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Groundwater flow measurements in permanently installed boreholes

Test campaign no. 14, 2020

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Geosigma AB

Keywords: Groundwater flow, Dilution test, Tracer test, AP SFK-20-023.

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Summary

This report describes the performance and evaluation of groundwater flow measurements in 19 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 fourteenth test campaign performed within the monitoring program and the first 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 0.05 to 12 ml/min with calculated Darcy velocities from 2.5×10^{-10} to 7.3×10^{-8} m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.0001 and 2.3 m/m.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i 19 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 fjortonde mätkampanjen som genomförts i övervakningsprogrammet och den första som genomförs 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 0,05–12 ml/min med beräknade Darcy hastigheter mellan $2{,}5 \times 10^{-10}$ och $7{,}3 \times 10^{-8}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,0001 och 2,3 m/m.

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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 for both methods, 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.

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 14, autumn 2020, which is the first campaign using online measuring equipment. The work was carried out in accordance with activity plan AP SFK-20-023 and the field work was conducted from the middle of September 2020 to the middle of November 2020. 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 database 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 2020. (In Swedish.)	AP SFK-20-023	1.0
Method description	**Number**	**Version**
System för hydrologisk och meteorologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål. (In Swedish.)	SKB MD 368.010	2.0

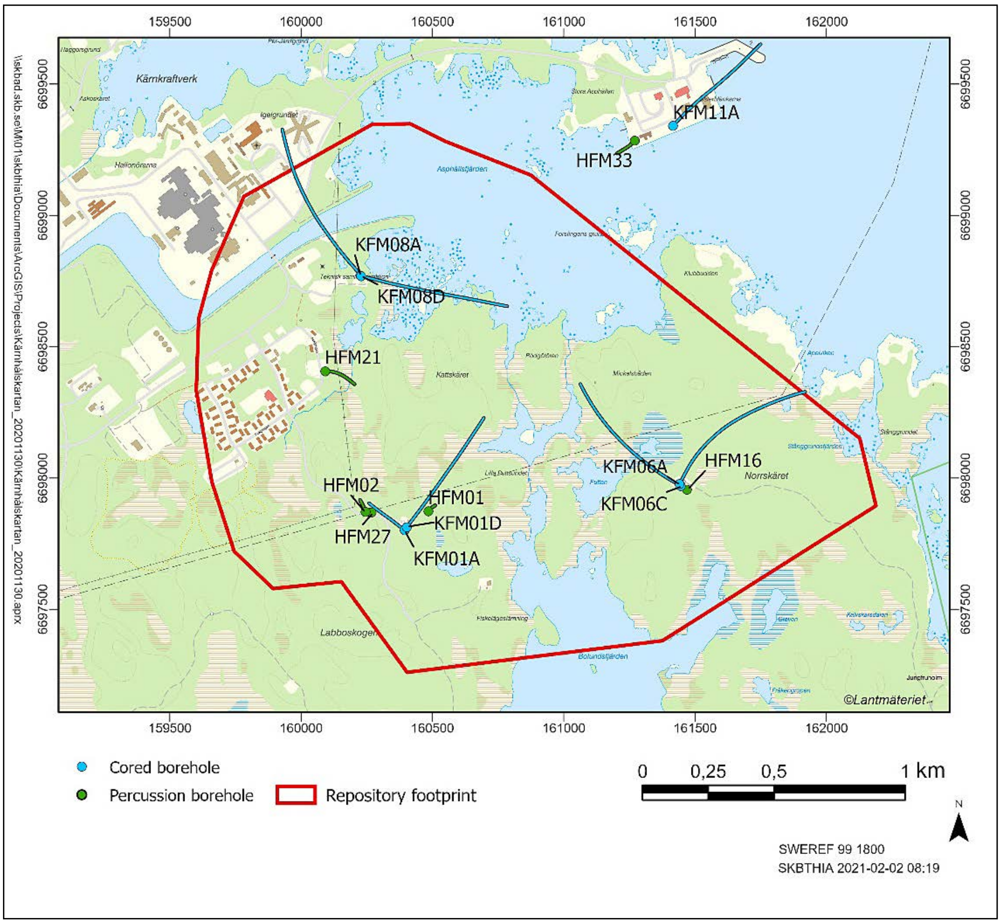

Figure 1-1. *Overview over the Forsmark site investigation area, showing locations of boreholes included in this activity.*

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 2005–2020.

Borehole	Section no	Secup (mbl)[1]	Seclow (mbl)	SecMid (mbl)	Elevation SecMid (m RH2000)	Geologic structure (Follin et al. 2007)	Measured 2020 (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	N
	5	411	442	426.5	−417.61	Zone ZFMA2	N
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	N
KFM05A	4	254	272	263	−221.22	Single fracture, FFM01	N
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	Y
	4	660	680	670	−537.88	Zone ZFMNNE2308	Y
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	N
HFM13	1	159	173	166	−138.44	Zone ZFMENE0401A	N
HFM15	1	85	99.5	92.25	−60.45	Zone ZFMA2	N
HFM16	2	54	67	60.5	−57.00	Zone ZFMA8	Y
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	N
HFM33 [2]	2	121	137.5	129.5	−102.02	Single fracture	Y

[1] Metre borehole length.

[2] New in 2020.

2 Objective and scope

The objective of this activity was to determine the groundwater flow in permanently installed borehole sections at Forsmark. In total fourteen selected borehole sections instrumented for this purpose were measured, cf Table 1-2. This was the fourteenth 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.

An additional objective of the measurement campaign in 2020 was to increase the experience of the new online measurement methodology.

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 "System för hydrologisk och meteorologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål" (SKB MD 368.010), cf Table 1-1.

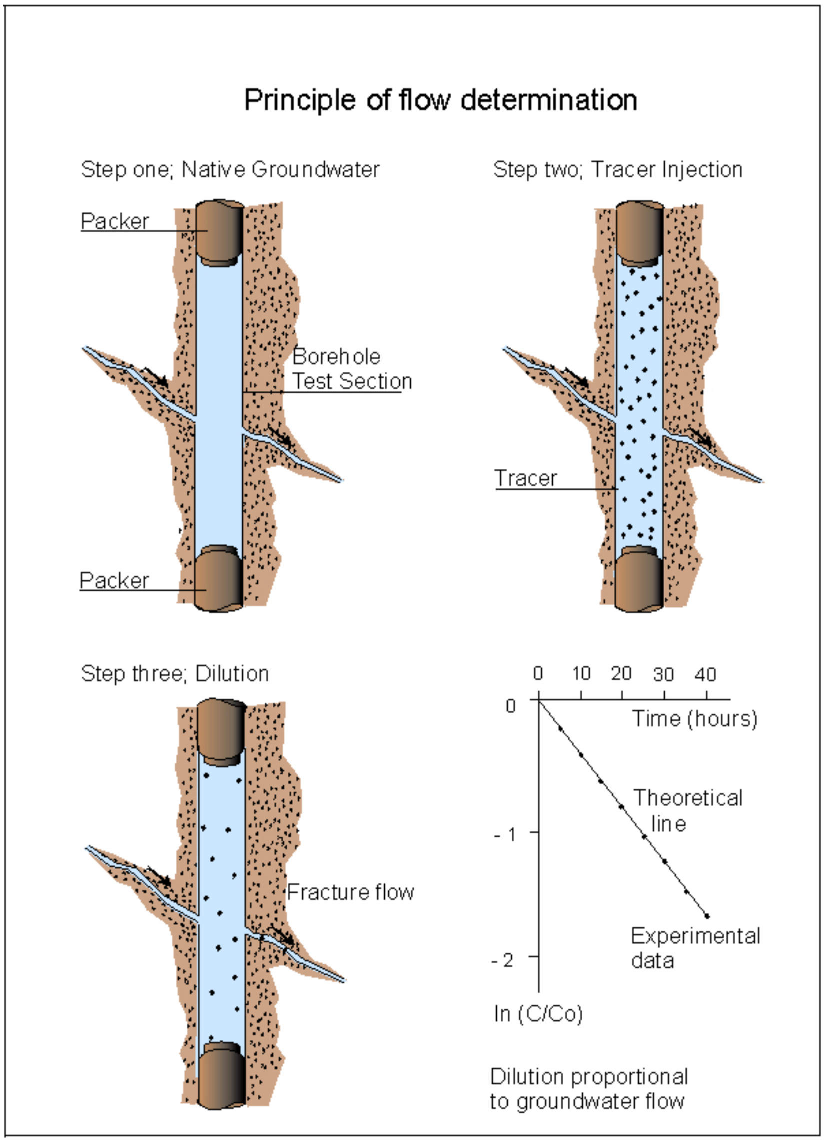

***Figure 3-1.** General principles of dilution and flow determination (Andersson et al. 2018).*

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.

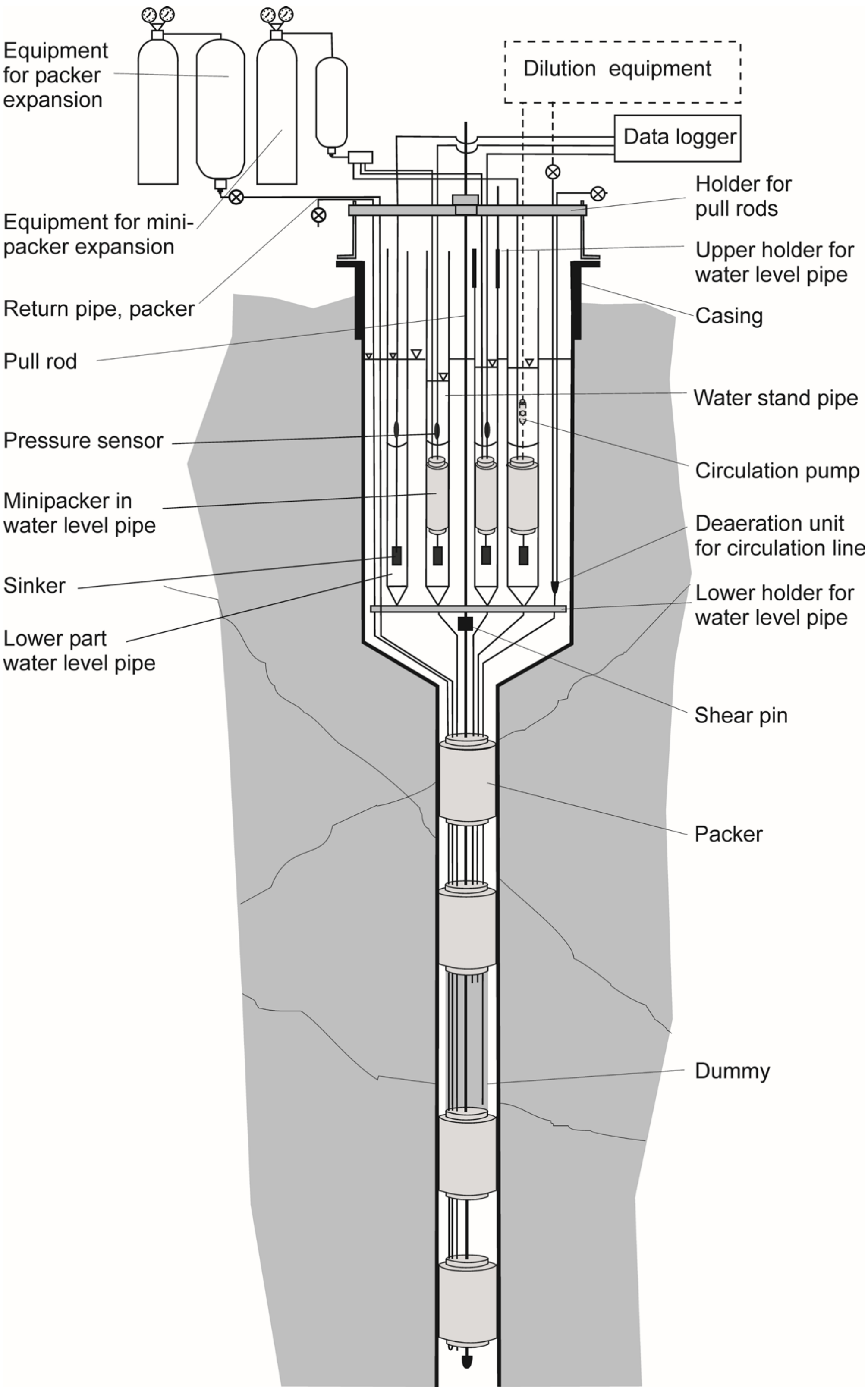

***Figure 3-2**. Example of permanent instrumentation in core and percussion boreholes with circulation sections.*

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.

3.3 Dilution test equipment and methodology

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

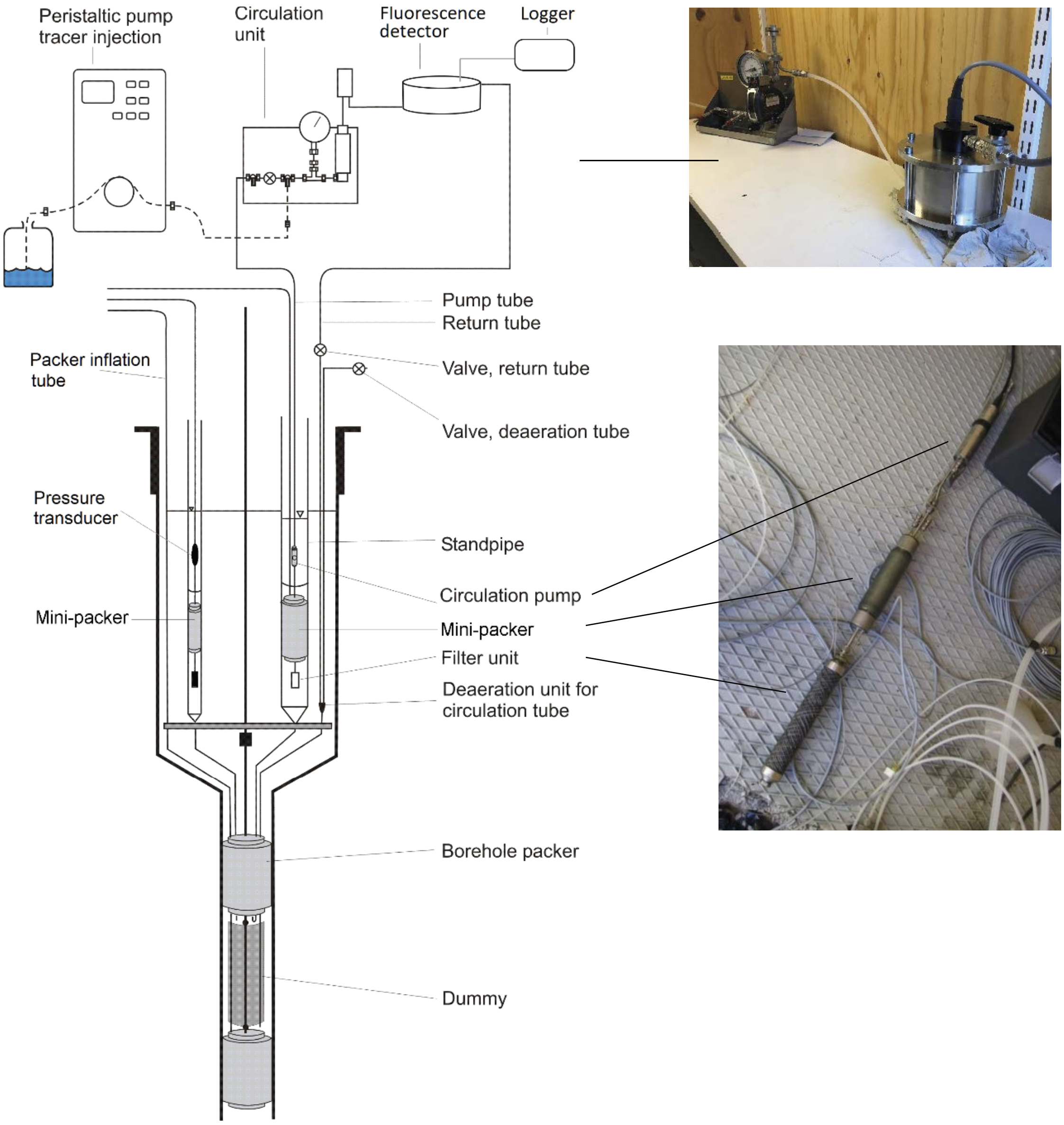

***Figure 3-3**. Schematic drawing of the equipment used in tracer dilution measurements.*

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, se 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 Appendix 1. 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 ± 5 % (Andersson et al. 2018).

The test procedure principles and parts of the equipment are described in detail in SKB MD 368.010, see Table 1-1. The document is written based on earlier sampling procedure used for measuring during 2005–2017 and the use of online measurement is not described in the document.

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):

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

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.

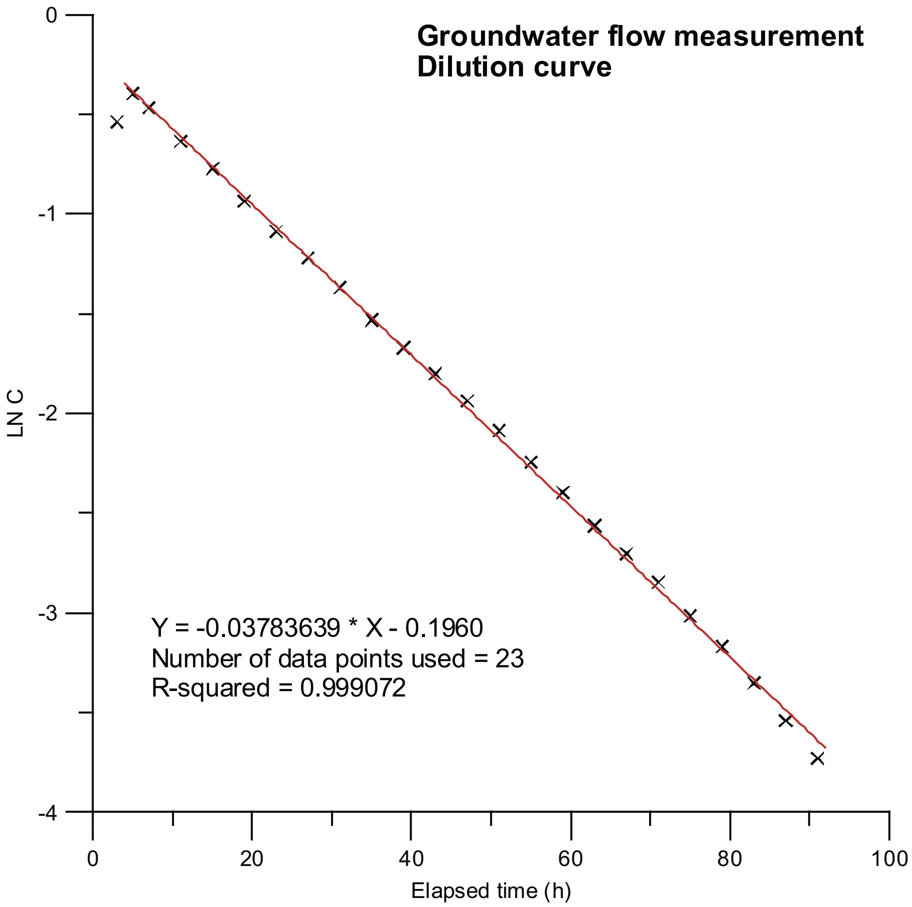

Figure 3-7. *Example of a tracer dilution graph (logarithm of concentration versus time), including straight-line fit. The used interval is chosen by eye assessment as the injection and start-up effects varies from section to section (Andersson et al. 2018).*

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 90° 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 90°, the calculation of the hydraulic gradient is a rough estimation.

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 1 000 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 in September 2020, before field campaign, with solutions of 100 and 1 000 ppb.

Logger (number)	Data signal (mv) at calibration	
	Solution: 100 ppb	Solution: 1 000 ppb
1943	25.61	226.15
1955	38.52	341.75
1957	33.42	299.46
1956	36.01	327.18

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 490 and 506 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. Validation was performed both before and after rinsing with citric acid. The measured value with 500 ppb solution differed maximum 9 ppb, about 2 %, between the validation before and after field measurements. The rinsing procedure after field measurement had no effect on the measured value.

Table 4-2. Concentrations obtained at validation with 500 ppb solutions in September 2020, before field campaign, and November 2020, after field campaign.

Logger (number)	Concentration (ppb) at validation	
	September 2020 Solution 500 ppb	November 2020 Solution 500 ppb
1943	490	481
1955	505	515
1957	505	512
1956	506	509

When using several detectors and loggers the FLUO program must be started through the script FLUINIT which is connecting the data to the calibration file unique for each detector and logger. When converting the output signal (mV) to concentration (ppb) for data measured at 10 seconds interval or more sparse data, FLUO automatically uses a one-point calibration curve only based on the 100 ppb calibration value. Although, it is possible to use the two-point calibration curve by unchecking the check boxes for tracers not used in the main window in FLUO. By choosing only the boxes for Amino-G and turbidity the two-point calibration curve is used for conversion.

