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Groundwater flow measurements in permanently installed boreholes

Test campaigns no. 12, 2016-2017 and no. 13, autumn 2017

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Keywords: Groundwater flow, Dilution test, Tracer test, AP SFK-16-028, AP SFK-17-031.

Abstract

This report describes the performance and evaluation of groundwater flow measurements in, in total, fourteen selected borehole sections in permanently installed boreholes within the Forsmark investigation area. These were the twelfth and thirteenth test campaigns performed within the monitoring program and measurements are planned to be repeated every year. The objective for these campaigns was to determine groundwater flow rates in all, at the time available, borehole sections instrumented for this purpose. An extended aim was to increase understanding of the natural variation in groundwater flow that can be seen from year to year, but also changes during ongoing measurement. Frequently repeated and/or continuous measurements also provide a good picture of how the flow is influenced by e.g. rainfall or snow melt, so that these effects later can be distinguished from effects emanating from construction of the repository.

The groundwater flow rates were determined through dilution measurements during natural conditions. Measured flow rates ranged from 0.02 to 81 ml/min with calculated Darcy velocities from 9.5×10^{-11} to 4.9×10^{-7} m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.00007 and 0.8.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i totalt fjorton utvalda borrhålssektioner i permanent installerade borrhål inom Forsmarks undersökningsområde. Det här är den tolfte och trettonde mätkampanjen som har genomförts i moniteringsprogrammet och mätningarna är planerade att återupprepas varje år. Syftet var att bestämma grundvattenflödet i samtliga, vid denna tidpunkt och för detta ändamål, instrumenterade sektioner. Ett utökat syfte var att öka förståelsen för de naturliga variationer i flödena som kan ses från år till år, men också förändringar under pågående mätning. Frekvent upprepade och/eller kontinuerliga mätningar ger också en bra bild över hur flödena påverkas av till exempel nederbörd eller snösmältning så att dessa effekter senare kan särskiljas från effekter av slutförvarsbygget.

Grundvattenflödet mättes med utspädningsmetoden under naturliga förhållanden i utvalda borrhålssektioner. Uppmätta grundvattenflöden låg i intervallet 0,02–81 ml/min med beräknade Darcy hastigheter mellan $9{,}5 \times 10^{-11}$ och $4{,}9 \times 10^{-7}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,00007 och 0,8.

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1 Introduction

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaigns no. 12, 2016–2017 and no. 13, autumn 2017, which is part of the programme for monitoring of geoscientific parameters and biological objects within the Forsmark site investigation area (SKB 2007). Monitoring commenced during the Forsmark site investigations 2002–2007, and a monitoring programme was established as an independent project starting in July 2007, after completion of the Forsmark site investigation in June 2007.

The work was carried out in accordance with activity plans AP SFK-16-028 and AP SFK-17-031 and the field work was conducted from the middle of September 2016 to the beginning of July 2017 and from the middle of October to the end of December 2017, respectively. In Table 1-1 controlling documents for performing this activity are listed. The activity plan and the method description are SKB's internal controlling documents.

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

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

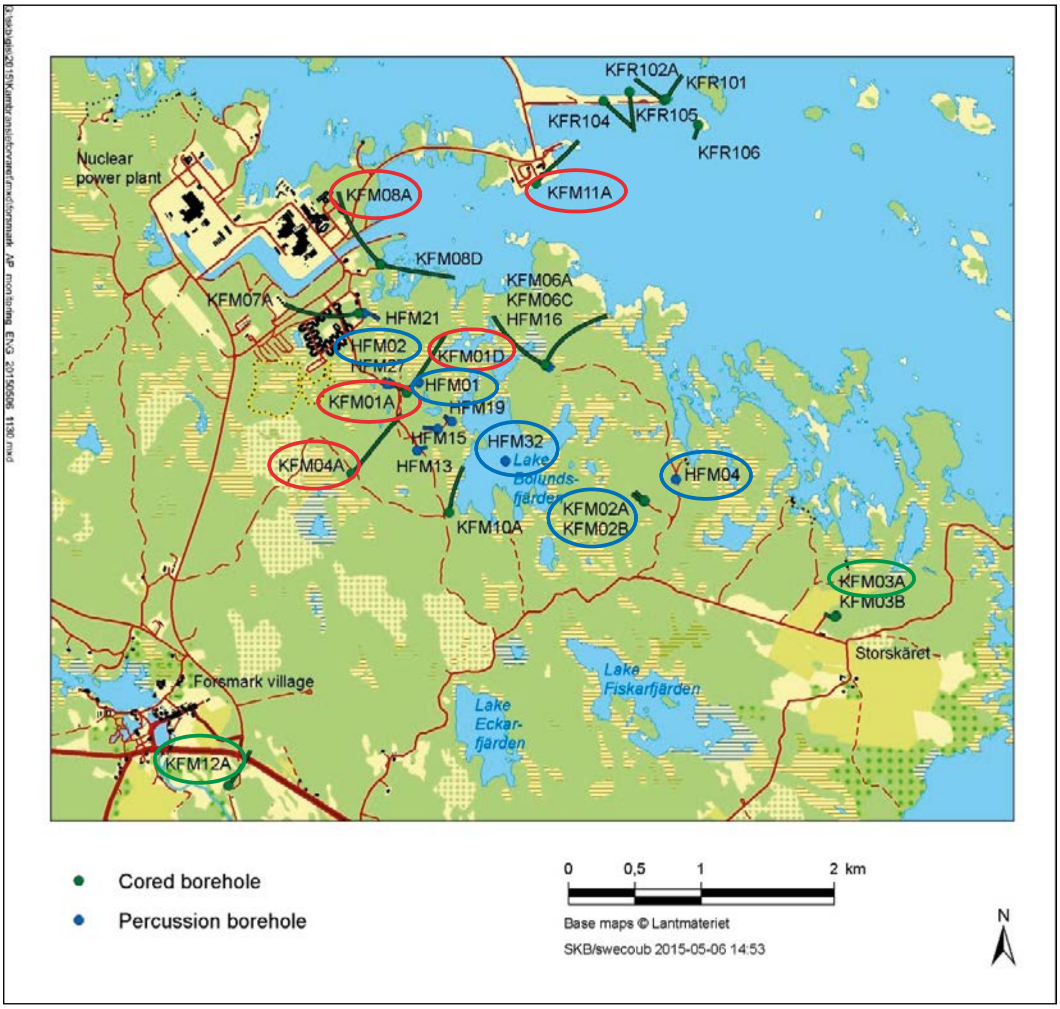

Figure 1-1. *Overview over the Forsmark area, showing locations of boreholes included in the groundwater flow monitoring program. Red markings show the boreholes measured September–December 2016, blue markings show the boreholes measured January–July 2017 and green markings show the boreholes measured October–December 2017, all presented in this report.*

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

Document	Number	Version
Activity plan		
Monitering av grundvattenflöde Forsmark 2016–2017.	AP SFK-16-028	1.0
Grundvattenflödesmätningar i Forsmark hösten 2017.	AP SFK-17-031	1.0
Method description		
System för hydrologisk och meteorologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål.	SKB MD 368.010	1.0

2 Objective and scope

The objective of this activity was to determine the groundwater flow in permanently installed borehole sections at Forsmark. In total fourteen selected borehole sections instrumented for this purpose were measured, cf. Table 4-1. These were the twelfth and thirteenth test campaigns performed within the monitoring program and measurements are planned to be repeated every year. The measurements will serve as a basis to study undisturbed groundwater flow as well as to monitor changes caused by future activities in the area such as underground construction and drilling. An extended aim was to increase understanding of the natural variation in groundwater flow that can be seen from year to year, but also changes during ongoing measurement. Frequently repeated and/or continuous measurements also provide a good picture of how the flow is influenced by e.g. rainfall or snow melt, so that these effects later can be distinguished from effects emanating from construction of the repository. These are the fourth and fifth campaigns with measurements performed over longer periods. The extended analysis is presented in a separate report (Andersson et al. 2019).

The selection of borehole sections was made to represent different depths and types of fractures/fracture zones in the Forsmark area. The maximum number of sections measured at the same time was set to six due to availability of personnel and equipment. This means that six sections were measured during the autumn 2016, another six during the spring 2017 and the remaining two sections were measured during the autumn 2017.

The groundwater flow in the selected borehole sections was determined through tracer dilution measurements. The measurements may, on the whole, be regarded as performed during natural, i.e. undisturbed, hydraulic conditions.

3 Equipment

3.1 Borehole equipment

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

All isolated borehole sections are connected to the Hydro Monitoring System (HMS) for pressure monitoring. In general, the sections intended for tracer tests 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.

3.2 Dilution test equipment

The tracer dilution tests were performed using six identical equipment set-ups, allowing all six sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-2. 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 in order to monitor the dilution of the tracer with time.

Circulation is controlled via a down-hole pump with adjustable speed and measured by a flow meter. Tracer injections are performed with a peristaltic pump and sampling is made by continuously extracting a small volume of water from the system through another peristaltic pump (constant leak) to a fractional sampler. The equipment and test procedure is described in detail in SKB MD 368.010, see Table 1-1. The sampler was put in a plastic box together with four small bottles containing fresh water in order to prevent, or at least reduce, evaporation of water from the samples, see Figure 3-3. The tracer used was a fluorescent dye tracer, Amino-G Acid from Aldrich (techn. quality).

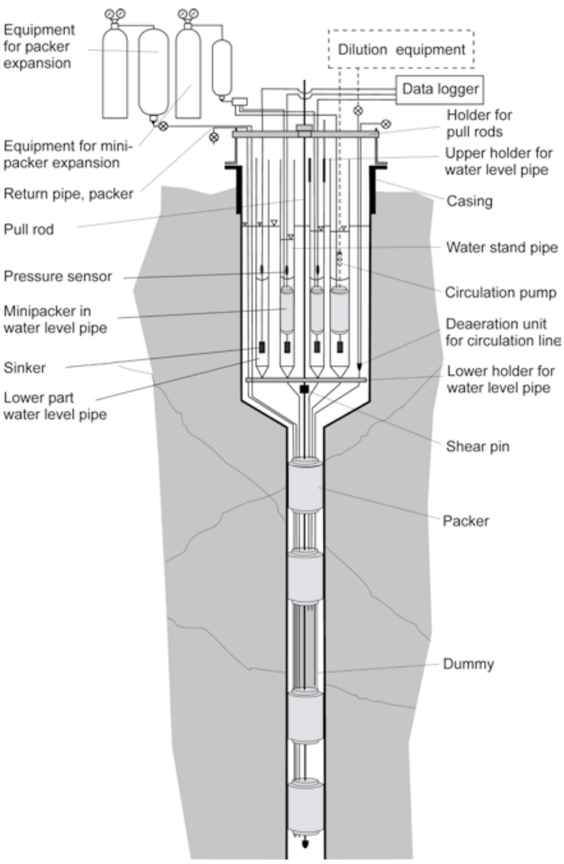

Figure 3-1. Example of permanent instrumentation in core and percussion boreholes with circulation sections.

