Technical Report
TR-18-16
July 2019

Analysis and evaluation of groundwater flow measurements in permanently installed boreholes at Forsmark 2005–2017

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ISSN 1404-0344
SKB TR-18-16
ID 1700729

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Keywords: Groundwater flow, Tracer, Dilution test.

Abstract

This report describes the analysis and evaluation of groundwater flow measurements performed during 2013–2017 in the Forsmark groundwater flow monitoring programme. The overall objective of the study has been to recommend improvements of the test methodology and update the monitoring programme. The aim of the analysis has been to determine how and why flow varies over time (months-year) by performing long-term tracer dilution tests in 32 monitoring sections at Forsmark. The results have been compared to short-term measurements (4–5 days) performed during 2005–2012 in the same monitoring sections. The analysis has included influences of precipitation, groundwater level, hydraulic transmissivity distribution, hydraulic gradient and measurement methodology.

The results of the analysis show that groundwater flow may vary considerably over longer periods (months-year). In some sections more than a factor 10 while in others the flow is almost constant. The span of measured flow rates is 0.01–81 ml/min, i.e. a factor of 10 000, which is similar to the span of hydraulic transmissivity. Influence of precipitation and groundwater level are only seen in a few shallow monitoring sections in percussion holes. In at least seven of the monitored sections, there is an influence of the pressure disturbance caused by the initiation of the test resulting in an enhanced flow during the first 4–8 days of measurement. There is also a disturbance caused by evaporation of water from the sampling tubes, which may influence the interpretation and give too high flow rates in low flow sections (< 0.5 ml/min). In summary, the analysis has increased the understanding of the varying groundwater flow measured and revealed that the measurement procedures and techniques need to be adjusted, to get representative values of flow for some of the monitoring sections. Based on the results of the study, an updated measurement programme has been suggested.

Sammanfattning

Denna rapport behandlar analys och utvärdering av grundvattenflödesmätningar utförda inom Forsmarks övervakningsprogram under åren 2013–2017. Det övergripande målet med studien har varit att rekommendera förbättringar i testmetodiken samt att föreslå ett uppdaterat mätprogram. Syftet med analysen har varit att ta reda på hur och varför flödet varierar över tiden (månader–år) genom att utföra långtidsmätningar med utspädningsmetoden i 32 borrhålssektioner i Forsmark. Resultaten har jämförts med korttidsmätningar (4–5 dagar) som utförts under 2005–2012 i samma borrhålssektioner. Analysen har inkluderat påverkan av nederbörd, grundvattennivå, hydraulisk transmissivitetsfördelning, hydraulisk gradient samt mätmetodik.

Resultatet av analysen visar att grundvattenflödet kan variera avsevärt över längre perioder (månader till år). I några sektioner med mer än en faktor 10, medan andra sektioner är nästan konstanta. Uppmätta flöden varierar i ett spann på 0,01–81 ml/min, d.v.s. en faktor 10 000 vilket är i samma storleksordning som variationen i hydraulisk transmissivitet. Påverkan av nederbörd och grundvattennivå kan bara ses i ett fåtal ytliga sektioner i hammarborrhål. Det finns en påverkan i åtminstone sju av mätsektionerna under de första 4–8 dagarna som orsakas av tryckförändringen som sker vid initieringen av testet. Det finns också en störning orsakad av avdunstning från provrören med spårämne som tas under mätningen vilket kan påverka utvärderingen och ge för höga utvärderade flöden i lågfödande sektioner (< 0,5 ml/min). Sammanfattningsvis så har analysen ökat förståelsen för de stora variationerna i flöde och uppdagat att mätprocedurer och mätteknik behöver justeras i några av mätsektionerna, så att representativa flöden mäts. Baserat på studien har ett uppdaterat mätprogram föreslagits.

Contents

1 Introduction

1.1 Background

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, it was decided to change strategy for the measurements and measure over a much longer time (4–10 months) to study the variability of groundwater flow and try to evaluate possible reasons for the variations, e.g. seasonal variations or influence of precipitation.

The monitoring programme at Forsmark has earlier been evaluated (Berglund and Lindborg 2017) and recommendations for a programme update have been made. However, there were no specific recommendations made for groundwater flow measurements as the analysis presented in this report was ongoing.

This document reports a study where the results gained from test campaigns no. 9–12, performed over the years 2013–2017 (Wass 2014, 2016, 2018a, b), are evaluated and compared with previous campaigns and focused on the aspects described above. The report also contains recommendations for equipment, measurement time and measurement strategy in future test campaigns.

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

Figure 1-1. *Overview over the Forsmark area, showing locations of boreholes included in the groundwater flow monitoring programme.*

In Table 1-1 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 2.2 (Follin et al. 2007).

Table 1-1. Summary of borehole sections used for groundwater flow monitoring in Forsmark 2005–2017.

Borehole	Section no	Vol. (L)	Secup (mbl)*	Seclow (mbl)	SecMid (mbl)	Elevation SecMid (m RHB70)	Geologic structure
KFM01A	5	33.21	109.00	130.00	119.5	–115.79	Multiple fractures, FFM02
KFM01D	2	38.33	429.00	438.00	433.5	–343.03	Single fracture, FFM01
	4	31.27	311.00	321.00	316.0	–252.53	Single fracture, FFM01
KFM02A	3	66.33	490.00	518.00	504.0	–494.97	Zone ZFMF1
	5	60.78	411.00	442.00	426.5	–417.80	Zone ZFMA2
KFM02B	2	48.63	491.00	506.00	498.5	–483.83	Zone ZFMF1
	4	47.58	410.00	431.00	420.5	–407.05	Zone ZFMA2
KFM03A	1	70.33	969.50	995.50	982.0	–969.10	Single fracture, FFM03
	4	58.04	633.50	650.00	641.75	–631.13	Zone ZFMB1
KFM04A	4	35.00	230.00	245.00	237.5	–199.83	Zone ZFMA2
KFM05A	4	40.62	254.00	272.00	263.0	–221.40	Single fracture, FFM01
KFM06A	3	58.25	738.00	748.00	743.0	–622.78	Zone ZFMNNE0725
	5	46.64	341.00	362.00	351.5	–298.54	Zone ZFMENE0060A
KFM06C	3	64.00	647.00	666.00	656.5	–527.04	Possible DZ5
	5	43.61	531.00	540.00	535.5	–434.84	Zone ZFMWNW044
KFM08A	2	55.15	684.00	694.00	689.0	–550.55	Possible DZ4 (S-WNW)
	6	34.67	265.00	280.00	272.5	–227.79	Zone ZFMENE1061A
KFM08D	2	62.64	825.00	835.00	830.0	–662.55	Zone ZFMENE0168
	4	63.33	660.00	680.00	670.0	–538.06	Zone ZFMNNE2308
KFM10A	2	39.52	430.00	440.00	435.0	–299.83	Zone ZFMA2
KFM11A	2	68.91	690.00	710.00	700.0	–593.76	ZFMWNW0001
	4	40.47	446.00	456.00	451.0	–389.62	ZFMWNW3259
KFM12A	3	31.76	270.00	280.00	275.0	–226.74	ZFMWNW0004
HFM01	2	39.83	33.50	45.50	39.5	–37.02	Zone ZFMA2
HFM02	2	28.53	38.00	48.00	43.0	–39.91	Zone ZFM1203
HFM04	2	27.52	58.00	66.00	62.0	–57.92	Zone ZFM866
HFM13	1	39.28	159.00	173.00	166.0	–138.63	Zone ZFMENE0401A
HFM15	1	35.74	85.00	99.50	92.25	–60.63	Zone ZFMA2
HFM16	2	43.61	54.00	67.00	60.5	–57.18	Zone ZFMA8
HFM19	1	44.65	168.00	185.20	176.6	–137.36	Zone ZFMA2
HFM21	3	31.39	22.00	32.00	27.0	–18.82	Single fracture, FFM02
HFM27	2	40.29	46.00	58.00	52.0	–45.60	Zone ZFM1203
HFM32	3	20.06	26.00	31.00	28.5	–27.42	Single fracture, FFM03

* Metre borehole length.

1.2 Objectives

The objective of this analysis is to evaluate and analyse possible reasons for the large variations in groundwater flow rates determined within the monitoring programme at Forsmark. The study should also provide suggestions for improvement of the methodology if needed based on the findings. Finally, the study should suggest a measurement strategy and measurement programme for future measurements.

2 Equipment and methodology

2.1 The dilution method – general principles

In the dilution method, a tracer is introduced and homogeneously distributed within an isolated borehole section. The tracer is subsequently diluted by the ambient groundwater flow through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section, Figure 2-1.

If the background concentration is negligible, the dilution in a well-mixed borehole section, starting at time t = 0, is given by:

$$\ln(C/C_0) = -\frac{Q_w}{V} \cdot t \qquad \text{(Equation 2-1)}$$

where C is the concentration at time t (s), C_0 is the initial concentration, V is the water volume (m^3) in the test section and Q_w is the volumetric flow rate (m^3/s) through the borehole section. Since V is known, the flow rate may be determined from the slope of the line in a plot of ln (C/C_0), or ln C, versus t.

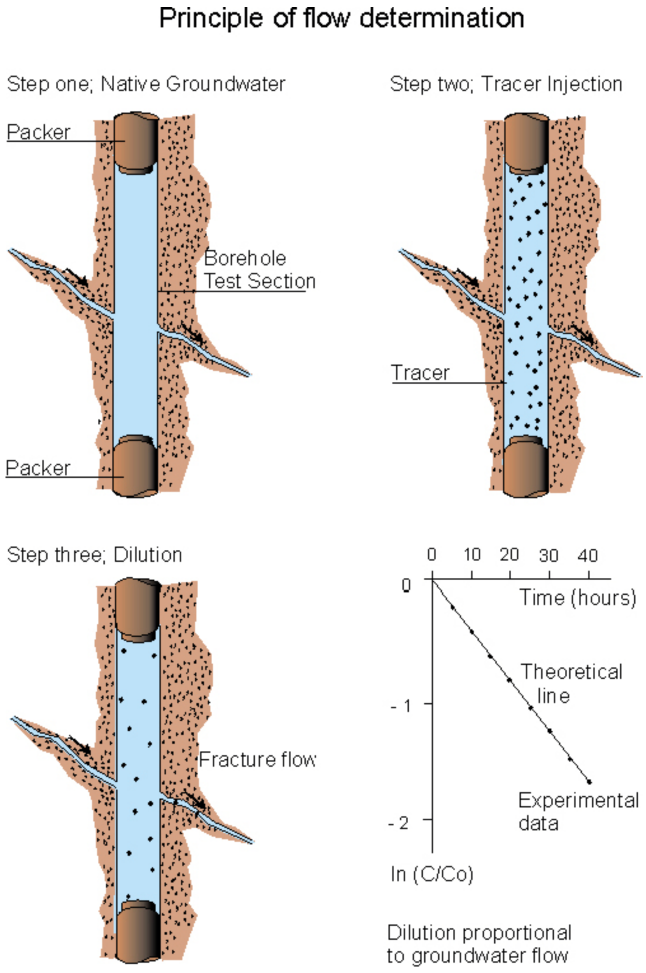

Figure 2-1. General principles of dilution and flow determination.

If the background concentration, C_b, of the diluted tracer is significant, the dilution equation becomes:

$$\ln[C(t) - C_b] = -\frac{Q_w}{V} t + \ln(C_0 - C_b) \quad \text{(Equation 2-2)}$$

Thus, plotting $\ln[C(t) - C_b]$ vs. t gives a linear slope equal to $-Q_w/V$. High background concentrations may occur, for example, if Uranine is used as a tracer and there is remaining Uranine from the drilling fluid around the borehole section. A typical result from a tracer dilution experiment is illustrated in Figure 2-2.

The measured groundwater flow rate through the borehole test section can be used to estimate the groundwater flow rate in the fracture/fracture zone straddled by the packers. The flow-field distortion must then be taken into consideration, i.e. the degree to which the groundwater flow converges and diverges near the borehole test section. With a correction factor, α, which is the ratio between the width of the undisturbed flow path trapped by the measurement section and the borehole diameter, it is possible to determine the cross-sectional area perpendicular to groundwater flow by:

$$A = 2 \cdot r \cdot L \cdot \alpha \quad \text{(Equation 2-3)}$$

where A is the cross-sectional area (m^2) perpendicular to groundwater flow, r is borehole radius (m), L is the length (m) of the borehole test section and α is the correction factor. The definition of L is not obvious because flow in fractured rock may in most cases not be expected to be evenly distributed along the entire borehole section. Instead, the flow is concentrated to one or several individual fractures or a group of fractures that may be defined as a fracture zone. Thus, it might be possible to define L, for example, as the width of some flowing zone in the borehole section, rather than the entire length of the section. Figure 2-3 schematically shows the cross-sectional area, A, and how flow lines converge and diverge near the borehole test section.

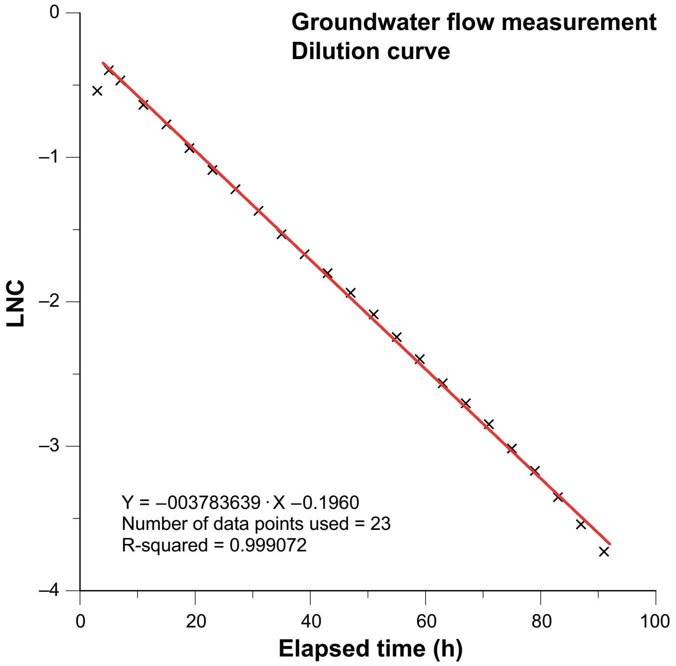

Figure 2-2. *Example of a tracer dilution graph (logarithm of concentration versus time), including straight-line fit.*

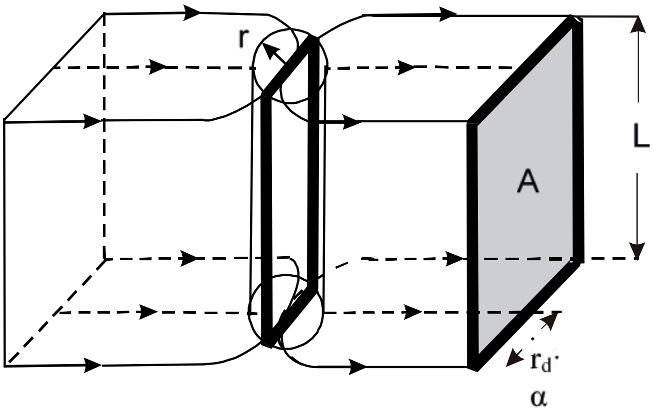

Figure 2-3. *Diversion and convergence of flow lines near a borehole test section.*

Assuming laminar flow in a plane parallel fissure or a homogeneous porous medium, the correction factor α may be calculated according to Equation (2-4), which often is called the formula of Ogilvi (Halevy et al. 1967). Here it is assumed that the disturbed zone, created by the presence of the borehole, has an axi-symmetrical and circular form.

$$\alpha = \frac{4}{1 + (r/r_d) + (K_2/K_1)\left(1 - (r/r_d)^2\right)} \qquad \text{(Equation 2-4)}$$

where r_d is the outer radius (m) of the disturbed zone, K_1 is the hydraulic conductivity (m/s) of the disturbed zone, and K_2 is the hydraulic conductivity of the aquifer. If the drilling has not caused any disturbances outside the borehole radius, then $K_1 = K_2$ and $r_d = r$ which will result in α = 2. With α = 2, the groundwater flow within a channel with a total width of twice the borehole diameter, will converge through the borehole test section, as illustrated in Figures 2-3 and 2-4.

If there is a disturbed zone around the borehole the correction factor α is given by the radial extent and hydraulic conductivity of the disturbed zone. If the drilling has caused a zone with a lower hydraulic conductivity near the borehole than in the fracture zone, e.g. positive skin due to drilling debris and clogging, the correction factor α will decrease. A zone of higher hydraulic conductivity around the borehole will increase α. Rock stress redistribution, when new boundary conditions are created by the drilling of the borehole, may also change the hydraulic conductivity around the borehole and thus affect α. In Figure 2-4, the correction factor, α, is given as a function of K_2/K_1 at different normalized radial extents of the disturbed zone (r/r_d).

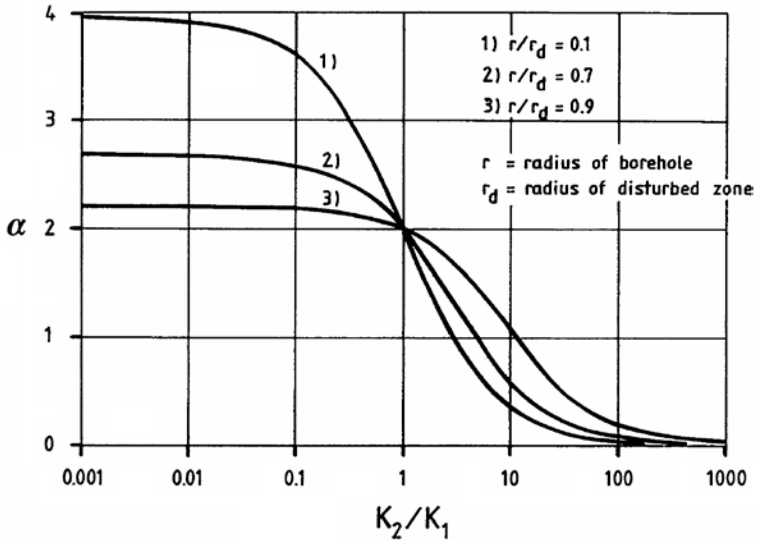

Figure 2-4. *The correction factor, α, as a function of K_2/K_1 at different radial extent (r/r_d) of the disturbed zone (skin zone) around the borehole.*

If the fracture/fracture zone and groundwater flow are not perpendicular to the borehole axis, this also must be accounted for. At a 45 degrees angle to the borehole axis the value of α will be about 41 % larger than in the case of perpendicular flow. This is further discussed in (Gustafsson 2002).

The measured flow through the borehole section may be used to estimate the hydraulic gradient that governs the flow through the borehole, if the transmissivity T (m^2/s) of the section is known. For the flow geometry shown in Figure 2-3, the gradient i (expressed with a positive sign) is given by:

$$i = \frac{Q_w}{T 2 r_w \alpha} \qquad \text{(Equation 2-5)}$$

Thus, the hydraulic gradient may be estimated without any assumptions about the vertical extent of the flowing feature(s). However, this also implies the assumption that the used transmissivity value is representative for the natural flow geometry through the borehole. The T-value is typically obtained from hydraulic testing involving either pumping or injection of water and is thus obtained under different hydraulic conditions than for the groundwater flow measurement.

The Darcy velocity, v_d, which is not an actual velocity but flow per unit cross-sectional area, and called the specific discharge, is obtained from:

$$v_d = \frac{Q_w}{A} \qquad \text{(Equation 2-6)}$$

Thus, it is necessary to make assumptions about the cross-sectional flow area when calculating the Darcy velocity. For borehole flow measurements within SKB investigations, the flow area is routinely assumed to be distributed along the entire borehole section. Thus, the calculated Darcy velocity is an average specific flow for the rock within the borehole section interval. It is conceivable that other assumptions may be made about the flow distribution within or around the borehole section, which then would result in different (larger) values of the Darcy velocity.

2.2 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 2-5.

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.

2.3 Dilution test equipment and methodology

A schematic drawing of the tracer test equipment is shown in Figure 2-6.

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 sample the tracer concentration outside the borehole to measure 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 exactly the time it takes to circulate one borehole volume. 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 thus avoiding density effects.

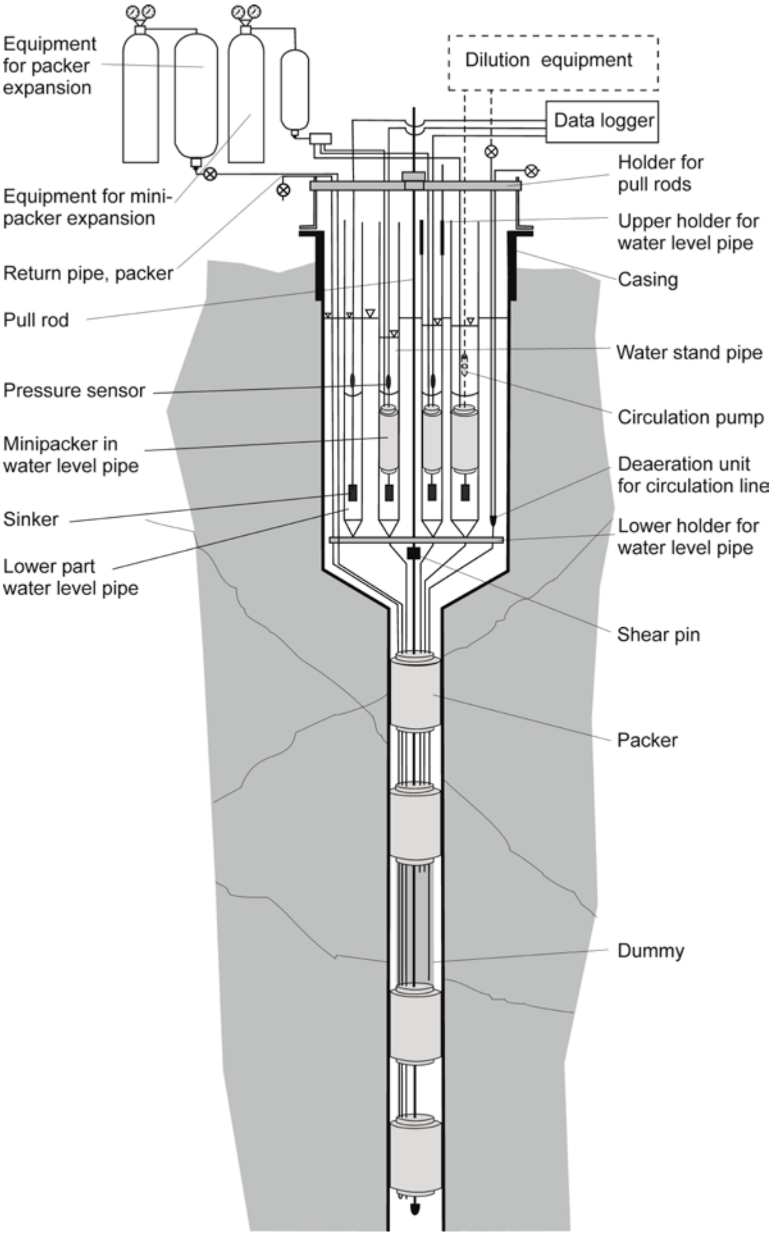

Figure 2-5. *Example of permanent instrumentation in core and percussion boreholes with circulation sections.*

Sampling is made by continuously extracting a small volume of water from the system using a peristaltic pump (constant leak) to a fractional sampler with 19 mL test tubes. The extraction flow is between 4–10 mL/h depending on the groundwater flow rate. Each test tube contains water from 2–4 hours of sampling. The sampler is contained in a plastic box together with four small bottles with fresh water to prevent, or at least reduce, evaporation of water from the sampling tubes, see Figure 2-7.

The tracers used are the fluorescent dyes Amino-G Acid and Sodium Fluorescein (Uranine). Both tracers have been frequently used in tracer tests at various sites in crystalline rocks in Sweden since early 1980s 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 was 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 analyse. The drawback is that they are easily degraded in sunlight, and therefore should be kept dark.

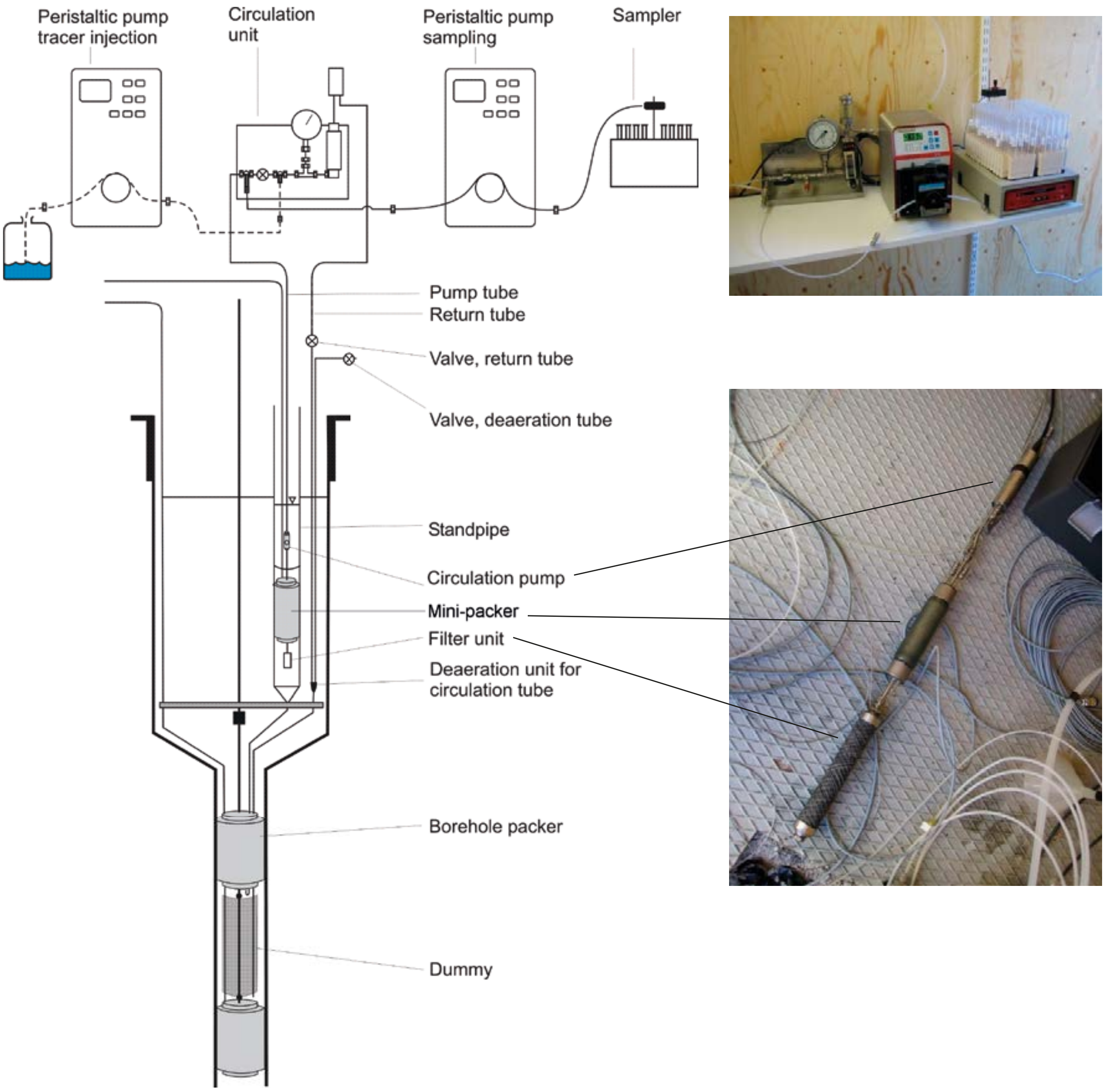

Figure 2-6. *Schematic drawing of the equipment used in tracer dilution measurements.*

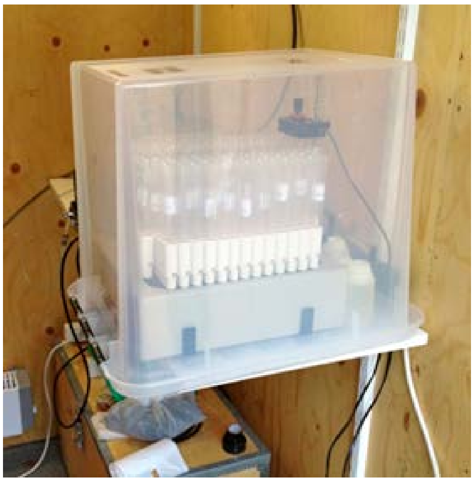

Figure 2-7. *The sampler was put in a plastic box to reduce evaporation from the samples.*

The test tubes are generally collected at the weekly attendance and stored cold and dark to avoid degeneration of the fluorescent dyes. Analyses are made using a spectrofluorometer at Geosigma laboratory, Uppsala.

The start concentration of 0.5–1 ppm allows a dilution of about 100 times for Amino G and 1 000 times for Sodium Fluorescein before being affected by background fluorescens. The error in the analysis is estimated to be within ± 5 %.

2.4 Test methodology during long-term tests 2013–2017

The test campaigns #1 to #8 during 2005–2012 included almost all the 32 available borehole sections each year. The tests were in general performed during 5 days in each borehole section during November–December. The reason for choosing this period was to avoid interference from other activities at the site, in particular groundwater samplings which were done during spring and early autumn every year in the same borehole sections. In general, six sections were measured simultaneously due to the limitations of how many test equipments that were available.

From 2013 to 2017, campaigns #9 to #12, measurements have been performed over much longer periods from 3 months up to 10 months in each section and measuring six sections at a time. The test procedure has been the same with the exception that samples have been analysed at lower frequency, cf. Chapter 3.

2.5 Evaluation

The data analysis and evaluation include the following parameters:

- Groundwater flow rate, Q_w (m^3/s), Equation 2-2.
- Hydraulic gradient, i (m/m), Equation 2-5.
- Darcy velocity, v_d (m/s), Equation 2-6.

Groundwater flow rates are determined from the plots of ln C versus time as described in Section 2.1. Sampling flow rate is then subtracted from the result. In some cases, changes in the slope could be observed in the dilution curves, see example in Figure 2-8, which is interpreted and reported as a change in flow rate. The interpretation is made purely by eye but is in general rather distinct.

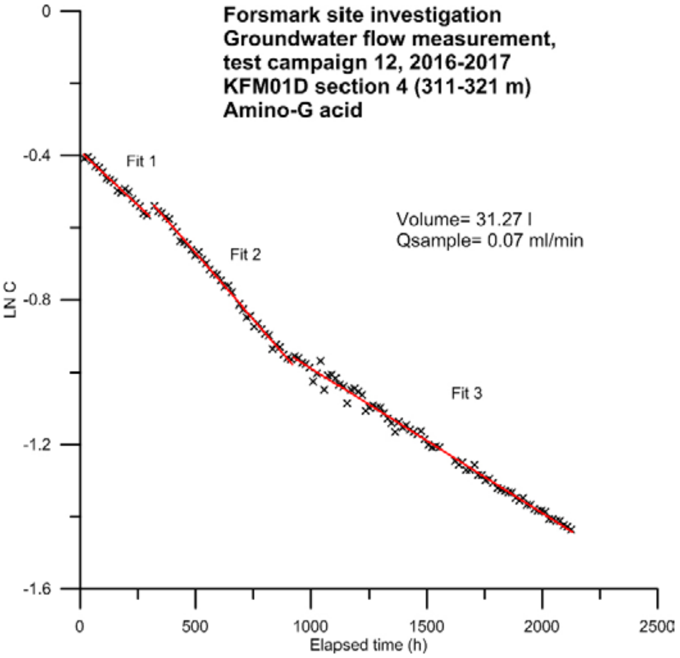

***Figure 2-8.** Example of tracer dilution curve with changing groundwater flow rates, in this case 0.14–0.31 ml/min.*

2.6 Measurement range and accuracy

The lower limit of groundwater flow measurement in general is set by the dilution caused by molecular diffusion of the tracer into the fractured/porous aquifer, relative to the dilution of the tracer due to advective groundwater flow through the test section (Gustafsson 2002). In a normally fractured granite, the lower limit of a groundwater flow measurement is approximately at a hydraulic conductivity, K, between 6×10^{-9} and 4×10^{-8} m/s, if the hydraulic gradient, i, is 0.01. This corresponds to a groundwater flux (Darcy velocity), v_d, in the range of 6×10^{-11} to 4×10^{-10} m/s, which in turn may be transformed into groundwater flow rates, Q_w, corresponding to 0.03–0.2 ml/hour through a one metre test section in a 76 mm diameter borehole. In a fracture zone with high flow porosity, and thus a higher rate of molecular diffusion from the test section into the fractures, the lower limit is about $K = 4 \times 10^{-7}$ m/s if $i = 0.01$. The corresponding flux value is in this case $v_d = 4 \times 10^{-9}$ m/s and flow rate $Q_w = 2.2$ ml/hour. The lower limit of flow measurements is, however, in most cases constrained by the time available for the dilution test and the sample retrieval. Sample flow rates are minimum 3 ml/hour which would correspond to a practical lower measurement limit.

The upper limit of groundwater flow measurements is determined by the capability of maintaining a homogeneous mix of tracer in the borehole test section. This limit is determined by several factors, such as length of the test section, volume, distribution of the water conducting fractures and how the circulation pump inlet and outlet are designed. The practical upper measurement limit is about 100 ml/min for the equipment described in this report.

The accuracy of determined flow rates through the borehole test section is affected by various measurement errors related to, for example, the accuracy of the calculated test section volume and determination of tracer concentration. The overall accuracy when determining flow rates through the borehole test section is better than ± 30 %, based on laboratory measurements in artificial borehole test sections (Nordqvist et al. 2008).

The groundwater flow rates in the rock formation are determined from the calculated groundwater flow rates through the borehole test section and by using some assumption about the flow field around the borehole test section. This flow field depends on the hydraulic properties close to the borehole and is given by the correction factor α, as discussed in Section 2.1. The value of α will, at least, vary within $\alpha = 2 \pm 1.5$ in fractured rock (Gustafsson 2002). Hence, the Darcy velocity calculated according to Equation 2-6 is determined with an accuracy within 60 ± 420 %.

2.7 Selection and characterisation of borehole sections

The overall aim of the dilution measurements is to characterise natural groundwater flow conditions within the site investigations with measurements located to obtain good areal coverage. Another consideration is that selected borehole sections should include a variety of measurement depths and be distributed among important zones.

The borehole sections in the monitoring programme have been selected with consideration of data needs for hydrogeochemistry, hydrogeology and transport properties. In some cases, the monitoring sections have been selected to approximately coincide with borehole sections selected for complete chemical characterisations or flow measurements with the dilution probe. The detailed positions of the packers (Table 1-1) are based on prior information about transmissivity along the borehole and other borehole measurements.

For the current analysis the following data have been used:

- Transmissivity values, T (m^2/s) from PFL (Posiva Flow Log) measurements, hydraulic injection tests, and pumping tests.
- Water volumes of the monitoring sections calculated from geometrical information about tubing, packers, volume reducers, etc., see Table 1-1 for the volumes used.
- Number and position of flowing fractures in each section from PFL measurements.
- Interpretation of the geological character from the Forsmark Site Descriptive Model (zone, fracture domain, single fracture, rock unit).
- Hydraulic gradients interpreted from data on hydraulic head.
- Data on precipitation from SKB local meteorological station at Forsmark.

In some cases, transmissivity data has been available from both PFL and hydraulic injection tests. PFL data has generally been used in the interpretation, as it is considered to represent a larger distance from the borehole than the rather short-term injection tests being more influenced by the vicinity and presence of the borehole itself.

2.8 Measurements with the dilution probe

During site investigations in Forsmark 2005–2007, groundwater flow measurements were also performed with the borehole dilution probe before permanent packer installation. Measurements with the dilution probe can only be performed in open boreholes, which means that packers have to be removed creating a rather large disturbance and costly operation. This rather unique equipment, manufactured for SKB purposes, may still be possible to use as a complement, if new boreholes are drilled or old holes are reinstalled during the construction phase of the planned repository.

The borehole dilution probe is a mobile system for groundwater flow measurements, Figure 2-9. Measurements can be made in boreholes with 76–77 mm diameter or larger and the test section length can be arranged for 1, 2, 3, 4 or 5 m with an optimised special packer/dummy system for 76–77 mm diameter boreholes and section lengths between 1 and 10 m with standard packers. The maximum measurement depth is at 1 030 m borehole length. The vital part of the equipment is the probe which measures the tracer concentration in the test section down hole and in-situ. The probe is equipped with two different measurement devices. One is the Optic device, which is a combined fluorometer and light-transmission meter. Several fluorescent and light absorbing tracers can be used with this device. The other device is the Electrical Conductivity device, which measures the electrical conductivity of the water and is used for detection/analysis of saline tracers. The probe and the packers that straddle the test section are lowered down the borehole with an umbilical hose. The hose contains a tube for hydraulic inflation/deflation of the packers and electrical wires for power supply and communication/data transfer. Besides tracer dilution detection, the absolute pressure and temperature are measured. The absolute pressure is measured during the process of dilution because a change in pressure indicates that the hydraulic gradient, and thus the groundwater flow, may have changed. The pressure gauge and the temperature gauge are both positioned in the dilution probe, about seven meters from top of test section. This bias is not corrected for as only changes and trends relative to the start value are of great importance for the dilution measurement. Since the dilution method requires homogenous distribution of the tracer in the test section, a circulation pump is also installed, and circulation flow rate measured.

A caliper log, attached to the dilution probe, is used to position the probe and test section at the pre-selected borehole length. The caliper detects reference marks previously made by a drill bit at exact length along the borehole, approximately every 50 m. This method makes it possible to position the test section with an accuracy of c. ± 0.10 m.

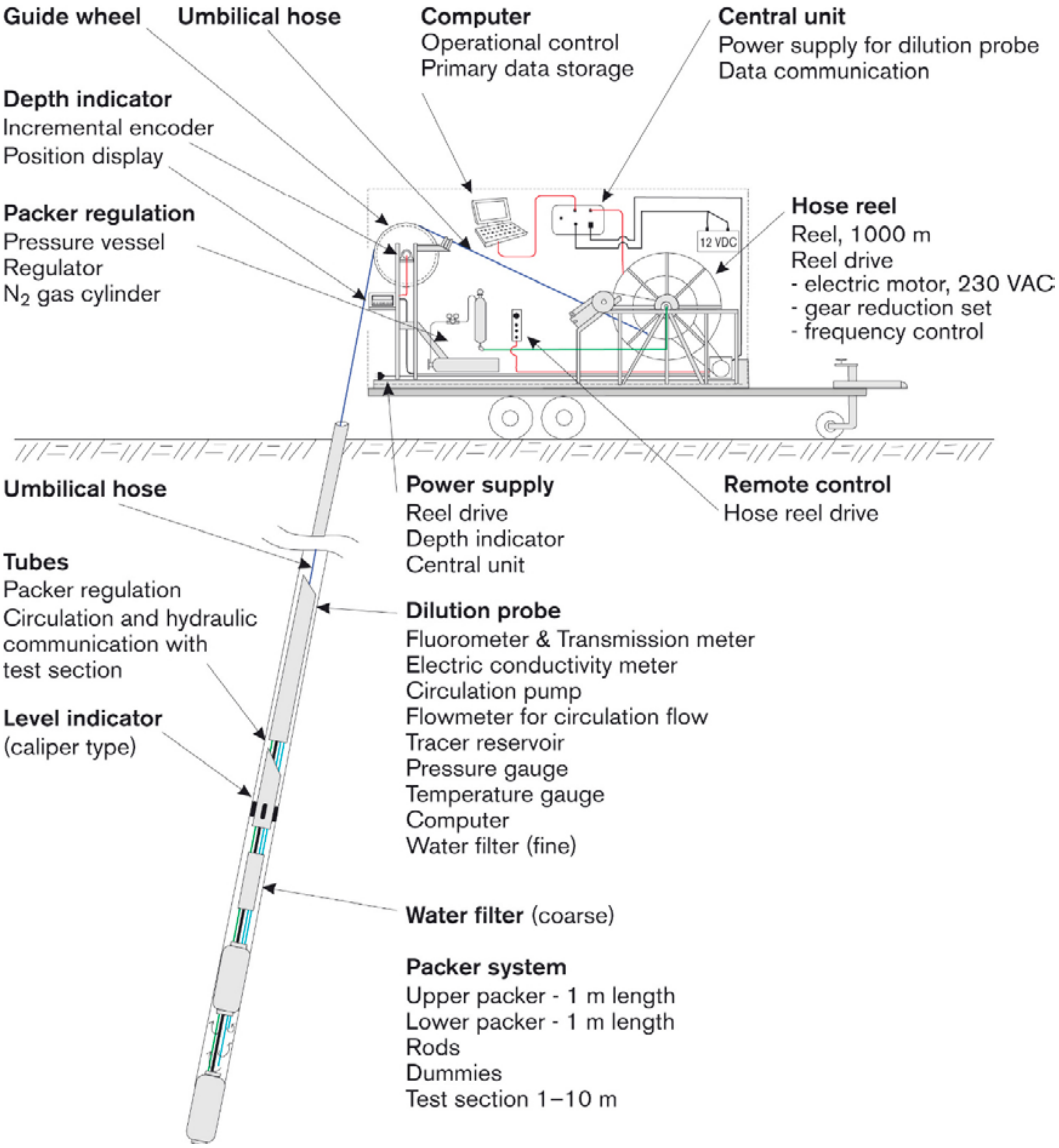

***Figure 2-9.** The SKB borehole dilution probe.*

3 Measurements performed

3.1 Yearly monitoring programme 2005–2012

The test programme (campaign #1) started in 2005 during the intense period of site investigations at Forsmark. At that time only 12 monitoring sections had been installed, and many boreholes were still not drilled. The following year, 2006, 18 sections were measured and from 2007 in total 34 sections were available. However, two very deep sections in KFM07A and KFM03A, were not possible to measure due to low transmissivity in combination with large frictional losses in the tubing used for pumping. Both sections are located at more than 950 m borehole length which is more than 100 meter lower than the closest section in length.

A lot of activities were ongoing at the site during 2005–2008, and it is very likely that some of the groundwater flow measurements are influenced by these to some degree. Activities performed in the Forsmark area during the test campaigns with groundwater flow measurements are compiled in Appendix 1. A summary of test campaigns #1–8 is presented in Table 3-1.

Table 3-1. Test campaigns #1–8.

Campaign #	Sections measured	Test period	Reference
1	11	Nov–Dec 2005	Wass 2006 (SKB P-06-59)
2	17	Nov 2006	Wass 2007 (SKB P-07-50)
3	31	Nov 2007–Jan 2008	Wass 2008 (SKB P-08-32)
4	32	Nov–Dec 2008	Wass 2009 (SKB P-09-30)
5	31	Nov–Dec 2009	Wass 2010 (SKB P-10-21)
6	31	Nov–Dec 2010, March 2011	Thur and Wass 2011 (SKB P-10-51)
7	31	Nov–Dec 2011	Thur and Wass 2012 (SKBdoc 1358144)
8	30	Nov–Dec 2012	Ragvald and Wass 2013 (SKBdoc 1384539)

Table 3-2 shows a summary of calculated groundwater flow rates from all eight test campaigns between 2005–2012. The table shows a large variation of measured flow rates, from over 100 ml/min down to 0.01 ml/min, the latter representing the lower measurement limit.

The measurements have generally been performed during a period of 4–5 days in each section and only one flow value has been reported, although in some cases a higher flow can be seen in data from the first 1–2 days. In these cases, the later, lower flow rate has been reported.

Table 3-2. Results from groundwater flow measurements performed between 2005–2012.

Borehole: section	Borehole length (m)	T[1] (m^2/s)	Nov–Dec 2005 (ml/min)	Nov 2006 (ml/min)	Nov/Jan 2007–08 (ml/min)	Nov–Dec 2008 (ml/min)	Nov–Dec 2009 (ml/min)	Nov–Dec 2010/Mar 2011 (ml/min)	Nov–Dec 2011 (ml/min)	Nov–Dec 2012 (ml/min)
KFM01A:5	109–130	1.0 E–7	–	0.1	0.2	0.1	0.06	0.05	0.1	0.05
KFM01D:2	429–438	6.2 E–8	–	–	0.3	0.04	0.06	0.04	0.08	0.1
KFM01D:4	311–321	1.8 E–7	–	–	0.2	0.2	0.7	0.1	0.2	0.1
KFM02A:3	490–518	4.0 E–6	2.1	0.8	0.8	1.2	1.6	1.4	1.2	0.8
KFM02A:5	411–442	2.9 E–6	1.0	0.4	0.7	0.1	0.5	0.8	0.9	0.4
KFM02B:2	491–506	3.5 E–5	–	–	4.6	12	8.9	9.1	25	16
KFM02B:4	410–431	3.9 E–5	–	–	23	35	30	27	23	30
KFM03A:4	633.5–650	2.5 E–6	0.5	0.5	0.6	1.1	0.4	0.4	0.8	0.3
KFM04A:4	230–245	4.6 E–5	–	–	16	8.0	2.5	6.1	6.8	3.0
KFM05A:4	254–272	1.9 E–8	0.5	1.4	0.1	0.1	2.3	0.1	0.1	0.02
KFM06A:3	738–748	3.1 E–7	0.3	0.6	0.2	0.05	0.4	0.5	0.3	0.3
KFM06A:5	341–362	9.2 E–7	0.5	0.6	5.7	0.2	0.2	0.3	0.9	0.7
KFM06C:3	647–666	9.0 E–8	–	0.4	0.05	0.03	0.3	0.1	0.2	0.4
KFM06C:5	531–540	1.2 E–6	–	0.3	0.2	0.4	0.4	0.2	0.8	0.4
KFM08A:2	684–694	1.4 E–6	–	–	0.8	0.7	0.7	0.8	3.1	0.9
KFM08A:6	265–280	1.3 E–6	–	–	0.2	0.06	0.1	0.1	0.2	0.2
KFM08D:2	825–835	2.9 E–8	–	–	2.6	1.8	4.1	0.9	2.1	–
KFM08D:4	660–680	1.8 E–7	–	–	(91)[2]	(123)[2]	(21)[2]	(55)[2]	(53)[2]	–
KFM10A:2	430–440	2.9 E–5	–	–	2.7	1.6	1.2	1.4	1.4	1.4
KFM11A:2	690–710	1.0 E–6	–	–	0.2	0.3	0.5	0.9	0.6	0.6
KFM11A:4	446–456	3.1 E–8	–	–	0.04	0.01	0.03	0.2	0.04	0.3
KFM12A:3	270–280	4.3 E–6	–	–	0.3	1.8	0.3	0.4	1.2	0.6
HFM01:2	33.5–45.5	4.5 E–5	–	–	7.8	6.3	5.7	5.8	3.4	5.3
HFM02:2	38–48	5.9 E–4	38	8.9–38	33	23	22	13	6.9	5.2
HFM04:2	58–66	7.9 E–5	2.2	10.4	0.8	2.6	1.4	1.8	1.6	1.0
HFM13:1	159–173	2.9 E–4	24	4.3	13	17	8.2	12	3.9	3.3
HFM15:1	85–95	1.0 E–4	0.8	5.2	8.5	4.0	1.8	1.3	0.6	1.3
HFM16:2	54–67	3.5 E–4	–	1.6–6.6	1.0	2.8	2.4	4.4	0.5	1.5
HFM19:1	168–182	2.7 E–4	9.7	3.4	24	18	9.9	15	8.8	8.7
HFM21:3	22–32	1.0 E–4	–	–	1.9	2.1	1.0	1.0	0.9	1.1
HFM27:2	46–58	4.0 E–5	–	0.4	0.5	0.8	0.4	0.7	0.3	0.3
HFM32:3	26–31	2.3 E–4	–	0.5	–	1.2	–	–	–	0.8

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.