4.2 Execution of field work

The borehole sections included in the monitoring program during the test campaign 2020 are listed in Table 4-3. Measuring was performed with equipment described in Section 3.3 and four sections were measured simultaneously.

Before injection background concentrations in each section was measured during approximately 24 hours of circulation at a logging interval of 5 minutes. Background measurement for 24 hours is introduced during the campaign in 2020 according to suggestions from the test-campaign in 2019 (Andersson and Wass 2020).

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 ratio to ensure that desired tracer concentrations are reached in the system. During injection data was detected with a denser logging interval of 10 seconds.

After injection, data was monitored with an interval of 5 minutes. If the test period for a section were two weeks, 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 2020.

Borehole: section	Depth (m)	T (m^2/s) [1)]	Geologic character	Test period (yymmdd)	(No. weeks)
KFM01A:5	109–130	1.0E−7	Multiple fractures, FFM02	201027–201110	2
KFM01D:2	429–438	6.2E−8	Single fracture, FFM01	201027–201103	1
KFM01D:4	311–321	1.8E−7	Single fracture, FFM01	201103–201110	1
KFM06A:3	738–748	3.1E−7	Zone ZFMNNE0725	200929–201006	1
KFM06A:5	341–362	9.2E−7	Zone ZFMENE0060A	200929–201006	1
KFM06C:3	647–666	9.0E−8	Possible DZ5	200929–201013	2
KFM06C:5	531–540	1.2E−6	Zone ZFMWNW044	200929–201013	2
KFM08A:2	684–694	1.4E−6	Possible DZ4 (S-WNW)	201013–201027	2
KFM08A:6	265–280	1.3E−6	Zone ZFMENE1061A	201013–201027	2
KFM08D:2	825–835	2.9E−8	Zone ZFMENE0168	201013–201027	2
KFM08D:4	660–680	1.8E−7	Zone ZFMNNE2308	201013–201027	2
KFM11A:2	690–710	1.0E−6	ZFMWNW0001	201006–201013	1
KFM11A:4	446–456	3.1E−8	ZFMWNW3259	201006–201013	1
HFM01:2	33.5–45.5	4.5E−5	Zone ZFMA2	201110–201117	1
HFM02:2	38–48	5.9E−4	Zone ZFM1203	201110–201117	1
HFM16:2	54–67	3.5E−4	Zone ZFMA8	201027–201110	2
HFM21:3	22–32	1.0E−4	Single fracture, FFM02	201110–201117	1
HFM27:2	46–58	4.0E−5	Zone ZFM1203	201027–201110	2
HFM33:2	121–137.5	4.7E−04	Single fracture	201110–201117	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).

4.2.1 Nonconformities

- In KFM08D:2 the pump stopped in the early morning of 2020-10-23, nine days after tracer injection and four days before planned circulation stop. The pumping was not repeated due to the unplanned pump stop.

- In KFM01A:5 a valve on the return tube was held partly closed during the measurements to minimize gas formation. When attendance was made one week after the start, the pressure in the section had increased to undesirable level during the week. To avoid pump stop the valve was opened a little bit more and pressure decreased. This also resulted in more scattered data due to gas formation for the second half of the measured period.

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 groundwater flow in the section, the data must be filtered before evaluation.

Since this was the first campaign using the new equipment on a larger scale, a data filtering procedure had to be developed. After some testing, it was decided in consultation with SKB's Activity leader to do as follows. 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 4-1.

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. This year, the first one with online measurements in larger scale, background concentrations were measured with 5 minutes scan during 24 hours before tracer injection. Evaluation of data reveals a non-stable level during these hours. In general, the background concentration behavior could be divided into two groups depending on type of borehole (Figure 4-2). In percussion boreholes higher concentrations were measured during the first hours followed by relatively stable concentrations. A mean value of the main period is used as background concentration. In core boreholes, a short initial phase with low concentrations were followed by a fluctuating phase where the concentration slowly stabilized at a new concentration level. A mean value of the short initial phase is used as background concentration.

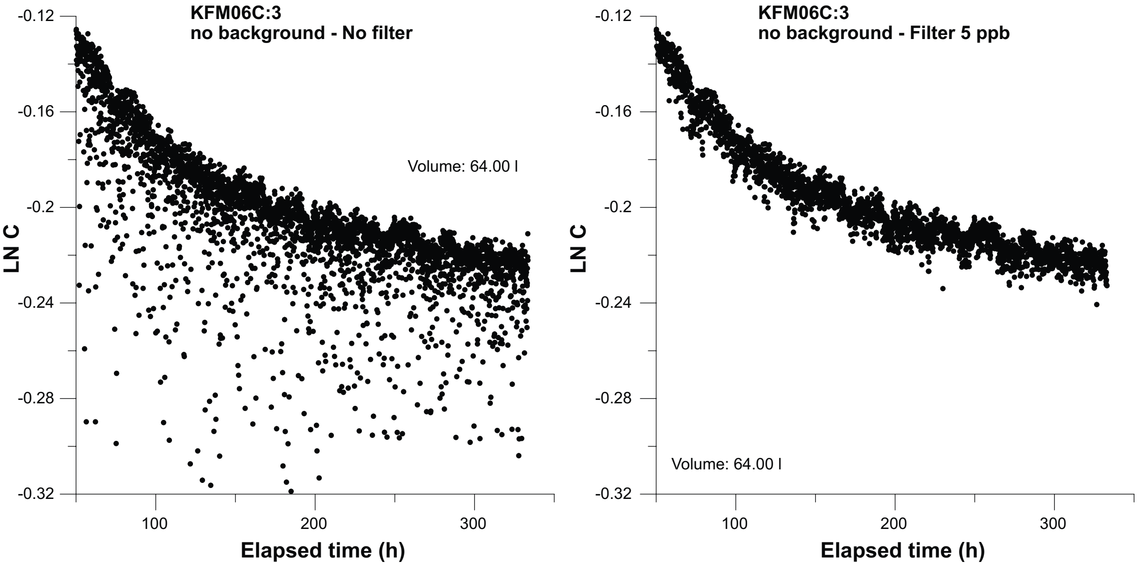

Figure 4-1. *Unfiltered and filtered data. Fluctuations are due to gas bubbles.*

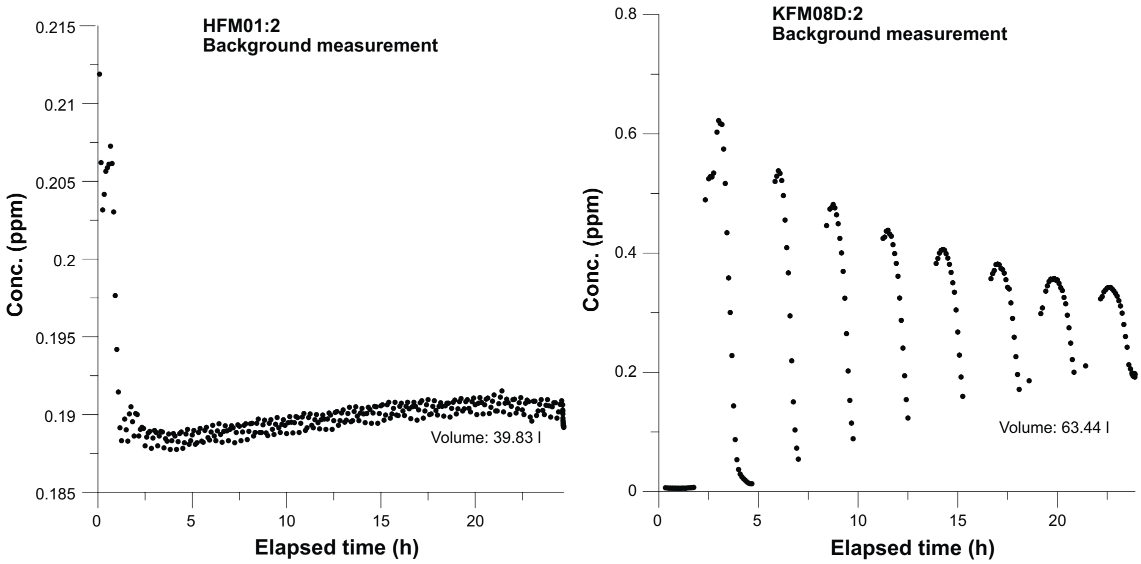

Figure 4-2. *Background concentrations measured during the day before tracer injection. Percussion borehole section HFM01:2 (left) and cored borehole section KFM08D:2 (right).*

The fluctuations in core boreholes are assumed to be related to remaining tracer from previous measurements in the return tube. The return tubes are mainly used when circulating water during the groundwater flow measurements and stationary water could have been stagnant in the return tube since the last tracer measurements. The water in the return tube is not affected by the final pumping in purpose to remove the remaining tracer and the concentrations at the end of the measurement period could be captured in the tube. When water circulation is started in the initial phase of the next groundwater flow measurement the remaining tracer in the return tube causes a small addition of tracer in the section. The difference in behavior in core- and percussion boreholes are assumed to be due to longer return tubes in core boreholes and that the remaining concentration in the percussion boreholes generally is much lower than in the core boreholes.

The background measurements in this campaign show that the most representing part occurs during the first hours of pumping. Later on the concentration is rising as an effect of remaining tracer in the return tube from a previous measurement. Hence, the upstart procedure is proposed to be altered for next campaign. As a suggestion the background measurement can be shortened and injection can start after pumping a volume corresponding to three tube volumes of the pump hose.

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-20-023). 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. 14, 2020

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 0.05 to 12 ml/min in the measured sections with Darcy velocities ranging from 2.5×10^{-10} to 7.3×10^{-8} 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. 14, 2020.

Borehole: section	Depth (m)	Transmissivity (m^2/s) [1]	Vol. (l)	Time Interval (h)		Background (ppb)	Measured flow, *Q* (ml/min)	Darcy velocity, *v* (m/s) $\times 10^{-9}$	Hydraulic gradient, *I* (m/m)
				From	To				
KFM01A:5	109–130	1.0E−07*	33.21	260	345	37	0.05	0.3	0.05
KFM01D:2	429–438	6.2E−8	38.33	100	150	19	1.0	12	1.7
KFM01D:4	311–321	1.8E−7	31.27	100	165	30	0.07	0.8	0.04
KFM06A:3	738–748	3.1E−7	58.25	60	166	26	0.2	2.1	0.07
KFM06A:5	341–362	9.2E−7	46.64	76	166	15	1.5	7.5	0.2
KFM06C:3	647–666	9.0E−8	64.00	120	333	0 [2]	0.2	1.1	0.2
KFM06C:5	531–540	1.2E−6	43.61	195	333	0 [2]	0.8	9.4	0.07
KFM08A:2	684–694	1.4E−6	55.15	150	333	13	0.2	2.5	0.02
KFM08A:6	265–280	1.3E−6	34.67	150	334	20	0.05	0.4	0.004
KFM08D:2	825–835	2.9E−8	63.44	- [4]	- [4]	6	- [4]	- [4]	- [4]
KFM08D:4	660–680	1.8E−7	64.13	295	330	12	0.2	0.8	0.09
KFM11A:2	690–710	1.0E−6	68.91	95	168	3	1.8	9.7	0.2
KFM11A:4	446–456	3.1E−8	40.47	90	165	6	0.7	7.1	2.3
HFM01:2	33.5–45.5	4.5E−5	39.83	32	145	190	4.3	21	0.006
HFM02:2	38–48	5.9E−4	28.53	40	100	141	12	73	0.001
HFM16:2	54–67	3.5E−4	43.61	100	330	0 [3]	0.9	3.9	0.0001
HFM21:3	22–32	1.0E−4	31.39	45	145	150	0.2	1.3	0.0001
HFM27:2	46–58	4.0E−5	40.29	265	331	81	0.08	0.4	0.0001
HFM33:2	121–137.5	4.7E−04	54.10	100	164	34	6.5	24	0.0008

[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] No background measured, assumptions made from previous years with background close to zero.

[3] No reliable background obtained.

[4] No evaluation possible in KFM08D:2 during 2020.

In Appendix 2 the precipitation in the Forsmark area and the groundwater level is presented for the selected boreholes during the test period, see also Table 4-3 for actual measurement periods for each section. The groundwater levels were generally very stable during the measurement period although a rather heavy rain period occurred during October. Some effects of rain may be seen in the shallow percussion boreholes HFM16 and HFM27 in the early parts of the measurement period. In KFM01A:5 and KFM01D:2, measured during the same period, no effect could be seen. This agrees to earlier campaigns where no influence from precipitation were seen in any of the cored borehole sections. Some activities that were performed in the Forsmark area during the test period, and thus may have affected the ongoing groundwater flow measurements, are compiled in Table 5-2.

Table 5-2. Activities performed in the Forsmark area during test campaign no. 14, 2020.

Start date	Stop date	Borehole	Activity
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

Hydraulic gradients are calculated according to the Darcy concept and are within the expected range (< 10 %) in the majority 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 KFM01D:2, KFM06A:5, KFM06C:3, KFM11A:2 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. In KFM01D:2 and in KFM11A:4 the measured flow rates are much higher than expected considering the transmissivity of the sections. However, comparing other hydraulic measurements in the sections, the evaluated transmissivity may vary a lot and can be up to two orders of magnitude higher. It can also be mentioned that there are problems with the equipment in borehole KFM11A and the installation is planned to be lifted and reinstalled. However, this may only affect the pressure measurements in some of the sections and not the flow measurements as they are performed in separate standpipes. KFM01D:2 represent a single fracture (cf Table 4-3) where the Darcy concept may be questioned. The same applies to KFM01D:4 and HFM21:3 even though the results are not deviant in these sections.

In general, the new online equipment has worked well, and further use of the new measurement method is well motivated. An advantage is that the new method eliminates earlier problems with malfunctioning samplers and evaporation from the test tubes. There is still a risk of pump failures or leakage in the system, but the most vulnerable parts of the field procedure have been replaced. Evaluation of data are also much easier and less time consuming as no samples have to be analyzed afterwards in the lab. As the online equipment measures concentration without removing any water from the system, the water volume remains the same during the whole test and the uncertain evaluation step of compensation for the withdrawal of sample volumes are no longer needed. It was earlier suggested (Ragvald and Wass 2013) that the used sampling flow rate, calculated from the measured sample volume in the tubes, could be expected to be somewhat underestimated due to evaporation. This may be a contributing factor to that the campaign in 2020 gave higher flow rates in several sections. Probably this may have largest effect in sections with small flow rates, where the groundwater flow rate is low and consists to a substantial part of the sampling flow rate.

Another advantage with the new equipment is the possibility to monitor the injection phase and the background values. It gives the possibility to adjust the injection flow to make sure that the aimed concentration is obtained in the water going into the borehole and system. It also makes it possible to follow and monitor the mixture of tracers in the section afterwards (Figure 5-1). However, the denser data leads to new questions of how data should be interpreted and evaluated. Especially regarding background concentration as discussed in Section 4.3.2. The possibility to pump the remaining tracer from the return tubes or to measure background values after longer pumping periods without circulation, e.g. in connection to the water sampling for chemistry monitoring, should be investigated.

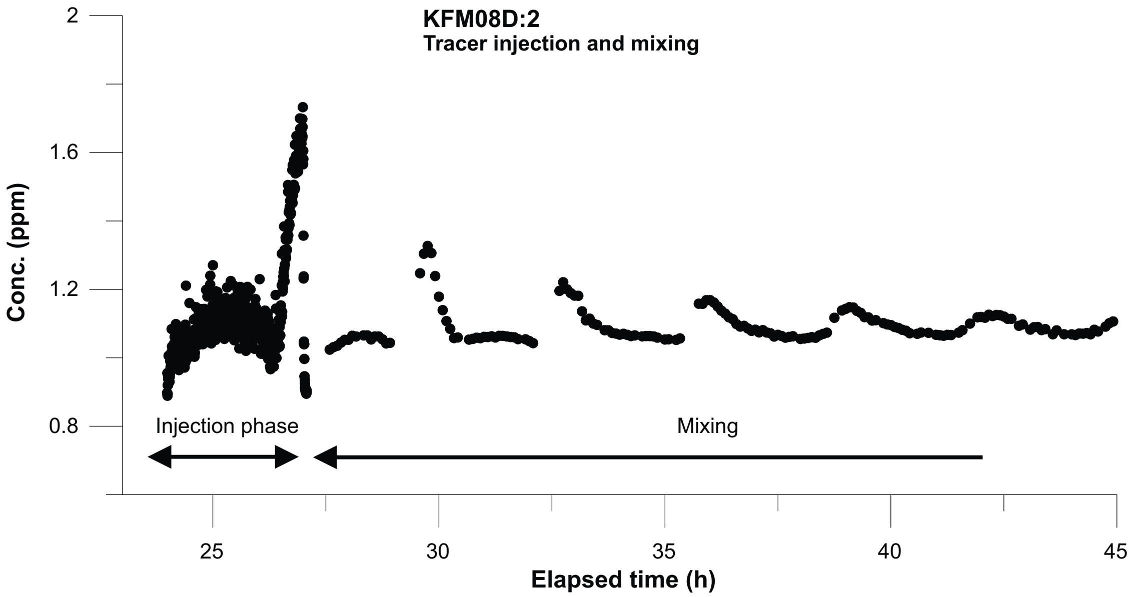

Figure 5-1. *Injection phase and mixing in KFM08D:2.*

In some sections the tracer concentration at the end of the measurement were lower than the obtained background values from the time period prior injection. In these sections the lower concentration measured at the end was used as background. An exception is HFM16 where 0 ppb was used as background in the end. After two weeks of pumping a lower concentration was obtained and the concentration was still decreasing without signs of stabilization. As no reliable estimation of background concentration could be done, 0 ppb has been used. The uncertain background concentration affects the evaluated results up to a factor of ten, and it may be discussed if the section should be excluded from the measuring program in the future. Also in previous years the background concentrations in HFM16 has been discussed due to unexpected high concentrations. In 2005 a tracer experiment in HFM01 and HFM02 which could explain the higher background in these sections and possible some more due to potential geographical distribution during the last decades.

In borehole sections HFM01:2, HFM02:2 and HFM33:2 the dilution of tracer was quite fast. In HFM02:2 higher injection concentration should be considered for the next test campaign. In HFM27:2 and KFM01D:2 it took quite long time for the dilution to become stable, and the measuring period may have to be extended to obtain reliable evaluated flow rates for these sections.

In KFM08D:2 no flow rate could be calculated due to a pump failure. Data from the first week of pumping contains fluctuating data and no time period stable enough for evaluation. Also, in KFM08D:4 data is fluctuating more than expected, and only a short more stable period occurred during the last 35 hours which have been used for evaluation. Hence, the flow rate obtained should be considered as being more uncertain relative the other measurements. The fluctuations in data were at first supposed to be due to uneven pump flow and periods of no water circulation in the sections. By comparing the fluctuations in KFM08D:2 and KFM08D:4 an interesting and unexpected co-variation between these sections was found (Figure 5-2). The fluctuations seem to occur in 24 hours cycles with higher concentrations in the afternoon and closely related to the water temperature in the measuring probe, the temperature in the container and the outside temperature in Forsmark (Figure 5-3). The correlation between temperature and concentration in both sections in KFM08D may be due to disturbance in pump flow or more likely due to the low pump flow and the long tubes associated to the docking equipment in this borehole.

