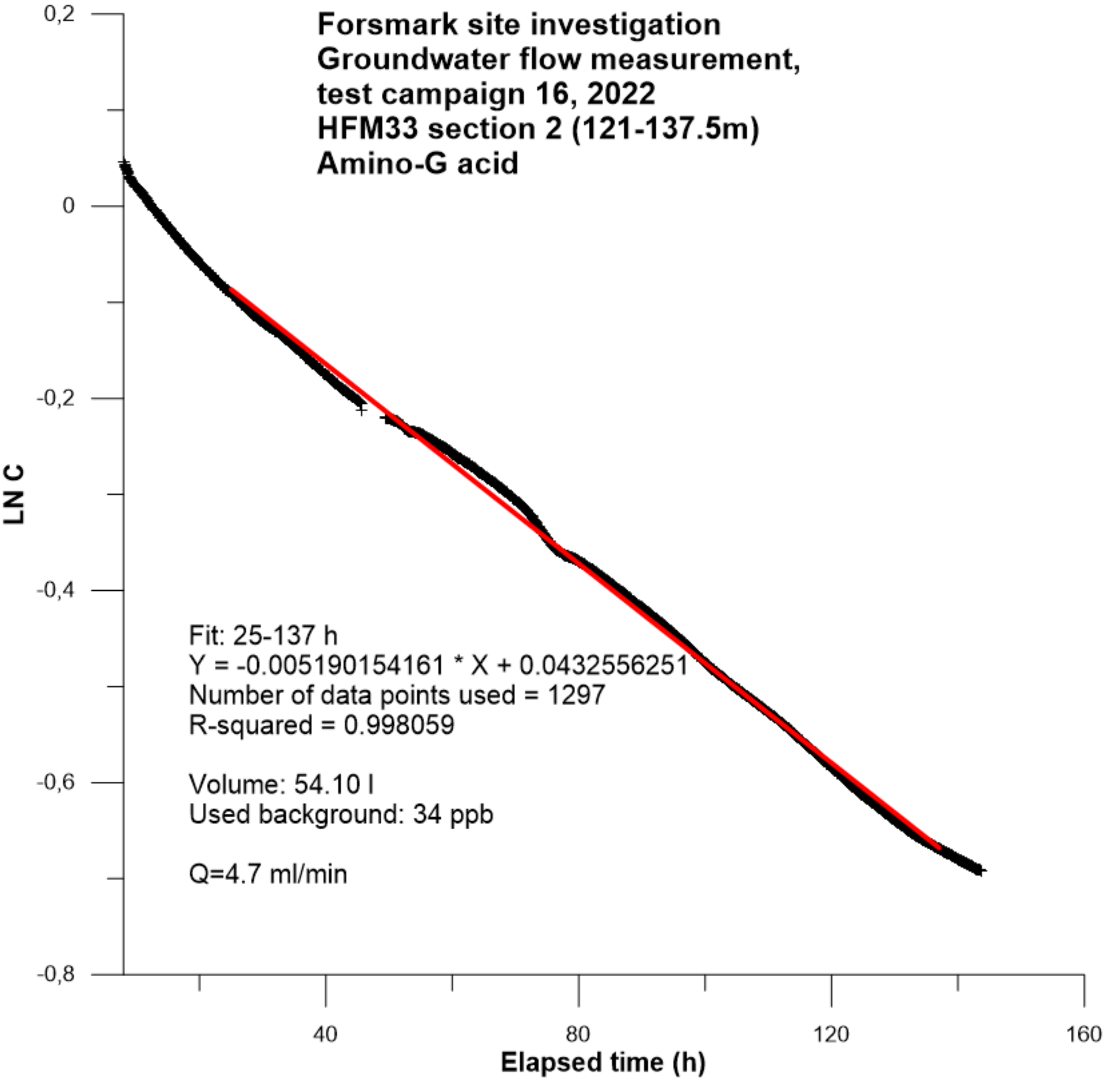

Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM13 section 1 (159-173m)
Amino-G acid
Fit: 12-42 h
Y = -0.04816697389 * X - 0.225996809
Number of data points used = 357
R-squared = 0.998694
Volume: 39.28 l
Used background: 147 ppb
Q=32 ml/min
LN C
0
-1
-2
-3
-4
20
40
60
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM15 section 1 (85-95m)
Amino-G acid
0,4
0
-0,4
-0,8
LN C
Fit: 40-167 h
Y = -0.003100963319 * X - 0.01524675421
Number of data points used = 1522
R-squared = 0.996318
Volume: 35.74 l
Used background: 145 ppb
Q=1.9 ml/min
40
80
120
160
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM21 section 3 (22-32m)
Amino-G acid
Fit: 15-215 h
Y = -0.001914602844 * X - 0.4243399687
Number of data points used = 2382
R-squared = 0.964478
Volume: 31.39 l
Used background: 151 ppb
Q=1.0 ml/min
LN C
Elapsed time (h)
1
0
-1
-2
0
50
100
150
200
250


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM27 section 2 (22-32m)
Amino-G acid
Fit: 200-499 h
Y = -0.0003514725129 * X - 0.523752813
Number of data points used = 3579
R-squared = 0.989049
Volume: 40.29 l
Used background: 113 ppb
Q=0.24 ml/min
LN C
-0,2
-0,4
-0,6
-0,8
-1
100
200
300
400
500
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM32 section 3 (26-31m)
Amino-G acid
Fit: 95-170 h
Y = -0.001092023284 * X - 0.3653024174
Number of data points used = 899
R-squared = 0.984652
Volume: 20.06 l
Used background: 64 ppb
Q=0.37 ml/min
LN C
-0,2
-0,3
-0,4
-0,5
-0,6
40
80
120
160
200
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 16, 2022
HFM33 section 2 (121-137.5m)
Amino-G acid
Fit: 25-137 h
Y = -0.005190154161 * X + 0.0432556251
Number of data points used = 1297
R-squared = 0.998059
Volume: 54.10 l
Used background: 34 ppb
Q=4.7 ml/min
LN C
0,2
0
-0,2
-0,4
-0,6
-0,8
40
80
120
160
Elapsed time (h)

Appendix 2

Precipitation (mm/24 hours) 2022-10-01 – 2022-11-20

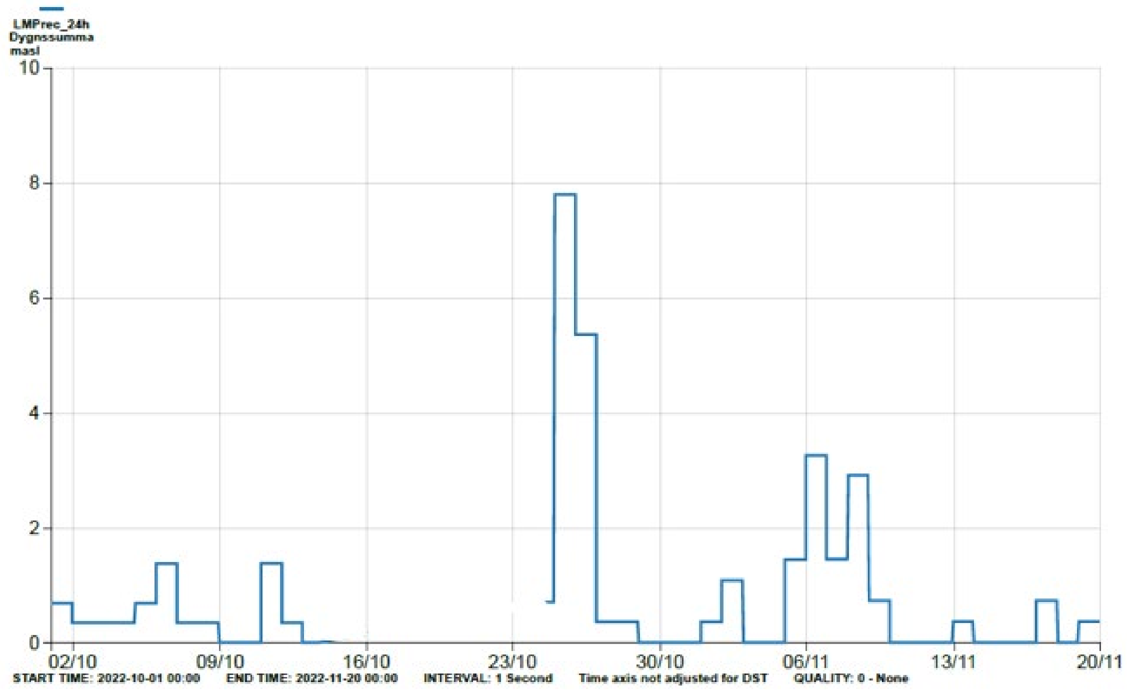


Figure A2-1. *Daily precipitation in Forsmark at the meteorological station "Labbomasten" during the field campaign, autumn 2022. Unfortunately, data are missing for the period 2022-10-14 – 23.*

