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Groundwater flow measurements in permanently installed boreholes

Test campaign no. 15, 2021

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Summary

This report describes the performance and evaluation of groundwater flow measurements in 22 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 fifteenth test campaign performed within the monitoring program and the second 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 0.02 to 21 ml/min with calculated Darcy velocities from 1.3·10-10 to 1.0·10-7 m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.00009 and 0.1 m/m.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i 22 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 femtonde mätkampanjen som genomförts i övervakningsprogrammet och den andra 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 0,02 - 21 ml/min med beräknade Darcy hastigheter mellan 1,3·10-10 och 1,0·10-7 m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,00009 och 0,1 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 much longer time (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 to the variations were evaporation in sampling tubes and the measuring time. Another factor that affected the quality of the measurements was the fact that the equipment is 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, no measurements were made with the previously used sampling equipment (Föhlinger and Wass 2021). The measurements performed in 2021 in 22 borehole sections were made in the same way.

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 15, autumn 2021, which is the second campaign using online measuring equipment. The work was carried out in accordance with activity plan AP SFK-21-029 and the field work was conducted from the end of September 2021 to the middle of November 2021. In Table 1-1 controlling documents for performing this 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 2021	1949384 – AP SFK-21-029	1.0
Method description	**Number**	**Version**
Metodbeskrivning för grundvattenflödesmätningar	1189502 – SKB MD 350.001	3.0

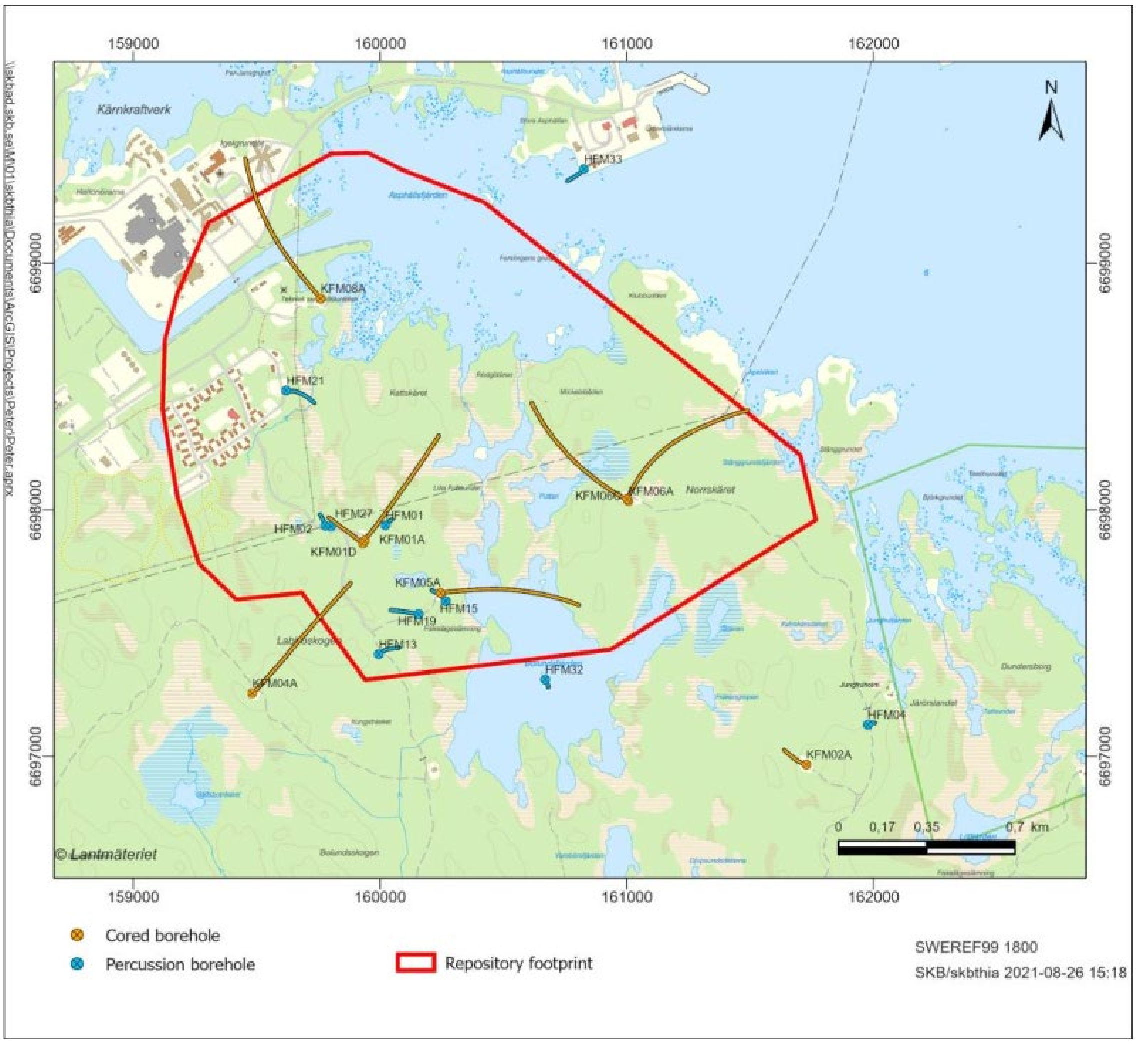

Figure 1-1. *Overview over the Forsmark site investigation area, showing locations of boreholes included in this activity.*

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 2005–2021.

Borehole	Section no	Secup (mbl)[1)]	Seclow (mbl)	SecMid (mbl)	Elevation SecMid (m RH2000)	Geologic Character[2)]	Measured 2021 (Yes/No)
KFM01A	5	109	130	119.5	-115.60	Multiple fractures, FFM02	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	N
	4	446	456	451	-389.44	ZFMWNW3259	N
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 22 selected borehole sections instrumented for this purpose were measured, cf. Table 1-2. This was the 15th test campaign performed within the monitoring program and measurements are planned to be repeated every year. The measurements will serve as a basis to study 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.

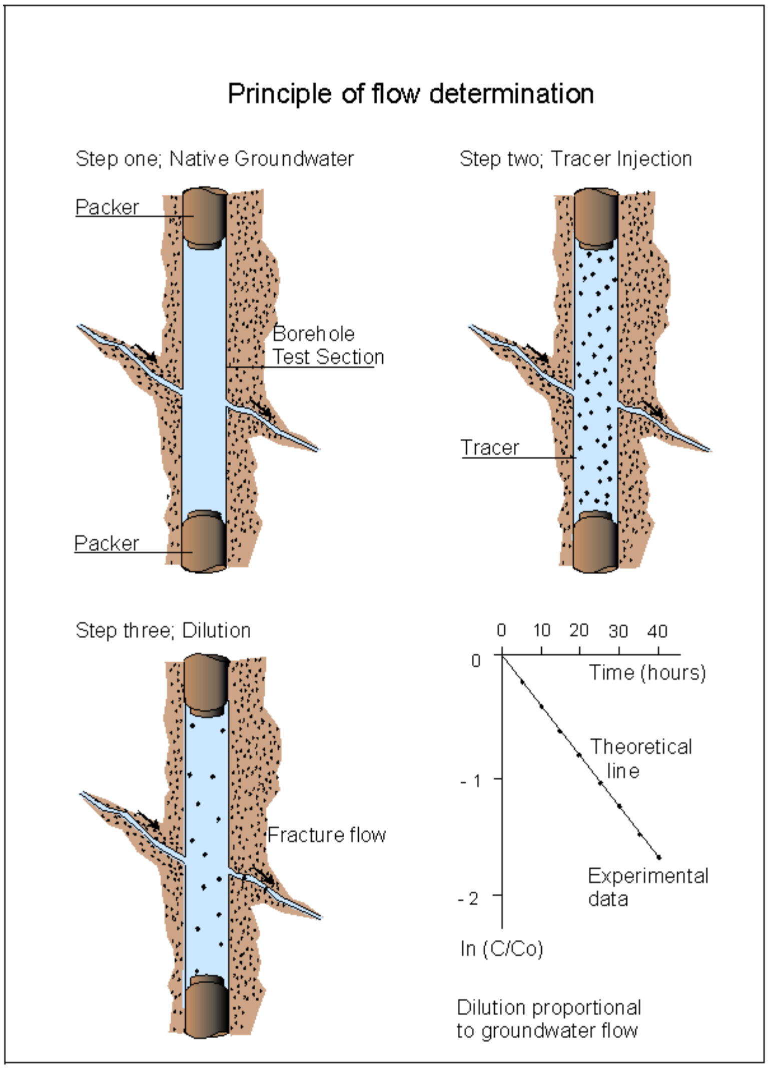

Figure 3-1. *General principles of dilution and flow determination (SKB MD 350.001).*

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. The sections intended for groundwater flow measurements are each equipped with three polyamide tubes connecting the borehole section in question with the ground surface. Two 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.

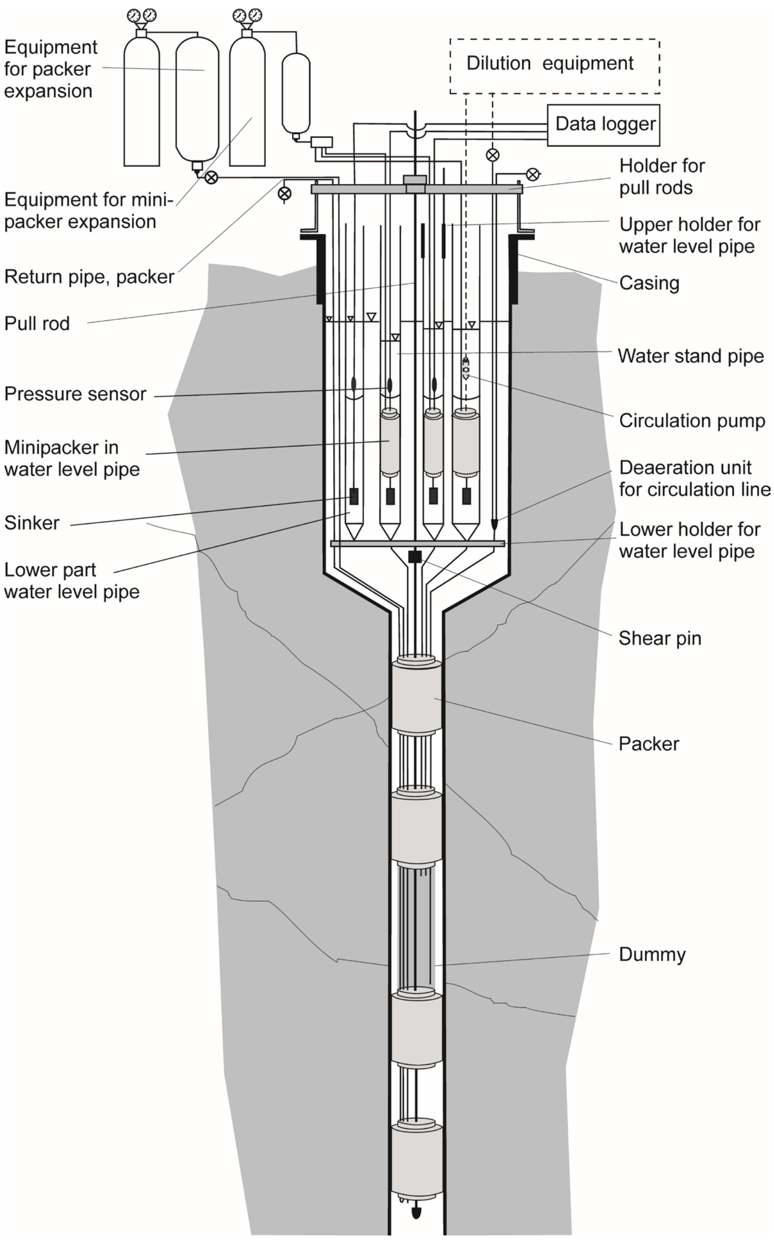

***Figure 3-2**. Example of permanent instrumentation in core and percussion boreholes with circulation sections.*

3.3 Dilution test equipment and methodology

The tracer dilution tests were performed using six identical equipment set-ups, allowing six 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.

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 close 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 Chapter 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.

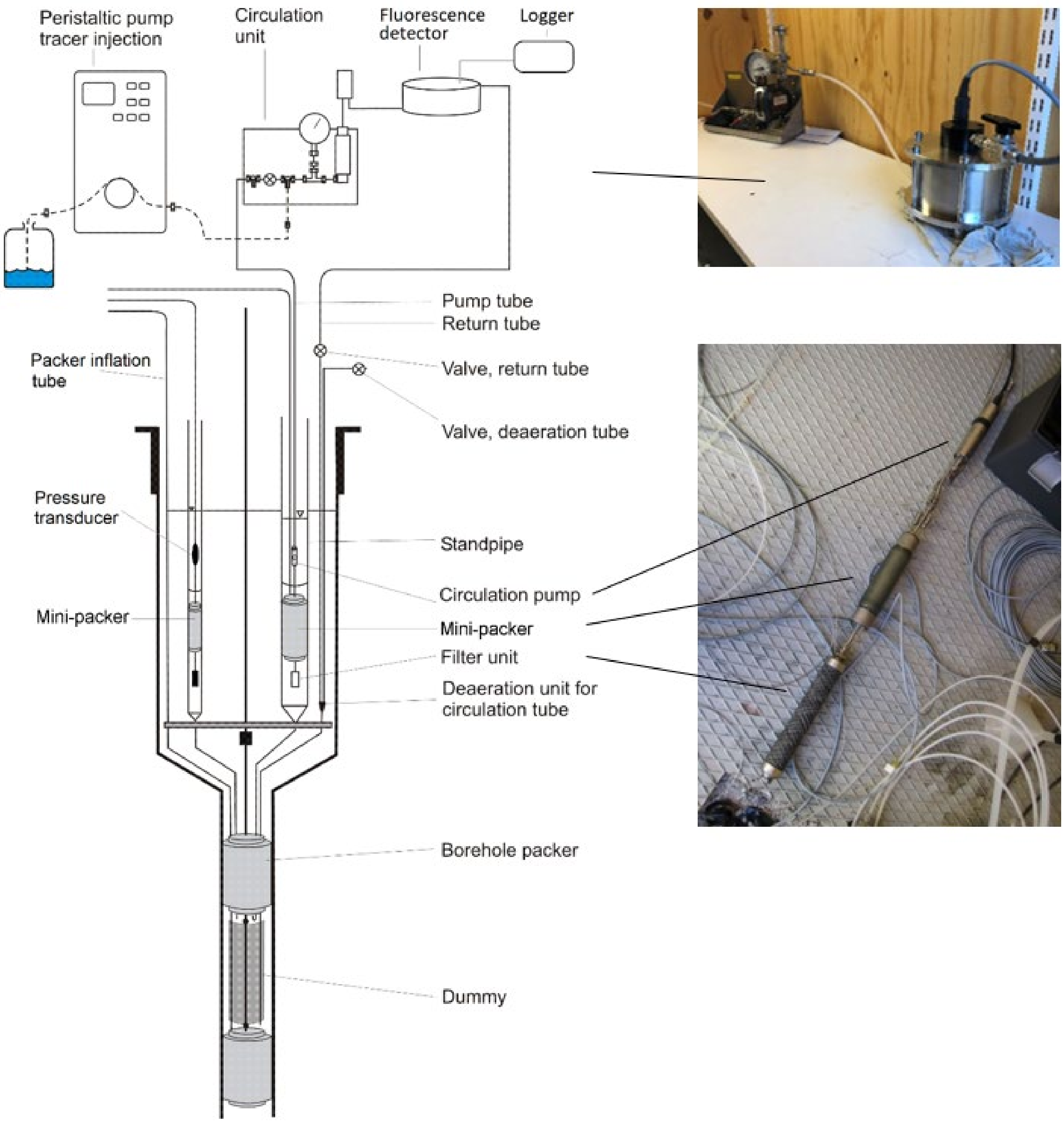

Figure 3-3. *Schematic drawing of the equipment used in tracer dilution measurements.*

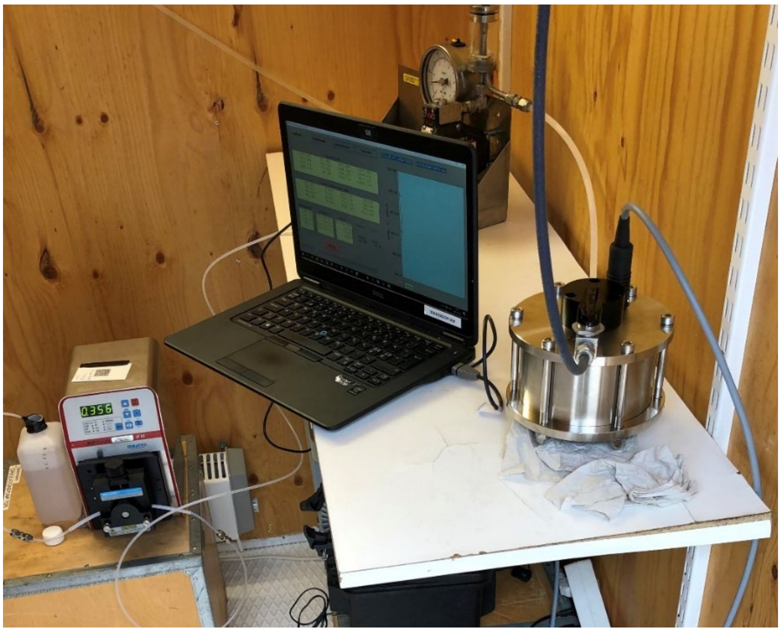

Figure 3-4. *All equipment during injection. Pump for tracer injection to the left, circulation unit in the back, fluorescence detector in the front connected to the logger under the bench. The logger is during injection connected to the computer, which makes it possible to follow the concentration in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

Equation 3-1:

$$\ln (c/c_0) = -(Q_{bh}/V) \cdot t$$

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:

Equation 3-2:

$$Q_{bh} = v \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha$$

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):

Equation 3-3:

$$I = \frac{v}{K} = \frac{Q_{bh} \cdot L_{bh}}{\alpha \cdot A \cdot T_{bh}} = \frac{Q_{bh} \cdot L_{bh}}{2 \cdot d_{bh} \cdot L_{bh} \cdot T_{bh}}$$

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.

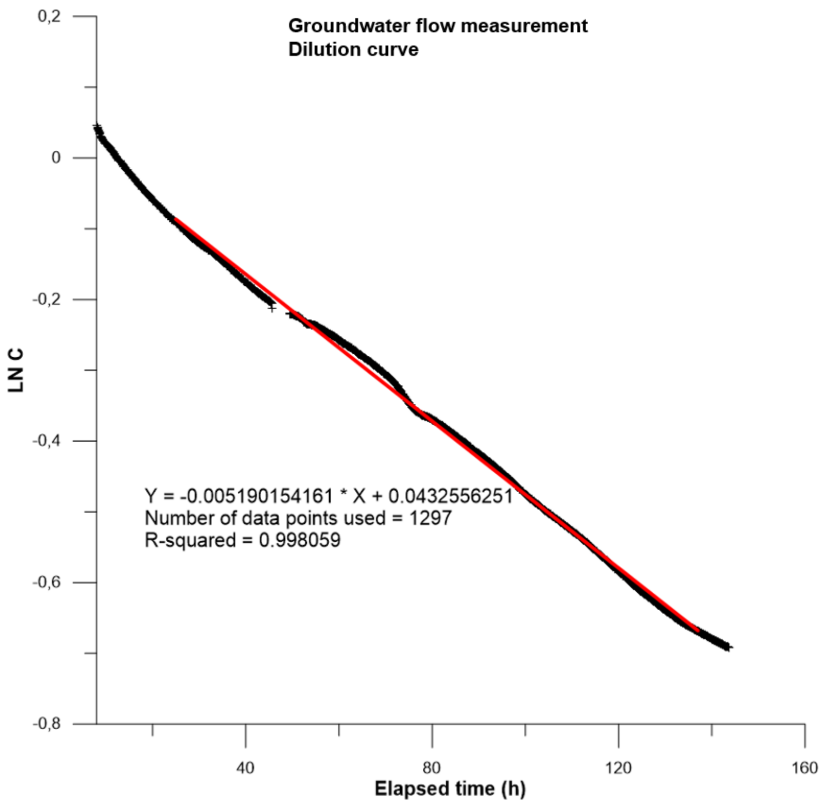

Figure 3-7. *Example of a tracer dilution graph (logarithm of concentration versus time), including straight-line fit. The used interval is chosen by eye assessment as the injection and start-up effects varies from section to section (Andersson et al. 2018).*

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 Geosigma 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°C), which differs from the section water in field that often has a temperature around 10°C (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 12°C 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 error.

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	25.61	226.15
1955	38.52	341.75
1956	36.01	327.18
1957	33.42	299.46
1984	46.31	424.13
1985	56.31	509.03
1986	39.15	354.14

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 484 and 509 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 12 ppb, about 2 %, between the validation before and after field measurements for all detectors except one. The deviating detector number 1986 differed 35 ppb, about 7 %. This detector was used in both sections in KFM06A and KFM06C, respectively. However, there is no indication this has affected the evaluated flow rates in these sections.