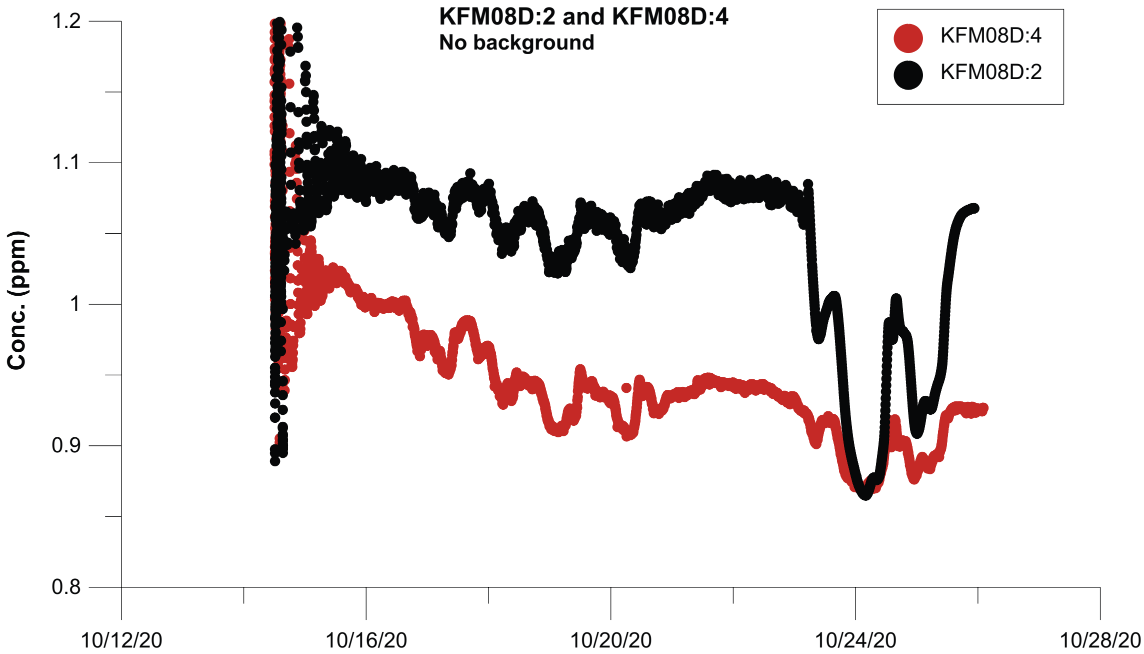

Figure 5-2. *Measured concentration in KFM08D:2 and KFM08D:4.*

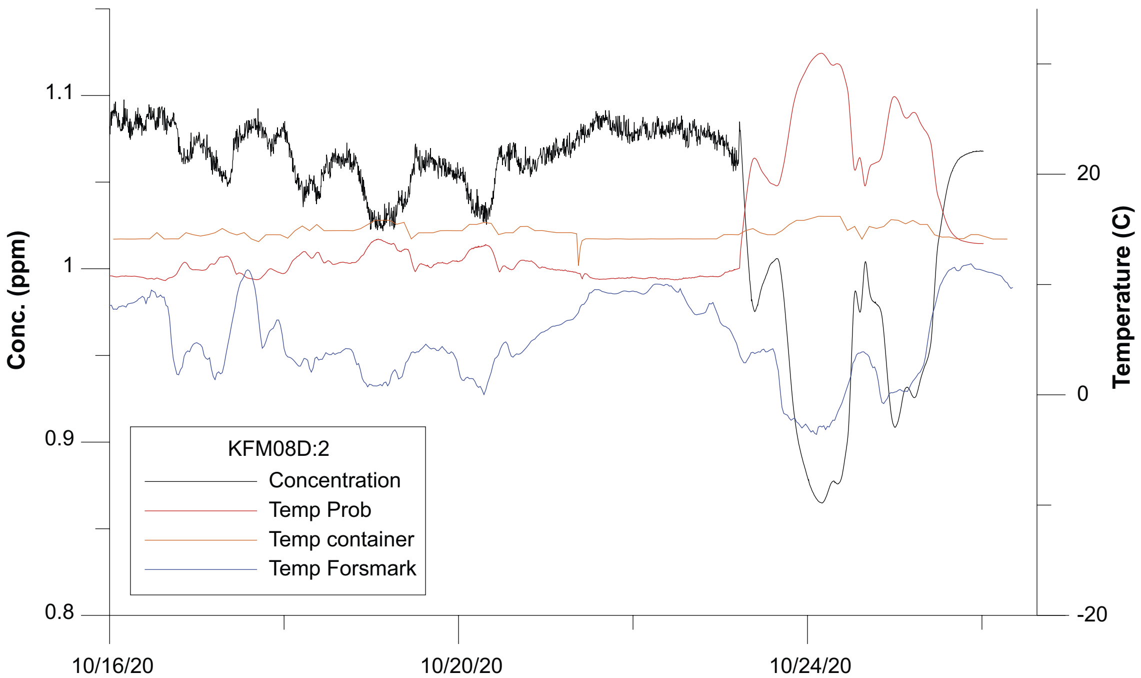

Figure 5-3. *Measured concentration in KFM08D:2 and water temperature in the measuring probe, the temperature in the container and outside temperature in Forsmark. The pump stop probably occurred during the morning hours of 23rd October as indicated by the large increase in water temperature inside the detector due to stagnant water heated by the detector lamp.*

5.3 Flow rate comparison

For comparison reasons flow rates obtained from previously performed test campaigns are compiled in Table 5-3 and Figure 5-4. Activites in the Forsmark area during the campaigns in 2005–2020 are found in Appendix 3.

The comparison shows that the flow rates measured 2020 are within the range of the values measured in previous campaigns in most borehole sections. In several sections the flow measured during the first 100–200 hours is much higher compared to the flow towards the end of the measurement period. During the last years (2013–2017) of long-time measurement and evaluation 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.

The sections were the measured flow in 2020 differs most compared to previous results are KFM01D:2, KFM06A:5, KFM11A:2 and KFM11A:4. In sections with lower flow rates the difference may be due to the changed measuring method. Earlier the sampling procedure with a constant flow rate also created a 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 and sometimes also malfunctioning samplers.

Table 5-3. Results from groundwater flow measurements in 2005–2020. For detailed data from each year see Andersson et al. 2018).

Borehole: section	T[1] (m^2/s)	2005–2012 (ml/min)	2013–2017 (ml/min)	Oct–Nov 2020 (ml/min)
KFM01A:5	1.0E−7	0.05 − 0.2	0.02 − 0.7	0.05
KFM01D:2	6.2E−8	0.04 − 0.3	0.06	1.0
KFM01D:4	1.8E−7	0.1 − 0.7	0.1 − 0.3	0.07
KFM06A:3	3.1E−7	0.05 − 0.6	0.01 − 0.3	0.2
KFM06A:5	9.2E−7	0.2 − 5.7	0.01 − 0.4	1.5
KFM06C:3	9.0E−8	0.03 − 0.4	0.01 − 0.23	0.2
KFM06C:5	1.2E−6	0.2 − 0.8	0.02 − 0.5	0.8
KFM08A:2	1.4E−6	0.7 − 3.1	0.02 − 0.5	0.2
KFM08A:6	1.3E−6	0.06 − 0.2	0.02 − 0.3	0.05
KFM08D:2	2.9E−8	0.9 − 4.1	0.01 − 0.3	-
KFM08D:4	1.8E−7	21 − 123 [2]	0.02 − 0.4	0.2
KFM11A:2	1.0E−6	0.2 − 0.9	0.2 − 0.8	1.8
KFM11A:4	3.1E−8	0.01 − 0.3	0.01 − 0.07	0.7
HFM01:2	4.5E−5	3.4 − 7.8	1.5 − 11	4.3
HFM02:2	5.9E−4	5.2 − 38	6.5 − 81	12
HFM16:2	3.5E−4	0.5 − 6.6	0.5 − 4.3	0.9
HFM21:3	1.0E−4	0.9 − 2.1	0.2 − 0.6	0.2
HFM27:2	4.0E−5	0.3 − 0.8	0.02 − 0.2	0.08
HFM33:2	4.7E−04	-	-	6.5

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) Flow influenced by leakage in the downhole equipment of KFM08D.

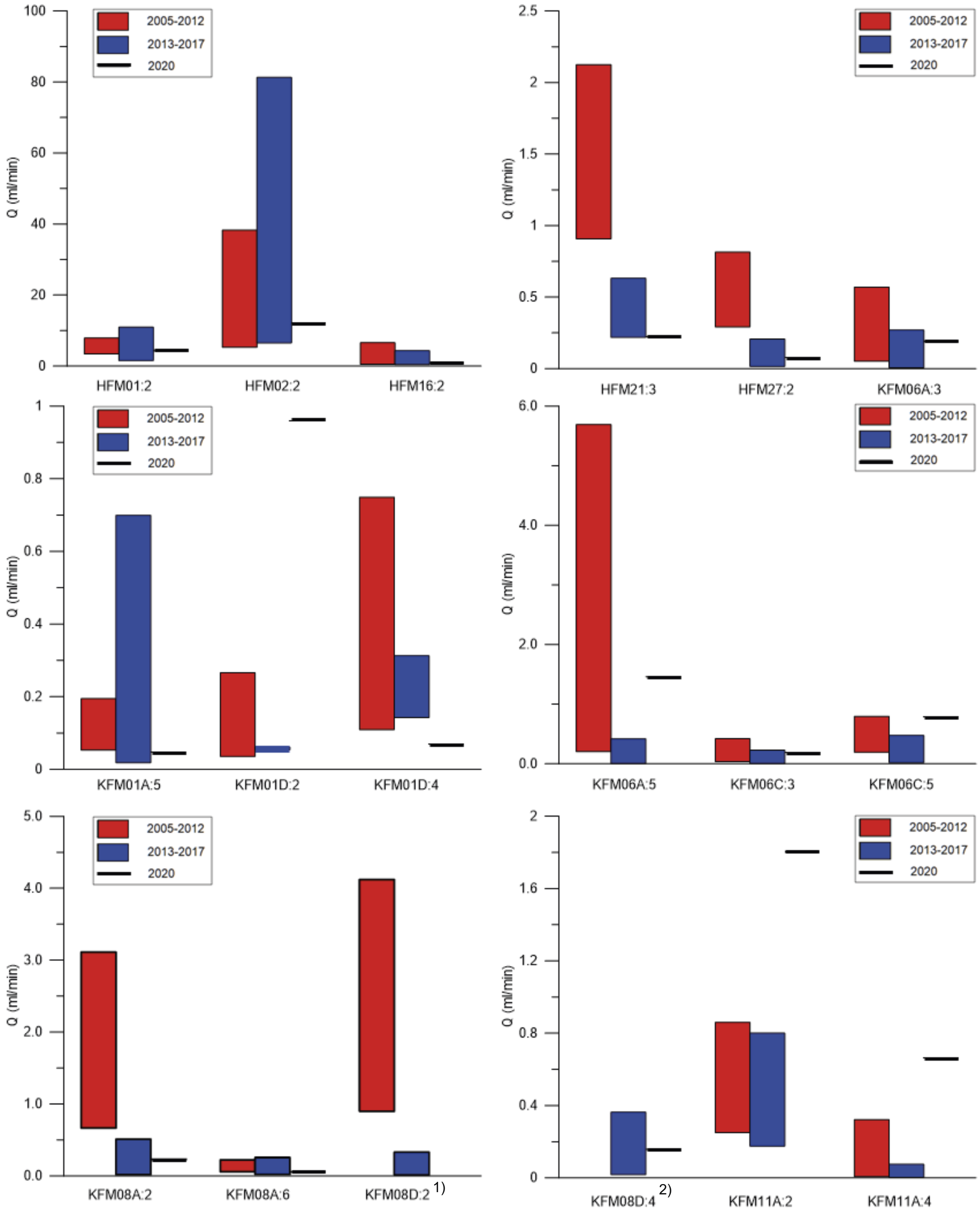

Figure 5-4. *Summarized results from groundwater flow measurements in 2005–2020. HFM33 was measured the first time in 2020 and is excluded from the figure. 1) In KFM08D:2 no flow was obtained in 2020. 2) For KFM08D:4 the leakage influenced flow from 2005–2012 is excluded in the figure.*

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SKBdoc documents will be submitted upon request to document@skb.se.

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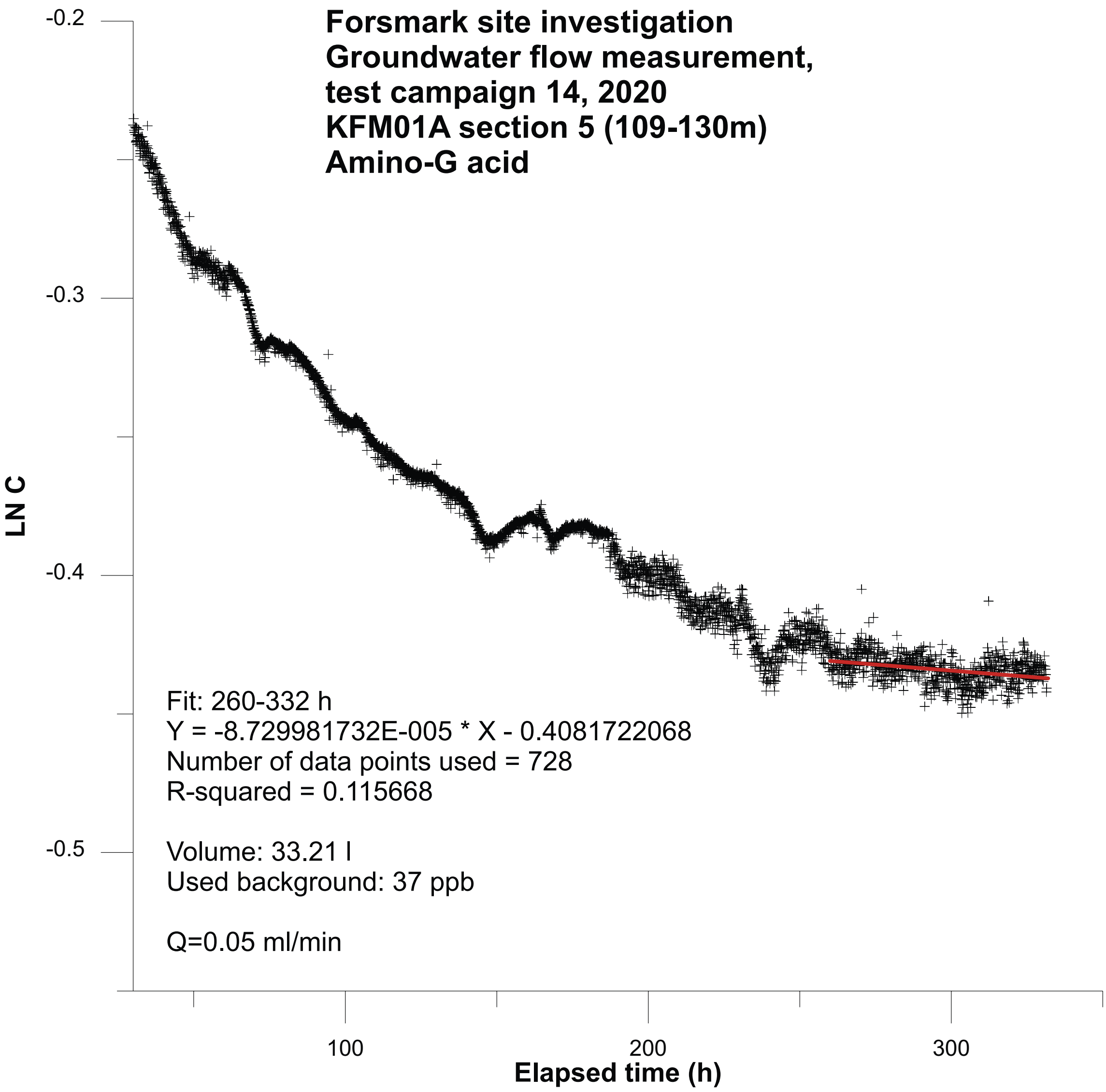
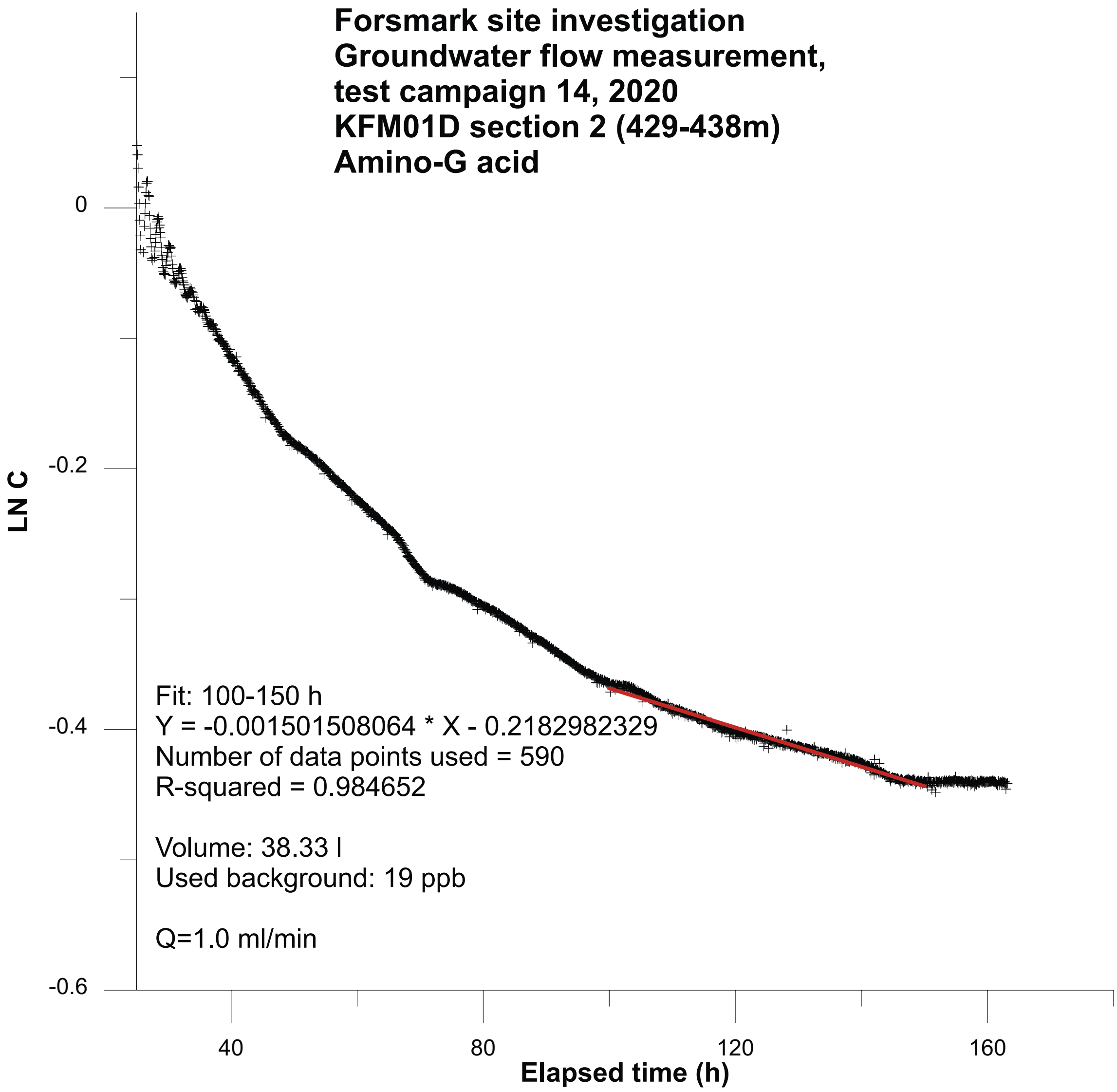
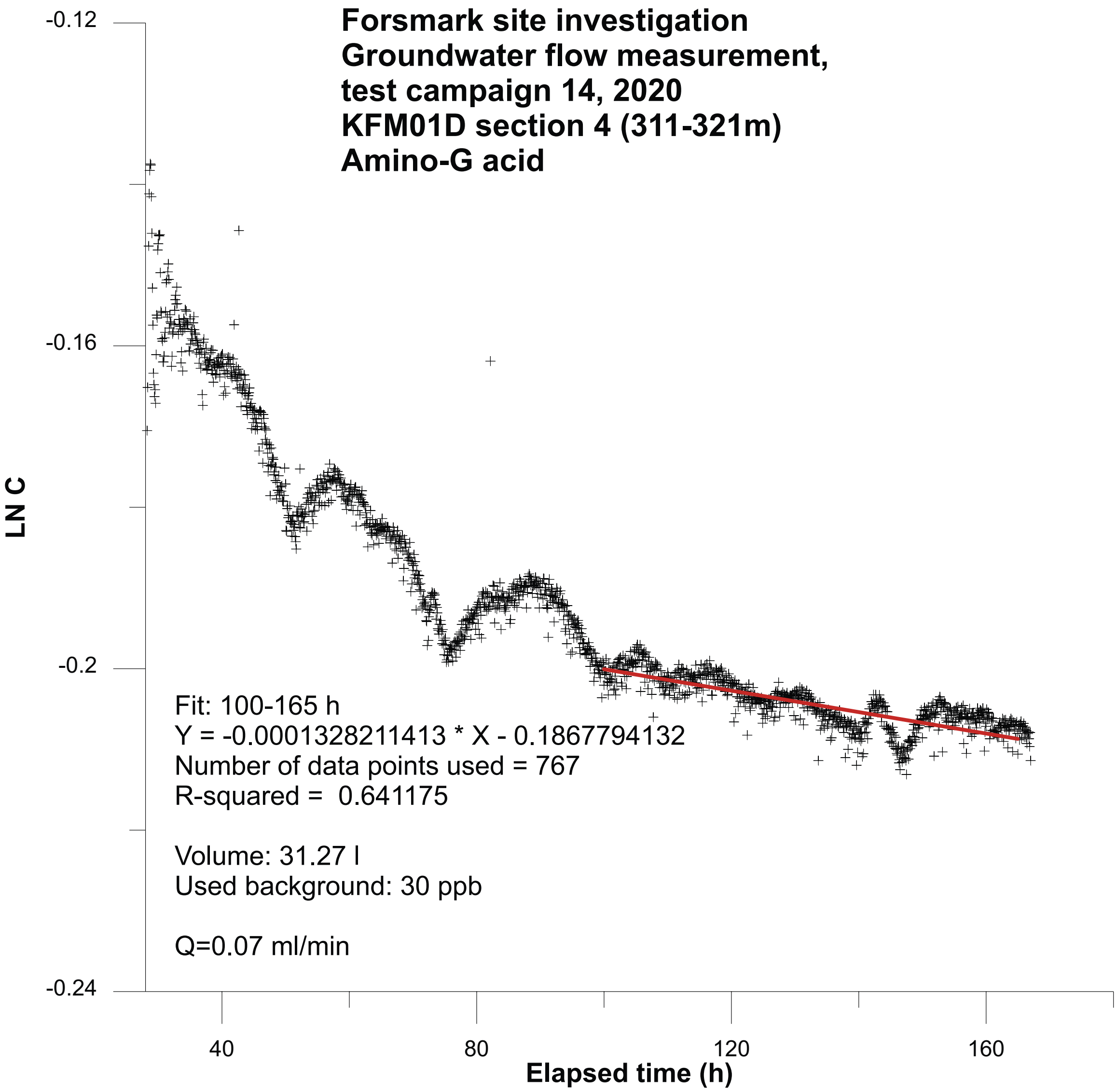
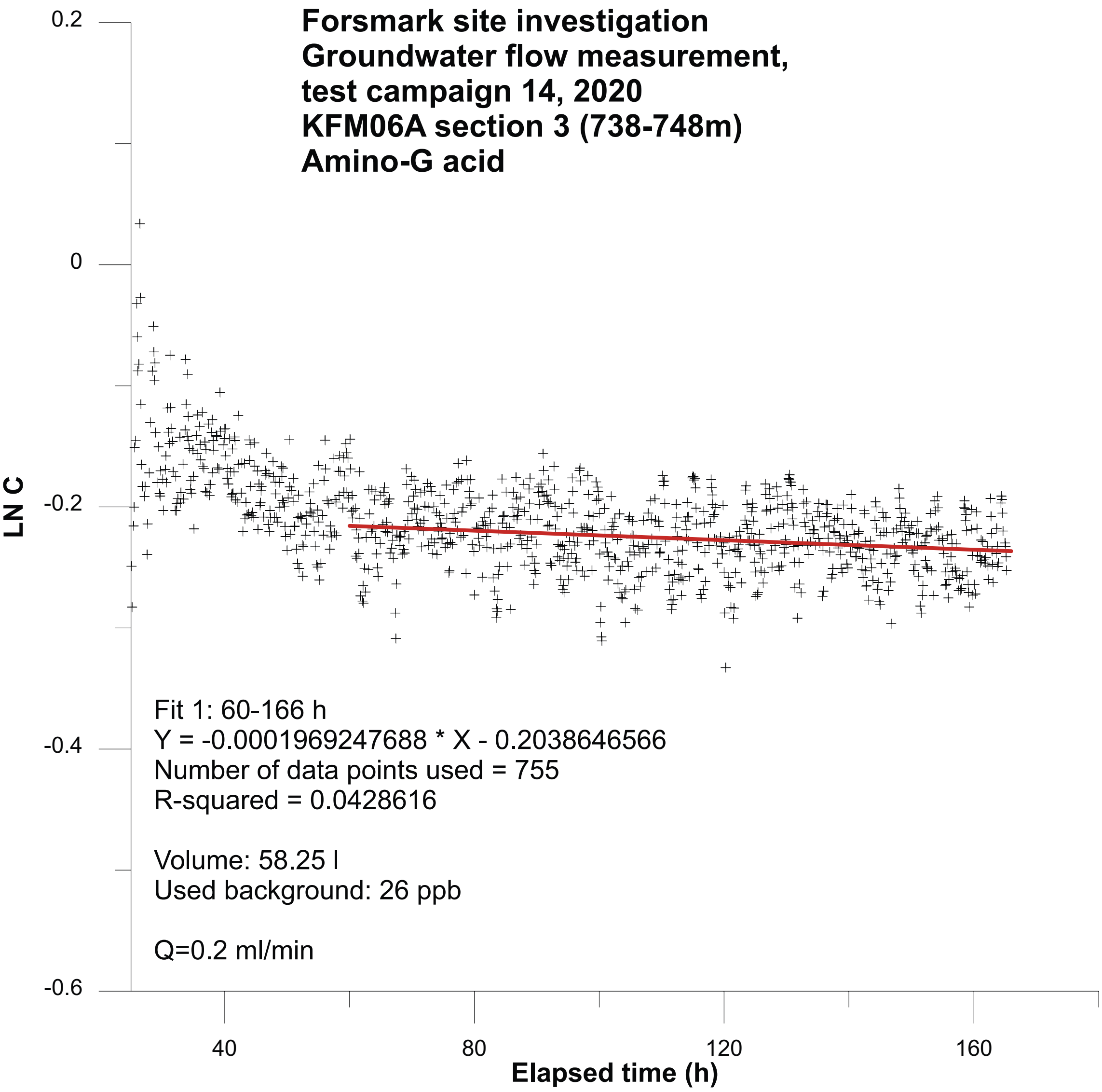
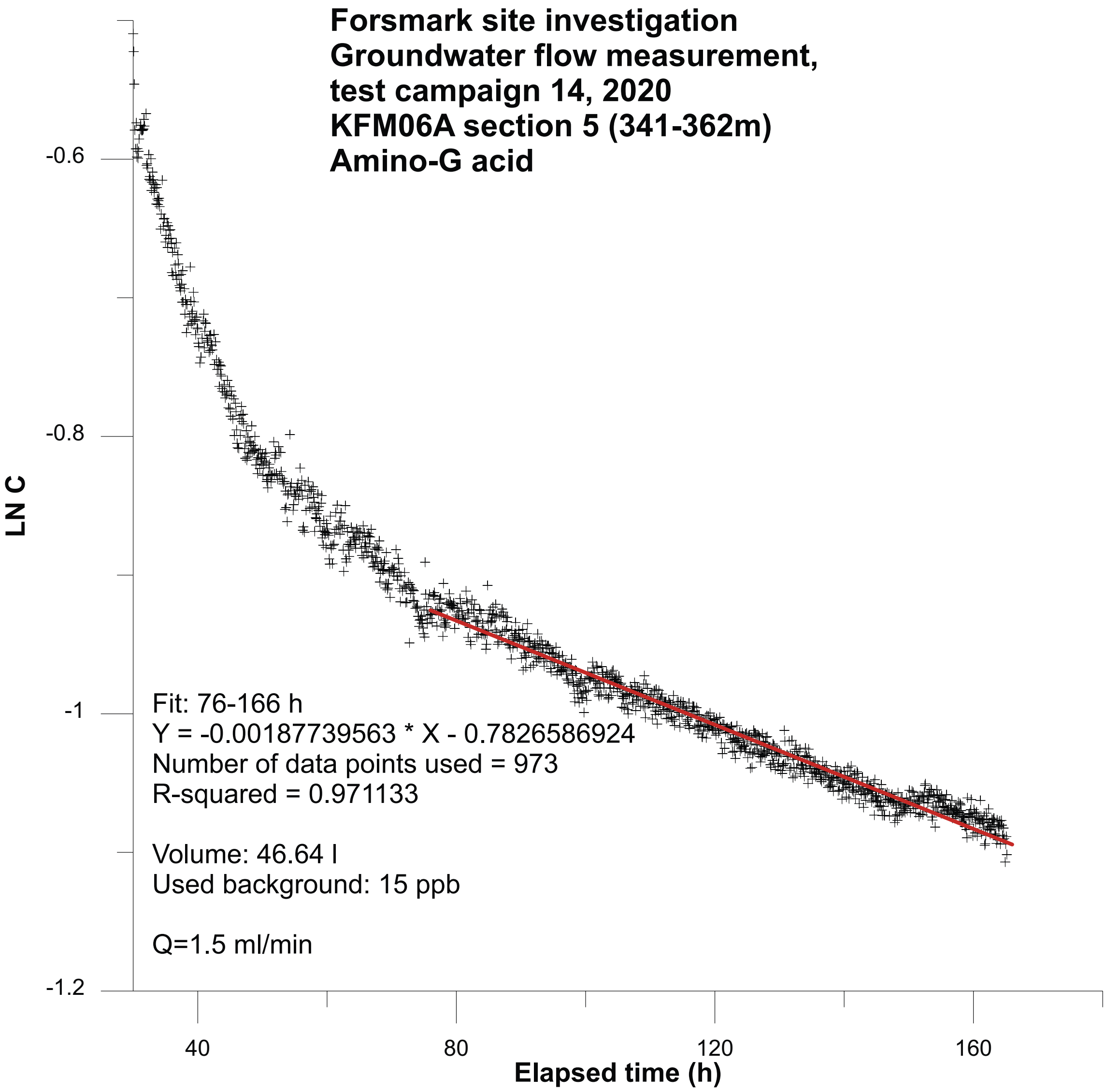
Tracer dilution graphs