3.2 Measurements with the dilution probe

In total 34 borehole sections in seven boreholes at Forsmark were measured with the dilution probe during 2005–2007. The measurements were performed prior to installing permanent monitoring equipment in the boreholes. A summary of all measurements with the dilution probe is presented in Nordqvist et al. (2008). In nine of the measured sections, the measurement intervals partly coincide with sections thereafter measured in permanently installed boreholes. In all nine cases the dilution probe measurements were made within a smaller length interval of the corresponding monitoring section. One may therefore expect that measured flow rates are lower, or in the lower range of what has been measured in the monitoring sections. However, seven of the dilution probe sections cover the same flowing fractures as the corresponding longer permanently installed test sections and the other two dilution probe sections, KFM01A and KFM02A, cover 53 % and 37 %, respectively, of the transmissivity in the corresponding longer permanently installed test sections, cf. Tables 3-2 and 3-3. The groundwater flow rates are also within the same range to what has been measured in the monitoring sections. The only exception is KFM04A, which has a flow slightly higher than in the monitoring programme. It is plausible to think that flow could be slightly higher during the measurement with the dilution probe in this case due to disturbance from other activities at the site.

Table 3-3. Results from tracer dilution measurements with the dilution probe at Forsmark for sections coinciding with monitoring sections. The results from the measurements performed in the corresponding monitoring borehole sections are also shown.

Borehole	Section (m)	Section length	T (m^2/s)	Q (mL/min)	Test period (yymmdd)	Measurements performed in monitoring sections, 2005–2012	
		(m)				Section (m)	Q (mL/min)
KFM01A	117.8–118.8	1.0	5.3 E–08	0.02	041105–041108	109–130	0.05–0.2
KFM01D	431.0–432.0	1.0	6.2 E–08	0.17	061214–061217	429–438	0.04–0.3
KFM01D	316.4–317.4	1.0	1.8 E–07	0.02	070215–070219	311–321	0.1–0.7
KFM02A	511.5–514.5	3.0	3.9 E–06	0.60	050302–050304	490–518	0.8–2.1
KFM02A	414.7–417.7	3.0	9.5 E–07	0.03	050214–050216	411–442	0.1–1.0
KFM03A	643.5–644.5	1.0	2.5 E–06	0.17	041214–041216	633.5–650	0.3–1.1
KFM04A	232.0–237.0	5.0	5.5 E–05	17	060221–060223	230–245	2.5–16
KFM08A	685.5–688.5	3.0	1.4 E–06	0.25	051116–051121	684–694	0.7–3.1
KFM08A	274.5–277.5	3.0	1.3 E–06	0.39	051114–051116	265–280	0.06–0.2

3.3 Extended monitoring programme 2013–2017

The extended monitoring programme (campaigns # 9–13) included all 32 sections previously measured, six sections in each campaign (twelve in campaign #12 and two in campaign #13), see Table 3-4. The duration of each measurement varied between 3–10 months instead of the one-week measurements performed during 2005–2012.

Table 3-4. Test campaigns #9–13.

Campaign #	Sections measured	Test period	Reference
9	KFM05A:4, KFM06A:3, KFM06A:5, KFM06C:5, HFM15:1, HFM16:2	March–Dec 2013	Wass 2014 (SKBdoc 1384642)
10	KFM02A:5, KFM02B:2, KFM06C:3, KFM08A:2, HFM19:1, HFM27:2	Sept 2014–June 2015	Wass 2016 (SKBdoc 1542046)
11	KFM08D:2, KFM08D:4, KFM10A:2, KFM11A:4, HFM13:1, HFM21:3	Sept 2015–June 2016	Wass 2018a (SKB P-17-13)
12	KFM01A:5, KFM01D:2, KFM01D:4, KFM04A:4, KFM08A:6, KFM11A:2	Sept 2016–Dec 2016	Wass 2018b (SKB P-18-04)
	KFM02A:3, KFM02B:4, HFM01:2, HFM02:2, HFM04:2, HFM32:3	Jan–June 2017	Wass 2018b (SKB P-18-04)
13	KFM03A:4, KFM12A:3	Oct–Dec 2017	Wass 2018b (SKB P-18-04)

In Table 3-5 a summary of measured flow rates is given where variations are presented as number of interpreted flow rates and a range. In addition, calculated Darcy velocities and hydraulic gradients determined from Equations 2-5 and 2-6 are presented.

The results show large variations of flow in some sections, more than a factor 10 in twelve sections, while seven sections have almost constant flow over time (less than a factor 2). The variations and reasons for these are further discussed in Chapter 4.

Table 3-5. Summary of results from extended groundwater flow measurements performed between 2013–2017. The flow results from measurements performed between 2005–2012 are also shown for comparison.

Borehole: section	Borehole length (m)	T[1] (m^2/s)	No of flow rates	Flow, Q (ml/min) 2005–2012	Flow, Q (ml/min) 2013–2017	Darcy velocity, v (m/s) × E09 2013–2017	Hydraulic gradient, i (m/m) 2013–2017
KFM01A:5	109–130	1.0 E–7	4	0.05–0.2	0.02–0.7	0.1–3.6	0.02–0.8
KFM01D:2	429–438	6.2 E–8	1	0.04–0.3	0.06	0.7	0.1
KFM01D:4	311–321	1.8 E–7	3	0.1–0.7	0.1–0.3	1.6–3.4	0.09–0.2
KFM02A:3	490–518	4.0 E–6	4	0.8–2.1	0.1–1.3	0.5–5.0	0.004–0.03
KFM02A:5	411–442	2.9 E–6	5	0.1–1.0	0.2–0.35	0.65–1.2	0.007–0.01
KFM02B:2	491–506	3.5 E–5	17	4.6–25	0.35–7.3	2.5–53	0.001–0.02
KFM02B:4	410–431	3.9 E–5	6	23–35	19–22	100–120	0.05–0.06
KFM03A:4	633.5–650	2.5 E–6	1	0.3–1.1	0.03	0.18	0.001
KFM04A:4	230–245	4.6 E–5	5	2.5–16	1.1–4.0	8.2–29	0.003–0.009
KFM05A:4	254–272	1.9 E–8	4	0.02–2.3	0.03–0.2	0.19–1.1	0.2–1.0
KFM06A:3	738–748	3.1 E–7	8	0.05–0.6	0.01–0.3	0.12–2.9	0.004–0.09
KFM06A:5	341–362	9.2 E–7	6	0.2–5.7	0.01–0.4	0.05–2.2	0.0001–0.05
KFM06C:3	647–666	9.0 E–8	5	0.03–0.4	0.01–0.23	0.06–1.3	0.01–0.3
KFM06C:5	531–540	1.2 E–6	8	0.2–0.8	0.02–0.5	0.24–5.7	0.002–0.04
KFM08A:2	684–694	1.4 E–6	6	0.7–3.1	0.02–0.5	0.18–5.5	0.001–0.04
KFM08A:6	265–280	1.3 E–6	2	0.06–0.2	0.02–0.3	0.15–1.8	0.002–0.02
KFM08D:2	825–835	2.9 E–8	3	0.9–4.1	0.01–0.3	0.14–3.6	0.05–1.2
KFM08D:4	660–680	1.8 E–7	3	(21–123)[2]	0.02–0.4	0.1–2.0	0.01–0.2
KFM10A:2	430–440	2.9 E–5	7	1.2–2.7	1.0–1.2	11–14	0.004–0.005
KFM11A:2	690–710	1.0 E–6	2	0.2–0.9	0.2–0.8	1.0–4.3	0.02–0.09
KFM11A:4	446–456	3.1 E–8	3	0.01–0.3	0.01 –0.07	0.1–0.8	0.03–0.3
KFM12A:3	270–280	4.3 E–6	4	0.3–1.8	0.2–2.9	1.7–31	0.004–0.07
HFM01:2	33.5–45.5	4.5 E–5	13	3.4–7.8	1.5–11	7.6–54	0.002–0.1
HFM02:2	38–48	5.9 E–4	11	5.2–38	6.5–81	40–490	0.0007–0.008
HFM04:2	58–66	7.9 E–5	5	0.8–10.4	0.7–1.3	4.9–9.5	0.0005–0.001
HFM13:1	159–173	2.9 E–4	11	3.3–24	22–31	192–130	0.004–0.006
HFM15:1	85–95	1.0 E–4	9	0.6–8.5	0.8–2.9	5.0–18	0.0005–0.002
HFM16:2	54–67	3.5 E–4	9	0.5–4.4	0.5–4.3	2.1–20	0.0001–0.0007
HFM19:1	168–182	2.7 E–4	21	3.4–24	1.2–11	5.4–46	0.0003–0.002
HFM21:3	22–32	1.0 E–4	8	0.9–2.1	0.2–0.6	1.3–3.8	0.0001–0.0004
HFM27:2	46–58	4.0 E–5	5	0.3–0.8	0.02–0.2	0.08–1.0	0.00002–0.0003
HFM32:3	26–31	2.3 E–4	8	0.5–1.2	0.3–1.0	3.3–12	0.00007–0.0003

[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.

4 Interpretation of results from groundwater flow measurements 2013–2017

The results show quite large flow variations in most of the measured borehole sections. Factors that may have an influence on measured groundwater flow rates are:

- Precipitation, temperature and groundwater level.
- Test methodology and equipment.
- Hydraulic gradient variations.
- Hydraulic transmissivity of the test section.
- Fracture distribution in test section.

In this chapter dilution curves and determined groundwater flow rates are compared with data on the above-mentioned factors to see if any influence on measured flow rates by one or several of these factors can be observed. The interpretation and classification of the influences is not a simple straightforward mathematical process but rather a subjective interpretation. For that reason, three classes were chosen, no effect (N), clear effect (Y) and possible effect (P), c. f. Table 4-1. The judgement was done independently by two persons and found to differ very little between them.

4.1 Influence by precipitation, temperature and groundwater level

The results of the extended groundwater flow measurements have been compared with data on local precipitation and measured groundwater levels in the test sections to see if there is any direct influence on groundwater flow from precipitation or groundwater level in the test section. Flow rates, precipitation and groundwater level are shown graphically for all sections in Appendix 2. An example for section HFM21:3 is shown in Figure 4-1. The effect of temperature is mainly that precipitation may fall as snow resulting in accumulation at the surface and sinking groundwater levels like from end of December to end of January in Figure 4-1.

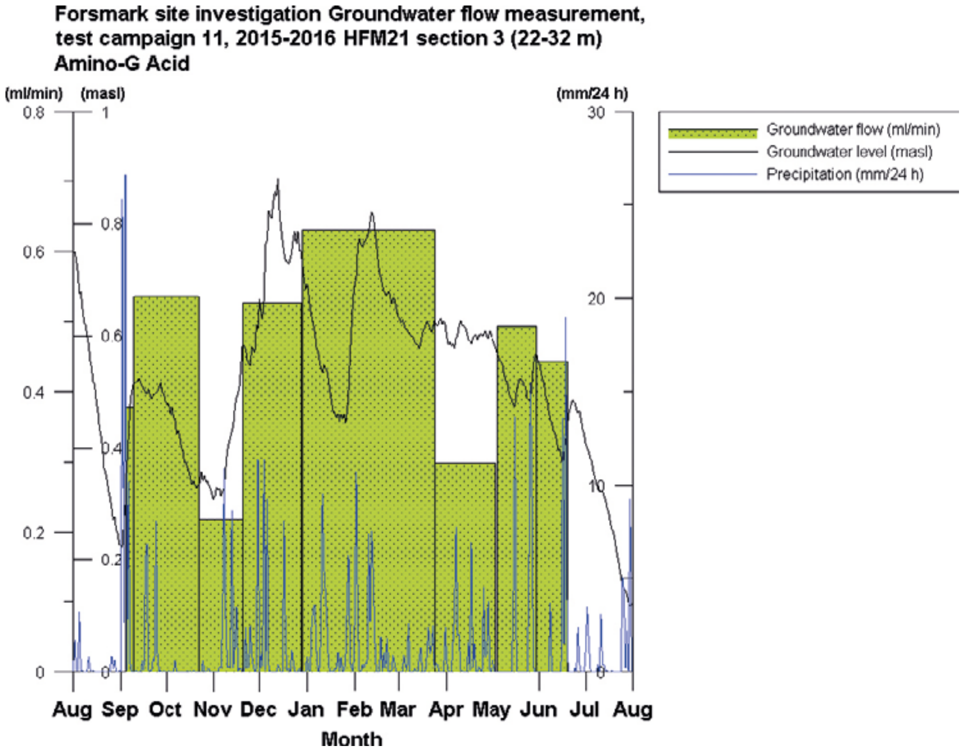

Figure 4-1. *Plot of interpreted flow rates (green bars), groundwater level (black line) and local precipitation (blue line).*

The results of the comparisons are compiled in Table 4-1. Influence of precipitation and groundwater level can be identified only in some of the shallow percussion drilled boreholes, all at elevations above 100 m except for HFM19:1 (see Table 1-1 for elevations).

Table 4-1. Summary of results from extended groundwater flow measurements performed between 2013–2017 (N=No, Y=Yes, P=Possible).

Borehole: section	Borehole length (m)	T[1] (m^2/s)	Flow, Q (ml/min)	Influence of precipitation	Influence of gw level	Influence of measurement time	Influence of evaporation
KFM01A:5	109–130	1.0 E–7	0.02–0.7	N	N	Y	Y
KFM01D:2	429–438	6.2 E–8	0.06	N	N	N	Y
KFM01D:4	311–321	1.8 E–7	0.1–0.3	N	N	N	N
KFM02A:3	490–518	4.0 E–6	0.1–1.3	N	N	P	N
KFM02A:5	411–442	2.9 E–6	0.19–0.35	N	N	N	N
KFM02B:2	491–506	3.5 E–5	0.35–7.3	N	N	Y	N
KFM02B:4	410–431	3.9 E–5	19–22	N	N	N	N
KFM03A:4	633.5–650	2.5 E–6	0.03	N	N	N	Y
KFM04A:4	230–245	4.6 E–5	1.1–4.0	N	N	P	N
KFM05A:4	254–272	1.9 E–8	0.03–0.2	N	N	P	Y
KFM06A:3	738–748	3.1 E–7	0.01–0.3	N	N	N	Y
KFM06A:5	341–362	9.2 E–7	0.01–0.4	N	N	N	Y
KFM06C:3	647–666	9.0 E–8	0.01–0.23	N	N	P	Y
KFM06C:5	531–540	1.2 E–6	0.02–0.5	N	N	P	Y
KFM08A:2	684–694	1.4 E–6	0.02–0.51	N	N	Y	Y
KFM08A:6	265–280	1.3 E–6	0.02–0.3	N	N	Y	Y
KFM08D:2	825–835	2.9 E–8	0.01–0.3	N	N	Y	Y
KFM08D:4	660–680	1.8 E–7	0.02–0.4	N	N	P	Y
KFM10A:2	430–440	2.9 E–5	1.0–1.2	N	N	N	N
KFM11A:2	690–710	1.0 E–6	0.2–0.8	N	N	P	N
KFM11A:4	446–456	3.1 E–8	0.01–0.07	N	N	N	Y
KFM12A:3	270–280	4.3 E–6	0.2–2.9	N	N	Y	Y
HFM01:2	33.5–45.5	4.5 E–5	1.5–11	N	N	N	N
HFM02:2	38–48	5.9 E–4	6.5–81	P	P	N	N
HFM04:2	58–66	7.9 E–5	0.7–1.3	N	N	N	N
HFM13:1	159–173	2.9 E–4	22–31	N	N	N	N
HFM15:1	85–95	1.0 E–4	0.8–2.9	P	P	N	N
HFM16:2	54–67	3.5 E–4	0.5–4.3	P	P	N	N
HFM19:1	168–182	2.7 E–4	1.2–10.6	Y	Y	N	N
HFM21:3	22–32	1.0 E–4	0.2–0.6	Y	Y	N	N
HFM27:2	46–58	4.0 E–5	0.02–0.21	Y	Y	N	N
HFM32:3	26–31	2.3 E–4	0.3–1.0	N	N	N	N

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 Influence by equipment and measurement procedures

As shown in Table 4-1 and in the dilution graphs in Appendix 3, the slope of tracer dilution often changes in time, i.e. groundwater flow rate is not constant in time. This is particularly evident for the first 100–200 hours of measurement, where a higher flow rate has been measured in many of the sections. In at least seven of the 32 test sections, and in several of the core drilled boreholes, there is a clear influence from the initiation of the test, see Table 4-1. In Figure 4-2 an example from KFM02B:2 is shown where tracer injections have been repeated six times over the measurement period. On each occasion there is an enhanced flow period the first 200 hours after injection. This contrasts with the shallower percussion drilled holes where there are only one or two boreholes that are possibly influenced by the initiation of the test.

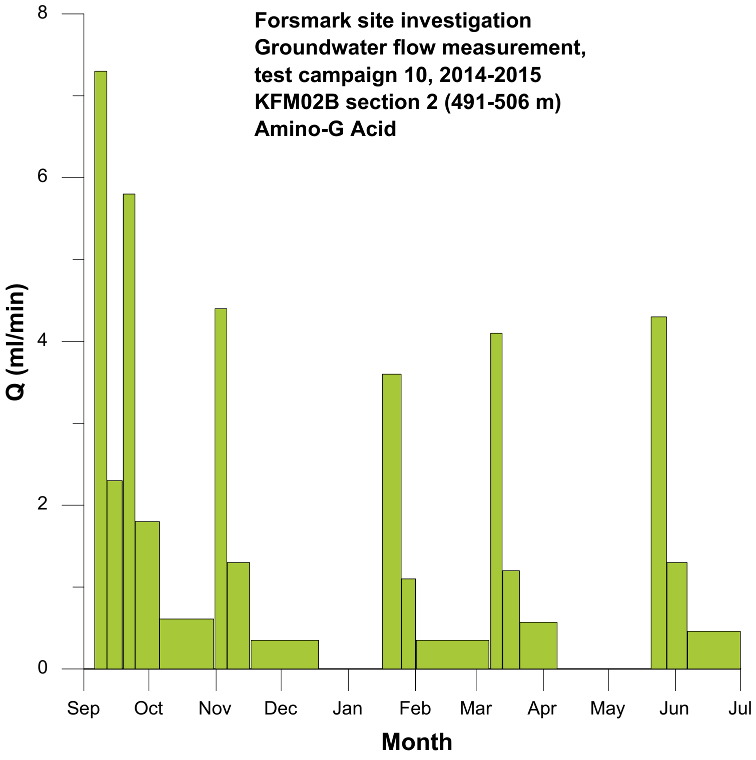

Figure 4-2. *Results of repeated flow measurements in borehole KFM02B:2 showing effects of injection procedure.*

The process behind the time dependence is not fully clarified but it is judged that the later part of the dilution curve, i.e. long time (more than one week) after tracer injection gives a more representative groundwater flow rate for the tested borehole section. This is further discussed in Chapter 5.

The tracer dilution graphs in Appendix 3 also show that the expected tracer concentration of 1 ppm, corresponding to a lnC-value of zero, is not reached in most of the sections, indicating an initial loss of tracer during the first hours after injection and circulation of tracer. A study of all tracer injections performed over the years in each section shows that the initial loss of tracer may vary somewhat over the years, but that there is a clear dependency on transmissivity of the section. High transmissivity in general gives a high initial loss of tracer, in the worst cases, sections HFM02:2 and HFM16:2, up to 90 % loss. These two sections are also the most high transmissive of all sections measured. It is likely that this is caused by the injection procedure where water is first redrawn from the section to fill up the system, and then, shortly after, tracer is injected. The injected tracer solution may then disappear into the fractures due to the slight overpressure from the injection and the pressure recovery due to the initial redraw of water.

Another factor that influences the measurements and data quality is evaporation from the sampling tubes. The influence of evaporation is often more obvious during the winter period when the air is drier and the electric heaters in the measurement containers are on. This effect is shown in Figure 4-3 for KFM11A:4 where evaporation creates a zig-zag pattern where the first high value comes from the first sampling tube, while the lowest value represents the last sample taken to the laboratory, which is unaffected by evaporation. In general samples have been collected once a week.

The evaporation effect is larger, or at least more visible, for low transmissivity sections, see Table 4-1. The effect is clearly visible for all sections but one (KFM01D:4) having transmissivity lower than 10^{-6} m^2/s.

In the case of KFM11A:4, an evaporation of 0.5 mL for one week would result in the differences shown in Figure 4-3. This is also what has been noted while measuring the volume of each sample, although this is close to the resolution of the volume measurement.

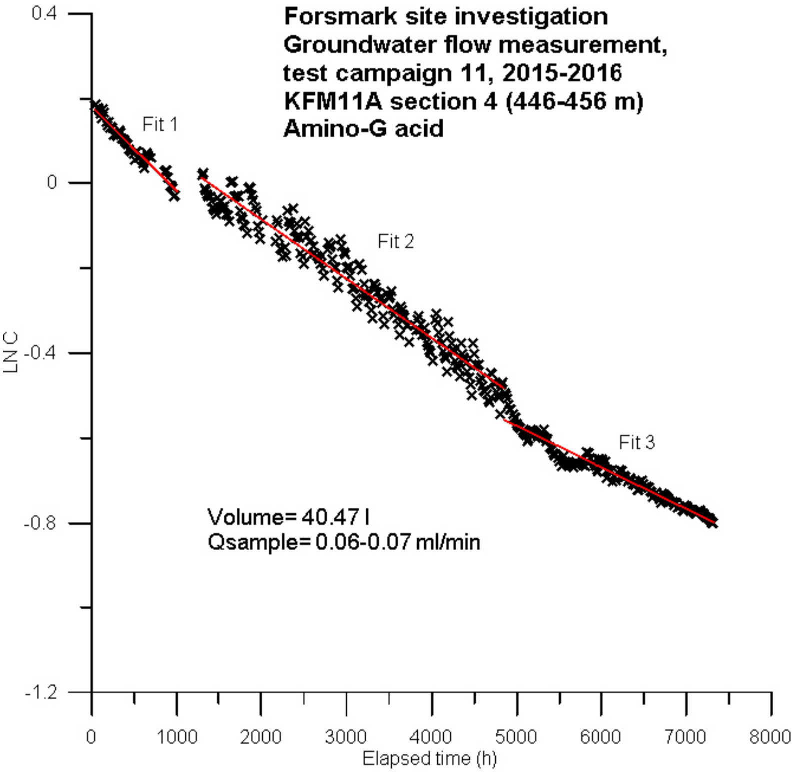

Figure 4-3. *Tracer dilution graph (ln concentration versus time) for KFM11A:4 showing effects of evaporation in the sampling tubes in the time interval 1 000–4 500 hours.*

4.3 Influence by hydraulic gradient variations

Eighteen of the borehole test sections used for groundwater flow measurement intersect fracture zones that are monitored for hydraulic head (groundwater level m.a.s.l.) also in other boreholes by the SKB hydro monitoring system (HMS). Groundwater levels in borehole test sections intersecting these fracture zones are presented in Appendix 4. Based on the HMS data and distances along the fracture zone, the hydraulic gradients from a test section to other distant borehole sections within a specific fracture zone were calculated. The gradient was calculated at six occasions during the groundwater flow measurement. The calculated hydraulic gradients are presented in Appendix 4.

Groundwater levels vary distinctly in many test sections and the individual span from minimum to maximum is within 0.1–1.2 m. Figure 4-4 shows groundwater levels in borehole sections intersecting fracture zone ZFMA2, including test section HFM15:1 with the highest groundwater level variation (1.2 m) during groundwater flow measurements in Forsmark 2005–2017. The variation of the hydraulic gradient in specific directions, as exemplified in Figure 4-5, and in multiple directions were also calculated. For test section HFM15:1 and fracture zone ZFMA2, shown in Table 4-2, the hydraulic gradient to other specific borehole sections (directions) vary within a factor of 1.5 and the gradient in multiple directions vary within a factor of 10–15 during the groundwater flow measurement. In most cases the hydraulic gradient in a specific direction vary within a factor of 5 and the hydraulic gradient in multiple directions from a test section in most cases vary within a factor of 15, see Table 4-3.

Table 4-2. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2013. Gradients calculated from borehole section HFM15:1 (−61 m.a.s.l.) to sections given in the table.

Borehole:sec	2013-03-31	2013-04-26	2013-07-01	2013-09-01	2013-11-01	2013-12-15	Variation factor individual directions
HFM19:1	0.003	0.003	0.003	0.003	0.003	0.003	1
KFM02A:5	0.0005	0.0006	0.0005	0.0004	0.0005	0.0006	1.5
HFM01:2	0.0002	0.0003	0.0002	0.0002	0.0003	0.0003	1.5
KFM02B:4	0.0006	0.0007	0.0006	0.0005	0.0006	0.0005	1.4
KFM10A:2	0.0013	0.0014	0.0013	0.0013	0.0015	0.0015	1.5
Variation factor multiple directions	15	10	15	15	10	10	

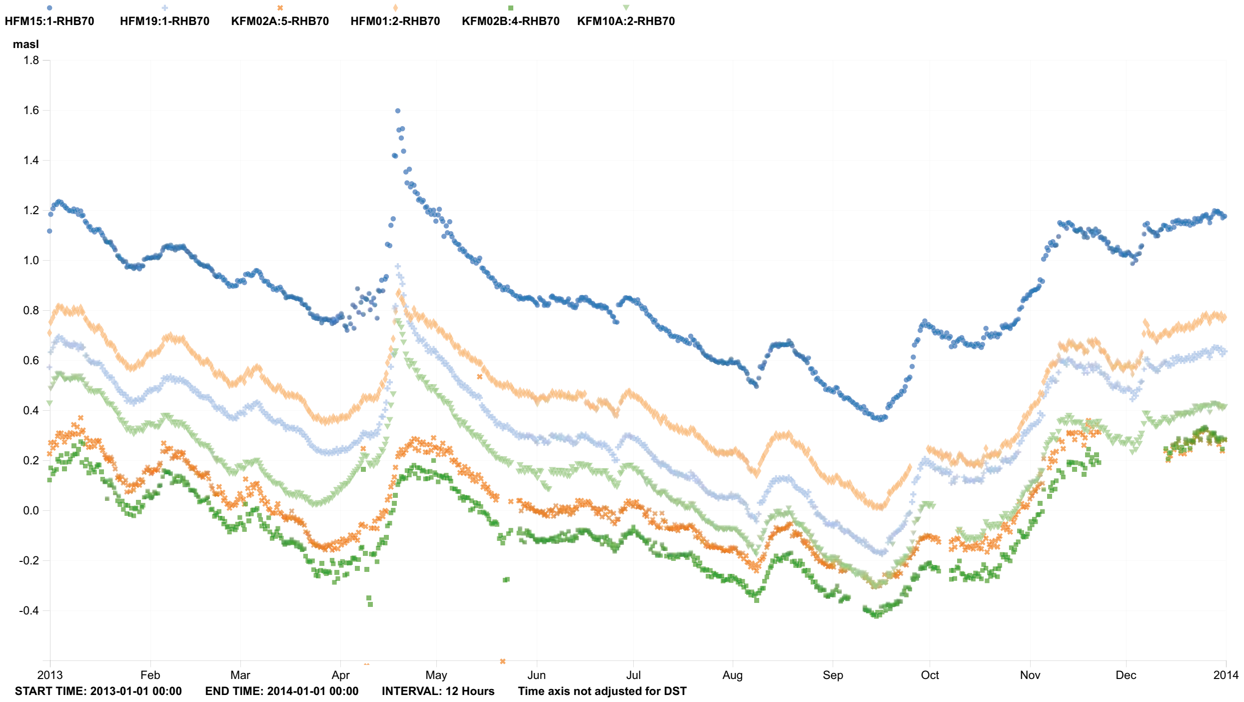

Figure 4-4. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2013, 2013-01-01 – 2014-01-01. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green) −407 m, KFM10A:2 (pale green) −300 m.*

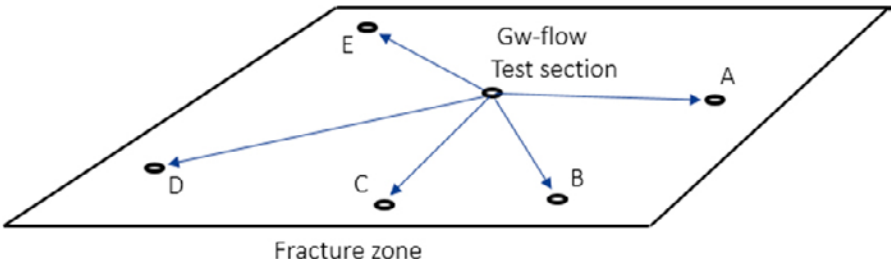

Figure 4-5. *Example of hydraulic gradient directions in a fracture zone intersected by the borehole test section used for groundwater flow measurement and five other boreholes (A–E), with packed-off sections straddling the fracture zone.*

In Table 4-3 the hydraulic gradients determined from the HMS data are compared to gradients calculated from the groundwater flow measurements. Hydraulic gradient variations in fracture zones calculated from HMS data are also tabulated. The hydraulic gradients calculated from groundwater flow measurements are in 4 cases completely within the span of gradients determined from HMS data. In 10 cases the lowest calculated gradient from groundwater flow measurements is within the gradient determined from HMS data and in 4 cases the lowest gradient calculated from groundwater flow measurements is higher than the highest gradient determined from HMS data. As shown in Appendix 4 and Table 4-3 it is not the test sections/fracture zones with the largest variation in groundwater level or in hydraulic gradient that have the greatest difference between hydraulic gradient determined from HMS data and calculated from groundwater flow. The discrepancy must depend on other factors, for example, how hydraulically conductive fractures, with potentially different pressures, are distributed in the test section and if the test section is of considerable length, etc. This is further analysed in Section 4.4.

In general terms groundwater flow, as expected, is influenced by hydraulic gradient variations which in most cases have been within a factor of 5 during groundwater flow measurement campaigns during the years 2013–2017.

Table 4-3. Comparison of hydraulic gradients calculated from groundwater flow measurements, at flow rates judged representative according to Table 3-5, and calculated from HMS data on groundwater levels (Appendix 4). Also tabulated are hydraulic gradient variations in fracture zones, calculated from HMS data.

Borehole: section	Section elevation (m.a.s.l.)	Test campaign	Fracture zone	a) Hydraulic gradient from grw flow measurements	b) Hydraulic gradient from HMS data	c) HMS gradient variation factor in specific directions	d) HMS gradient variation factor in multiple directions	e) Gradient calculated from Grw flow completely within HMS gradient	f) Lowest Grw flow gradient within HMS gradient	g) Lowest Grw flow gradient higher than HMS gradient	h) Gradient factor Grw flow lowest to HMS highest
HFM15:1	−61	2013	ZFMA2	0.0005–0.002	0.0002–0.003	1.0–1.5	10–15	X			
HFM16:2	−57	2013	ZFMA8	0.0001–0.0007	0.00006–0.0013	5–21	1–13	X			
KFM06A:5	−298	2013	ZFMB7/ZFMENE0060A	0.0001–0.05	0.00006–0.005	2–13	1.2–33		X		
HFM19:1	−137	2014–2015	ZFMA2	0.0003–0.002	0.0002–0.003	1.2–3	10–15	X			
HFM27:2	−46	2014–2015	ZFMF1203	0.00002–0.0003	0.00002–0.003	1.5–2.8	3–150	X			
KFM02A:5	−418	2014–2015	ZFMA2	0.007–0.01	0.00003–0.001	1.2–17	3–25			X	7
KFM02B:2	−484	2014–2015	ZFMF1	0.001–0.02	0.000004–0.006	1.3–250	3–1500		X		
HFM13:1	−139	2015–2016	ZFMENE0401A	0.004–0.006	0.00008–0.002	3.7–10	3–12			X	2
KFM10A:2	−300	2015–2016	ZFMA2	0.004–0.005	0.00008–0.001	1–2.5	5–12			X	4
KFM04A:4	−200	2016–2017	ZFMA2	0.003–0.009	0.0009–0.003	1–2	2–3		X		
KFM08A:6	−228	2016–2017	ZFMENE1061A	0.002–0.02	0.0007–0.009	1.5–5	3–8		X		
KFM11A:2	−594	2016–2017	ZFMWNW0001	0.02–0.09	0.009–0.03	1–1.1	3–3.3		X		
HFM01:2	−37	2016–2017	ZFMA2	0.002–0.02	0.0002–0.003	1–1.5	10–10		X		
HFM02:2	−40	2016–2017	ZFMF1203	0.0007–0.008	0.0003–0.004	1.3–1.7	7.5–13		X		
HFM04:2	−58	2016–2017	ZFM866	0.0005–0.001	0.00008–0.0005	1.5–2.5	1.5–6.2		X		
KFM02A:3	−495	2016–2017	ZFMF1	0.004–0.03	0.00003–0.003	2–33	3–100		X		
KFM02B:4	−407	2016–2017	ZFMA2	0.05–0.06	0.00009–0.001	1–5	5–11			X	50
KFM12A:3	−227	Autumn 2017	ZFMWNW0004	0.004–0.07	0.00008–0.006	1–25	3–75		X		

4.4 Influence by hydraulic transmissivity and fracture distribution in borehole test section

A correlation that may be expected is the one between flow rate and transmissivity. Although the measured flow rate also depends on the local hydraulic gradient, one might expect a general dependence on the transmissivity of the tested section. Figure 4-6 shows a log-log plot of flow rate vs. transmissivity for all the measured sections. In this case the lowest flow rate determined during the extended measurements 2013–2017 was chosen but the correlation is similar also if the highest flow rates are chosen. There is a clear correlation between flow rates and transmissivity and a fitted line (based on all points) is shown in Figure 4-6. The spread around the line is roughly one order of magnitude.

The fracture distribution for the core drilled boreholes (KFM) determined from analysis of PFL logs in combination with optical televiewer logs is presented in Table 4-4. For percussion drilled boreholes (HFM) there are no PFL logs, thus the distribution of water conducting fractures was determined from spinner loggings, see Table 4-5. Boreholes KFM06C and KFM12A are omitted as there is no PFL in these holes.

Tables 4-4 and 4-5 show that many of the sections have quite a large number of water conducting fractures. The lengths of the monitoring sections are between 9–31 m for the KFM boreholes and 5–14 m for the HFM boreholes. In some of the longer sections fractures having slightly different pressures (or salinity) might create a short-circuit resulting in an enhanced flow through the section. Another effect could be if one set of relatively high transmissivity fractures are located close to the bottom of the section, where the outlet tube for the tracer circulation also is placed. It is then plausible that the dilution of the injected tracer is influenced by tracer loss to high transmissivity fractures close to tracer outlet and thus giving a somewhat higher groundwater flow rate than should be.

A higher groundwater flow rate than should be is also indicated if the hydraulic gradient calculated from the groundwater flow measurement is much higher than the gradient calculated from HMS data. This is the case for test sections KFM02A:5 and KFM02B:4 having much higher hydraulic gradient calculated from groundwater flow measurement than calculated from HMS data, see Table 4-3. As shown in Table 4-4, both sections are long, 31 and 21 metres, respectively, and intersected by six to seven sets of fractures, each consisting of several open fractures.

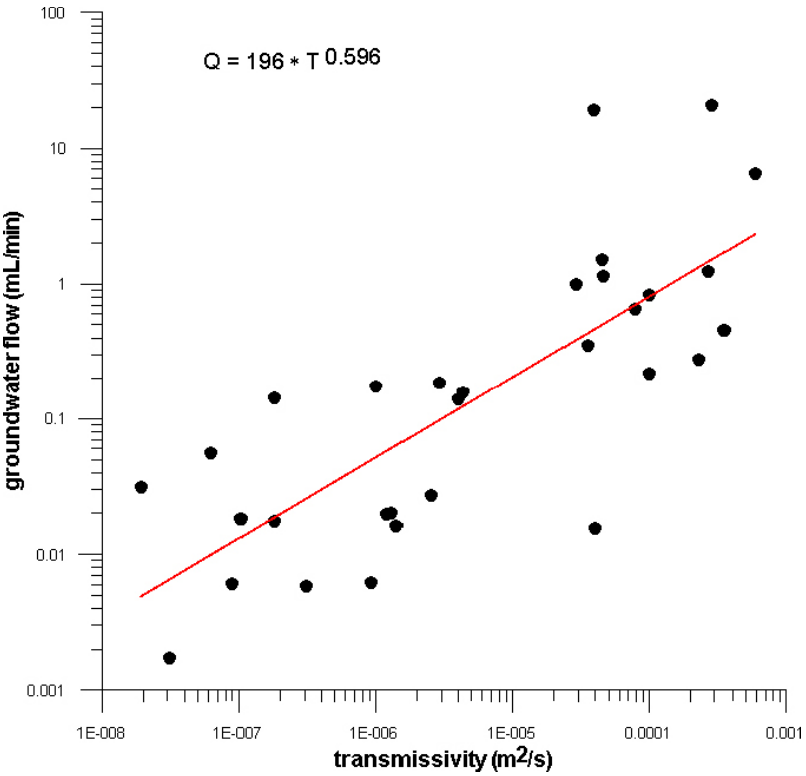

Figure 4-6. *Groundwater flow versus transmissivity for all sections at Forsmark.*

Table 4-4. Open fractures from PFL measurements, core drilled boreholes (KFM).

Borehole section	Borehole length (m)	Number of open fractures	Fractures at borehole length (m)	Transmissivity (m^2/s)	Reference
KFM01A:5	109–130	2–3 1 4–5 4–5	113.8–115.2 118.3 121.7–123.3 128.1–128.4	3.9 E–8 5.4 E–8 8.3 E–9 1.6 E–9	Forssman et al. 2004
KFM01D:2	429–438	1	431.5	6.2 E–8	Teurneau et al. 2008
KFM01D:4	311–321	1	317.0	1.8 E–7	Teurneau et al. 2008
KFM02A:3	490–518	10–20 Crush	493.3–506.5 512.3–513.8	1.0 E–7 3.8 E–6	Forssman et al. 2004
KFM02A:5	411–442	2 3–5 2–5 4–8 2–3 4–6	411.0–411.8 416.5–418.5 419.7–423.8 425.1–427.3 428.5–434.5 437.2–441.2	2.4 E–8 1.0 E–6 1.4 E–8 1.5 E–6 1.5 E–8 1.9 E–7	Forssman et al. 2004
KFM02B:2	491–506	2–4 Crush	497.1–497.9 499.8–502.2	5.6 E–8 3.5 E–5	Forssman et al. 2007
KFM02B:4	410–431	1–2 3–10 3–9 7–17 9–17 4–16 10–12	410.8–410.9 412.1–413.3 414.4–415.3 419.4–421.3 422.2–423.4 426.0–427.0 428.4–429.6	2.9 E–7 1.6 E–6 1.7 E–5 6.2 E–6 1.0 E–5 1.2 E–6 1.2 E–6	Forssman et al. 2007
KFM03A:4	633.5–650	3–4	642.2–643.9	2.5 E–6	Forssman et al. 2004
KFM04A:4	230–245	Crush 1–2 6	232.7 234.0 235.5–235.6	1.8 E–5 3.9 E–7 2.7 E–5	Forssman et al. 2004
KFM05A:4	254–272	1	264.4	1.9 E–8	Forssman et al. 2004
KFM06A:3	738–748	3–5	743.1–743.5		
KFM06A:5	341–362	1–3 1–2	345.4–345.5 356.6–356.9	1.7 E–8 9.0 E–7	Forssman et al. 2006
KFM08A:2	684–694	1–3	686.8–687.0	1.4E–6	Teurneau et al. 2008
KFM08A:6	265–280	1 2–3 2–4	272.4 274.9–275.4 276.2–276.9	2.1 E–9 1.3 E–6 1.3 E–8	Teurneau et al. 2008
KFM08D:2	825–835	1–3	832.3–832.4	2.9 E–8	Forssman et al. 2007
KFM08D:4	660–680	1–3 1–2	676.2–676.4 677.9–678.2	1.8 E–7 1.5 E–9	Forssman et al. 2007
KFM10A:2	430–440	1–5 1–2 1–4	431.7–432.1 436.1–436.4 437.2–438.2	2.8 E–5 1.3 E–6 2.1 E–8	Teurneau et al. 2008
KFM11A:4	446–456	1–4	452.6–452.7	2.9 E–8	Forssman et al. 2007

Table 4-5. Open fractures from HTHB measurements, percussion drilled boreholes (HFM).

Borehole section	Borehole lentgh (m)	Fractures at borehole length (m)	Transmissivity (m^2/s)	Reference
HFM01:2	33.5–45.5	34.5–43	4.5 E–5	Ludvigson et al. 2003a
HFM02:2	38–48	42–44.5	5.9 E–4	Ludvigson et al. 2003a
HFM04:2	58–66	60–63.5	7.9 E–5	Ludvigson et al. 2003b
HFM13:1	159–173	162.5–163.5	2.9 E–4	Ludvigson et al. 2004a
HFM15:1	85–95	88–89	1.0 E–4	Ludvigson et al. 2004a
HFM16:2	54–67	56.0–56.5 58.5–59.5	4.1 E–5 3.1 E–4	Ludvigson et al. 2004b
HFM19:1	168–182	170–182*	2.7 E–4	Ludvigson et al. 2004c
HFM21:3	22–32	26–27	1.0 E–4	Jönsson et al. 2005
HFM27:2	46–58	54.0–54.8	4.0 E–5	Jönsson and Ludvigson 2006b
HFM32:3	26–31	27.3–27.8 29.8–30–3	1.0 E–4 1.3 E–4	Jönsson and Ludvigson 2006a

* Could only be measured down to 171.5 m due to some obstacle in the borehole (182 m = hole bottom)

5 Conclusions and recommendations for future groundwater flow measurements in permanently installed boreholes

5.1 General

In this report, experiences and results from 13 years of groundwater flow measurements at Forsmark have been summarised. In general, measurements have been performed without major technical problems or disturbances. In summary the results of the extended measurement programme 2013–2017 show:

- Flow may vary considerably over longer periods (months-year), in some sections more than a factor 10 while in others almost constant. The span of measured flow rates is 0.01–81 ml/min, i.e. a factor of 10 000.
- In 12 of the 32 monitoring sections flow rates close to the measurement limit (0.01 ml/min) are measured.
- Influence of precipitation and groundwater level are only seen in a few shallow monitoring sections in percussion holes.
- The extended measurements give lower flow rates than ever measured in the original campaigns in 25 out of 32 monitoring sections and higher flow rates than before in six sections.

There are two main effects that may influence data quality and in worst case, give erroneous data. The first and most important factor is the length of the measurement period. The injection procedure, when first water is withdrawn from the test section to fill the surface part of the equipment and start the circulation of water, and then, when tracer solution is added to the section, introduces a small excess pressure with enhanced dilution and sometimes loss of tracer. This mixing period can be seen in almost all sections lasting for a period of about one day in most sections. In the extended measurements however, it has been shown that the effect of injection may last up to more than a week (200 hours) in some sections, which means that the flow measured during about 5 days in the original programme may have represented a transient stage and consequently been higher than they should have been in the steady-state. This effect is clear in at least six of the measured sections and to a more uncertain degree in another seven sections. The initial loss of tracer is clearly seen in most of the high transmissive sections, whereas the enhanced dilution shows up in sections with lower transmissivity.

The second effect that affects data quality is evaporation from sampling tubes. The effect is strong during winter time with dry air and high temperature in the measurement containers from the electric heaters, which often has been the case as measurements have been done during late autumn and winter. This effect is clearly visible in 13 monitoring sections with low flow rates (< 0.5 ml/min).

The aim of this study was to understand what causes the large variations in flow measured by the tracer dilution method. It is clear that the initial enhanced flow, caused by the pressure disturbance in the injection procedure, is the most serious problem and affects flow measurements the most in the deeper and less transmissive sections. The long-term measurements performed in this study show lower flow rates and much less variation in flow if the initial measurement period is excluded for these sections. The uncertainty caused by evaporation also adds to this, and it is difficult in some cases to separate the two effects when they both appear in the same measurement sections. However, in shallow sections with high transmissivity, the main cause of variation in flow is changes in the hydraulic gradient caused by seasonal variations of groundwater level. The flow may vary more than a factor 10 over a year.

Other uncertainties from analysis of samples, the manual interpretation of flow changes, and conceptual uncertainties like the flow field distortion caused by the borehole are all judged to be within −60 ± 420 % of the calculated value.