Table 4-2. Concentrations obtained at validation with 500 ppb solutions in September 2021, before field campaign, and November 2021, after field campaign.

Detector (number)	Concentration (ppb) at validation	
	September 2021 Solution 500 ppb	November 2021 Solution 500 ppb
1943	487	489
1955	498	499
1956	498	492
1957	502	496
1984	509	498
1985	509	497
1986	484	449

4.2 Execution of field work

The borehole sections included in the monitoring program during the test campaign 2021 are listed in Table 4-3. Measuring was performed with equipment described in Chapter 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 campaign was the first time using this approach for measuring of background concentrations, see Chapter 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 2021.

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	210930 – 211013	2
KFM01D:2	429 – 438	6.2 E-8	Single fracture, FFM01	211014 – 211026	2
KFM01D:4	311 – 321	1.8 E-7	Single fracture, FFM01	211027 – 211103	1
KFM02A:3	490 – 518	4.0 E-6	Zone ZFMF1	210929 – 211019	3
KFM02A:5	411 – 442	2.9 E-6	Zone ZFMA2	211019 – 211026	1
KFM04A:4	230 – 245	4.6 E-5	Zone ZFMA2	211028 – 211111	2
KFM05A:4	254 – 272	1.9 E-8	Single fracture, FFM01	210930 – 211019	2
KFM06A:3	738 – 748	3.1 E-7	Zone ZFMNNE0725	210928 – 211005	1
KFM06A:5	341 – 362	9.2 E-7	Zone ZFMENE0060A	201006 – 211013	1
KFM06C:3	647 – 666	9.0 E-8	Possible DZ5	211013 – 211026	2
KFM06C:5	531 – 540	1.2 E-6	Zone ZFMWNW044	211028 – 211111	2
KFM08A:2	684 – 694	1.4 E-6	Possible DZ4 (S-WNW)	210930 – 211013	2
KFM08A:6	265 – 280	1.3 E-6	Zone ZFMENE1061A	211014 – 211027	2
HFM01:2	33.5 – 45.5	4.5 E-5	Zone ZFMA2	211104 – 211112	1
HFM02:2	38 – 48	5.9 E-4	Zone ZFM1203	211027 – 211103	1
HFM04:2	58 – 66	7.9 E-5	Zone ZFM866	211012 – 211019	1
HFM13:1	159 – 173	2.9 E-4	Zone ZFMENE0401A	211020 – 211027	1
HFM15:1	85 – 95	1.0 E-4	Zone ZFMA2	211026 – 211103	1
HFM21:3	22 – 32	1.0 E-4	Single fracture, FFM02	211103 – 211112	1
HFM27:2	46 – 58	4.0 E-5	Zone ZFM1203	211020 – 211111	3
HFM32:3	26 – 31	2.3 E-4	Single fracture, FFM03	211005 – 211012	1
HFM33:2	121 – 137.5	4.7E-04	Single fracture	210929 – 211005	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)

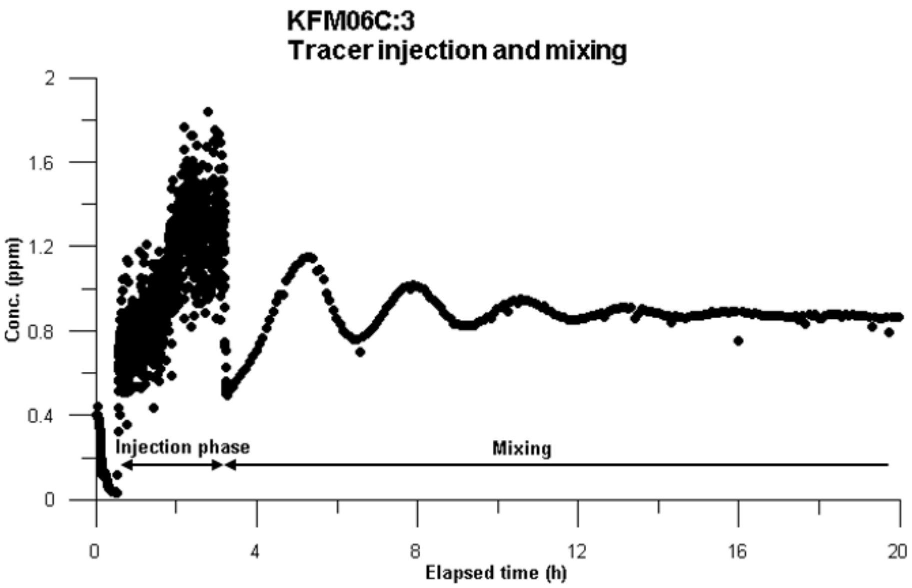

Figure 4-1. Injection phase and mixing in KFM06C:3.

4.2.1 Nonconformities

- In KFM05A:4 a pump failure occurred 2021-10-15, fifteen days after the tracer injection. Originally the measurement period for this section was planned to last two weeks but during the test it was decided to extend the measurement period by one week to increase the quality of data. Hence, the unplanned pump stop did not affect the evaluation of data. Due to the pump failure no purge pumping could be performed right after the measurement period, it was later performed in June 2022.
- In KFM08A:6 the pump stopped 2021-10-20, six days after the tracer injection and unfortunately the day after the weekly attendance. The measurement period was planned to last for two weeks. The circulation was not restarted after the unplanned pump stop as it was not discovered in time, but after release of the mini packer it was possible to restart the pump to get rid of the remaining tracer. The measurement time of six days was probably too short and the evaluated flow rate was overestimated.
- In HFM32:3 the mini packer was released by remote control two days after the measurements started. In theory, the unplanned release of the mini packer means that the volume of the section changes and that any water above the mini packer can reach the section and contribute to the dilution. However, the incident does not appear to have affected the evaluation of the flow rate.

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.

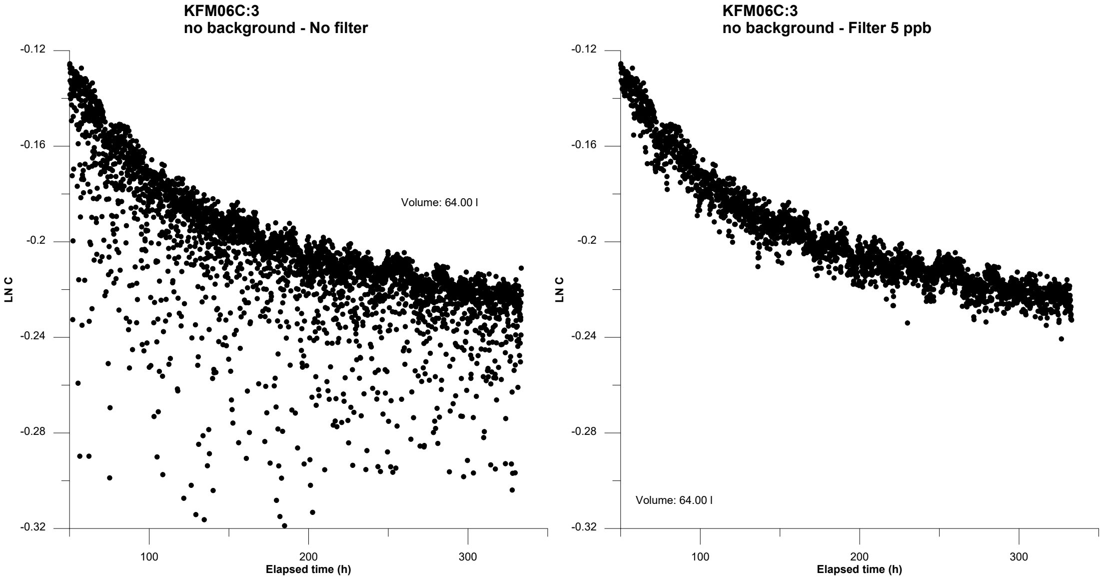

Figure 4-2. *Unfiltered and filtered data. Fluctuations are due to gas bubbles.*

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, in this campaign the background concentration was measured during approximately 15-20 minutes of circulation at a logging interval of 10 seconds while the logging was monitored in real time at a computer. The background measurements were considered complete when the real time monitored data showed stable values.

4.3.3 Evaluation of dilution graphs

Data is evaluated, as described in Chapter 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 Chapter 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-21-029). 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. 15, 2021

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 0.02 to 21 ml/min in the measured sections with Darcy velocities ranging from $1.3 \cdot 10^{-10}$ to $1.0 \cdot 10^{-7}$ 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.

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 KFM11A and KFR102A, cf. Table 5-2. However, this is not believed to have affected the ongoing groundwater flow measurements.

Table 5-1. Results from groundwater flow measurements, test campaigns no. 15, 2021.

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	100	305	40	0.06	0.3	0.06
KFM01D:2	429 - 438	6.2 E-8	38.33	32	290	18	0.05	0.6	0.09
KFM01D:4	311 - 321	1.8 E-7	31.27	30	170	28	0.09	1.0	0.06
KFM02A:3	490 - 518	4.0 E-6	66.33	200	475	33	0.7	2.7	0.02
KFM02A:5	411 - 442	2.9 E-6	60.78	90	164	40	0.5	1.6	0.02
KFM04A:4	230 - 245	4.6 E-5	35.00	130	330	17	1.4	10	0.003
KFM05A:4	254 - 272	1.9 E-8	40.62	30	365	120	0.02	0.1	0.1
KFM06A:3	738 - 748	3.1 E-7	58.25	90	160	25	0.2	2.6	0.08
KFM06A:5	341 - 362	9.2 E-7	46.64	100	165	27	0.8	4.0	0.09
KFM06C:3	647 - 666	9.0 E-8	64.00	165	310	39	0.08	0.4	0.09
KFM06C:5	531 - 540	1.2 E-6	43.61	150	340	39	0.7	7.9	0.06
KFM08A:2	684 - 694	1.4 E-6	55.15	120	310	12	0.1	1.4	0.01
KFM08A:6	265 - 280	1.3 E-6	34.67	50	140	18	0.3	2.1	0.02
HFM01:2	33.5 - 45.5	4.5 E-5	39.83	25	180	186	3.2	16	0.004
HFM02:2	38 - 48	5.9 E-4	28.53	40	100	144	17	100	0.002
HFM04:2	58 - 66	7.9 E-5	27.52	53	160	150	1.4	11	0.001
HFM13:1	159 - 173	2.9 E-4	39.28	25	130	54	21	91	0.004
HFM15:1	85 - 95	1.0 E-4	35.74	80	190	145	1.7	10	0.001
HFM21:3	22 - 32	1.0 E-4	31.39	27	140	143	1.0	5.8	0.0006
HFM27:2	46 - 58	4.0 E-5	40.29	200	500	92	0.2	1.0	0.0003
HFM32:3	26 - 31	2.3 E-4	20.06	75	165	45	0.4	4.3	0.00009
HFM33:2	121 -137.5	4.7E-04	54.10	45	139	24	3.9	14	0.0005

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).

Table 5-2. Activities performed in the Forsmark area during test campaign no. 15, 2021.

Start date	Stop date	Borehole	Activity
2021-10-06		KFR102A	Borehole packer release
2021-11-10		KFM11A	Borehole packer release

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 the hydraulic gradient is very large. This indicates that the flow rate measured during this period is higher than expected. The large gradient may be due to rough estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. KFM05A:4 also 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. Activities in the Forsmark area during the campaigns in 2005-2021 are found in Appendix 3.

The comparison shows that the flow rates measured 2021 are within the range of the values measured in previous campaigns in most borehole sections. However, 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 evaluation (2013-2017) it has become increasingly clear that the last period of the curve should be used to obtain an evaluated value as reliable as possible. In previous test campaigns (2005-2012) the measurement duration has only been about 200 hours, why the flow rates presented in Table 5-3 probably are overestimated.

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 2021 would be to the results from 2020, as the new online detectors were used both years. The sections where the measured flow in 2021 differs most compared to the results in 2020 are KFM01D:2, KFM08A:6 and HFM21:3.

For KFM01D:2, the flow measured in 2020 was higher than ever measured in that section before and the flow measured in 2021 is more consistent with earlier measurements. The measurement period of one week was probably too short in 2020 and in 2021 it was extended to two weeks.

In KFM08A:6 a pump stop occurred six days after the tracer injection. Unfortunately, this happened the day after the weekly attendance, why it was not discovered until a week later when it was time to end the measurement. The measurement period was planned to last for two weeks, only six days of measurement (140 hours) was probably too short and the evaluated flow rate was overestimated.

Table 5-3. Results from groundwater flow measurements in 2005–2021. For detailed data from each year see Andersson et al. (2018) and Föhlinger and Wass (2021).

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

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).

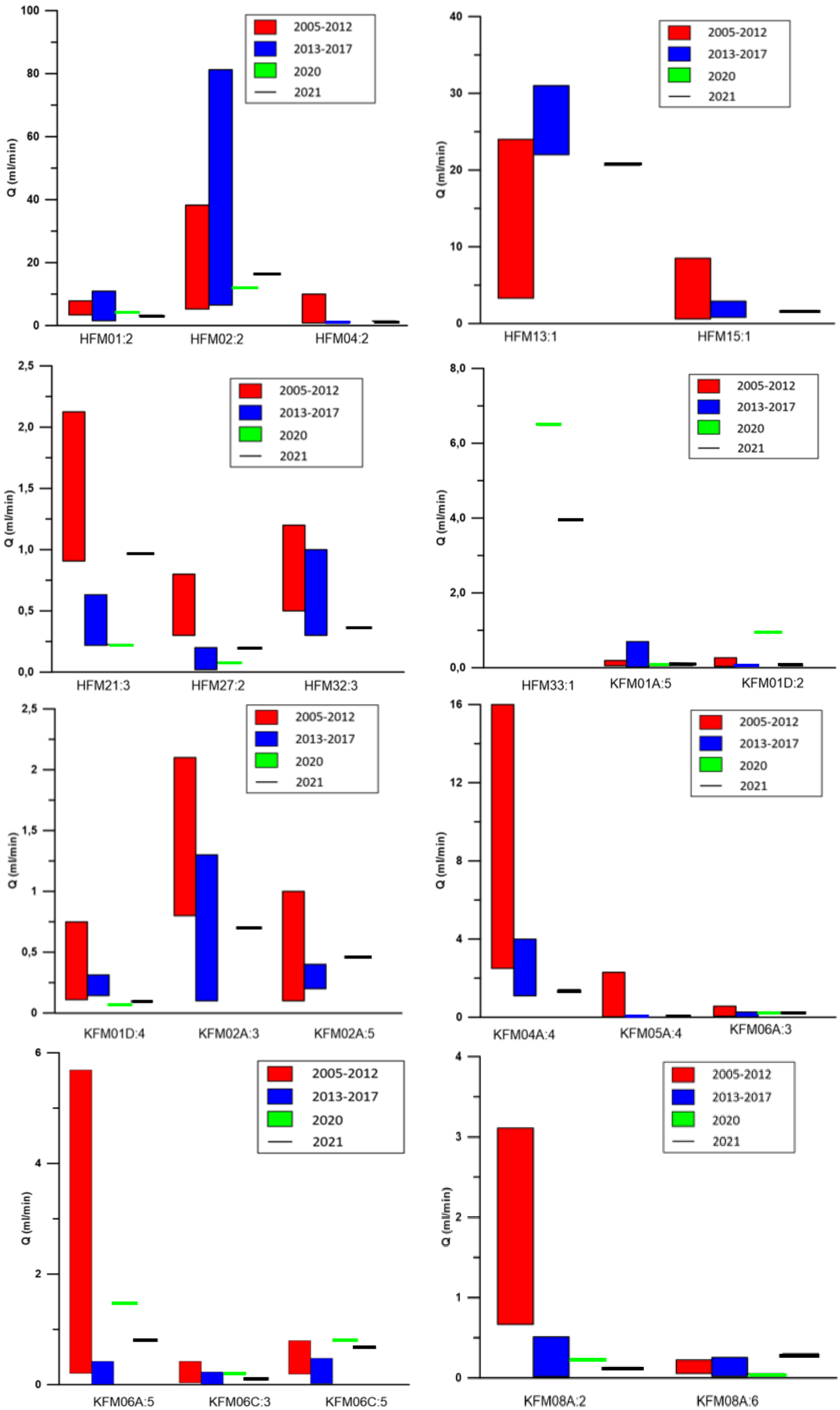

***Figure 5-1**. Summarized results from groundwater flow measurements 2005-2021. Only sections measured during 2021 are shown in the figure.*