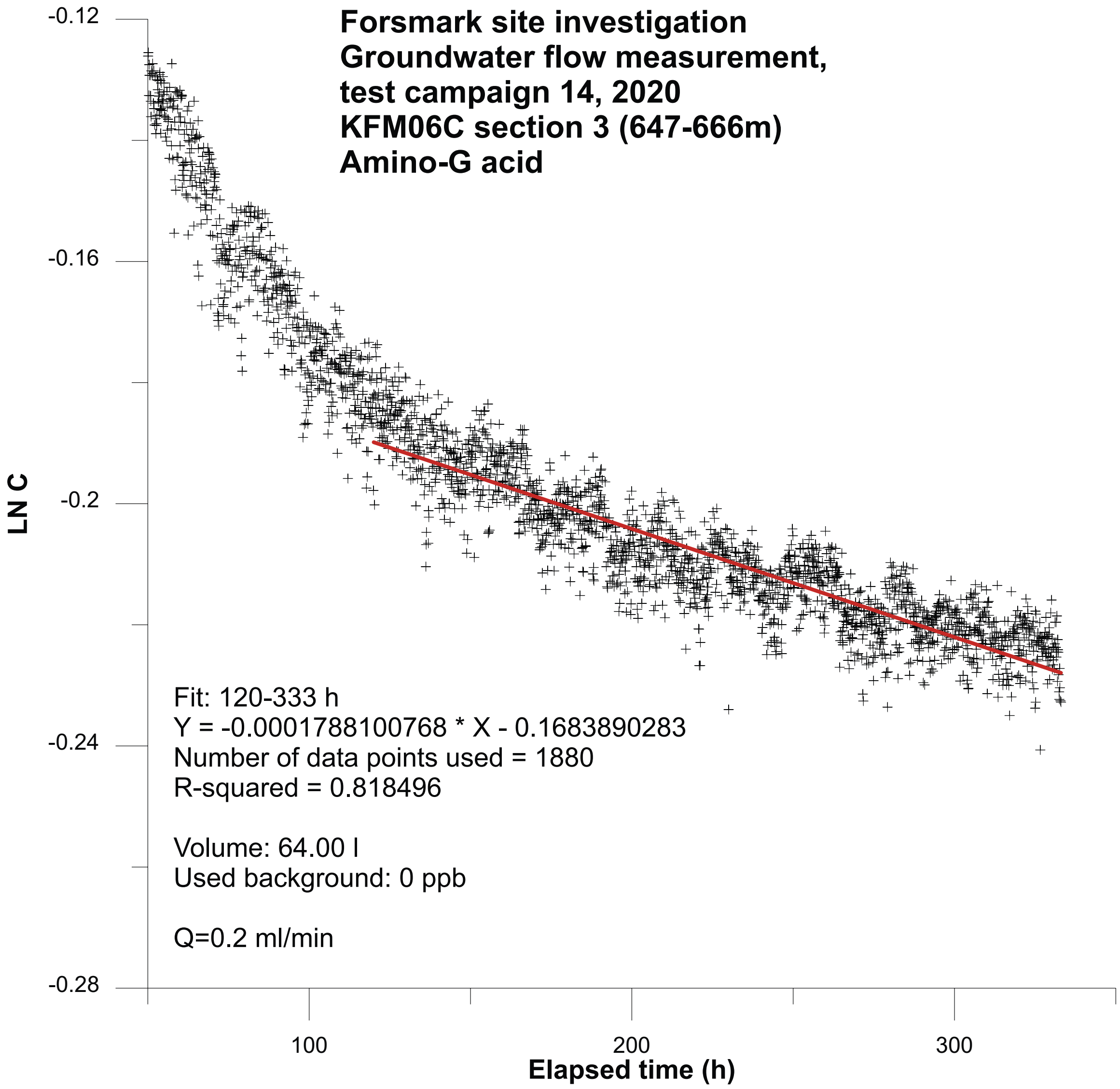

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM01D section 2 (429-438m)
Amino-G acid
Fit: 100-150 h
Y = -0.001501508064 * X - 0.2182982329
Number of data points used = 590
R-squared = 0.984652
Volume: 38.33 l
Used background: 19 ppb
Q=1.0 ml/min
LN C
0
-0.2
-0.4
-0.6
40
80
120
160
Elapsed time (h)

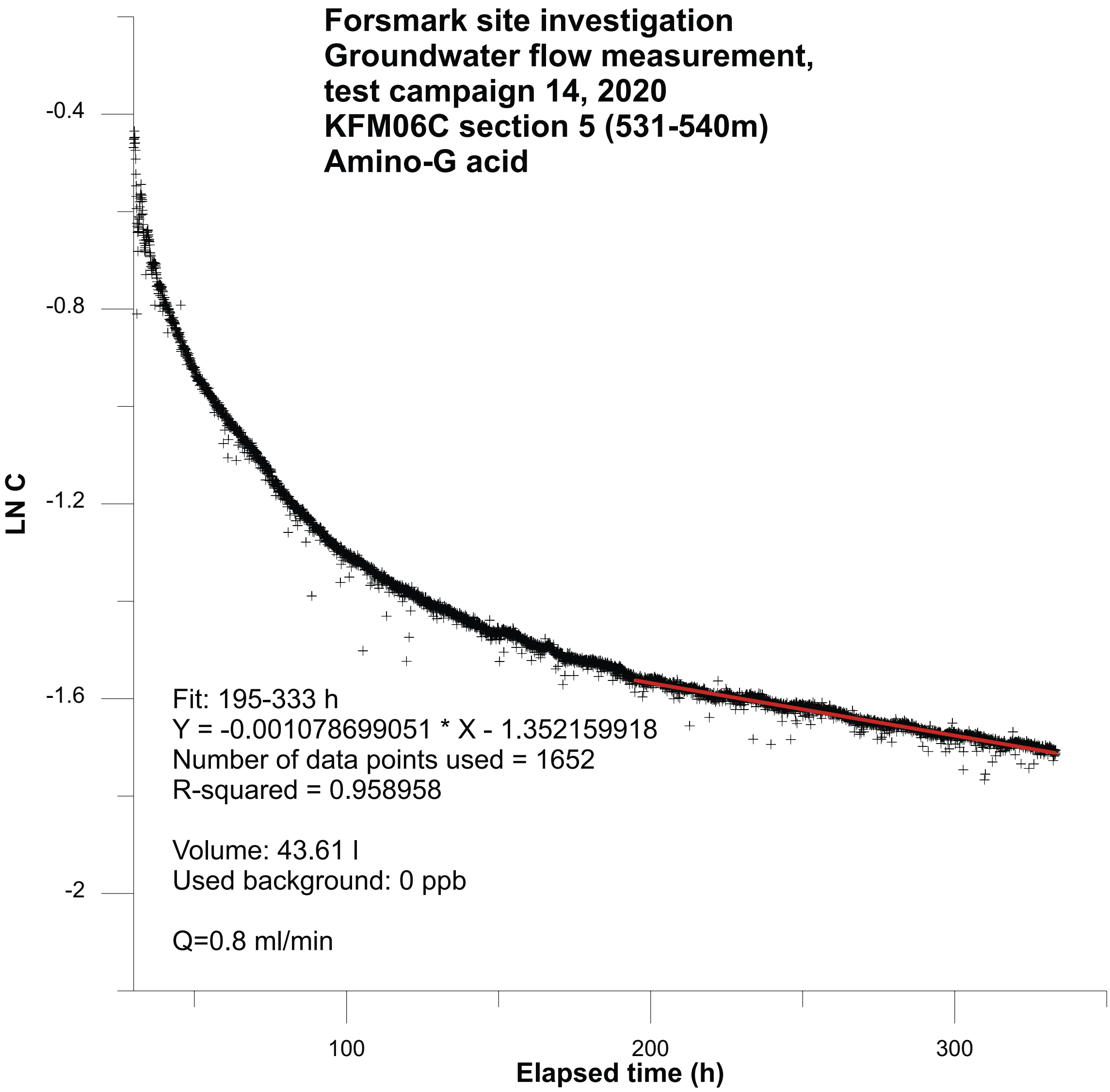

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM01D section 4 (311-321m)
Amino-G acid
-0.12
-0.16
-0.2
-0.24
LN C
Fit: 100-165 h
Y = -0.0001328211413 * X - 0.1867794132
Number of data points used = 767
R-squared = 0.641175
Volume: 31.27 l
Used background: 30 ppb
Q=0.07 ml/min
40
80
120
160
Elapsed time (h)

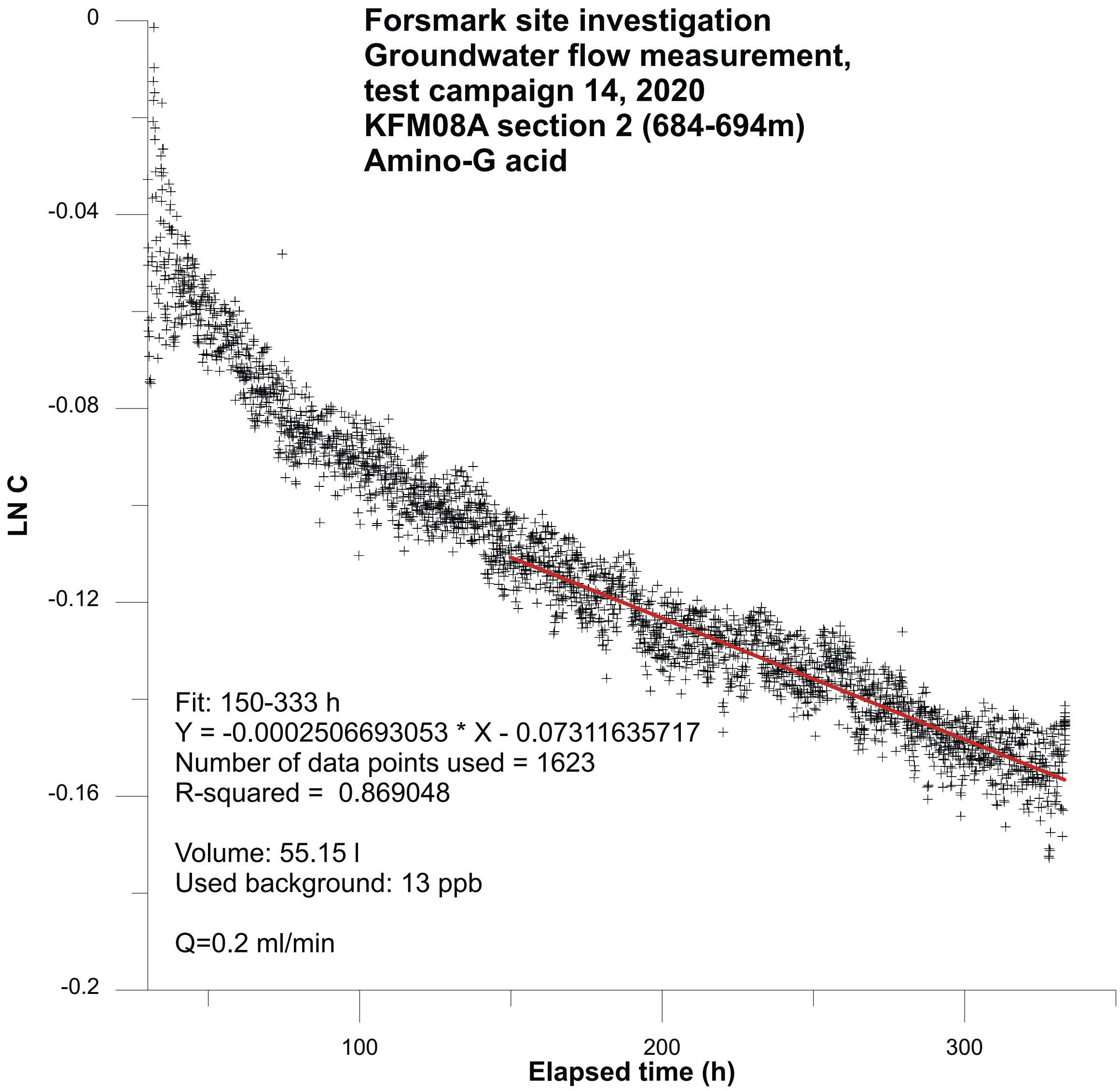

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM06A section 3 (738-748m)
Amino-G acid
0.2
0
-0.2
-0.4
-0.6
LN C
Fit 1: 60-166 h
Y = -0.0001969247688 * X - 0.2038646566
Number of data points used = 755
R-squared = 0.0428616
Volume: 58.25 l
Used background: 26 ppb
Q=0.2 ml/min
40
80
120
160
Elapsed time (h)