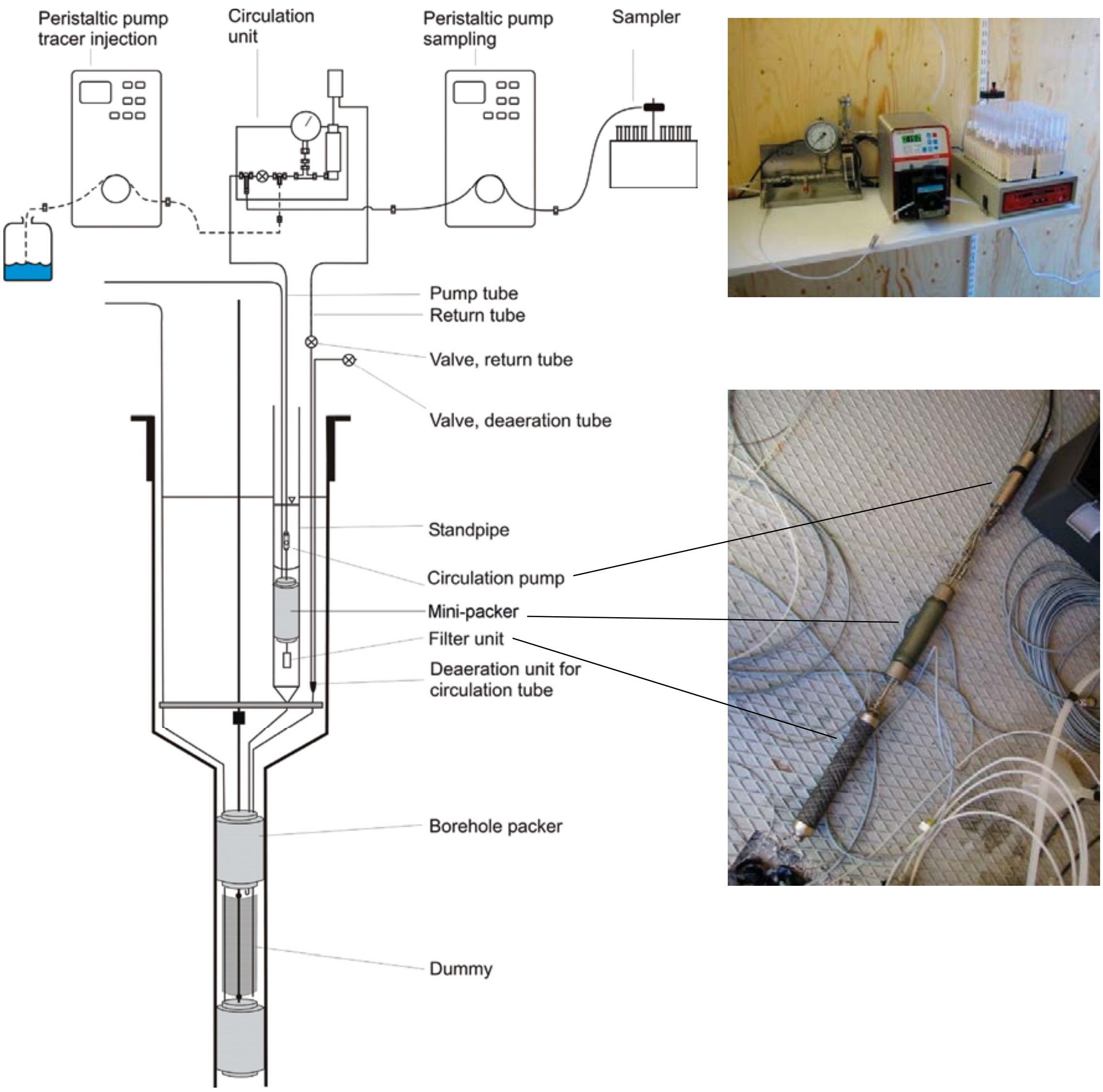

Figure 3-2. *Schematic drawing of the equipment used in tracer dilution measurements.*

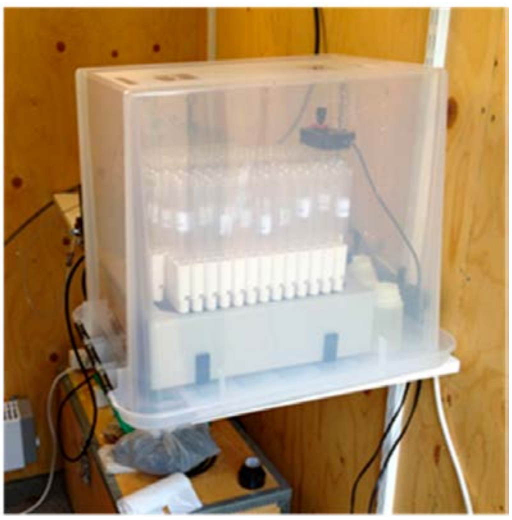

Figure 3-3. *The sampler was put in a plastic box in order to reduce evaporation from the samples.*

4 Execution

4.1 General

In the dilution method a tracer is introduced and homogeneously distributed into a borehole section. The tracer is subsequently diluted by the ambient groundwater flowing through the borehole section. The dilution rate is proportional to the water flow through the borehole section and the groundwater flow rate is calculated as a function of the decreasing tracer concentration with time, Figure 4-1.

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

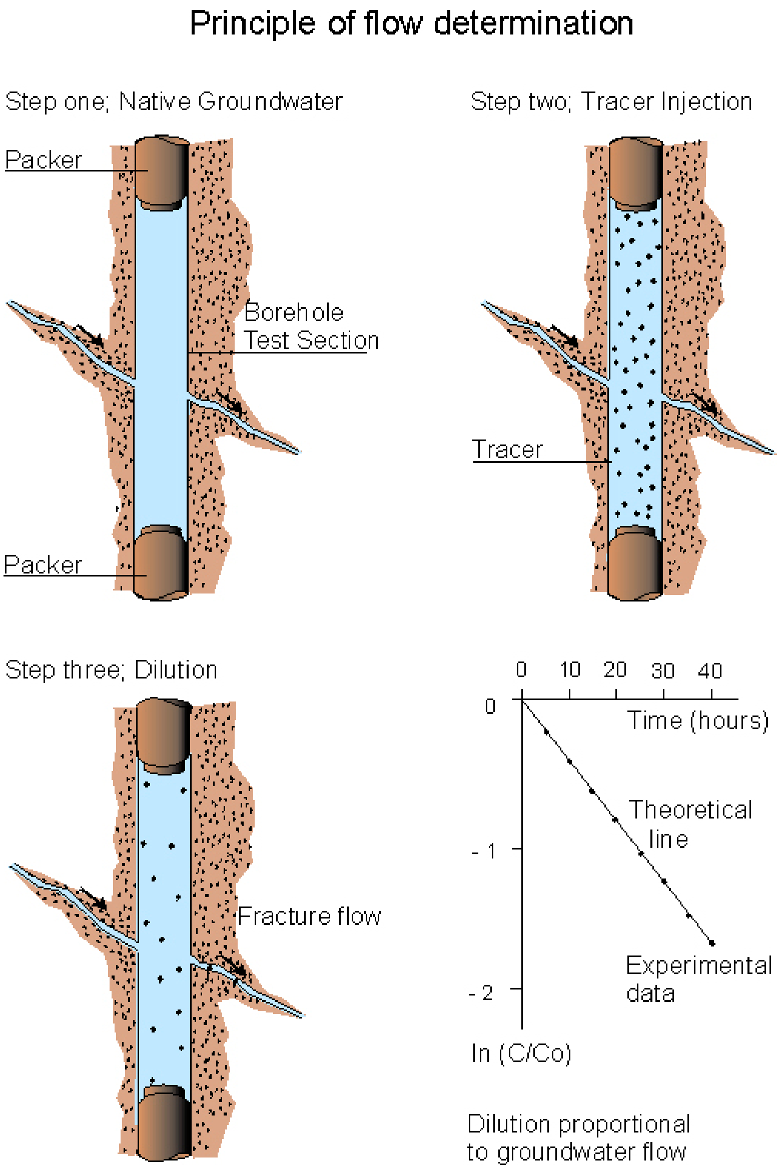

Figure 4-1. General principles of dilution and flow determination.

4.2 Preparations

The preparations included mixing of the tracer stock solution, function checks of the equipment and printing of field protocols and labels with sample numbers.

4.3 Execution of field work

The borehole sections included in the monitoring program during the test campaigns 2016–2017 and autumn 2017 are listed in Table 4-1.

Table 4-1. Borehole sections included in the monitoring program, test campaigns 2016–2017 and autumn 2017.

Borehole:section	Depth (m)	T (m^2/s)	Geologic character***	Test period (yymmdd)
KFM01A:5	109–130	1.0E−7*	Single fracture, Fracture domain FFM02	160922–161220
KFM01D:2	429–438	8.0E−7*	Single fracture, Fracture domain FFM01	160922–161220
KFM01D:4	311–321	2.0E−7*	Single fracture, Fracture domain FFM01	160922–161220
KFM04A:4	230–245	2.0E−5*	Zone ZFMA2	160923–161220
KFM08A:6	265–280	1.0E−6*	Zone ZFMENE1061A	160920–161220
KFM11A:2	690–710	1.0E−6*	Not included in Follin et al. (2007)	160930–161220
KFM02A:3	490–518	2.1E−6*	Zone ZFMF1	170111–170705
KFM02B:4	410–431	2.0E−5*	Not included in Follin et al. (2007)	170112–170705
HFM01:2	33.5–45.5	4.0E−5**	Zone ZFMA2	170112–170705
HFM02:2	38–48	5.9E−4**	Zone ZFM1203	170112–170615
HFM04:2	58–66	7.9E−5**	Zone ZFM866	170111–170705
HFM32:3	26–31	2.3E−4**	Single fracture, Fracture domain FFM03	170209–170705
KFM03A:4	633.5–650	2.4E−6*	Zone ZFMB1	171018–171221
KFM012:3	270–280	1.0E−6*	Not included in Follin et al. (2007)	171018–171221

* From PSS (Pipe String System) or PFL (Posiva Flow Logging) measurements (Ludvigson et al. 2004, Källgården et al. 2004a, b, Hjerne and Ludvigson 2005, Sokolnicki and Rouhiainen 2005, Florberger et al. 2006, Väisäsvaara et al. 2006, Väisäsvaara and Pekkanen 2007, Väisäsvaara and Pöllänen 2007, Harrström et al. 2007a, b).

** From HTHB (HydroTester HammarBorrhål) measurements (Ludvigson et al. 2003a, b, Jönsson and Ludvigson 2006).

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

The tests were made by injecting a finite volume of tracer solution (Amino-G acid, 1 000 mg/l) into the selected borehole sections and allowing the natural groundwater flow to dilute the tracer. The tracer was injected during a time period equivalent to the time needed to circulate one section volume. The injection/circulation flow ratio was set to 1/1 000, implying that the initial concentration in the borehole section should be about 1 mg/l for Amino-G acid. All six sections were measured simultaneously. The tracer solution was continuously circulated and sampled using the equipment described in Section 3.2.

No interruptions in the measurements due to groundwater sampling were made in any of the measured sections.

In borehole sections HFM01:2, HFM02:2, KFM02B:4 and KFM04A:4, the dilution of tracer was quite fast and tracer injections had to be frequently repeated and were made once a month. In HFM02:2 and KFM02B:4 sampling was temporarily ended about one and two weeks, respectively, after each injection when the tracer concentration had been diluted to background level. HFM04:2 and HFM32:3 also required recurrent tracer injections, in these cases every second month.

The samples were analysed for dye tracer content at the Geosigma Laboratory using a Jasco FP 777 Spectrofluorometer.

4.4 Analyses and interpretations

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural, unlabelled groundwater, cf. Gustafsson (2002). The so-called "dilution curves" were plotted as the natural logarithm of concentration versus time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (c/c_0) and time, t (s):

$$\ln (c/c_0) = -(Q_{bh}/V) \cdot t \qquad \text{Equation 4-1}$$

where Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V (m^3) is the volume of the borehole section. By plotting ln (c/c_0) or ln c versus t, and by knowing the borehole volume V, Q_{bh} may then be obtained from the straight-line slope. In some of the measurements, the slope changes over time and thus also the flow rate. These changes may occur gradually or suddenly due to changes in the hydraulic gradient. The interpretation is made directly "by eye" from the graphs (see Appendix 1).

The sampling procedure with a constant flow rate of approximately 0.06 ml/min also creates a dilution of tracer. The sampling flow rate is therefore subtracted from the value obtained from Equation 4-1.

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

$$Q_{bh} = v \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha \qquad \text{Equation 4-2}$$

where L_{bh} is the length of the borehole section (m), r_{bh} is the borehole radius (m) and α is the factor accounting for the distortion of flow caused by the borehole.

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

$$I = \frac{v}{K} = \frac{Q_{bh} \cdot L_{bh}}{\alpha \cdot A \cdot T_{bh}} = \frac{Q_{bh} \cdot L_{bh}}{2 \cdot d_{bh} \cdot L_{bh} \cdot T_{bh}} \qquad \text{Equation 4-3}$$

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

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

4.5 Nonconformities

At installation of the dilution equipment in KFM11A:2 the wrong return tube was used and the one belonging to the other circulation section in the borehole, section 4, was connected instead. The mix-up was possible due to insufficient or even nonexistent marking of the tubes and valves belonging to the borehole equipment. However, this was discovered after a few days from the pressure monitoring in the borehole, the tubes were switched, a new tracer injection was made and the measurement was re-started ten days after the first time.

Due to malfunctioning samplers, samples are missing for longer periods (month) in KFM02A:3 and HFM04:2 and for shorter periods (week) in KFM03A:4 and KFM11A:2.

In KFM01D:2 sampling was interrupted for about one week in the middle of November 2016 due to a clogged tube in the sampling equipment.

Borehole HFM32 is situated on a small island in the middle of Lake Bolundsfjärden and the ice conditions prevented the weekly attendance to be performed during the second half of March 2017. In consequence of this some samples were filled twice and could therefore not be used.

Some interruptions were caused by circulation pump failures such as in HFM04 and HFM01 in the beginning of May and June 2017, respectively, and also in KFM12A in the middle of December 2017.

Each sampler was placed in a plastic box together with four small bottles containing fresh water in order to prevent, or at least reduce, evaporation. However, evaporation of water from the samples, resulting in false higher values of tracer concentration could still be seen. No correction of data has been made because it has not been possible to determine to which extent each sample has been affected.