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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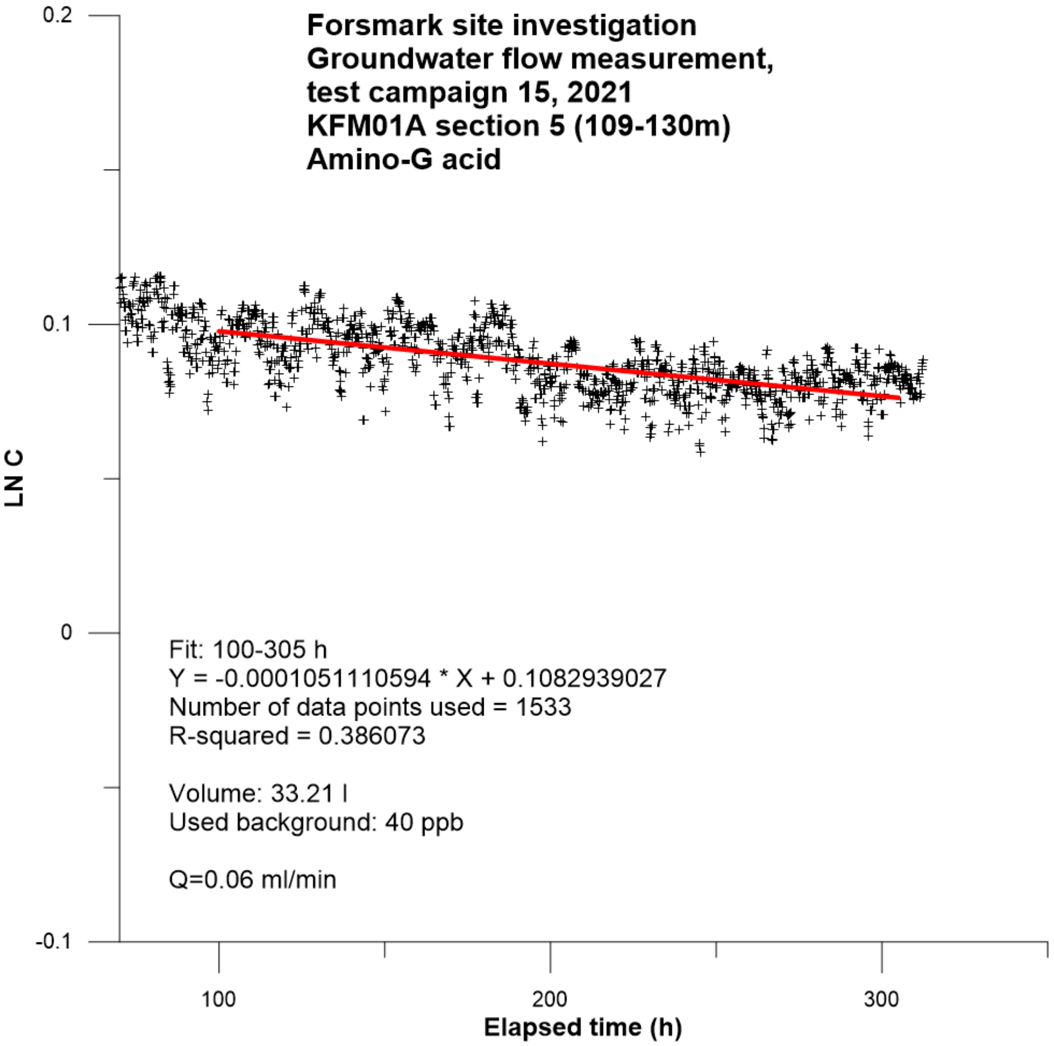
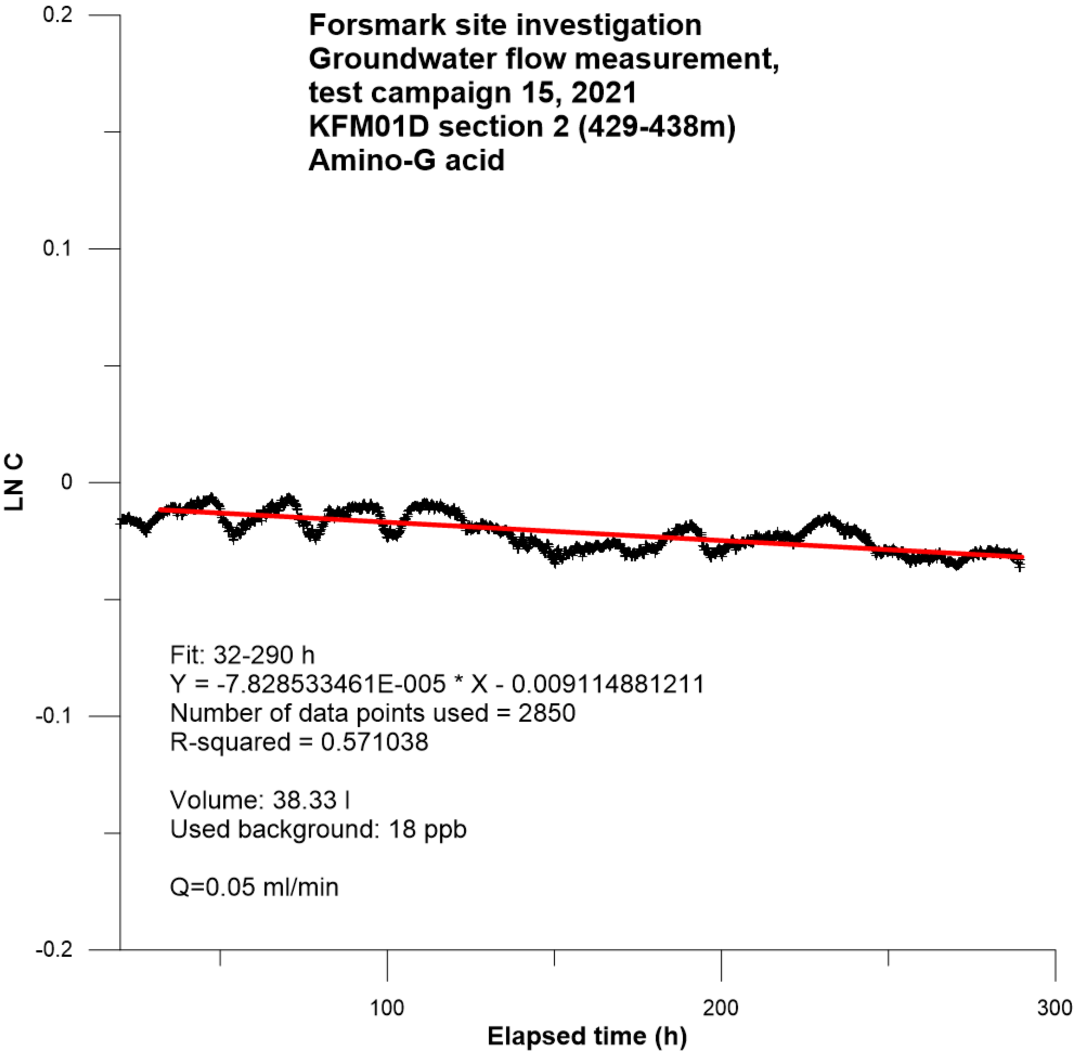
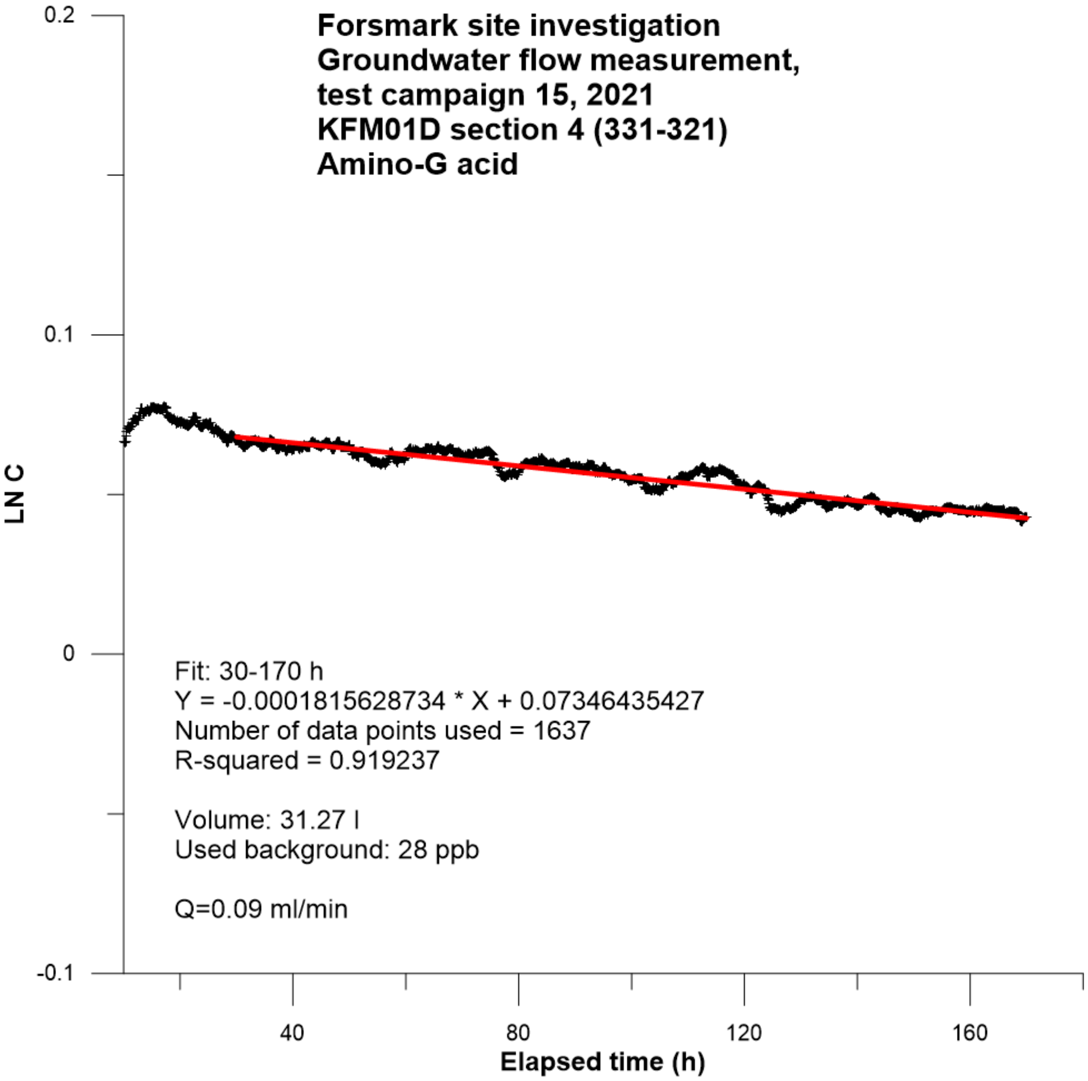
Appendix 1

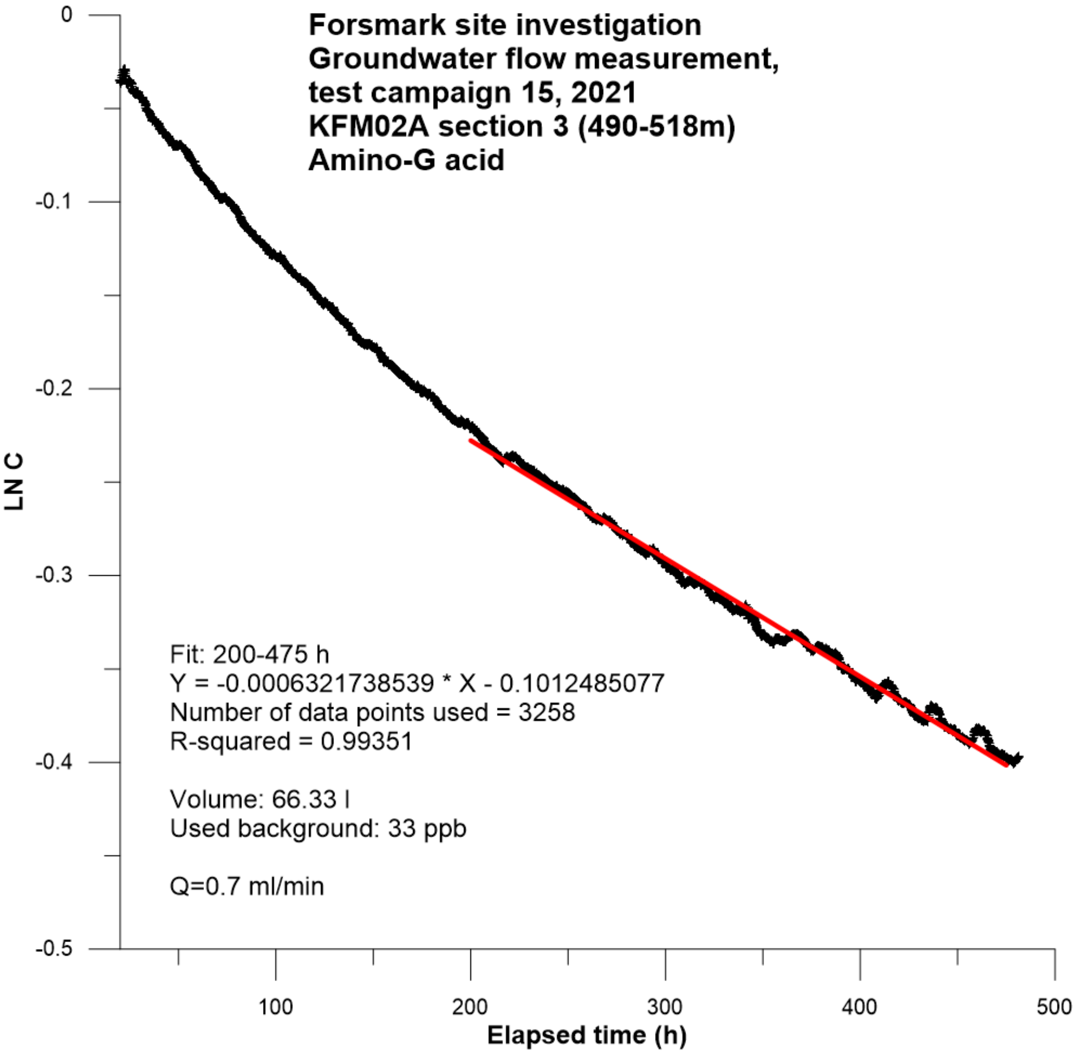
Tracer dilution graphs



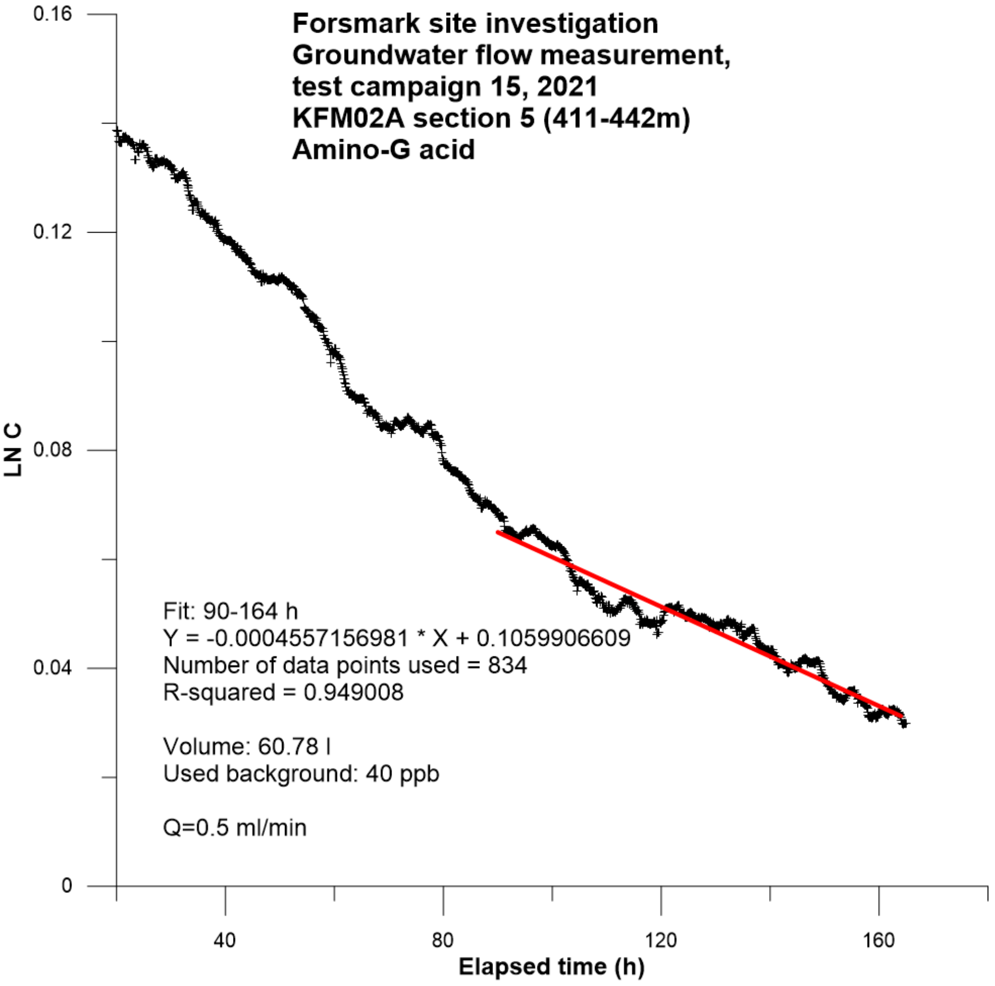

Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM01D section 2 (429-438m)
Amino-G acid
0.2
0.1
0
-0.1
-0.2
LN C
Fit: 32-290 h
Y = -7.828533461E-005 * X - 0.009114881211
Number of data points used = 2850
R-squared = 0.571038
Volume: 38.33 l
Used background: 18 ppb
Q=0.05 ml/min
100
200
300
Elapsed time (h)



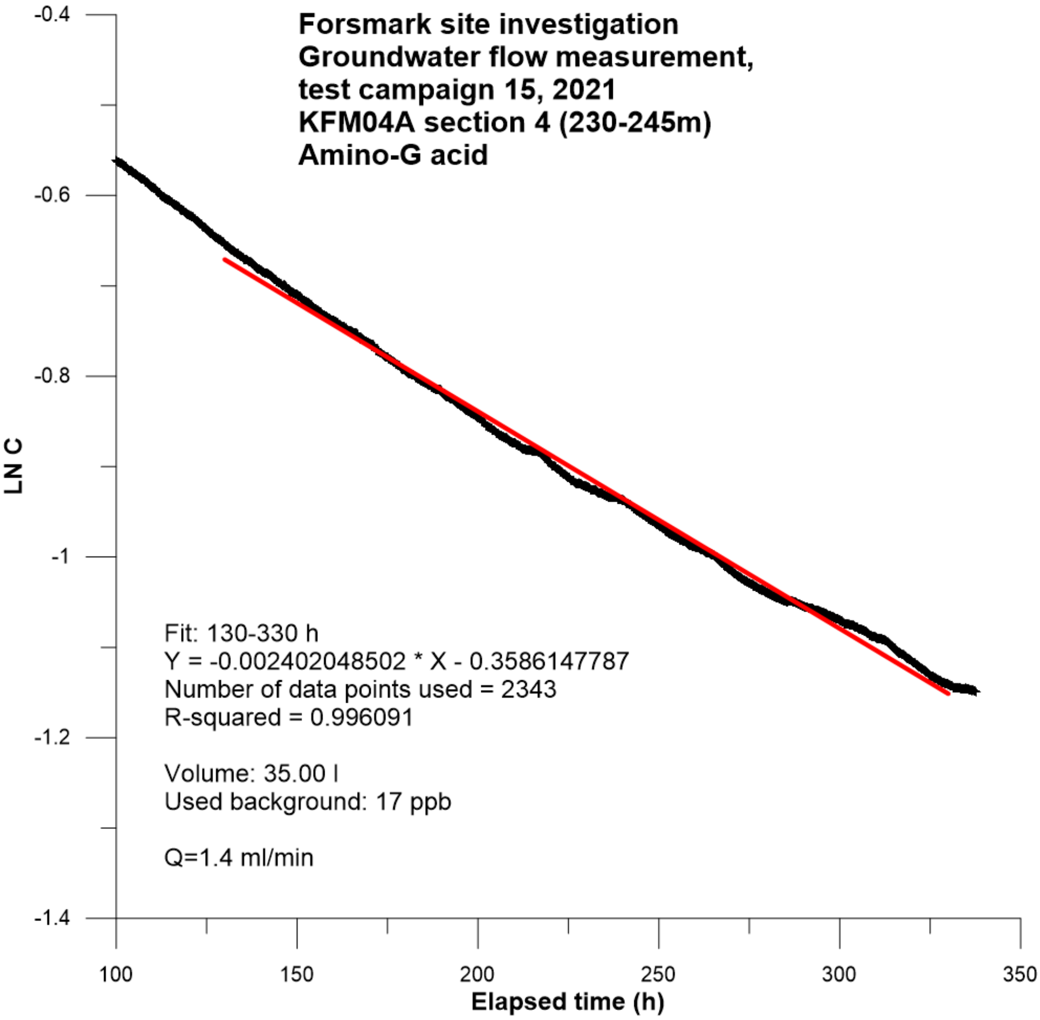
Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM01D section 4 (331-321)
Amino-G acid
Fit: 30-170 h
Y = -0.0001815628734 * X + 0.07346435427
Number of data points used = 1637
R-squared = 0.919237
Volume: 31.27 l
Used background: 28 ppb
Q=0.09 ml/min
LN C
Elapsed time (h)
0.2
0.1
0
-0.1
40
80
120
160



Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM02A section 3 (490-518m)
Amino-G acid
Fit: 200-475 h
Y = -0.0006321738539 * X - 0.1012485077
Number of data points used = 3258
R-squared = 0.99351
Volume: 66.33 l
Used background: 33 ppb
Q=0.7 ml/min
LN C
Elapsed time (h)
0
-0.1
-0.2
-0.3
-0.4
-0.5
100
200
300
400
500



Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM02A section 5 (411-442m)
Amino-G acid
Fit: 90-164 h
Y = -0.0004557156981 * X + 0.1059906609
Number of data points used = 834
R-squared = 0.949008
Volume: 60.78 l
Used background: 40 ppb
Q=0.5 ml/min
LN C
0.16
0.12
0.08
0.04
0
40
80
120
160
Elapsed time (h)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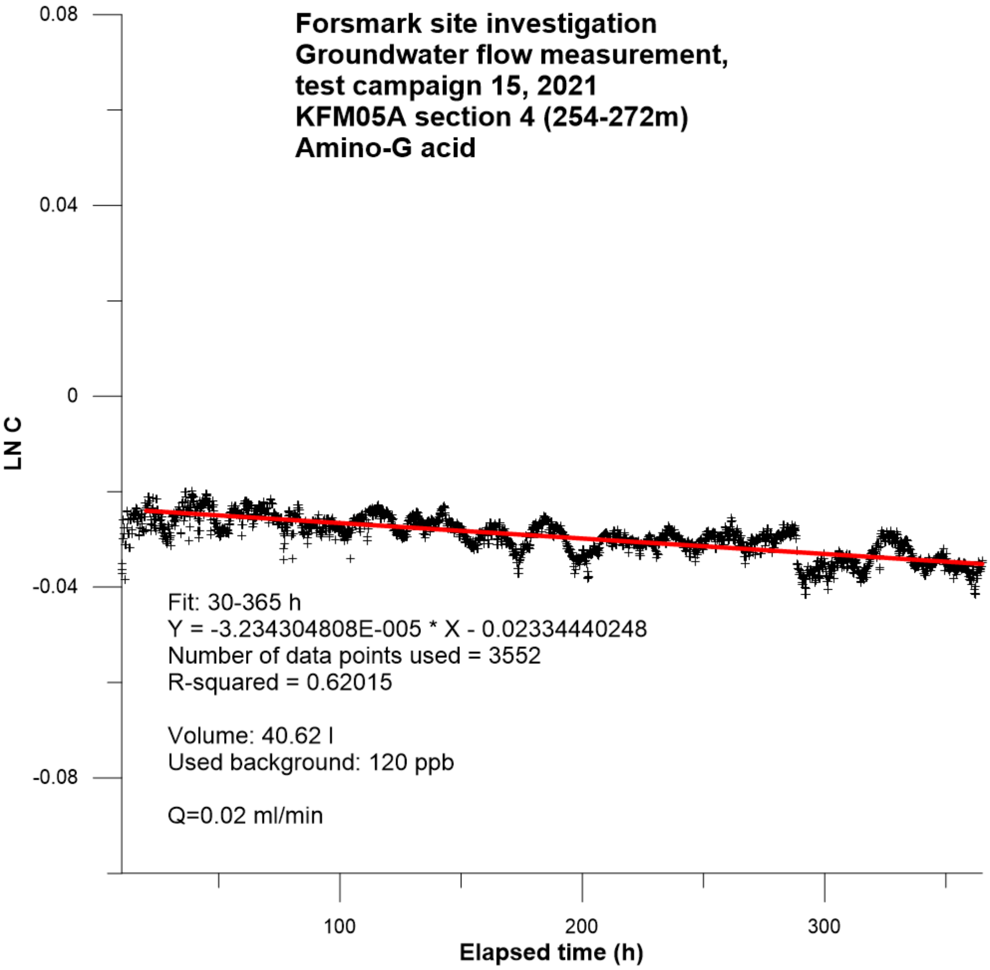
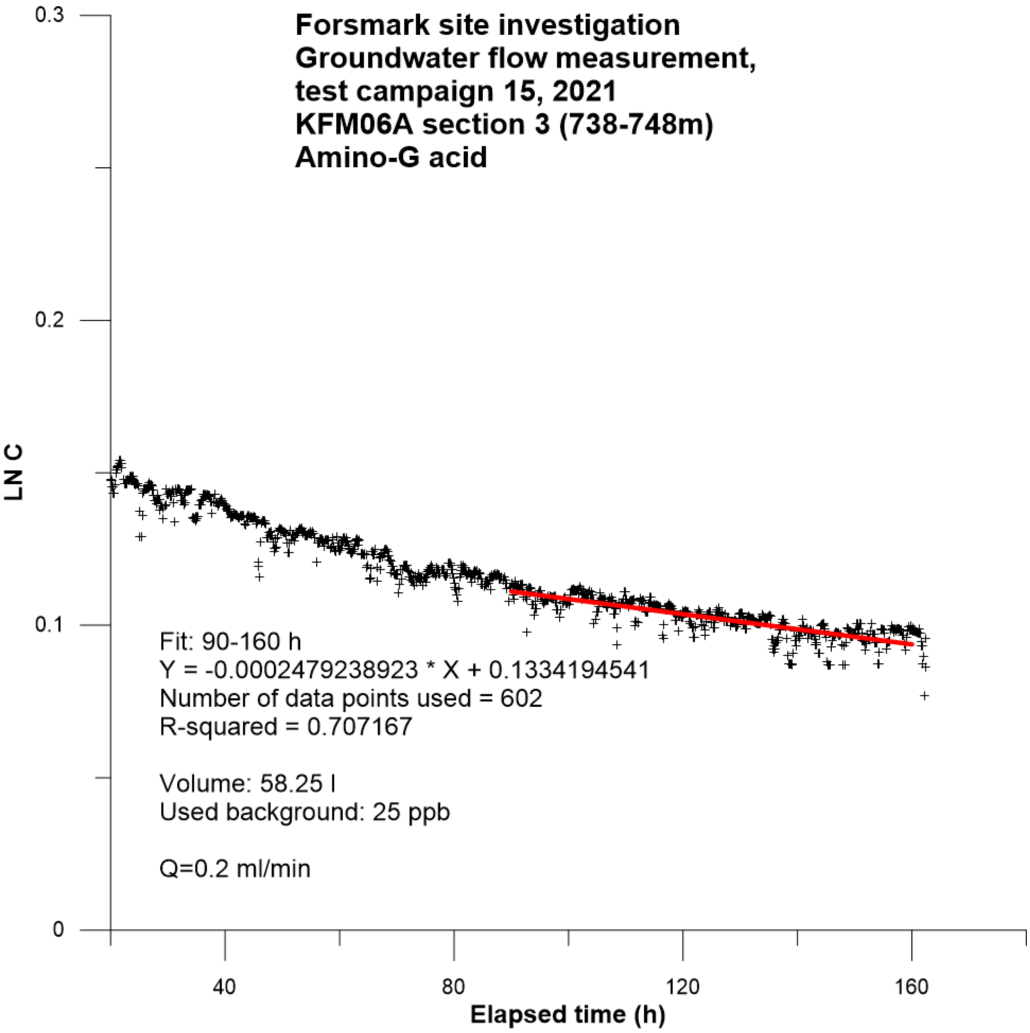
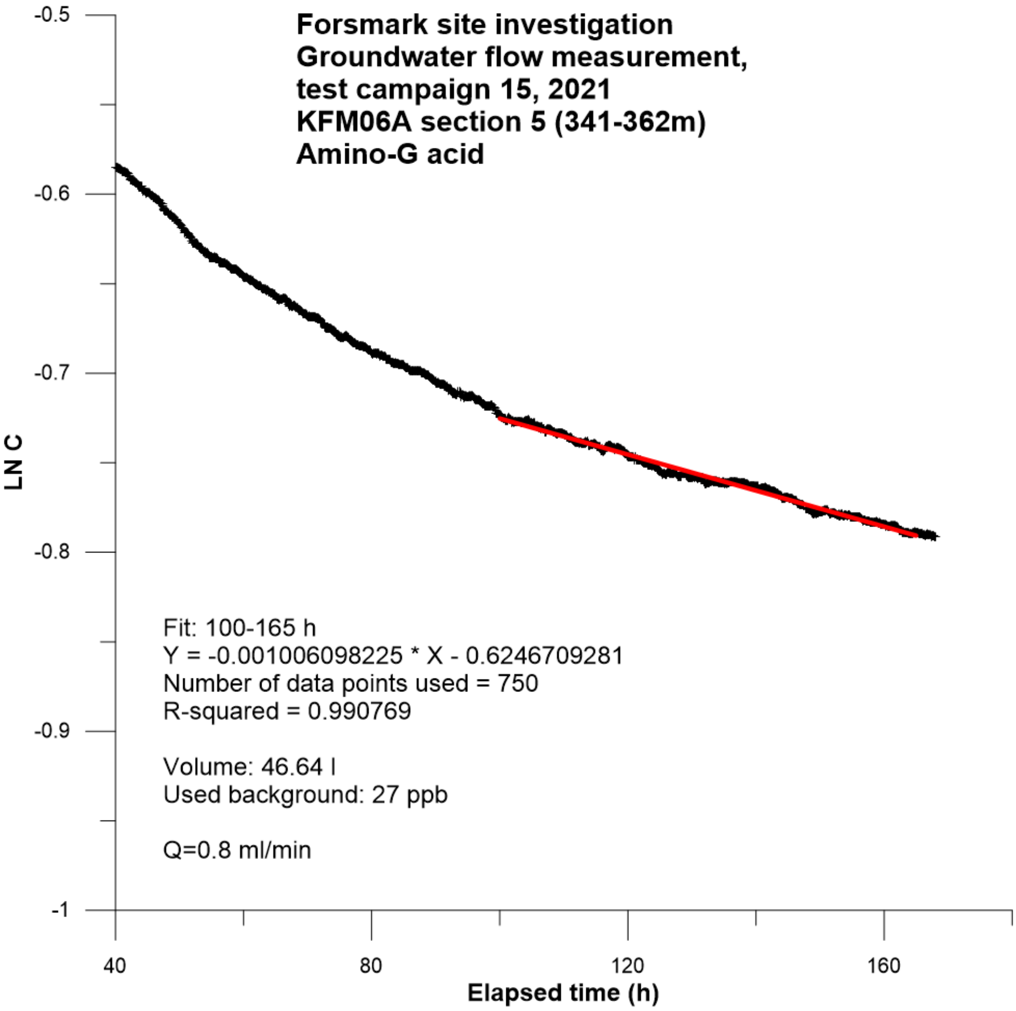
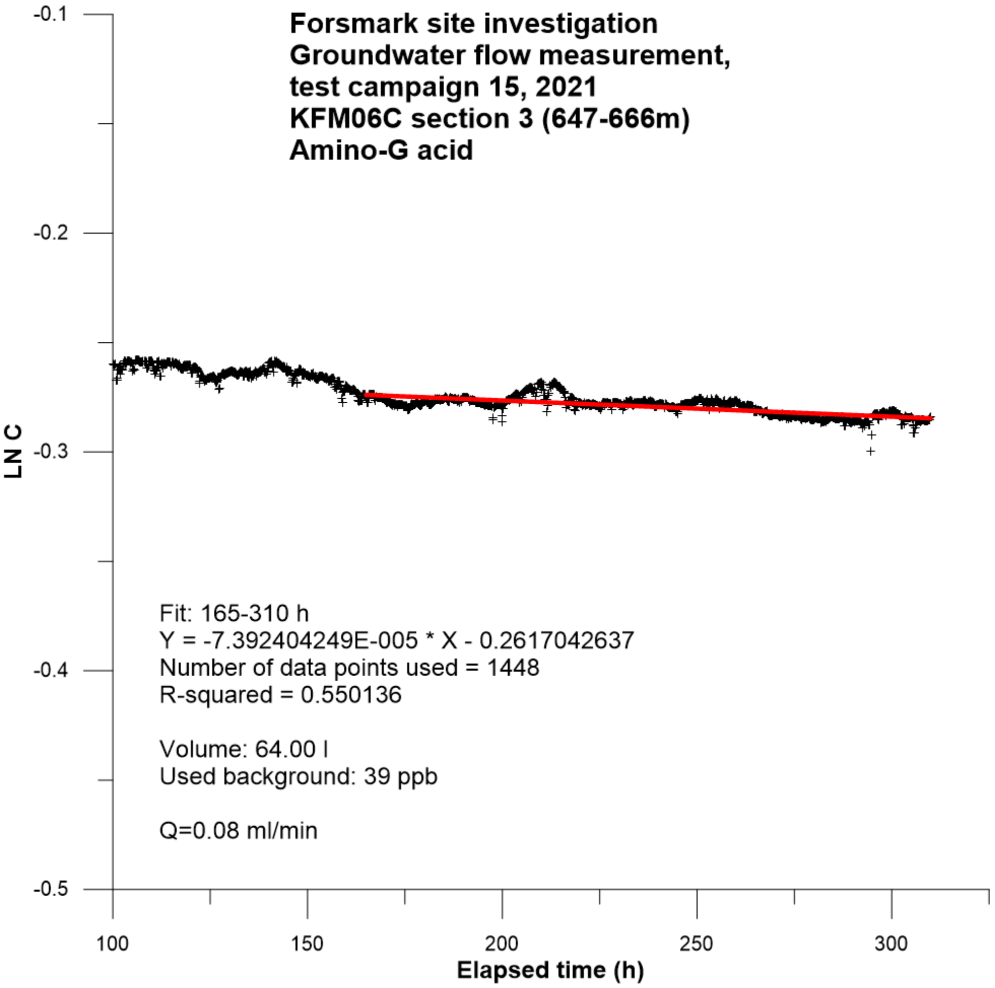
Groundwater flow measurement,
test campaign 15, 2021
KFM04A section 4 (230-245m)
Amino-G acid
Fit: 130-330 h
Y = -0.002402048502 * X - 0.3586147787
Number of data points used = 2343
R-squared = 0.996091
Volume: 35.00 l
Used background: 17 ppb
Q=1.4 ml/min
LN C
-0.4
-0.6
-0.8
-1
-1.2
-1.4
100
150
200
250
300
350
Elapsed time (h)

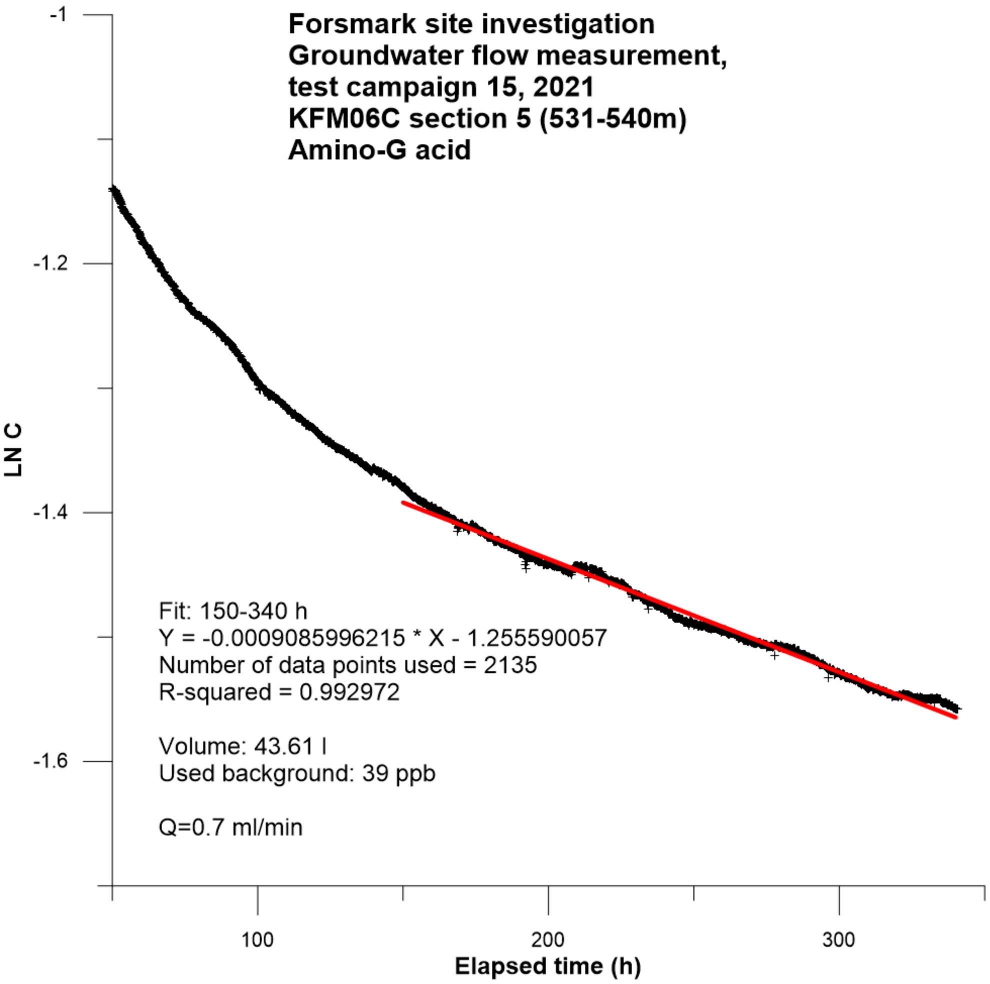

Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM05A section 4 (254-272m)
Amino-G acid
0.08
0.04
0
-0.04
-0.08
LN C
Fit: 30-365 h
Y = -3.234304808E-005 * X - 0.02334440248
Number of data points used = 3552
R-squared = 0.62015
Volume: 40.62 l
Used background: 120 ppb
Q=0.02 ml/min
100
200
300
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM06A section 3 (738-748m)
Amino-G acid
Fit: 90-160 h
Y = -0.0002479238923 * X + 0.1334194541
Number of data points used = 602
R-squared = 0.707167
Volume: 58.25 l
Used background: 25 ppb
Q=0.2 ml/min
LN C
0.3
0.2
0.1
0
40
80
120
160
Elapsed time (h)

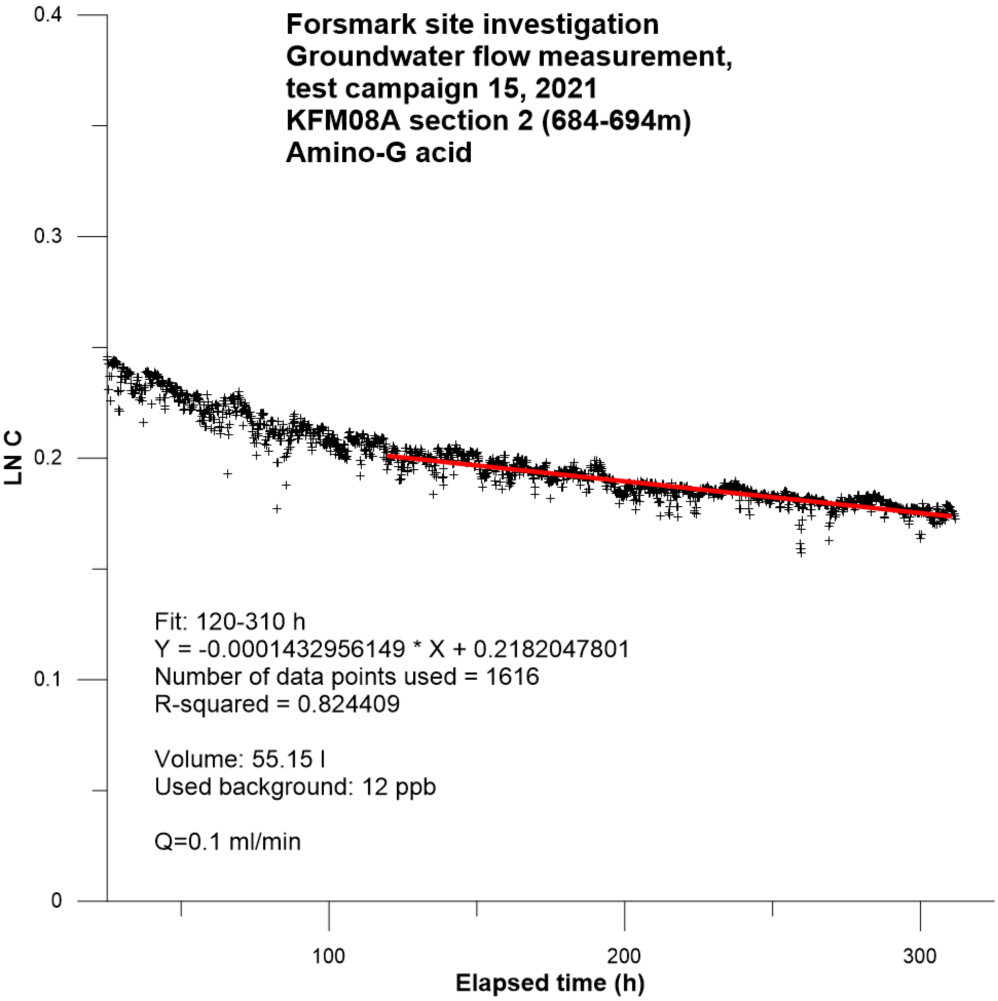

Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM06A section 5 (341-362m)
Amino-G acid
Fit: 100-165 h
Y = -0.001006098225 * X - 0.6246709281
Number of data points used = 750
R-squared = 0.990769
Volume: 46.64 l
Used background: 27 ppb
Q=0.8 ml/min
LN C
-0.5
-0.6
-0.7
-0.8
-0.9
-1
40
80
120
160
Elapsed time (h)



Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM06C section 3 (647-666m)
Amino-G acid
Fit: 165-310 h
Y = -7.392404249E-005 * X - 0.2617042637
Number of data points used = 1448
R-squared = 0.550136
Volume: 64.00 l
Used background: 39 ppb
Q=0.08 ml/min
LN C
-0.1
-0.2
-0.3
-0.4
-0.5
100
150
200
250
300
Elapsed time (h)



Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM06C section 5 (531-540m)
Amino-G acid
Fit: 150-340 h
Y = -0.0009085996215 * X - 1.255590057
Number of data points used = 2135
R-squared = 0.992972
Volume: 43.61 l
Used background: 39 ppb
Q=0.7 ml/min
LN C
Elapsed time (h)
-1
-1.2
-1.4
-1.6
100
200
300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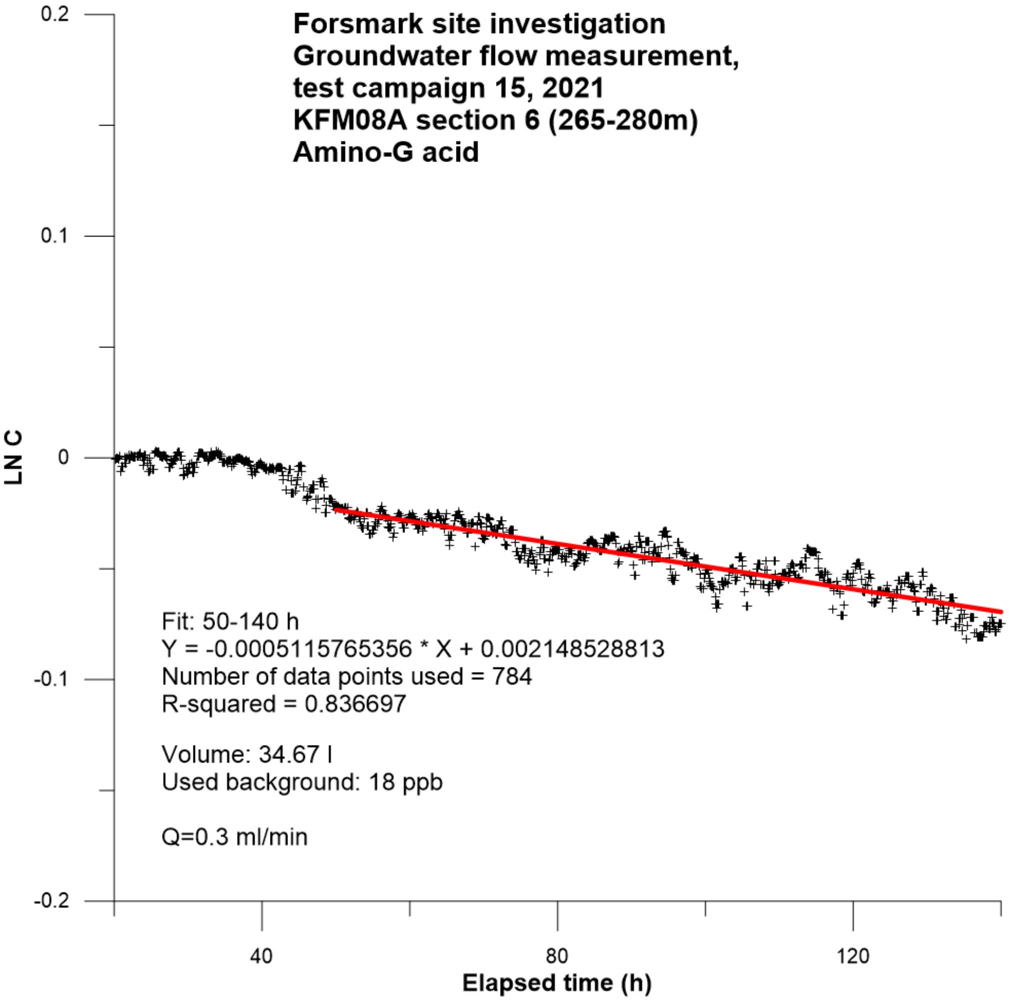
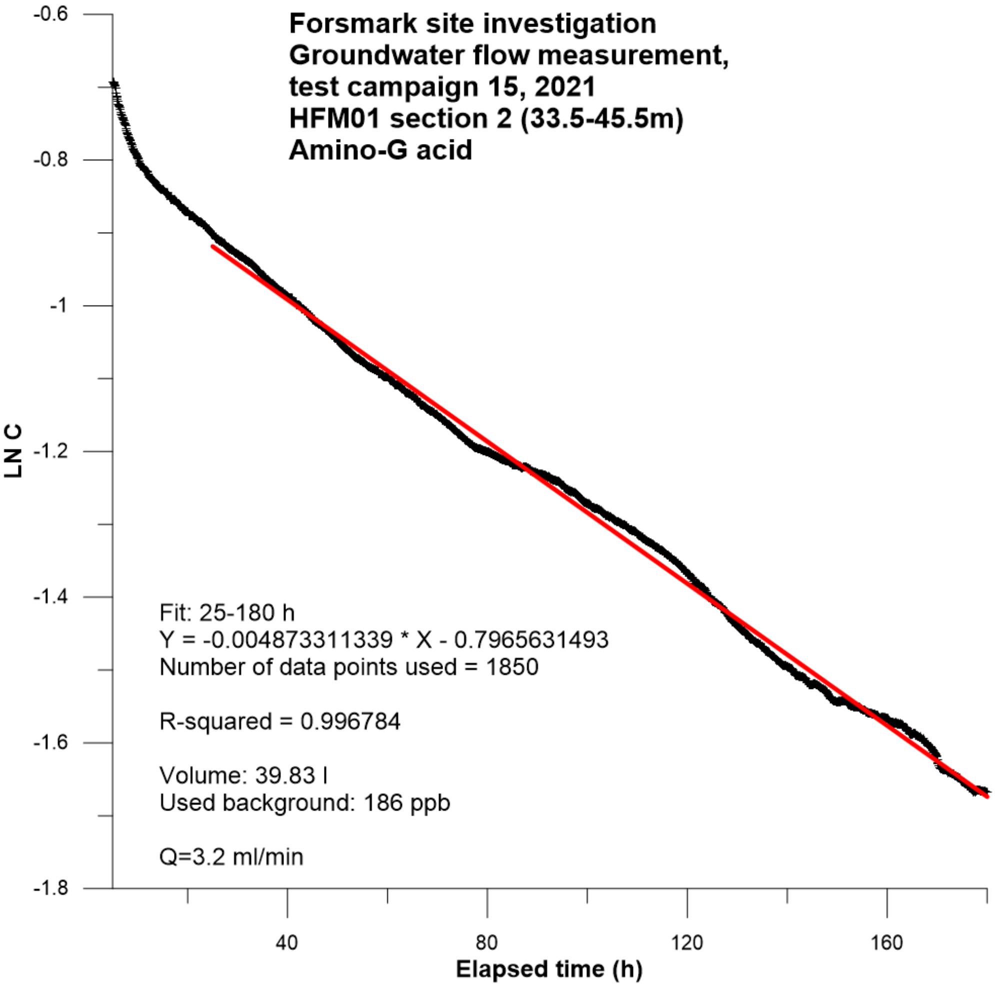
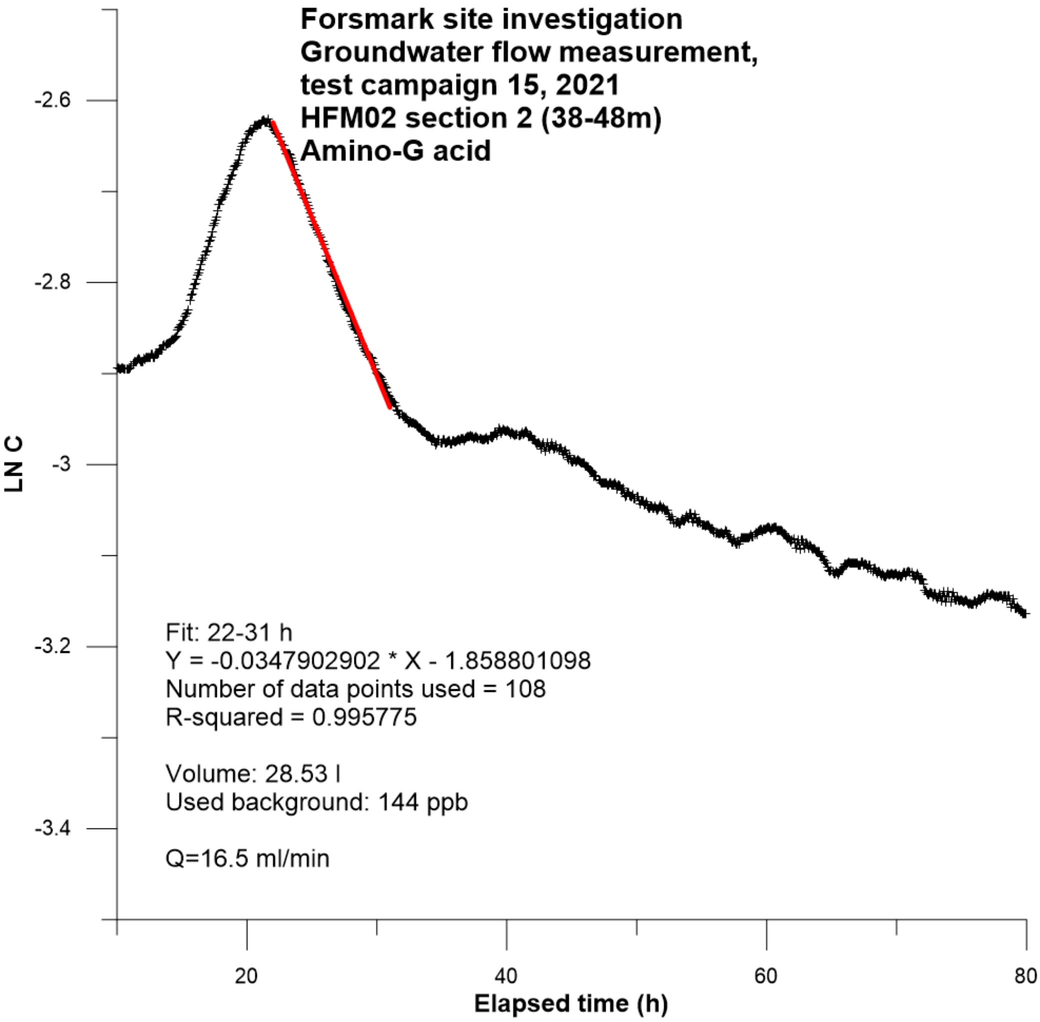
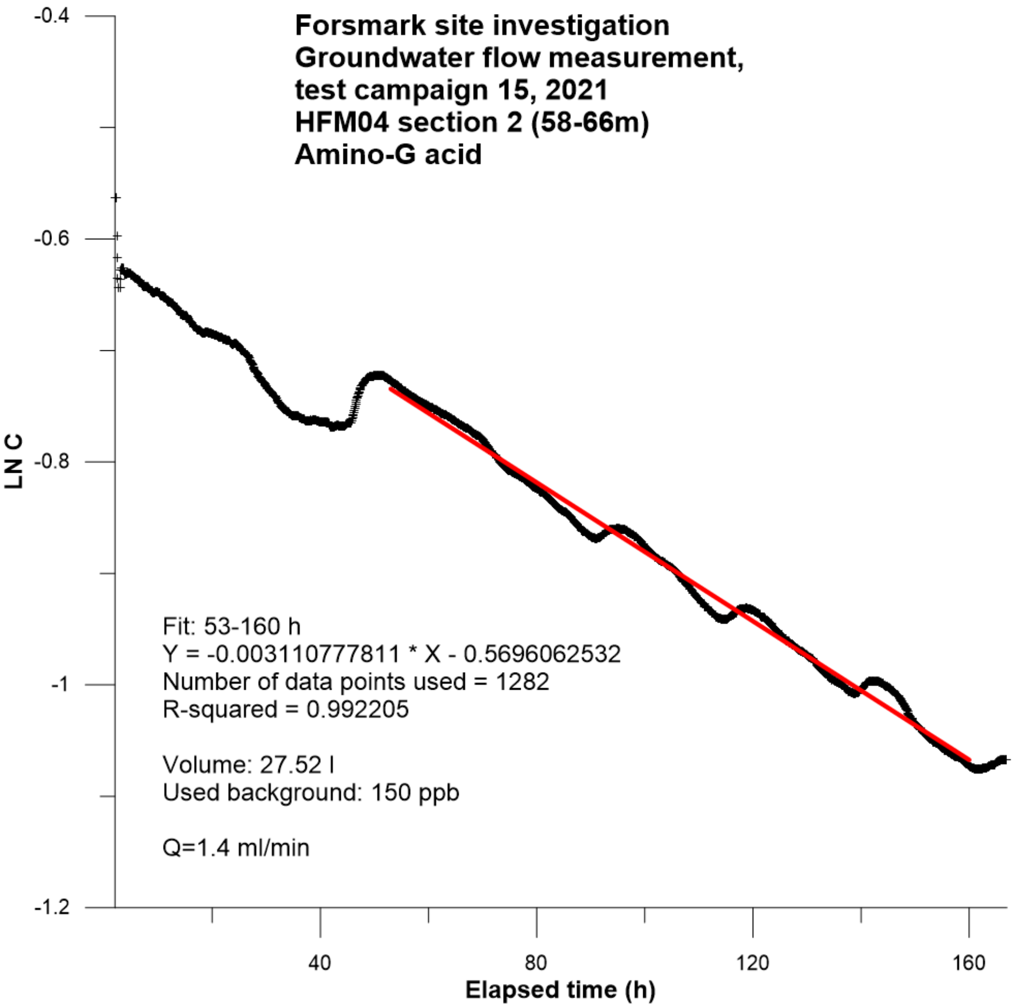
Groundwater flow measurement,
test campaign 15, 2021
KFM08A section 2 (684-694m)
Amino-G acid
Fit: 120-310 h
Y = -0.0001432956149 * X + 0.2182047801
Number of data points used = 1616
R-squared = 0.824409
Volume: 55.15 l
Used background: 12 ppb
Q=0.1 ml/min
0.4
0.3
0.2
0.1
0
LN C
100
200
300
Elapsed time (h)

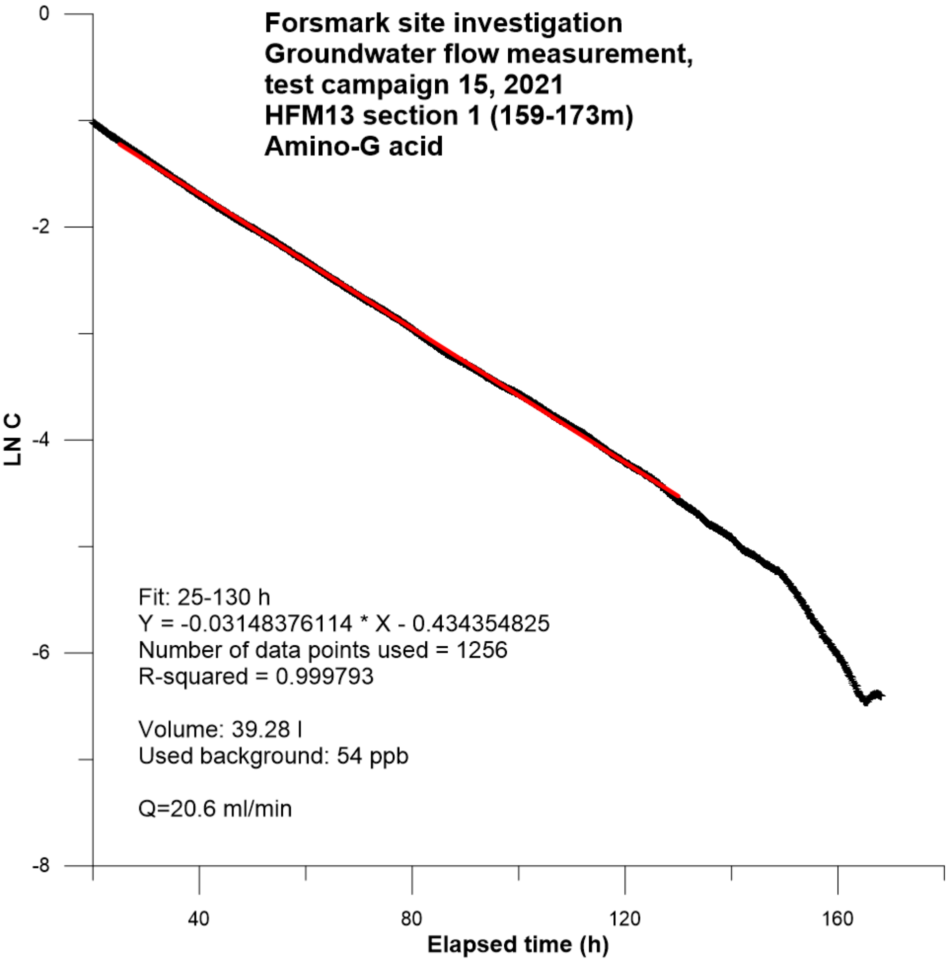

Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
KFM08A section 6 (265-280m)
Amino-G acid
Fit: 50-140 h
Y = -0.0005115765356 * X + 0.002148528813
Number of data points used = 784
R-squared = 0.836697
Volume: 34.67 l
Used background: 18 ppb
Q=0.3 ml/min
LN C
0.2
0.1
0
-0.1
-0.2
40
80
120
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM01 section 2 (33.5-45.5m)
Amino-G acid
Fit: 25-180 h
Y = -0.004873311339 * X - 0.7965631493
Number of data points used = 1850
R-squared = 0.996784
Volume: 39.83 l
Used background: 186 ppb
Q=3.2 ml/min
LN C
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
40
80
120
160
Elapsed time (h)

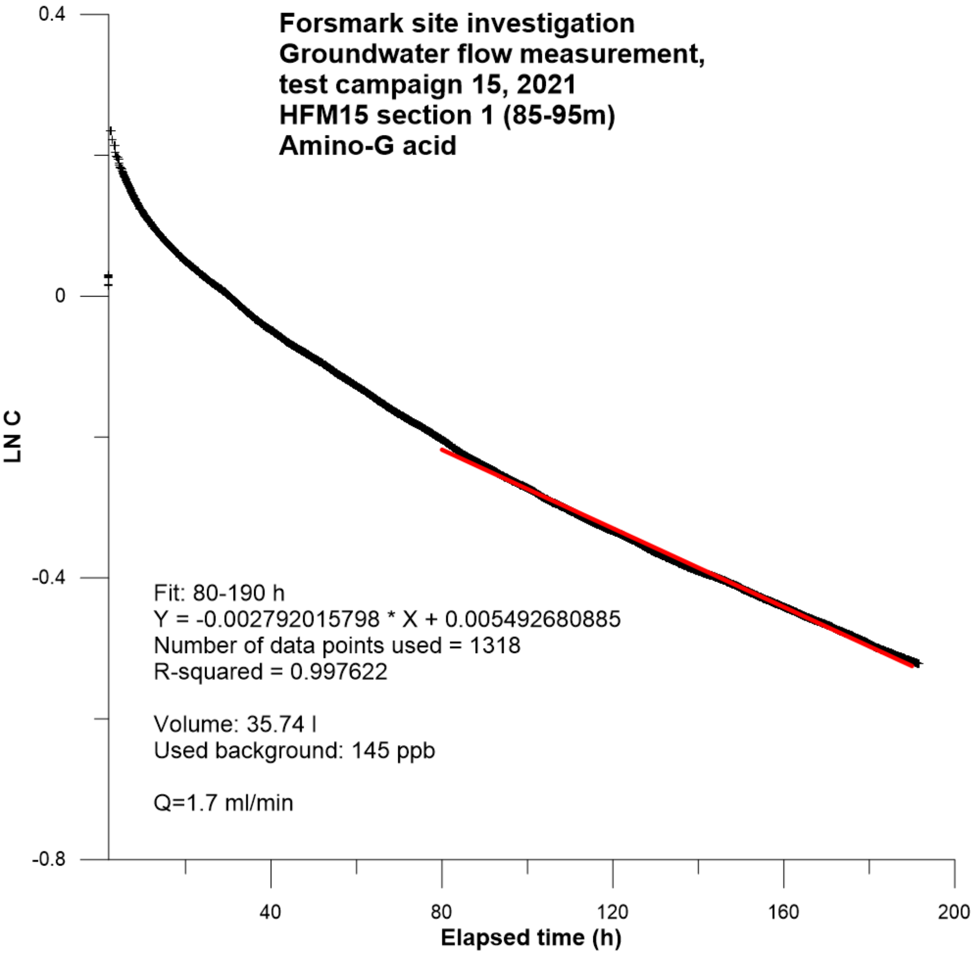

Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM02 section 2 (38-48m)
Amino-G acid
Fit: 22-31 h
Y = -0.0347902902 * X - 1.858801098
Number of data points used = 108
R-squared = 0.995775
Volume: 28.53 l
Used background: 144 ppb
Q=16.5 ml/min
LN C
-2.6
-2.8
-3
-3.2
-3.4
20
40
60
80
Elapsed time (h)



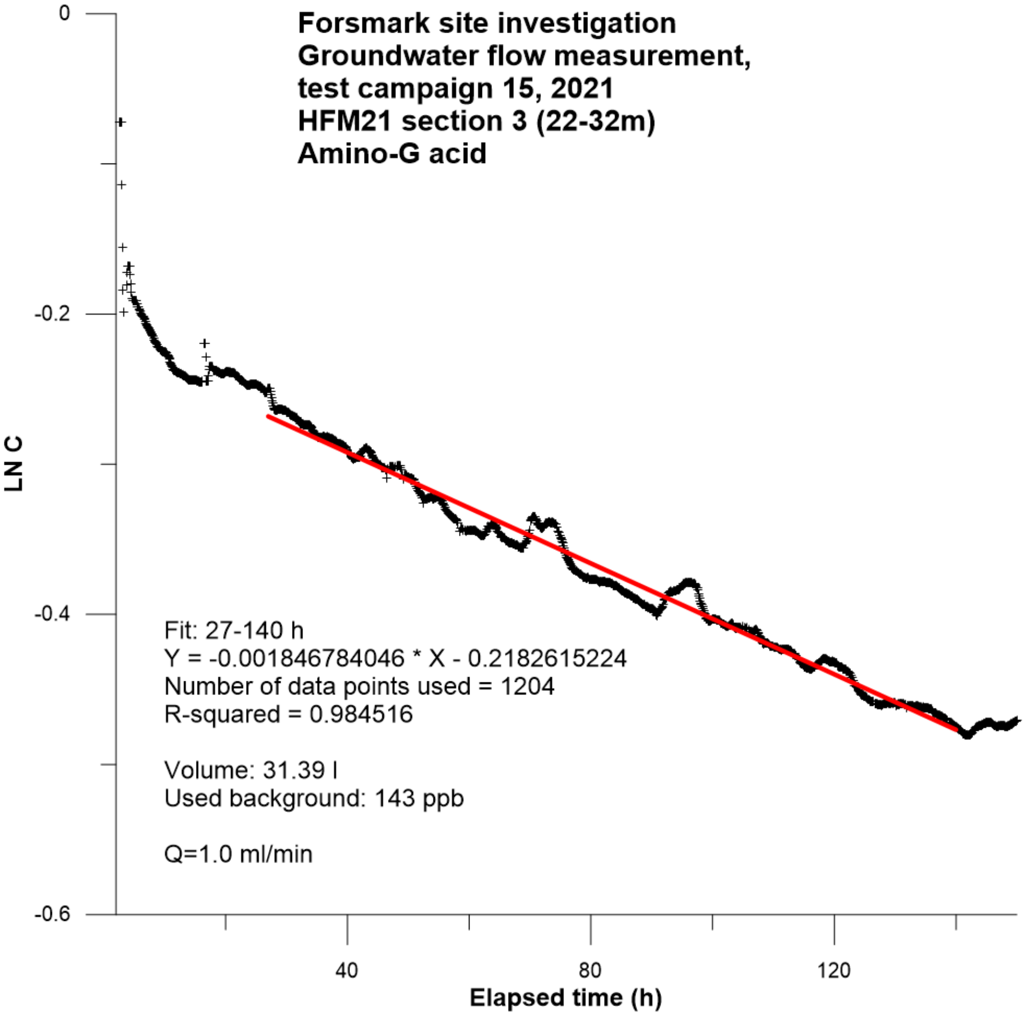
Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM04 section 2 (58-66m)
Amino-G acid
Fit: 53-160 h
Y = -0.003110777811 * X - 0.5696062532
Number of data points used = 1282
R-squared = 0.992205
Volume: 27.52 l
Used background: 150 ppb
Q=1.4 ml/min
LN C
-0.4
-0.6
-0.8
-1
-1.2
40
80
120
160
Elapsed time (h)