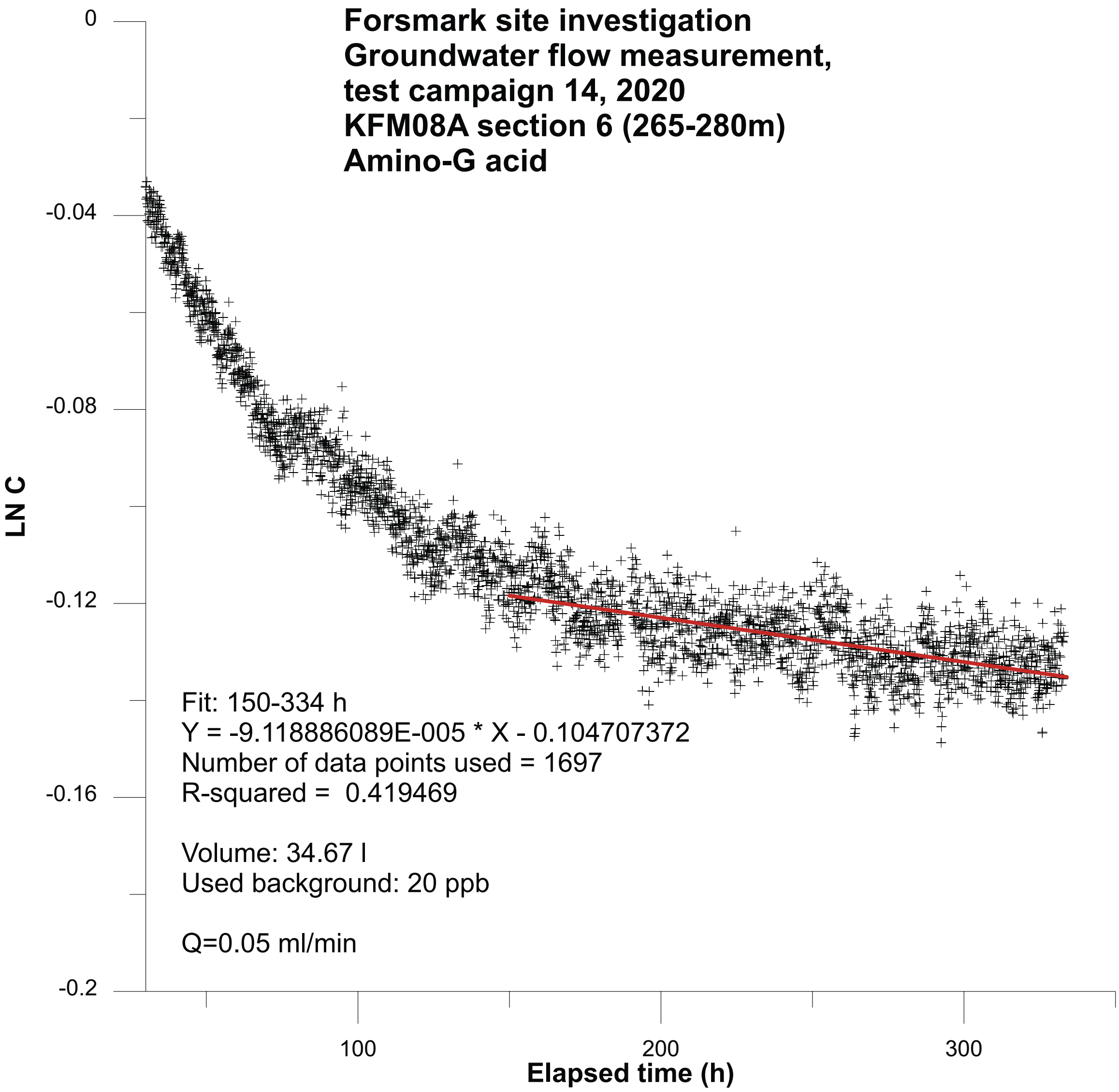
Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM06A section 5 (341-362m)
Amino-G acid
-0.6
-0.8
-1
-1.2
LN C
Fit: 76-166 h
Y = -0.00187739563 * X - 0.7826586924
Number of data points used = 973
R-squared = 0.971133
Volume: 46.64 l
Used background: 15 ppb
Q=1.5 ml/min
40
80
120
160
Elapsed time (h)

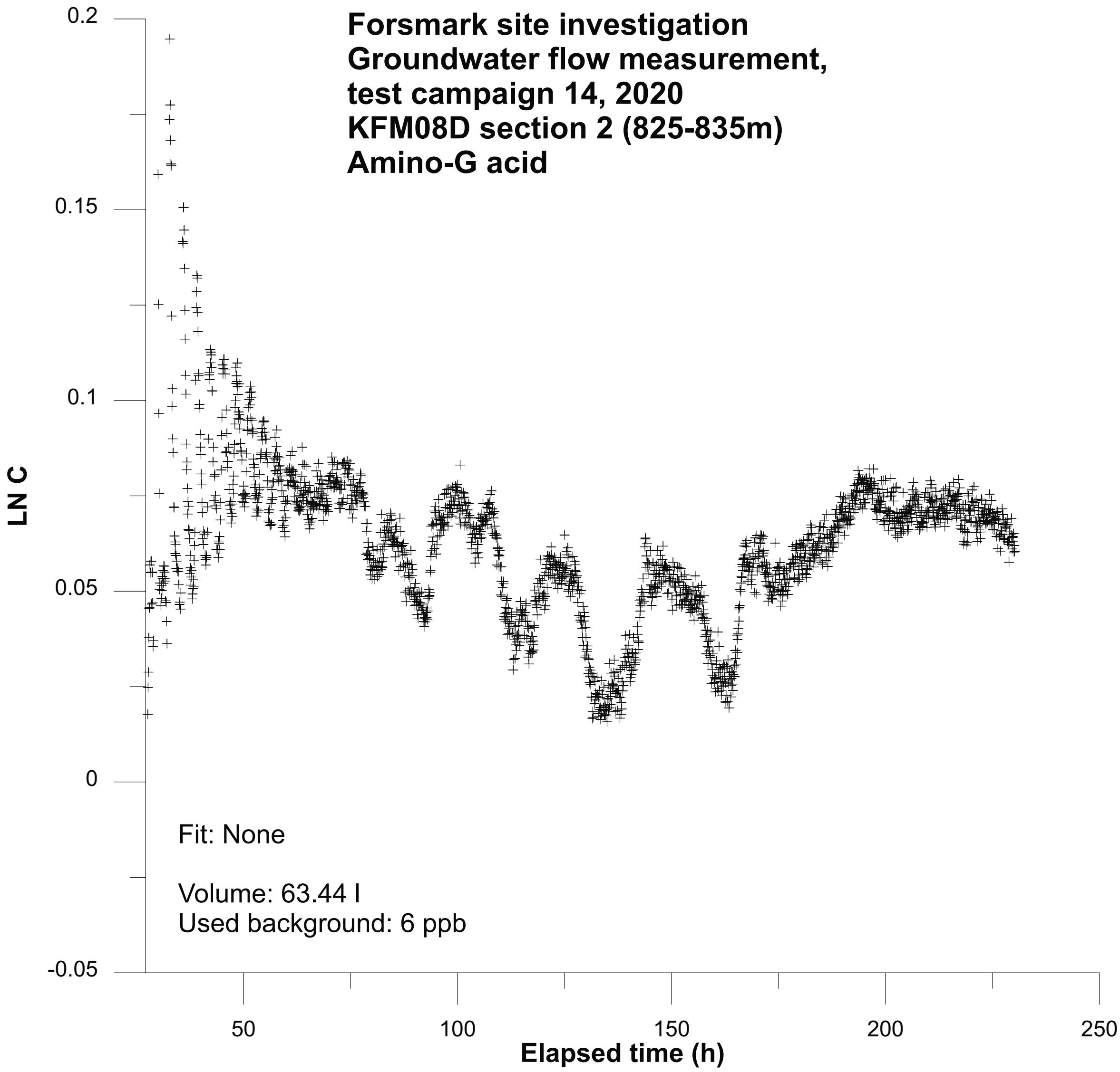

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM06C section 3 (647-666m)
Amino-G acid
-0.12
-0.16
-0.2
-0.24
-0.28
LN C
Fit: 120-333 h
Y = -0.0001788100768 * X - 0.1683890283
Number of data points used = 1880
R-squared = 0.818496
Volume: 64.00 l
Used background: 0 ppb
Q=0.2 ml/min
100
200
300
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM06C section 5 (531-540m)
Amino-G acid
-0.4
-0.8
-1.2
-1.6
-2
LN C
Fit: 195-333 h
Y = -0.001078699051 * X - 1.352159918
Number of data points used = 1652
R-squared = 0.958958
Volume: 43.61 l
Used background: 0 ppb
Q=0.8 ml/min
100
200
300
Elapsed time (h)

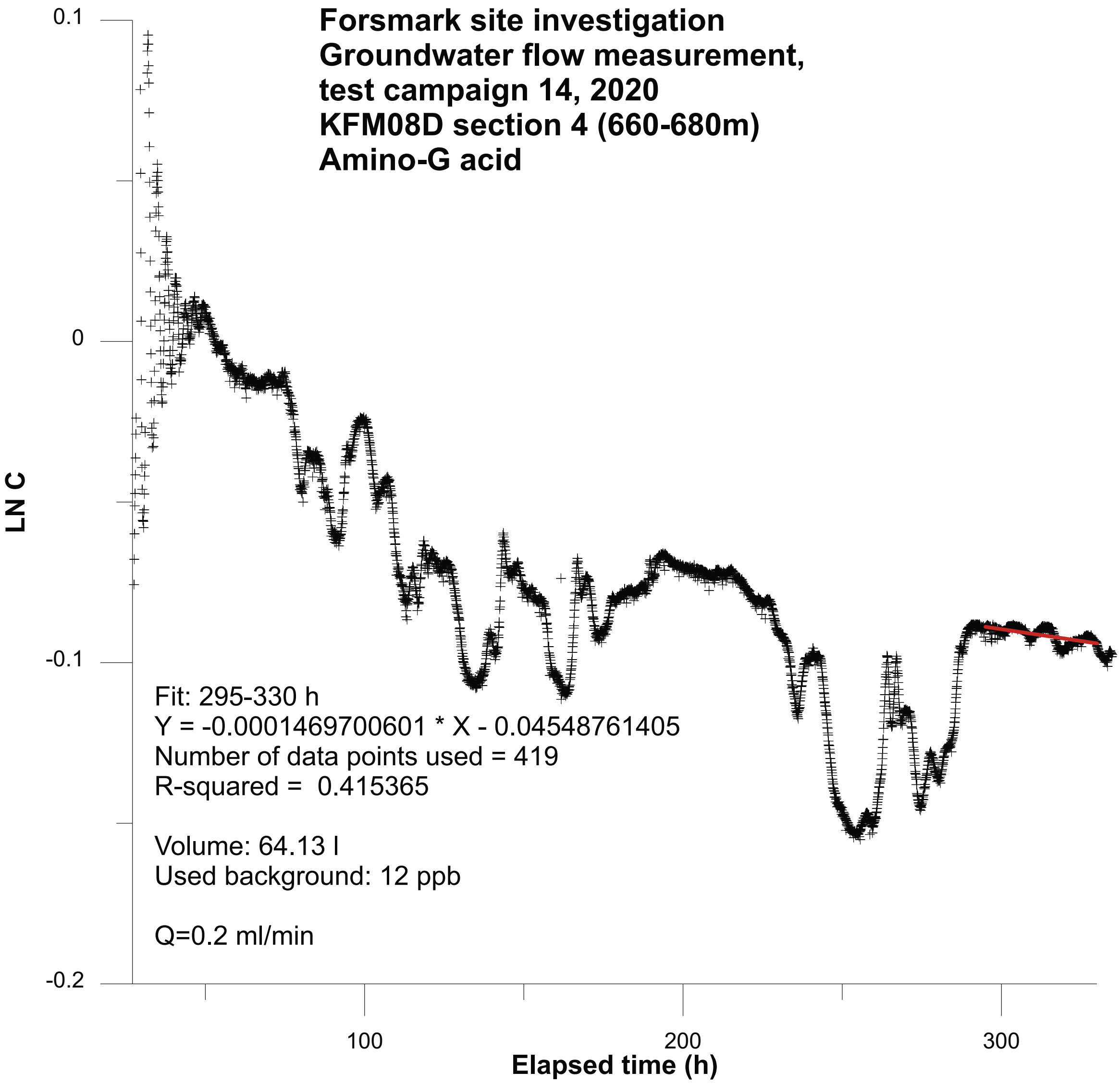


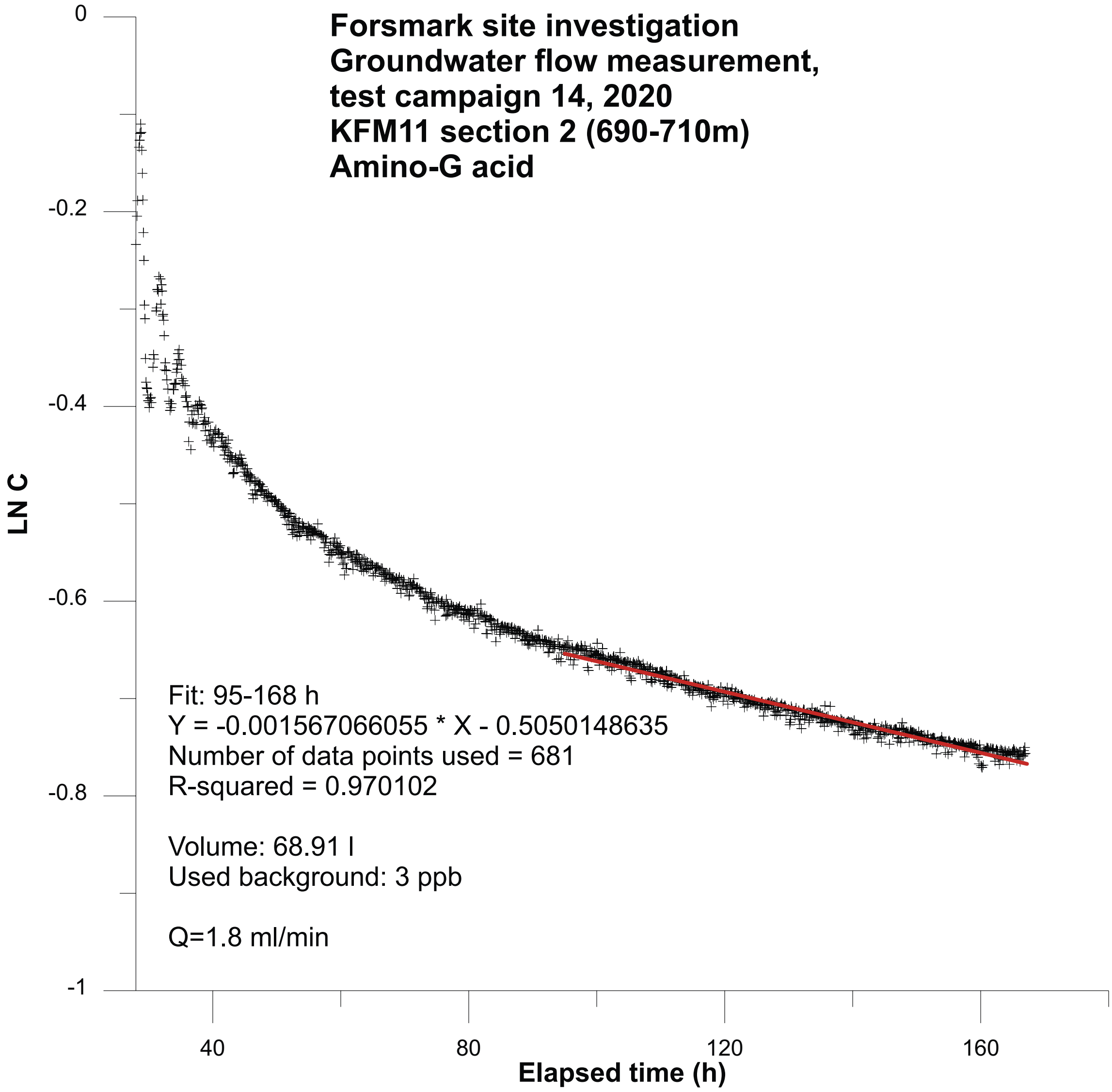
Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM08A section 2 (684-694m)
Amino-G acid
Fit: 150-333 h
Y = -0.0002506693053 * X - 0.07311635717
Number of data points used = 1623
R-squared = 0.869048
Volume: 55.15 l
Used background: 13 ppb
Q=0.2 ml/min
LN C
0
-0.04
-0.08
-0.12
-0.16
-0.2
100
200
300
Elapsed time (h)

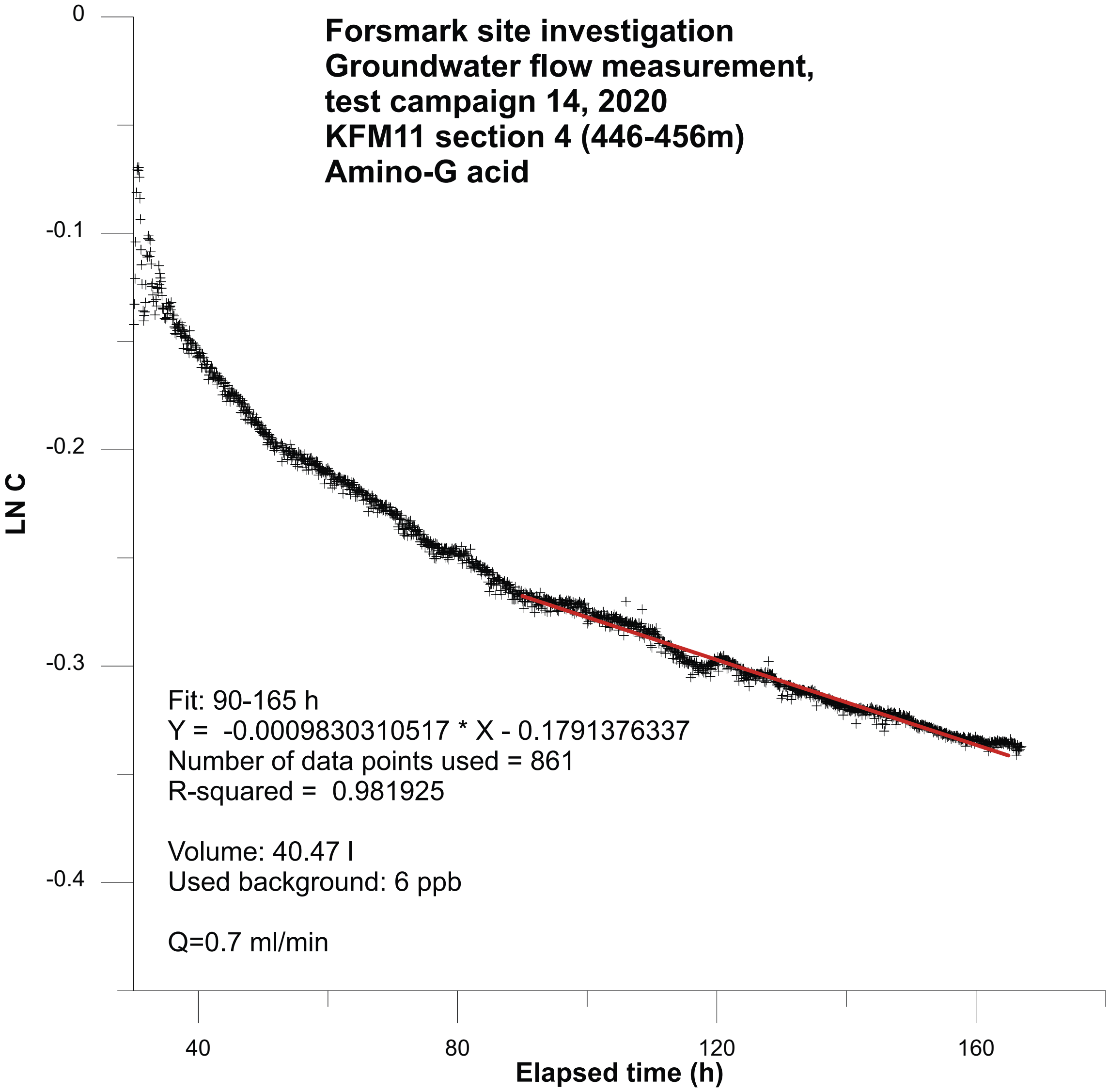

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM08A section 6 (265-280m)
Amino-G acid
0
-0.04
-0.08
-0.12
-0.16
-0.2
LN C
100
200
300
Elapsed time (h)
Fit: 150-334 h
Y = -9.118886089E-005 * X - 0.104707372
Number of data points used = 1697
R-squared = 0.419469
Volume: 34.67 l
Used background: 20 ppb
Q=0.05 ml/min