Groundwater levels (m.a.s.l. RHB70) and local precipitation (mm/24 hours)

The symbols and colours representing the various borehole sections in the diagrams are:

The deepest section = section 1

section 2

section 3

section 4

section 5

section 6

section 7

section 8

section 9

section 10

Precipitation at Labbomasten

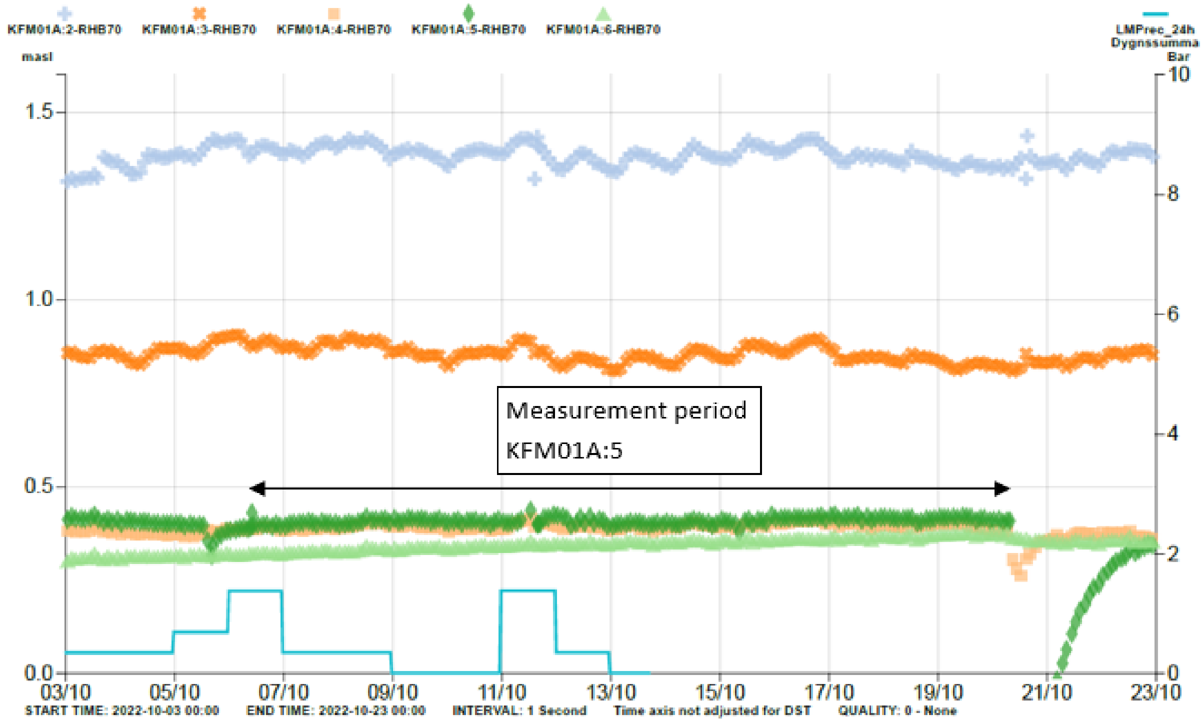


Figure A2-2. *Measured section: KFM01A:5 (dark green).*

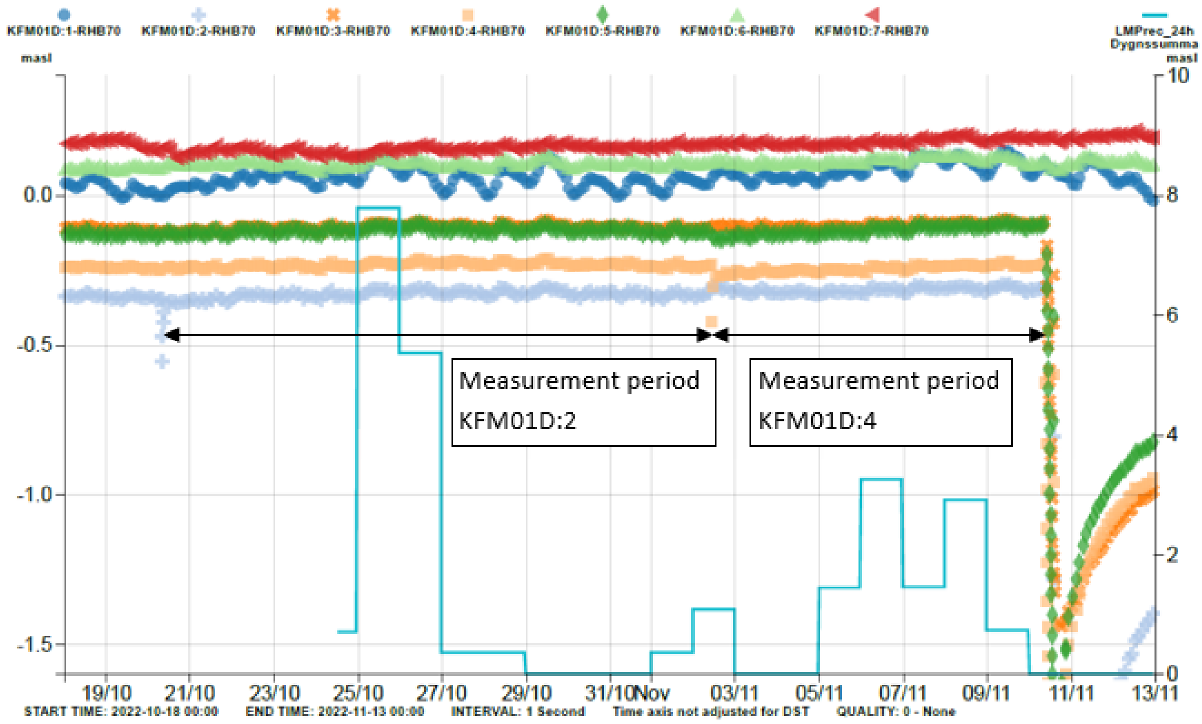


Figure A2-3. *Measured sections: KFM01D:2 (pale blue) and KFM01D:4 (pale orange).*

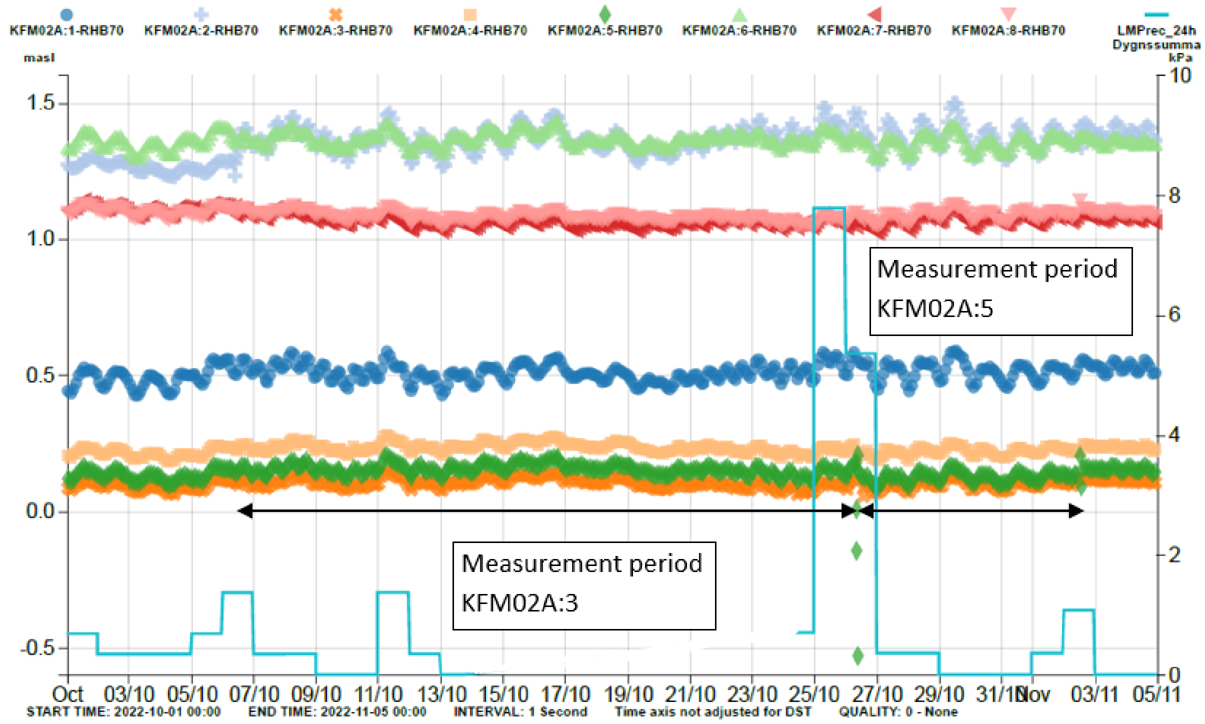


Figure A2-4. *Measured sections: KFM02A:3 (dark orange) and KFM02A:5 (dark green).*