5 Results

5.1 General

Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan numbers (AP SFK-16-028 and AP SFK-17-031). Only data in databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. However, such revision of the database will not necessarily result in a revision of this report, although the normal procedure is that major data revisions entail a revision also of the report.

5.2 Test campaign no. 12, 2016–2017 and no. 13, autumn 2017

An example of a typical tracer dilution curve is shown in Figure 5-1. The flow rate is calculated from the slope of the straight-line fit. Tracer dilution graphs for each borehole section are presented in Appendix 1.

A summary of the results obtained is presented in Table 5-1 including measured groundwater flow rates, Darcy velocities and hydraulic gradients together with transmissivities and volumes of the borehole sections. Measured flow rates during each measurement period are shown graphically in Figure 5-2 through Figure 5-4 for each section.

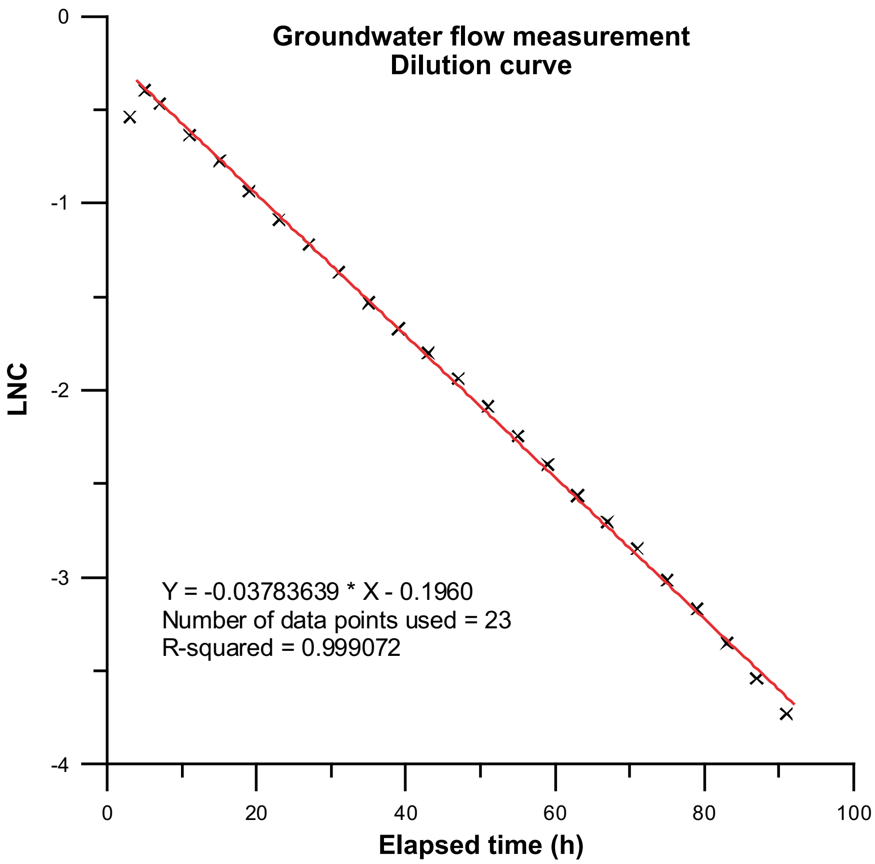

Figure 5-1. *Example of a tracer dilution graph (logarithm of concentration versus time), including straight-line fit.*

Table 5-1. Results from groundwater flow measurements, test campaigns no. 12, 2016–2017 and no. 13, autumn 2017.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Vol. (l)	Time interval (h) From	To	Measured flow, Q (ml/min)	Darcy velocity, v (m/s)	Hydraulic gradient, I (m/m)
KFM01A:5	109–130	1.0E−07*	33.21	10	100	0.7	3.6E−09	0.8
				110	520	0.03	1.6E−10	0.03
				520	1430	0.02	9.5E−11	0.02
				1480	2140	0.03	1.4E−10	0.03
KFM01D:2	429–438	8.0E−07*	38.33	10	1300	0.06	7.3E−10	0.008
				1470	2140	0.06	6.8E−10	0.008
KFM01D:4	311–321	2.0E−07*	31.27	10	300	0.2	2.7E−09	0.1
				320	920	0.3	3.4E−09	0.2
				920	2130	0.1	1.6E−09	0.08
KFM04A:4	230–245	2.0E−05*	35.00	20	170	4.0	2.9E−08	0.02
				170	630	1.9	1.4E−08	0.01
				650	1000	2.1	1.5E−08	0.01
				1000	1400	1.4	1.0E−08	0.008
				1420	2100	1.1	8.2E−09	0.006
KFM08A:6	265–280	1.0E−06*	34.67	20	190	0.3	1.8E−09	0.03
				190	1880	0.02	1.5E−10	0.002
KFM11A:2	690–710	1.0E−06*	68.91	190	400	0.8	4.3E−09	0.09
				420	2115	0.2	9.5E−10	0.02
KFM02A:3	490–518	2.1E−06*	66.33	30	160	1.3	5.0E−09	0.07
				160	380	0.8	3.2E−09	0.04
				380	1700	0.3	1.1E−09	0.02
				1700	4200	0.1	5.4E−10	0.007
KFM02B:4	410–431	2.0E−05*	47.58	10	230	19	1.0E−07	0.1
				700	940	20	1.0E−07	0.1
				1340	1570	21	1.1E−07	0.1
				2140	2340	21	1.1E−07	0.1
				2840	3040	22	1.2E−07	0.1
				3530	3750	21	1.1E−07	0.1
HFM01:2	33.5–45.5	4.0E−05**	39.83	10	350	4.7	2.3E−08	0.007
				350	520	6.0	3.0E−08	0.009
				520	630	11	5.4E−08	0.02
				670	840	8.8	4.4E−08	0.01
				840	1080	6.4	3.2E−08	0.01
				1120	1230	6.6	3.3E−08	0.01
				1360	1630	6.6	3.3E−08	0.01
				1630	1840	5.4	2.7E−08	0.008
				1850	2030	5.7	2.8E−08	0.008
				2140	2820	4.1	2.0E−08	0.006
				2860	3260	4.2	2.1E−08	0.006
				3540	3800	3.5	1.7E−08	0.005
				3800	4150	1.5	7.6E−09	0.002
HFM02:2	38–48	5.9E−04**	28.53	20	100	17	1.0E−07	0.002
				700	735	54	3.3E−07	0.006
				1350	1390	51	3.1E−07	0.005
				2140	2160	81	4.9E−07	0.008
				2160	2200	27	1.6E−07	0.003
				2840	2880	44	2.7E−07	0.005
				3540	3600	15	9.0E−08	0.002
				3600	3690	6.5	4.0E−08	0.0007
HFM04:2	58–66	7.9E−05**	27.52	20	870	1.3	9.5E−09	0.001
				870	1220	0.9	7.1E−09	0.0007
				2160	2720	0.8	6.1E−09	0.0006
				2860	3610	1.0	7.6E−09	0.0008
				3610	4200	0.7	4.9E−09	0.0005
HFM32:3	26–31	2.3E−04**	20.06	20	170	1.0	1.2E−08	0.0003

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Vol. (l)	Time interval (h) From	To	Measured flow, Q (ml/min)	Darcy velocity, v (m/s)	Hydraulic gradient, I (m/m)
				170	660	0.6	6.9E−09	0.0002
				810	1000	0.6	7.3E−09	0.0002
				1000	1460	0.4	4.5E−09	0.0001
				1480	2110	0.6	7.7E−09	0.0002
				2120	2370	0.9	1.1E−08	0.0002
				2370	2850	0.3	3.3E−09	0.00007
				2870	3500	0.4	5.1E−09	0.0001
KFM03A:4	633.5 –650	2.4E−06*	58.04	50	1530	0.03	1.8E−10	0.001
KFM12A:3	270–280	1.0E−06*	31.76	10	100	2.9	3.1E−08	0.3
				110	490	0.6	6.0E−09	0.06
				495	820	0.3	3.1E−09	0.03
				830	1340	0.2	1.7E−09	0.02

* From PSS (Pipe String System) or PFL (Posiva Flow Logging) measurements (Ludvigson et al. 2004, Källgården et al. 2004a, b, Hjerne and Ludvigson 2005, Sokolnicki and Rouhiainen 2005, Florberger et al. 2006, Väisäsvaara et al. 2006, Väisäsvaara and Pekkanen 2007, Väisäsvaara and Pöllänen 2007, Harrström et al. 2007a, b).

** From HTHB (HydroTester HammarBorrhål) measurements (Ludvigson et al. 2003a, b, Jönsson and Ludvigson 2006).

In Appendix 2 the groundwater level during the entire test period is presented for the selected boreholes, see also Table 4-1 for actual measurement periods for each section. Some activities that were performed in the Forsmark area during the test period, and thus may have affected the ongoing groundwater flow measurements, are compiled in Table 5-2. However, the pumping for groundwater sampling performed in many sections in May 2017 has most likely not caused any disturbances in the measured sections since the pumping rate is low and the sections are not located close to each other.

Table 5-2. Activities performed in the Forsmark area during the test campaign with groundwater flow measurements, 2016–autumn 2017.

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

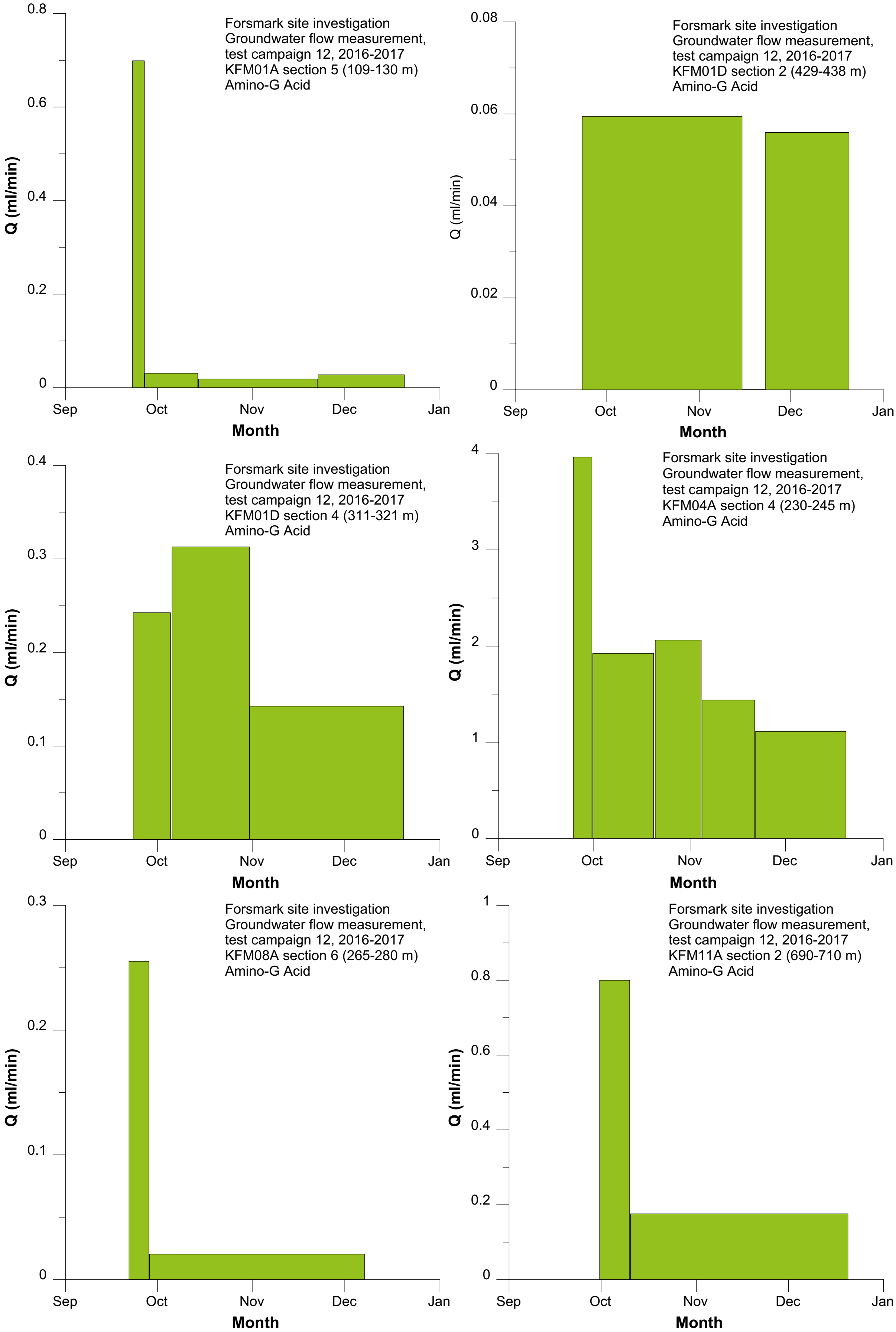

Figure 5-2. *Measured flow rates September – December 2016 for each section, test campaign 12, 2016–2017.*