The conclusion is that the uncertainty caused by these two effects need to be reduced. Some general recommendations are:

- Decrease evaporation from sampling tubes (new type of sampling tubes, temperature control, etc.).
- Investigate the possibility to use on-line measurement of tracer concentration.
- Decrease lower measurement limit by decreasing sample flow or use on-line measurement.
- Measurement times should be adjusted (increased) to avoid influence of injection procedure in some sections.
- Extended analysis in the yearly reports to include effects of precipitation, groundwater levels and other activities.
- Measurement frequency should be differentiated depending on expected influence from, and importance for, construction of the repository.

Based on the 13 years of groundwater flow measurements and the extended programme in particular we recommend that the strategy for measuring groundwater flow from now and at least until the underground constructions starts, is revised. During construction, the programme may be changed to more frequent or even long-term measurements in specific boreholes or fracture zones. The previous strategy was to measure all 32 sections within one campaign for as short time period as possible, and during late autumn and winter. The main reason for that was that this was a relatively calm period in terms of pressure disturbing activities in the area. The extended programme shows that flow varies considerably in some sections but are almost constant in others, i.e. the measurements may be spread out more over the year in some sections but should be done at the same time of year in others. In Section 5.2 a short summary of the main features and recommendations for each of the 32 sections is given.

This report does not deal with the data needs on groundwater flow during the construction phase. It is however foreseen that measurements of groundwater flow will help in verifying connectivity between different hydraulic units (fracture zones, fracture domains, single fractures) and the repository. This was earlier done during the construction of the Äspö Hard Rock Laboratory (Almén and Stenberg 2005). This is of course the main input to the programme but has not been within the scope of this report to evaluate.

A suggestion for a revised programme including motivations is given in Section 5.3.

5.2 Summary of conclusions and recommendations for each section

5.2.1 KFM01A:5, 109–130 m

This low conductive section, not associated with any fracture zone, has been monitored since 2006. Measured flow rates are low, 0.02–0.19 ml/min, in the same range as the sampling flow. All measurements performed indicate that the initial flow (0-about 100 hours) is influenced by the injection procedure. In general, the first 40–50 hours has not been evaluated in the original measurement programme, and a flow rate of 0.70 ml/min was measured during the first 100 hours in the extended measurement. There are no indications of influences of precipitation, groundwater level or fracture transmissivity distribution. There is also influence of evaporation in the sampling tubes.

It is recommended that this section is measured for at least 300 hours (two weeks) during each measurement campaign and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured annually.

5.2.2 KFM01D:2, 429–438 m

This section, including only a single flowing fracture, has been monitored since 2007. Apart from the first year, which may have been influenced by other activities in the area, flow rates are low and stable 0.04–0.12 ml/min which is in the same range as the sampling flow. There is a tendency in some of the measurements that there is a small initial influence of the injection, but it seems to disappear after about one day and this part is generally omitted in the evaluation. There are no indications of influences of precipitation, groundwater level or fracture transmissivity distribution (single fracture). There is a clear influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured annually.

5.2.3 KFM01D:4, 311–321 m

This section, including only one single flowing fracture, has been monitored since 2007. Flow rates are low and stable 0.11–0.24 ml/min with one exception 2009 where a significantly higher flow rate, 0.75 ml/min, was measured. It is likely that this is an effect of some other activity in the area. There is no influence of the injection and there are no indications of influences of precipitation, groundwater level or fracture transmissivity distribution (single fracture). There is no influence of evaporation in the sampling tubes as this effect is small when flow is higher.

It is recommended that this section is measured for one week during each measurement campaign. The section is located relatively close to the planned repository and should therefore be measured annually.

5.2.4 KFM02A:3, 490–518 m

This section, located in fracture zone ZFMF1, has been monitored since 2005. Flow rates are relatively high in the original programme, 0.8–2.1 ml/min, but significantly lower during the extended measurements, down to 0.1 ml/min. Based on the extended measurement it seems that there is an influence of the injection for a period of up to 200 hours, but this may also be a seasonal effect. The lower flow rates were measured during late spring and summer, with lower groundwater levels while most of the original measurements were made in November with higher groundwater levels. There are no indications of influences of precipitation or fracture transmissivity distribution. There is no influence of evaporation in the sampling tubes as this effect is small when flow is higher.

It is recommended that this section is measured for at least three weeks during each measurement campaign. The section is located relatively far away from the planned repository, but at repository depth, and could therefore be measured every second year.

5.2.5 KFM02A:5, 411–442 m

This section, located in fracture zone ZFMA2, has been monitored since 2005. Flow rates are relatively low and varying both in the original programme and in the extended measurement, 0.1–1.0 ml/min. Most of the measurements show no influence of the injection, but in a few cases, there is a small influence during the first 10–20 hours. The section is intersected by at least 17 water conducting fractures, relatively evenly distributed over the section length. It is likely that short-circuiting of fractures may give somewhat increased flow across the section. There are no indications of influences of precipitation or groundwater level. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located relatively far away from the planned repository, but at repository depth, and could therefore be measured every second year.

5.2.6 KFM02B:2, 491–506 m

This section, located in fracture zone ZFMF1, has been monitored since 2007. Flow rates measured during the original programme were generally high, 5–25 ml/min, while flow rates measured during the extended campaign varied between 0.35–7.3 ml/min. Six repeated tracer injections were made, all with the same pattern of a high initial flow during the first 200 hours, then gradually decreasing. This suggests a clear influence of the injection. It is also noted a significant loss of tracer mass during injection (about 60 %) possibly because the outlet of the injection tube is quite close to the major high conductive flowing fracture in the section. There are no indications of influences of precipitation or groundwater level. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for at least three weeks during each measurement campaign. The section is located relatively far away from the planned repository and in the same fracture zone as, and close to, KFM02A:3. Measurements may therefore be made more seldom, or even entirely stopped.

5.2.7 KFM02B:4, 410–431 m

This section, located in fracture zone ZFMA2, has been monitored since 2007. Flow rates are quite stable and high, both during the original and the extended measurements, 19–35 ml/min. The section has a high calculated flow and hydraulic gradient, 0.1, and many flowing fractures distributed over the entire length of the section. It is likely that the high flow rates are caused by short-circuiting effects. There are no indications of influence of injection procedure, precipitation or groundwater level and there is no influence of evaporation in the sampling tubes.

It is recommended that no further measurements are made in this section due to the unrealistically high flow rates possibly caused by short-circuiting effects. The section is located relatively far away from the planned repository in the same fracture zone as, and close to, KFM02A:5.

5.2.8 KFM03A:4, 633.5–650 m

This section, located in fracture zone ZFMB1, has been monitored since 2005. Flow rates have varied between 0.3–1.1 ml/min during the original programme but as low as 0.03 ml/min during the extended measurements. This is close to the measurement limit and lower than the sampling flow 0.06 ml/min. There is no effect of the injection procedure but a clear effect of evaporation. It is likely that the higher flow rates measured during the original programme is resulting from evaporation in the sampling tubes. There are no indications of influences from precipitation or groundwater level.

It is recommended that this section is measured for one week and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively far away from the planned repository and could therefore be measured every second year or even be removed from the monitoring programme.

5.2.9 KFM04A:4, 230–245 m

This section, located in fracture zone ZFMA2, has been monitored since 2007. Flow rates have been high and varying, 2.5–16 ml/min, during the original programme. In the extended measurement flow varied between 1.1–4 ml/min. Three separate tracer injections were performed, and some minor influence of the injection may be seen during the first 100–200 hours. There are no indications of influence of precipitation, groundwater level or fracture transmissivity distribution. There is no influence of evaporation from the sampling tubes.

It is recommended that this section is measured for at least 300 hours (two weeks) during each measurement campaign. Measurement frequency may be decreased to every second year.

5.2.10 KFM05A:4, 254–272 m

This low conductive section, located in fracture domain FFM01 and including a single fracture, has been monitored since 2005. Flow has varied considerably over the years, between 0.02–2.3 ml/min. In the extended measurement flow varied between 0.03–0.18 ml/min. There is a possible small influence of the injection, but the major influence is from evaporation in the sampling tubes. There are no indications of influences from precipitation or groundwater level.

It is recommended that this section is measured for at least two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively far away from the central parts of the planned repository and could therefore be measured every second year.

5.2.11 KFM06A:3, 738–748 m

This section, intersected by fracture zone ZFMNNE0725, has been monitored since 2005. Flow has varied between 0.05–0.6 ml/min during the original programme. In the extended measurement, flow varied between 0.01–0.3 ml/min, but the evaluation is uncertain due to influence of evaporation in the sampling tubes and low flow rates, in the same order, or even lower than the sampling flow (0.05–0.07 ml/min). There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for one week and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.12 KFM06A:5, 341–362 m

This section, intersected by fracture zone ZFMENE0060A, has been monitored since 2005. Flow has varied during the original programme between 0.2–0.9 ml/min, with one exception in 2007 when flow was as high as 5.7 ml/min. This value is possibly influenced by large-scale pumping test in HFM14 or possibly water samplings in KFM08A performed prior to and during the flow measurements. In the extended measurement, flow varied between 0.01–0.4 ml/min, but the evaluation is uncertain due to influence of evaporation in the sampling tubes and low flow rates, in the same order, or even lower than the sampling flow (0.05–0.07 ml/min). There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for one week and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.13 KFM06C:3, 647–666 m

This low conductive section, intersected by a possible fracture zone, has been monitored since 2006. Flow has varied during the original programme between 0.03–0.4 ml/min and in the extended measurement 0.01–0.3 ml/min. The evaluation is uncertain due to influence of evaporation in the sampling tubes and low flow rates, in the same order, or even lower than the sampling flow (0.05–0.07 ml/min). There is also an influence of the injection, but it is difficult to assess for how long due to the larger effect of evaporation. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.14 KFM06C:5, 531–540 m

This section, intersected by fracture zone ZFMWNW044, has been monitored since 2006. Flow rates measured during the original programme only vary between 0.2–0.4 ml/min, except for 2011 when flow was measured to 0.8 ml/min. The extended measurement varied between 0.02–0.5 ml/min. There is a possible influence of the injection, but it may also be natural variation. The effect of evaporation during the extended measurement is much less pronounced than in KFM06C:3, which is somewhat surprising as they are measured in the same measurement container, but not in the same campaign. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.15 KFM08A:2, 684–694 m

This section, intersected by a possible fracture zone, has been monitored since 2007. Flow rates measured during the original programme only vary between 0.7–0.9 ml/min, except for 2011 when flow was measured to 3.1 ml/min. The extended measurement varied between 0.02–0.5 ml/min. There is a clear influence of the injection for about 200 hours. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution. There is only a minor influence of evaporation in the sampling tubes.

It is recommended that this section is measured for two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.16 KFM08A:6, 265–280 m

This section, intersected by fracture zone ZFMENE1061A, has been monitored since 2007. Flow rates measured during the original programme only vary between 0.06–0.2 ml/min. The extended measurement varied between 0.02–0.3 ml/min. There is a clear influence of the injection for about 200 hours. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution. There is only a minor influence of evaporation in the sampling tubes.

It is recommended that this section is measured for at least two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured every year.

5.2.17 KFM08D:2, 825–835 m

This deep and low conductive section, intersected by fracture zone ZFMENE0168, has been monitored since 2007. Flow rates measured during the original programme varies between 0.9–4.1 ml/min which is unrealistically high for this low conductive section. This borehole was re-instrumented during 2013 and it is likely that the high flow rates were caused by internal leakage in the tubing of the borehole. The flow rates in the extended measurement varied between 0.01–0.3 ml/min, which is more realistic. There is a clear influence of the injection for about 200 hours and from evaporation in the sampling tubes. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.18 KFM08D:4, 660–680 m

This section, intersected by fracture zone ZFMNNE2308, has been monitored since 2007. Measured flow rates in this section were found to be extremely high, 20–120 ml/min due to the leakage discussed for section KFM08D:2. After re-instrumentation and during the extended measurement, flow rates were considerably lower, 0.02–0.4 ml/min. The measurement is significantly influenced by evaporation in the sampling tubes, but it is likely that there also is some influence from the injection. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located relatively close to the planned repository and should therefore be measured once every year.

5.2.19 KFM10A:2, 430–440 m

This section, intersected by fracture zone ZFMA2, has been monitored since 2007. The measured flow rates are quite stable, both during the original programme and during the extended measurement, 1.0–2.7 ml/min. There are no influences from any of the investigated parameters.

It is recommended that this section is measured for one week during each measurement campaign. The section is located relatively far from the planned repository and could be measured more seldom or even removed from the programme.

5.2.20 KFM11A:2, 690–710 m

This section, intersected by fracture zone ZFMWNW0001, has been monitored since 2007. Flow rates vary between 0.2–0.9 ml/min during the original programme, and between 0.2–0.8 ml/min during the extended measurement. There is a small influence of the injection in early data, possibly up to about 100 hours. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution and there is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for at least one week during each measurement campaign. The section is located close to the planned repository and the SFR facility and should be measured once every year.

5.2.21 KFM11A:4, 446–456 m

This low conductive section, intersected by fracture zone ZFMWNW3259, has been monitored since 2007. Flow rates measured in both the original programme and in the extended measurement are very low, 0.01–0.3 ml/min. There is a clear influence of evaporation in the sampling tubes but no indication of influence of injection, precipitation, groundwater level or fracture transmissivity distribution.

It is recommended that this section is measured for at least one week during each measurement campaign and that further measures are taken to prevent evaporation from the sampling tubes. The section is located close to the planned repository and the SFR facility and should be measured once every year.

5.2.22 KFM12A:3, 270–280 m

This section, intersected by fracture zone ZFMWNW0004, has been monitored since 2007. Flow rates measured during the original programme vary between 0.3–1.8 ml/min. The extended measurement varied between 0.2–2.9 ml/min with the highest flow in the first 200 hours of the measurement indicating a clear influence of the injection. There are no indications of influences from precipitation, groundwater level or fracture transmissivity distribution. There is only a minor influence of evaporation in the sampling tubes.

It is recommended that this section is measured for at least two weeks and that further measures are taken to prevent evaporation from the sampling tubes. The section is located far away from planned repository but could be used as a reference section measured more seldom.

5.2.23 HFM01:2, 33.5–45.5 m

This shallow and high conductive section, intersected by fracture zone ZFMA2, has been monitored since 2007. Flow rates are high and seem to vary a lot over a year, 1.5–11 ml/min in the extended measurement. The measurements in the original programme, made late autumn every year, show much less variation, 3.4–7.8 ml/min. Flow variations do not correlate so well with precipitation and changes in groundwater level. There is also an influence of the injection in data from the first 20 hours with faster dilution and an initial loss of about 50 % of the tracer mass. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located close to the planned repository and should be measured once every year during the same time.

5.2.24 HFM02:2, 38–48 m

This shallow and high conductive section, intersected by fracture zone ZFM1203, has been monitored since 2005. Flow rates are high and seem to vary a lot over a year, 6.5–81 ml/min in the extended measurement. The measurements in the original programme, made late autumn every year, show less variation, 5.2–38 ml/min. It is difficult to determine whether flow variations correlate with precipitation and changes in groundwater level as the dilution is so fast that tracer concentrations get below detection limit only after 3–5 days. However, it has been noticed in several of the measurements in the original programme that flow may vary quite a lot during this short period. There is also an influence of the injection in data from the first 20 hours with faster dilution and an initial loss of about 80–90 % of the initially injected tracer mass. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located close to the planned repository and should be measured once every year during the same time.

5.2.25 HFM04:2, 58–66 m

This shallow and high conductive section, intersected by fracture zone ZFM866, has been monitored since 2005. Measured flow rates have been relatively stable, 0.8–2.6 ml/min during the original programme, with one exception in 2006, 10.4 ml/min. The extended measurement showed flow rates varying between 0.7–1.3 ml/min. No correlation with precipitation or groundwater level can be identified. There is an initial loss of tracer mass of about 50–60 % possibly due to loss to the fracture zone during initiation of the test. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located relatively far away from the planned repository and the SFR facility and could be measured once every second year.

5.2.26 HFM13:1, 159–173 m

This shallow and high conductive section, intersected by fracture zone ZFMENE0401A, has been monitored since 2005. Measured flow rates have varied quite a lot during the original programme, 3.3–24 ml/min. The extended measurement showed stable flow rates varying between 22–31 ml/min. No correlation with precipitation or groundwater level can be identified. There is an initial loss of tracer mass of about 60–80 % possibly due to loss to the fracture zone during initiation of the test. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. Measurement frequency may be decreased to every second year.

5.2.27 HFM15:1, 85–95 m

This shallow and high conductive section, intersected by fracture zone ZFMA2, has been monitored since 2005. Measured flow rates have varied quite a lot during the original programme, 0.6–8.5 ml/min. Some of the measurements indicated variations in the flow during the one-week long measurement period. The extended measurement showed flow rates varying between 0.8–2.9 ml/min. Some correlation with precipitation and groundwater level can be identified. There is an initial loss of tracer mass of about 30 % possibly due to loss to the fracture zone during initiation of the test. There is no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. Measurement frequency may be decreased to every second year and measurements may be altered between HFM15:1 and HFM19:1 as they are in the same fracture zone.

5.2.28 HFM16:2, 54–67 m

This shallow and high conductive section, intersected by fracture zone ZFMA8, has been monitored since 2006. Measured flow rates vary quite a lot both during the original programme, 0.5–6.6 ml/min and in the extended measurement, 0.5–4.3 ml/min. There is an initial disturbance from the injection up to about 50 hours, where also an initial loss of about 80–90 % of the tracer mass can be observed. There is no clear correlation with precipitation or groundwater level and no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for two weeks during each measurement campaign to avoid the initial disturbance. The section is located relatively close to the planned repository and should be measured once every year during the same time.

5.2.29 HFM19:1, 168–182 m

This shallow and high conductive section, intersected by fracture zone ZFMA2, has been monitored since 2005. Measured flow rates vary quite a lot both during the original programme, 3.4–24 ml/min and in the extended measurement, 1.2–10.6 ml/min. There is a short initial disturbance the first day, where also an initial loss of about 50 % of the tracer mass can be observed. There is some correlation with precipitation or groundwater level but no influence of evaporation in the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. Measurement frequency may be decreased to every second year and measurements may be altered between HFM15:1 and HFM19:1 as they are in the same fracture zone.

5.2.30 HFM21:3, 22–32 m

This is the shallowest section, intersected by a single fracture in fracture domain FFM02 and measured since 2007. Measured flow rates have been quite stable both in the original programme, 0.9–2.1 ml/min, and in the extended measurement, 0.2–0.6 ml/min. The measured flow rates seem to correlate quite well with precipitation and groundwater level although the flow variations are less dramatic. There is an initial loss of tracer of about 50 % during the injection, but no other visible effect of the injection. There is no influence of evaporation from the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located quite close to the site for the initial underground works and should be measured at least once a year.

5.2.31 HFM27:2, 46–58 m

This shallow and high conductive section, intersected by fracture zone ZFM1203, has been monitored since 2006. Measured flow rates are relatively low and stable, 0.3–0.8 ml/min during the original programme but lower during the extended measurement, 0.02–0.2 ml/min. The reason for this is most probably that flow is influenced by the injection for the first 80–100 hours. There is also an initial loss of tracer mass of about 40–60 %. The measured flow variations seem to correlate with precipitation and groundwater level although the flow variations are few and relatively small. There is no influence of evaporation from the sampling tubes.

It is recommended that this section is measured for two weeks during each measurement campaign. The section is located close to the planned repository and should be measured once every year during the same time.

5.2.32 HFM32:3, 26–31 m

This high conductive section, located in fracture domain FFM03 and including a single fracture, has been monitored only four times since 2006. The reason for this is mainly that it is located on an island in Lake Bolundsfjärden and difficult to reach. Measured flow rates are relatively low 0.5–1.2 ml/min during the original programme and 0.3–1.0 ml/min during the extended measurement. There is only a small influence of tracer injection during the first day but also in this section a loss of tracer mass of approximately 50 %. Flow variations do not seem to correlate so well with precipitation and groundwater level and there is no influence of evaporation from the sampling tubes.

It is recommended that this section is measured for one week during each measurement campaign. The section is located some distance from the planned repository and not so easy to access. Measurement frequency may therefore be decreased to once every second year.

5.3 Summary of suggested revised test programme

The basis for the suggestions regarding measurement time is that the section either is clearly affected by the initiation of the test or that evaporation in the sampling tubes has masked the effect of the initiation procedure. The suggested measurement frequencies are mainly based on distance from the planned deep repository, SFK, and the SFR facility, and which feature (fracture zone/geological unit) that is intersected. It is currently not clear what the data needs on groundwater flow will be during the construction phase of the repository. This suggested programme is mainly focusing on achieving good data quality and should therefore be revised when underground excavation starts, e.g if data on groundwater flow or connectivity within specific geological structures are needed as excavation proceeds. This may require denser or even long-term measurements in some sections.

Table 5-1 summarises the suggested revised test programme for monitoring of groundwater flow at Forsmark. The suggested programme includes 18 sections to be measured annually, 9 sections every second year and one section every third year or more seldom. One section is recommended to be removed from the monitoring programme, one section may be measured every second year or removed and two sections removed or measured every third year or even more seldom.

The suggested programme will require approximately the same resources (6 weeks of total measurement time per year) and equipment (six equipments) as the old programme.

Table 5-1. Suggested revised test programme.

Borehole: section	Depth (m)	Geologic structure	Measurement time length (weeks)	Measurement frequency (years)	Comments
KFM01A:5	109–130	Multiple fractures, FFM02	2	1	
KFM01D:2	429–438	Single fracture, FFM01	1	1	
KFM01D:4	311–321	Single fracture, FFM01	1	1	
KFM02A:3	490–518	Zone ZFMF1	3	2	
KFM02A:5	411–442	Zone ZFMA2	1	2	
KFM02B:2	491–506	Zone ZFMF1	3	> 3	Or removed
KFM02B:4	410–431	Zone ZFMA2	2	–	No more measurements
KFM03A:4	633.5–650	Zone ZFMB1	1	2	Or removed
KFM04A:4	230–245	Zone ZFMA2	2	2	
KFM05A:4	254–272	Single fracture, FFM01	2	2	
KFM06A:3	738–748	Zone ZFMNNE0725	1	1	
KFM06A:5	341–362	Zone ZFMENE0060A	1	1	
KFM06C:3	647–666	Possible DZ5	2	1	
KFM06C:5	531–540	Zone ZFMWNW044	2	1	
KFM08A:2	684–694	Possible DZ4 (S-WNW)	2	1	
KFM08A:6	265–280	Zone ZFMENE1061A	2	1	
KFM08D:2	825–835	Zone ZFMENE0168	2	1	
KFM08D:4	660–680	Zone ZFMNNE2308	2	1	
KFM10A:2	430–440	Zone ZFMA2	1	> 3	Or removed
KFM11A:2	690–710	ZFMWNW0001	1	1	
KFM11A:4	446–456	ZFMWNW3259	1	1	
KFM12A:3	270–280	ZFMWNW0004	2	> 3	
HFM01:2	33.5–45.5	Zone ZFMA2	1	1	
HFM02:2	38–48	Zone ZFM1203	1	1	
HFM04:2	58–66	Zone ZFM866	1	2	
HFM13:1	159–173	Zone ZFMENE0401A	1	2	
HFM15:1	85–95	Zone ZFMA2	1	2	
HFM16:2	54–67	Zone ZFMA8	2	1	
HFM19:1	168–182	Zone ZFMA2	1	2	
HFM21:3	22–32	Single fracture, FFM02	1	1	
HFM27:2	46–58	Zone ZFM1203	2	1	
HFM32:3	26–31	Single fracture, FFM03	1	2	

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Appendix 1

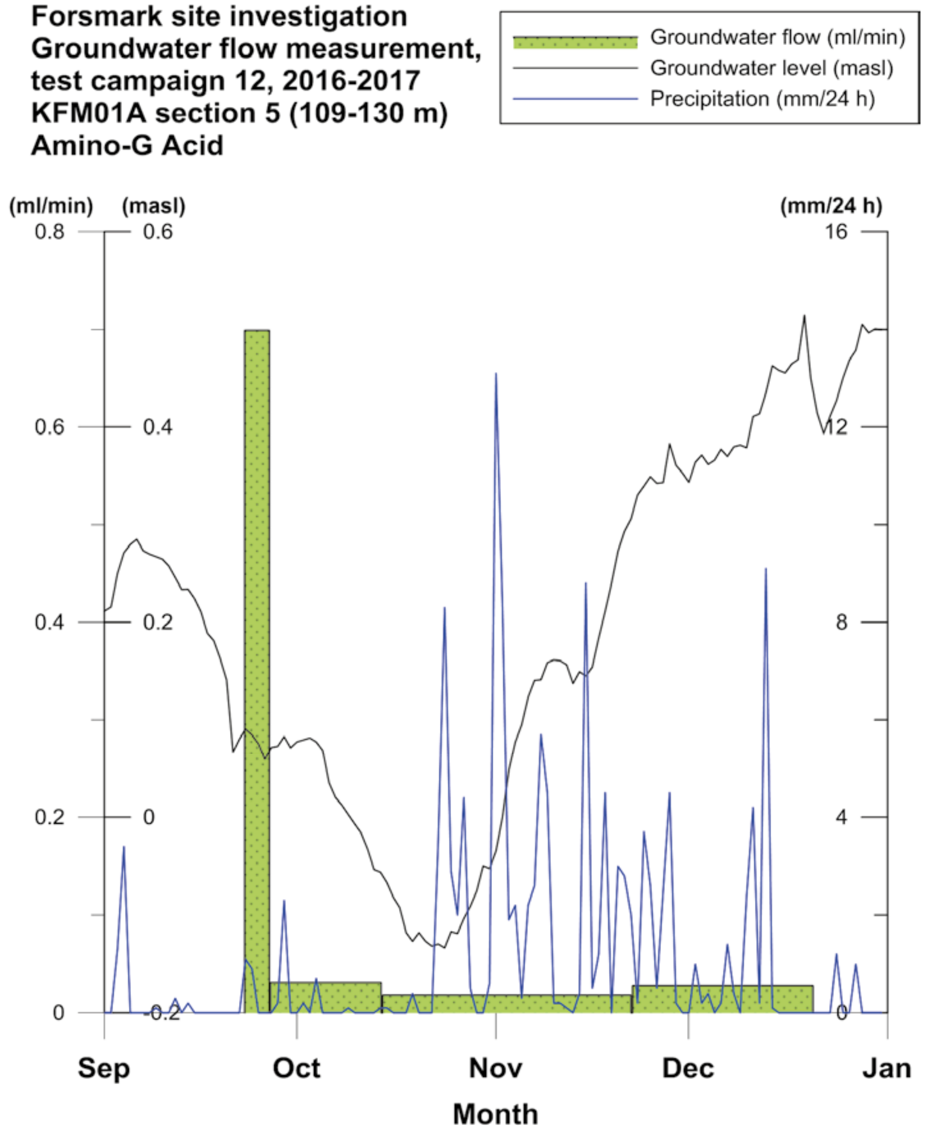
Activities performed in the Forsmark area during the test campaigns with groundwater flow measurements, 2005–2017

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

Start date	Stop date	Borehole	Activity
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

Flow rates, groundwater level and local precipitation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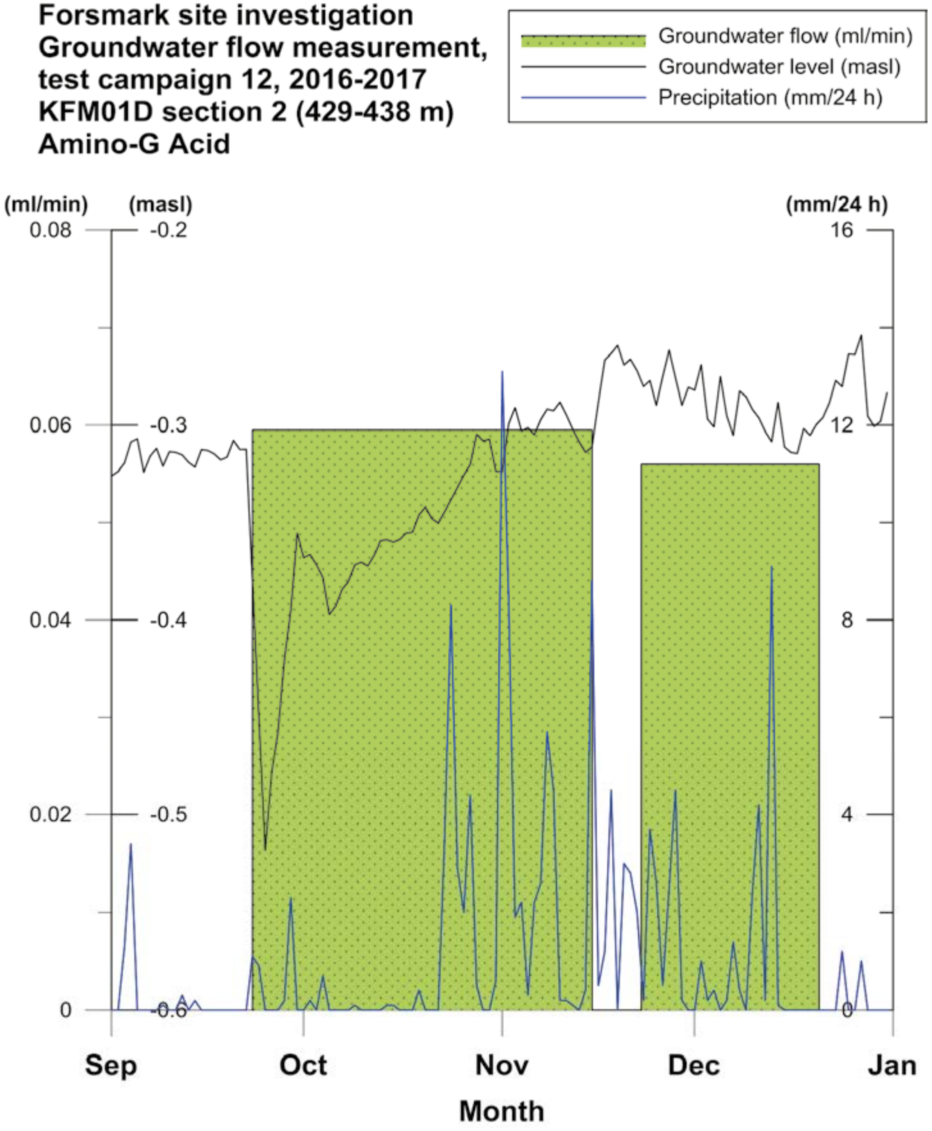
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM01A section 5 (109-130 m)
Amino-G Acid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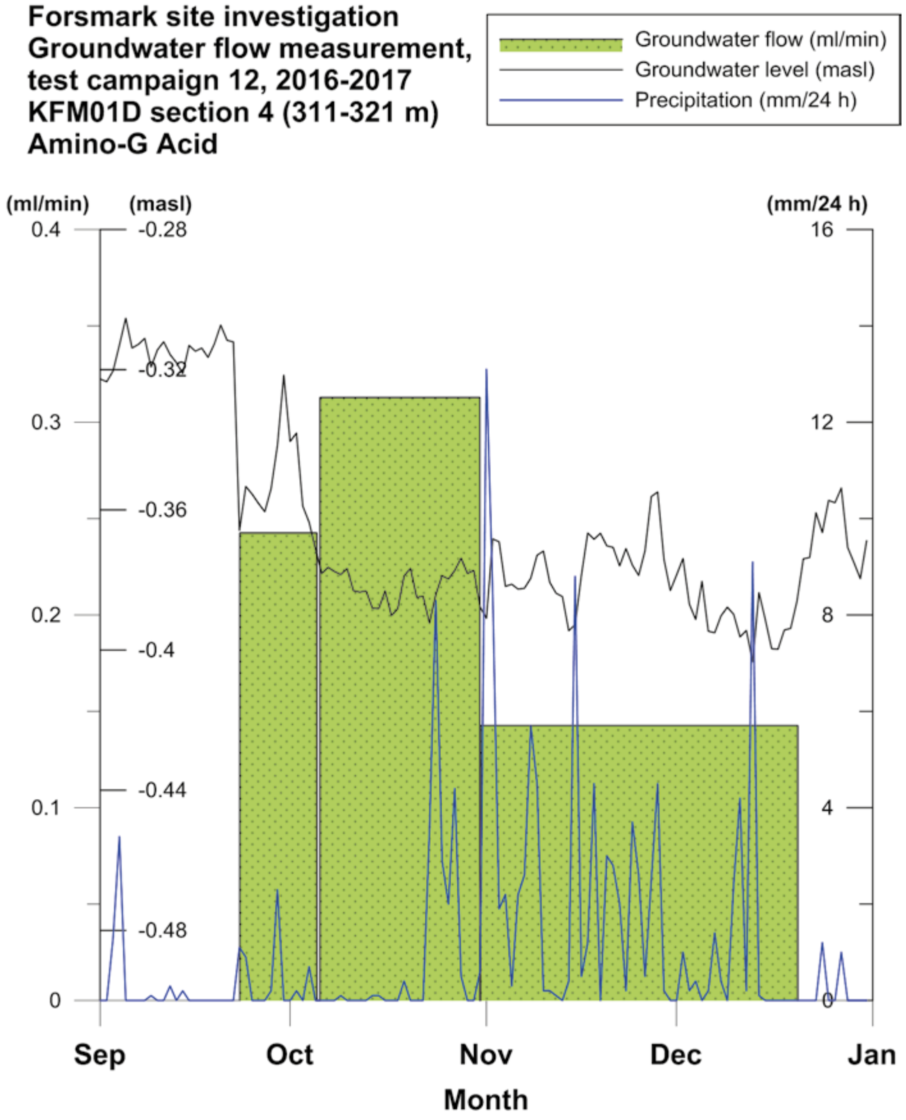
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM01D section 2 (429-438 m)
Amino-G Acid



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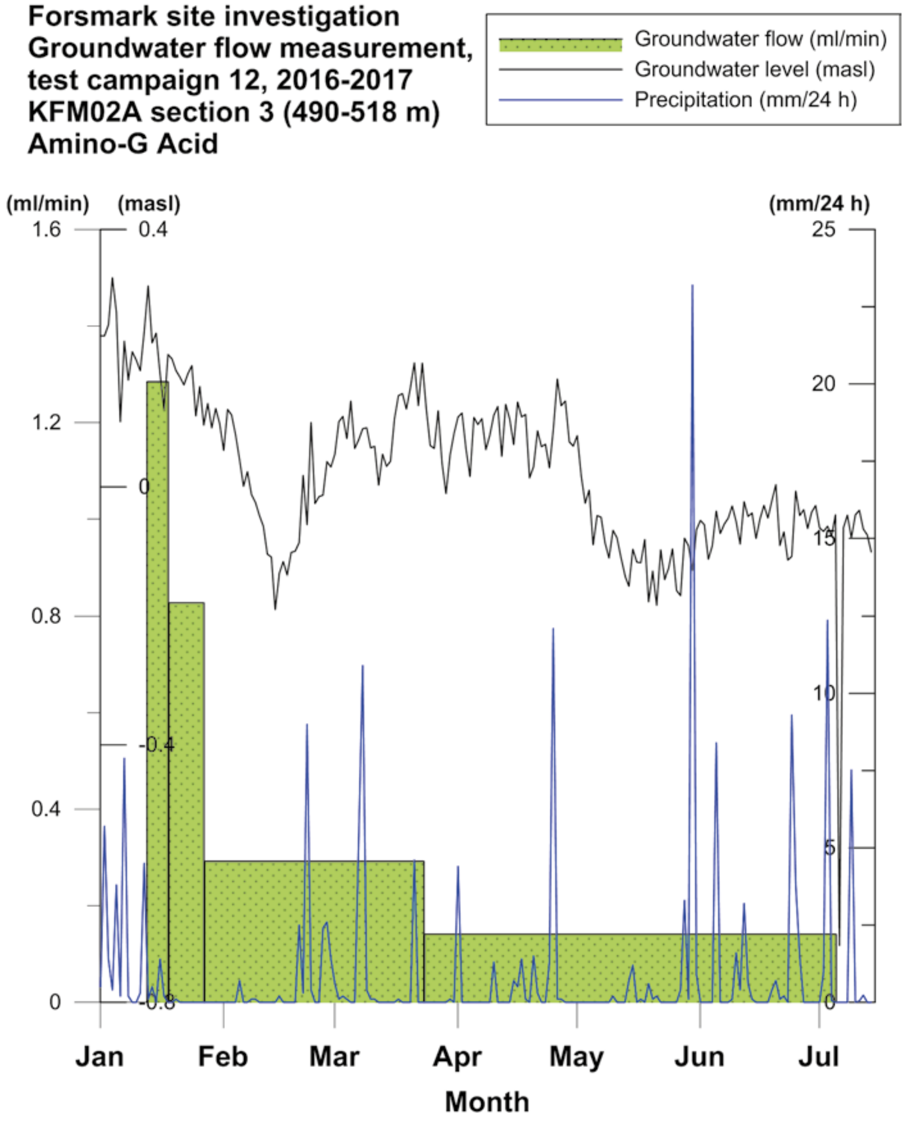
Groundwater flow measurement, test campaign 12, 2016-2017
KFM01D section 4 (311-321 m)
Amino-G Acid



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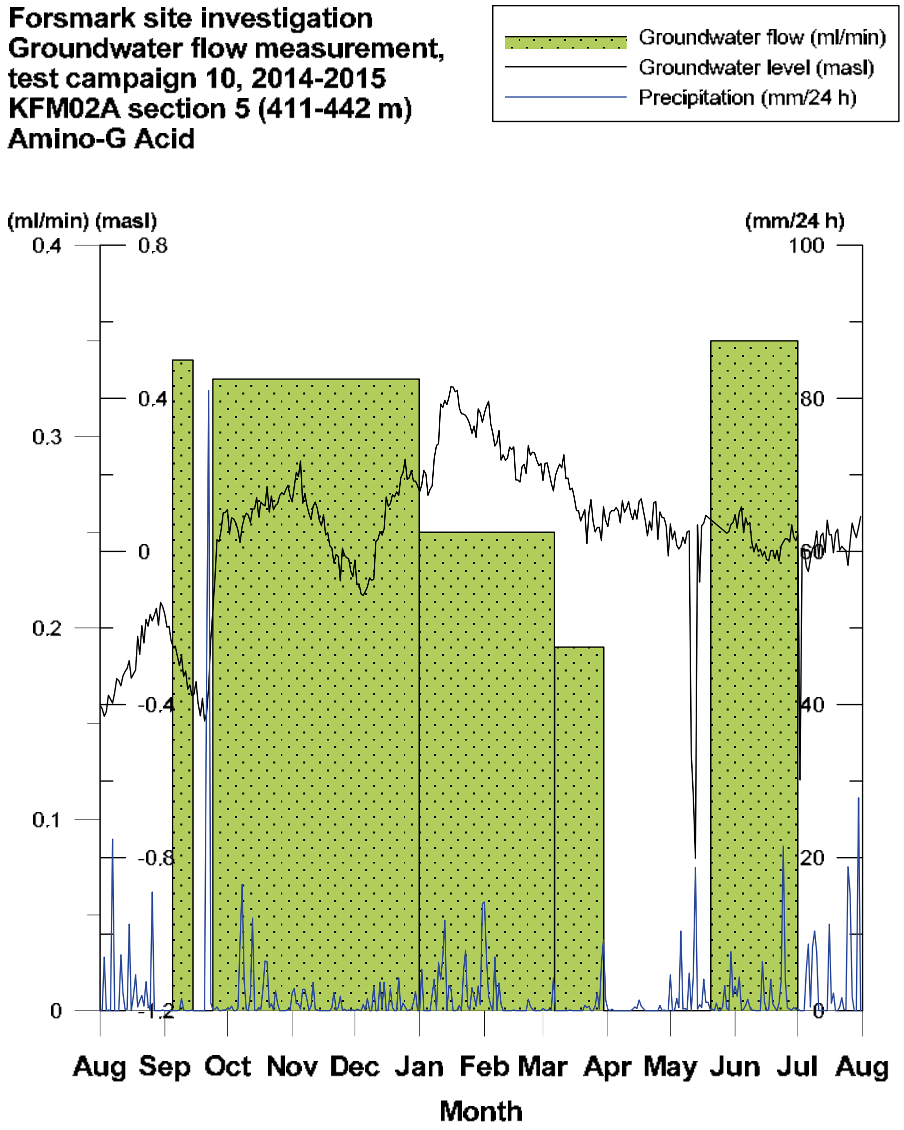
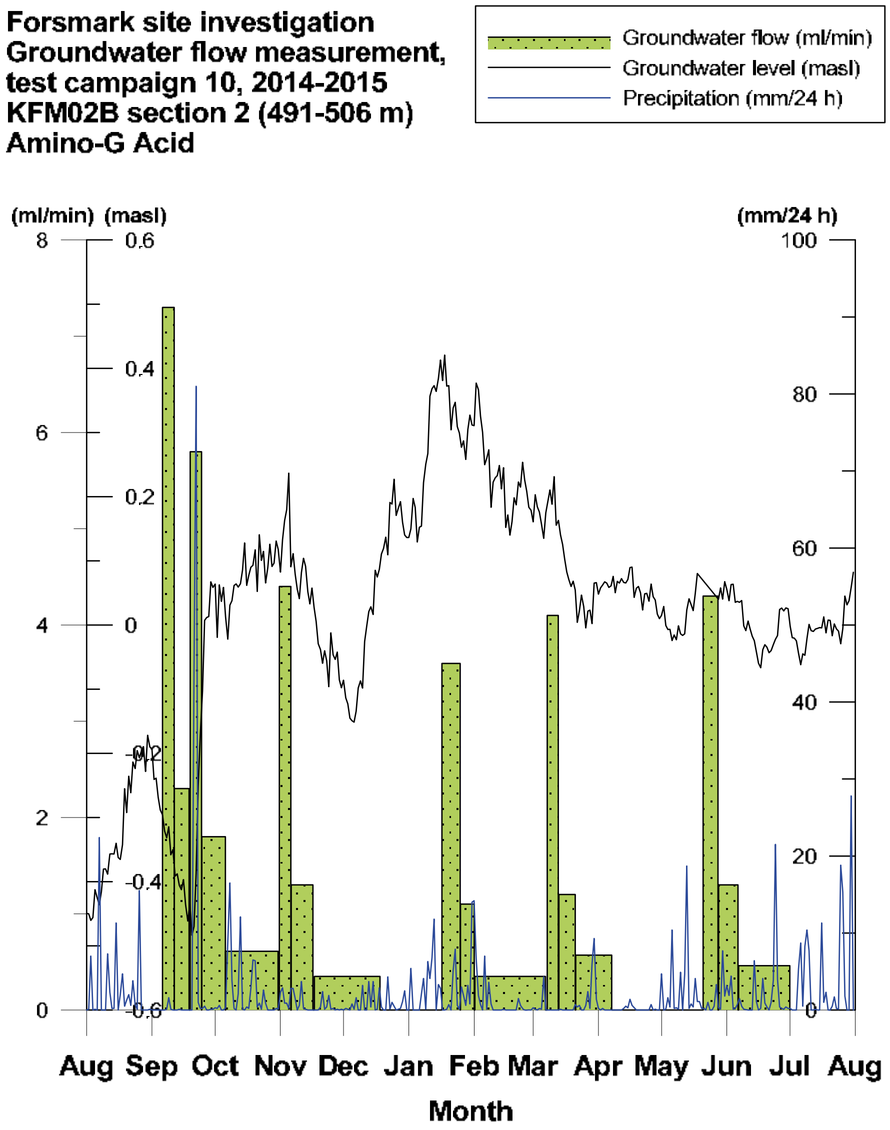
Groundwater flow measurement, test campaign 12, 2016-2017
KFM02A section 3 (490-518 m)
Amino-G Acid