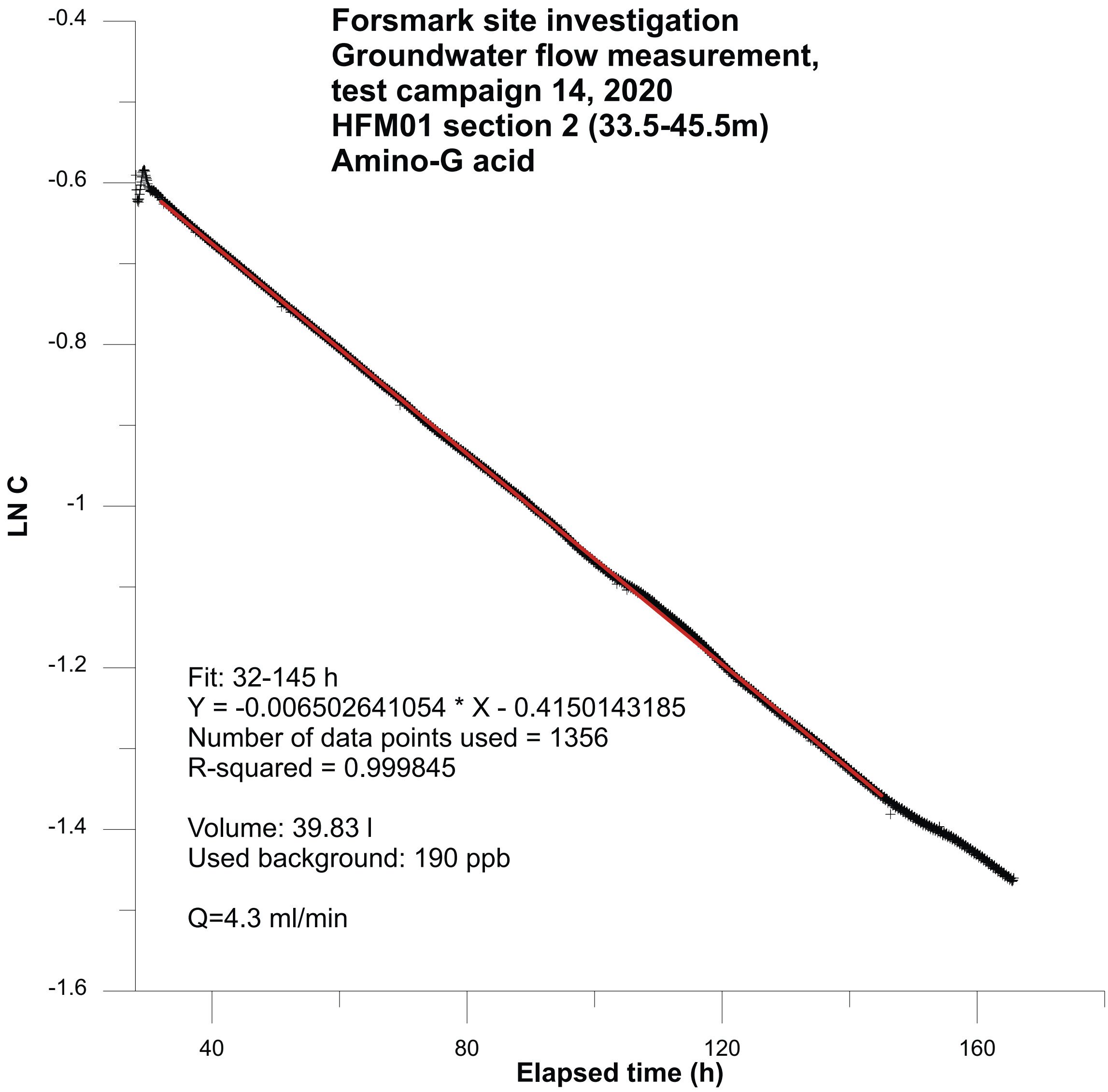


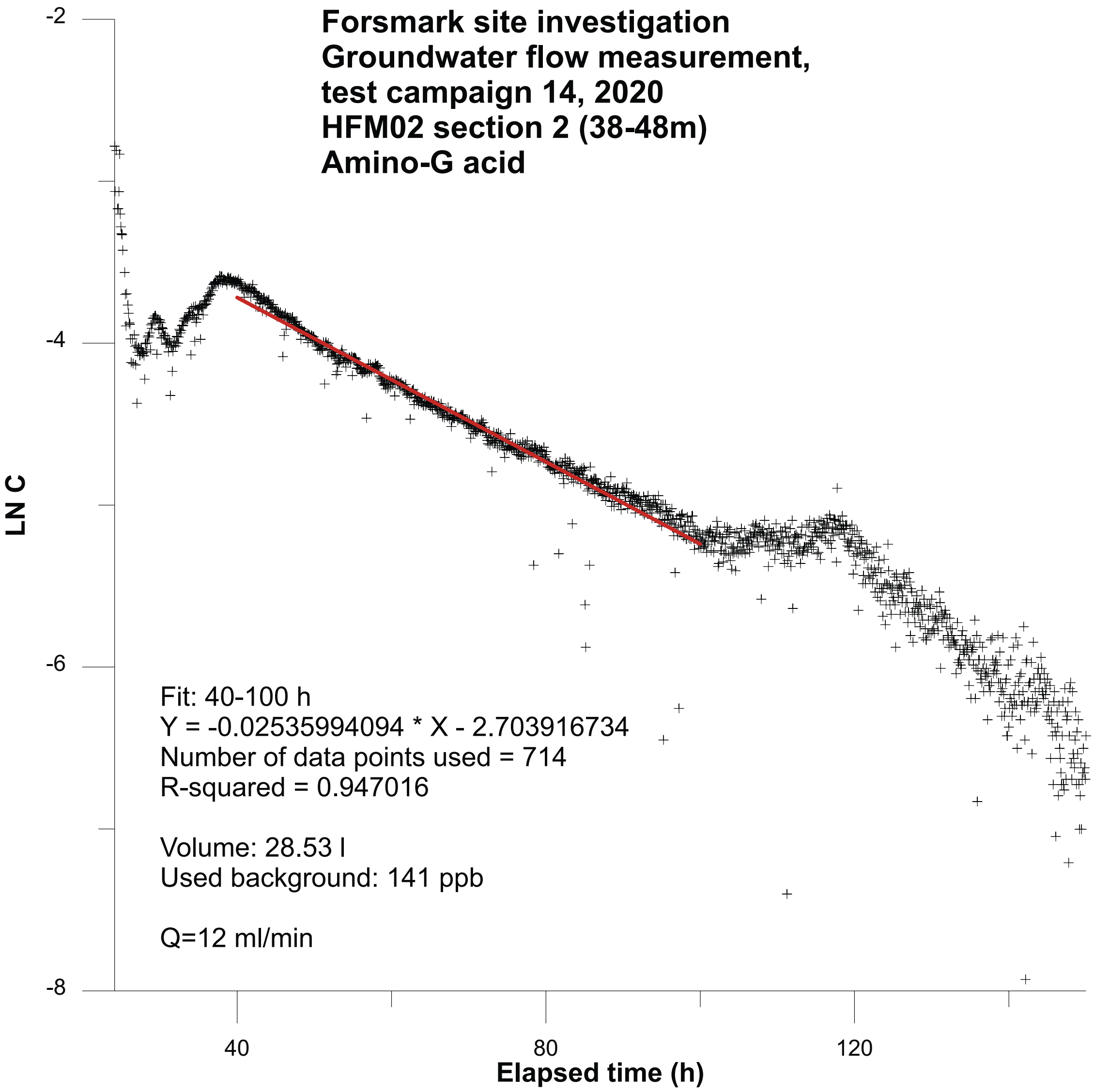
Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM08D section 2 (825-835m)
Amino-G acid
0.2
0.15
0.1
0.05
0
-0.05
LN C
Fit: None
Volume: 63.44 l
Used background: 6 ppb
50
100
150
200
250
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM08D section 4 (660-680m)
Amino-G acid
Fit: 295-330 h
Y = -0.0001469700601 * X - 0.04548761405
Number of data points used = 419
R-squared = 0.415365
Volume: 64.13 l
Used background: 12 ppb
Q=0.2 ml/min
0.1
0
-0.1
-0.2
LN C
100
200
300
Elapsed time (h)

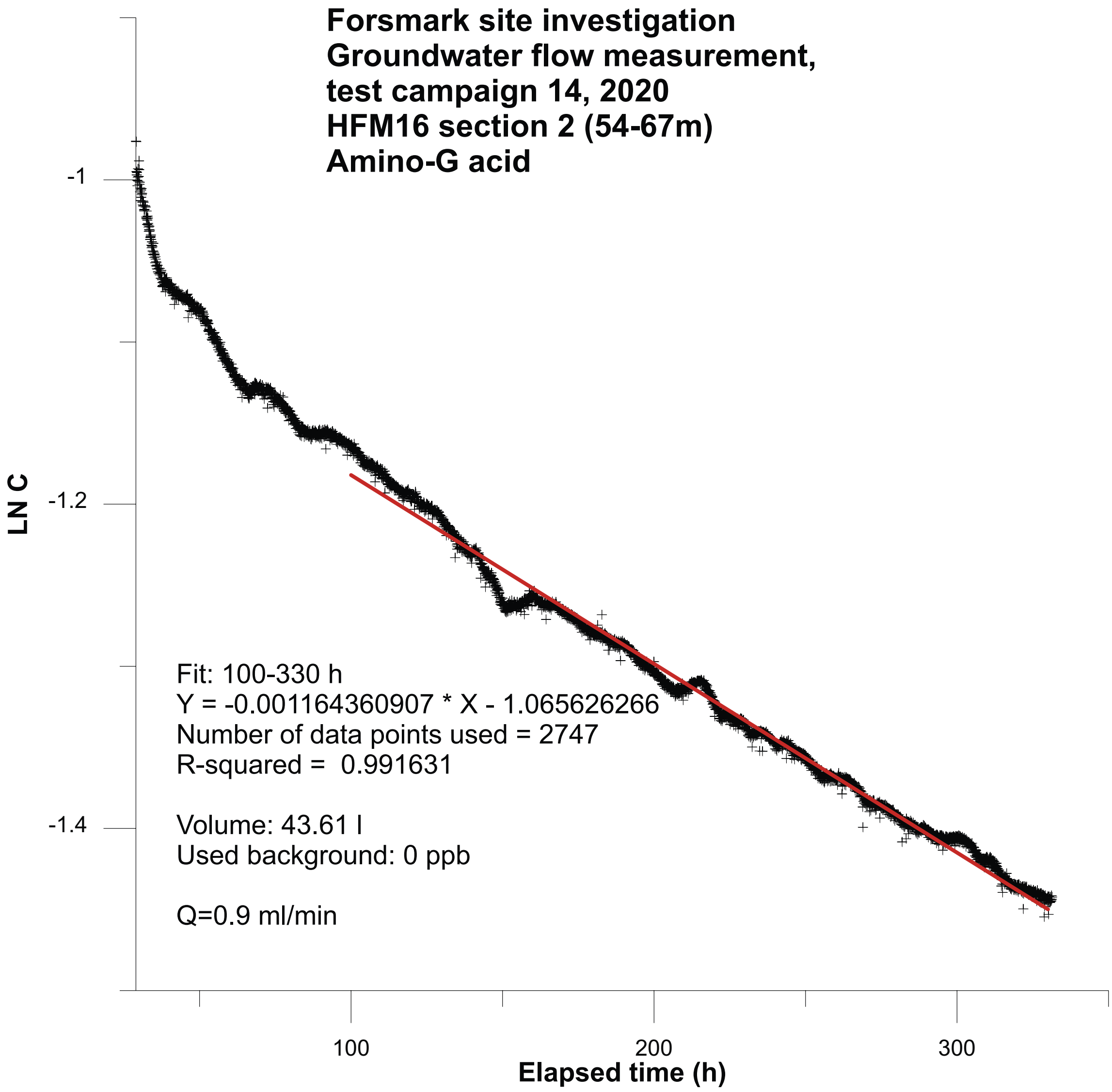

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM11 section 2 (690-710m)
Amino-G acid
Fit: 95-168 h
Y = -0.001567066055 * X - 0.5050148635
Number of data points used = 681
R-squared = 0.970102
Volume: 68.91 l
Used background: 3 ppb
Q=1.8 ml/min
LN C
0
-0.2
-0.4
-0.6
-0.8
-1
40
80
120
160
Elapsed time (h)

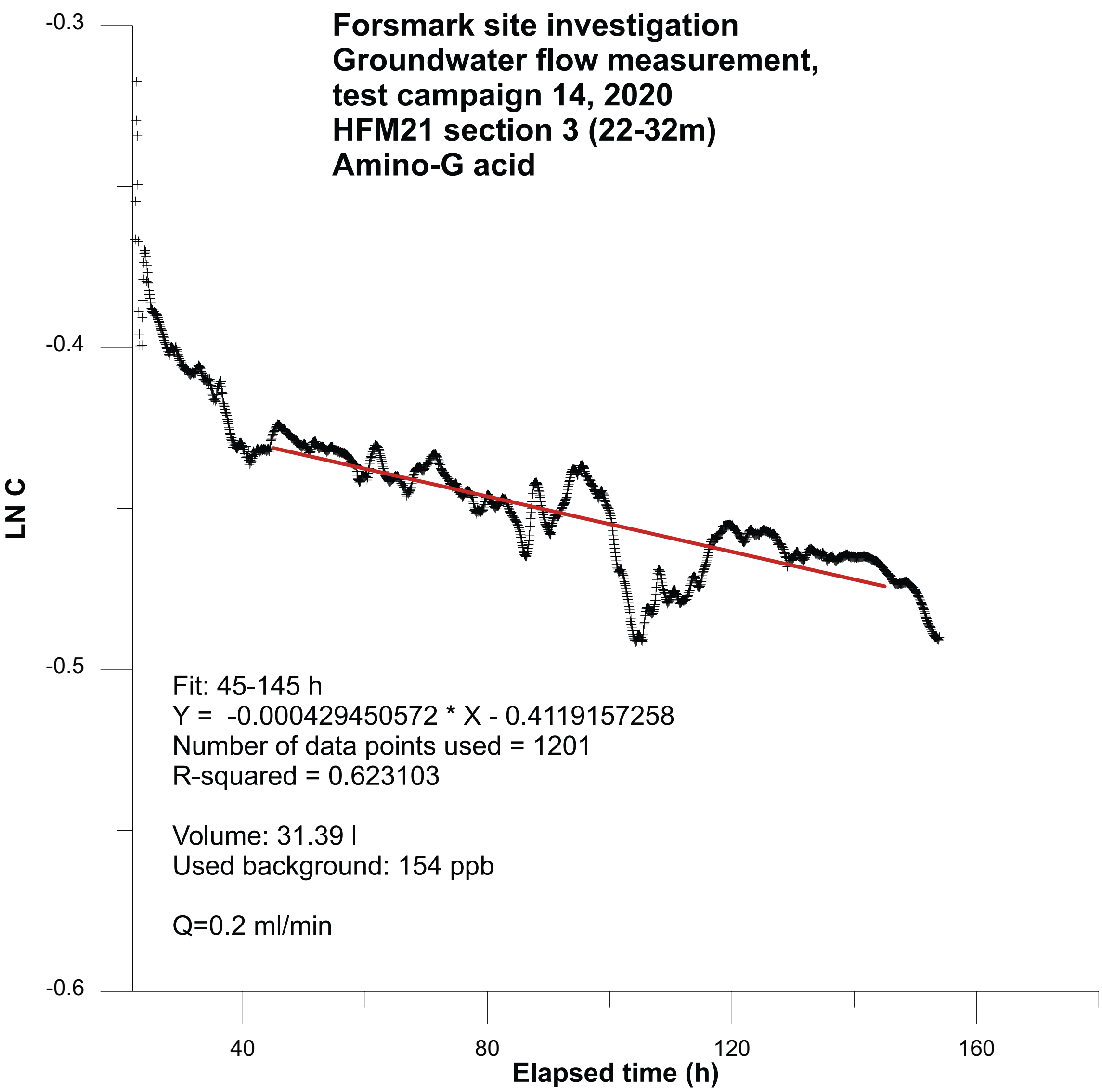

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
KFM11 section 4 (446-456m)
Amino-G acid
0
-0.1
-0.2
-0.3
-0.4
LN C
Fit: 90-165 h
Y = -0.0009830310517 * X - 0.1791376337
Number of data points used = 861
R-squared = 0.981925
Volume: 40.47 l
Used background: 6 ppb
Q=0.7 ml/min
40
80
120
160
Elapsed time (h)

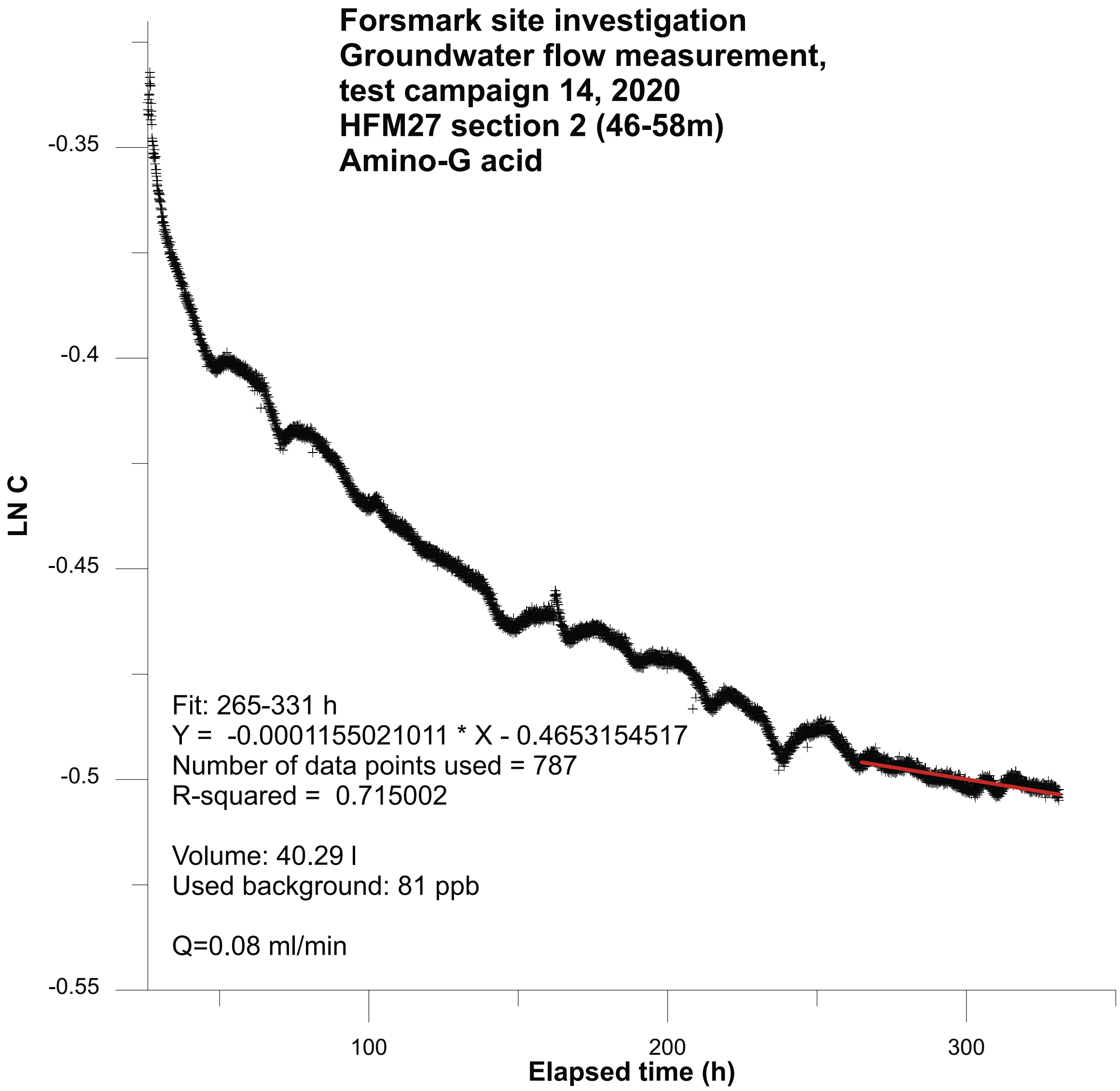

Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM01 section 2 (33.5-45.5m)
Amino-G acid
Fit: 32-145 h
Y = -0.006502641054 * X - 0.4150143185
Number of data points used = 1356
R-squared = 0.999845
Volume: 39.83 l
Used background: 190 ppb
Q=4.3 ml/min
LN C
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
40
80
120
160
Elapsed time (h)