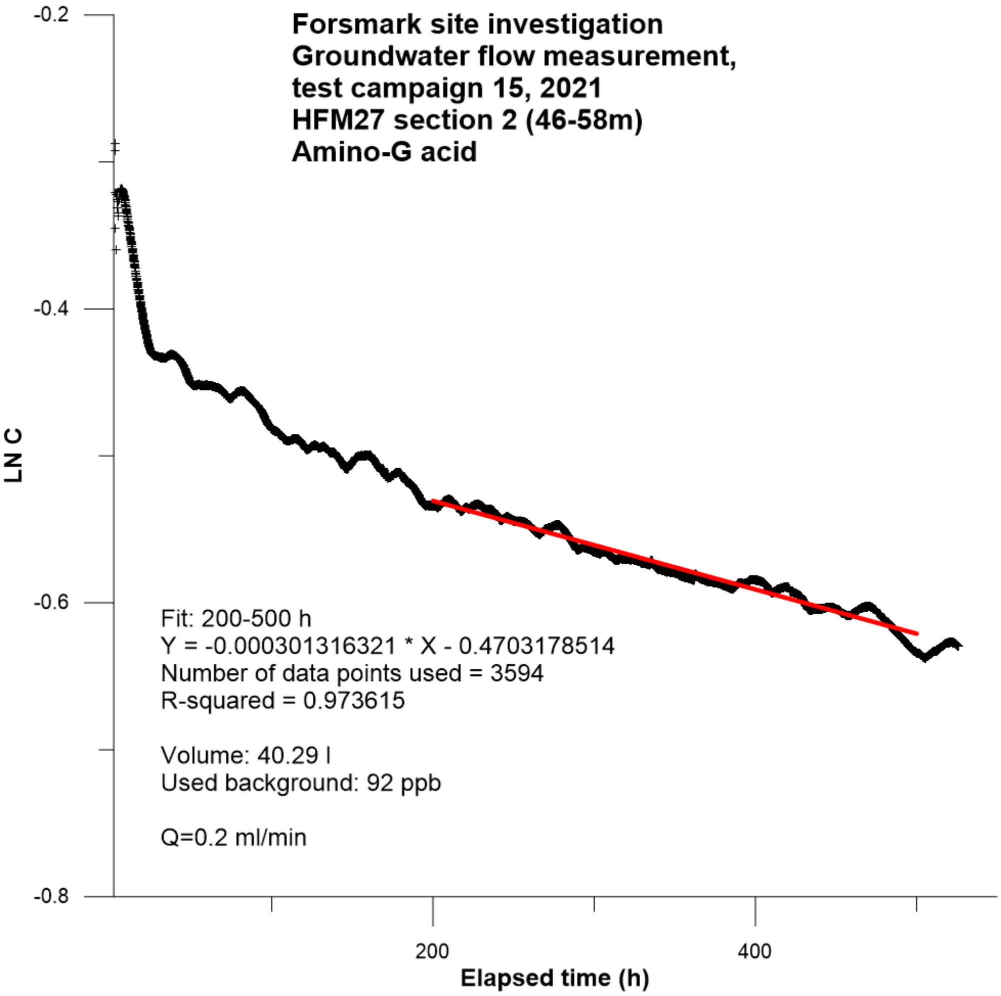
Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM13 section 1 (159-173m)
Amino-G acid
Fit: 25-130 h
Y = -0.03148376114 * X - 0.434354825
Number of data points used = 1256
R-squared = 0.999793
Volume: 39.28 l
Used background: 54 ppb
Q=20.6 ml/min
LN C
0
-2
-4
-6
-8
40
80
120
160
Elapsed time (h)



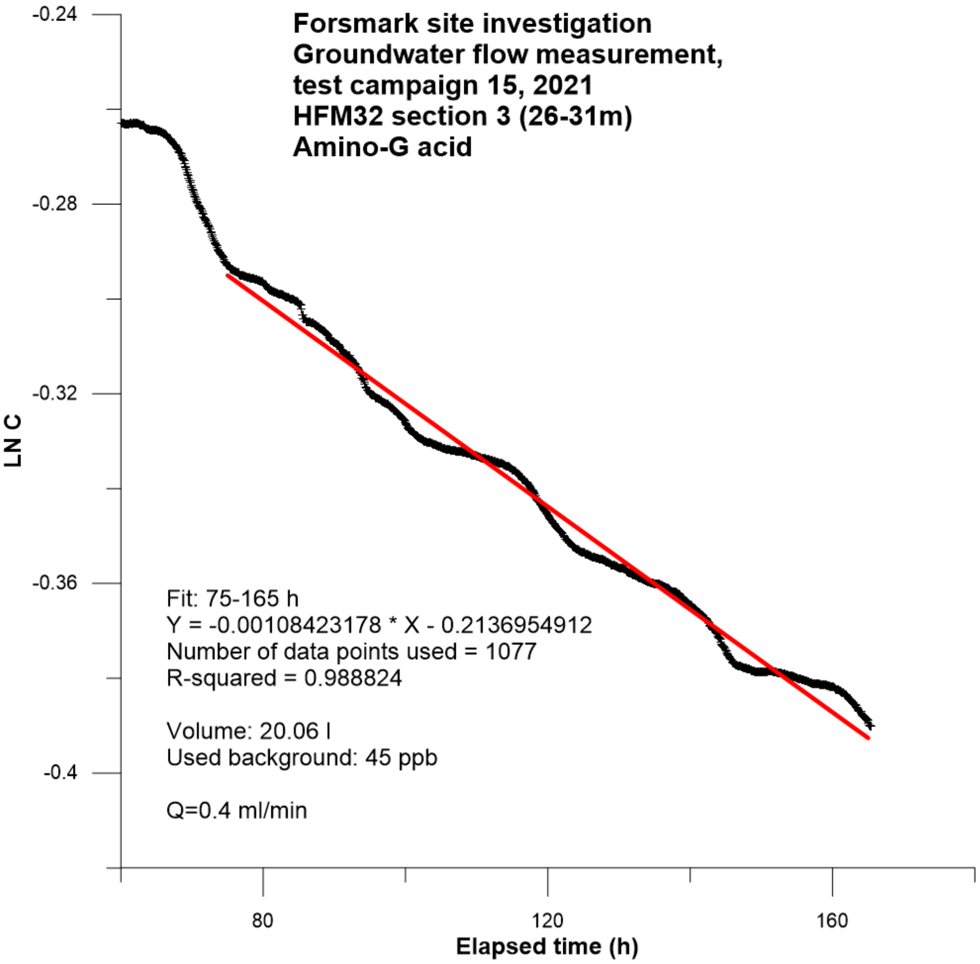
Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM15 section 1 (85-95m)
Amino-G acid
Fit: 80-190 h
Y = -0.002792015798 * X + 0.005492680885
Number of data points used = 1318
R-squared = 0.997622
Volume: 35.74 l
Used background: 145 ppb
Q=1.7 ml/min
0.4
0
-0.4
-0.8
LN C
40
80
120
160
200
Elapsed time (h)

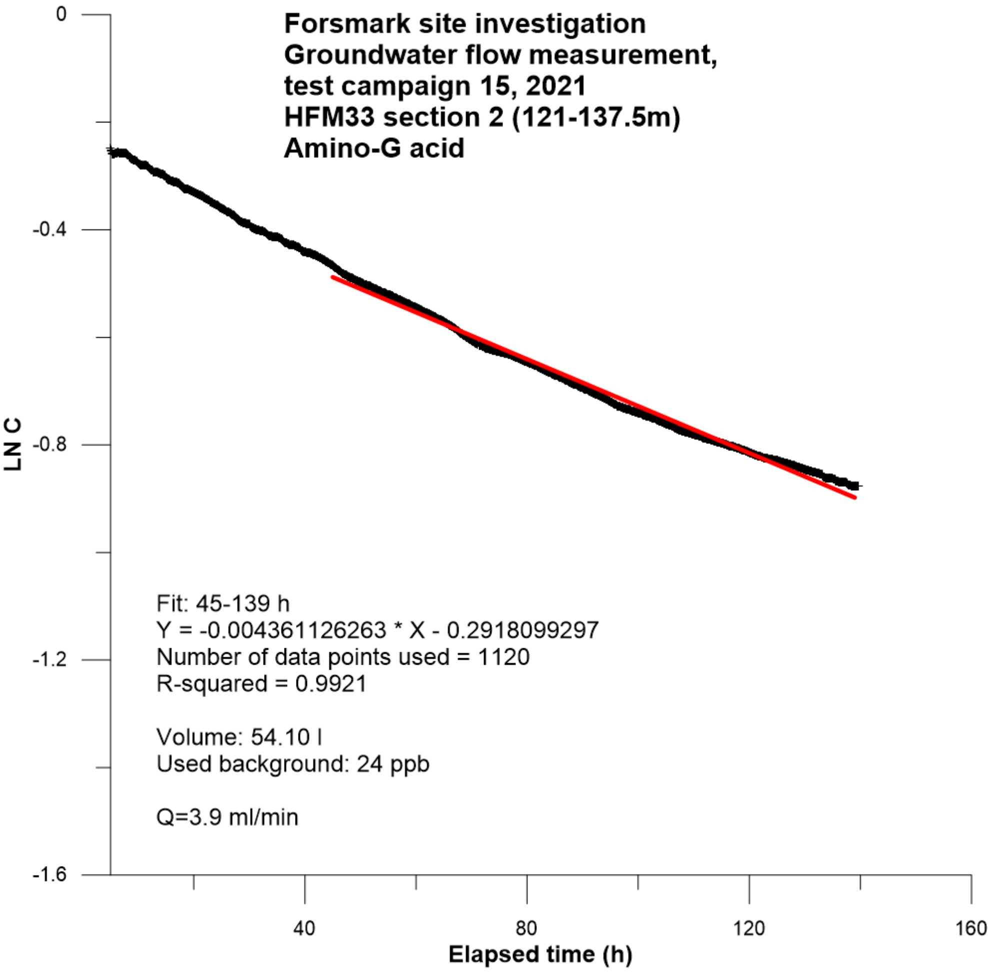


Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM21 section 3 (22-32m)
Amino-G acid
Fit: 27-140 h
Y = -0.001846784046 * X - 0.2182615224
Number of data points used = 1204
R-squared = 0.984516
Volume: 31.39 l
Used background: 143 ppb
Q=1.0 ml/min
LN C
Elapsed time (h)
0
-0.2
-0.4
-0.6
40
80
120



Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM27 section 2 (46-58m)
Amino-G acid
Fit: 200-500 h
Y = -0.000301316321 * X - 0.4703178514
Number of data points used = 3594
R-squared = 0.973615
Volume: 40.29 l
Used background: 92 ppb
Q=0.2 ml/min
-0.2
-0.4
-0.6
-0.8
LN C
200
400
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM32 section 3 (26-31m)
Amino-G acid
Fit: 75-165 h
Y = -0.00108423178 * X - 0.2136954912
Number of data points used = 1077
R-squared = 0.988824
Volume: 20.06 l
Used background: 45 ppb
Q=0.4 ml/min
-0.24
-0.28
-0.32
-0.36
-0.4
LN C
80
120
160
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 15, 2021
HFM33 section 2 (121-137.5m)
Amino-G acid
Fit: 45-139 h
Y = -0.004361126263 * X - 0.2918099297
Number of data points used = 1120
R-squared = 0.9921
Volume: 54.10 l
Used background: 24 ppb
Q=3.9 ml/min
LN C
0
-0.4
-0.8
-1.2
-1.6
40
80
120
160
Elapsed time (h)

Appendix 2

Precipitation Labbomasten (mm/24 hours) 2021-09-15 – 2021-11-15

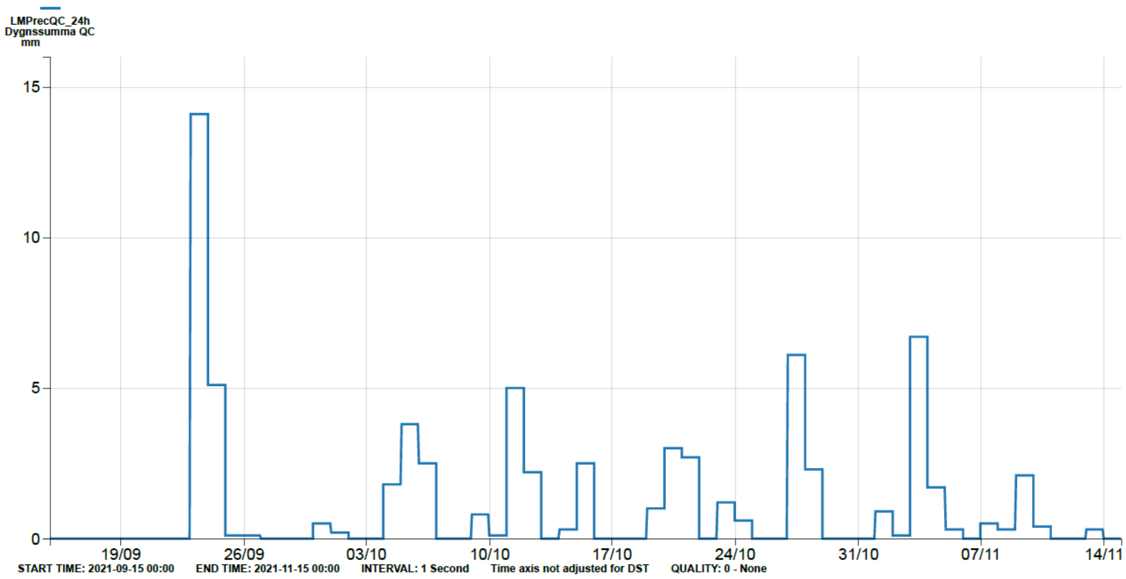


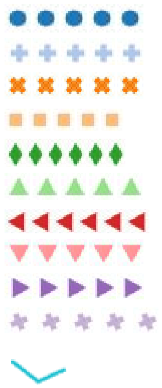
Figure A2-1. *Daily precipitation in Forsmark at the meteorological station "Labbomasten" during the field campaign, autumn 2021.*

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



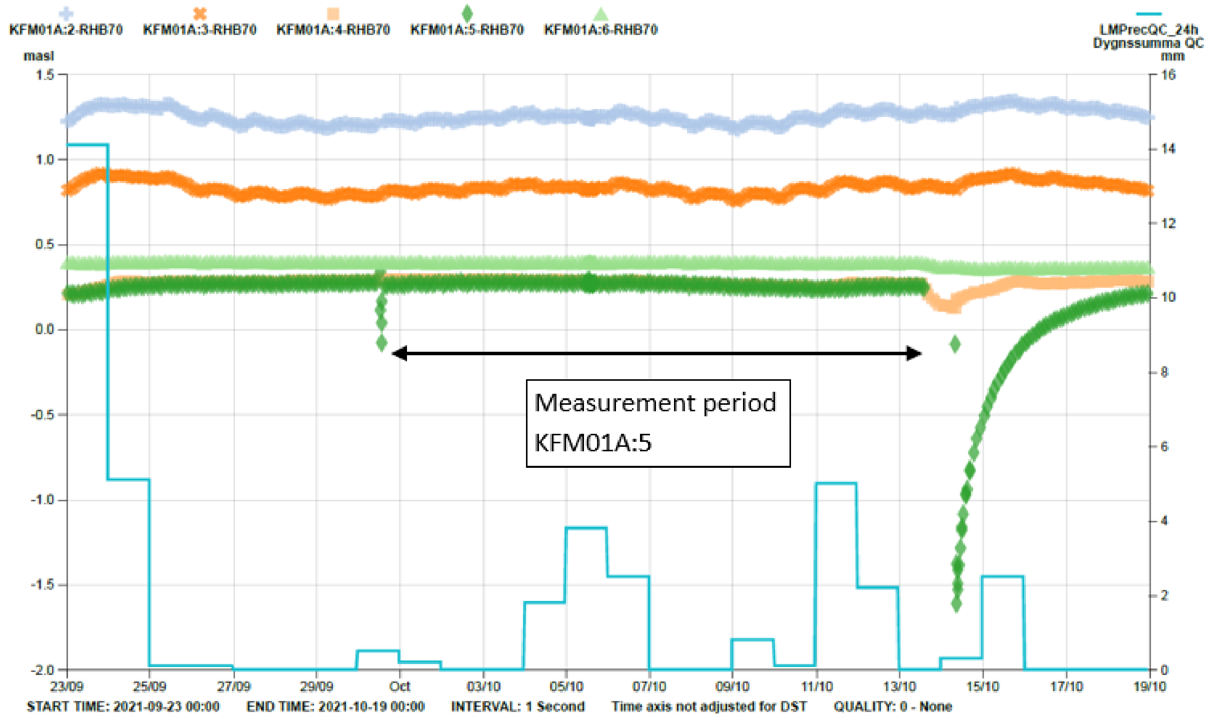


Figure A2-2. *Measured section: KFM01A:5 (dark green).*

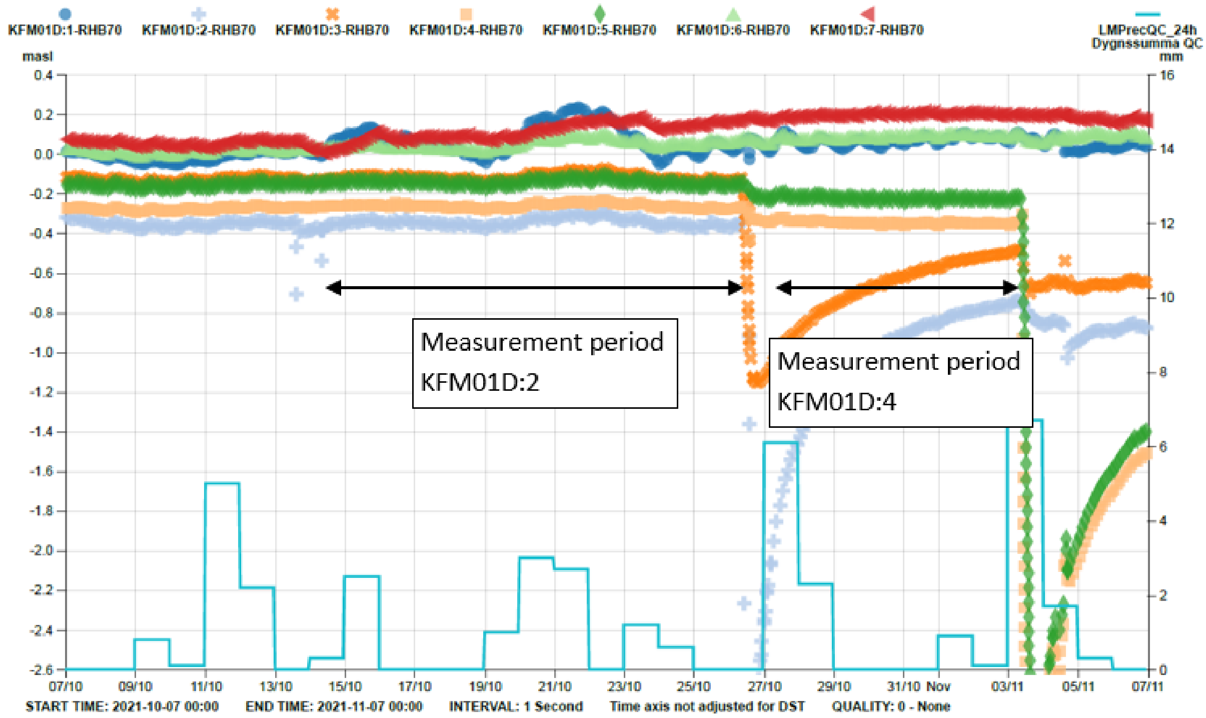


Figure A2-3. *Measured sections: KFM01D:2 (pale blue) and KFM01D:4 (pale orange).*