Forsmark site investigation
Groundwater flow measurement, test campaign 10, 2014-2015
KFM02A section 5 (411-442 m)
Amino-G Acid
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min) (masl)
(mm/24 h)
0.4
0.3
0.2
0.1
0
0.8
0.4
0
-0.4
-0.8
-1.2
100
80
60
40
20
0
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
Month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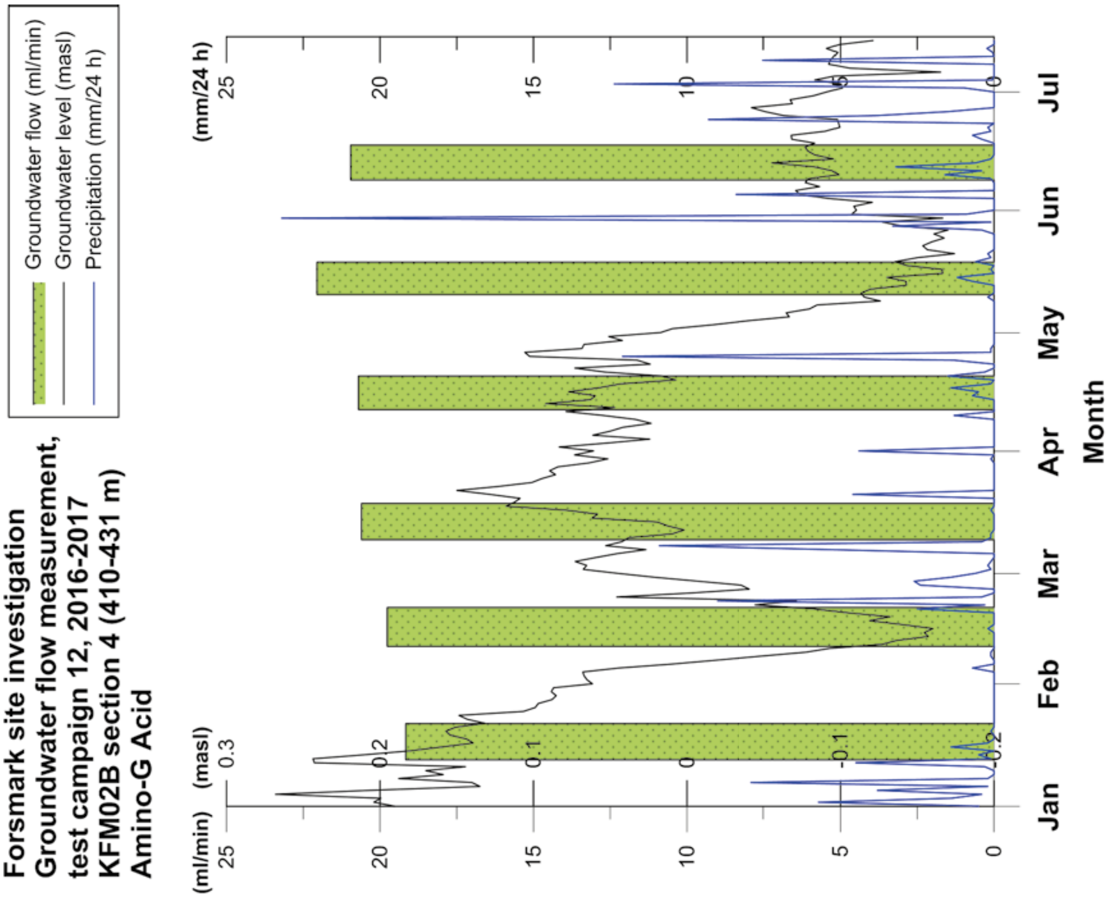
Groundwater flow measurement, test campaign 10, 2014-2015
KFM02B section 2 (491-506 m)
Amino-G Acid
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min) (masl)
(mm/24 h)
8
6
4
2
0
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
100
80
60
40
20
0
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
Month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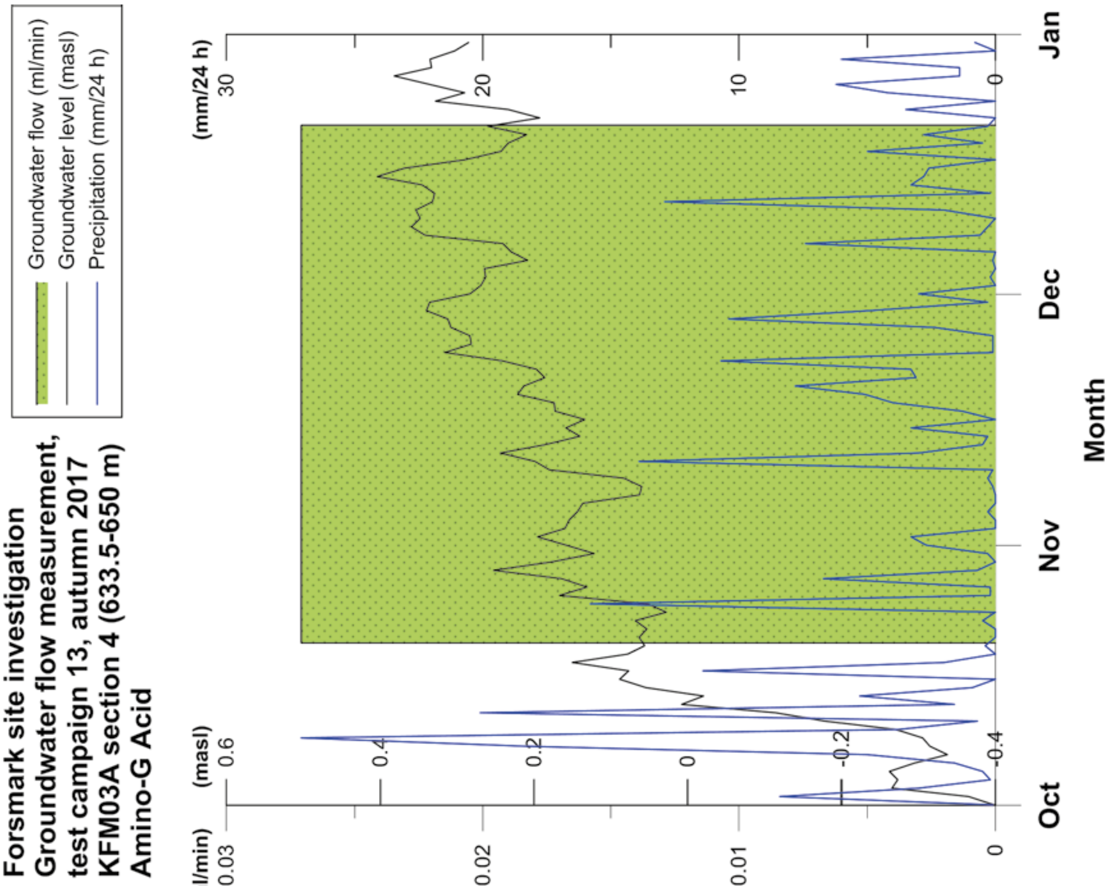
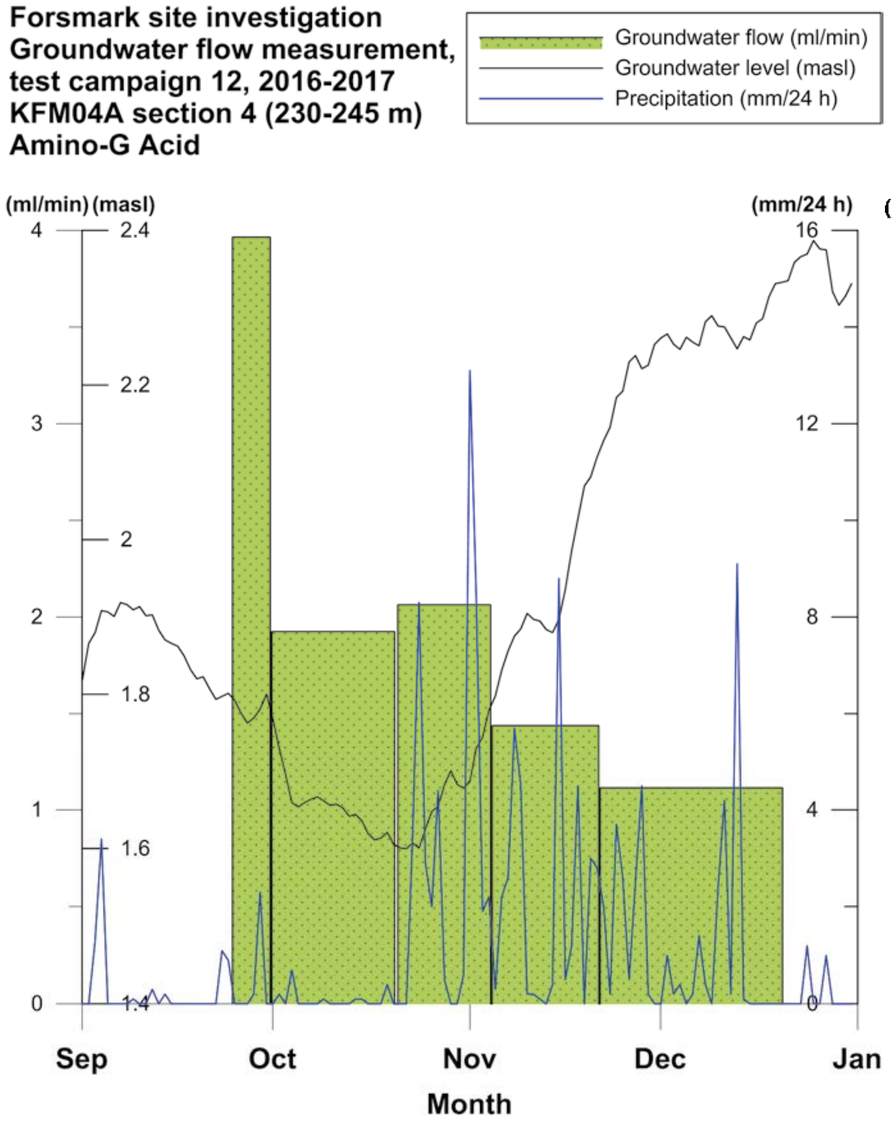
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM02B section 4 (410-431 m)
Amino-G Acid
🟩 Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
25
20
15
10
5
0
(masl)
0.3
0.2
0.1
0
-0.1
-0.2
(mm/24 h)
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Month


Forsmark site investigation
Groundwater flow measurement,
test campaign 13, autumn 2017
KFM03A section 4 (633.5-650 m)
Amino-G Acid
🟩 Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
0.03
0.02
0.01
0
(masl)
0.6
0.4
0.2
0
-0.2
-0.4
(mm/24 h)
30
20
10
0
Oct
Nov
Dec
Jan
Month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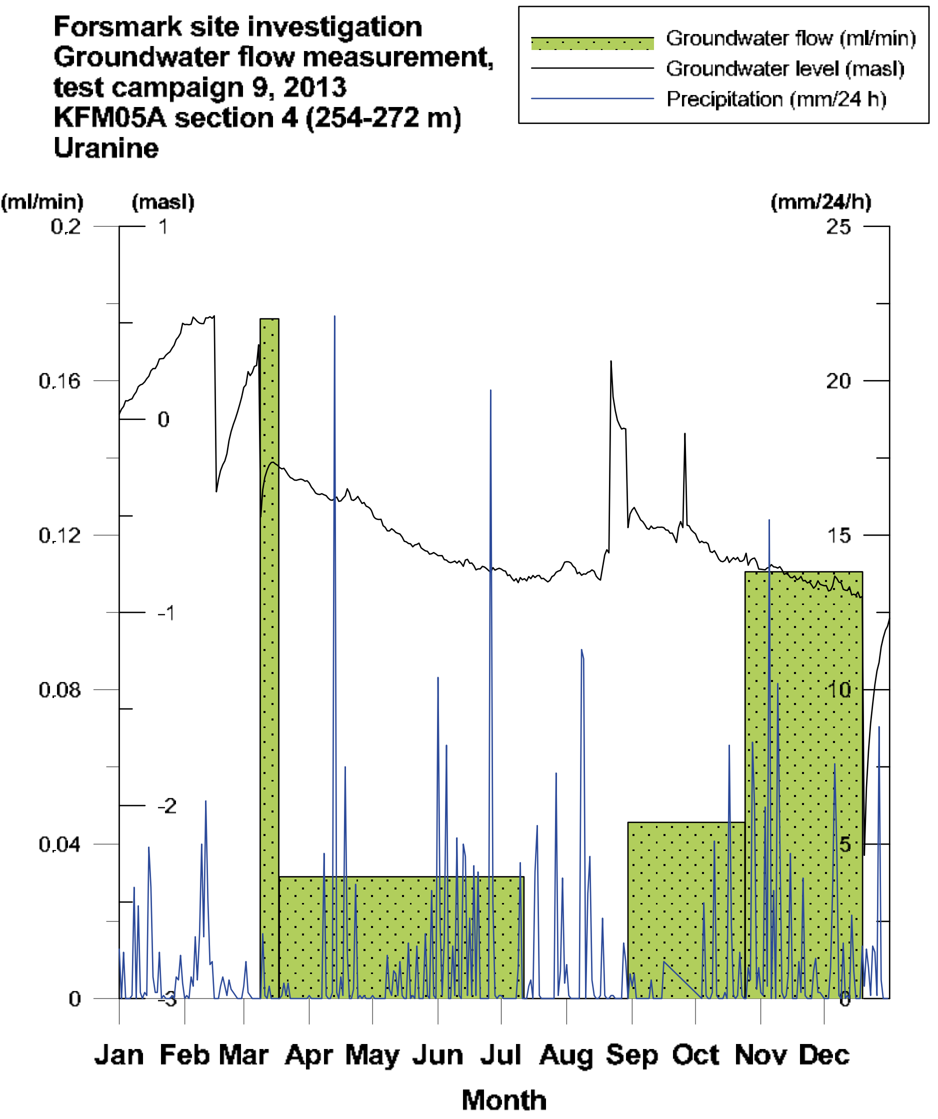
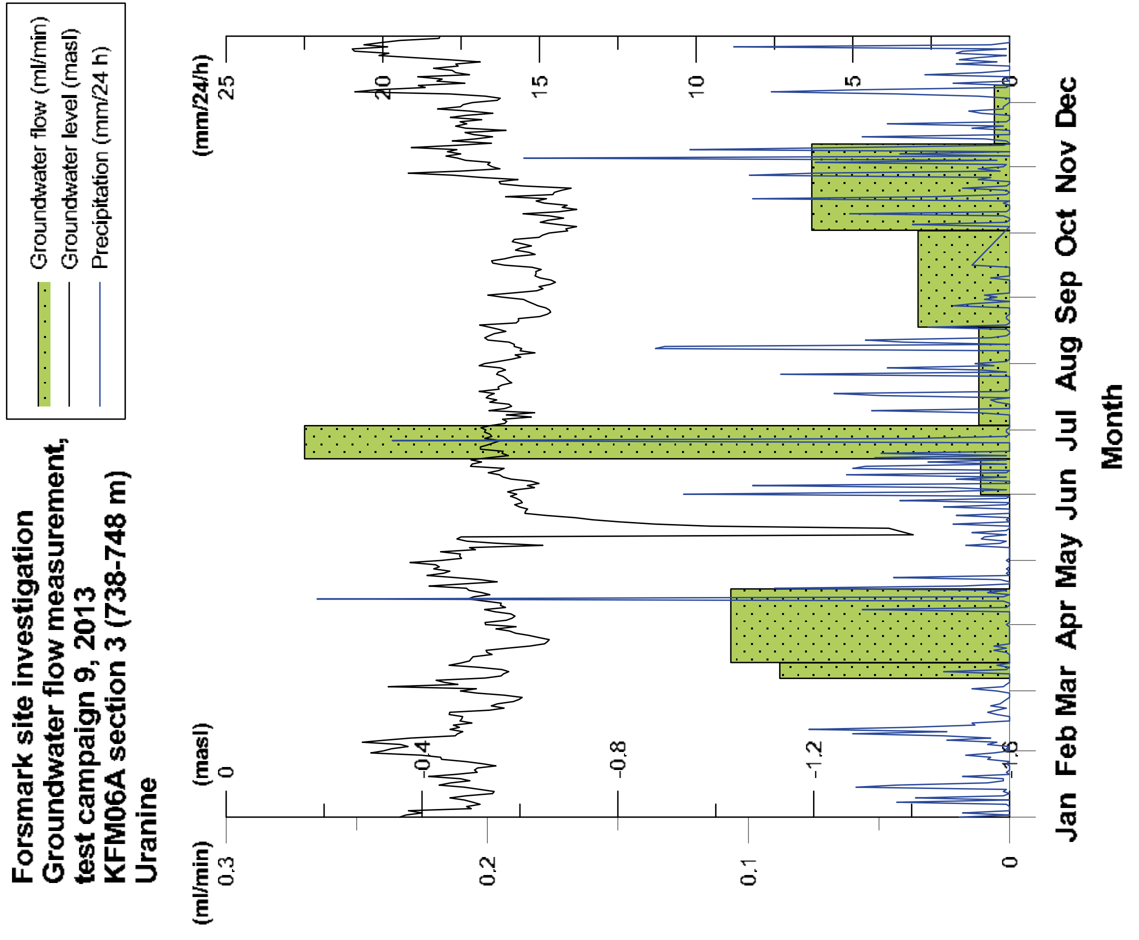
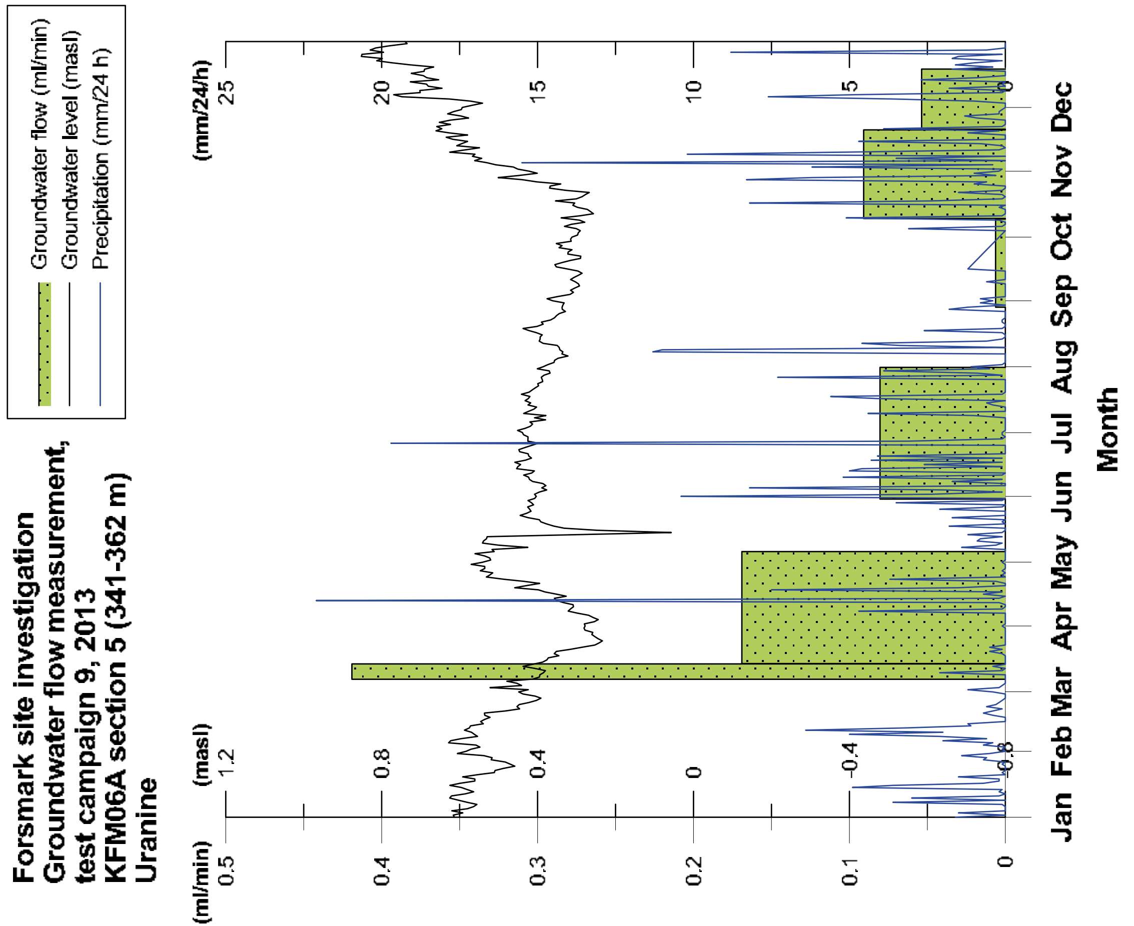
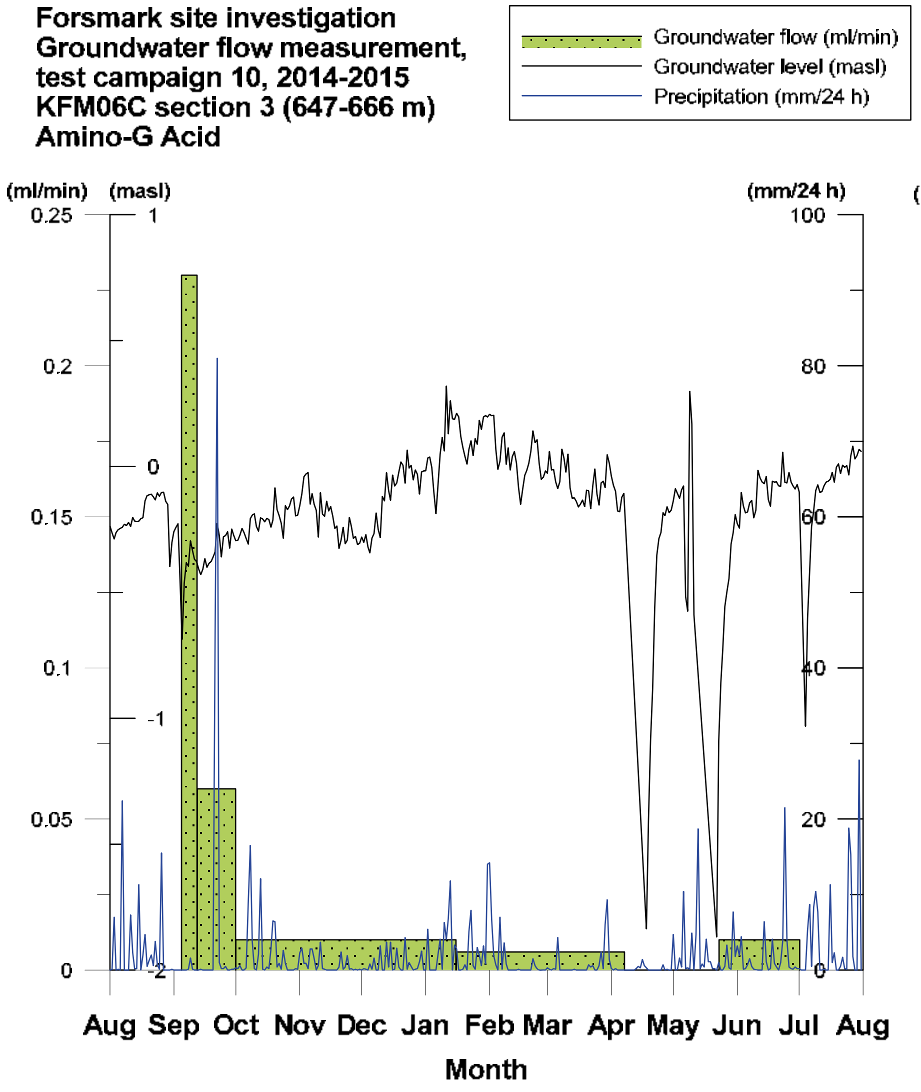
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM04A section 4 (230-245 m)
Amino-G Acid
🟩 Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24 h)
4
3
2
1
0
2.4
2.2
2
1.8
1.6
1.4
16
12
8
4
0
Sep
Oct
Nov
Dec
Jan
Month


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM05A section 4 (254-272 m)
Uranine
🟩 Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24/h)
0.2
0.16
0.12
0.08
0.04
0
1
0
-1
-2
-3
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06A section 3 (738-748 m)
Uranine
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
0.3
0.2
0.1
0
(masl)
0
-0.4
-0.8
-1.2
-1.6
(mm/24/h)
25
20
15
10
5
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06A section 5 (341-362 m)
Uranine
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
0.5
0.4
0.3
0.2
0.1
0
(masl)
1.2
0.8
0.4
0
-0.4
-0.8
(mm/24/h)
25
20
15
10
5
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month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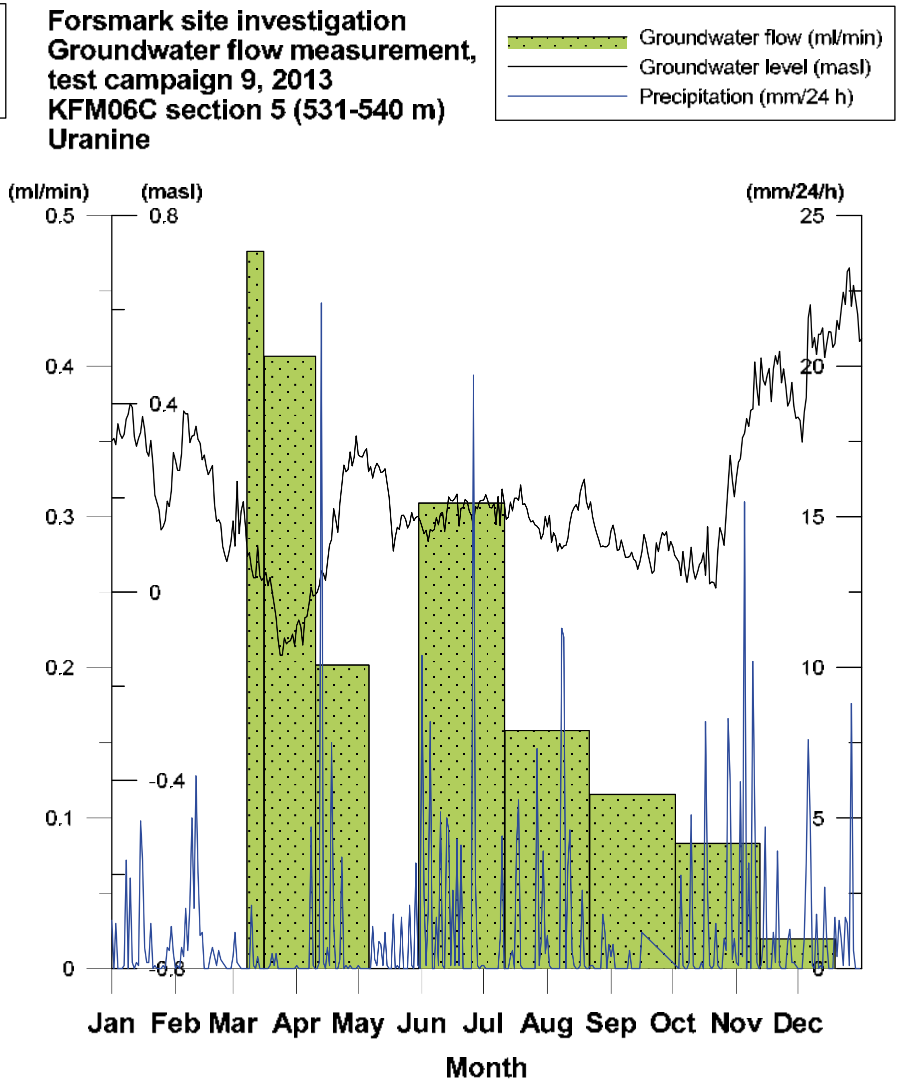
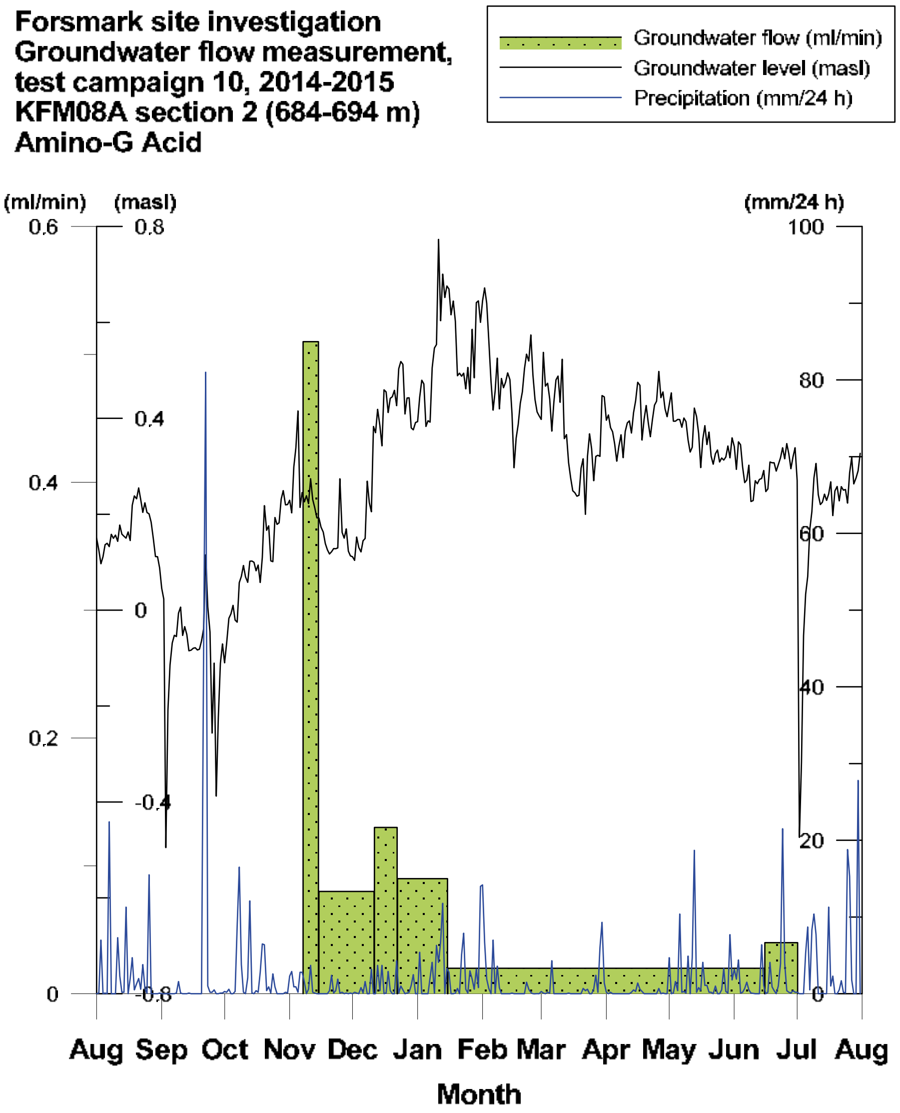
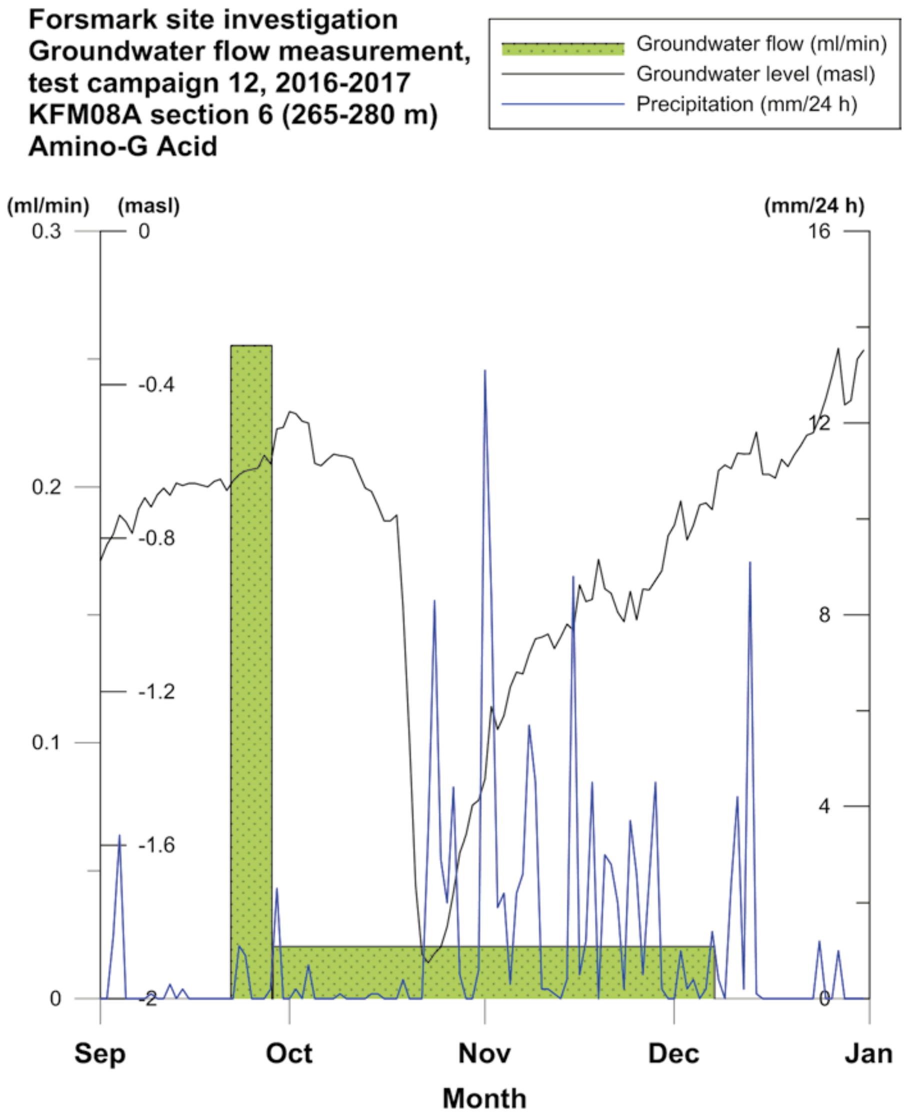
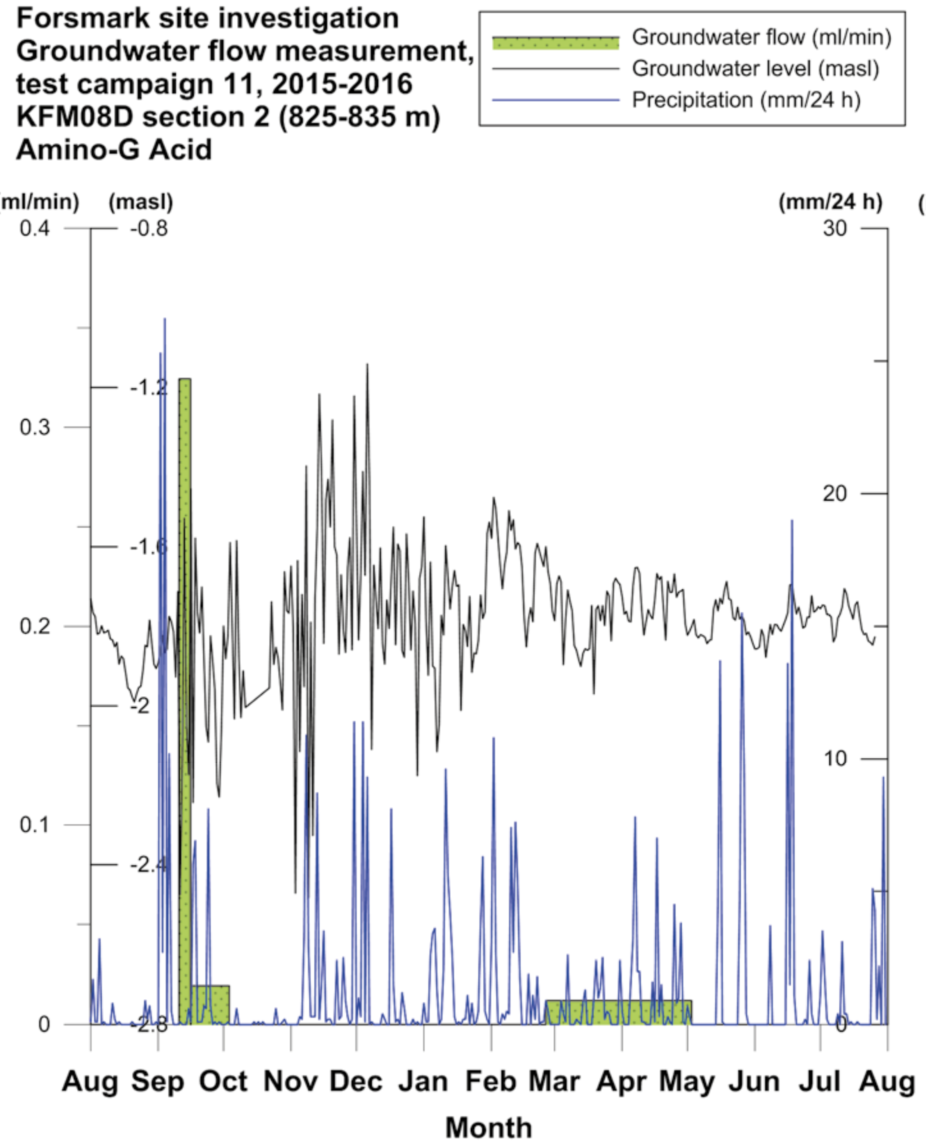
Groundwater flow measurement,
test campaign 10, 2014-2015
KFM06C section 3 (647-666 m)
Amino-G Acid

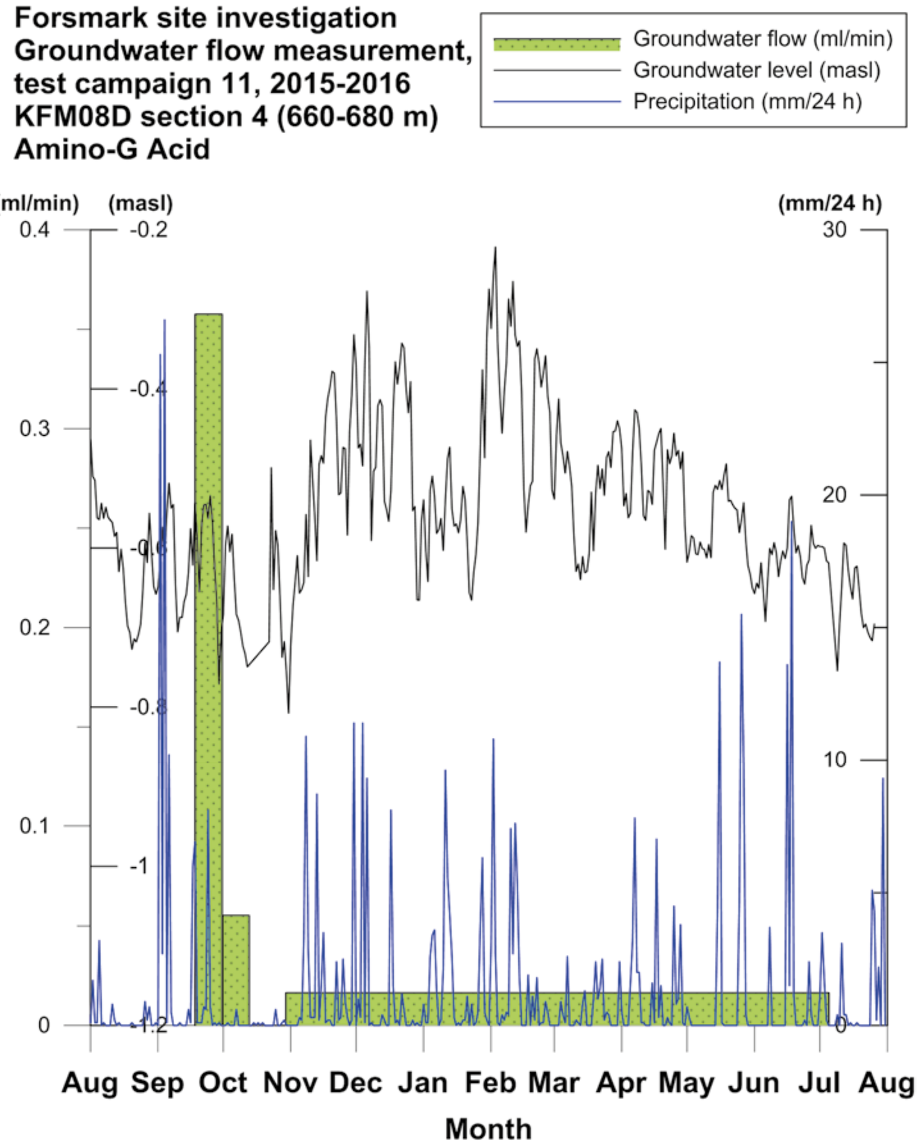

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06C section 5 (531-540 m)
Uranine


Forsmark site investigation
Groundwater flow measurement, test campaign 10, 2014-2015
KFM08A section 2 (684-694 m)
Amino-G Acid
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24 h)
0.6
0.4
0.2
0
0.8
0.4
0
-0.4
-0.8
100
80
60
40
20
0
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
Month

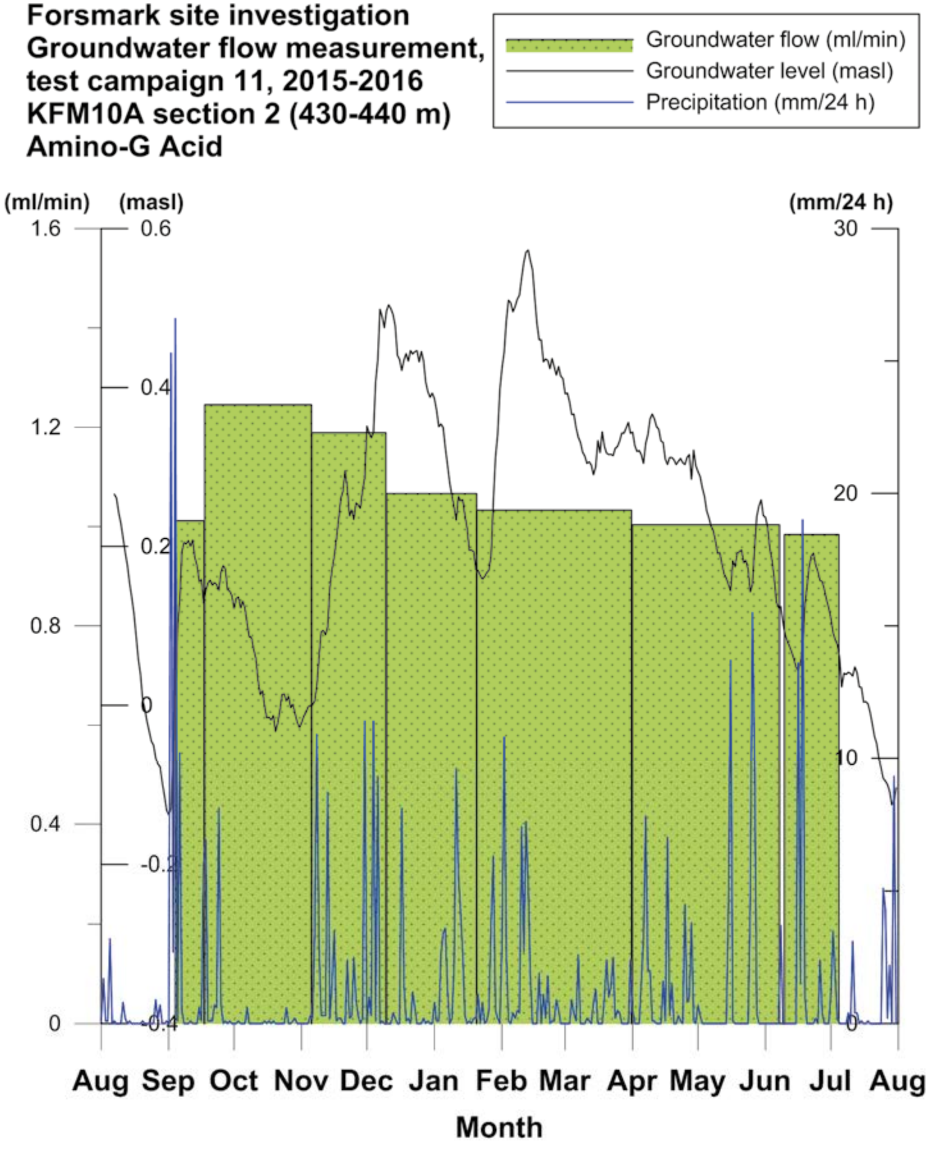

Forsmark site investigation
Groundwater flow measurement, test campaign 12, 2016-2017
KFM08A section 6 (265-280 m)
Amino-G Acid
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24 h)
0.3
0.2
0.1
0
0
-0.4
-0.8
-1.2
-1.6
-2
16
12
8
4
0
Sep Oct Nov Dec Jan
Month



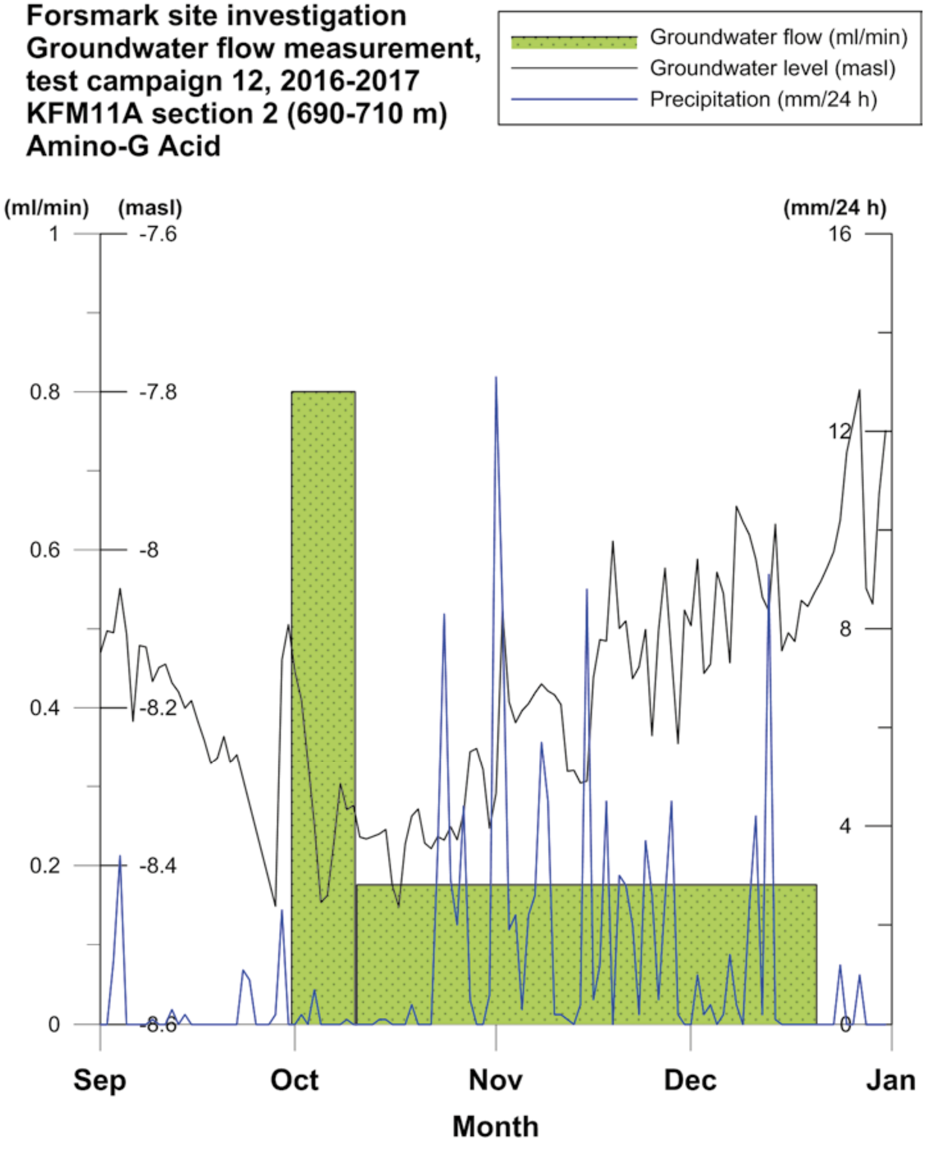
Forsmark site investigation
Groundwater flow measurement, test campaign 11, 2015-2016
KFM08D section 2 (825-835 m)
Amino-G Acid