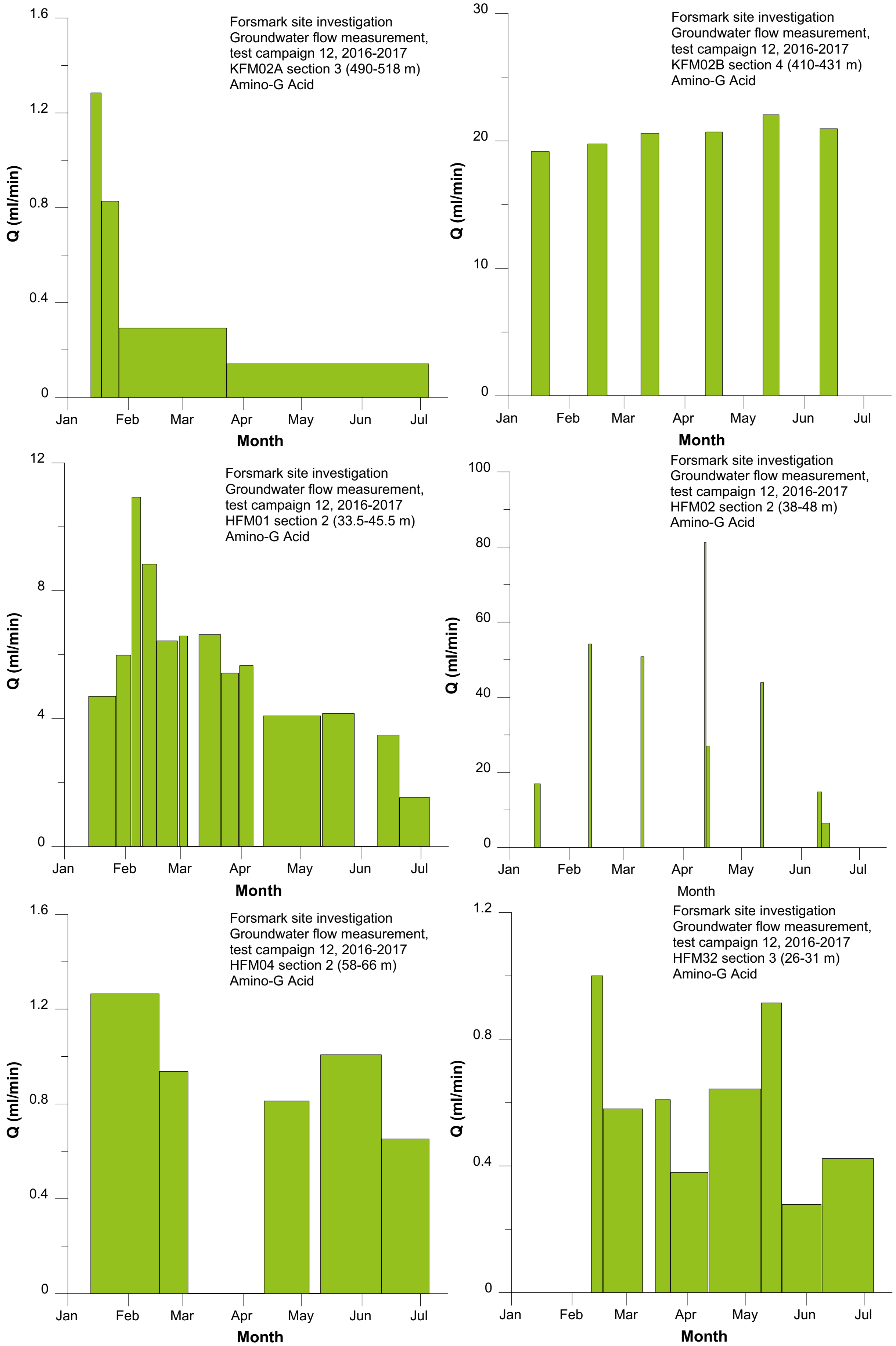

Figure 5-3. *Measured flow rates January – July 2017 for each section, test campaign 12, 2016–2017.*

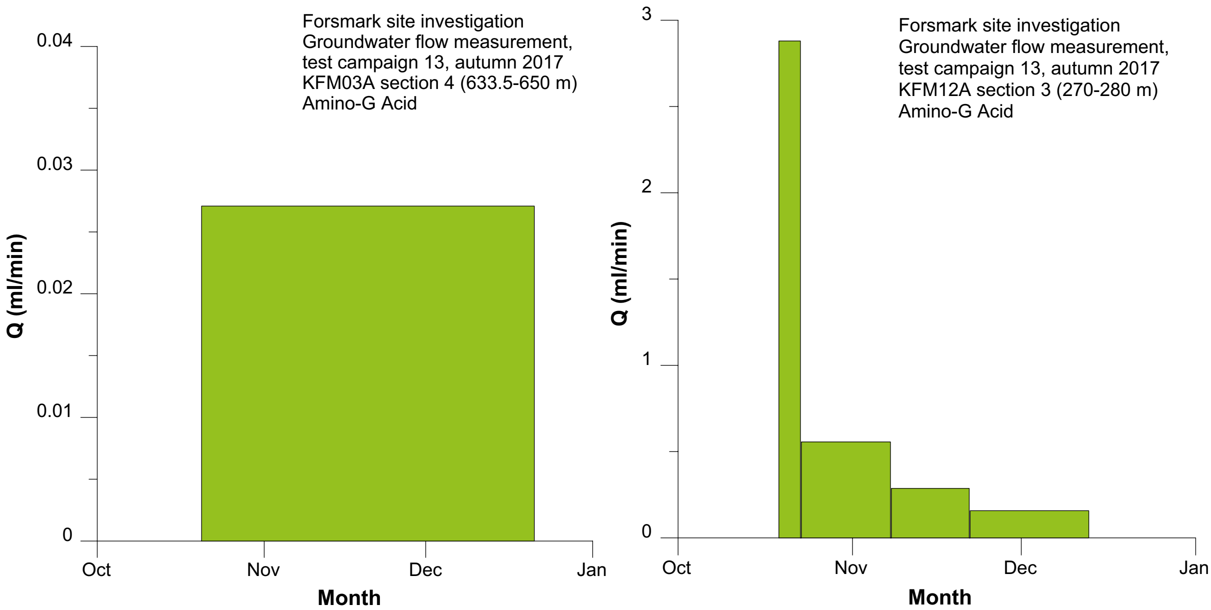

Figure 5-4. *Measured flow rates October – December 2017 for each section, test campaign 13, autumn 2017.*

The results show that the groundwater flow varies a lot over the year in most of the measured sections. In six sections out of fourteen the flow measured during the first 100 to 400 hours is about four up to more than thirty times higher compared to the flow towards the end of the measurement period. This is probably due to effects at start-up such as the mixing procedure and/or the injection process causing disturbances resulting in an enhanced flow.

In some sections the groundwater flow rate is low and consists to a substantial part of the sampling flow rate. One could also expect that the sampling rate, calculated from the measured sample volume in the tubes, is somewhat underestimated due to evaporation.

In general, the equipment has worked well and no major hydraulic disturbance has occurred during the tests, cf. Appendix 2. Malfunctioning samplers caused longer interruptions (month) in the measurements in boreholes KFM02A and HFM04. There were also minor interruptions (week) in some sections due to pump failures, clogging of tubes, malfunctioning samplers and, for HFM32, the ice-conditions. However, none of this is considered to have affected the results. Interference tests performed in October 2016 with pumping in KFM24 caused pressure responses in several sections in KFM08A, including section 6 where groundwater flow measurement was ongoing. No response in flow rate could be seen, minor responses could however be hidden behind the effect of evaporation discussed below.

During the long-term measurements performed 2013 (test campaign no. 9) a problem with evaporation of water from the samples was discovered (Wass 2015). Therefore, during the following test campaigns each sampler has been placed in a plastic box together with four small bottles containing fresh water in order to prevent, or at least reduce, evaporation. Attendance has been made about once a week including collection of samples, in-between the sampling tubes were open without caps inside the plastic box. When water evaporates from a sample the concentration of tracer becomes higher. Some effect of this could still be seen in most measured sections, with sudden jumps in tracer concentration that coincide with a set of collected samples. The influence of evaporation is also often more obvious during the winter period when the air is drier and the electric heaters in the containers are on. No correction of data has been made because it has not been possible to determine to which extent each sample has been affected.

The results show that the groundwater flow during natural conditions varies from 0.02 to 81 ml/min in the measured sections with Darcy velocities ranging from 9.5×10^{-11} to 4.9×10^{-7} m/s.

Hydraulic gradients are calculated according to the Darcy concept and are within the expected range in the majority of the measured sections. It should be noted that the Darcy concept is built on assumptions of a homogeneous porous medium and values for a fractured medium should therefore be treated with great care. For the first 100 hours in both KFM01A:5 and KFM12A:3, the first 900 hours in KFM01D:4 and for the whole measured period in KFM02B:4 the hydraulic gradient is very large. This indicates that the flow rates measured during these periods are higher than expected. The large gradients may also be due to rough estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture.

5.3 Flow rate comparison

For comparison reasons flow rates obtained from previously performed test campaigns are compiled in Table 5-3.

The comparison shows that the flow rates measured 2016–2017 and autumn 2017 are within the range of the values measured in previous campaigns in most borehole sections. In six sections the flow measured during the first 100 to 400 hours is much higher compared to the flow towards the end of the measurement period. The higher flow is in general consistent with the results gained from previous measurements. In previous test campaigns the measurement duration has been about 200 hours, why the flow rates presented in Table 5-3 probably are overestimated.

The flow rates in HFM01:2 and HFM02:2 were more varying through the measured period than during previous test campaigns. In KFM01D:2 and KFM02B:4 similar flow rates were measured throughout the entire period and they are also consistent with the results from earlier years. Also in KFM03A:4 an even flow rate was measured during the entire test period, however considerably lower than ever measured before.

Table 5-3. Results from groundwater flow measurements in previously performed test campaigns in the selected borehole sections.

Borehole: sec	2005 Wass (2006) (ml/min)	2006 Wass (2007) (ml/min)	2007 Wass (2008) (ml/min)	2008 Wass (2009) (ml/min)	2009 Wass (2010) (ml/min)	2010 Thur and Wass (2011) (ml/min)	2011 Thur and Wass (2012) (ml/min)	2012 Ragvald and Wass (2013) (ml/min)	2016–2017, autumn–17 (ml/min)
KFM01A:5	–	0.1	0.2	0.1	0.06	0.05	0.1	0.05	0.02–0.7
KFM01D:2	–	–	0.3	0.04	0.06	0.04	0.08	0.1	0.06
KFM01D:4	–	–	0.2	0.2	0.7	0.1	0.2	0.1	0.1–0.3
KFM04A:4	–	–	16	8.0	2.5	6.1	6.8	3.0	1.1–4.0
KFM08A:6	–	–	0.2	0.06	0.1	0.1	0.2	0.2	0.02–0.3
KFM11A:2	–	–	0.2	0.3	0.5	0.9	0.6	0.6	0.2–0.8
KFM02A:3	2.1	0.8	0.8	1.2	1.6	1.4	1.2	0.8	0.1–1.3
KFM02B:4	–	–	23	35	30	27	23	30	19–22
HFM01:2	–	–	7.8	6.3	5.7	5.8	3.4	5.3	1.5–11
HFM02:2	38	8.9–38	33	23	22	13	6.9	5.2	6.5–81
HFM04:2	2.2	10.4	0.8	2.6	1.4	1.8	1.6	1.0	0.7–1.3
HFM32:3	–	0.5	–	1.2	–	–	–	0.8	0.3–1.0
KFM03A:4	0.5	0.5	0.6	1.1	0.4	0.4	0.8	0.3	0.03
KFM12A:3	–	–	0.3	1.8	0.3	0.4	1.2	0.6	0.2–2.9