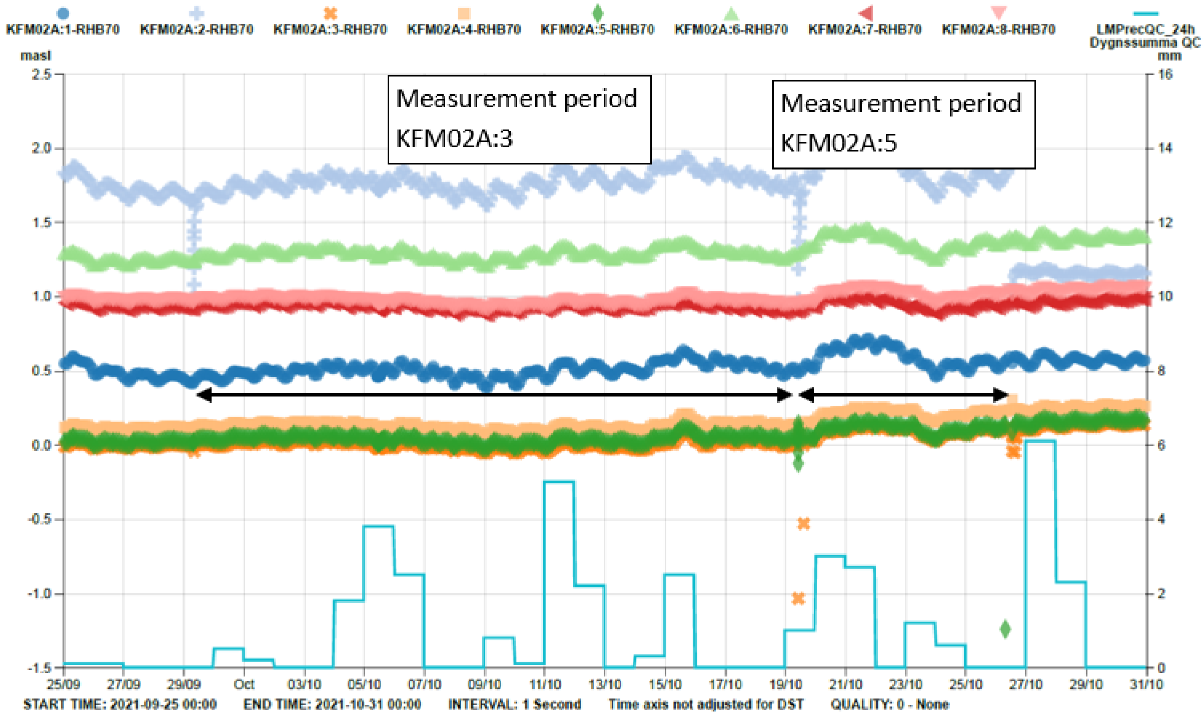


Figure A2-4. *Measured sections: KFM02A:3 (dark orange) and KFM02A:5 (dark green).*

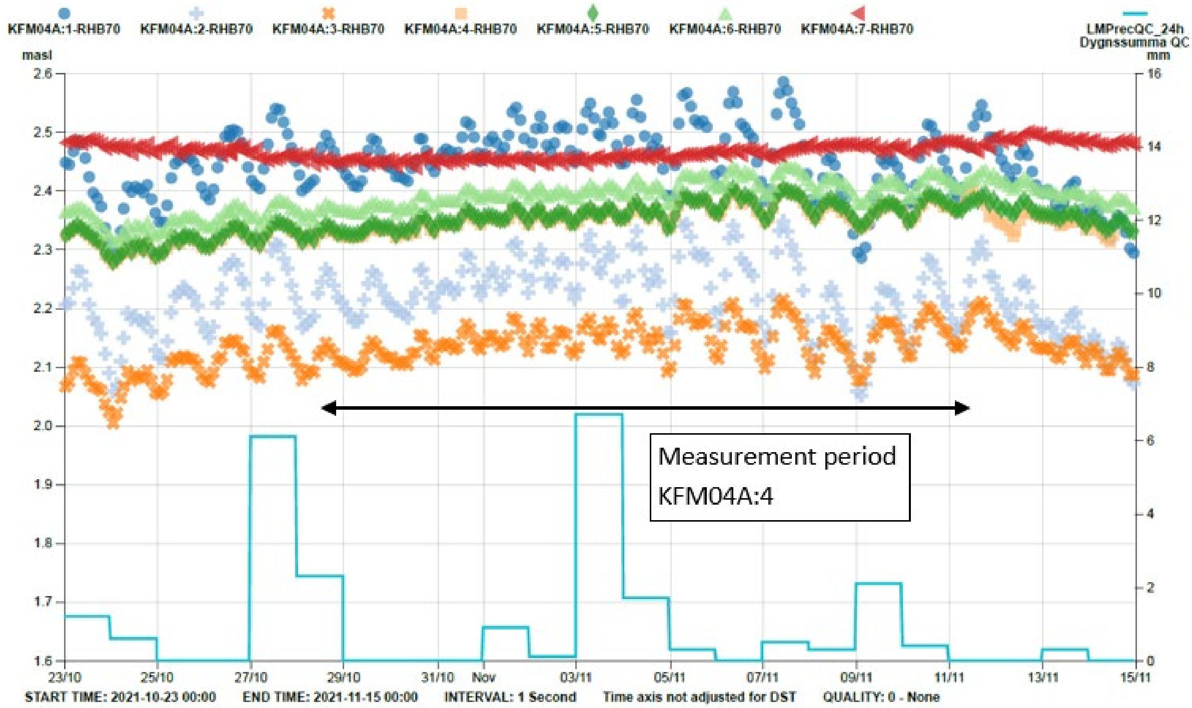


Figure A2-5. *Measured section: KFM04A:4 (pale orange, mostly hidden behind section 5, dark green).*

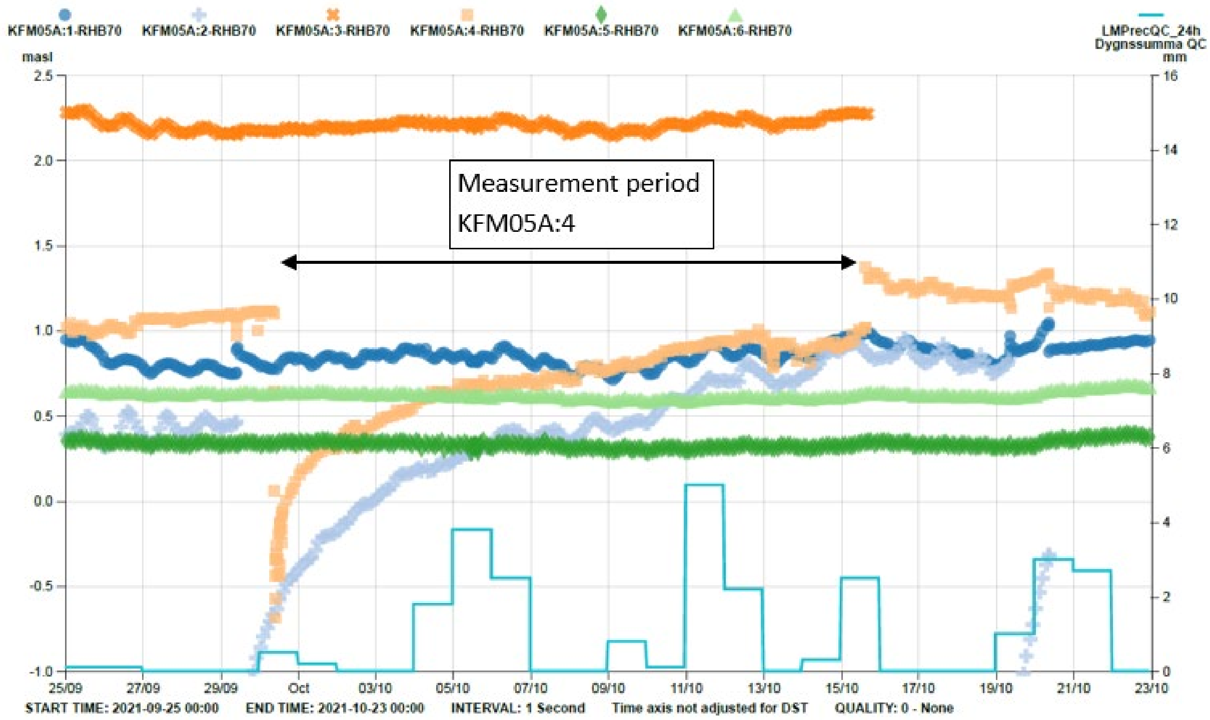


Figure A2-6. *Measured section: KFM05A:4 (pale orange).*

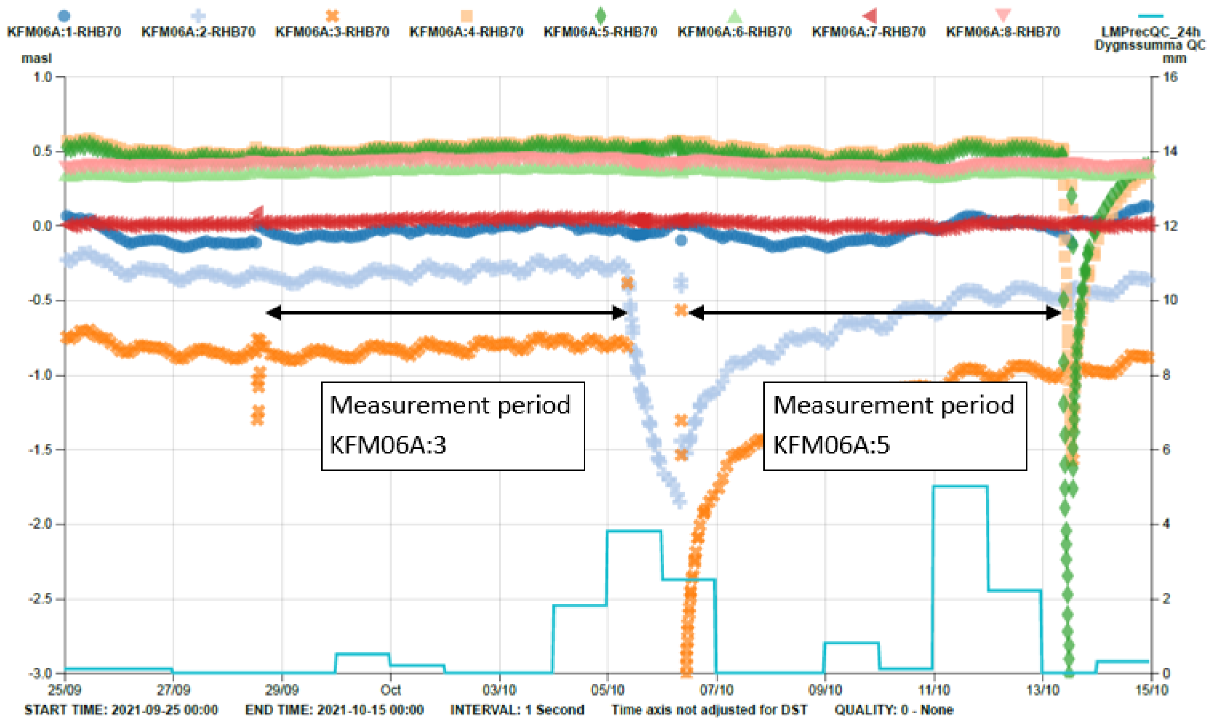


Figure A2-7. *Measured sections: KFM06A:3 (dark orange) and KFM06A:5 (dark green).*

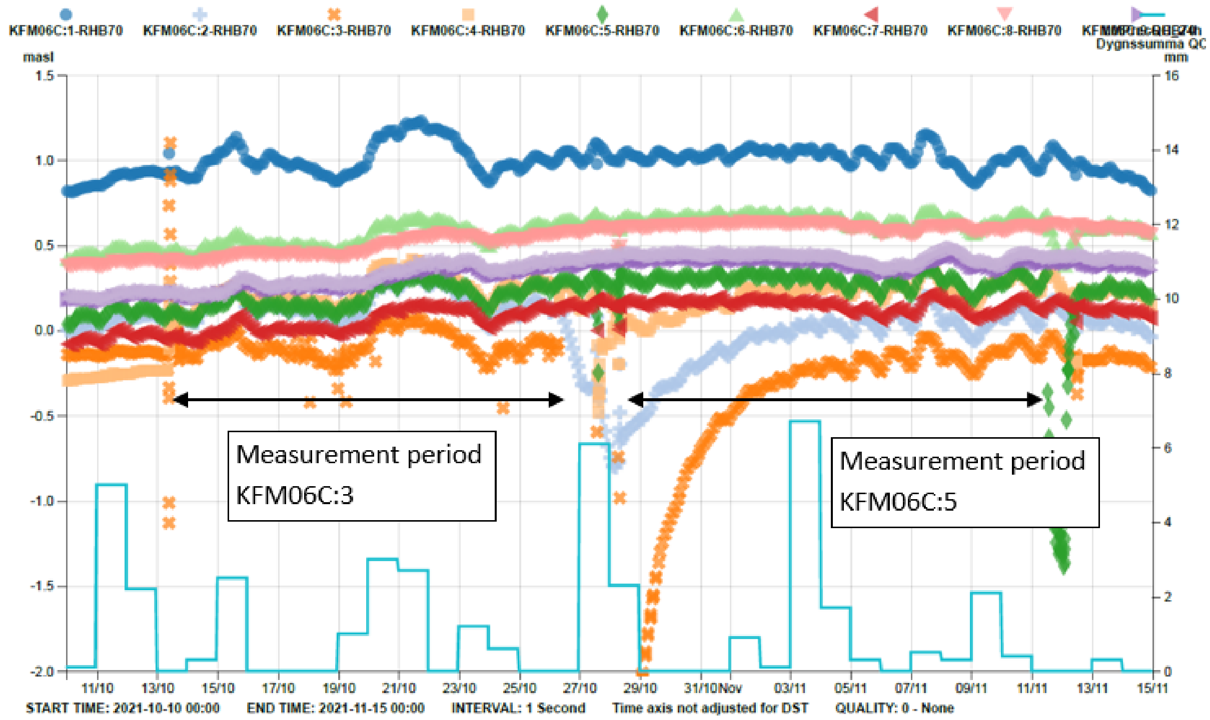


Figure A2-8. *Measured sections: KFM06C:3 (dark orange) and KFM06C:5 (dark green).*

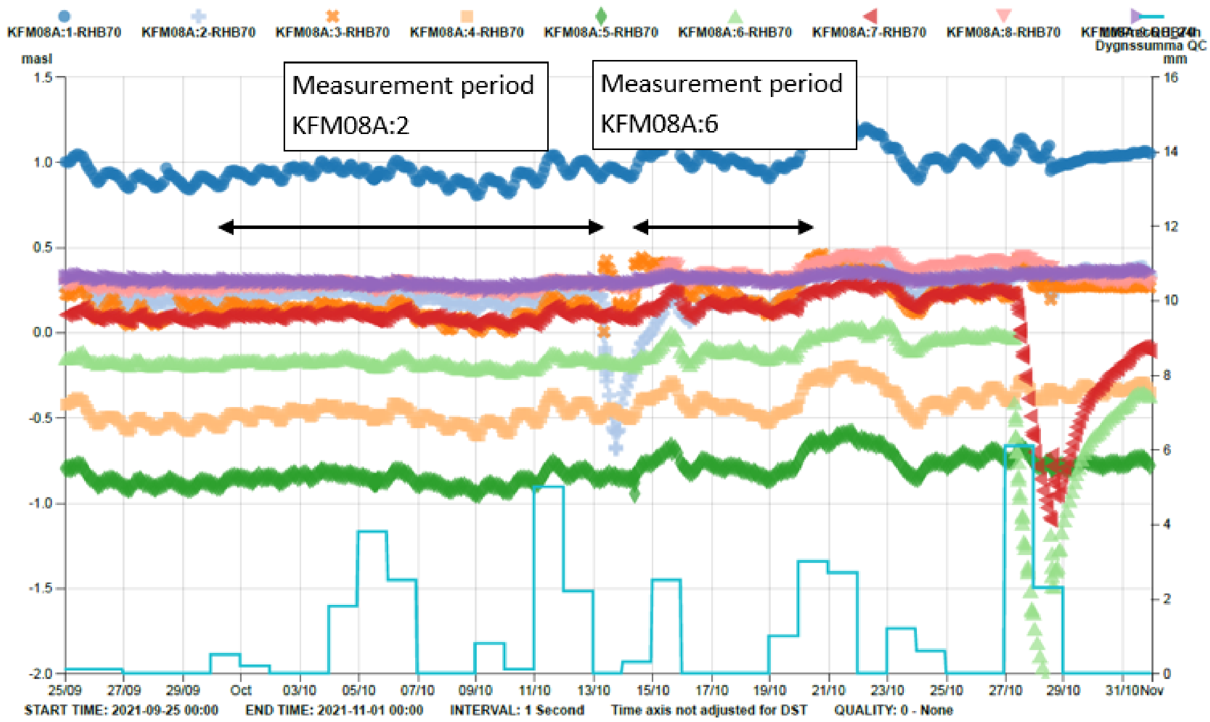


Figure A2-9. *Measured sections: KFM08A:2 (pale blue) and KFM08A:6 (pale green).*