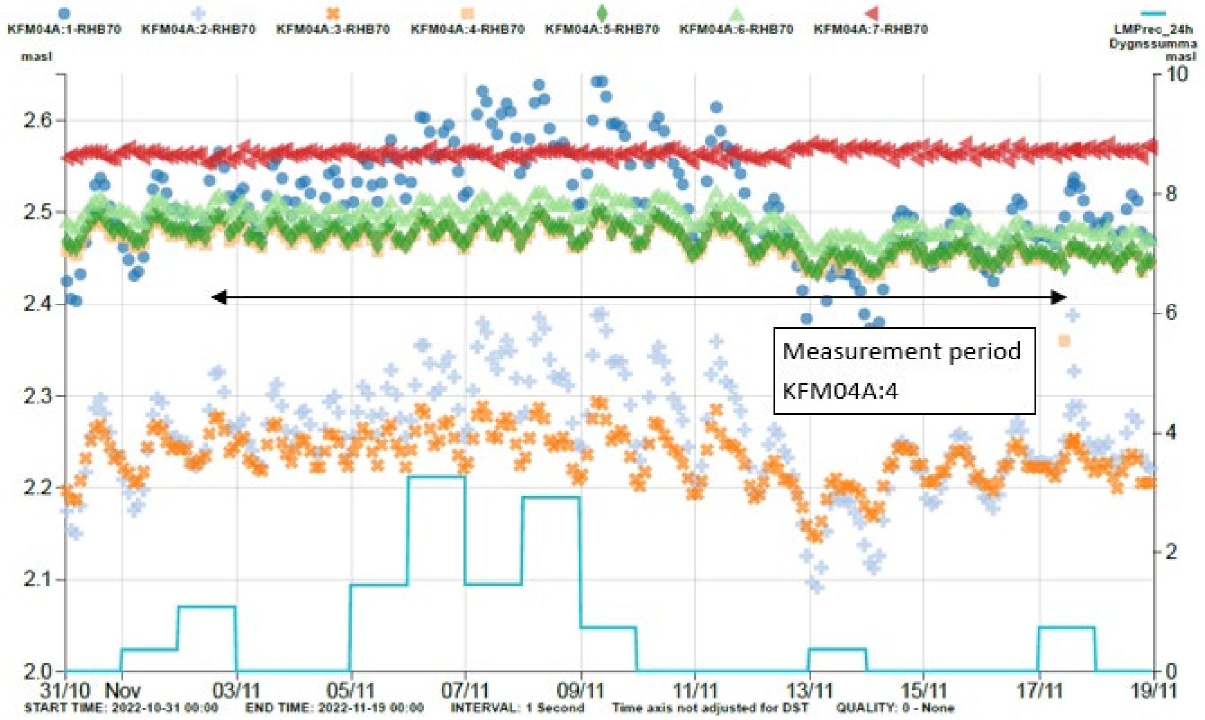


Figure A2-5. *Measured section: KFM04A:4 (pale orange, mostly hidden behind section 5, dark green).*

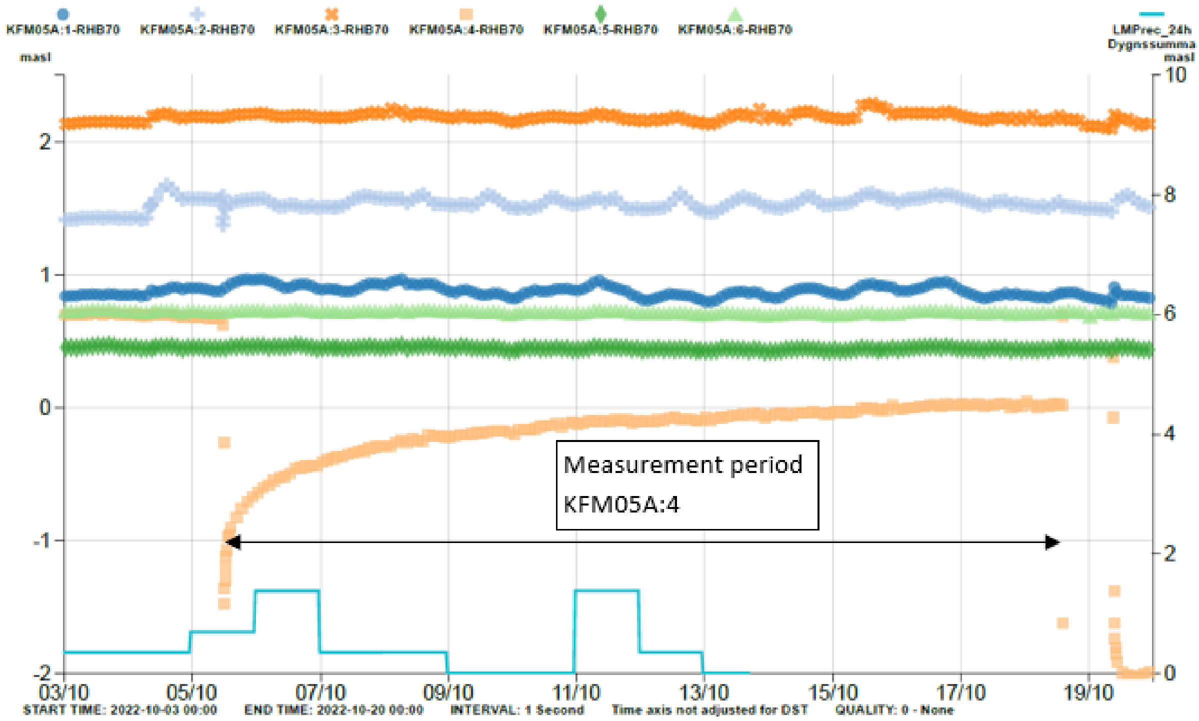


Figure A2-6. *Measured section: KFM05A:4 (pale orange).*

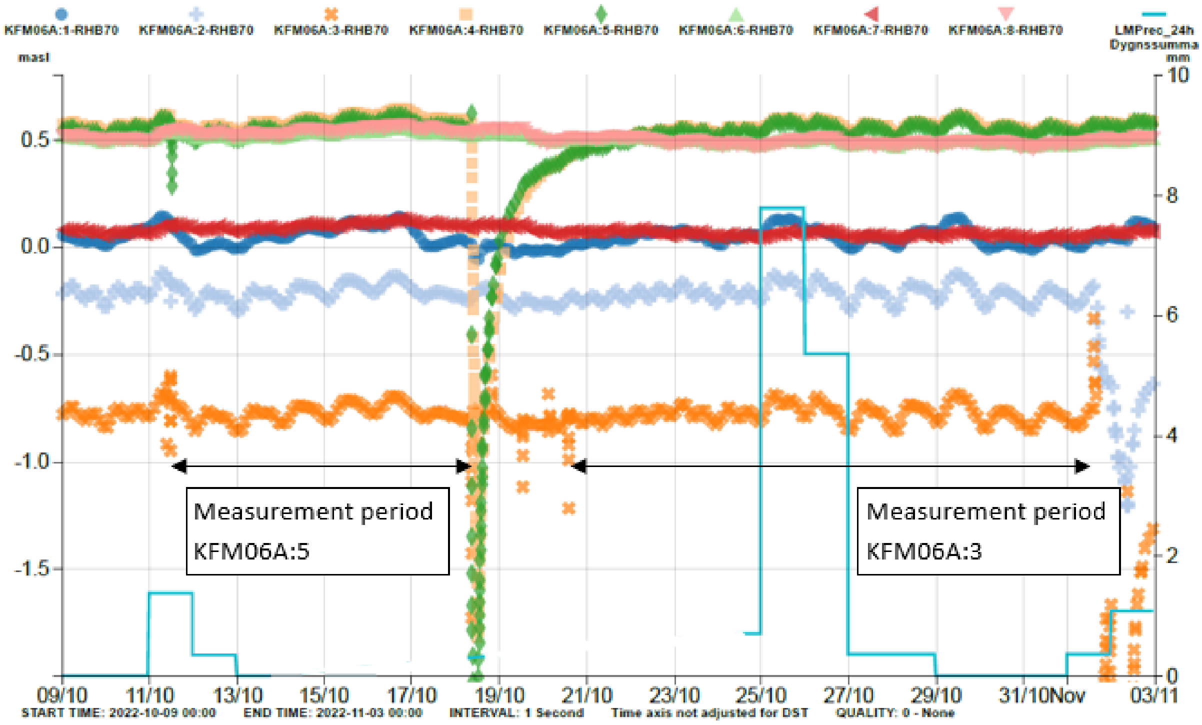


Figure A2-7. *Measured sections: KFM06A:3 (dark orange) and KFM06A:5 (dark green).*