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

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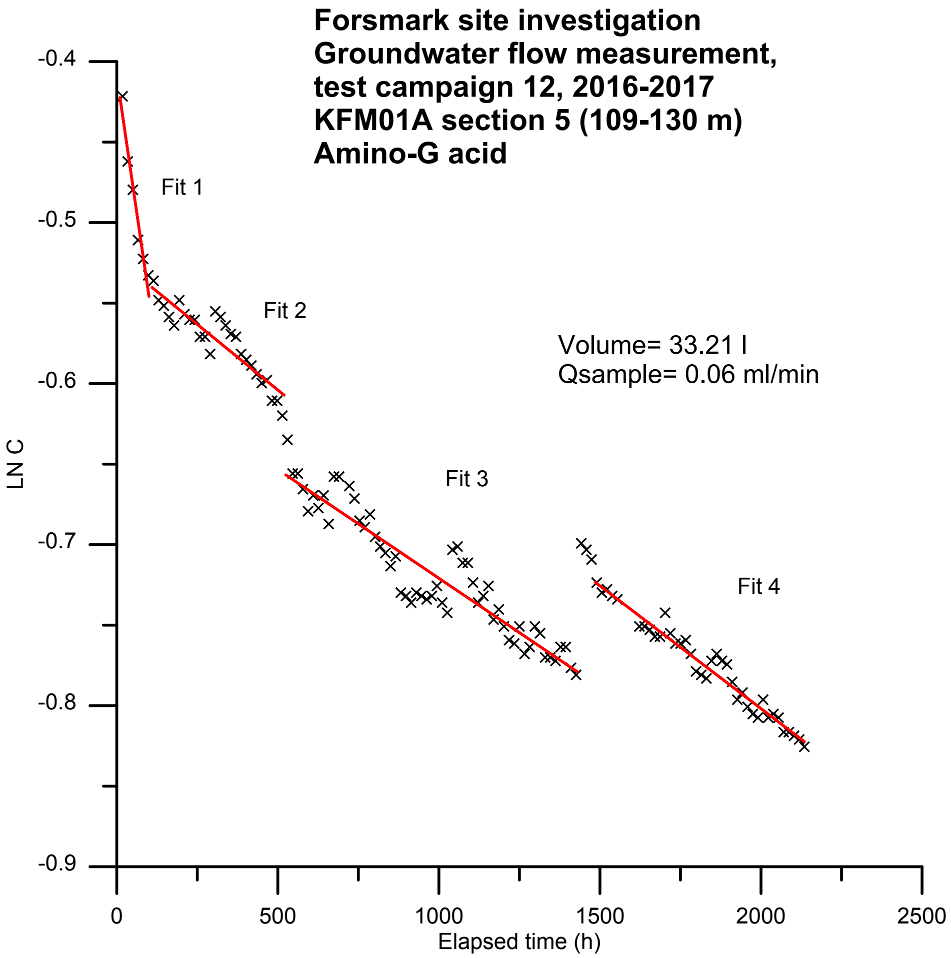
Tracer dilution graphs

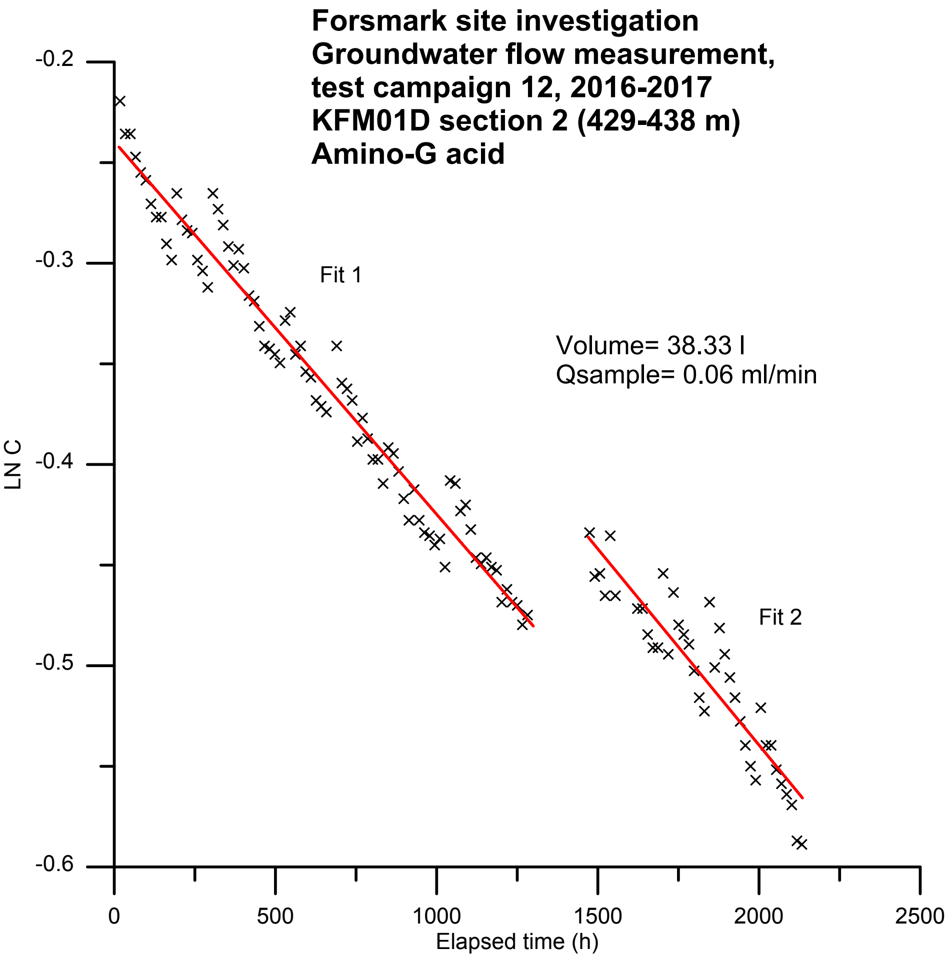


Fit 1: 10-100 h
Y = -0.00137220 * X - 0.4086
Number of data points used = 6
R-squared = 0.951069
Q= 0.70 ml/min

Fit 2: 110-520 h
Y = -0.00016312 * X - 0.5224
Number of data points used = 26
R-squared = 0.83712
Q= 0.03 ml/min

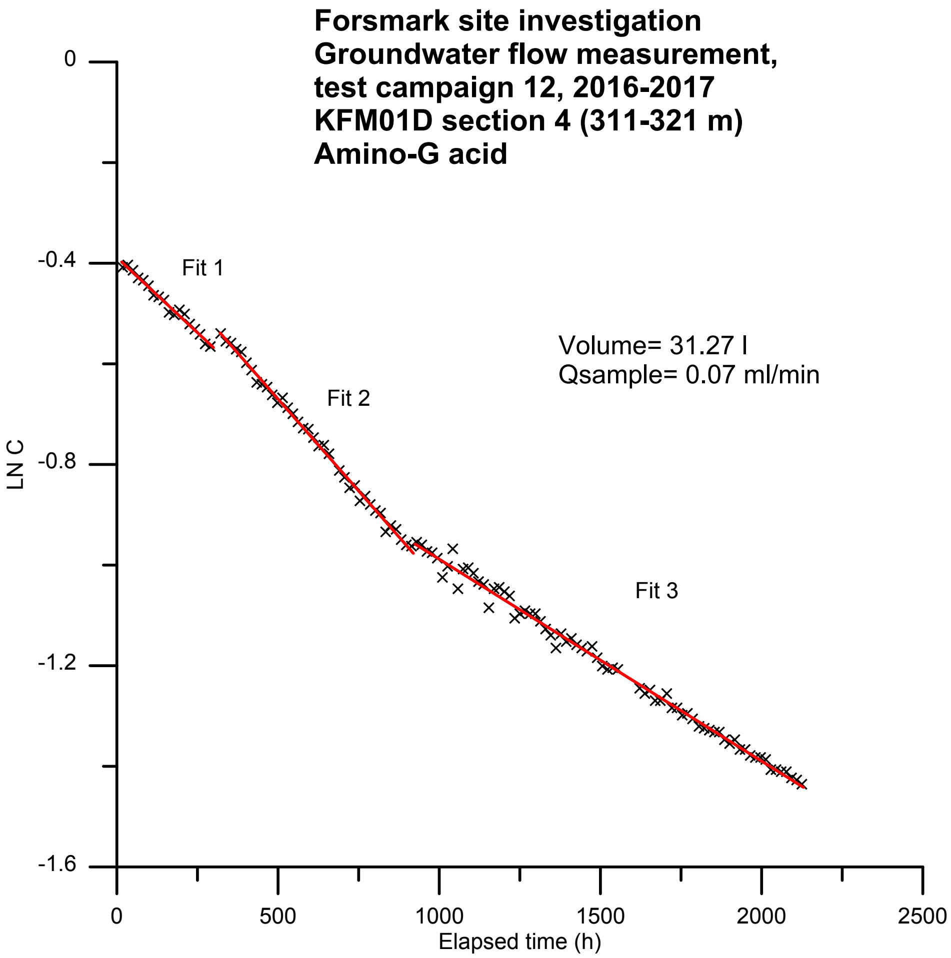
Fit 3: 520-1430 h
Y = -0.00013511 * X - 0.5858
Number of data points used = 56
R-squared = 0.878395
Q= 0.02 ml/min

Fit 4: 1480-2140 h
Y = -0.00015246 * X - 0.4969
Number of data points used = 38
R-squared = 0.959932
Q= 0.03 ml/min



Fit 1: 10-1300 h
Y = -0.00018523 * X - 0.2395
Number of data points used = 79
R-squared = 0.965249
Q= 0.06 ml/min

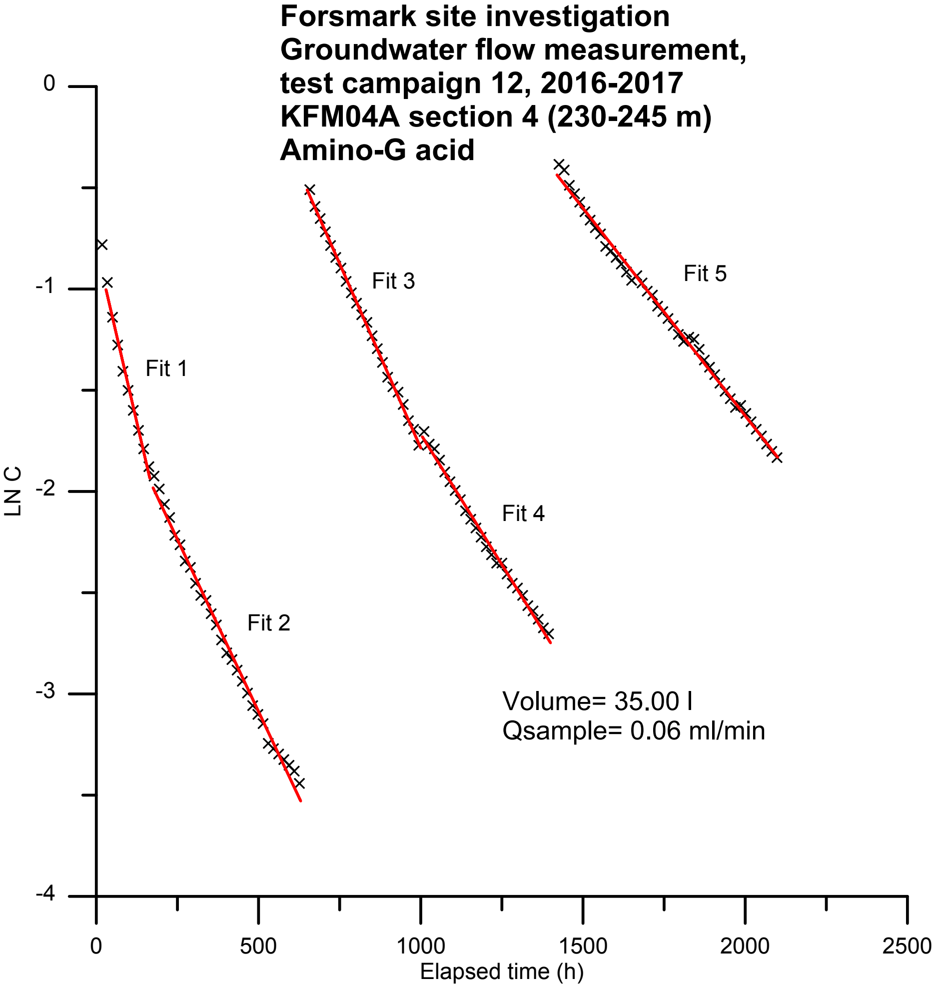
Fit 2: 1470-2140 h
Y = -0.00019496 * X - 0.1495
Number of data points used = 39
R-squared = 0.842061
Q= 0.06 ml/min



Fit 1: 10-300 h
Y = -0.00059733 * X - 0.3886
Number of data points used = 18
R-squared = 0.981938
Q= 0.24 ml/min

Fit 2: 320-920 h
Y = -0.00073047 * X - 0.3046
Number of data points used = 37
R-squared = 0.996469
Q= 0.31 ml/min

Fit 3: 920-2130 h
Y = -0.00040140 * X - 0.5868
Number of data points used = 72
R-squared = 0.992941
Q= 0.14 ml/min