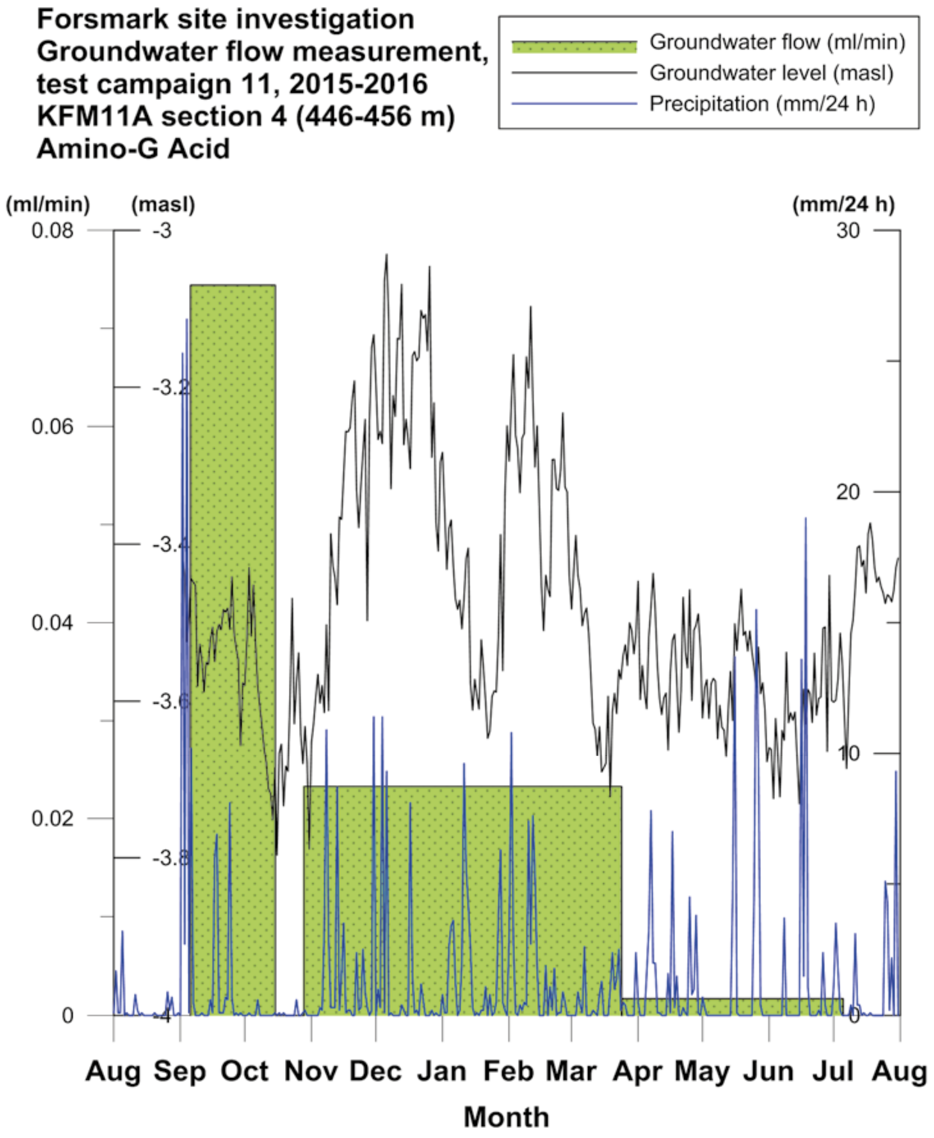
Forsmark site investigation
Groundwater flow measurement, test campaign 11, 2015-2016
KFM08D section 4 (660-680 m)
Amino-G Acid

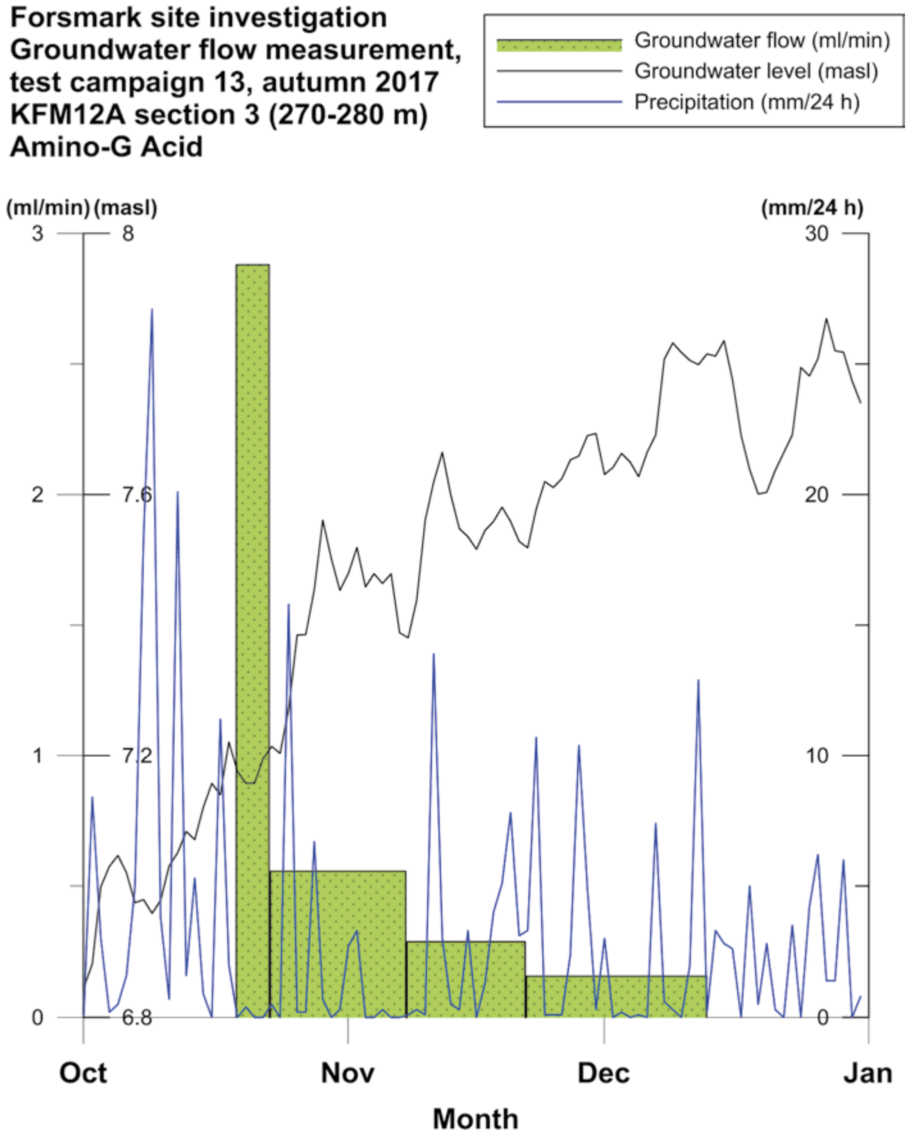


Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM10A section 2 (430-440 m)
Amino-G Acid



Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM11A section 2 (690-710 m)
Amino-G Acid


Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM11A section 4 (446-456 m)
Amino-G Acid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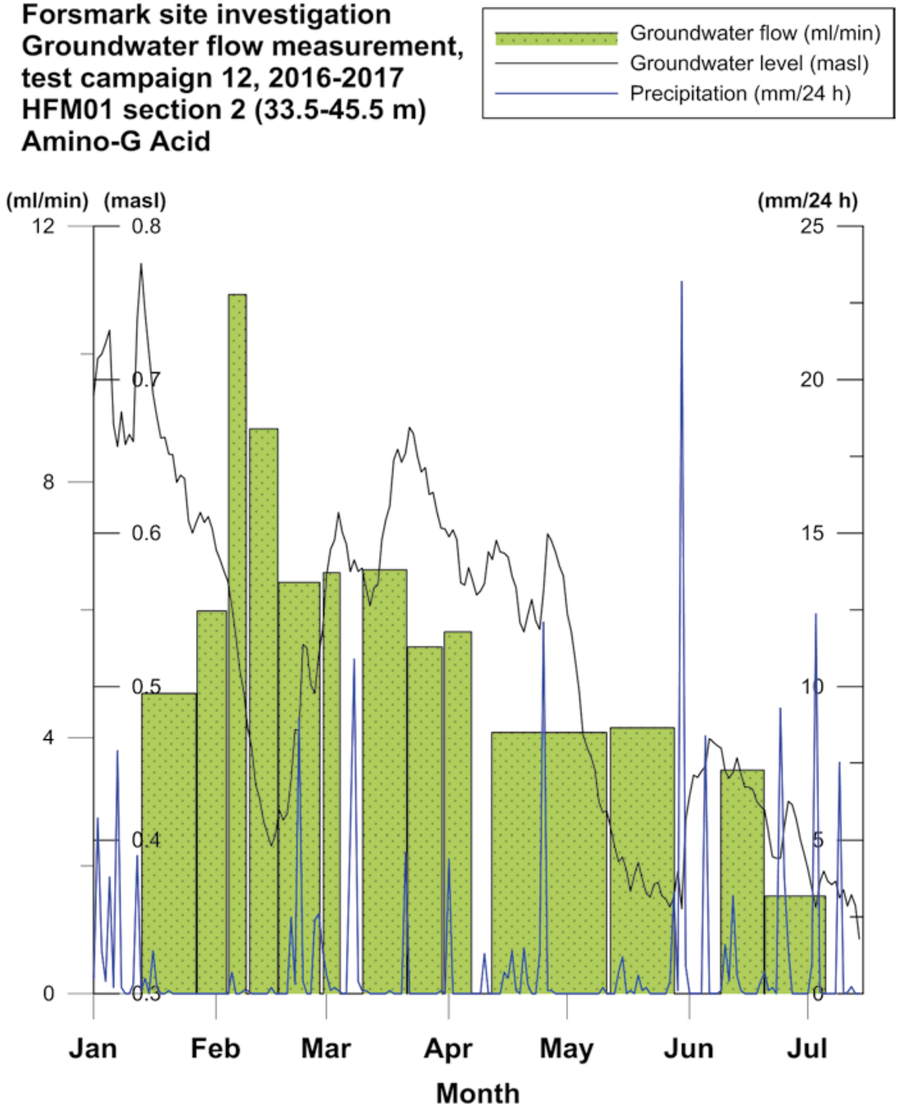
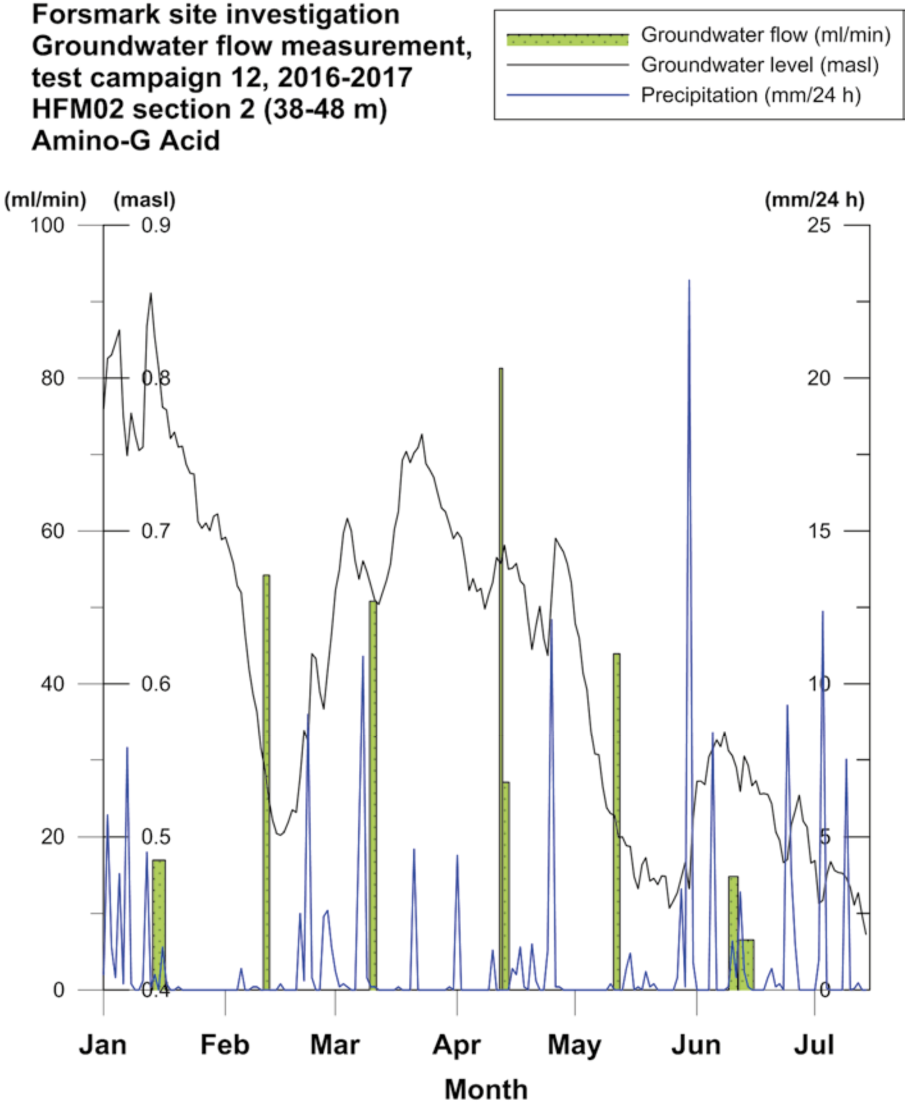
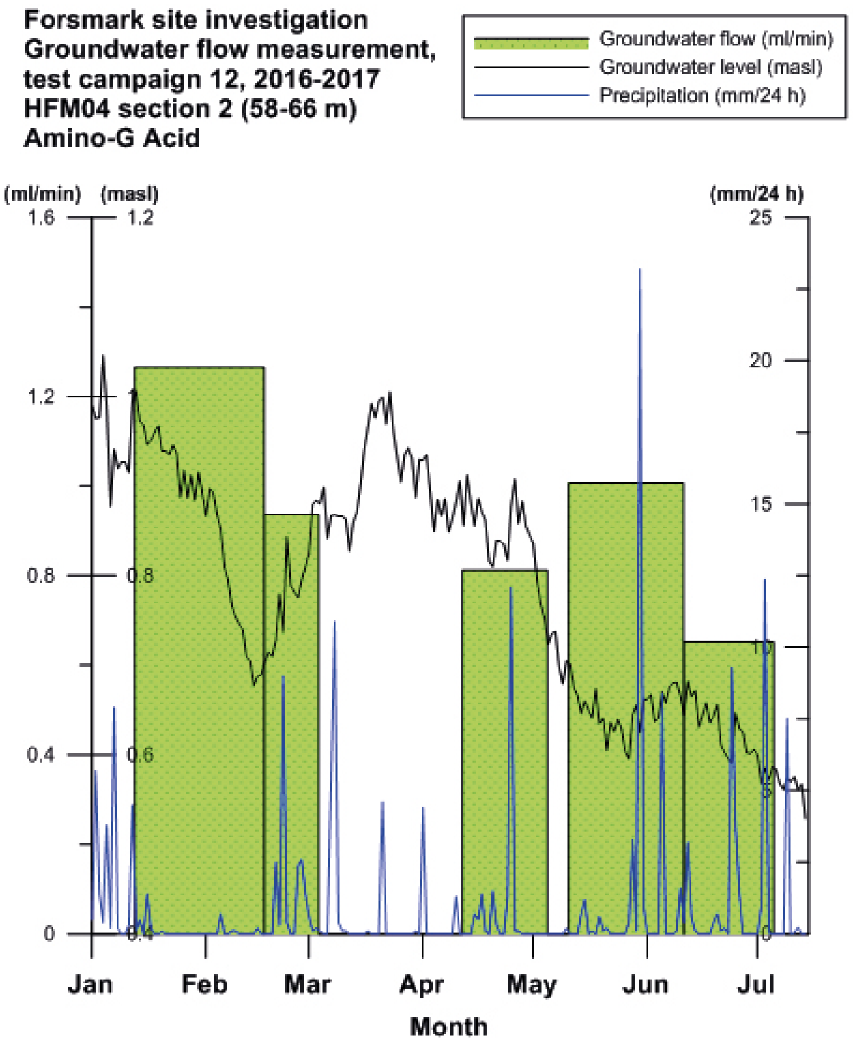
Groundwater flow measurement,
test campaign 13, autumn 2017
KFM12A section 3 (270-280 m)
Amino-G Acid



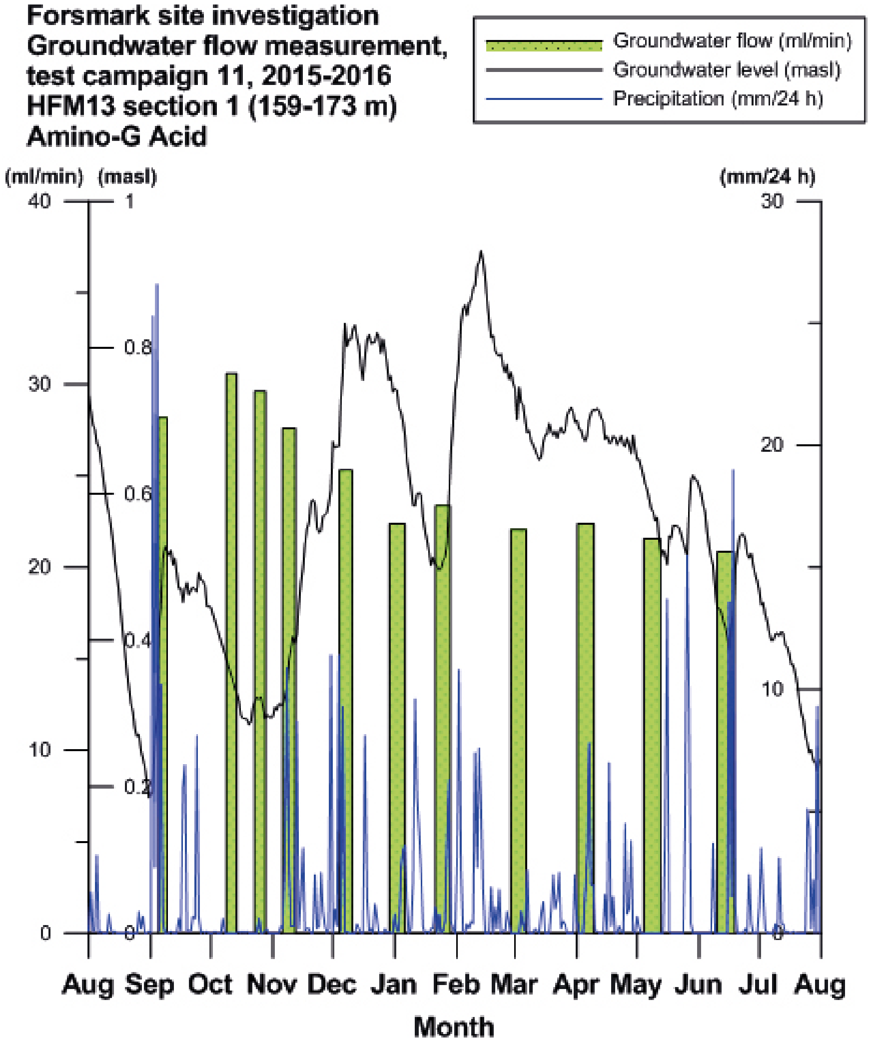
Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM01 section 2 (33.5-45.5 m)
Amino-G Acid



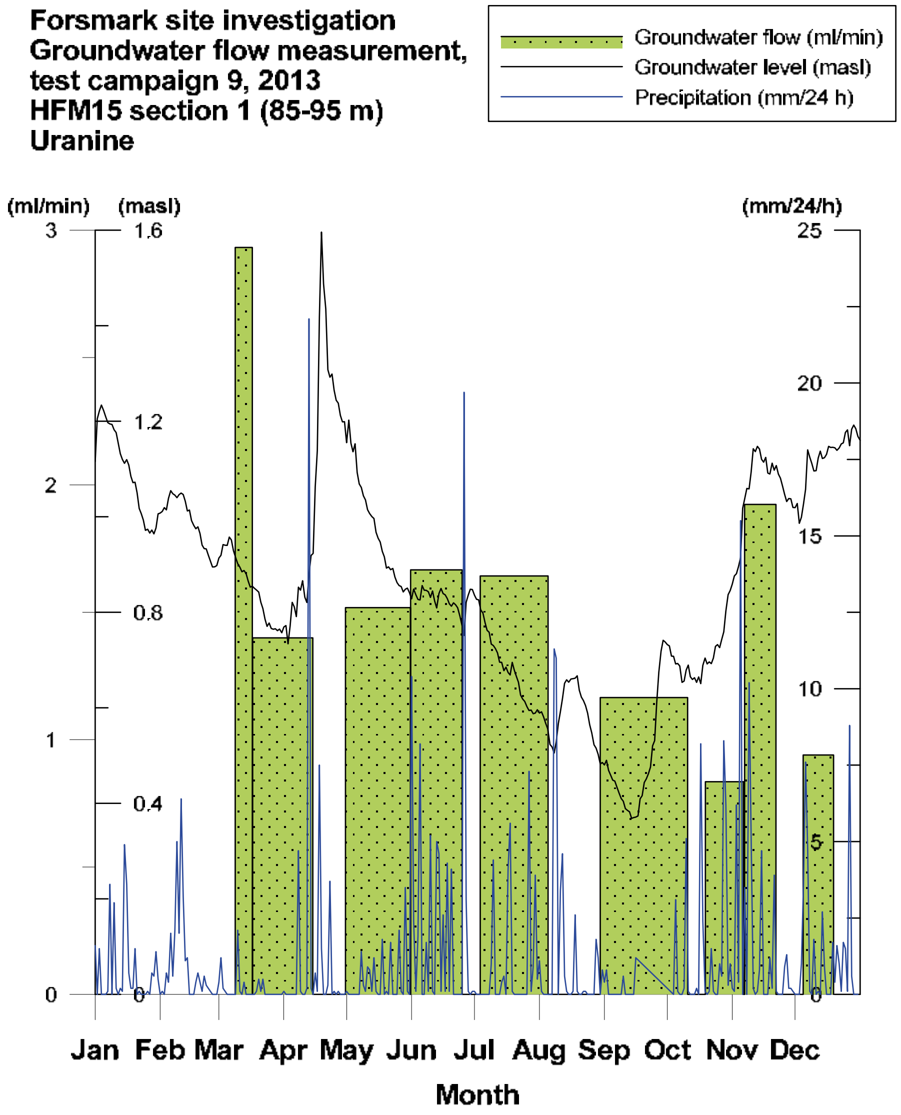
Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM02 section 2 (38-48 m)
Amino-G Acid

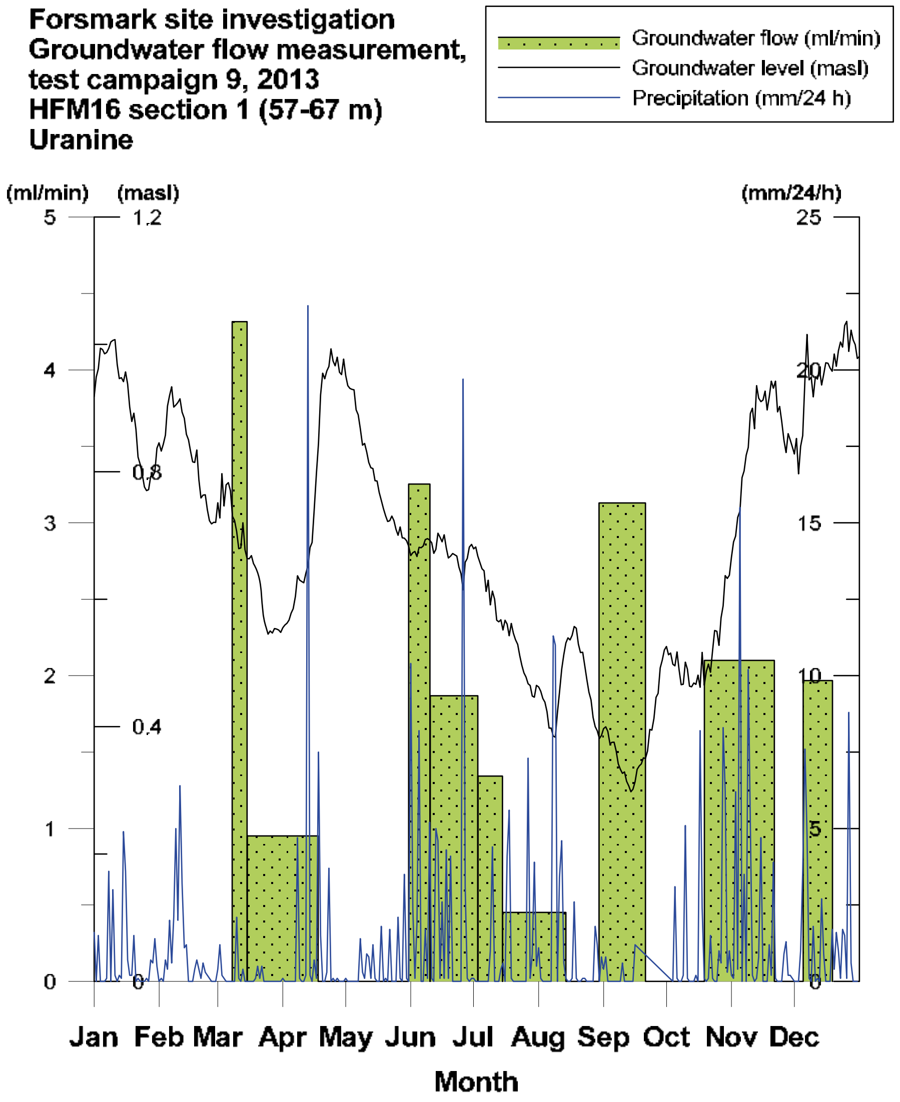


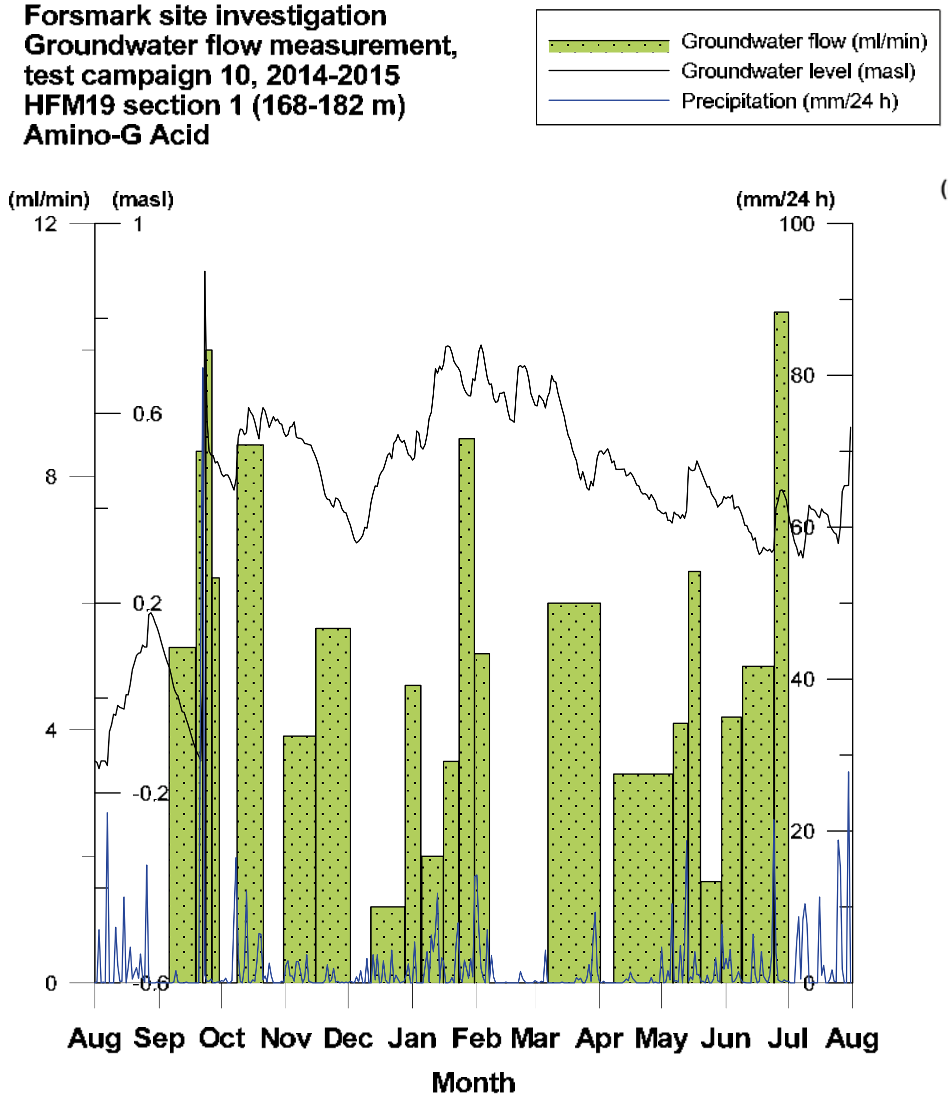
Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM04 section 2 (58-66 m)
Amino-G Acid

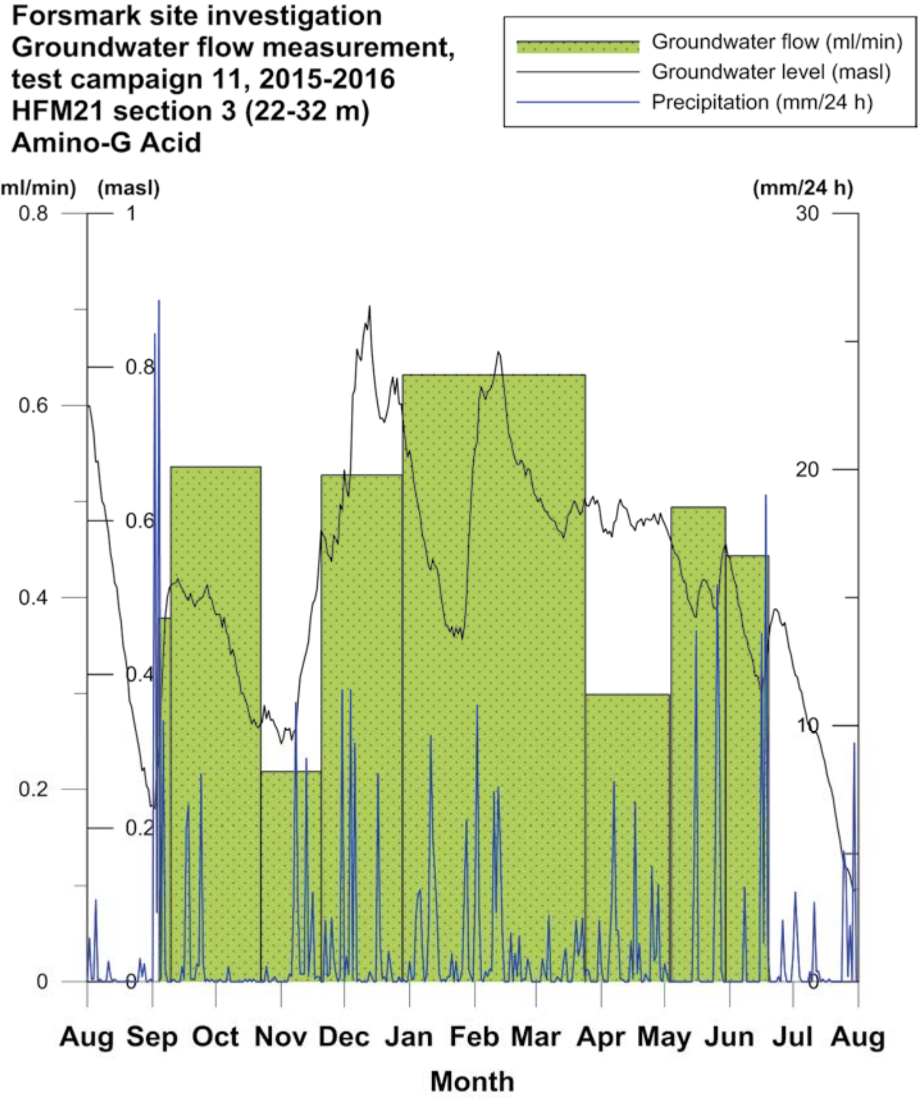


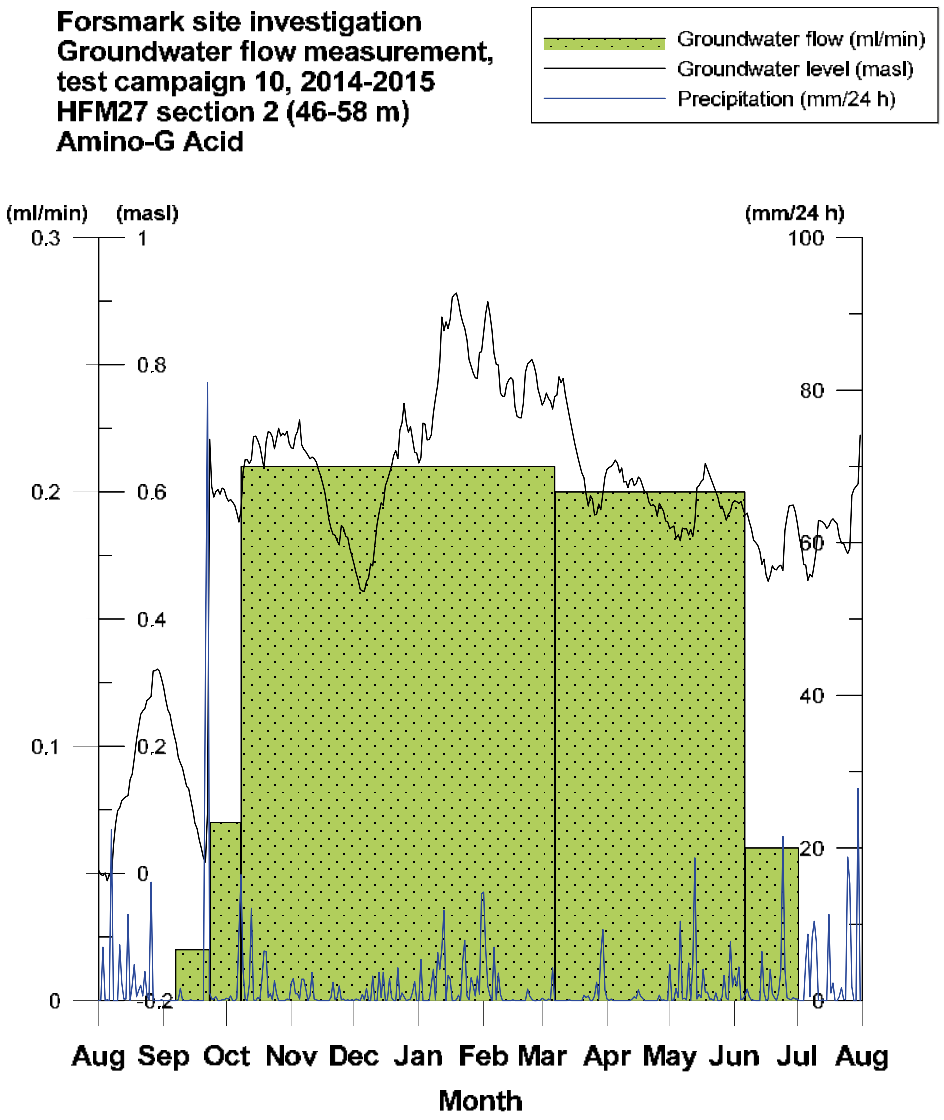
Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
HFM13 section 1 (159-173 m)
Amino-G Acid


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
HFM15 section 1 (85-95 m)
Uranine
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24/h)
3
2
1
0
1.6
1.2
0.8
0.4
0
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

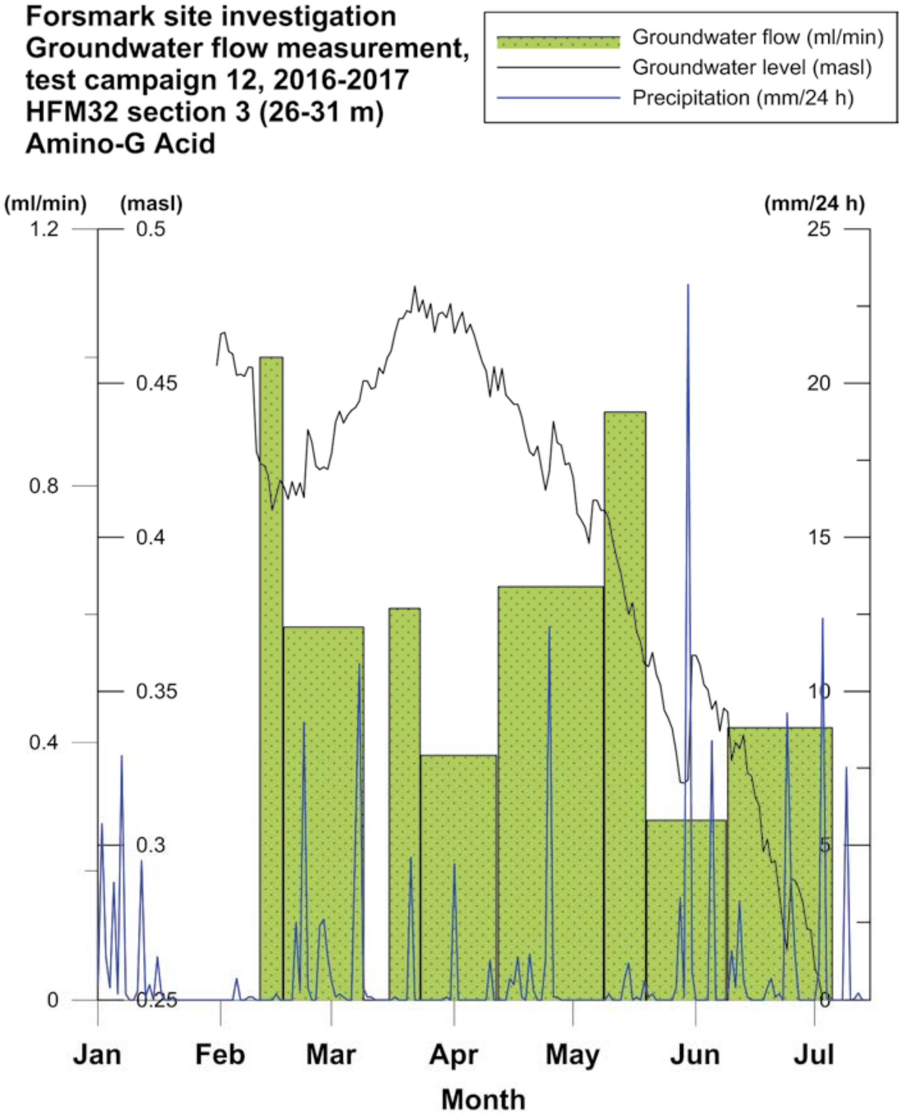

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
HFM16 section 1 (57-67 m)
Uranine
Groundwater flow (ml/min)
Groundwater level (masl)
Precipitation (mm/24 h)
(ml/min)
(masl)
(mm/24/h)
5
4
3
2
1
0
1.2
0.8
0.4
0
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014-2015
HFM19 section 1 (168-182 m)
Amino-G Acid


Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
HFM21 section 3 (22-32 m)
Amino-G Acid

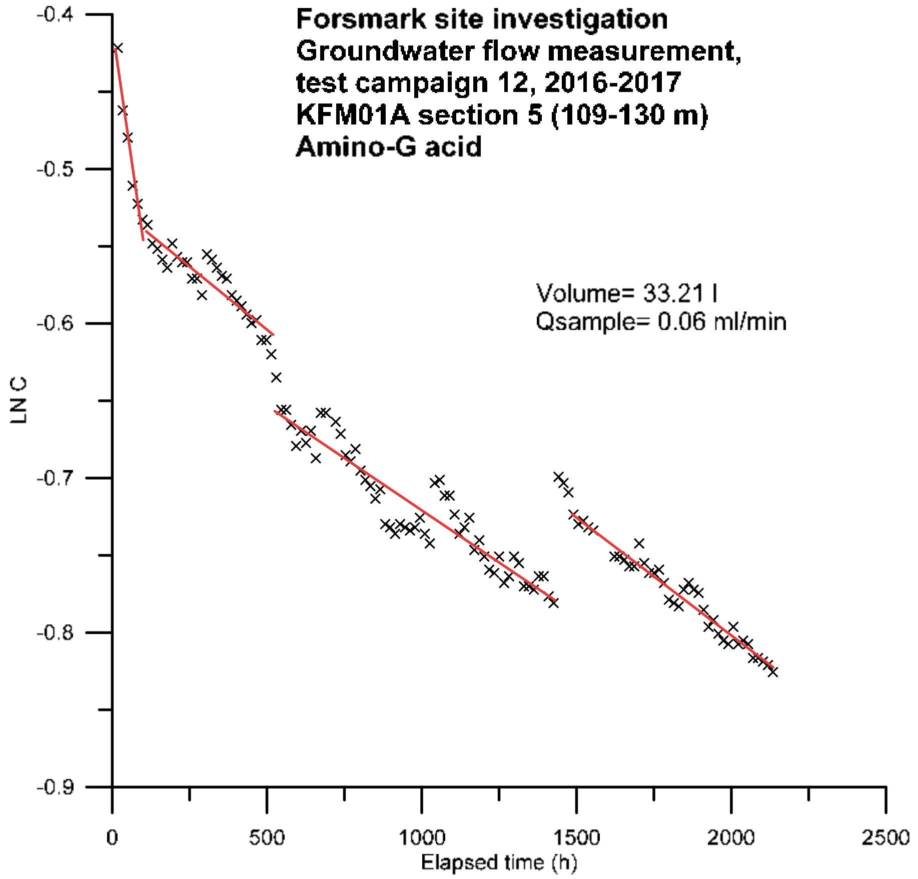


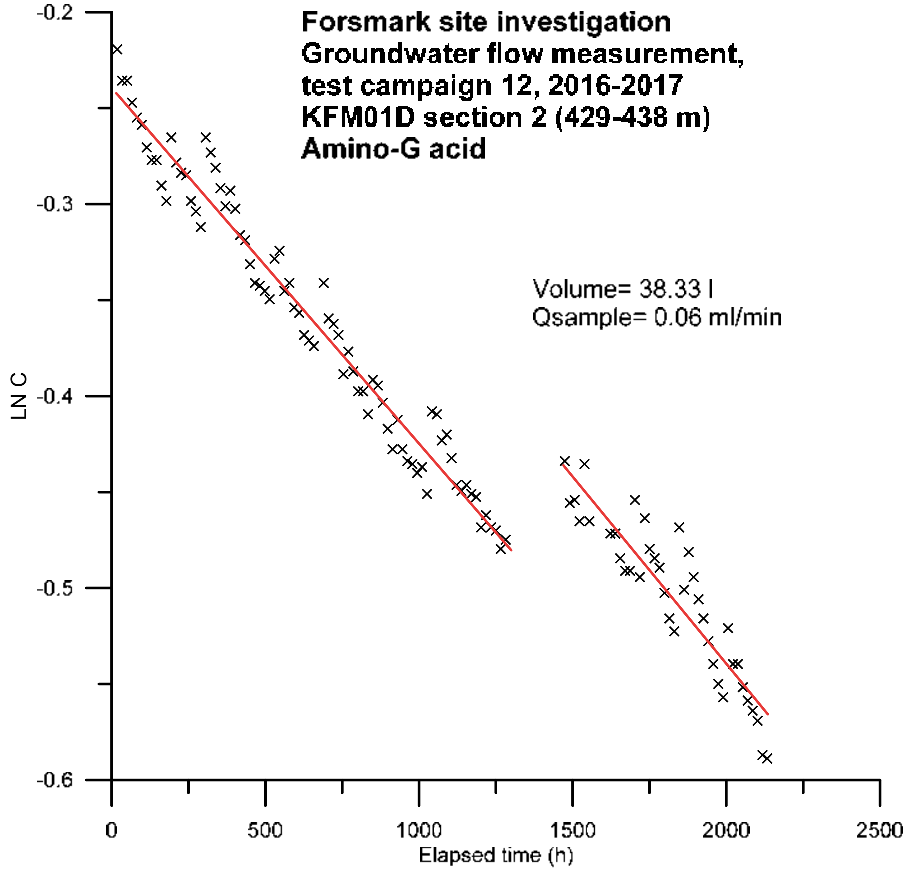
Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014-2015
HFM27 section 2 (46-58 m)
Amino-G Acid