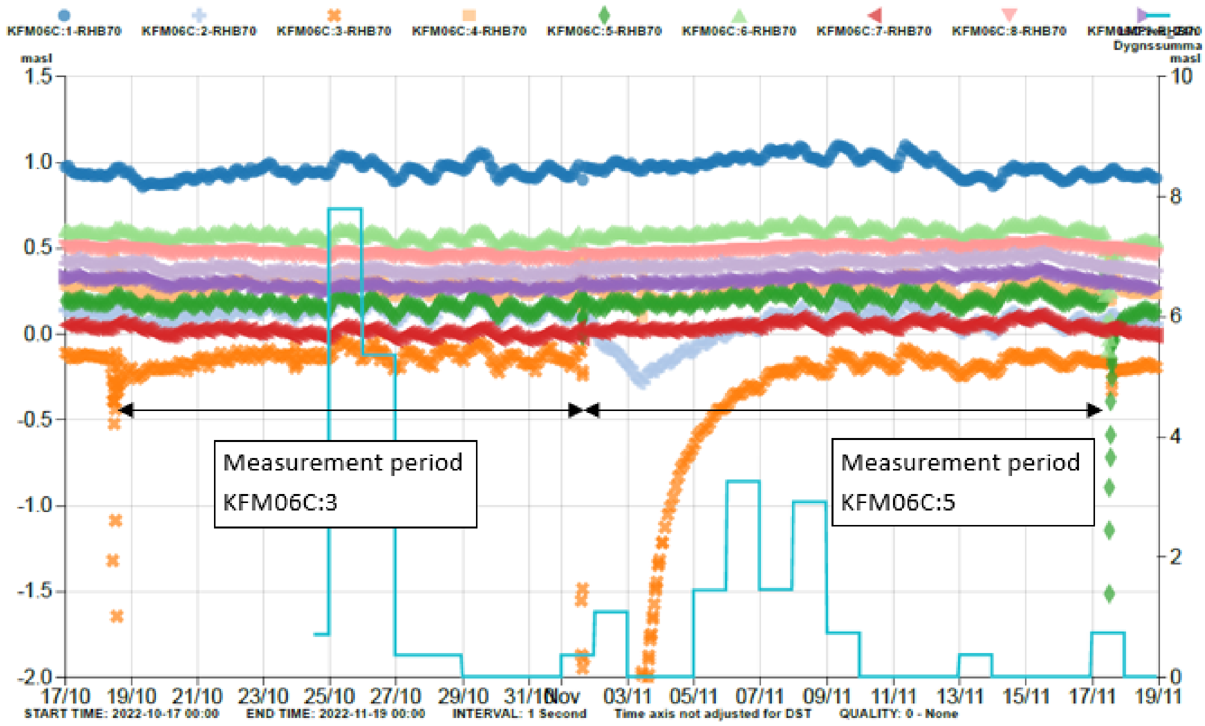


Figure A2-8. *Measured sections: KFM06C:3 (dark orange) and KFM06C:5 (dark green).*

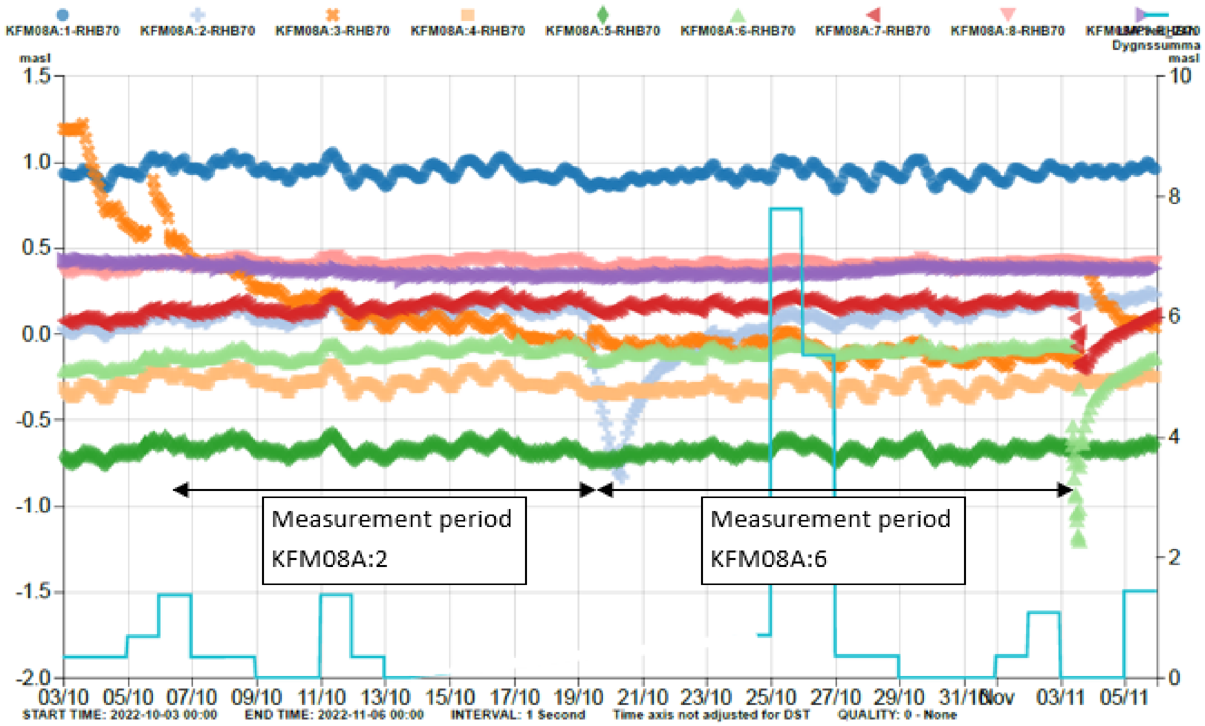


Figure A2-9. *Measured sections: KFM08A:2 (pale blue) and KFM08A:6 (pale green).*

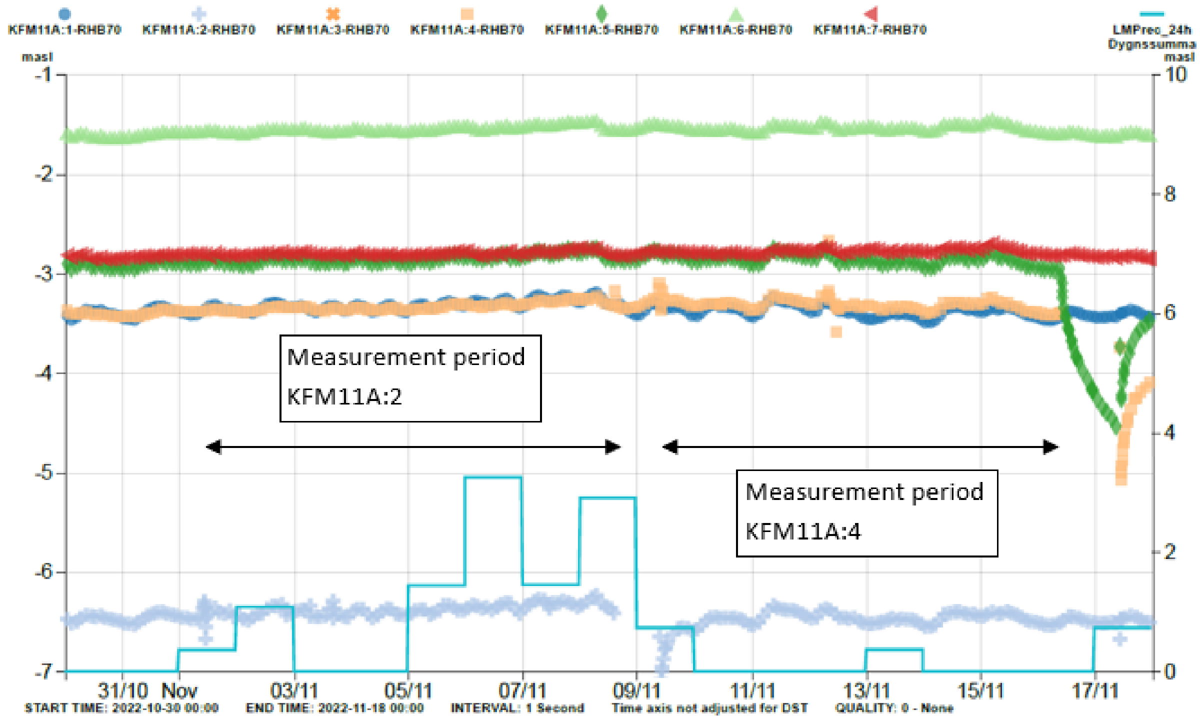


Figure A2-10. *Measured sections: KFM11A:2 (pale blue) and KFM11A:4 (pale orange).*