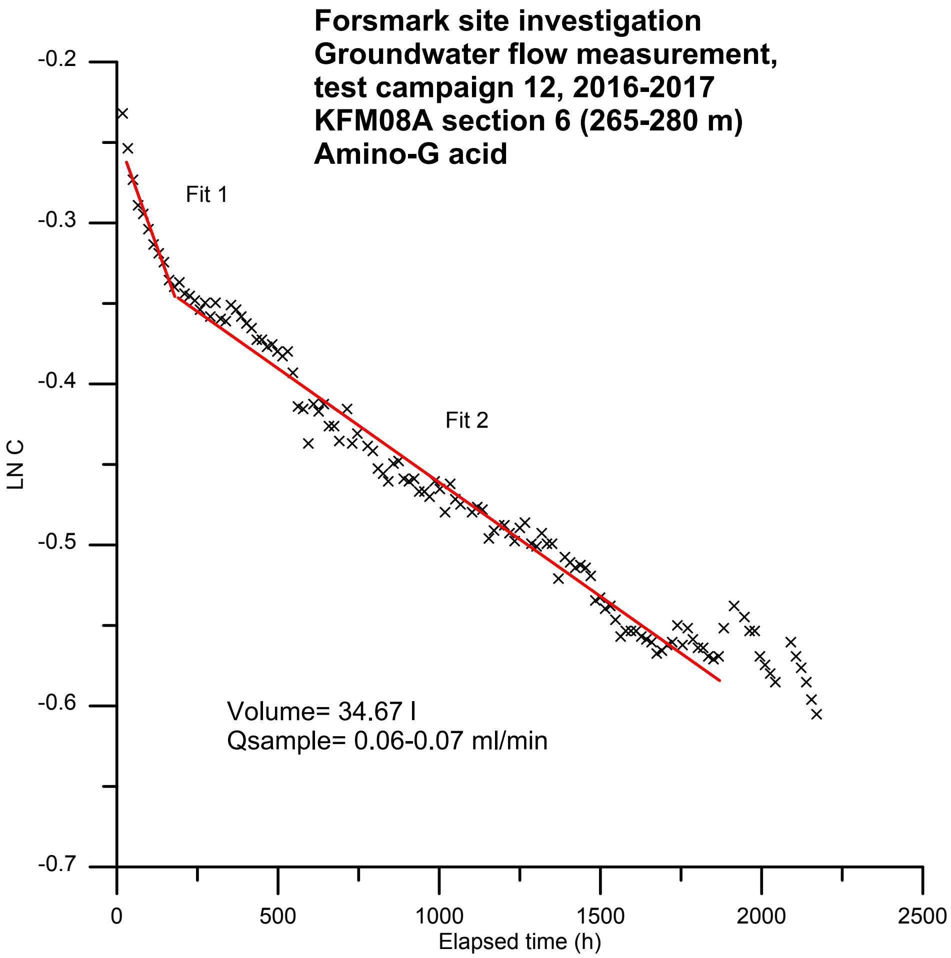
Fit 1: 20-170 h
Y = -0.00690245 * X - 0.7964
Number of data points used = 9
R-squared = 0.987537
Q= 4.0 ml/min

Fit 2: 170-630 h
Y = -0.00340020 * X - 1.387
Number of data points used = 29
R-squared = 0.993614
Q= 1.9 ml/min

Fit 3: 650-1000 h
Y = -0.00364146 * X + 1.856
Number of data points used = 22
R-squared = 0.998748
Q= 2.1 ml/min

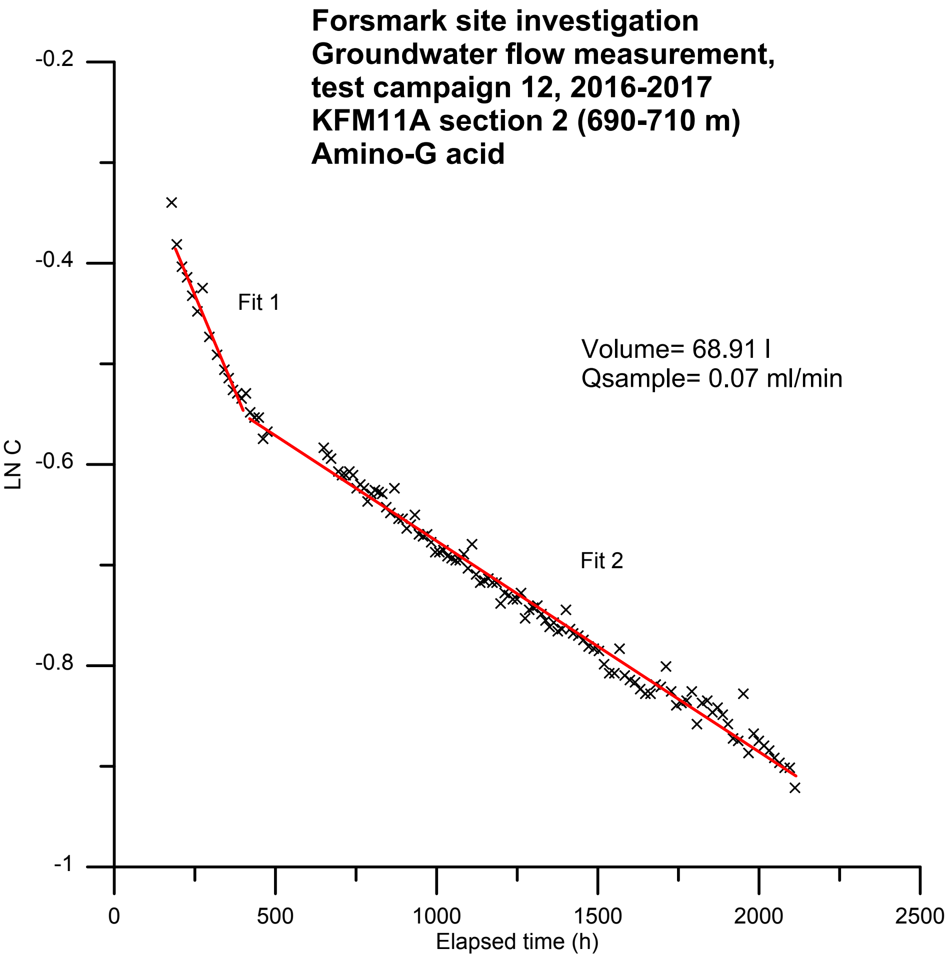
Fit 4: 1000-1400 h
Y = -0.00257672 * X + 0.8596
Number of data points used = 25
R-squared = 0.994568
Q= 1.4 ml/min

Fit 5: 1420-2100 h
Y = -0.00205062 * X + 2.475
Number of data points used = 43
R-squared = 0.995901
Q= 1.1 ml/min



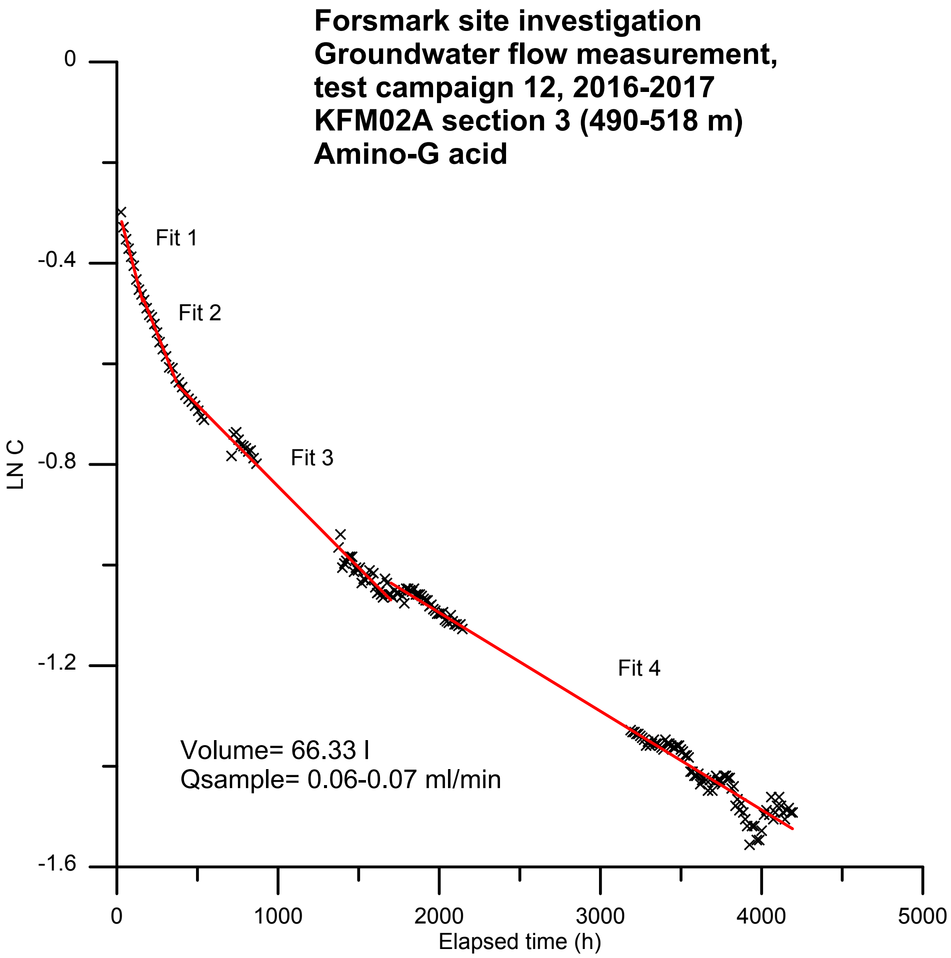
Fit 1: 20-190 h
Y = -0.00055708 * X - 0.2455
Number of data points used = 10
R-squared = 0.964993
Q= 0.26 ml/min

Fit 2: 190-1880 h
Y = -0.00014152 * X - 0.3196
Number of data points used = 102
R-squared = 0.976916
Q= 0.02 ml/min



Fit 1: 190-400 h
Y = -0.00076474 * X - 0.2404
Number of data points used = 13
R-squared = 0.968661
Q= 0.80 ml/min

Fit 2: 420-2115 h
Y = -0.00020949 * X - 0.4665
Number of data points used = 111
R-squared = 0.987142
Q= 0.18 ml/min

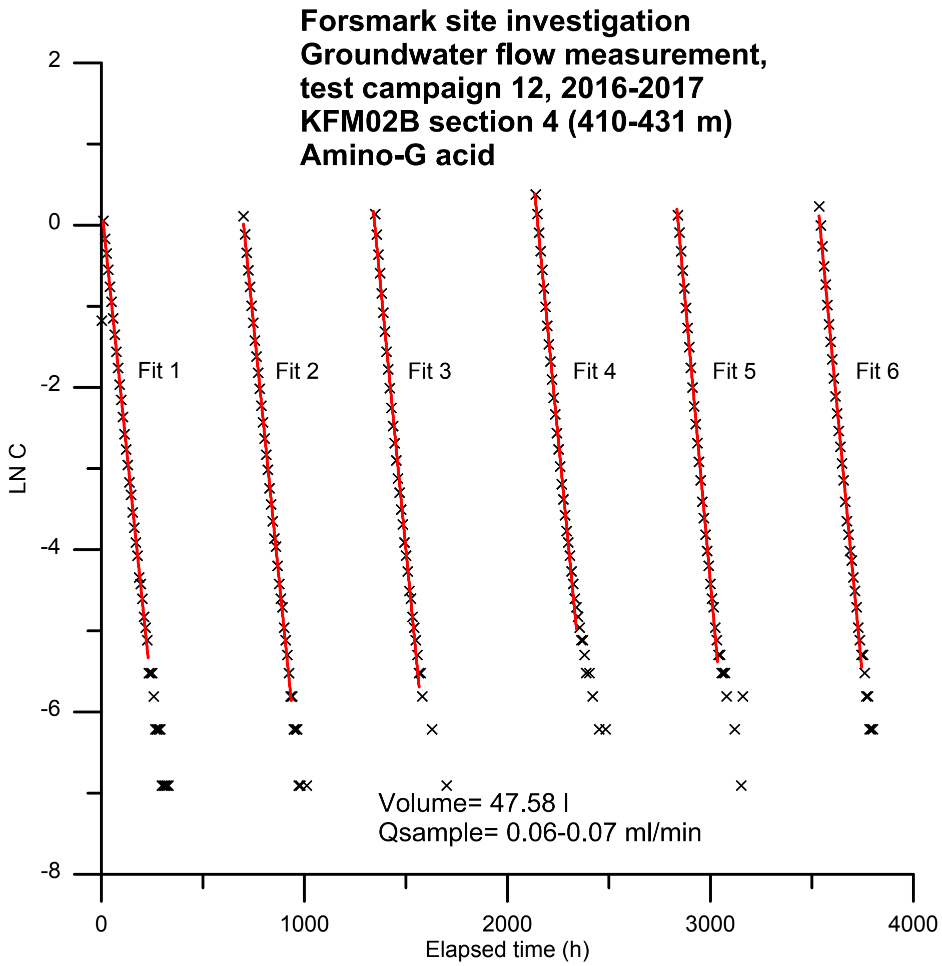


Fit 1: 30-160 h
Y = -0.00121809 * X - 0.2806
Number of data points used = 8
R-squared = 0.993961
Q= 1.3 ml/min