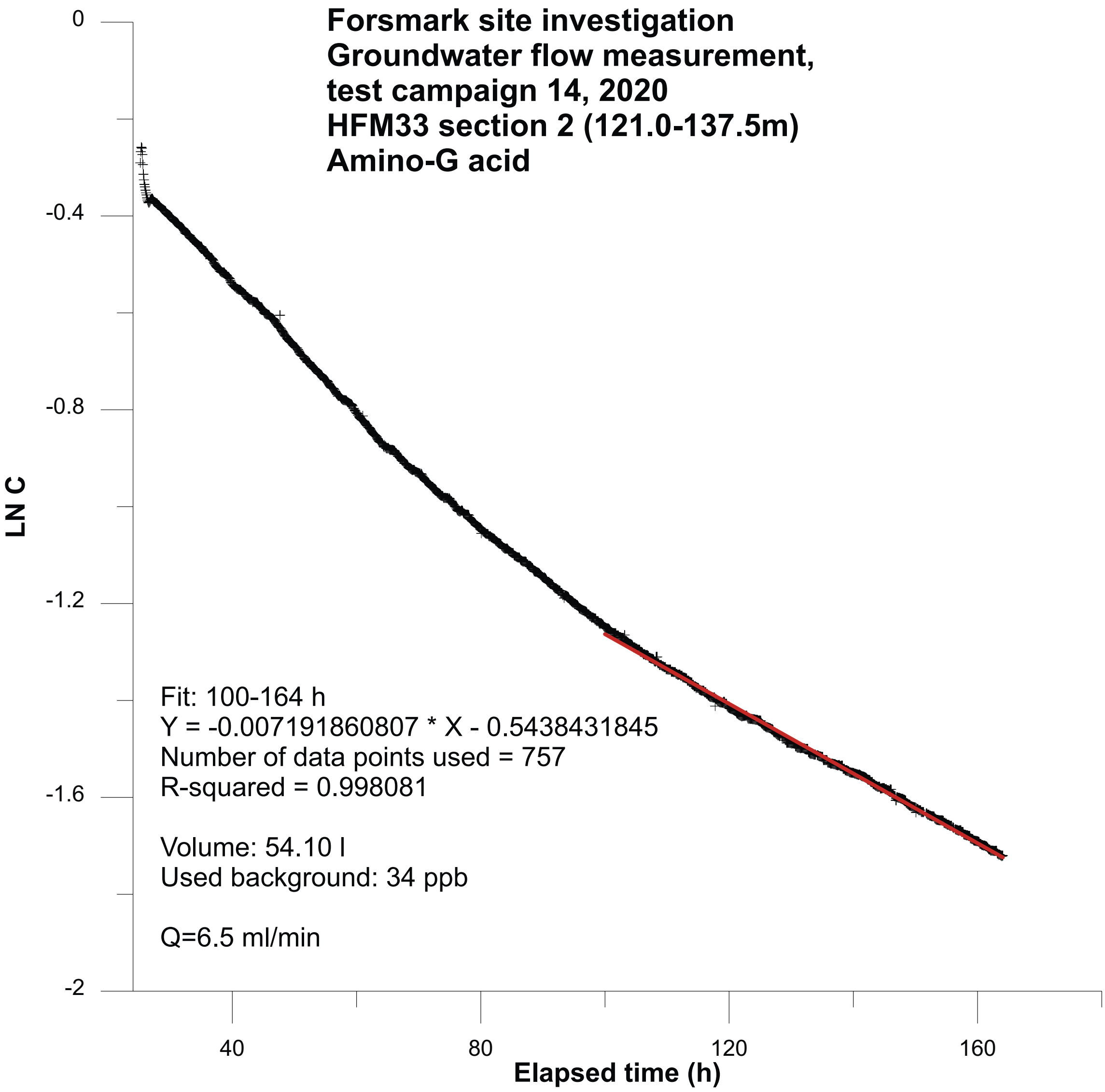


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM02 section 2 (38-48m)
Amino-G acid
Fit: 40-100 h
Y = -0.02535994094 * X - 2.703916734
Number of data points used = 714
R-squared = 0.947016
Volume: 28.53 l
Used background: 141 ppb
Q=12 ml/min
LN C
Elapsed time (h)
-2
-4
-6
-8
40
80
120


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM16 section 2 (54-67m)
Amino-G acid
Fit: 100-330 h
Y = -0.001164360907 * X - 1.065626266
Number of data points used = 2747
R-squared = 0.991631
Volume: 43.61 l
Used background: 0 ppb
Q=0.9 ml/min
LN C
-1
-1.2
-1.4
100
200
300
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM21 section 3 (22-32m)
Amino-G acid
Fit: 45-145 h
Y = -0.000429450572 * X - 0.4119157258
Number of data points used = 1201
R-squared = 0.623103
Volume: 31.39 l
Used background: 154 ppb
Q=0.2 ml/min
LN C
-0.3
-0.4
-0.5
-0.6
40
80
120
160
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM27 section 2 (46-58m)
Amino-G acid
LN C
-0.35
-0.4
-0.45
-0.5
-0.55
Fit: 265-331 h
Y = -0.0001155021011 * X - 0.4653154517
Number of data points used = 787
R-squared = 0.715002
Volume: 40.29 l
Used background: 81 ppb
Q=0.08 ml/min
100
200
300
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 14, 2020
HFM33 section 2 (121.0-137.5m)
Amino-G acid
Fit: 100-164 h
Y = -0.007191860807 * X - 0.5438431845
Number of data points used = 757
R-squared = 0.998081
Volume: 54.10 l
Used background: 34 ppb
Q=6.5 ml/min
LN C
0
-0.4
-0.8
-1.2
-1.6
-2
40
80
120
160
Elapsed time (h)

Precipitation (mm/24 hours) 2020-09-15 – 2020-12-01

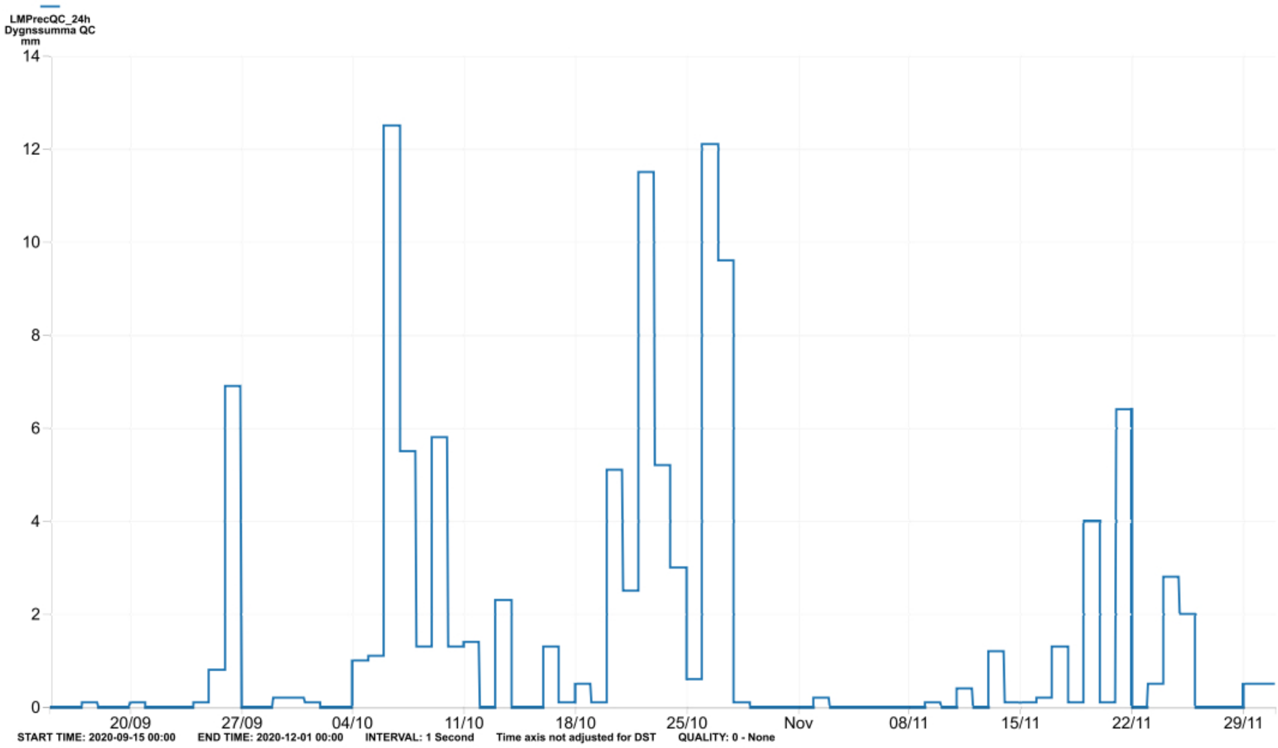
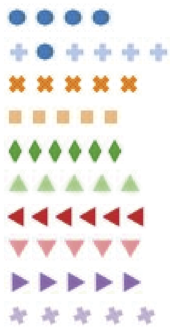


Figure A2-1. *Daily precipitation in Forsmark during the field campaign, autumn 2020.*

Groundwater levels (m.a.s.l. RHB70)

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



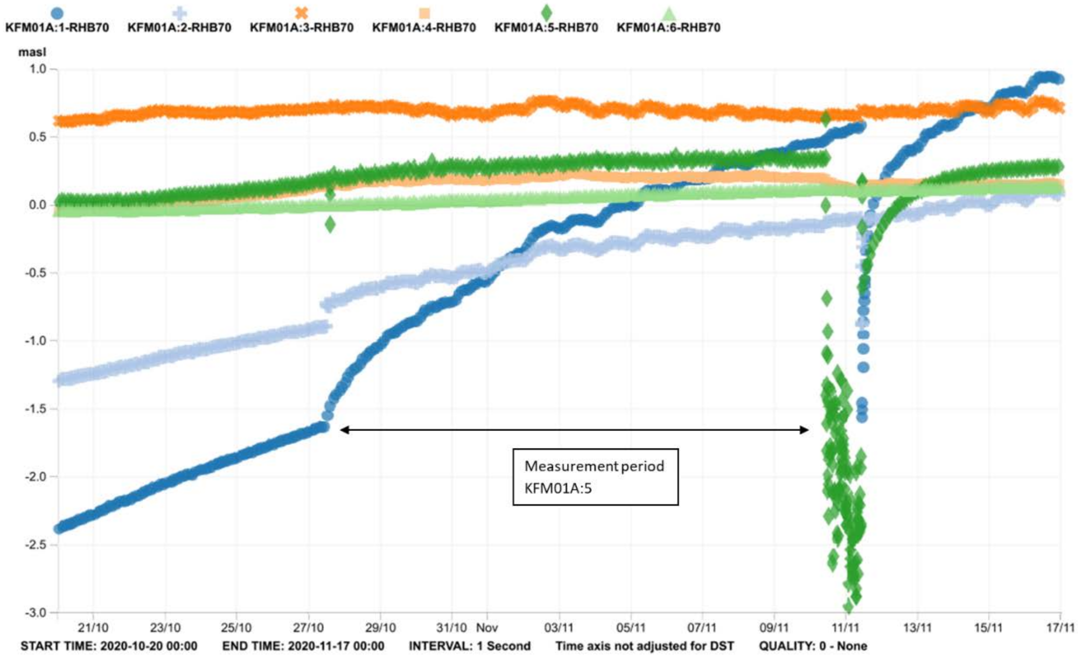


***Figure A2-2.** Measured section: KFM01A:5 (dark green).*

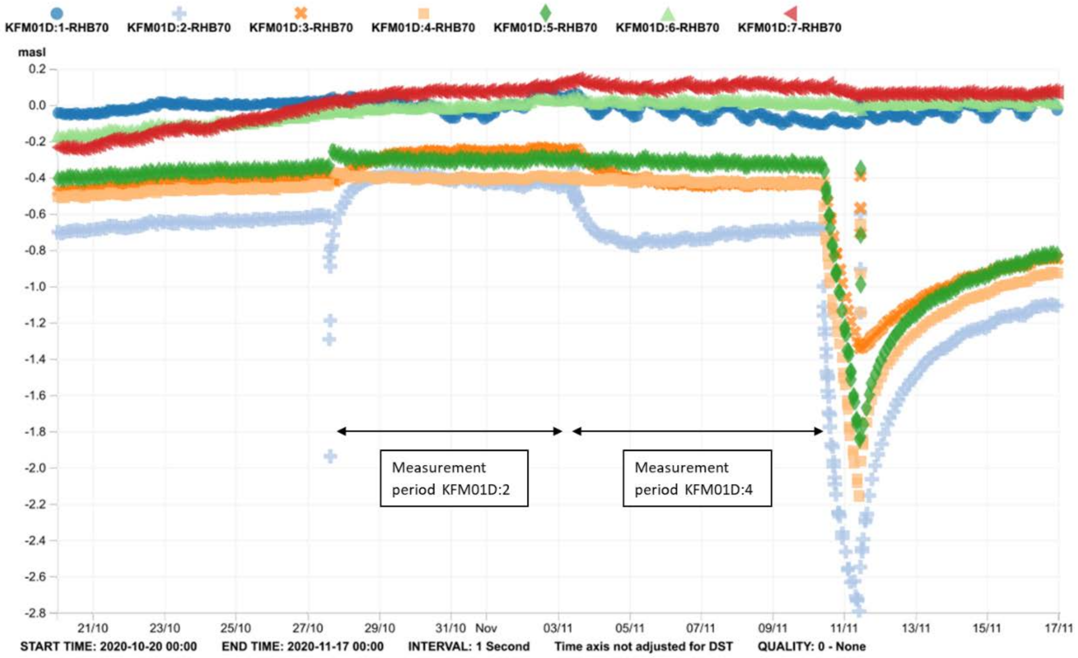


***Figure A2-3.** Measured section: KFM01D:2 (pale blue) and KFM01D:4 (pale orange).*

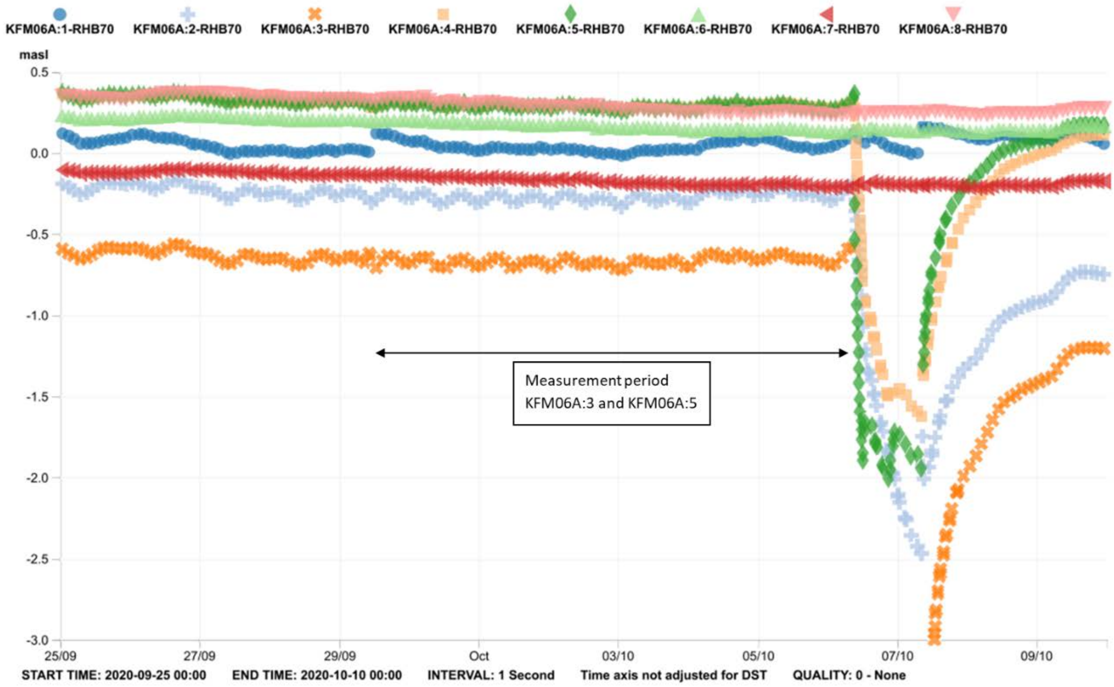


Figure A2-4. *Measured section: KFM06A:3 (dark orange) and KFM06A:5 (dark green).*

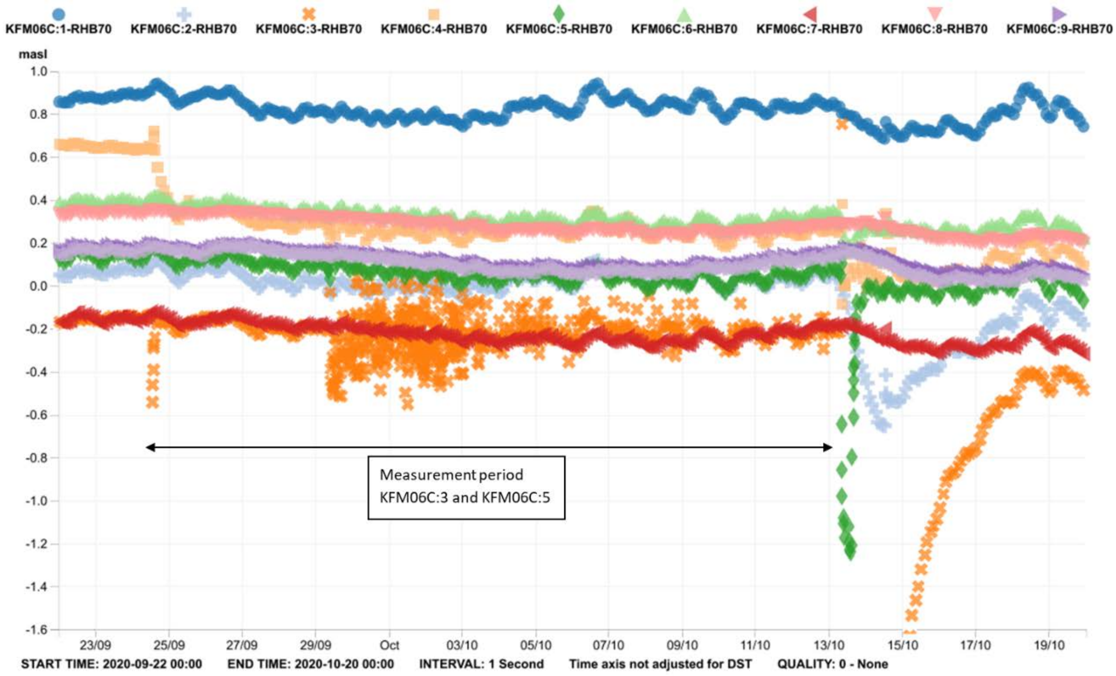


Figure A2-5. *Measured section: KFM06C:3 (dark orange) and KFM06C:5 (dark green).*