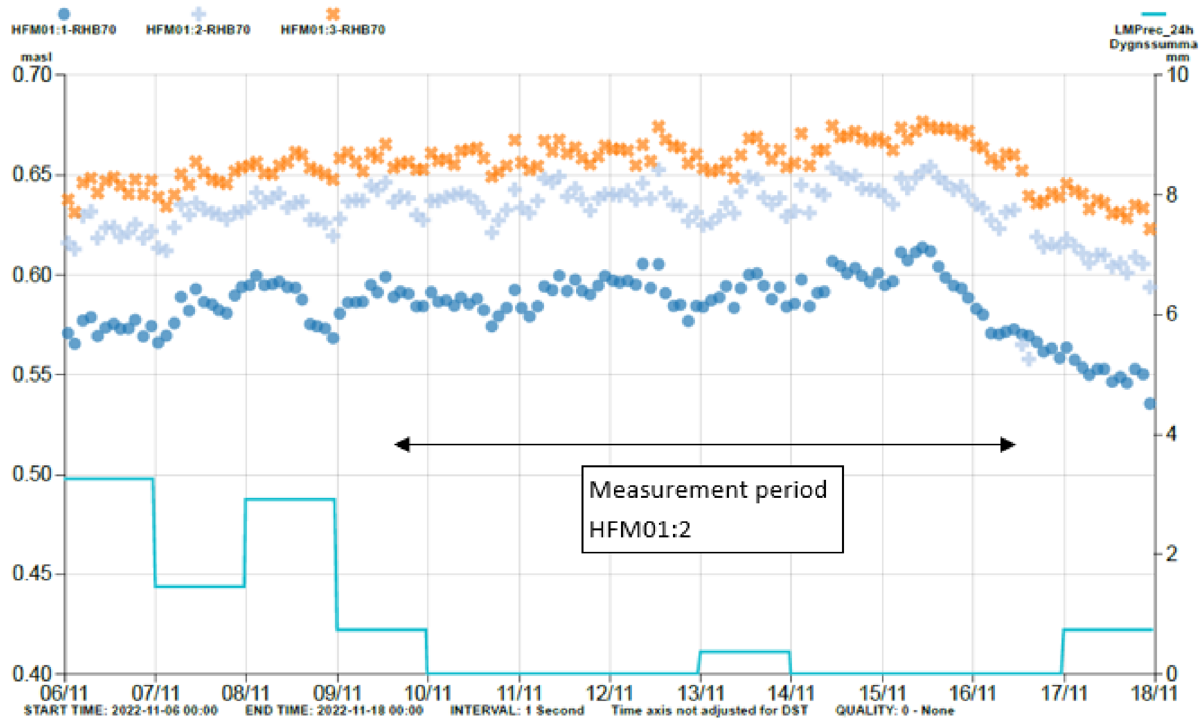


Figure A2-11. *Measured section: HFM01:2 (pale blue).*

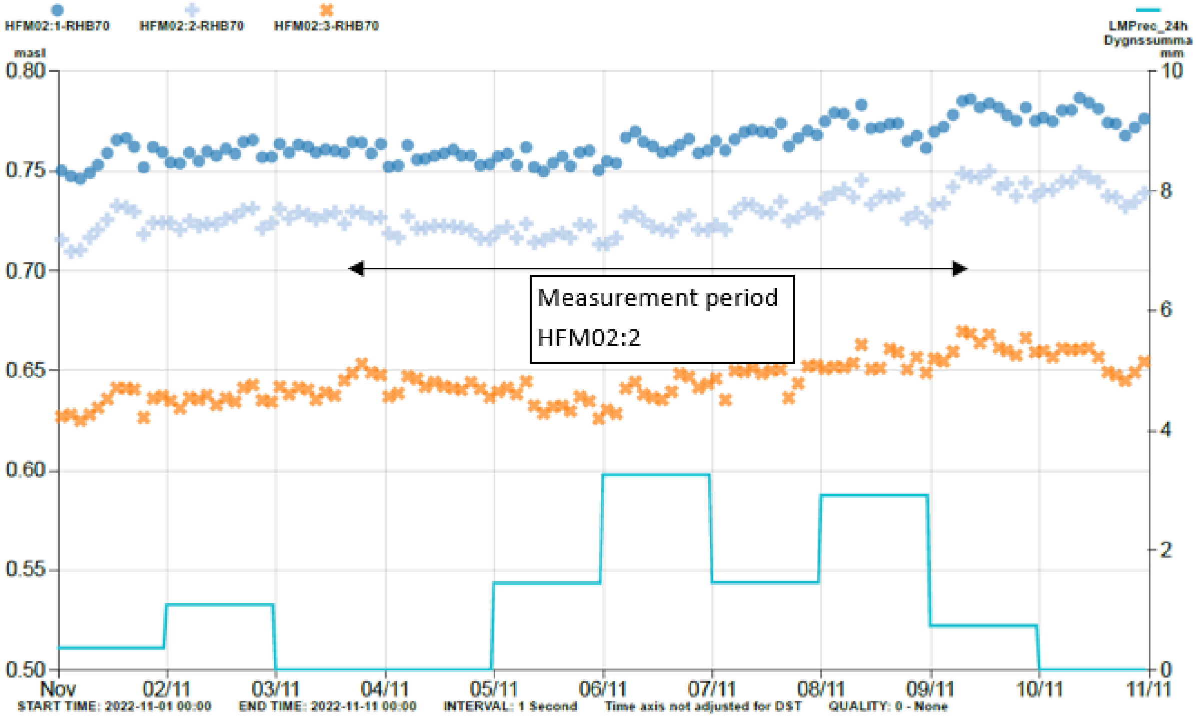


Figure A2-12. *Measured section: HFM02:2 (pale blue).*

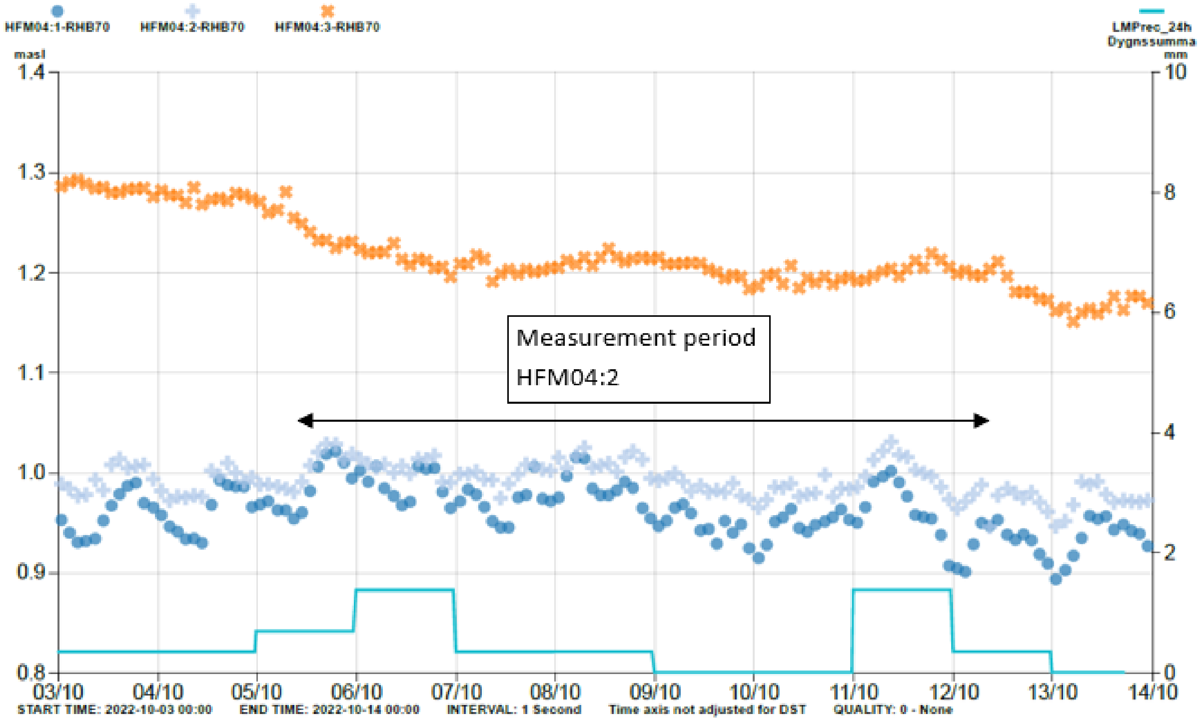


Figure A2-13. *Measured section: HFM04:2 (pale blue).*

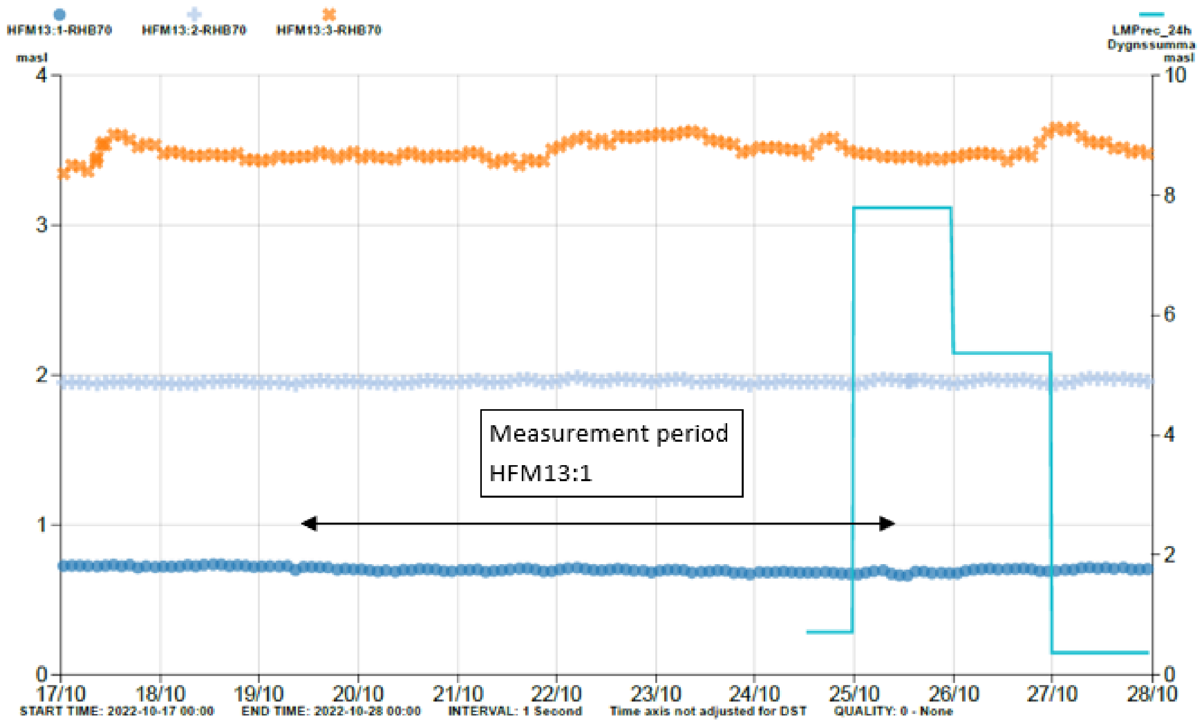