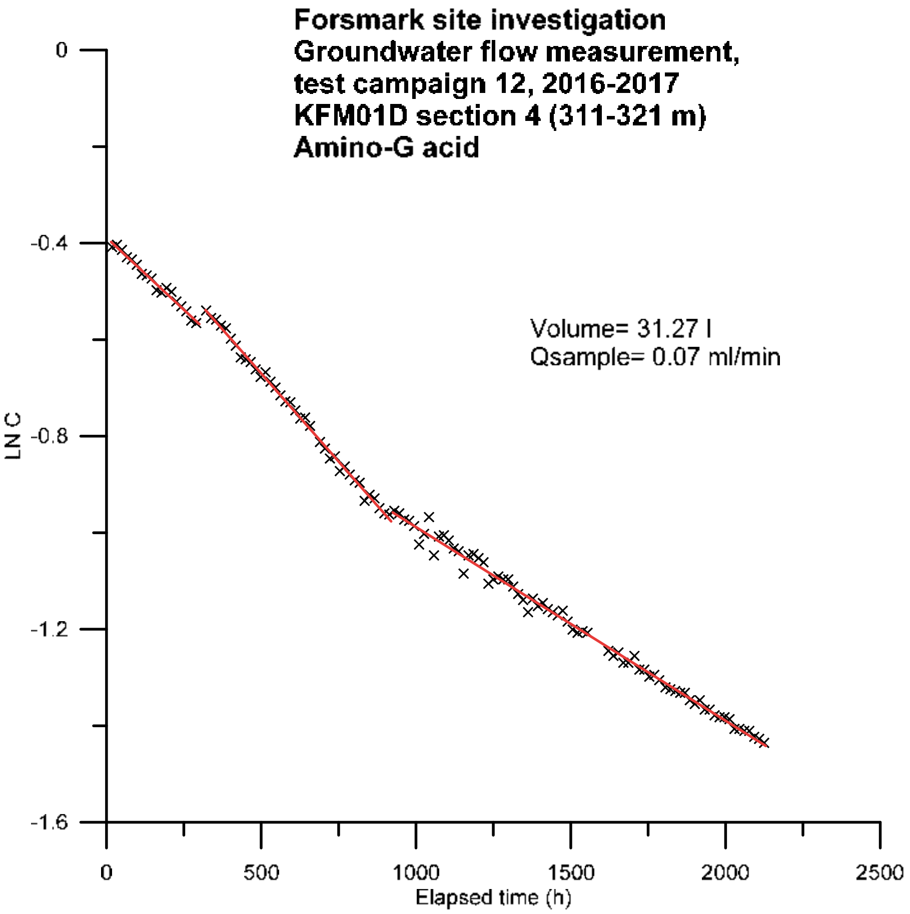


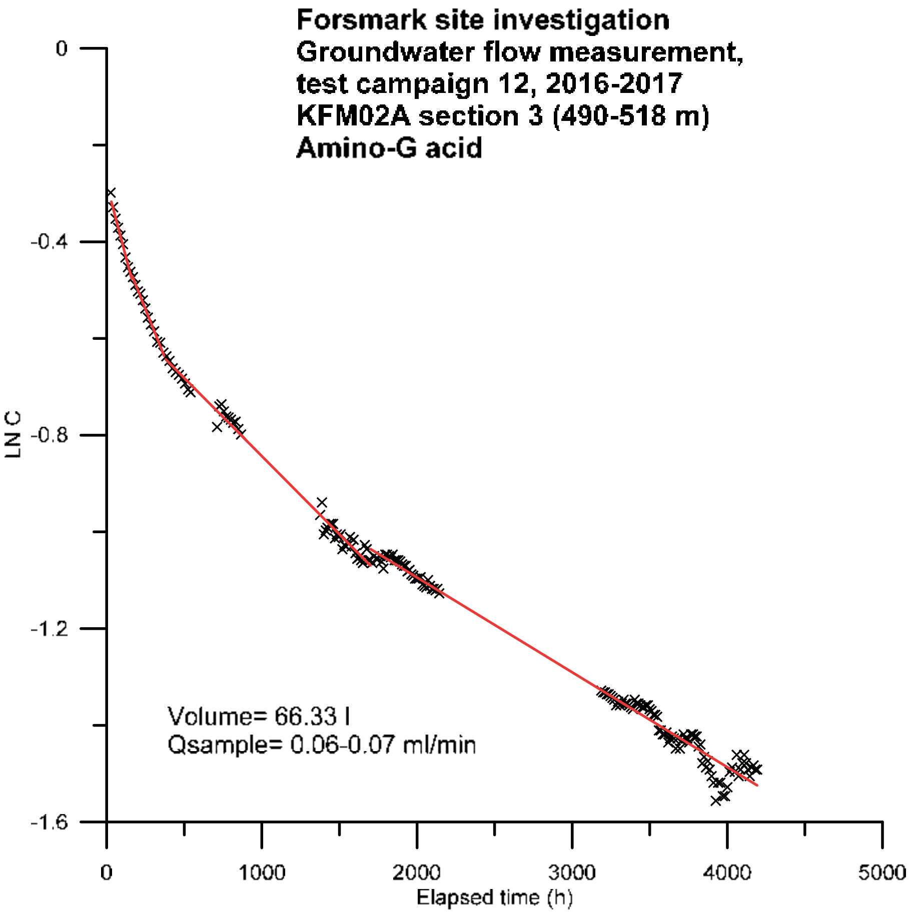
Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM32 section 3 (26-31 m)
Amino-G Acid

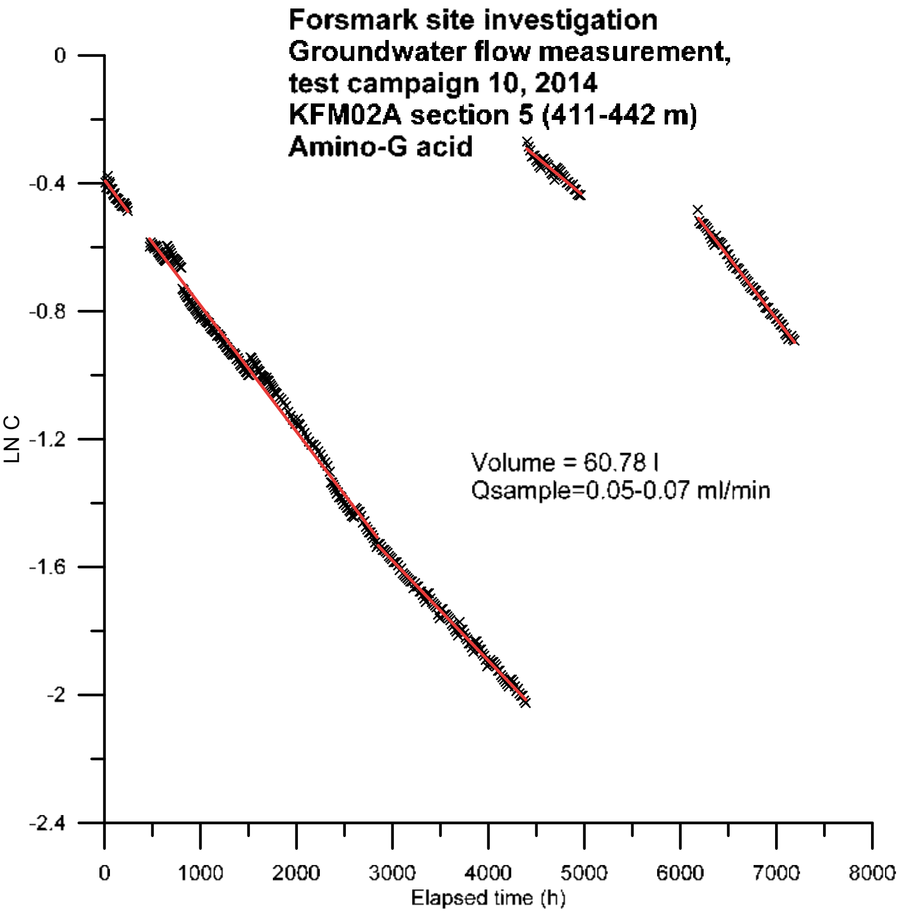
Tracer dilution graphs

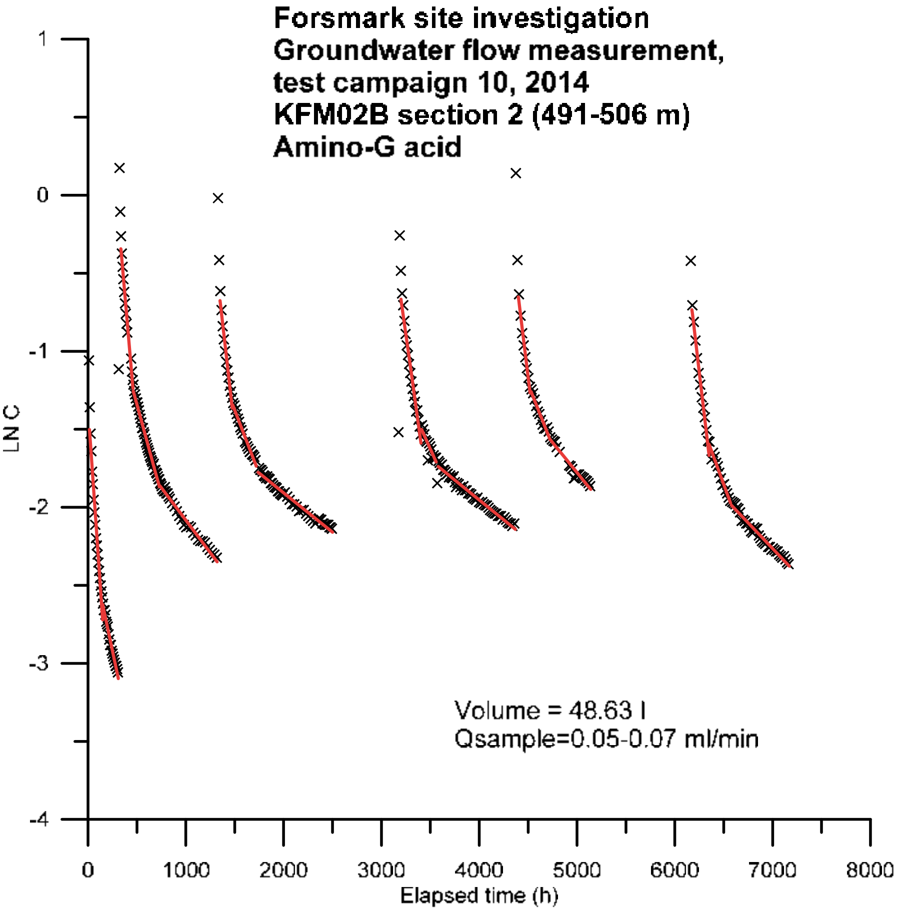


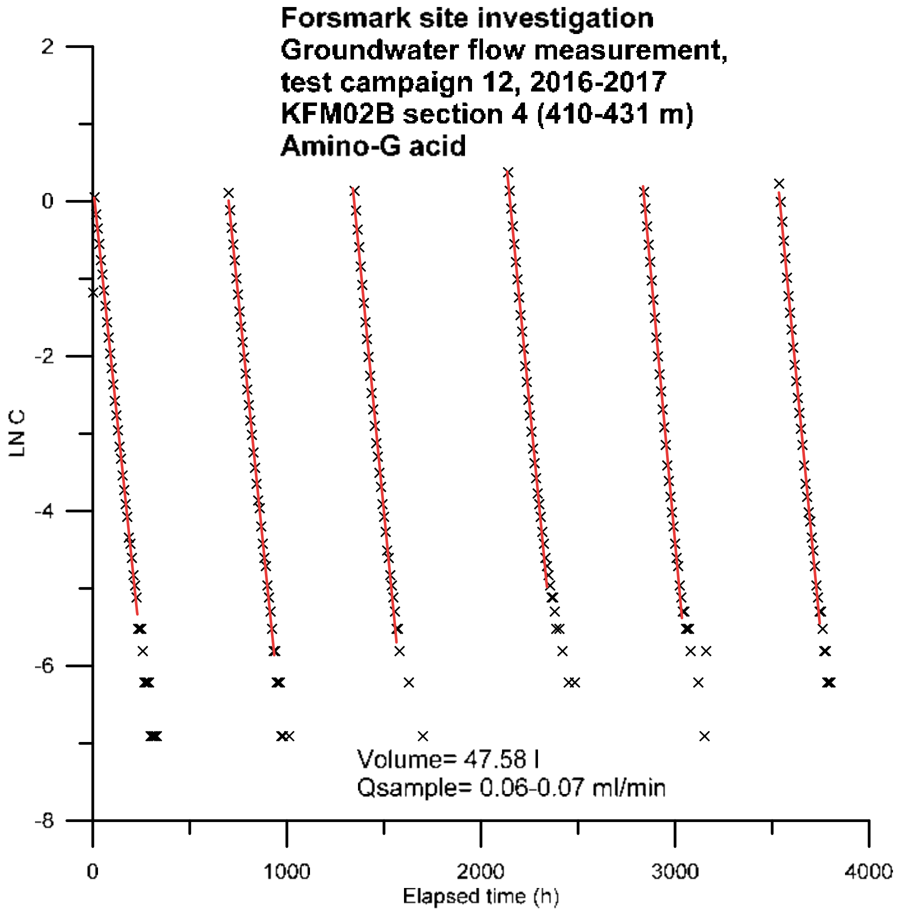


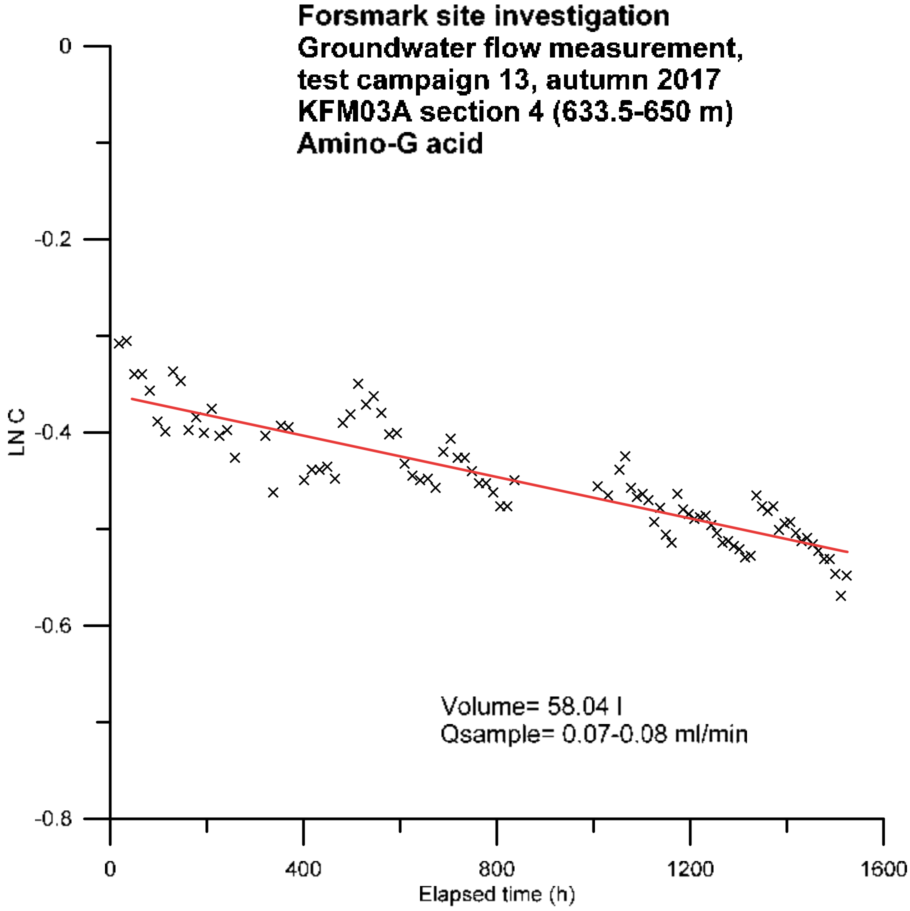

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM01D section 4 (311-321 m)
Amino-G acid
Volume= 31.27 l
Qsample= 0.07 ml/min
LN C
0
-0.4
-0.8
-1.2
-1.6
0
500
1000
1500
2000
2500
Elapsed time (h)

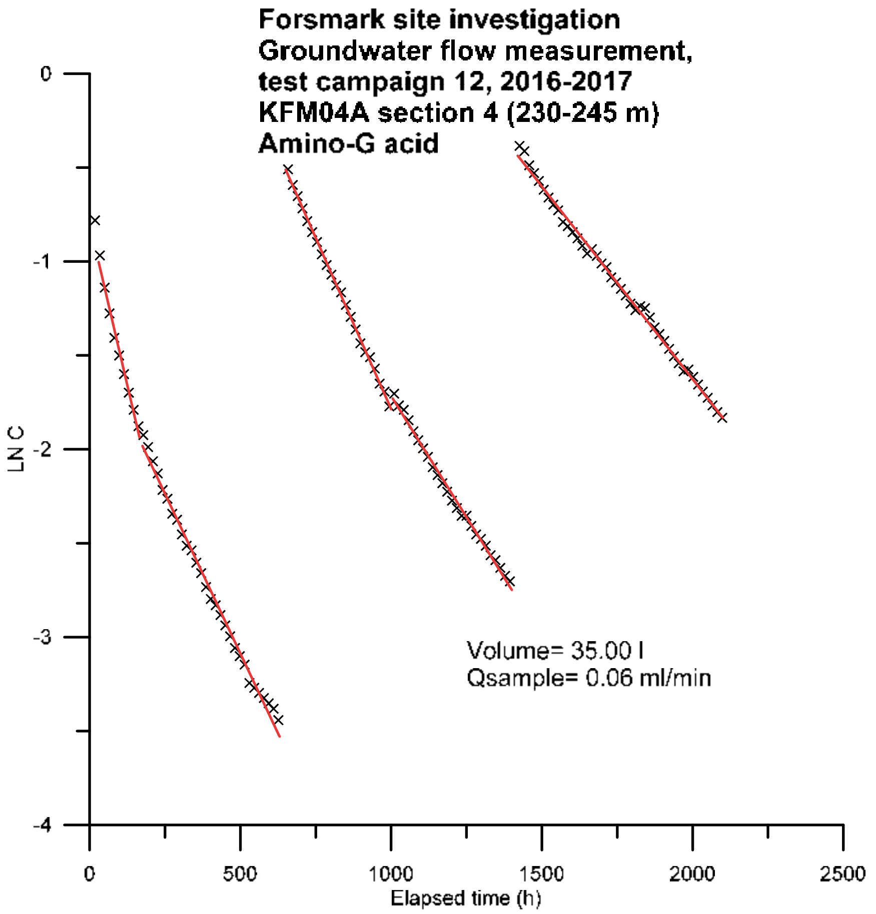

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM02A section 3 (490-518 m)
Amino-G acid
Volume= 66.33 l
Qsample= 0.06-0.07 ml/min
LN C
0
-0.4
-0.8
-1.2
-1.6
0
1000
2000
3000
4000
5000
Elapsed time (h)

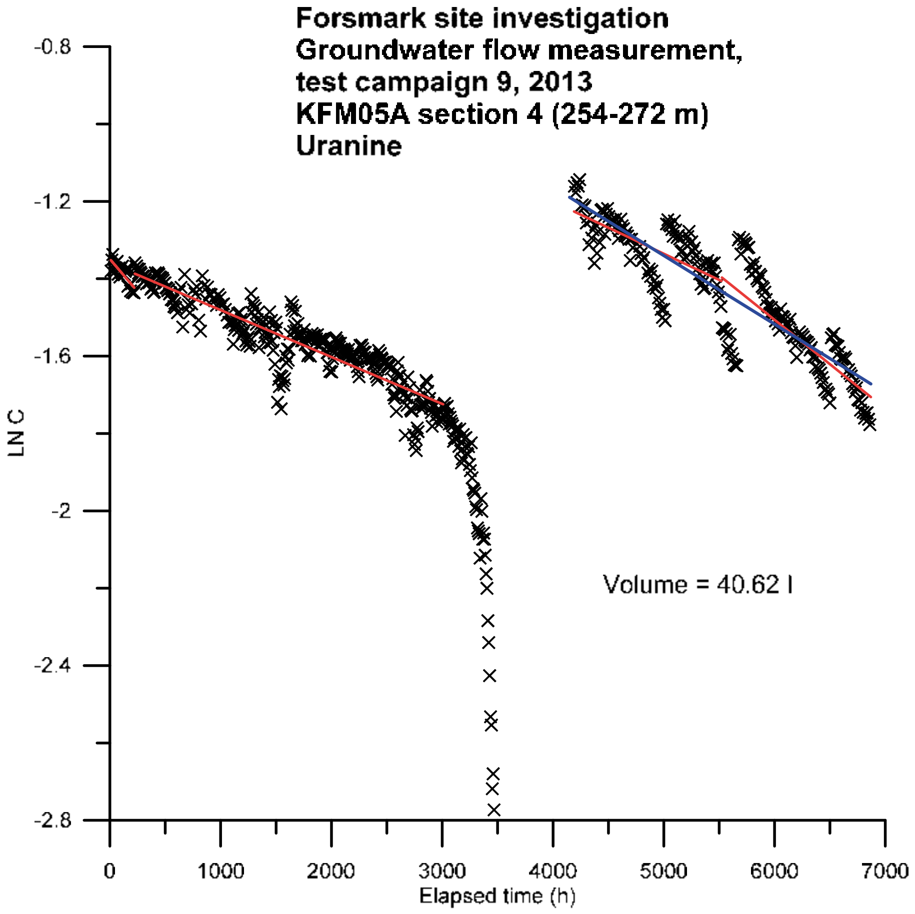

Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014
KFM02A section 5 (411-442 m)
Amino-G acid
Volume = 60.78 l
Qsample=0.05-0.07 ml/min
LN C
0
-0.4
-0.8
-1.2
-1.6
-2
-2.4
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

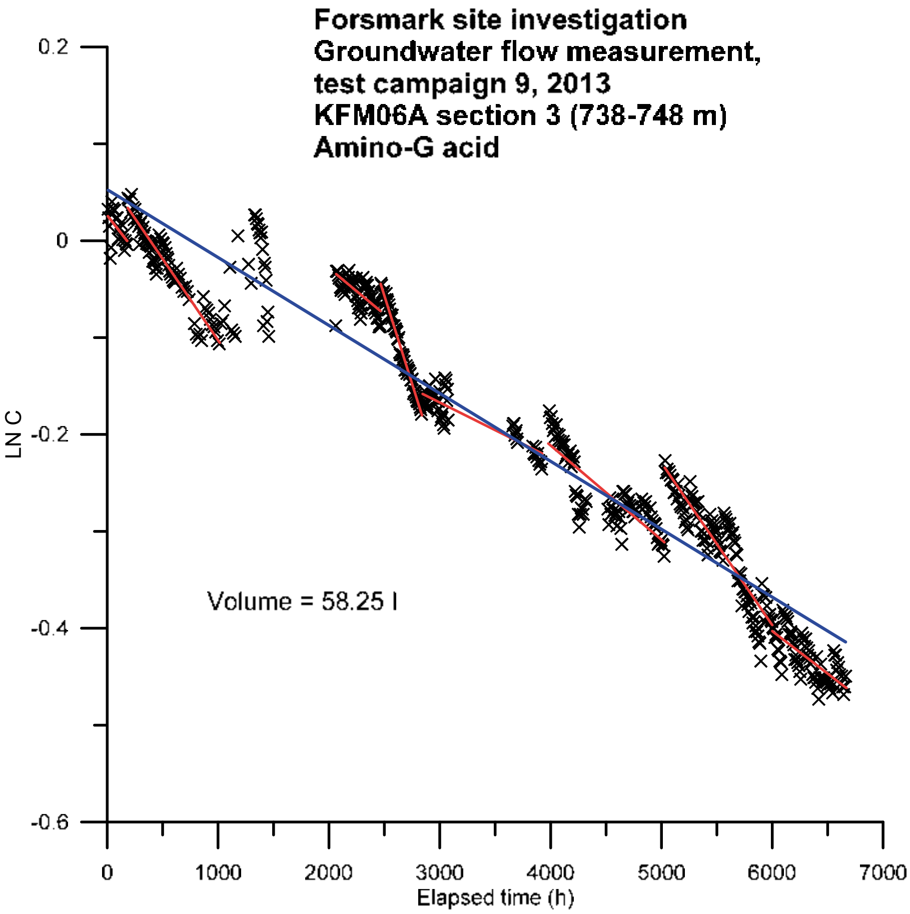

Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014
KFM02B section 2 (491-506 m)
Amino-G acid
Volume = 48.63 l
Qsample=0.05-0.07 ml/min
LN C
1
0
-1
-2
-3
-4
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

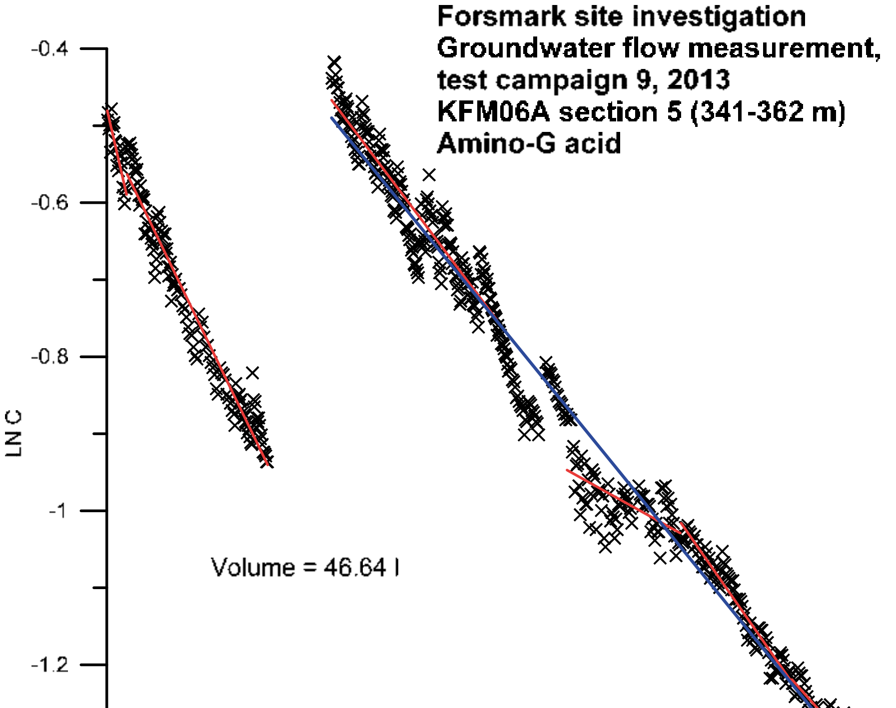

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM02B section 4 (410-431 m)
Amino-G acid
Volume= 47.58 l
Qsample= 0.06-0.07 ml/min
LN C
2
0
-2
-4
-6
-8
0
1000
2000
3000
4000
Elapsed time (h)

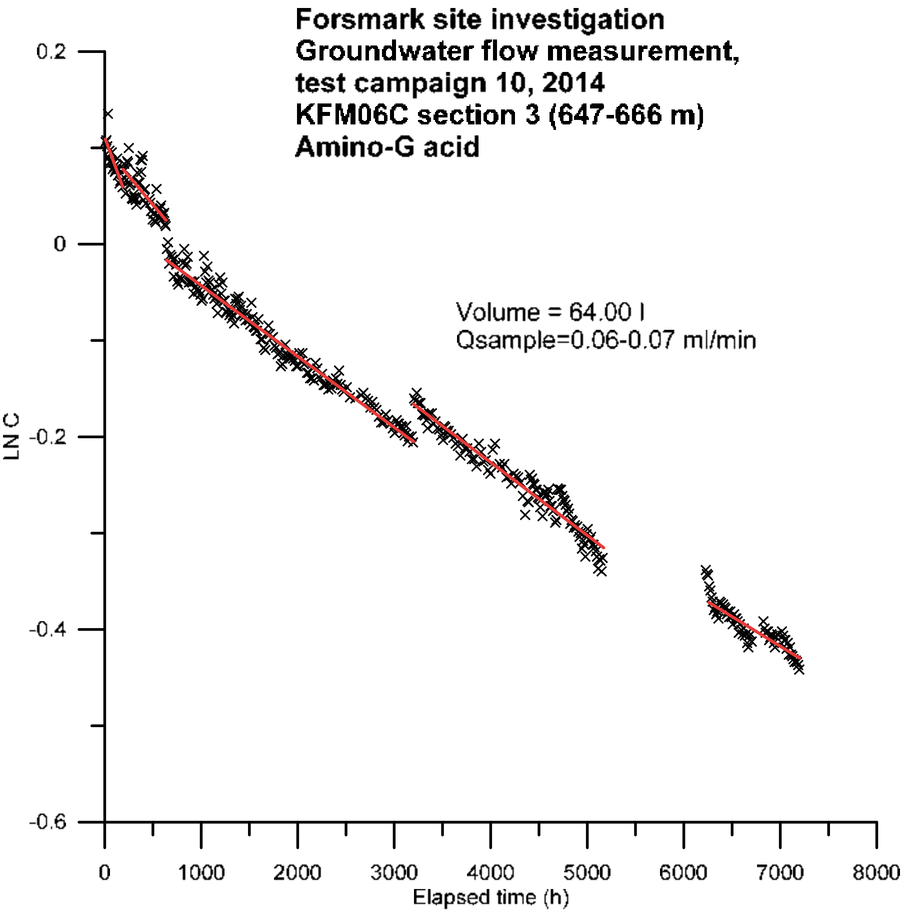

Forsmark site investigation
Groundwater flow measurement,
test campaign 13, autumn 2017
KFM03A section 4 (633.5-650 m)
Amino-G acid
Volume= 58.04 l
Qsample= 0.07-0.08 ml/min
LN C
0
-0.2
-0.4
-0.6
-0.8
0
400
800
1200
1600
Elapsed time (h)

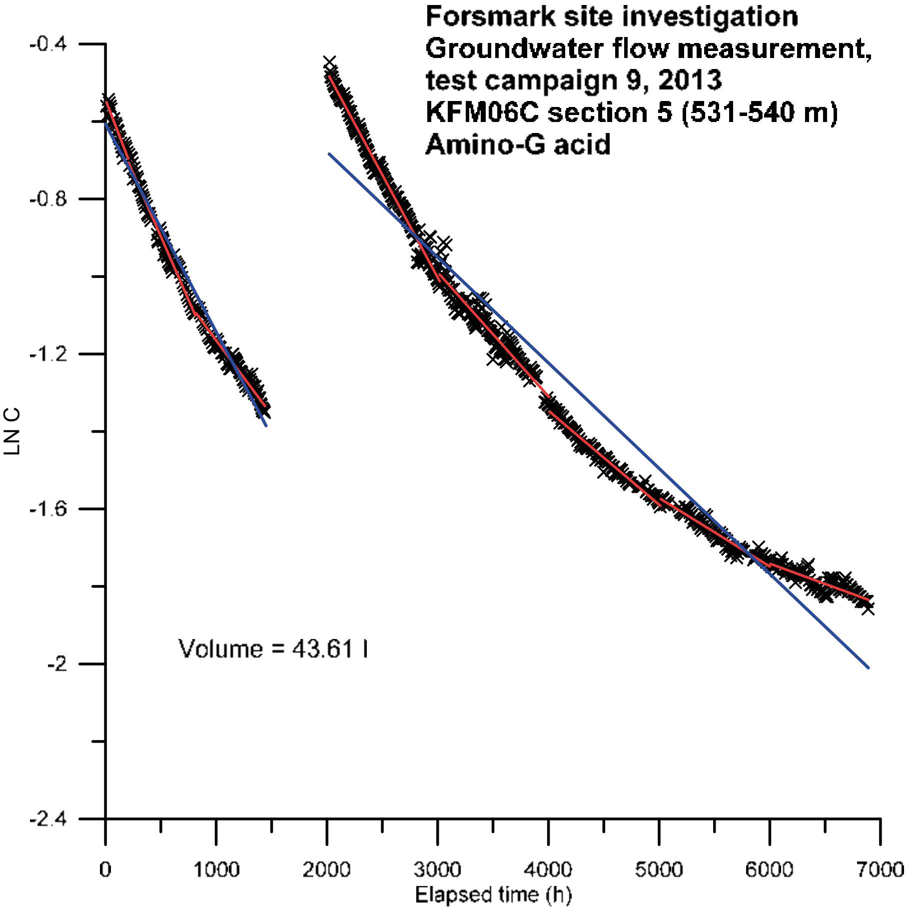

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM04A section 4 (230-245 m)
Amino-G acid
Volume= 35.00 l
Qsample= 0.06 ml/min
LN C
0
-1
-2
-3
-4
0
500
1000
1500
2000
2500
Elapsed time (h)

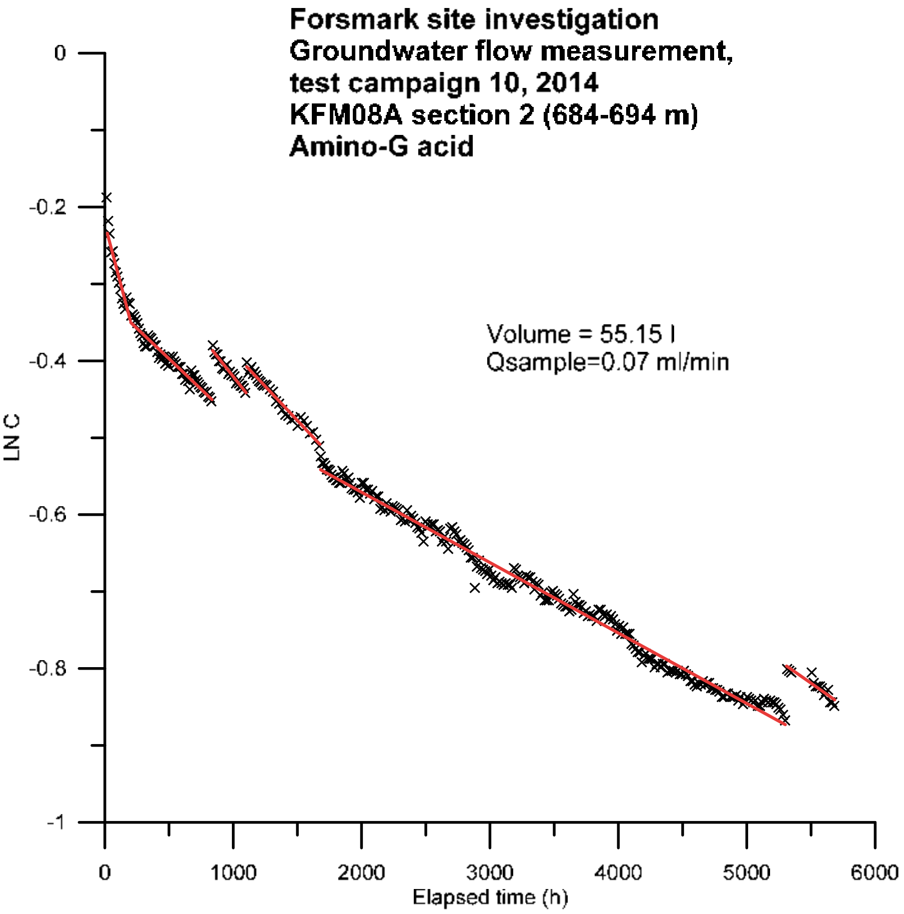

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM05A section 4 (254-272 m)
Uranine
Volume = 40.62 l
LN C
-0.8
-1.2
-1.6
-2
-2.4
-2.8
0
1000
2000
3000
4000
5000
6000
7000
Elapsed time (h)

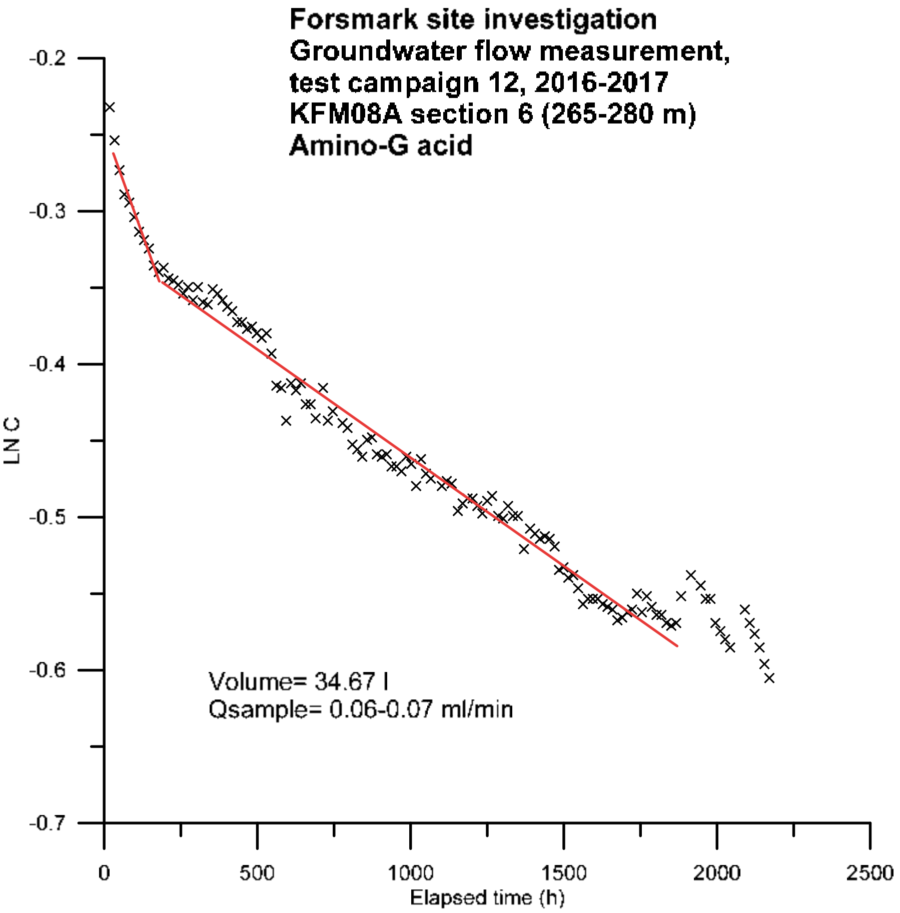

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06A section 3 (738-748 m)
Amino-G acid
Volume = 58.25 l
LN C
0.2
0
-0.2
-0.4
-0.6
0
1000
2000
3000
4000
5000
6000
7000
Elapsed time (h)

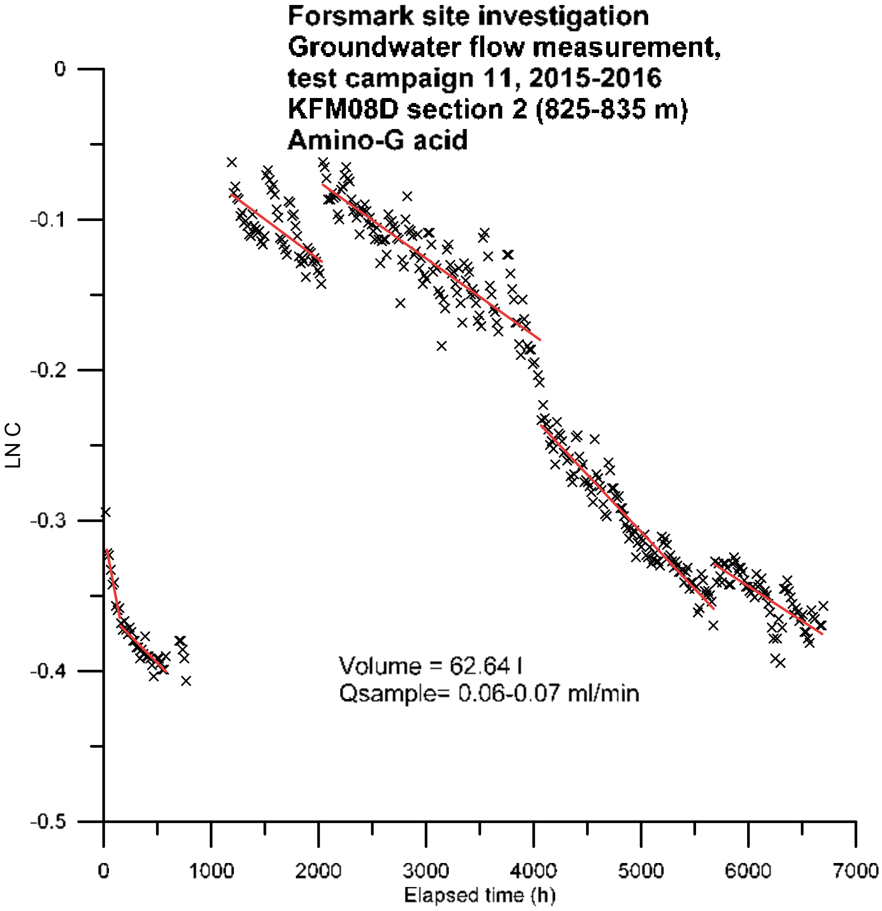

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06A section 5 (341-362 m)
Amino-G acid
Volume = 46.64 l
LN C
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0
1000
2000
3000
4000
5000
6000
7000
Elapsed time (h)

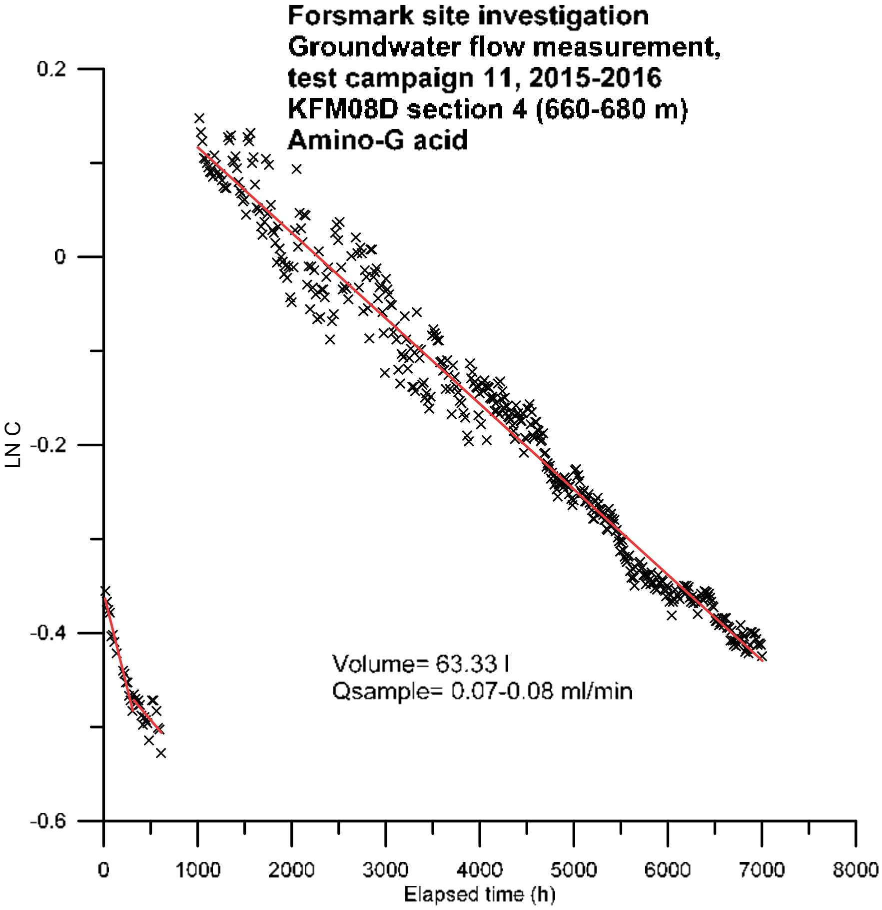

Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014
KFM06C section 3 (647-666 m)
Amino-G acid
Volume = 64.00 l
Qsample=0.06-0.07 ml/min
LN C
0.2
0
-0.2
-0.4
-0.6
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

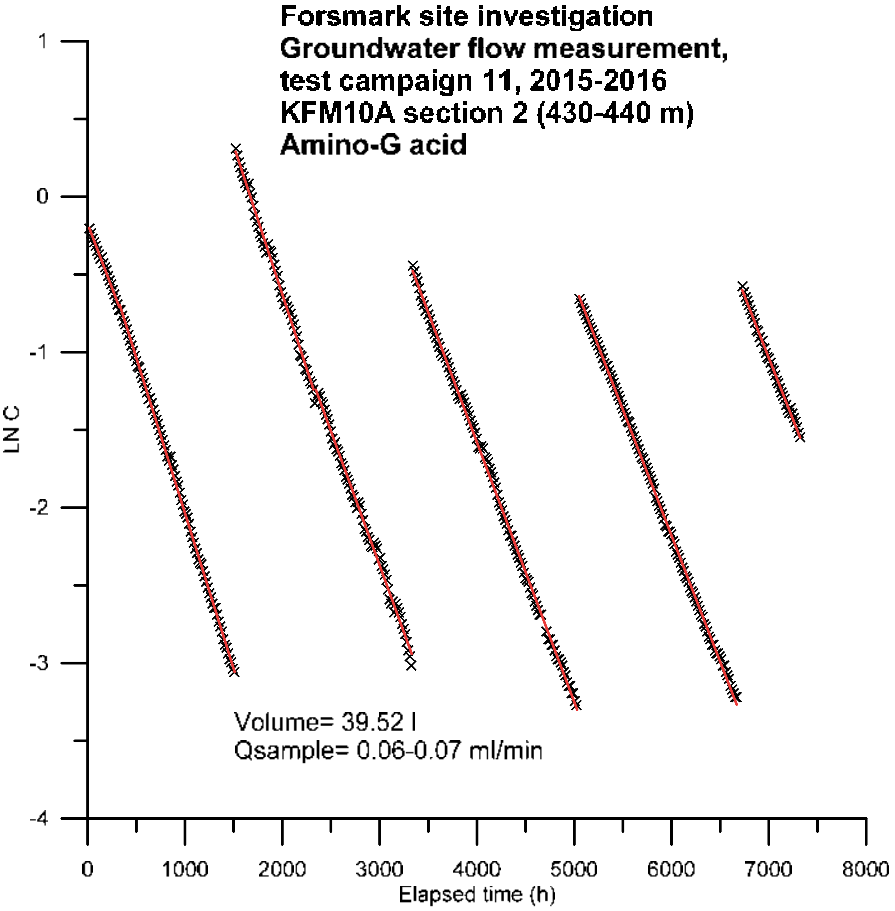

Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
KFM06C section 5 (531-540 m)
Amino-G acid
Volume = 43.61 l
LN C
-0.4
-0.8
-1.2
-1.6
-2
-2.4
0
1000
2000
3000
4000
5000
6000
7000
Elapsed time (h)