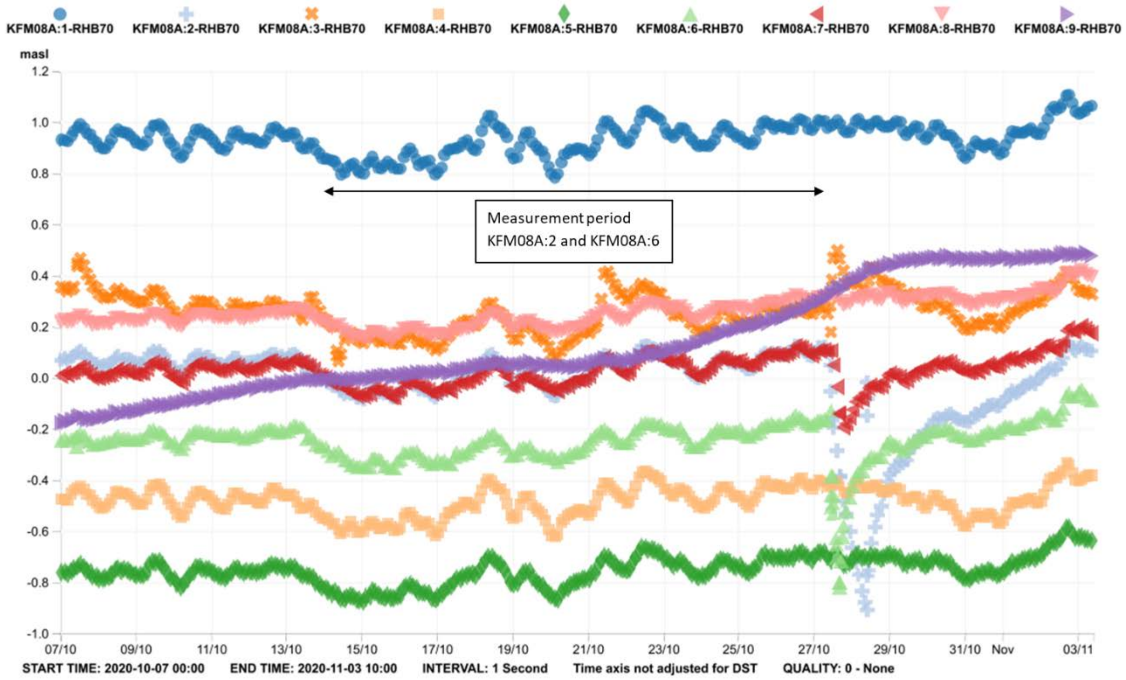


Figure A2-6. *Measured section: KFM08A:2 (pale blue) and KFM08A:6 (pale green).*

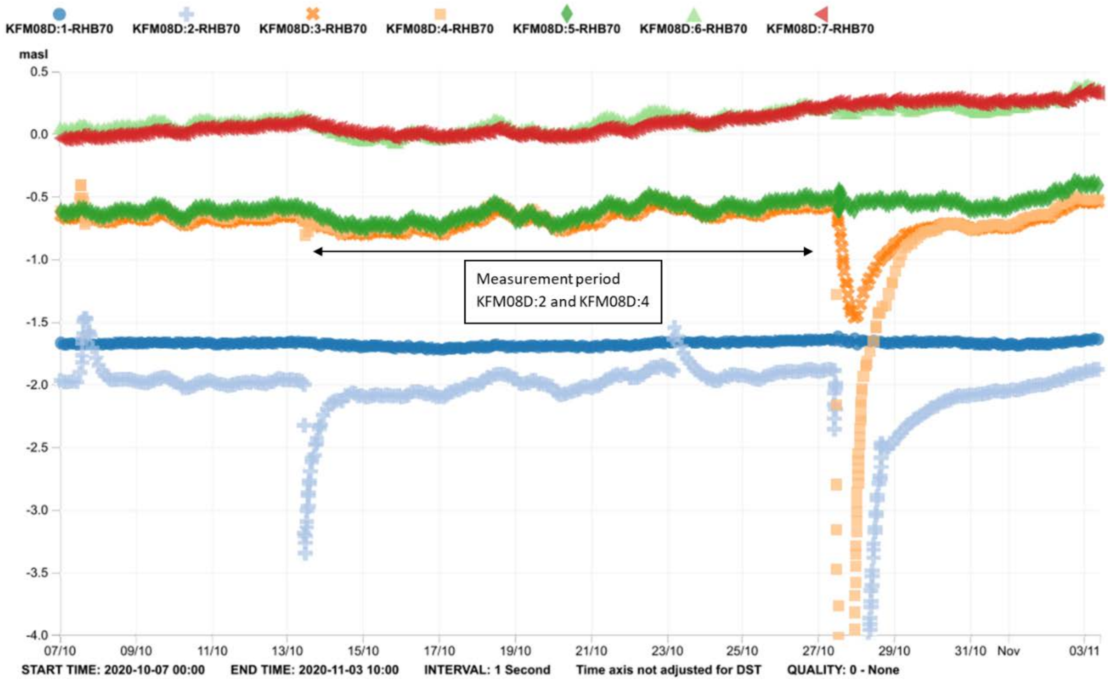


Figure A2-7. *Measured section: KFM08D:2 (pale blue) and KFM08D:4 (pale orange).*

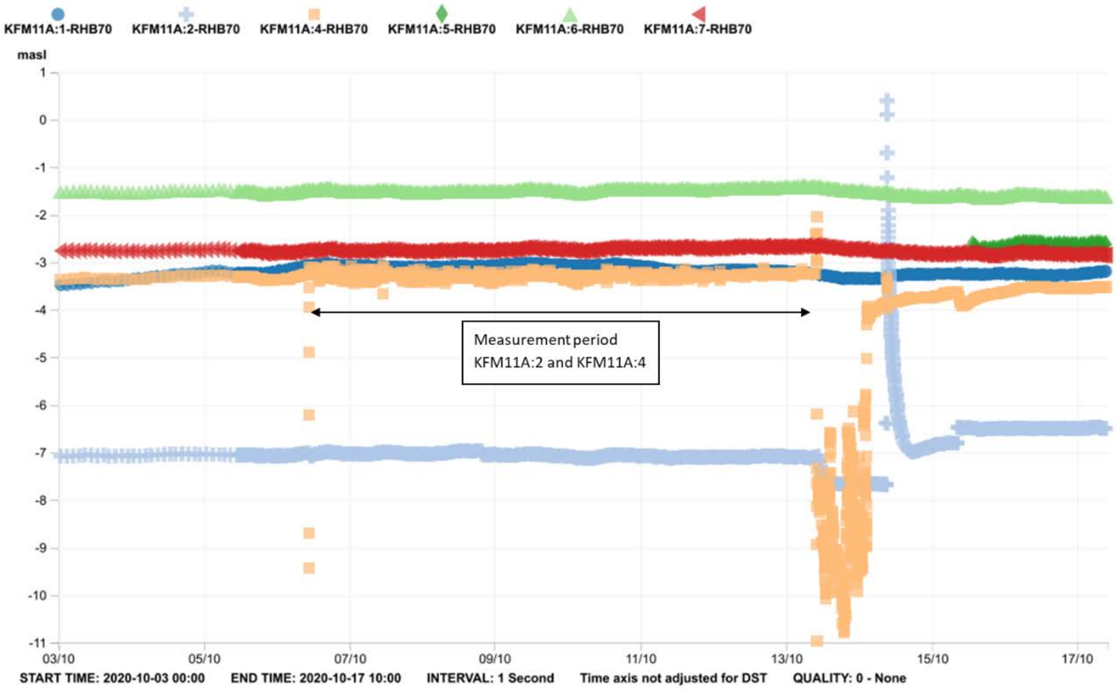


Figure A2-8. *Measured section: KFM011A:2 (pale blue) and KFM11A:4 (pale orange). KFM11A:3 is excluded from the figure due to scale.*

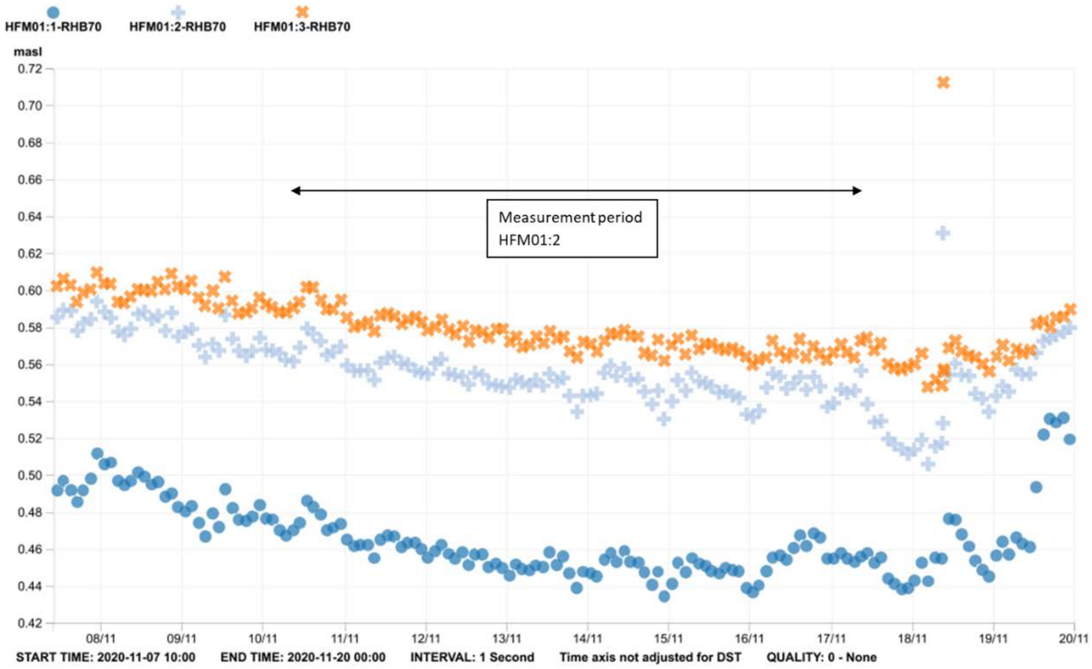


Figure A2-9. *Measured section: HFM01:2 (pale blue).*

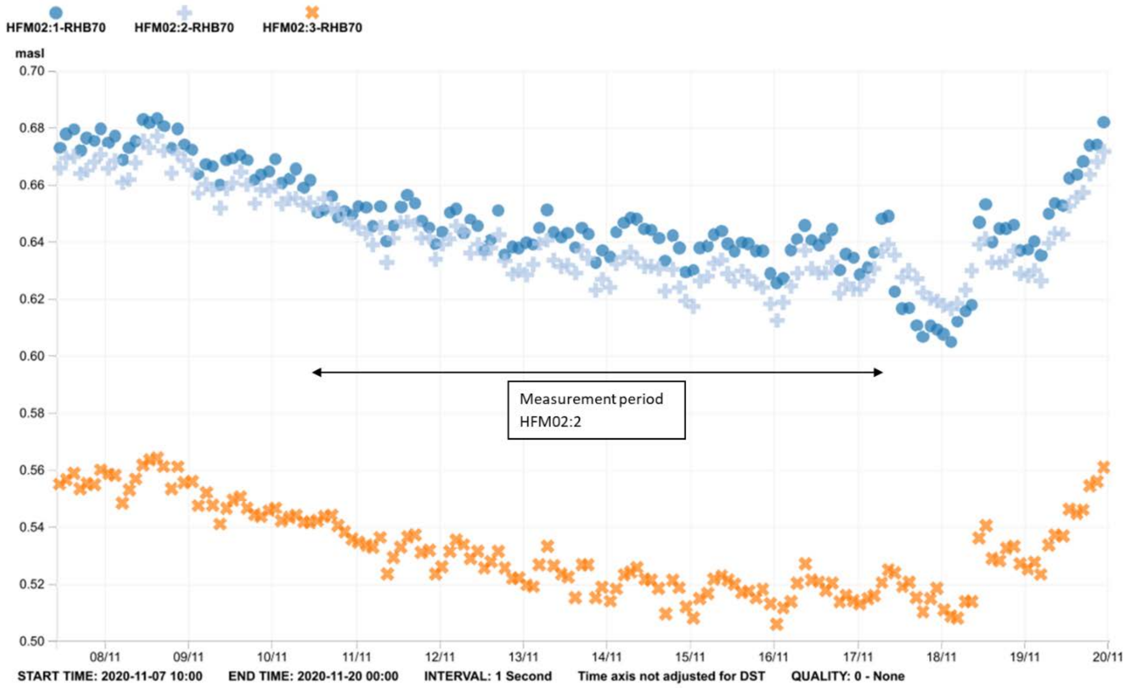


Figure A2-10. *Measured section: HFM02:2 (pale blue).*

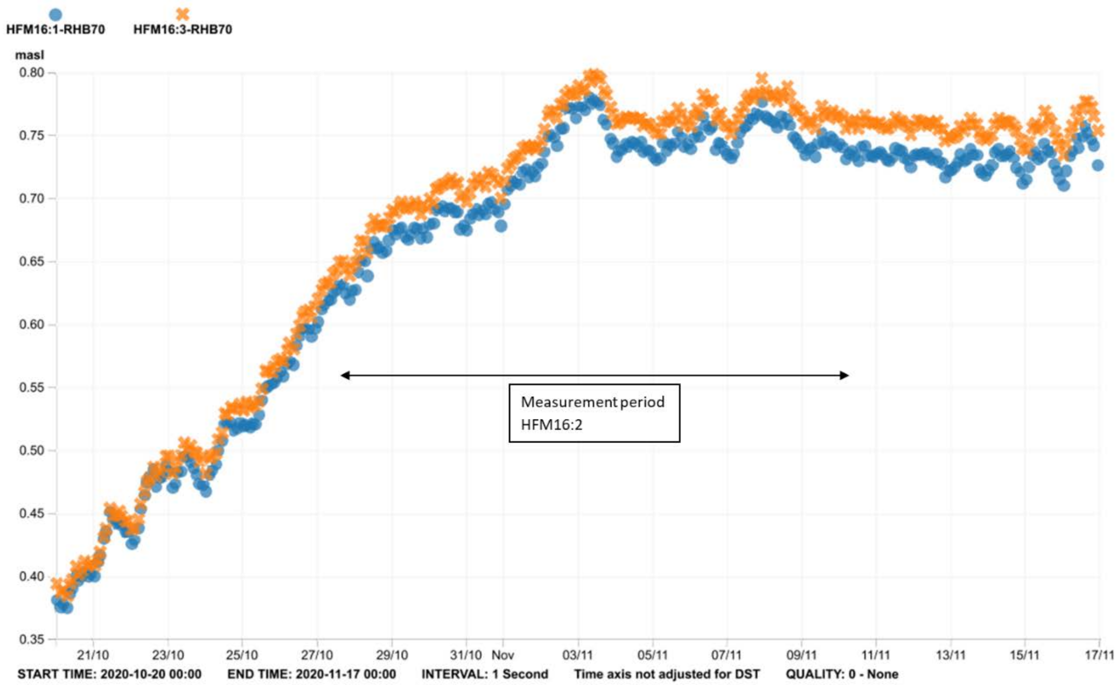


Figure A2-11. *Measured section: HFM16:2. Unfortunately, data is missing for section 2 due to malfunctioning monitoring equipment. However, the level in section 2 usually follows the two other sections within some centimeter.*

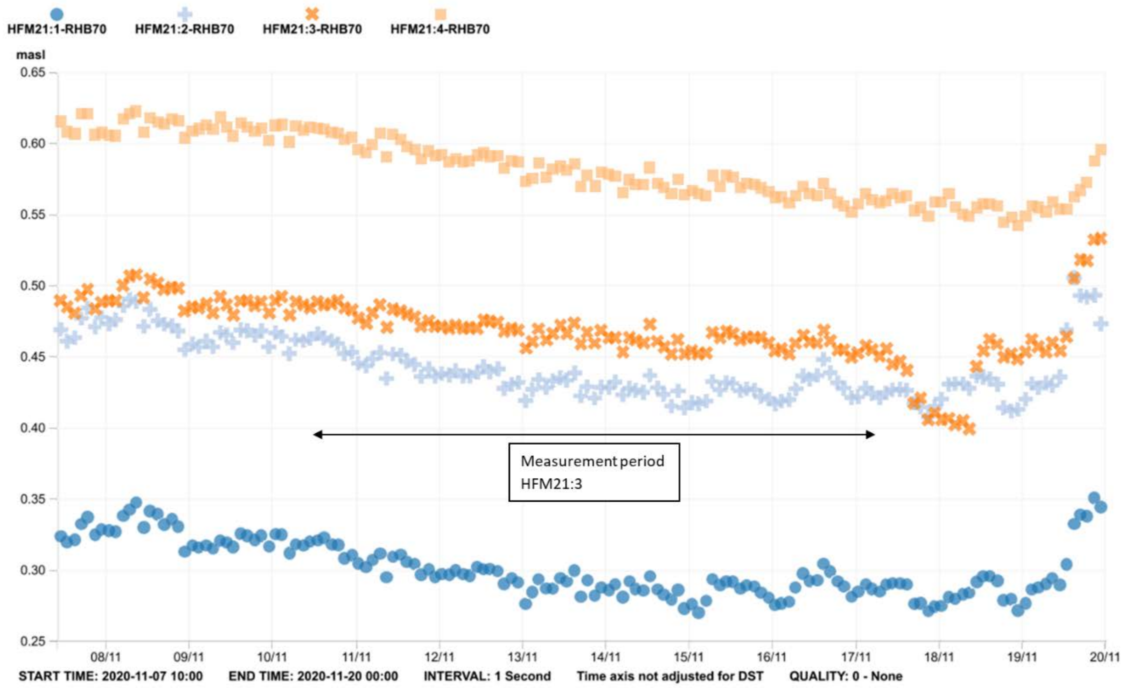


Figure A2-12. *Measured section: HFM21:3 (dark orange).*

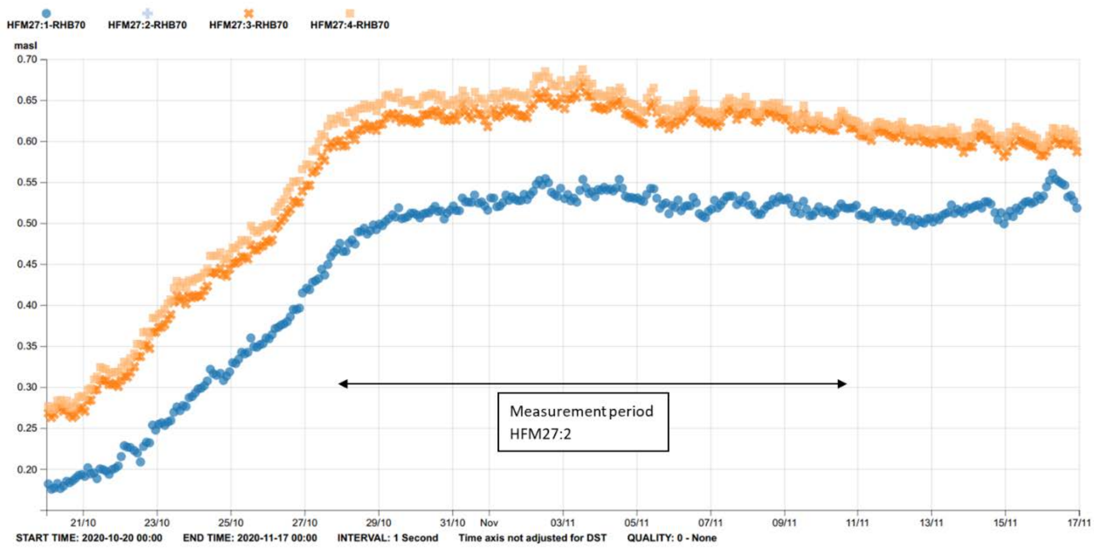


Figure A2-13. *Measured section: HFM27:2. Unfortunately, data is missing for section 2 due to malfunctioning monitoring equipment. However, the level in section 2 usually follows about 5 centimeters below sections 3 and 4.*

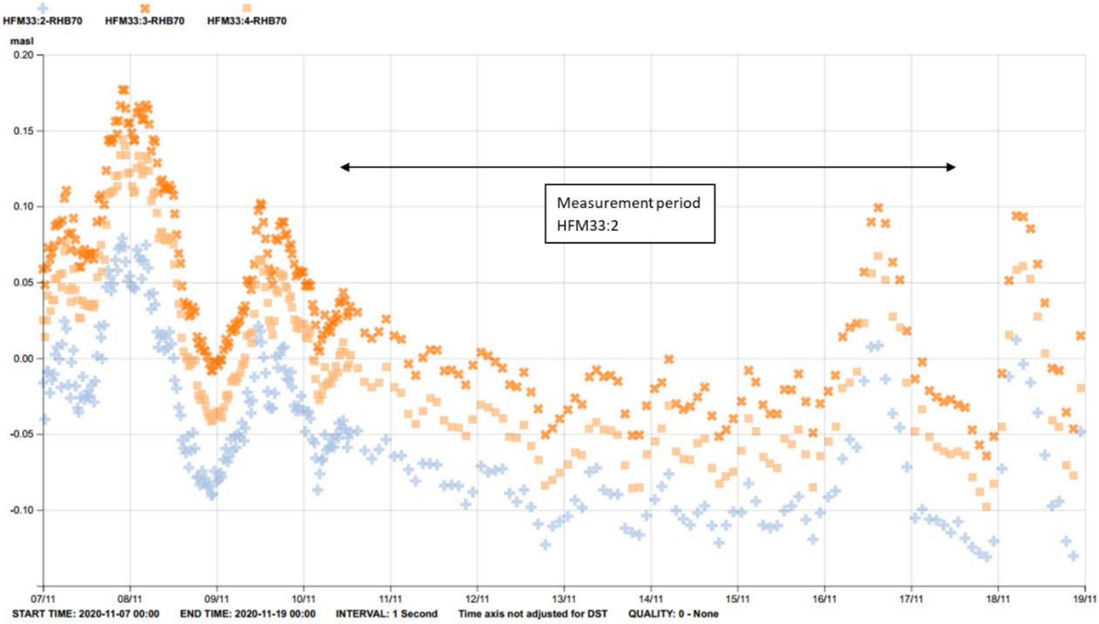


Figure A2-14. *Measured section: HFM33:2 (pale blue).*

Appendix 3

Activities during test campaigns in 2005–2020

Activities performed in the Forsmark area during the test campaigns with groundwater flow measurements, 2005–2020.

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 – 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

Start date	Stop date	Borehole	Activity
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
Test campaign no. 8, 2012-11-12 – 2012-12-17			
No disturbing 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

Start date	Stop date	Borehole	Activity
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
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

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Arkitektkopia AB, Bromma, 2023