Figure A2-14. *Measured section: HFM13:1 (dark blue).*

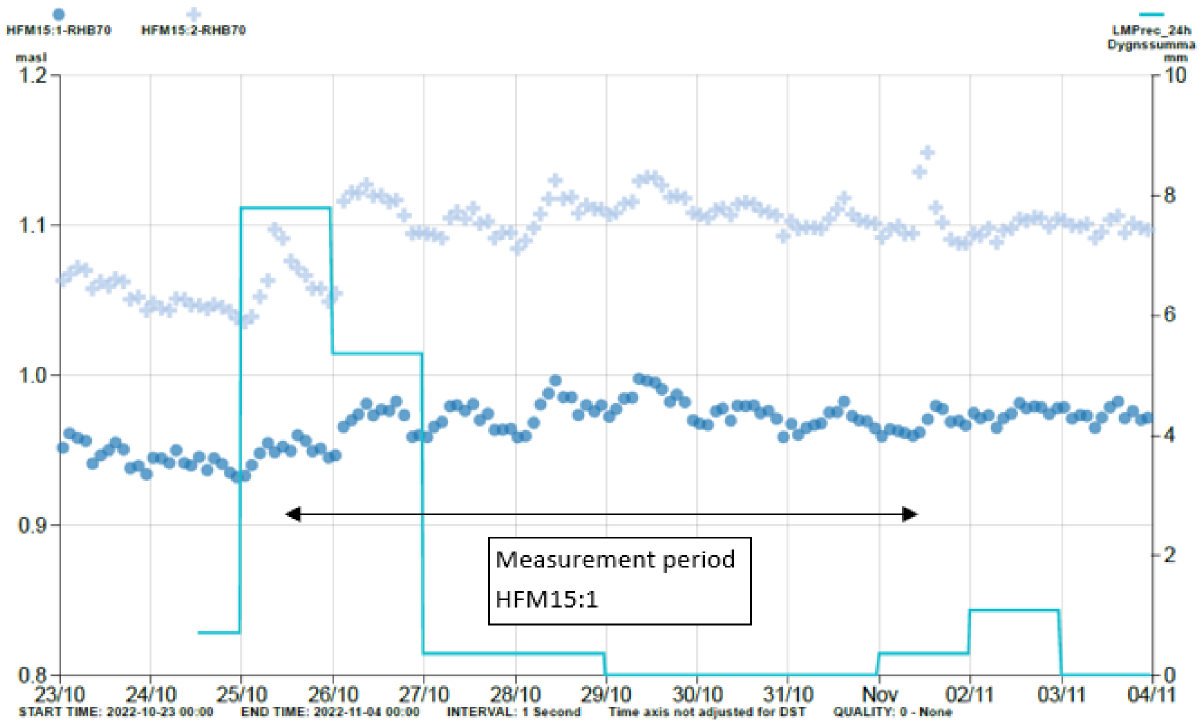


Figure A2-15. *Measured section: HFM15:1 (dark blue).*

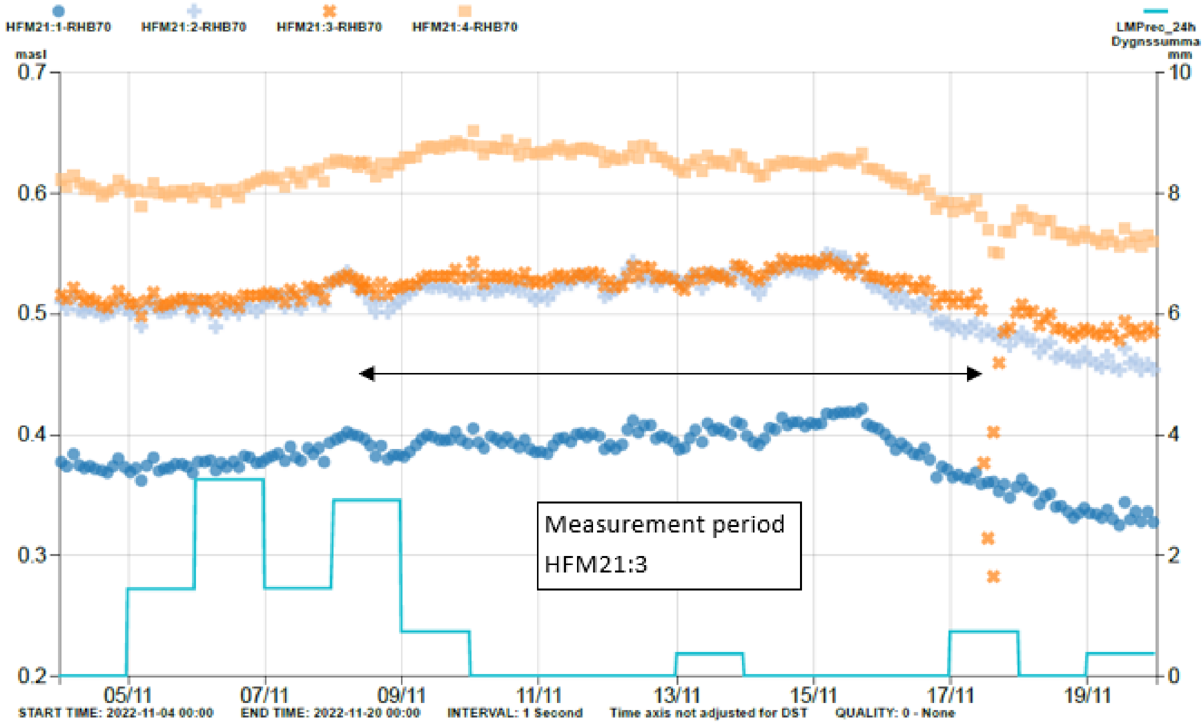


Figure A2-16. *Measured section: HFM21:3 (dark orange).*

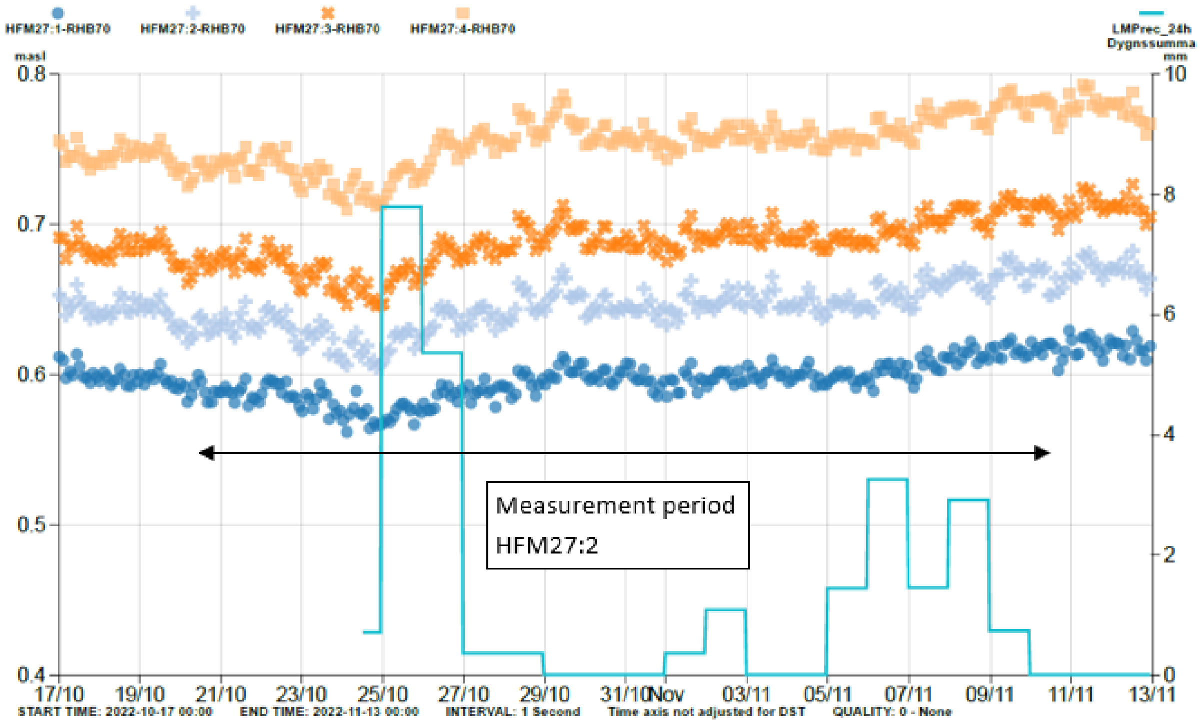


Figure A2-17. *Measured section: HFM27:2 (pale blue).*