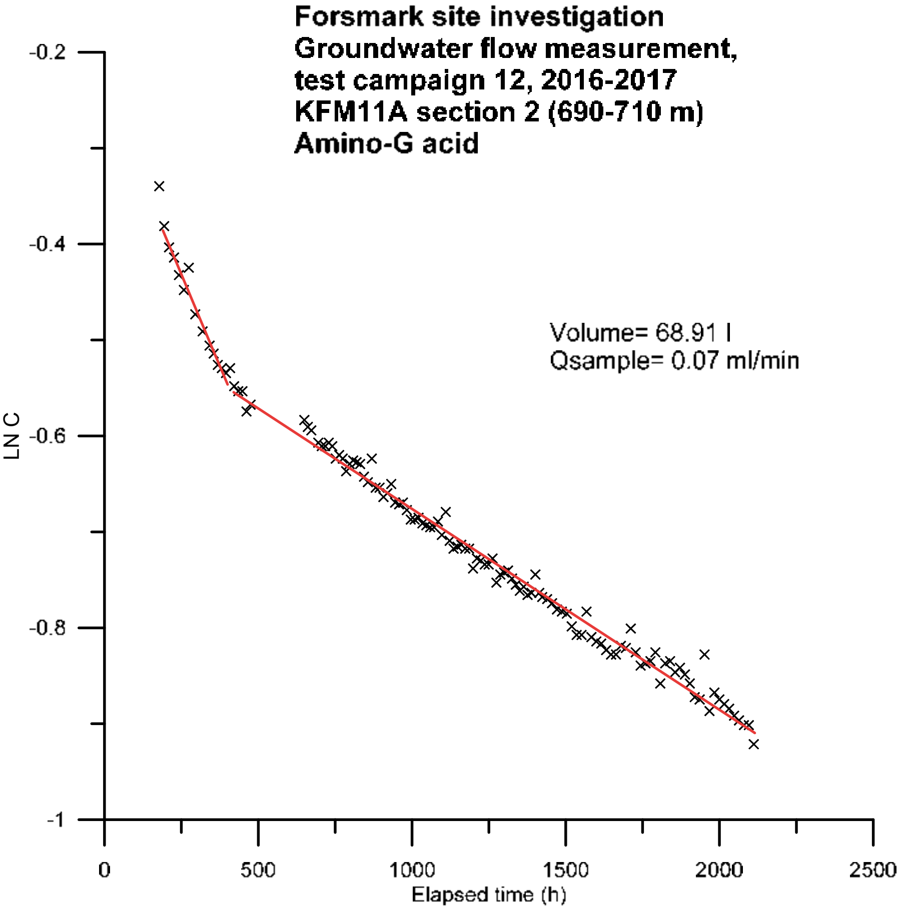

Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014
KFM08A section 2 (684-694 m)
Amino-G acid
Volume = 55.15 l
Qsample=0.07 ml/min
LN C
0
-0.2
-0.4
-0.6
-0.8
-1
0
1000
2000
3000
4000
5000
6000
Elapsed time (h)

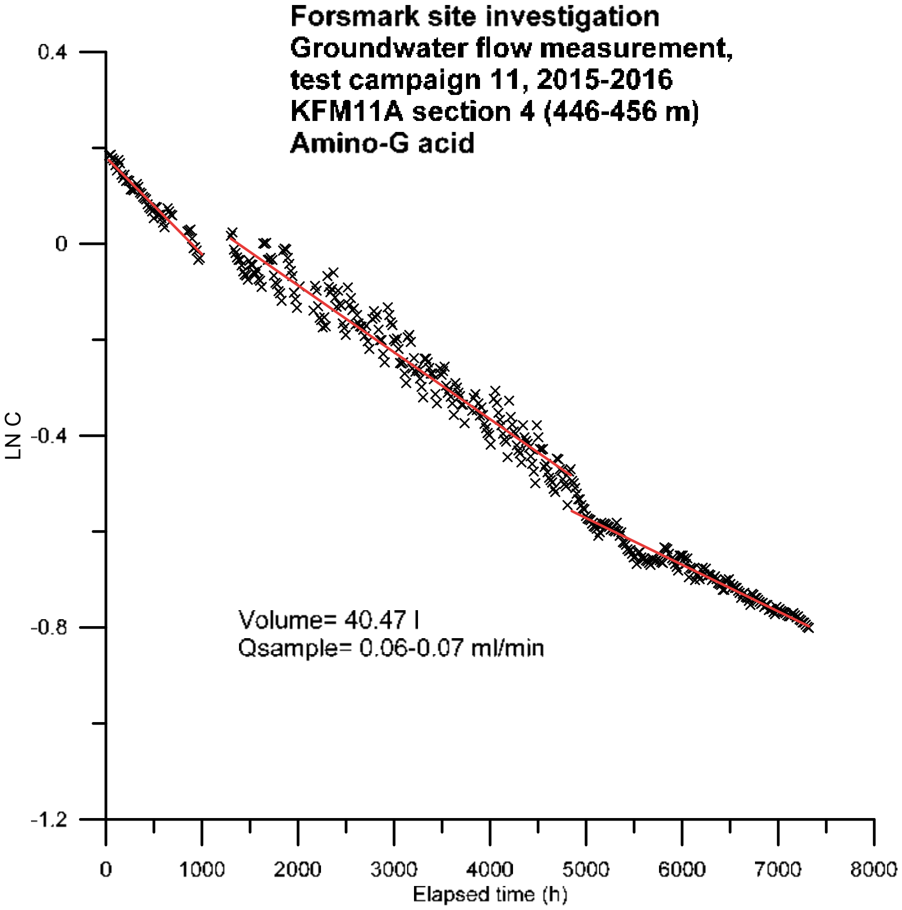

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM08A section 6 (265-280 m)
Amino-G acid
Volume= 34.67 l
Qsample= 0.06-0.07 ml/min
LN C
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
500
1000
1500
2000
2500
Elapsed time (h)

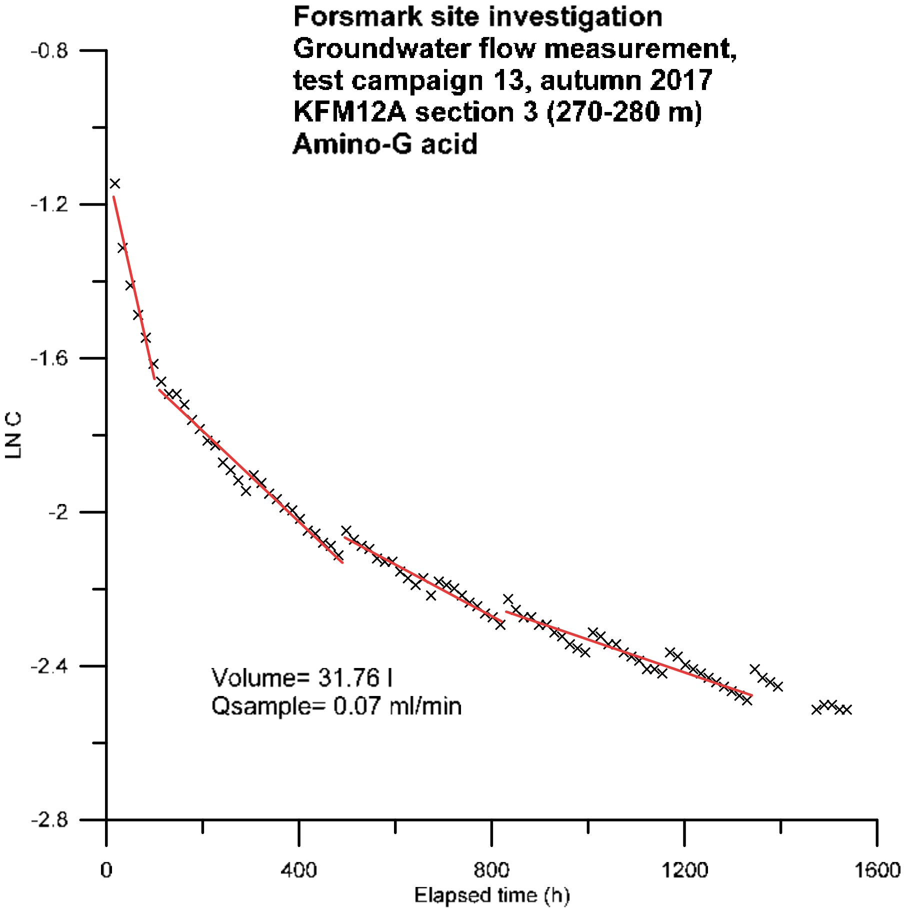

Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM08D section 2 (825-835 m)
Amino-G acid
Volume = 62.64 l
Qsample= 0.06-0.07 ml/min
LN C
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1000
2000
3000
4000
5000
6000
7000
Elapsed time (h)

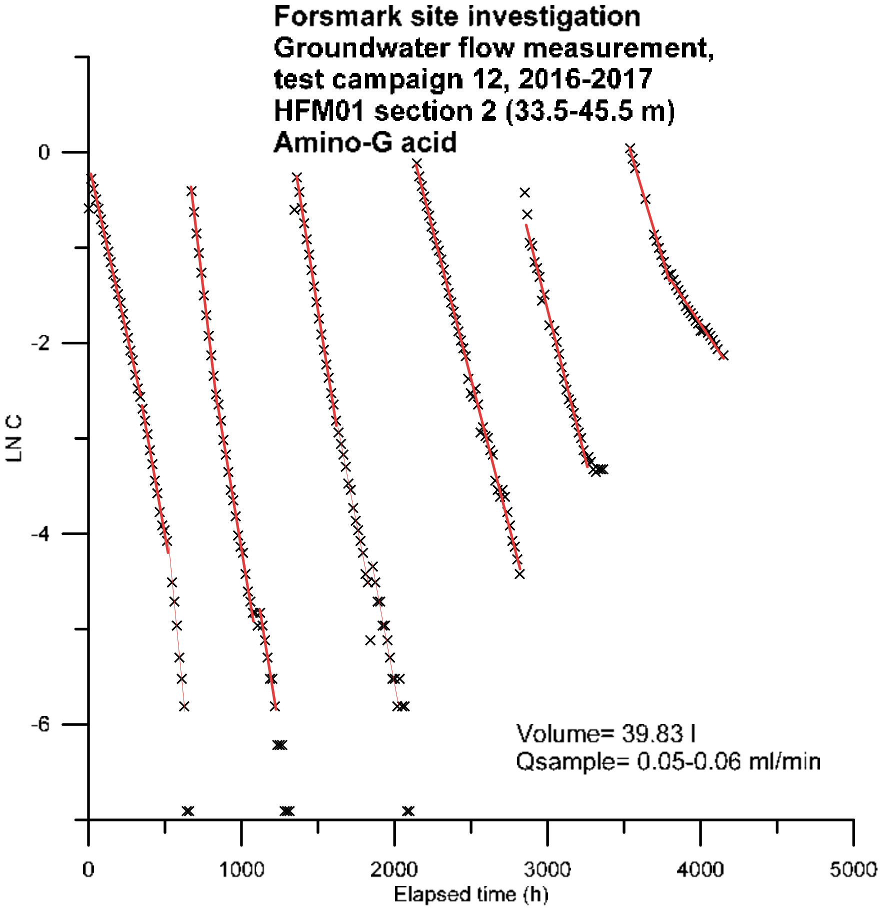

Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM08D section 4 (660-680 m)
Amino-G acid
Volume= 63.33 l
Qsample= 0.07-0.08 ml/min
LN C
0.2
0
-0.2
-0.4
-0.6
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

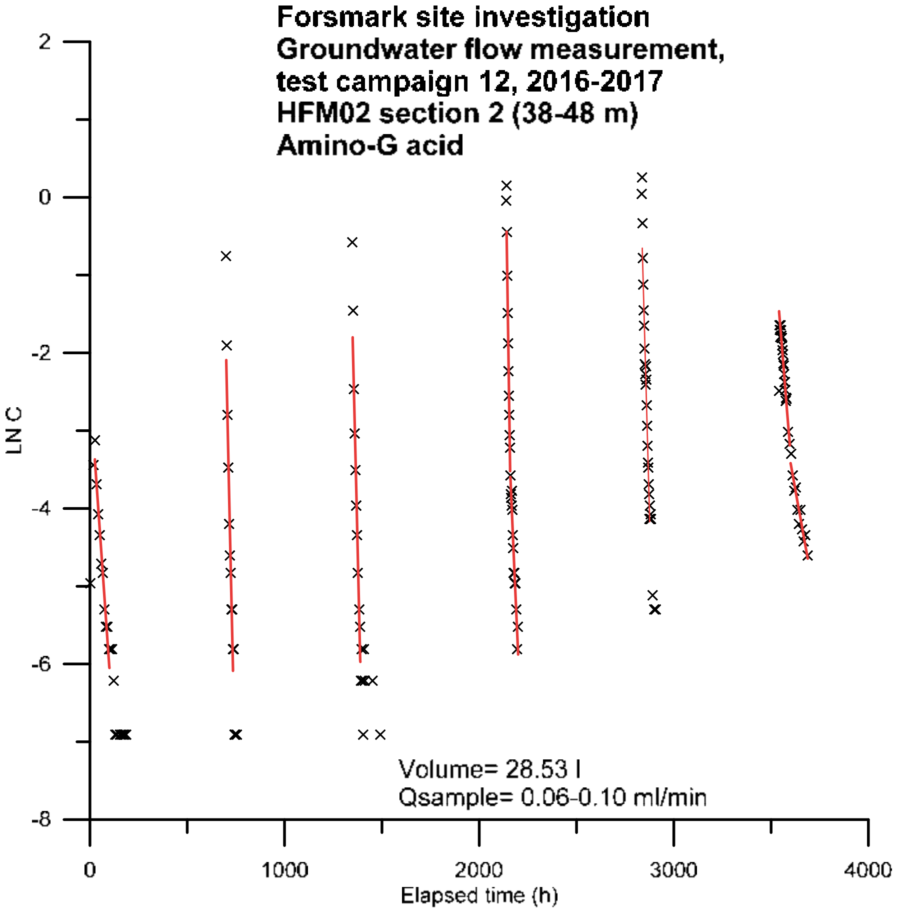

Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM10A section 2 (430-440 m)
Amino-G acid
Volume= 39.52 l
Qsample= 0.06-0.07 ml/min
LN C
1
0
-1
-2
-3
-4
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

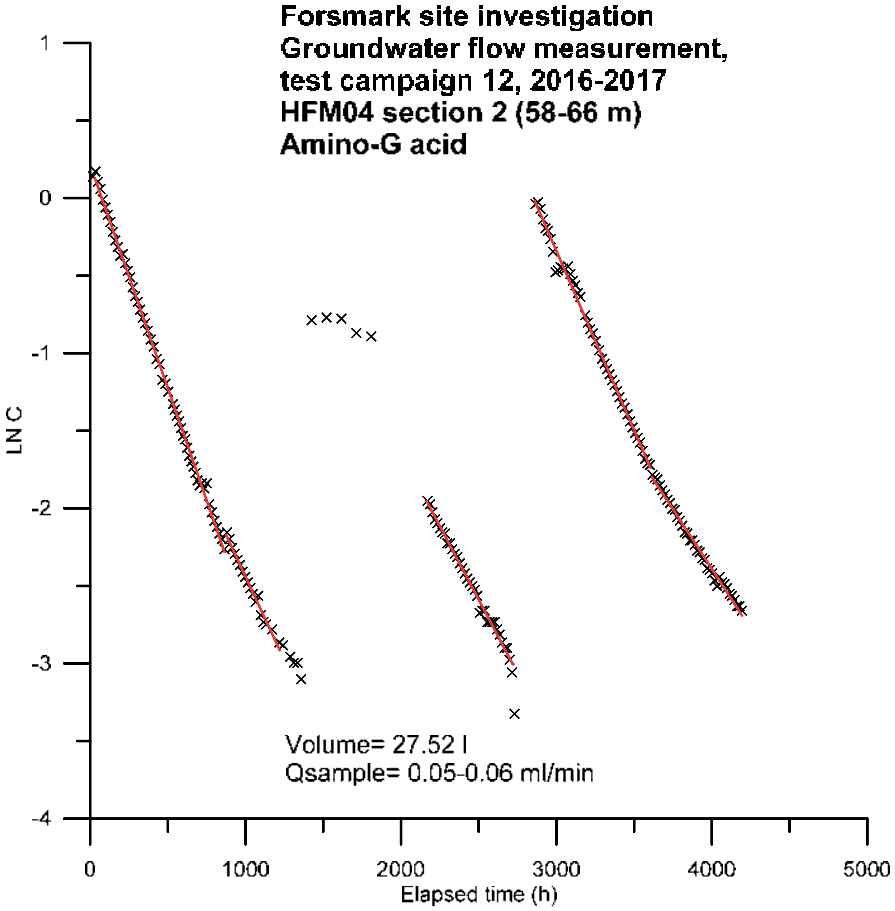

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
KFM11A section 2 (690-710 m)
Amino-G acid
Volume= 68.91 l
Qsample= 0.07 ml/min
LN C
-0.2
-0.4
-0.6
-0.8
-1
0
500
1000
1500
2000
2500
Elapsed time (h)

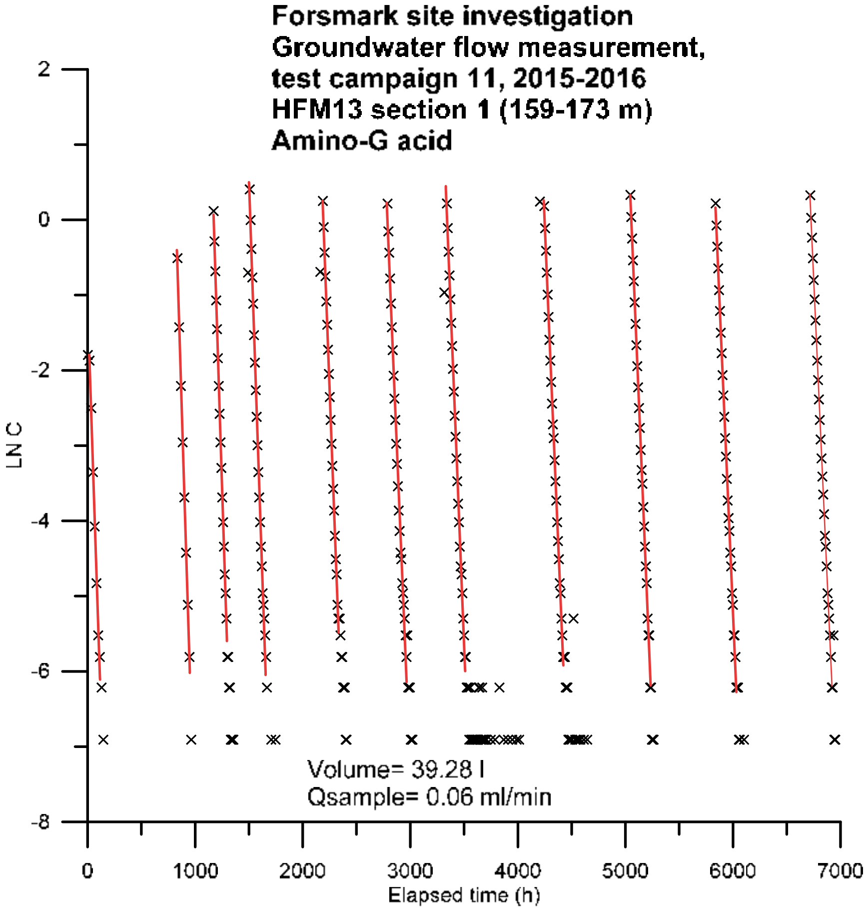

Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
KFM11A section 4 (446-456 m)
Amino-G acid
Volume= 40.47 l
Qsample= 0.06-0.07 ml/min
LN C
0.4
0
-0.4
-0.8
-1.2
0
1000
2000
3000
4000
5000
6000
7000
8000
Elapsed time (h)

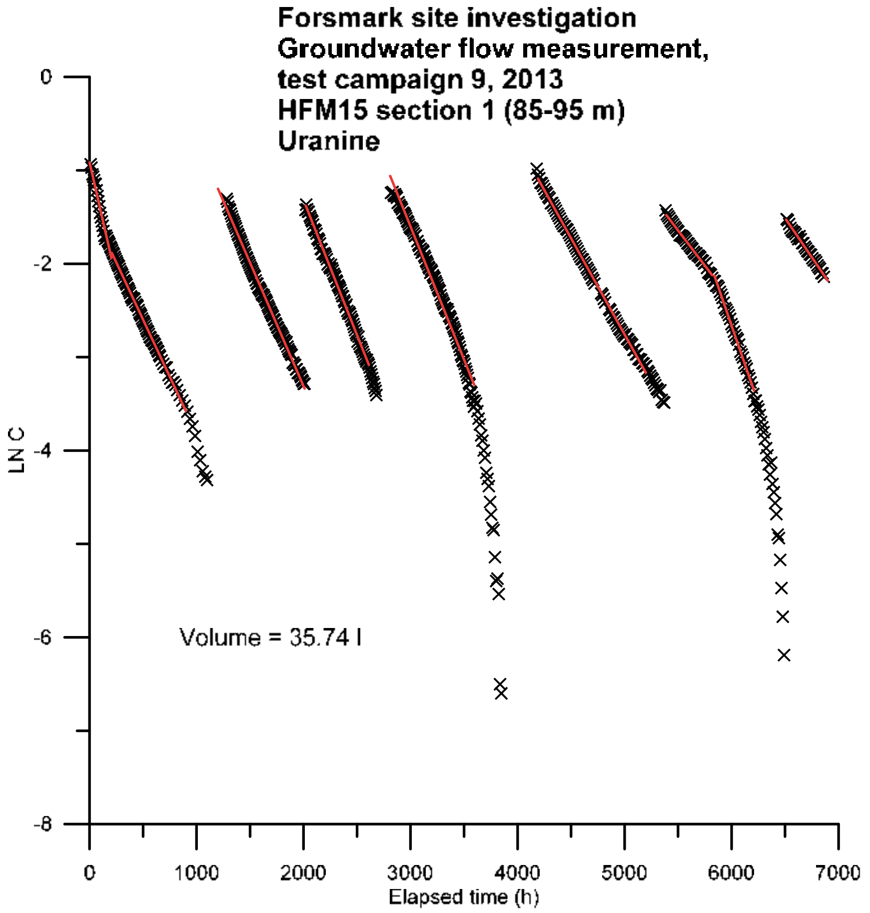

Forsmark site investigation
Groundwater flow measurement,
test campaign 13, autumn 2017
KFM12A section 3 (270-280 m)
Amino-G acid
Volume= 31.76 l
Qsample= 0.07 ml/min
LN C
-0.8
-1.2
-1.6
-2
-2.4
-2.8
0
400
800
1200
1600
Elapsed time (h)

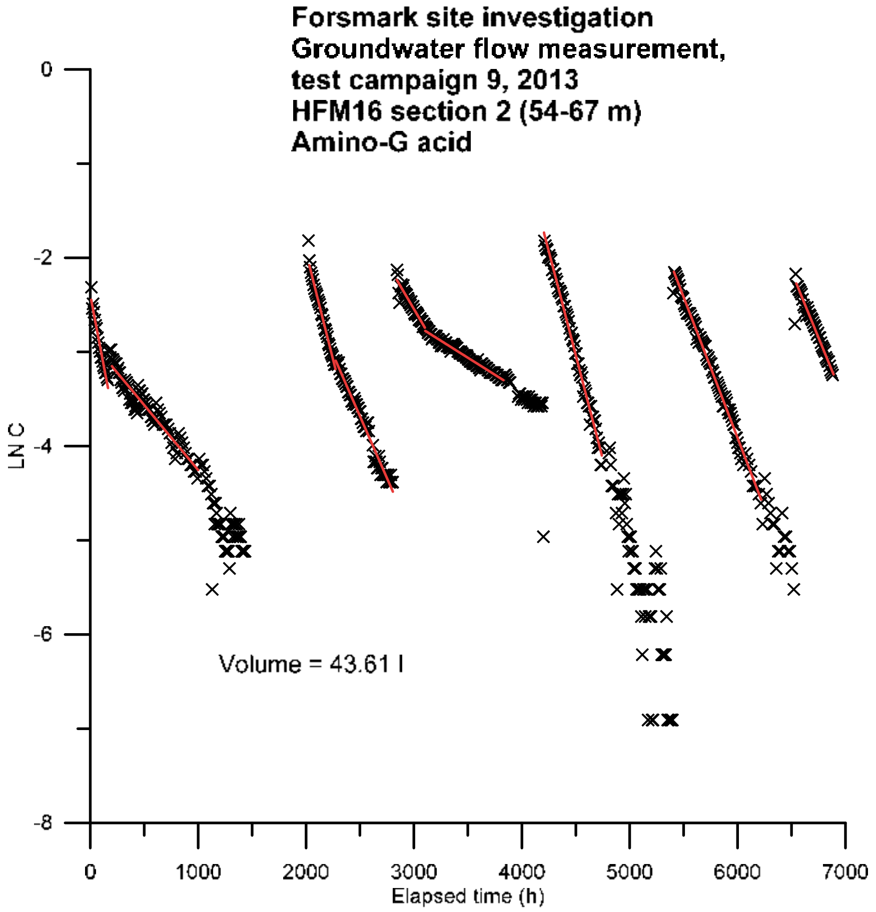

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM01 section 2 (33.5-45.5 m)
Amino-G acid
Volume= 39.83 l
Qsample= 0.05-0.06 ml/min
LN C
0
-2
-4
-6
0
1000
2000
3000
4000
5000
Elapsed time (h)

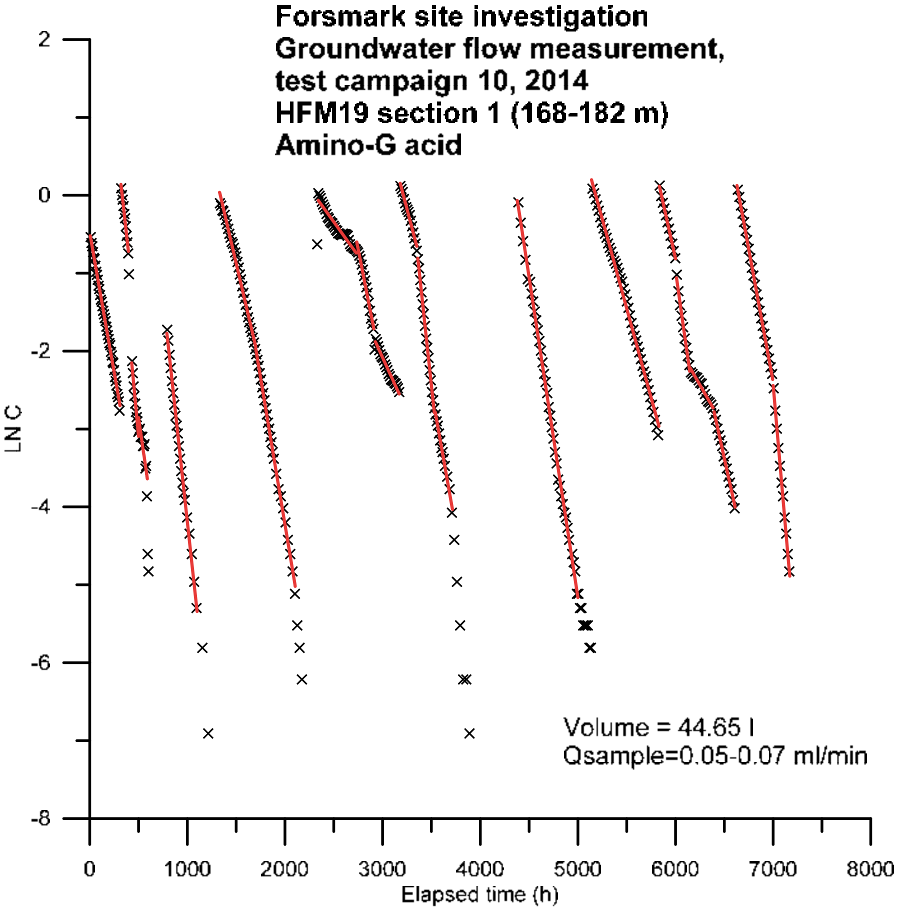

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM02 section 2 (38-48 m)
Amino-G acid
Volume= 28.53 l
Qsample= 0.06-0.10 ml/min
LN C
2
0
-2
-4
-6
-8
0
1000
2000
3000
4000
Elapsed time (h)

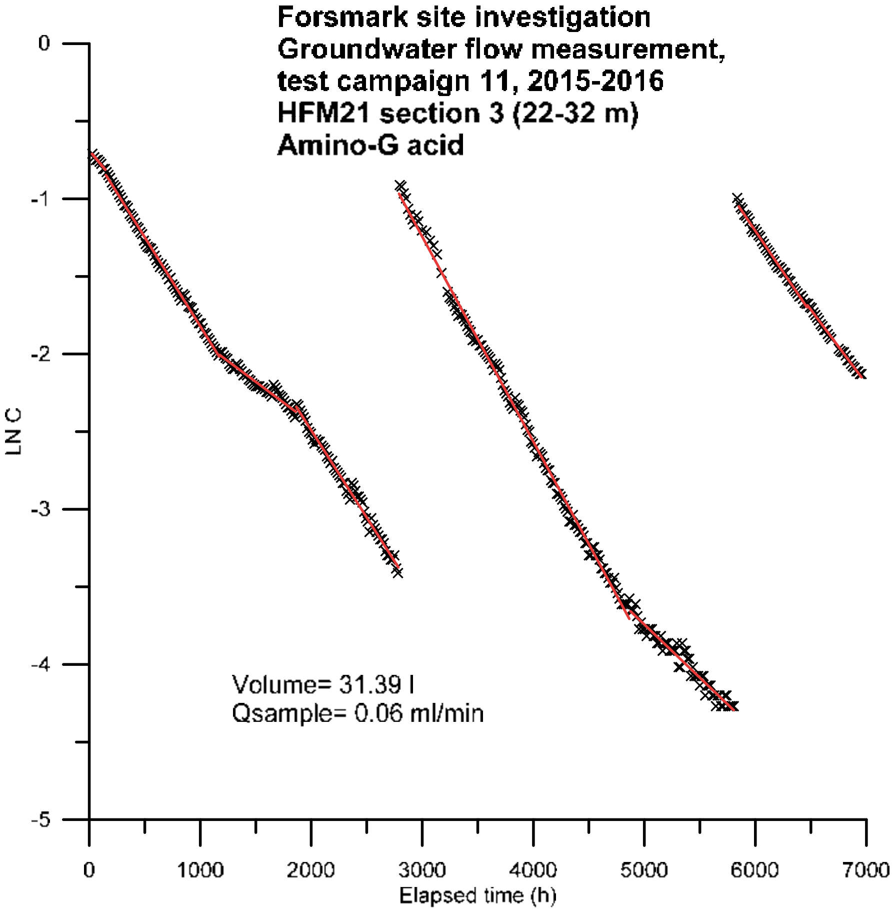

Forsmark site investigation
Groundwater flow measurement,
test campaign 12, 2016-2017
HFM04 section 2 (58-66 m)
Amino-G acid
Volume= 27.52 l
Qsample= 0.05-0.06 ml/min
LN C
Elapsed time (h)
1
0
-1
-2
-3
-4
0
1000
2000
3000
4000
5000


Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
HFM13 section 1 (159-173 m)
Amino-G acid
Volume= 39.28 l
Qsample= 0.06 ml/min
LN C
Elapsed time (h)
2
0
-2
-4
-6
-8
0
1000
2000
3000
4000
5000
6000
7000


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
HFM15 section 1 (85-95 m)
Uranine
Volume = 35.74 l
LN C
0
-2
-4
-6
-8
Elapsed time (h)
0
1000
2000
3000
4000
5000
6000
7000


Forsmark site investigation
Groundwater flow measurement,
test campaign 9, 2013
HFM16 section 2 (54-67 m)
Amino-G acid
Volume = 43.61 l
LN C
0
-2
-4
-6
-8
Elapsed time (h)
0
1000
2000
3000
4000
5000
6000
7000


Forsmark site investigation
Groundwater flow measurement,
test campaign 10, 2014
HFM19 section 1 (168-182 m)
Amino-G acid
Volume = 44.65 l
Qsample=0.05-0.07 ml/min
LN C
Elapsed time (h)
2
0
-2
-4
-6
-8
0
1000
2000
3000
4000
5000
6000
7000
8000


Forsmark site investigation
Groundwater flow measurement,
test campaign 11, 2015-2016
HFM21 section 3 (22-32 m)
Amino-G acid
Volume= 31.39 l
Qsample= 0.06 ml/min
LN C
Elapsed time (h)
0
-1
-2
-3
-4
-5
0
1000
2000
3000
4000
5000
6000
7000

Appendix 4

Hydraulic gradients, 2013–2017

2013

Table A4-1. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2013. Gradients calculated from borehole section HFM15:1 (−61 m.a.s.l.) to sections given in the table.

Borehole:sec	2013-03-31	2013-04-26	2013-07-01	2013-09-01	2013-11-01	2013-12-15
HFM19:1	0.003	0.003	0.003	0.003	0.003	0.003
KFM02A:5	0.0005	0.0006	0.0005	0.0004	0.0005	0.0006
HFM01:2	0.0002	0.0003	0.0002	0.0002	0.0003	0.0003
KFM02B:4	0.0006	0.0007	0.0006	0.0005	0.0006	0.0005
KFM10A:2	0.0013	0.0014	0.0013	0.0013	0.0015	0.0015

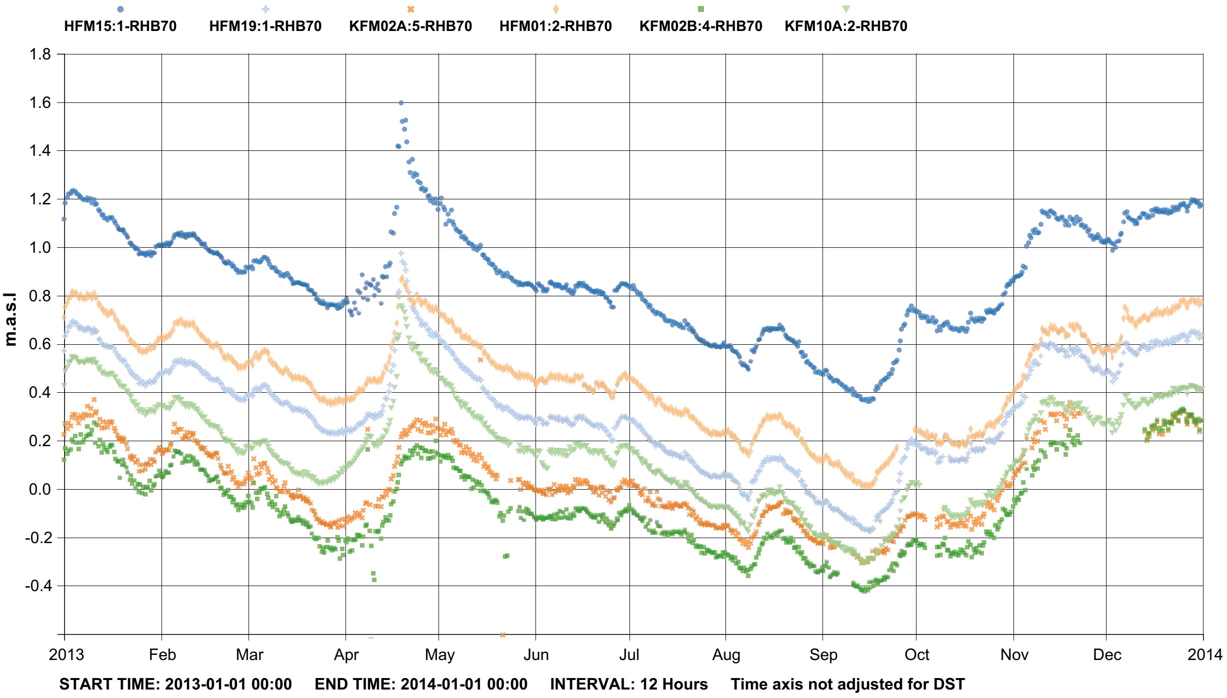


Figure A4-1. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2013, 2013-01-01–2014-01-01. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green)−407 m, KFM10A:2 (pale green) −300 m.*

Table A4-2. Hydraulic gradients in fracture zone ZFMA8 during test campaign 2013. Gradients calculated from borehole section HFM16:2 (−57 m.a.s.l.) to sections given in the table.

Borehole:sec	2013-03-31	2013-04-26	2013-07-01	2013-09-01	2013-11-01	2013-12-15
HFM16:3	0.00008	0.0002	0.0004	0.0003	0.0002	0.0001
KFM06B:1	−0.00006	0.0002	−0.0007	−0.0012	−0.0012	−0.0013

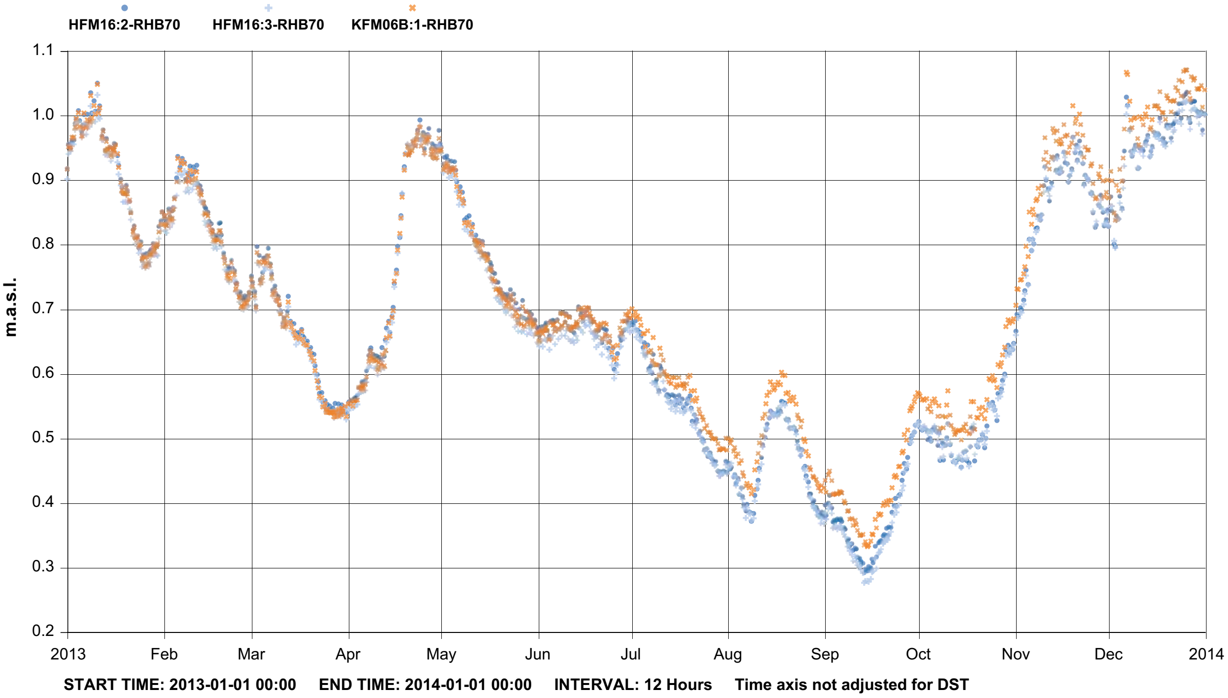


Figure A4-2. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA8. Test campaign 2013, 2013-01-01 – 2014-01-01. Test section elevation (m.a.s.l.) is given after colour code; HFM16:2 (blue) −57 m, HFM16:3 (pale blue) −23 m, KFM06B:1 (orange) −71 m.*

Table A4-3. Hydraulic gradients in fracture zone ZFMB7, ZFMENE0060A during test campaign 2013. Gradients calculated from borehole section KFM06A:5 (−298 m.a.s.l.) to sections given in the table.

Borehole:sec	2013-03-31	2013-04-26	2013-07-01	2013-09-15	2013-11-15	2013-12-15
KFM06A:6	0.005	0.002	0.003	0.005	0.0005	0.001
KFM06C:7	0.002	0.001	0.002	0.002	0.001	0.001
HFM09:1	−0.002	−0.002	−0.001	−0.001	−0.001	−0.001
KFM01C:1	−0.0003	−0.00006	−0.0001	−0.0002	0.001	0.0008

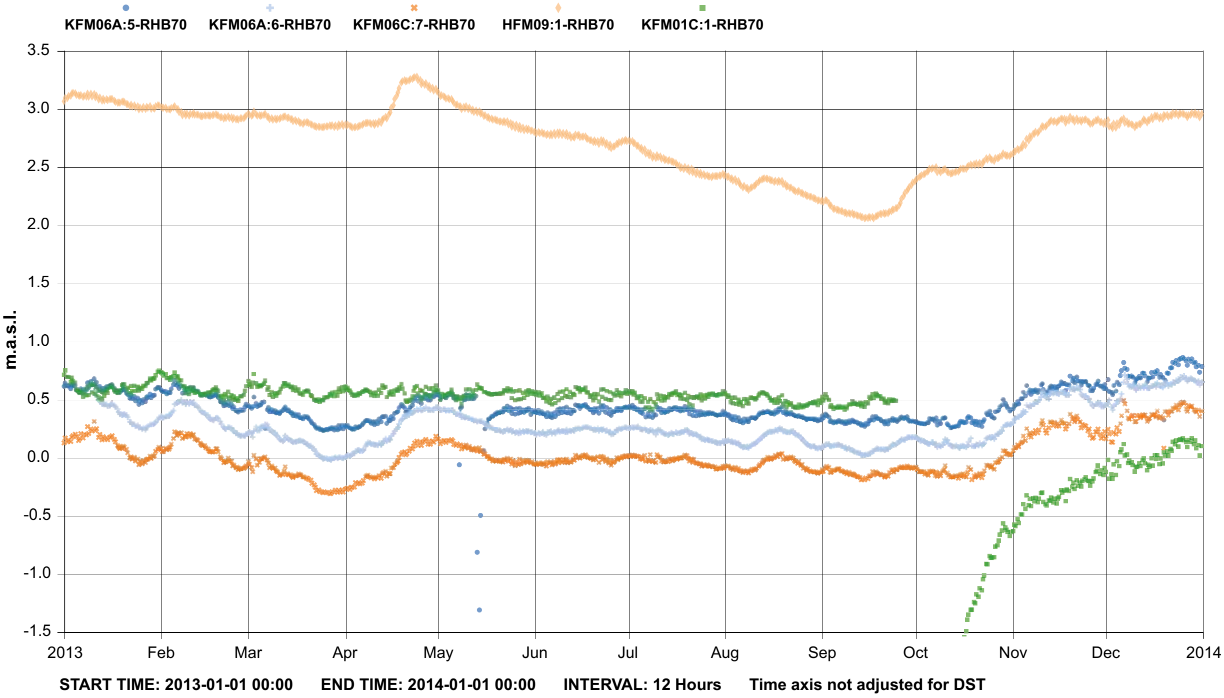


Figure A4-3. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMB7 and ZFMENE0060A. Test campaign 2013, 2013-01-01 – 2014-01-01. Test section elevation (m.a.s.l.) is given after colour code; KFM06A:5 (blue) −298 m, KFM06A:6 (pale blue) −249 m, KFM06C:7 (orange) −310 m, HFM09:1 (pale orange) −18 m, KFM01C:1 (green)−256 m.*

2014–2015

Table A4-4. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2014–2015. Gradients calculated from borehole section HFM19:1 (−137 m.a.s.l.) to sections given in the table.

Borehole:sec	2014-09-19	2014-10-15	2014-12-01	2015-01-15	2015-03-15	2015-06-15
HFM15:1	−0.003	−0.003	−0.002	−0.002	−0.003	−0.003
KFM02A:5	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002
HFM01:2	−0.0006	−0.0002	−0.0003	−0.0005	−0.0004	−0.0005
KFM02B:4	0.0002	0.0003	0.0003	0.0002	–	0.0002
KFM10A:2	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005

Table A4-5. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2014-2015. Gradients calculated from borehole section KFM02A:5 (-418 m.a.s.l.) to sections given in the table.

Borehole:sec	2014-09-19	2014-10-15	2014-12-01	2015-01-15	2015-03-15	2015-06-15
HFM15:1	−0.0005	−0.0006	−0.0005	−0.0005	−0.0006	−0.0005
HFM19:1	−0.0002	−0.0003	−0.0002	−0.0002	−0.0002	−0.0002
HFM01:2	−0.0002	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
KFM02B:4	0.001	0.0006	0.001	0.00006	–	0.0003
KFM10A:2	−0.00004	−0.0002	−0.0001	−0.00003	−0.0001	−0.00006

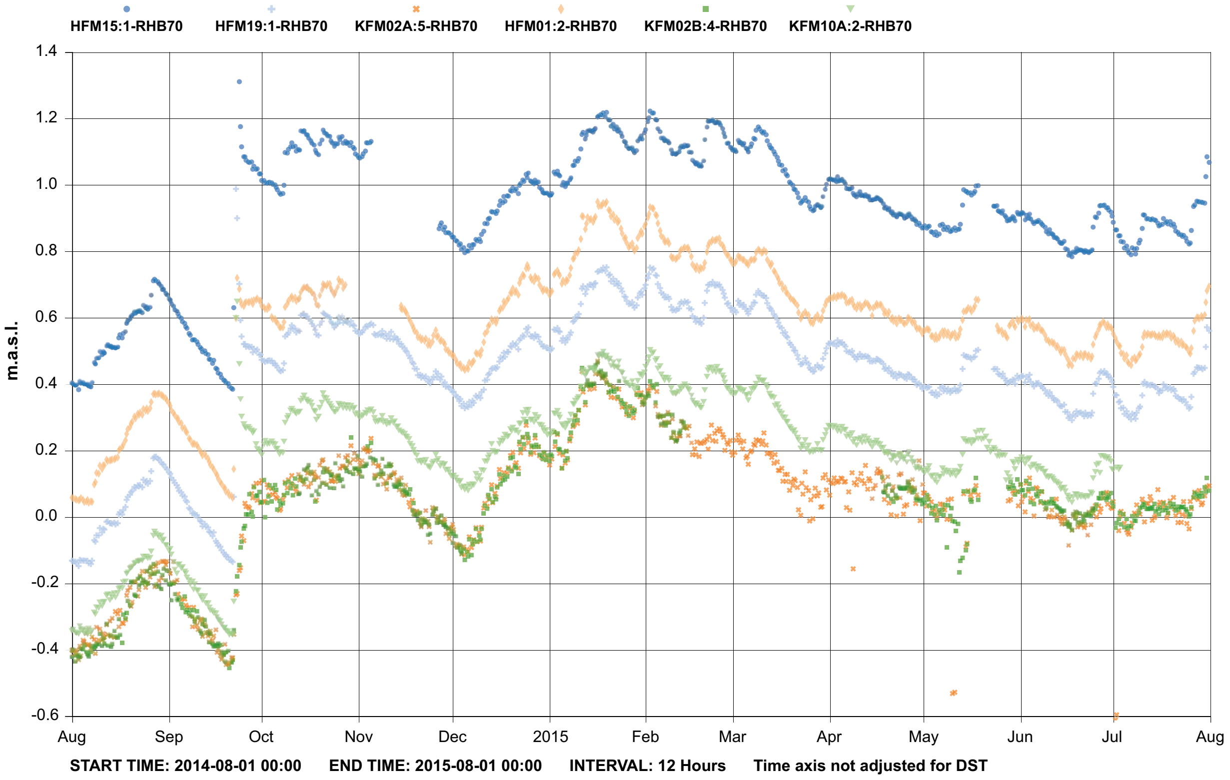


Figure A4-4. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2014-2015, 2014-08-01 – 2015-08-01. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green)−407 m, KFM10A:2 (pale green) −300 m.*

Table A4-6. Hydraulic gradients in fracture zone ZFM1203 during test campaign 2014–2015. Gradients calculated from borehole section HFM27:2 (−46 m.a.s.l.) to sections given in the table.