Fit 2: 160-380 h
Y = -0.00080255 * X - 0.3388
Number of data points used = 12
R-squared = 0.9926
Q= 0.83 ml/min

Fit 3: 380-1700 h
Y = -0.00032287 * X - 0.5205
Number of data points used = 48
R-squared = 0.990521
Q= 0.29 ml/min

Fit 4: 1700-4200 h
Y = -0.00019606 * X - 0.7022
Number of data points used = 119
R-squared = 0.984705
Q= 0.14 ml/min



Fit 1: 10-230 h
Y = -0.02423989 * X + 0.2407
Number of data points used = 28
R-squared = 0.999133
Q = 19 ml/min

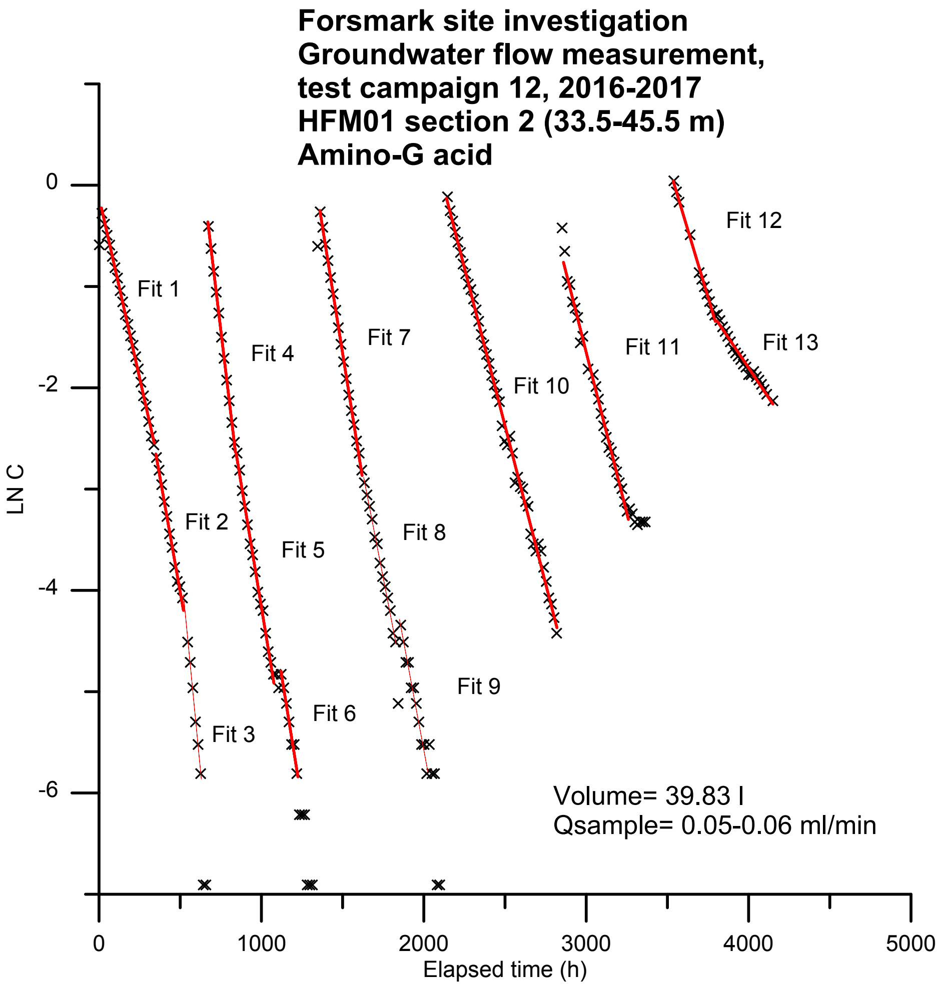
Fit 2: 700-940 h
Y = -0.02499584 * X + 17.51
Number of data points used = 30
R-squared = 0.999184
Q = 20 ml/min

Fit 3: 1340-1570 h
Y = -0.02606002 * X + 35.09
Number of data points used = 28
R-squared = 0.995918
Q = 21 ml/min

Fit 4: 2140-2340 h
Y = -0.02618270 * X + 56.29
Number of data points used = 25
R-squared = 0.997217
Q = 21 ml/min

Fit 5: 2840-3040 h
Y = -0.02788881 * X + 79.26
Number of data points used = 25
R-squared = 0.997692
Q = 22 ml/min

Fit 6: 3530-3750 h
Y = -0.02650739 * X + 93.82
Number of data points used = 27
R-squared = 0.99781
Q = 21 ml/min



Fit 1:10-350 h
Y = -0.00714812 * X - 0.1170
No. of data points used = 21
R-squared = 0.998763
Q = 4.7 ml/min

Fit 2: 350-520 h
Y = -0.00909114 * X + 0.5281
No. of data points used = 11
R-squared = 0.993356
Q = 6.0 ml/min

Fit 3: 520-630 h
Y = -0.01654585 * X + 4.561
No. of data points used = 6
R-squared = 0.995955
Q = 10.9 ml/min

Fit 4: 670-840 h
Y = -0.01337955 * X + 8.602
No. of data points used = 11
R-squared = 0.999806
Q = 8.8 ml/min

Fit 5: 840-1080 h
Y = -0.00975930 * X + 5.594
No. of data points used = 15
R-squared = 0.996503
Q = 6.4 ml/min

Fit 6: 1120-1230 h
Y = -0.00997139 * X + 6.373
No. of data points used = 7
R-squared = 0.979335
Q = 6.6 ml/min

Fit 7: 1360-1630 h
Y = -0.01006565 * X + 13.44
No. of data points used = 17
R-squared = 0.999402
Q = 6.6 ml/min

Fit 8: 1630-1840 h
Y = -0.00824658 * X + 10.56
No. of data points used = 13
R-squared = 0.99707
Q = 5.4 ml/min

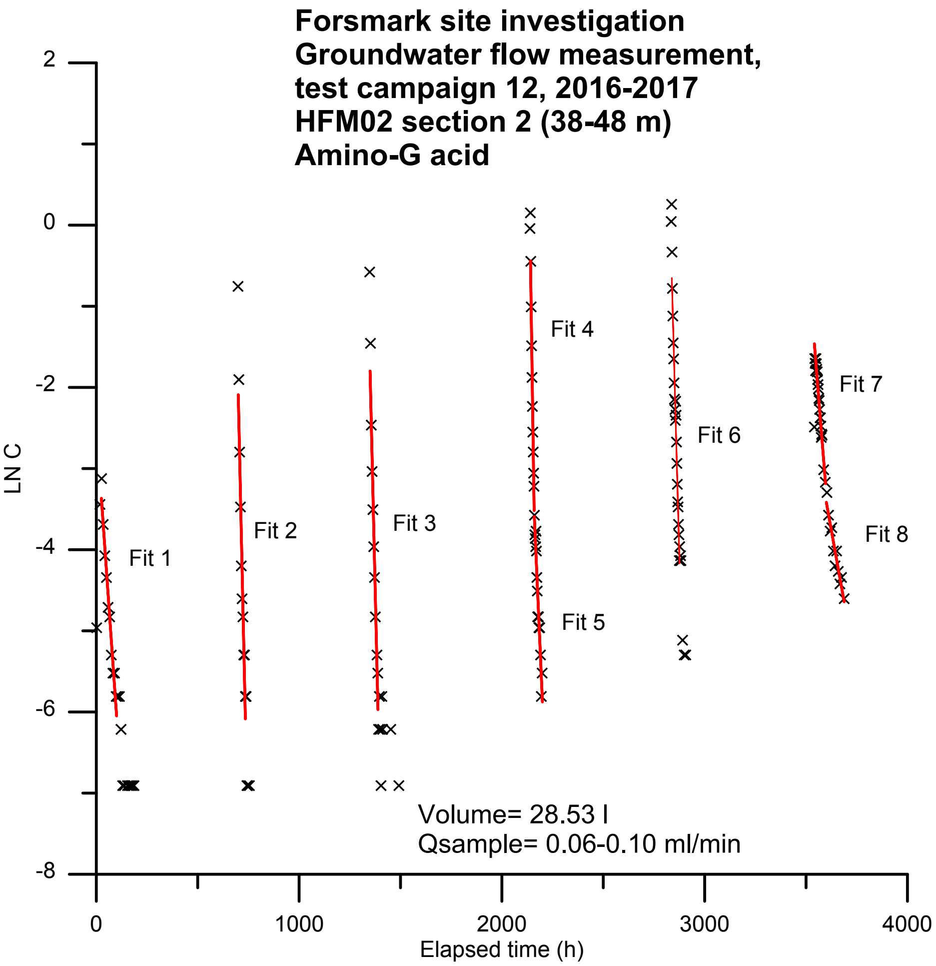
Fit 9: 1850-2030 h
Y = -0.00860262 * X + 11.63
No. of data points used = 11
R-squared = 0.981119
Q = 5.7 ml/min

Fit 10: 2140-2820 h
Y = -0.00623477 * X + 13.21
No. of data points used = 43
R-squared = 0.997297
Q = 4.1 ml/min

Fit 11: 2860-3260 h
Y = -0.00634873 * X + 17.40
No. of data points used = 23
R-squared = 0.994445
Q = 4.2 ml/min

Fit 12: 3540-3800 h
Y = -0.00534315 * X + 18.93
No. of data points used = 11
R-squared = 0.997041
Q = 3.5 ml/min

Fit 13: 3800-4150 h
Y = -0.00238731 * X + 7.746
No. of data points used = 21
R-squared = 0.977228
Q = 1.5 ml/min



Fit 1: 20-100 h
Y = -0.03577059 * X - 2.474
Number of data points used = 10
R-squared = 0.967901
Q=17 ml/min

Fit 2: 700-735 h
Y = -0.11418063 * X + 77.83
Number of data points used = 9
R-squared = 0.940287
Q=54 ml/min

Fit 3: 1350-1390 h
Y = -0.10703866 * X + 142.7
Number of data points used = 9
R-squared = 0.953655
Q=51 ml/min

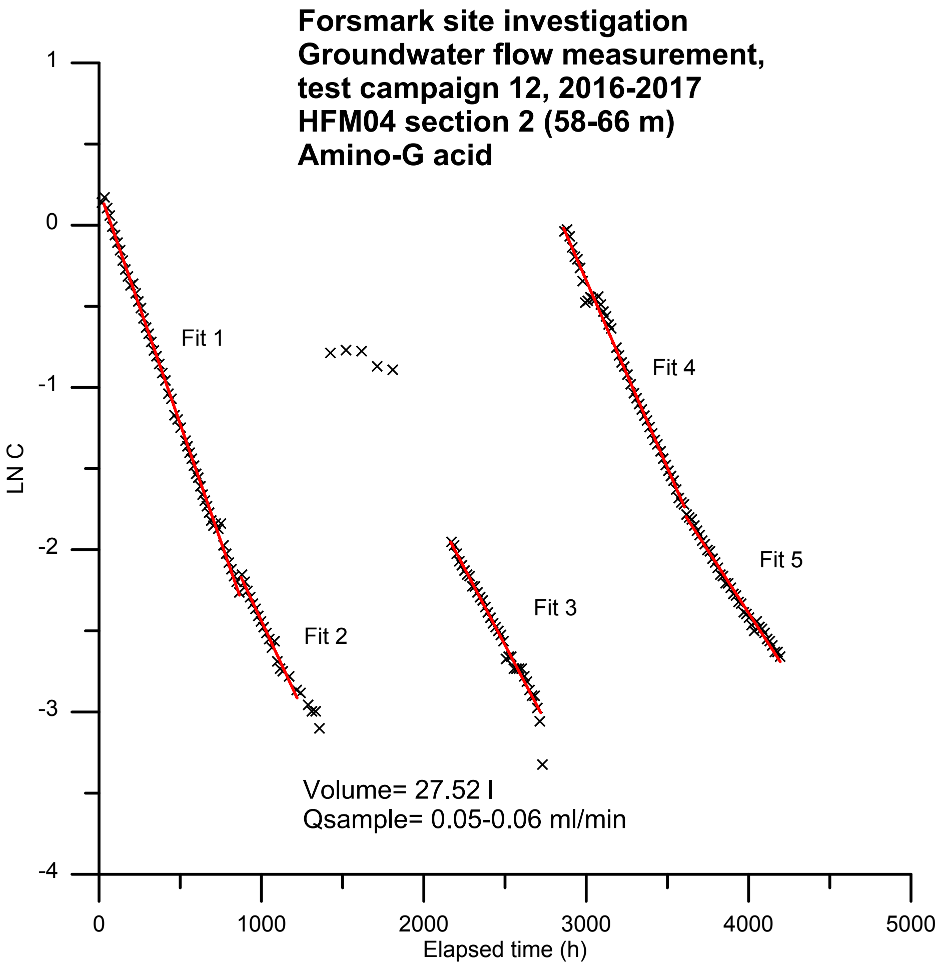
Fit 4: 2140-2160 h
Y = -0.17110546 * X + 365.9
Number of data points used = 9
R-squared = 0.972749
Q=81 ml/min