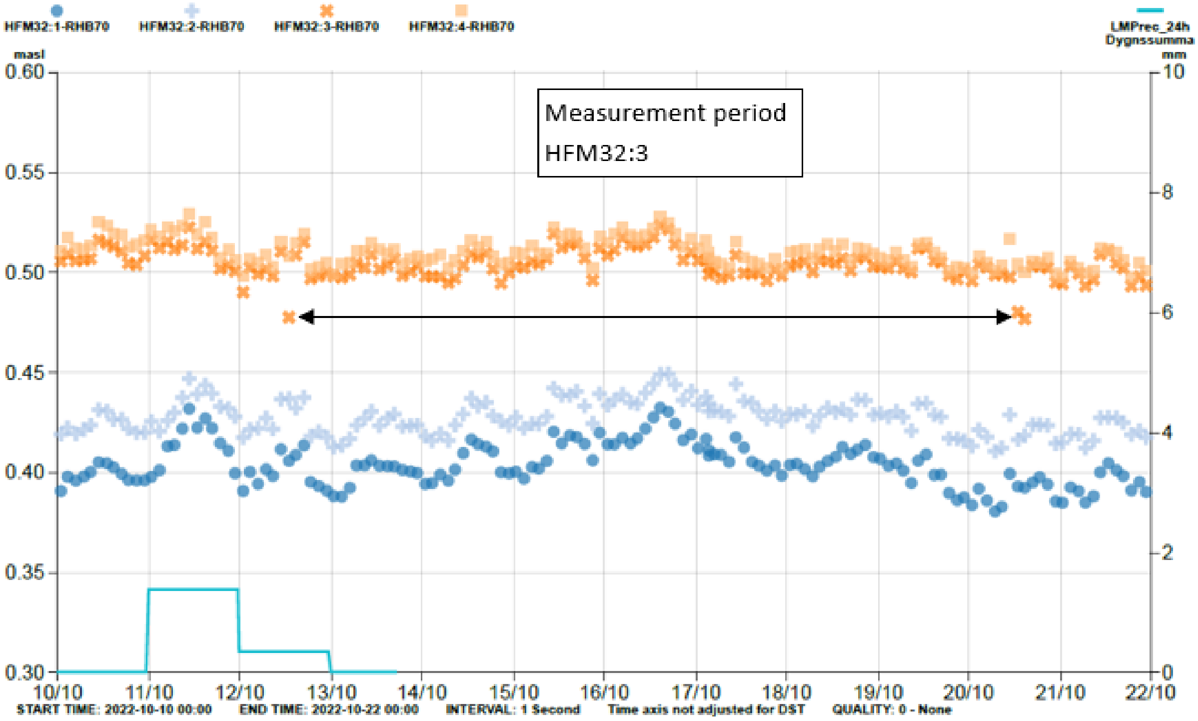


Figure A2-18. *Measured section: HFM32:3 (dark orange).*

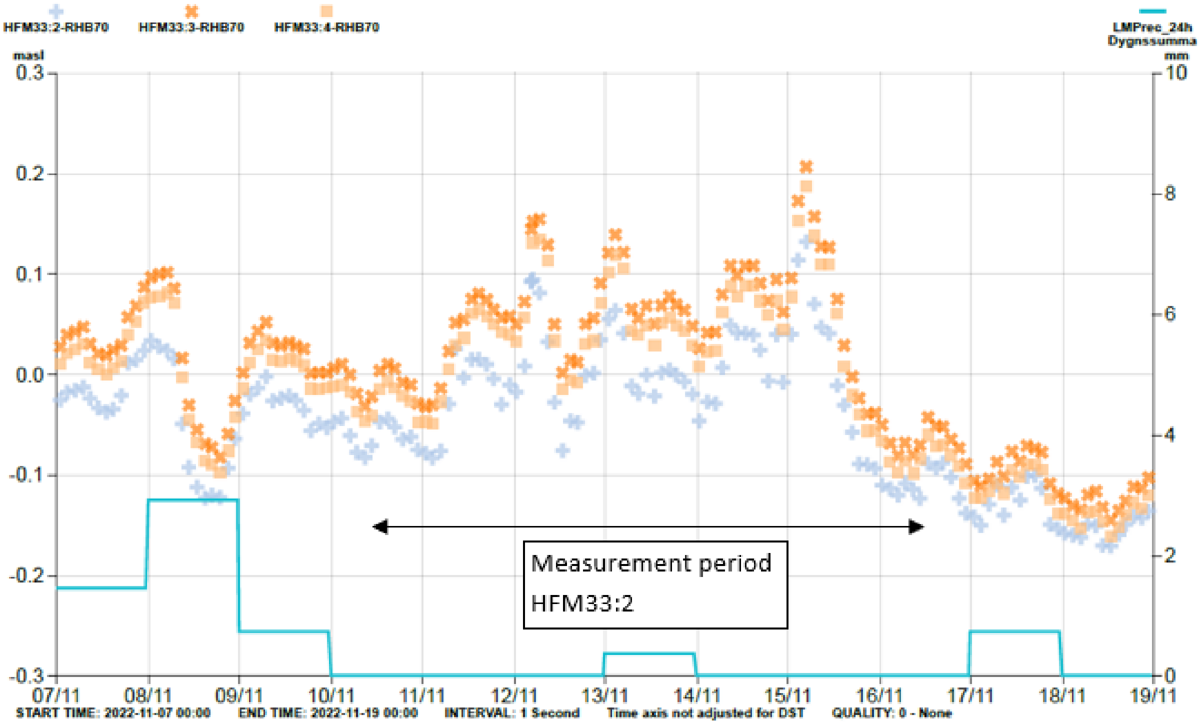


Figure A2-19. *Measured section: HFM33:2 (pale blue).*

Appendix 3

Activities during test campaigns in 2005–2022

Activities performed in the Forsmark area during the test campaigns with groundwater flow measurements. 2005–2022.