Borehole:sec	2014-09-19	2014-10-15	2014-12-01	2015-01-15	2015-03-15	2015-06-15
HFM02:2	−0.003	−0.003	−0.002	−0.002	−0.002	−0.002
HFM21:2	−0.00002	–	0.0002	0.00007	0.0003	0.0002
HFM27:1	0.0007	0.001	0.001	0.002	0.002	0.002

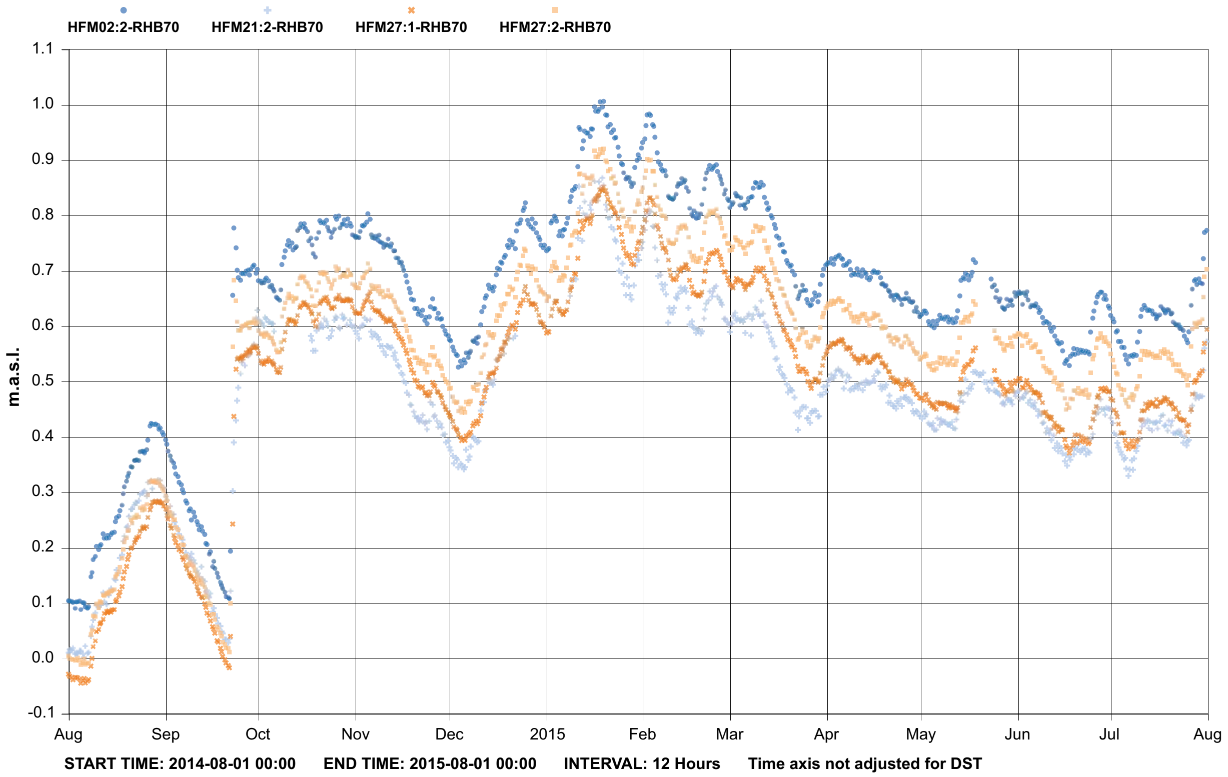


Figure A4-5. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFM1203. Test campaign 2014–2015, 2014-08-01 – 2015-08-01. Test section elevation (m.a.s.l.) is given after colour code; HFM02:2 (blue) −40 m, HFM21:2 (pale blue) −54 m, HFM27:1 (orange) −83 m, HFM27:2 (pale orange) −46 m.*

Table A4-7. Hydraulic gradients in fracture zone ZFMF1 during test campaign 2014–2015. Gradients calculated from borehole section KFM02B:2 (−484 m.a.s.l.) to sections given in the table.

Borehole:sec	2014-09-19	2014-10-15	2014-12-01	2015-01-15	2015-03-15	2015-06-15
KFM02B:1	−0.006	0.002	−0.001	0.001	0.0008	−0.006
KFM02B:3	−0.004	−0.003	−0.004	−0.004	−0.004	−0.004
KFM02A:3	0.000004	0.001	0.00003	−0.0001	−0.0003	−0.0008

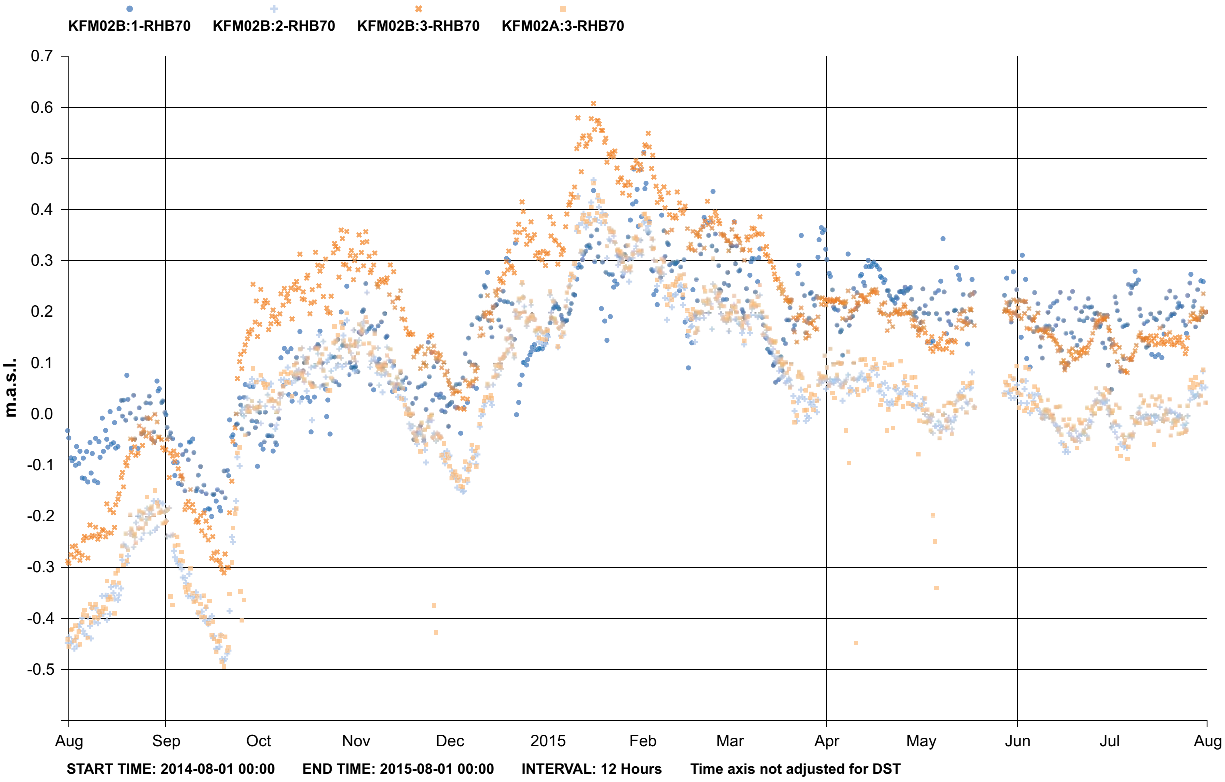


***Figure A4-6.** Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMF1. Test campaign 2014–2015, 2014-08-01 – 2015-08-01. Test section elevation (m.a.s.l.) is given after colour code; KFM02B:1 (blue) −525 m, KFM02B:2 (pale blue) −484 m, KFM02B:3 (orange) −447 m, KFM02A:3 (pale orange) −495 m.*

2015–2016

Table A4-8. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2015–2016. Gradients calculated from borehole section KFM10A:2 (−300 m.a.s.l.) to sections given in the table.

Borehole:sec	2015-10-01	2015-11-20	2016-01-10	2016-03-01	2016-04-20	2016-06-10
HFM15:1	−0.001	−0.001	−0.001	−0.001	−0.001	−0.001
HFM19:1	−0.0004	−0.0004	−0.0004	−0.0004	−0.0004	−0.0005
KFM02A:5	0.0001	0.0002	0.00008	0.0001	0.0001	0.0002
HFM01:2	−0.0005	−0.0004	−0.0004	−0.0004	−0.0004	−0.0004
KFM02B:4	0.0001	0.0001	0.00009	0.0001	0.0001	0.0002

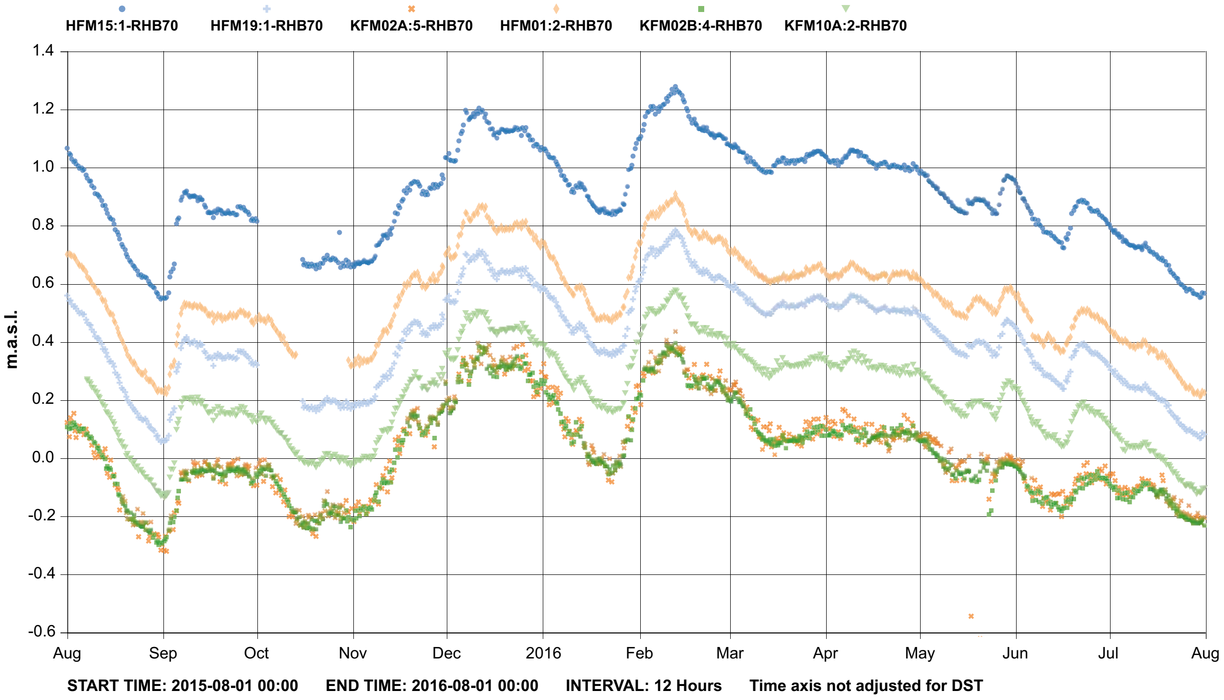


Figure A4-7. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2015–2016, 2015-08-01 – 2016-08-01. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green)−407 m, KFM10A:2 (pale green) −300 m.*

Table A4-9. Hydraulic gradients in fracture zone ZFMENE0401A during test campaign 2015–2016. Gradients calculated from borehole section HFM13:1 (−139 m.a.s.l.) to sections given in the table.

Borehole:sec	2015-10-01	2015-11-20	2016-01-10	2016-03-01	2016-04-20	2016-06-10
KFM05A:1	−0.0003	−0.0002	−0.0003	−0.0002	−0.00008	−0.0003
KFM05A:2	−0.001	−0.002	−0.0002	−0.001	−0.001	−0.002

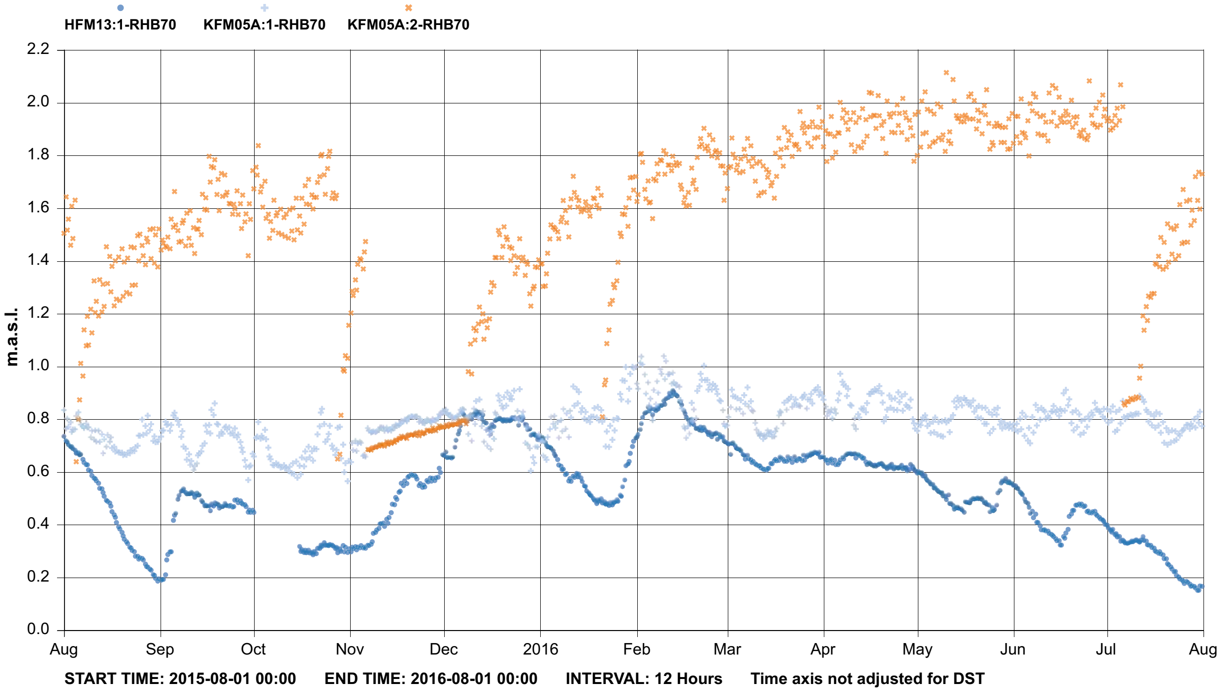


Figure A4-8. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMENE0401A. Test campaign 2015–2016, 2015-08-01 – 2016-08-01. Test section elevation (m.a.s.l.) is given after colour code; HFM13:1 (blue) −139 m, KFM05A:1 (pale blue) −704 m, KFM05A:2 (orange) −496 m.*

2016–2017

Table A4-10. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2016–2017. Gradients calculated from borehole section KFM04A:4 (−200 m.a.s.l.) to sections given in the table.

Borehole:sec	2016-10-01	2016-10-15	2016-11-01	2016-11-15	2016-12-01	2016-12-15
HFM15:1	0.001	0.002	0.002	0.002	0.002	0.002
HFM19:1	0.003	0.003	0.003	0.003	0.003	0.003
KFM02A:5	0.0009	0.001	0.0009	0.001	0.001	0.001
HFM01:2	0.002	0.002	0.002	0.002	0.002	0.002
KFM02B:4	0.0009	0.001	0.001	0.001	0.001	0.001
KFM10A:2	0.002	0.002	0.003	0.003	0.002	0.003

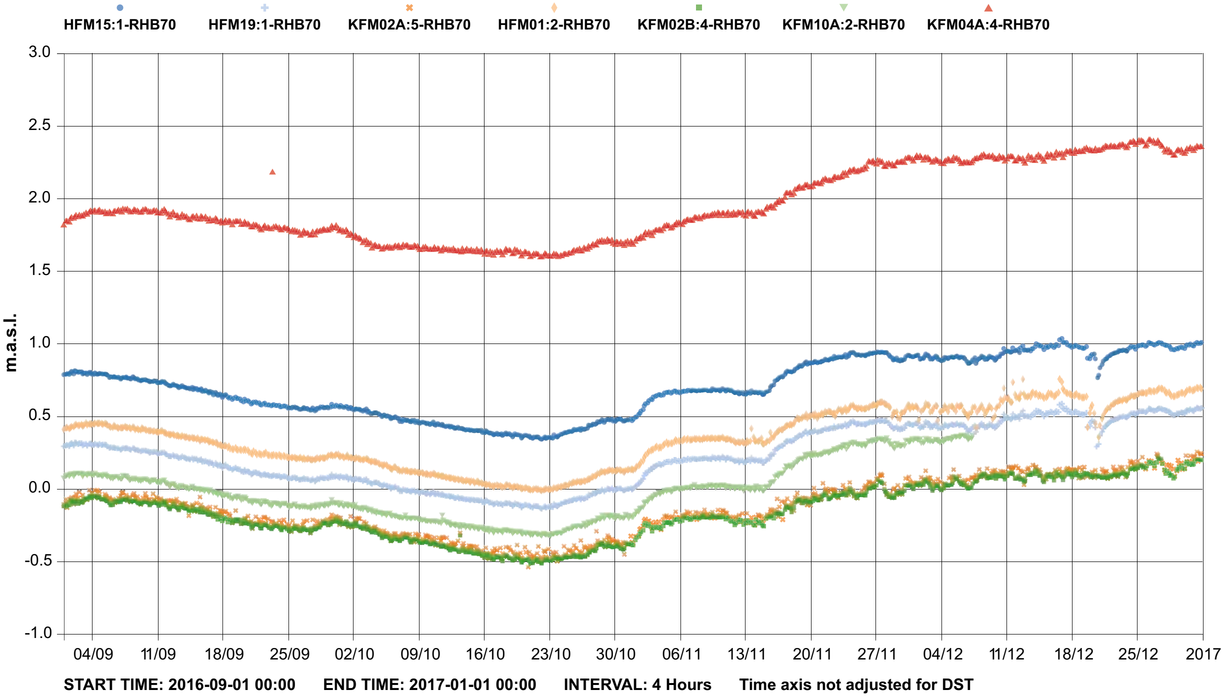


Figure A4-9. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2016–2017, 2016-09-01 – 2017-01-01. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green) −407 m, KFM10A:2 (pale green) −300 m, KFM04A:4 (red) −200 m.*

Table A4-11. Hydraulic gradients in fracture zone ZFMENE1061A during test campaign 2016–2017. Gradients calculated from borehole section KFM08A:6 (−228 m.a.s.l.) to sections given in the table.

Borehole:sec	2016-10-01	2016-10-15	2016-11-01	2016-11-15	2016-12-01	2016-12-15
KFM08A:5	0.007	0.006	0.0007	0.006	0.007	0.009
KFM08A:7	−0.008	−0.008	−0.006	−0.009	−0.007	−0.007
KFM19:1	−0.002	−0.001	−0.005	−0.003	−0.003	−0.003

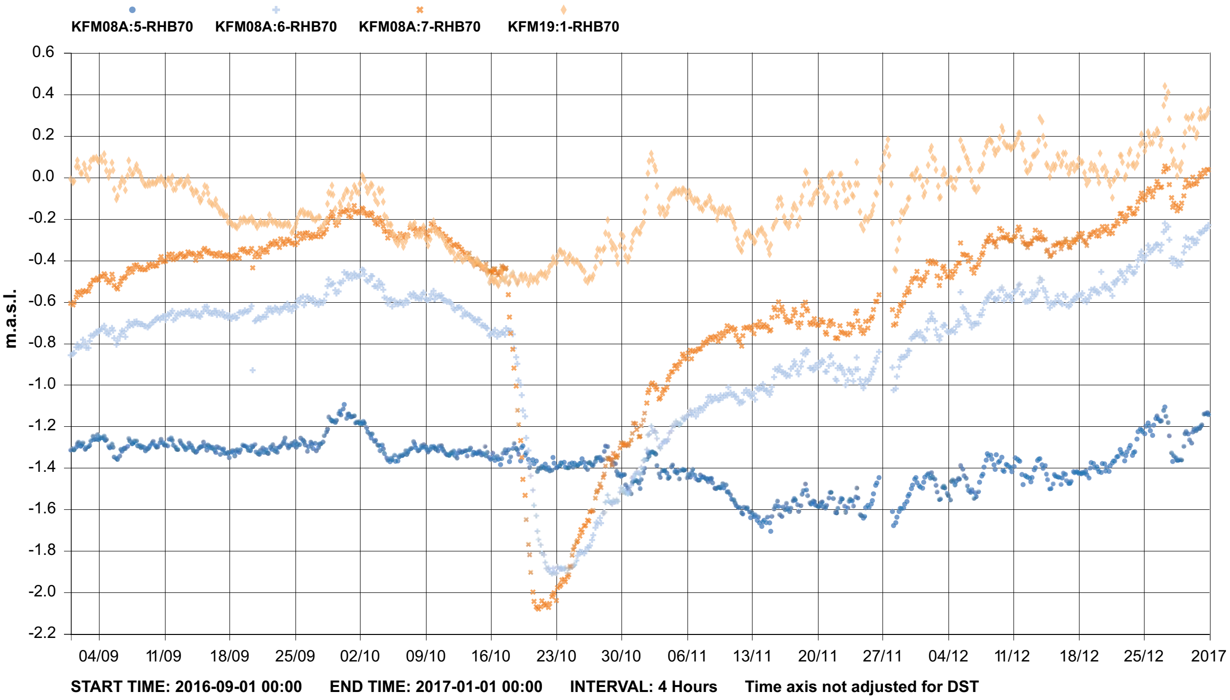


Figure A4-10. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMENE1061A. Test campaign 2016–2017, 2016-09-01 – 2017-01-01. Test section elevation (m.a.s.l.) is given after colour code; KFM08A:5 (blue) −312 m, KFM08A:6 (pale blue) −228 m, KFM08A:7 (orange) −201 m, KFM19:1 (pale orange) −44 m.*

Table A4-12. Hydraulic gradients in fracture zone ZFMWNW0001 during test campaign 2016–2017. Gradients calculated from borehole section KFM11A:2 (−594 m.a.s.l.) to sections given in the table.

Borehole:sec	2016-10-01	2016-10-15	2016-11-01	2016-11-15	2016-12-01	2016-12-15
KFM11A:1	−0.03	−0.03	−0.03	−0.03	−0.03	−0.03
KFM11A:3	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02
HFM34:2	−0.01	−0.009	−0.01	−0.01	−0.01	−0.01

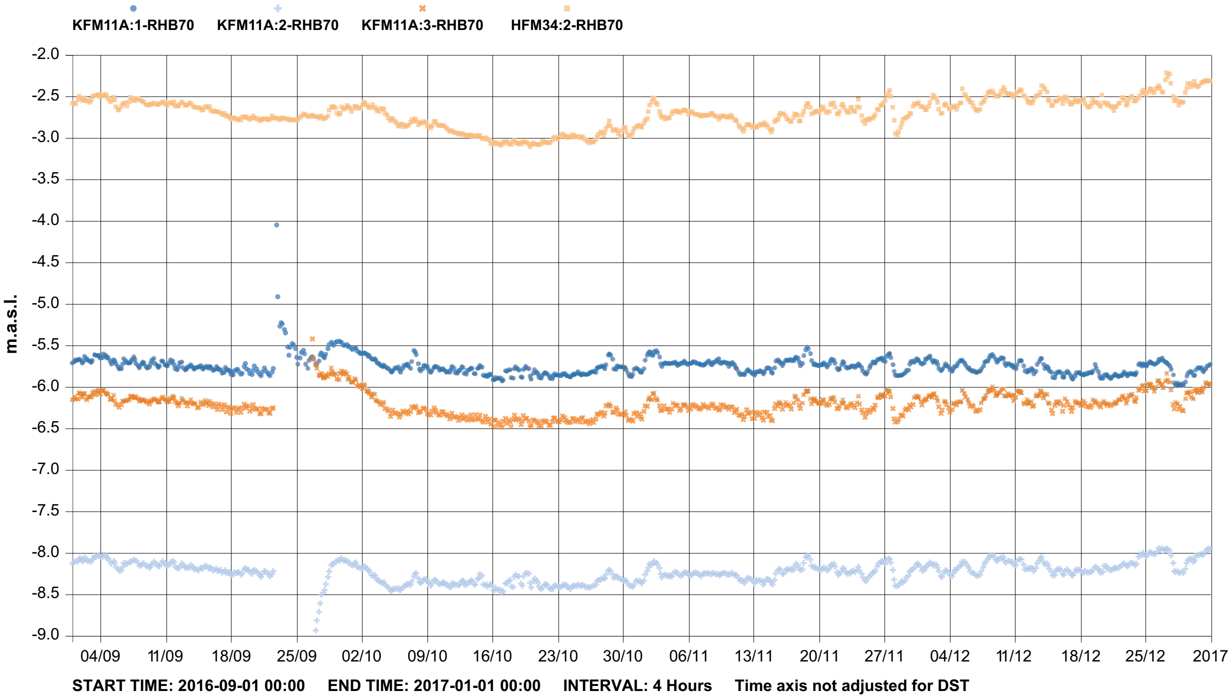


Figure A4-11. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMWNW0001. Test campaign 2016–2017, 2016-09-01 – 2017-01-01. Test section elevation (m.a.s.l.) is given after colour code; KFM11A:1 (blue) −658 m, KFM11A:2 (pale blue) −594 m, KFM11A:3 (orange) −491 m, HFM34:2 (pale orange) −45 m.*

Table A4-13. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2016–2017. Gradients calculated from borehole section HFM01:2 (−37 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
HFM15:1	−0.001	−0.001	−0.001	−0.001	−0.001	−0.0009
HFM19:1	0.0003	0.0004	0.0003	0.0003	0.0003	0.0004
KFM02A:5	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
KFM02B:4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
KFM10A:2	0.0004	–	0.0004	0.0004	0.0004	0.0004
KFM04A:4	−0.003	−0.003	−0.003	−0.003	−0.003	−0.003

Table A4-14. Hydraulic gradients in fracture zone ZFMA2 during test campaign 2016–2017. Gradients calculated from borehole section KFM02B:4 (−407 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
HFM15:1	−0.0005	−0.0005	−0.0006	−0.0005	−0.0005	−0.0005
HFM19:1	−0.0002	−0.0002	−0.0003	−0.0002	−0.0002	−0.0002
KFM02A:5	−0.0002	−0.0003	−0.0009	−0.0007	−0.0003	−0.001
HFM01:2	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
KFM10A:2	−0.0001	–	−0.0002	−0.0002	−0.0002	−0.00009
KFM04A:4	−0.001	−0.001	−0.001	−0.001	−0.001	−0.001

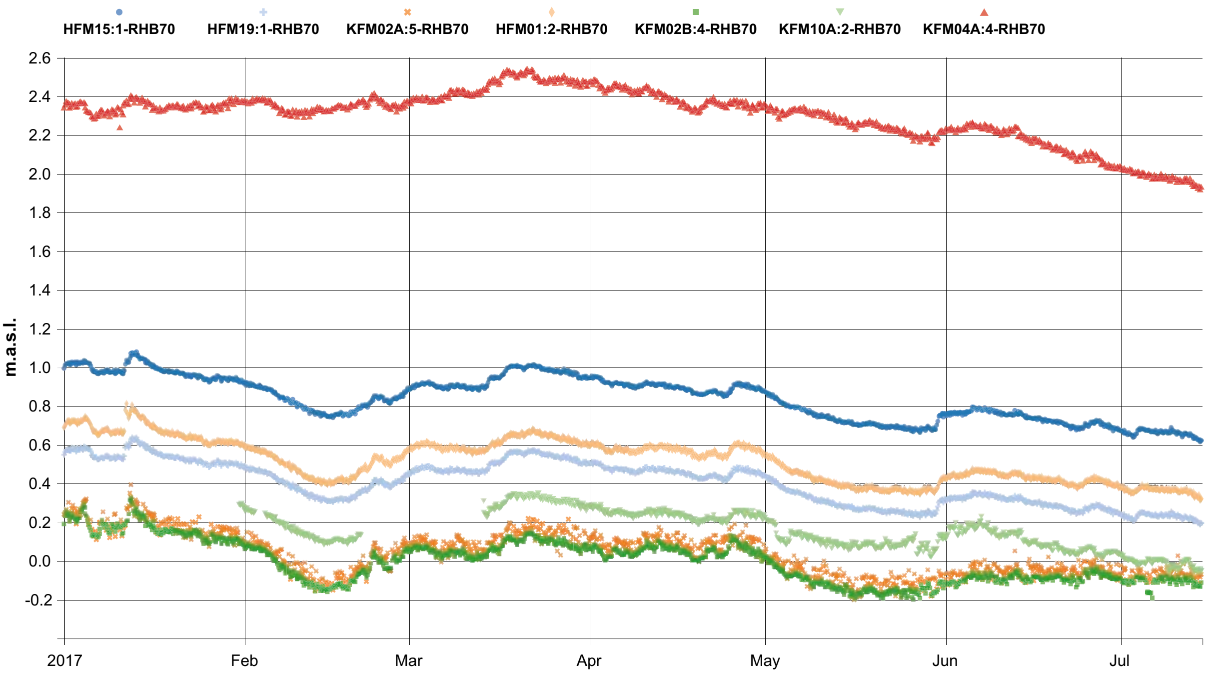


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Figure A4-12. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMA2. Test campaign 2016–2017, 2017-01-01 – 2017-07-15. Test section elevation (m.a.s.l.) is given after colour code; HFM15:1 (blue) −61 m, HFM19:1 (pale blue) −137 m, KFM02A:5 (orange) −418 m, HFM01:2 (pale orange) −37 m, KFM02B:4 (green)−407 m, KFM10A:2 (pale green) −300 m, KFM04A:4 (red) −200 m.*

Table A4-15. Hydraulic gradients in fracture zone ZFM1203 during test campaign 2016–2017. Gradients calculated from borehole section HFM02:2 (−40 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
HFM21:2	0.0005	0.0004	0.0005	0.0004	0.0004	0.0003
HFM27:1	0.002	0.002	0.002	0.002	0.003	0.002
HFM27:2	0.003	0.003	0.003	0.003	0.004	0.004
KFM07C:4	0.0004	0.0003	0.0004	0.0003	0.0003	0.0003

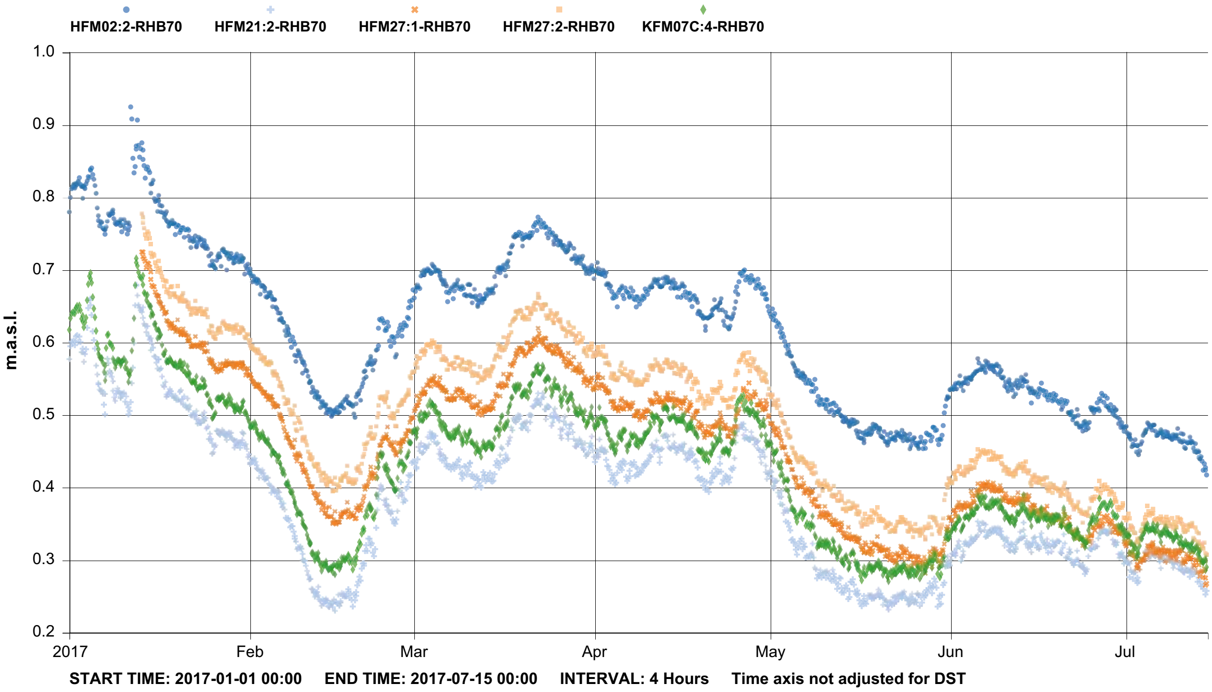

Figure A4-13. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFM1203. Test campaign 2016–2017, 2017-01-01 – 2017-07-15. Test section elevation (m.a.s.l.) is given after colour code; HFM02:2 (blue) −40 m, HFM21:2 (pale blue) −54 m, HFM27:1 (orange) −83 m, HFM27:2 (pale orange) −46 m, KFM07C:4 (green) −51 m.*

Table A4-16. Hydraulic gradients in fracture zone ZFM866 during test campaign 2016–2017. Gradients calculated from borehole section HFM04:2 (−58 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
HFM05:1	0.00008	0.00009	0.0002	0.0002	0.0002	0.0002
KFM02A:8	−0.0002	−0.0002	−0.0003	−0.0002	−0.0002	−0.0002
KFM02B:7	−0.0005	−0.0005	−0.0003	−0.0003	−0.0003	−0.0003

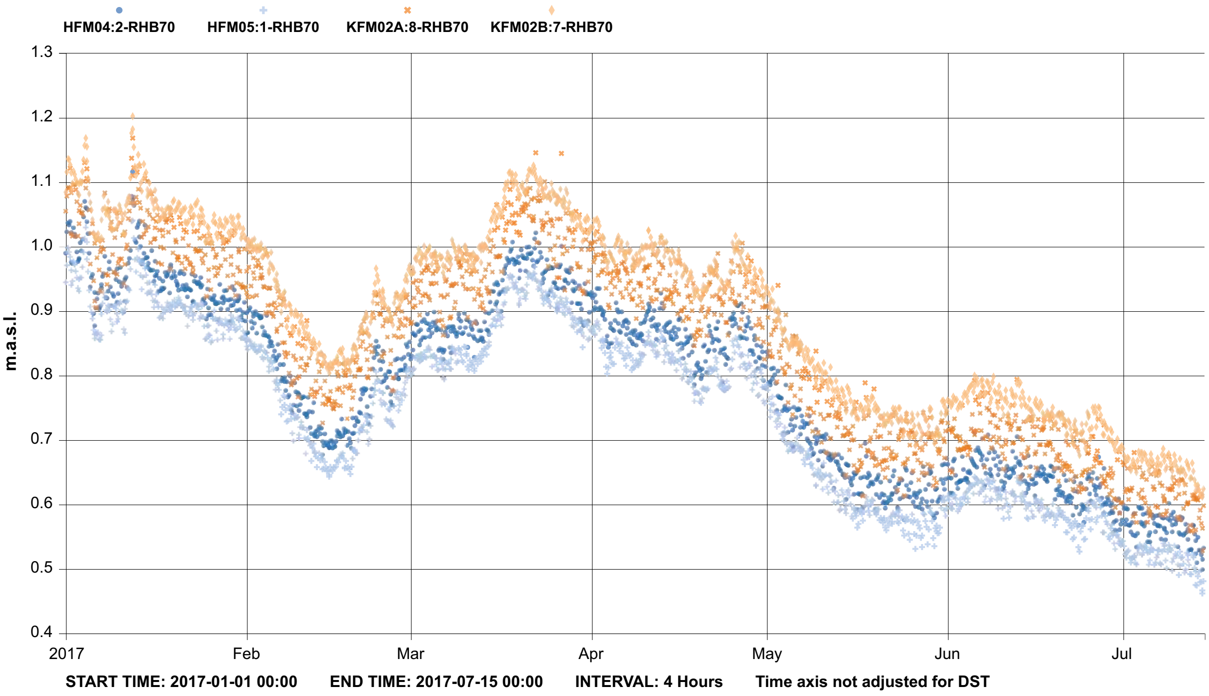

Figure A4-14. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFM866. Test campaign 2016–2017, 2017-01-01 – 2017-07-15. Test section elevation (m.a.s.l.) is given after colour code; HFM04:2 (blue) −58 m, HFM05:1 (pale blue) −160 m, KFM02A:8 (orange) −58 m, KFM02B:7 (pale orange) −56 m.*

Table A4-17. Hydraulic gradients in fracture zone ZFMF1 during test campaign 2016–2017. Gradients calculated from borehole section KFM02A:3 (−495 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
KFM02B:1	−0.002	−0.003	−0.0005	0.0006	−0.003	−0.003
KFM02B:2	−0.0001	−0.00003	0.0009	0.0009	0.001	0.0005
KFM02B:3	−0.002	−0.002	−0.002	−0.002	−0.001	−0.002

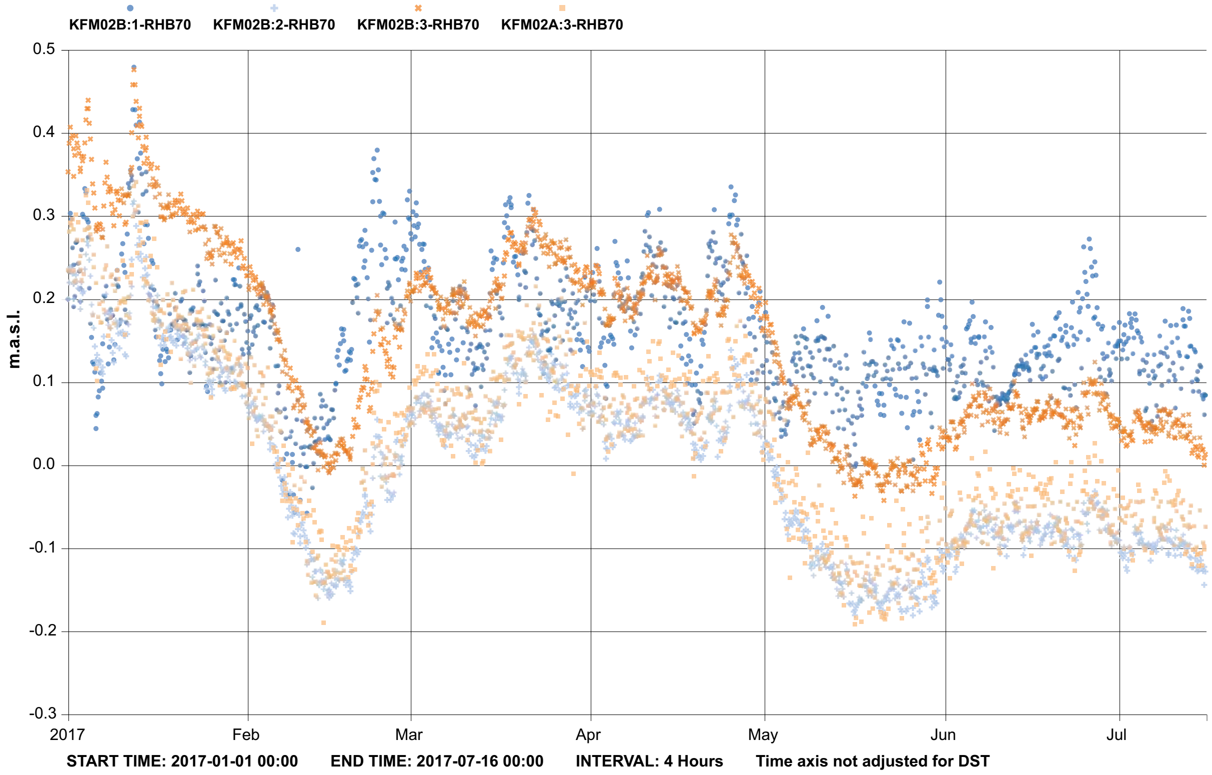

Figure A4-15. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMF1. Test campaign 2016–2017, 2017-01-01 – 2017-07-15. Test section elevation (m.a.s.l.) is given after colour code; KFM02B:1 (blue) −525 m, KFM02B:2 (pale blue) −484 m, KFM02B:3 (orange) −447 m, KFM02A:3 (pale orange)−495 m.*

Autumn 2017

Table A4-18. Hydraulic gradients in fracture zone ZFMWNW0004 during test campaign autumn 2017. Gradients calculated from borehole section KFM12A:3 (−227 m.a.s.l.) to sections given in the table.

Borehole:sec	2017-02-01	2017-03-01	2017-04-01	2017-05-01	2017-06-01	2017-07-01
KFM12A:2	−0.006	−0.006	−0.006	−0.006	−0.006	−0.005
KFM12A:4	0.002	0.002	0.002	0.002	0.002	0.002
KFM12A:5	−0.00008	0.0009	0.002	0.001	0.001	0.001

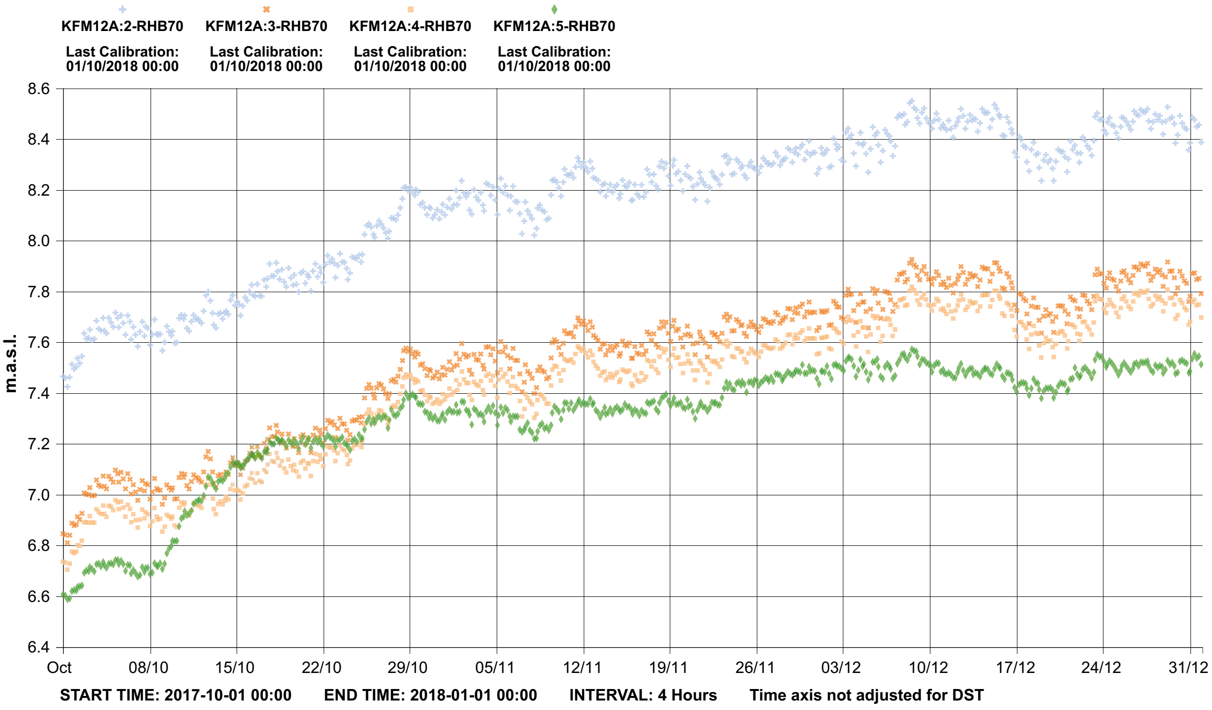

Figure A4-16. *Groundwater levels (m.a.s.l.) in borehole test sections intersecting fracture zone ZFMWNW0004. Test campaign autumn 2017, 2017-10-01 – 2018-01-01. Test section elevation (m.a.s.l.) is given after colour code; KFM12A:2 (pale blue) −321 m, KFM12A:3 (orange) −227 m, KFM12A:4 (pale orange) −177 m, KFM12A:5 (green)−61 m.*

Arkitektkopia AB, Bromma, 2019

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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