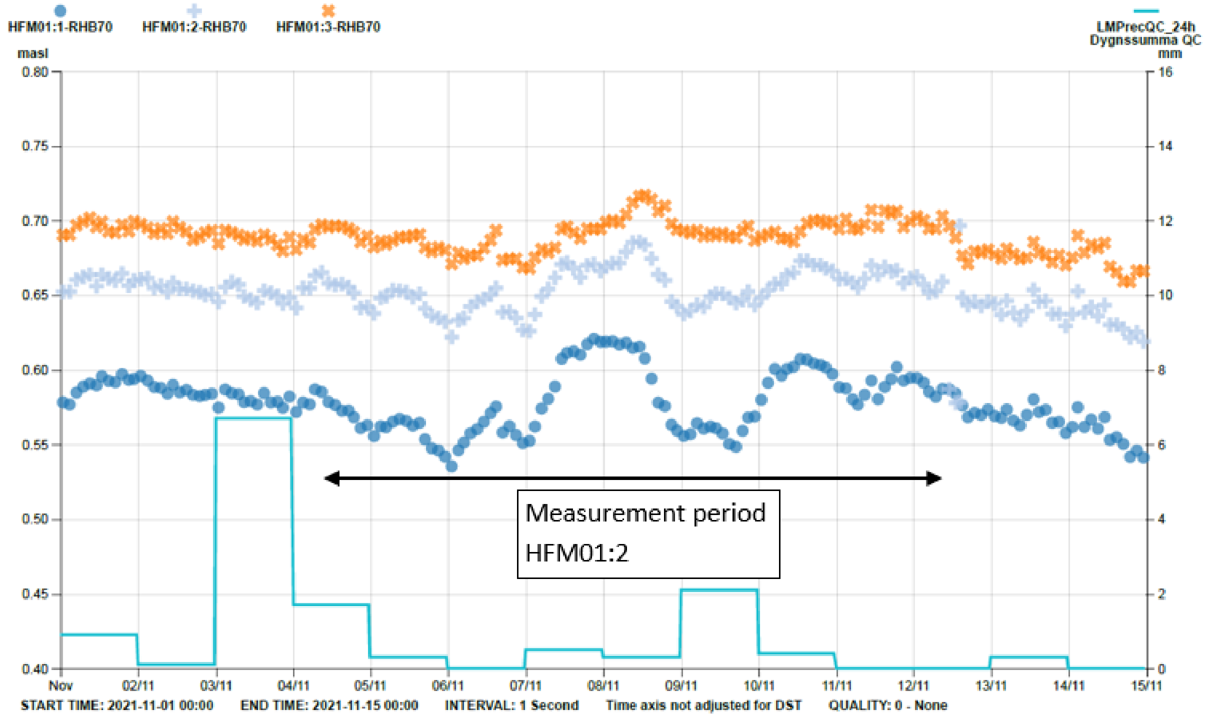


Figure A2-10. *Measured section: HFM01:2 (pale blue).*

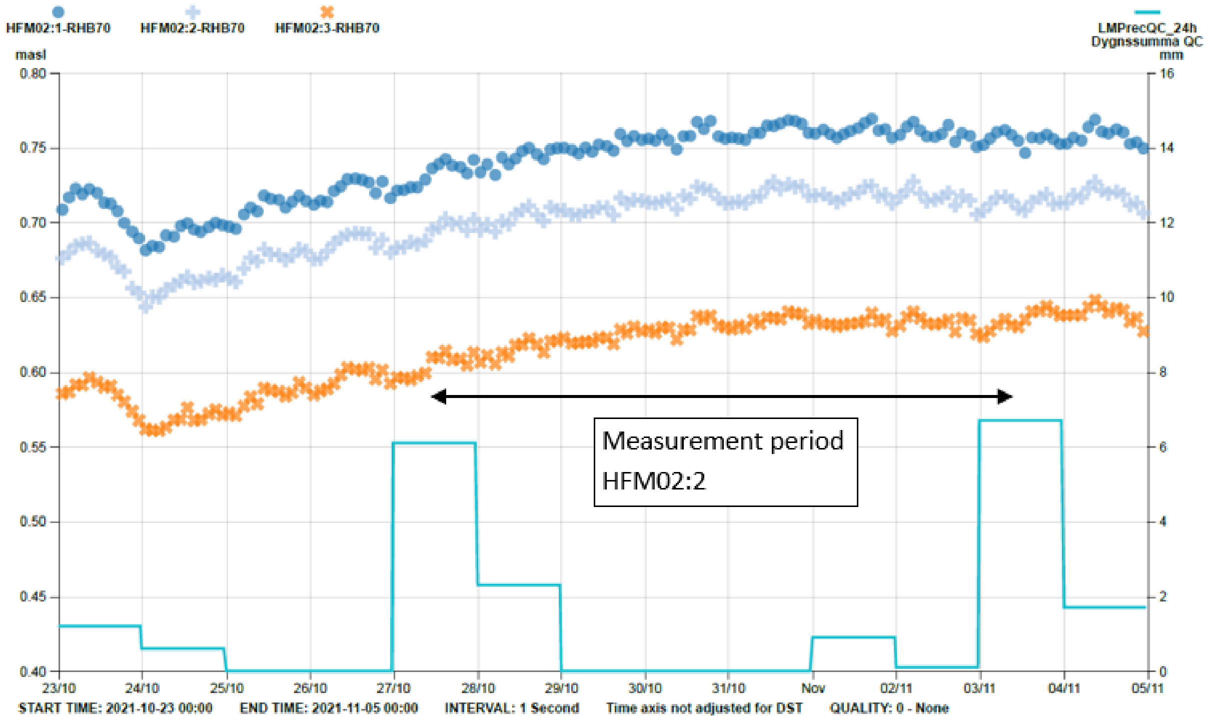


Figure A2-11. *Measured section: HFM02:2 (pale blue).*

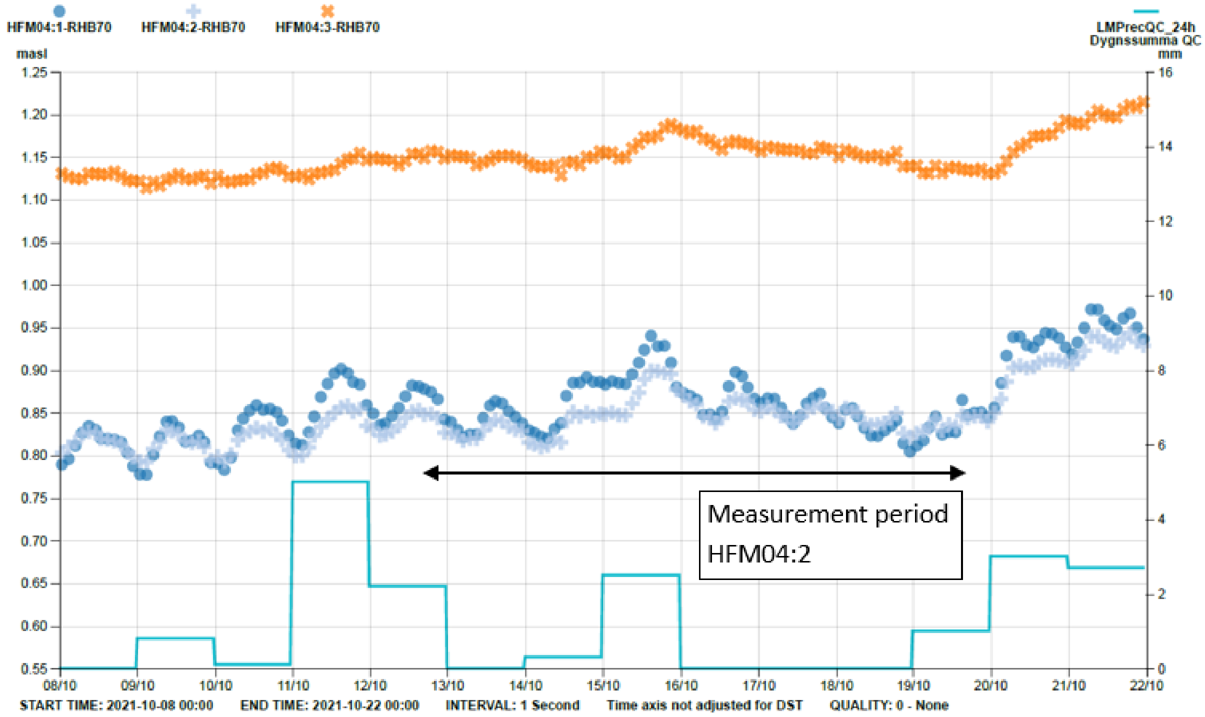


Figure A2-12. *Measured section: HFM04:2 (pale blue).*

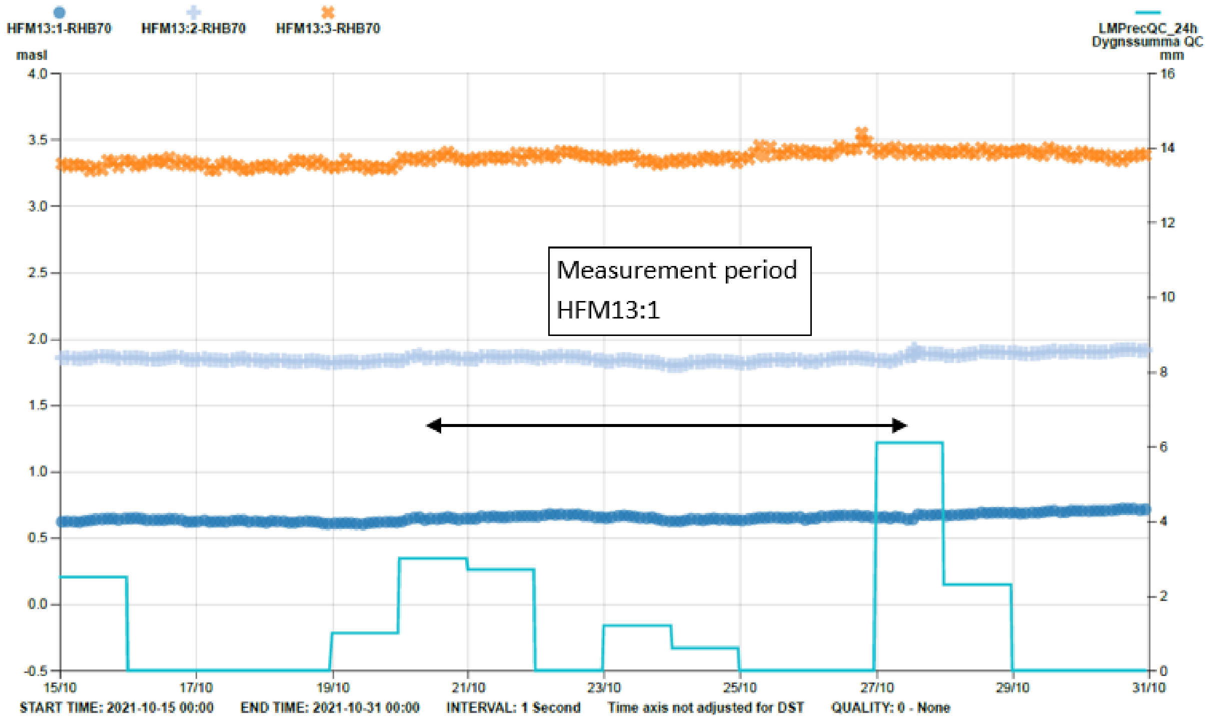


Figure A2-13. *Measured section: HFM13:1 (dark blue).*

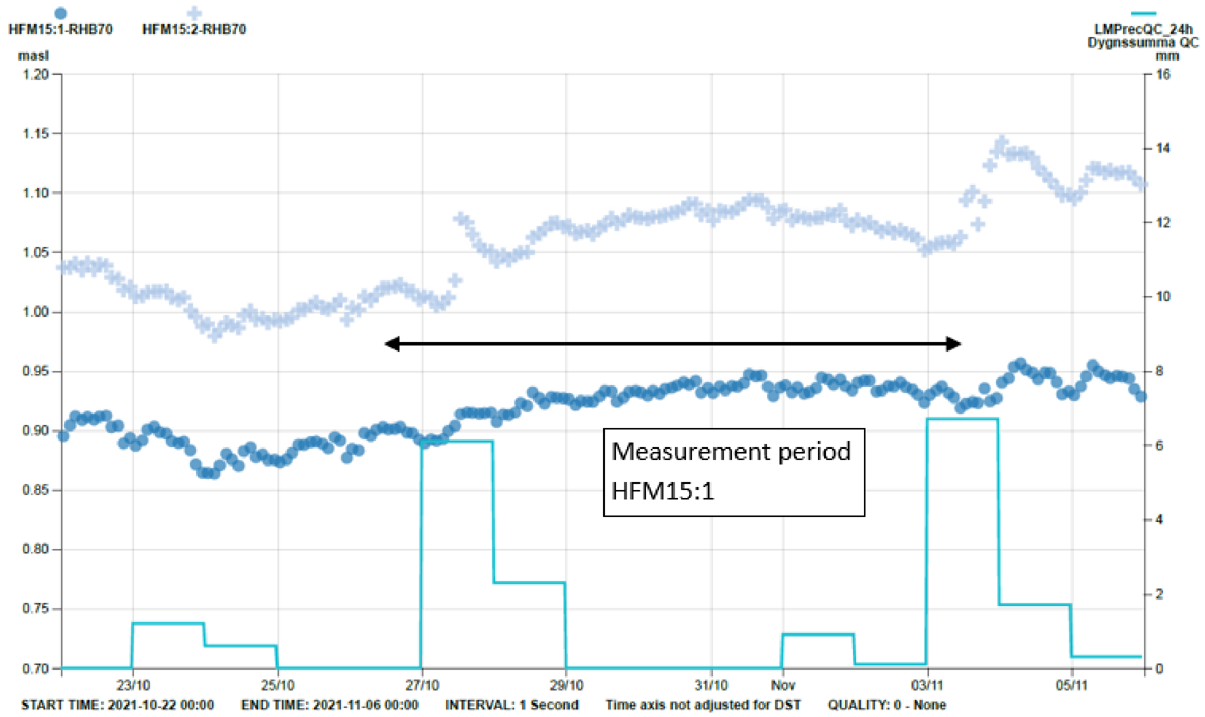


Figure A2-14. *Measured section: HFM15:1 (dark blue).*

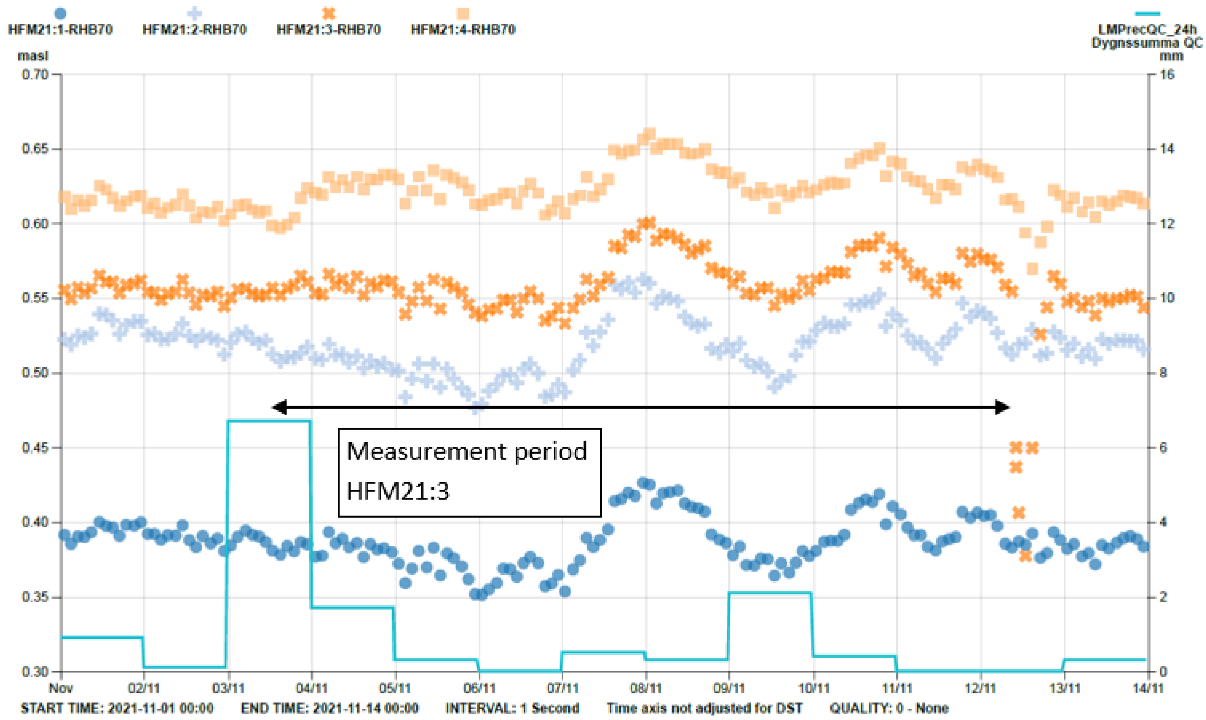


Figure A2-15. *Measured section: HFM21:3 (dark orange).*

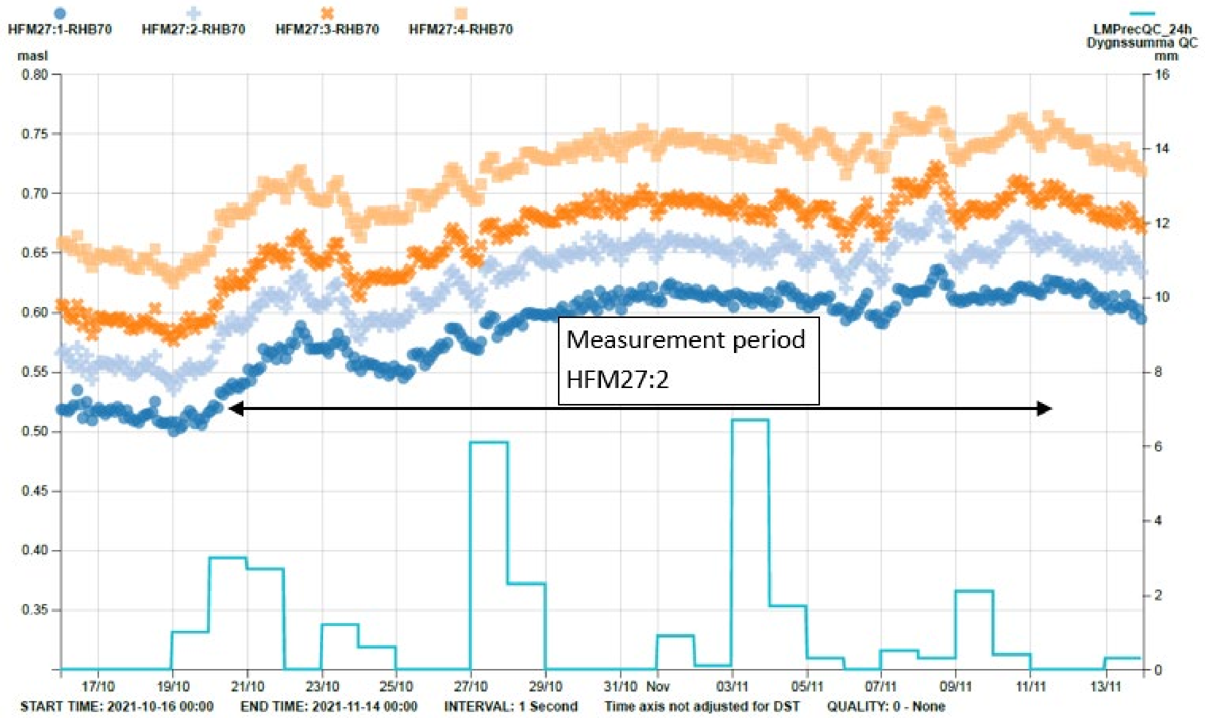


Figure A2-16. *Measured section: HFM27:2 (pale blue).*

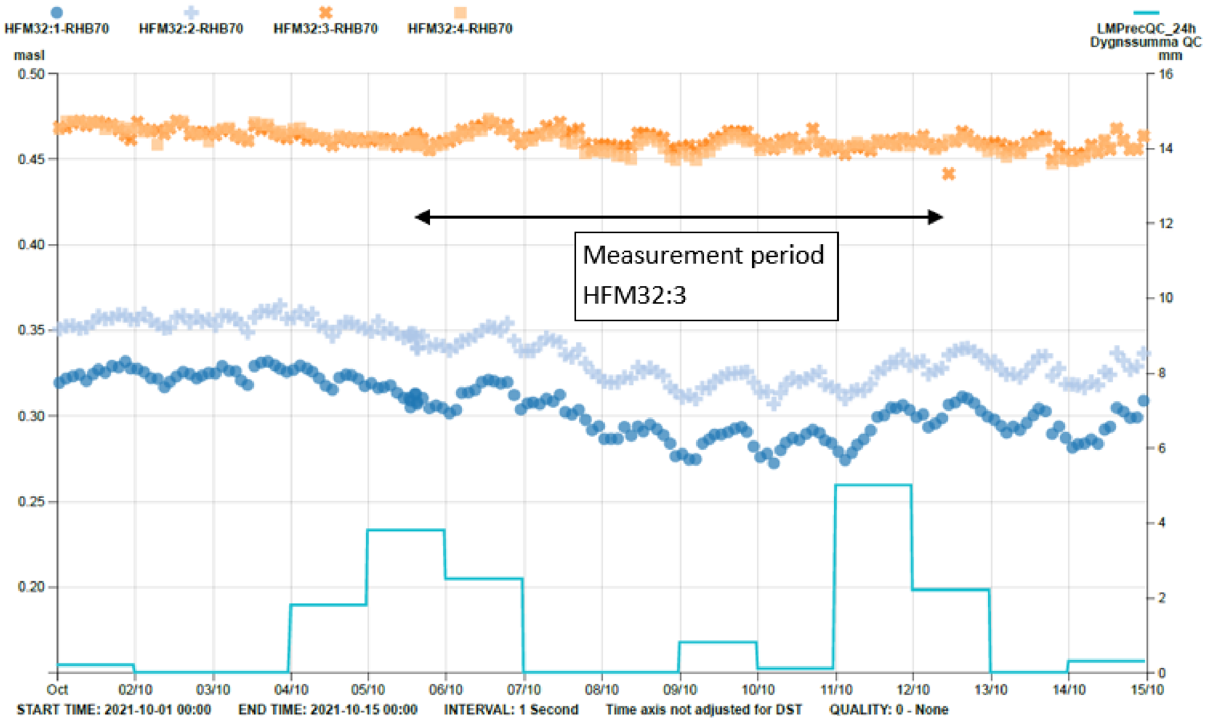


Figure A2-17. *Measured section: HFM32:3 (dark orange).*

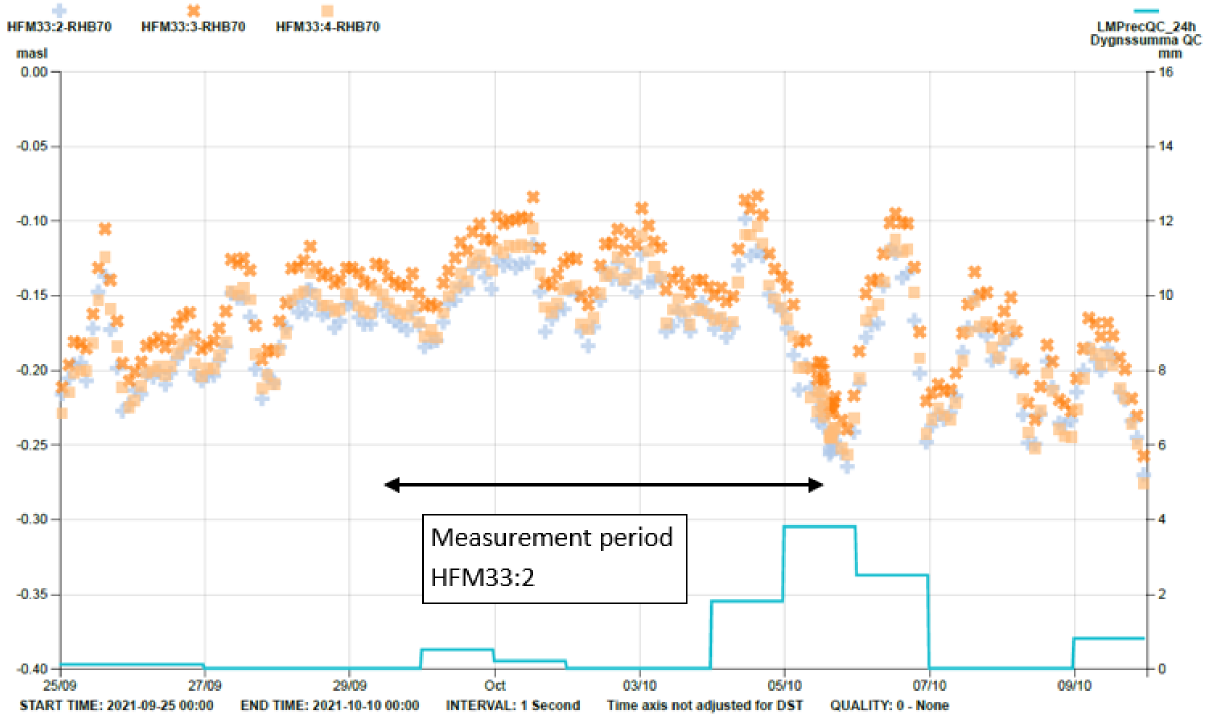


Figure A2-18. *Measured section: HFM33:2 (pale blue).*

Appendix 3

Activities during test campaigns in 2005-2021

Activities performed in the Forsmark area during the test campaigns with groundwater flow measurements, 2005-2021.

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
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 - 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

Start date	Stop date	Borehole	Activity
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
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
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

Start date	Stop date	Borehole	Activity
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