Start date	Stop date	Borehole	Activity
Test campaign no. 1, 2005-11-16 – 2005-12-12			
2005-11-05	2005-11-29	HFM01	Flush water source borehole
2005-11-05	2005-11-29	KFM01C	Core drilling
2005-11-10	2005-11-18	HFM26	Percussion drilling
2005-11-11	2006-01-15	KFM08A	Borehole probe dilution test,natural gradient
2005-11-16	2005-12-19	KFM09B	Core drilling
2005-11-17	2005-12-21	KFM09A	Injection test
2005-11-21	2005-11-29	HFM24	Percussion drilling
2005-11-21	2005-12-05	KFM01D	Percussion drilling
2005-11-23	2005-11-25	KFM09B	Injection test
2005-11-25	2006-01-03	KFM08A	SWIW- test
2005-12-06	2006-02-19	KFM10A	Percussion drilling
2005-12-12	2005-12-19	HFM29	Percussion drilling
Test campaign no. 2, 2006-11-06 – 2006-12-01			
2006-06-06	2007-02-13	KFM02B	Core drilling
2006-08-29	2006-11-20	HFM33	Flush water source borehole
2006-08-29	2006-11-20	KFM11A	Core drilling
2006-09-04	2007-04-23	KFM02B	Rock stress meas with overcoring method
2006-11-02	2006-11-28	KFM10A	Chemmac measurement
2006-11-13	2006-11-13	HFM38	Capacity test
2006-11-14	2006-11-14	HFM38	Water sampling, class 3
2006-11-15	2006-11-16	HFM38	Pumping test-submersible pump
2006-11-20	2006-11-20	HFM37	Capacity test
2006-11-21	2006-11-22	HFM37	Pumping test-submersible pump
2006-11-22	2006-12-05	KFM07A	Core drilling
2006-11-22	2006-11-22	HFM36	Capacity test
2006-11-23	2006-11-24	HFM36	Pumping test-submersible pump
2006-11-23	2006-12-04	KFM08D	Percussion drilling
Test campaign no. 3, 2007-11-09 – 2007-11-26, 2008-01-08 – 2008-02-08			
2007-11-01	2007-11-15	HFM33	Pumping test-submersible pump
2007-11-12	2007-11-12	HFM32:3	Water sampling, class 5
2007-11-27	2007-12-13	HFM14	Pumping test-submersible pump
2008-01-15	2008-02-04	HFM27	HMS - Maintenance
2008-01-22	2008-01-22	KFM08A:6	Water sampling, class 4

Start date	Stop date	Borehole	Activity
2008-01-22	2008-01-22	KFM08A:2	Water sampling, class 4, class 5
2008-01-22	2008-01-24	KFM08D:4	Water sampling, class 4
2008-01-30	2008-01-31	KFM01D:2	Water sampling, class 4
Test campaign no. 4, 2008-11-17 – 2008-12-22, 2009-03-16 – 2009-03-20			
2008-11-10	2008-11-17	KFR102A	Percussion drilling
2008-11-15	2008-11-21	KFR104	Pumping test-submersible pump
2008-11-23	2008-11-27	KFR27	Pumping test-submersible pump
2008-11-25	2008-12-12	KFR102A	Core drilling
Test campaign no. 5, 2009-11-06 – 2009-12-11			
2009-11-03	2009-11-06	KFM07A:2	Water sampling, class 5
2009-11-05	2009-11-06	KFM03A:1	Water sampling, class 5
Test campaign no. 6, 2010-11-15 – 2011-03-21			
2010-11-08	2010-11-15	KFM03A:1	Water sampling, class 3
2010-11-18	2010-11-19	KFM06A:3	Water sampling, class 3
2010-11-19	2010-11-22	KFM06A:3	Water sampling, class 4
2010-11-22	2010-11-23	KFM02A:3	Water sampling, class 4
Test campaign no. 7, 2011-11-14 – 2011-12-19			
2011-09-19	2011-09-19	KFM18	Flow log pumping
2011-09-20	2011-09-20	KFM13	Flow log pumping
2011-09-20	2011-09-20	KFM15	Flow log pumping
2011-09-21	2011-09-21	KFM17	Flow log pumping
2011-09-21	2011-09-21	KFM20	Flow log pumping
2011-09-22	2011-09-22	KFM21	Flow log pumping
2011-09-30	2011-09-30	KFM16	Flow log pumping
2011-09-30	2011-09-30	KFM21	Flow log pumping
2011-10-03	2011-10-03	KFM14	Flow log pumping
2011-10-03	2011-10-03	KFM23	Flow log pumping
2011-10-04	2011-10-04	KFM19	Flow log pumping
2011-10-04	2011-10-04	KFM22	Flow log pumping
2011-10-05	2011-10-05	HFM39	Flow log pumping
2011-10-06	2011-10-06	HFM41	Flow log pumping
2011-10-07	2011-10-07	HFM40	Flow log pumping
2011-11-14	2011-11-14	KFM23	Interference test
2011-11-15	2011-11-15	KFM23	Interference test
2011-11-24	2011-11-24	KFM23	Interference test
2011-12-01	2011-12-01	KFM16	Interference test
2011-12-02	2011-12-02	KFM16	Interference test

Start date	Stop date	Borehole	Activity
Test campaign no. 8, 2012-11-12 – 2012-12-17			
No distubring activities during the test campaign			
Test campaign no. 9, 2013-03-06 – 2013-12-19			
2013-04-23	2013-04-26	HFM15:1	Groundwater sampling
2013-05-09	2013-05-15	HFM16:2	Groundwater sampling
2013-05-13	2013-05-14	KFM06A:5	Groundwater sampling
2013-05-13	2013-05-15	KFM06A:3	Groundwater sampling
2013-05-16	2013-05-17	KFM06C:5	Groundwater sampling
2013-05-23		KFM08D	Packer release
2013-05-31	2013-06-12	KFM08D	Lifting borehole equipment
2013-08-21	2013-08-22	HFM15	Minipacker release and expand due to manual levelling
2013-08-21	2013-08-22	KFM05A	Minipacker release and expand due to manual levelling
2013-09-17		HFM34	Packer release
2013-10-24		HFM34	Packer expansion
Test campaign no. 10, 2014-09-04 – 2015-07-02			
2014-09-23		KFM08D	Packer expansion
2014-09-24	2014-09-26	KFM08A:2	Groundwater sampling
2014-09-25	2014-09-26	KFM02A:3	Groundwater sampling
2015-05-07	2015-05-08	KFM02B:2	Groundwater sampling
2015-05-10	2015-05-13	KFM02A:5	Groundwater sampling
2015-05-11	2015-05-18	KFM06C:3	Groundwater sampling
Test campaign no. 11, 2015-09-03 – 2016-07-06			
2015-09-13	2015-09-21	KFM08A:6	Groundwater sampling
2015-09-14	2015-09-14	KFM08A:2	Groundwater sampling
2015-12-09	2015-12-14	KFR27	Interference test pumping hole
2016-02-23	2016-02-26	KFR27	Interference test pumping hole
2016-03-30	2016-04-04	KFM24	Percussion drilling
2016-04-01	2016-04-04	KFR103	Interference test pumping hole
2016-04-07	2016-04-11	KFR103	Interference test pumping hole
2016-04-10	2016-06-13	KFM24	Core drilling
2016-04-26	2016-04-29	KFR105	Interference test pumping hole
2016-06-08	2016-06-10	KFM11A:2	Groundwater sampling
Test campaign no. 12 and no.13, 2016-09-20 – 2017-12-21			
2016-09-26	2016-09-30	KFM24	Pumping for interference test
2016-10-03	2016-10-07	KFM24	Pumping for interference test
2016-10-10	2016-10-14	KFM24	Pumping for interference test

Start date	Stop date	Borehole	Activity
2016-10-17	2016-10-20	KFM24	Pumping for interference test
2016-11-07	2016-12-13	KFM24	Groundwater sampling series
2016-11-11	2017-01-12	KFM01C	Core drilling
2017-05-02	2017-05-05	KFM10A:2	Pumping for groundwater sampling
2017-05-02	2017-05-24	KFM06C:3	Pumping for groundwater sampling
2017-05-03	2017-05-03	KFM04A:4	Pumping for groundwater sampling
2017-05-03	2017-05-05	KFM06C:5	Pumping for groundwater sampling
2017-05-03	2017-05-16	KFM08D:2	Pumping for groundwater sampling
2017-05-05	2017-05-15	KFM06A:3	Pumping for groundwater sampling
2017-05-08	2017-05-11	KFM06A:5	Pumping for groundwater sampling
2017-05-08	2017-05-29	KFM07A	Groundwater sampling series
2017-05-09	2017-05-19	KFM11A:2	Pumping for groundwater sampling
2017-05-10	2017-05-12	KFM11A:4	Pumping for groundwater sampling
2017-05-11	2017-05-12	KFM08A:2	Pumping for groundwater sampling
2017-05-14	2017-05-23	KFM08A:6	Pumping for groundwater sampling
2017-05-16	2017-05-17	KFM12A:3	Pumping for groundwater sampling
2017-05-17	2017-05-24	KFM08D:4	Pumping for groundwater sampling
2017-08-27	2017-08-28	KFM03A:1	Pumping
2017-08-28	2017-09-29	KFM03A:4	Pumping
2017-09-11	2017-09-13	KFM01C	Nitrogen lifting
Test campaign no. 14, 2020-09-29 – 2020-11-17			
2020-10-12	2020-10-27	HFM47	Pumping for interference test
2020-10-13	2020-10-23	KFR121	Pumping for PFL measurments
2020-10-29	2020-11-02	KFR119	Pumping for PFL measurments
Test campaign no. 15, 2021-09-28 – 2021-11-12			
2021-10-06		KFR102A	Borehole packer release
2021-11-10		KFM11A	Borehole packer release
Test campaign no. 16, 2022-10-04 – 2022-11-17			
2022-10-05		HFM05	Borehole packer release
2022-11-09		HFM38	Borehole packer release
2022-11-10	2022-11-10	HFM05	Instrumentation - packer removal
2022-11-12	2022-11-12	AFR	Power loss (from 08:16 to 11:45)