Fit 5: 2160-2200 h
Y = -0.05709928 * X + 119.7
Number of data points used = 17
R-squared = 0.939329
Q=27 ml/min

Fit 6: 2840-2880 h
Equation Y = -0.09256801 * X + 262.1
Number of data points used = 19
R-squared = 0.968254
Q= 44 ml/min

Fit 7: 3540-3600 h
Y = -0.03136086 * X + 109.6
Number of data points used = 21
R-squared = 0.971731
Q = 15 ml/min

Fit 8: 3600-3690 h
Y = -0.01394081 * X + 46.77
Number of data points used = 11
R-squared = 0.924294
Q = 6.5 ml/min



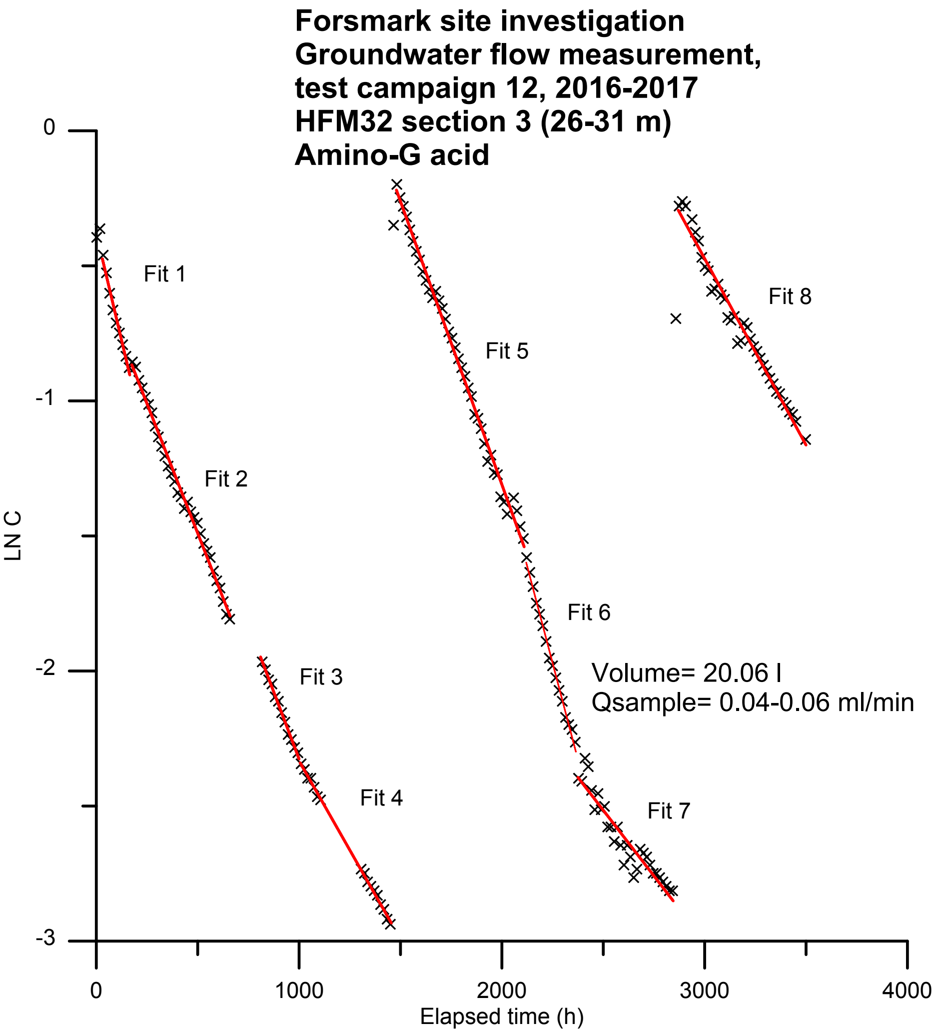
Fit 1: 20-870 h
Y = -0.00288932 * X + 0.2179
Number of data points used = 53
R-squared = 0.998603
Q = 1.3 ml/min

Fit 2: 870-1220 h
Y = -0.00215714 * X - 0.2834
Number of data points used = 18
R-squared = 0.984673
Q= 0.94 ml/min

Fit 3: 2160-2720 h
Y = -0.00189631 * X + 2.152
Number of data points used = 35
R-squared = 0.993793
Q= 0.81 ml/min

Fit 4: 2860-3610 h
Y = -0.00230946 * X + 6.59
Number of data points used = 45
R-squared = 0.994444
Q = 1.0 ml/min

Fit 5: 3610-4200 h
Y = -0.00153997 * X + 3.77
Number of data points used = 37
R-squared = 0.990863
Q = 0.65 ml/min



Fit 1: 20-170 h
Y = -0.00318608 * X - 0.3783
Number of data points used = 9
R-squared = 0.984674
Q= 1.0 ml/min

Fit 2: 170-660 h
Y = -0.00191877 * X - 0.5303
Number of data points used = 31
R-squared = 0.993796
Q= 0.58 ml/min

Fit 3: 810-1000 h
Y = -0.00198802 * X - 0.3378
Number of data points used = 12
R-squared = 0.995038
Q= 0.61 ml/min

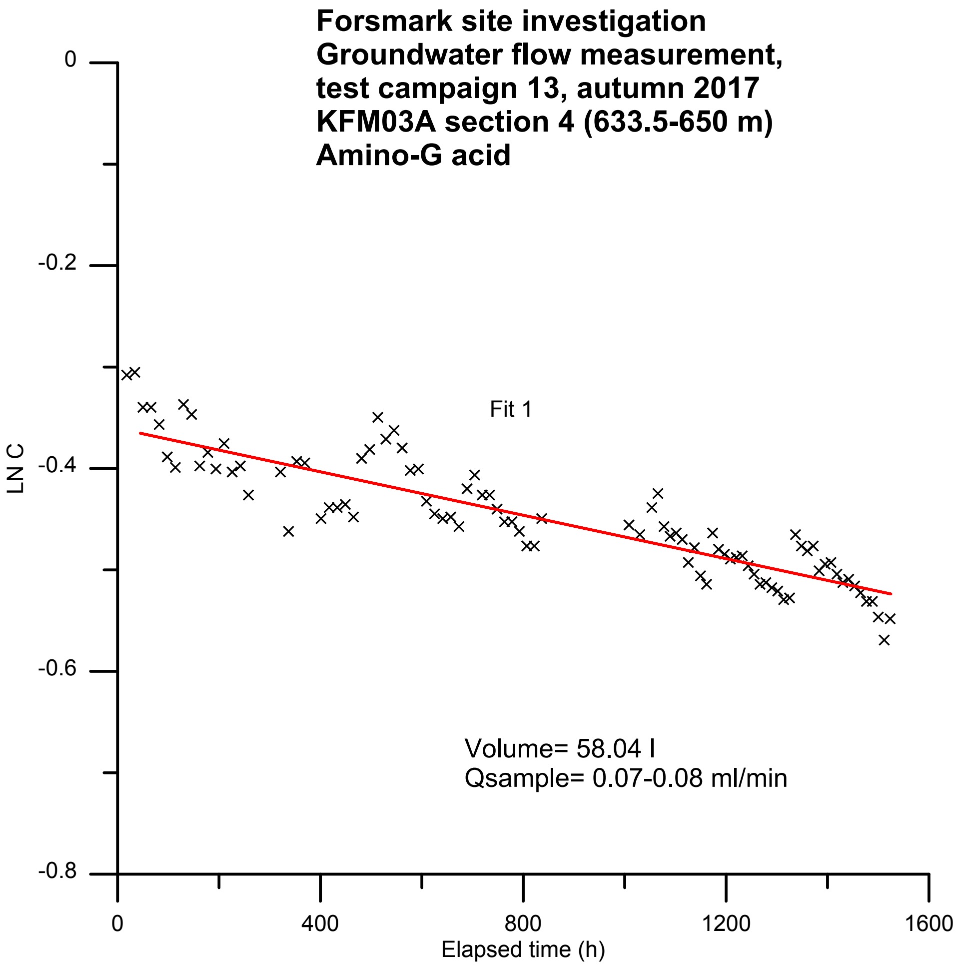
Fit 4: 1000-1460 h
Y = -0.00131959 * X - 1.013
Number of data points used = 17
R-squared = 0.998665
Q= 0.38 ml/min

Fit 5: 1480-2110 h
Y = -0.00209659 * X + 2.884
Number of data points used = 39
R-squared = 0.993582
Q= 0.64 ml/min

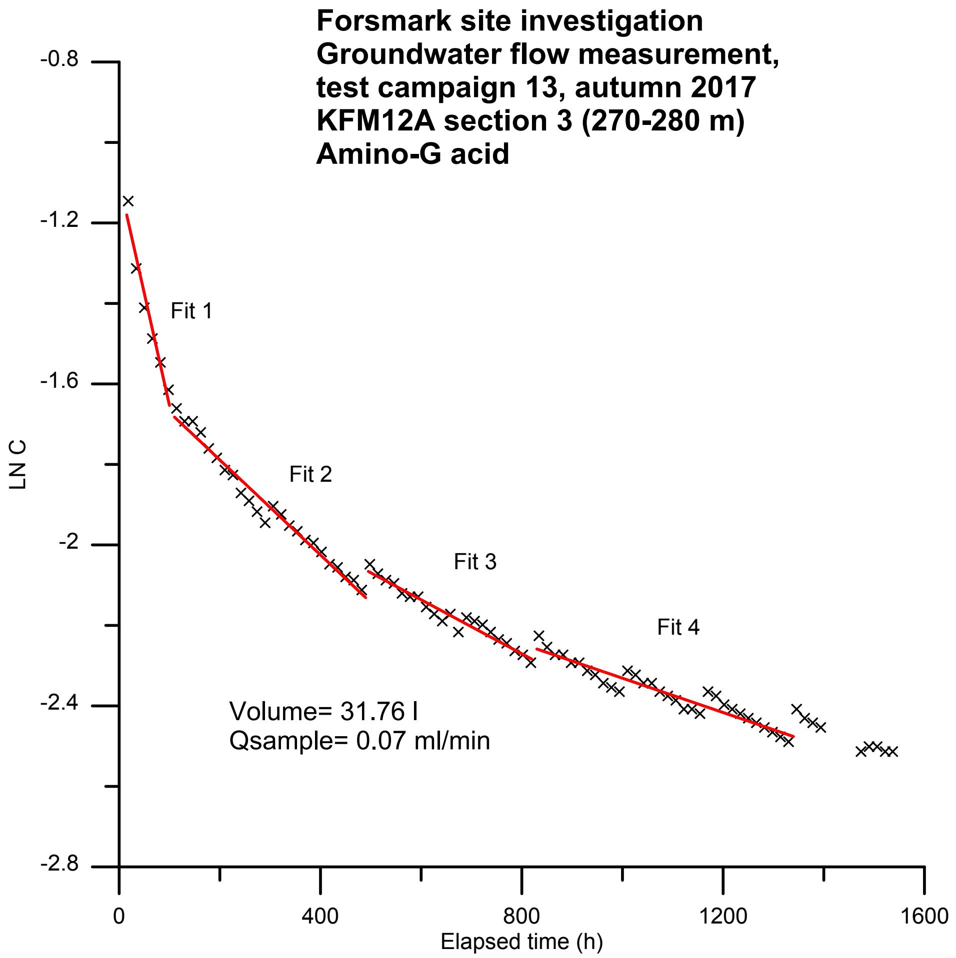
Fit 6: 2120-2370 h
Y = -0.00286033 * X + 4.466
Number of data points used = 16
R-squared = 0.994389
Q= 0.91 ml/min

Fit 7: 2370-2850 h
Y = -0.00097316 * X - 0.0823
Number of data points used = 30
R-squared = 0.893467
Q= 0.28 ml/min

Fit 8: 2870-3500 h
Y = -0.00137999 * X + 3.667
Number of data points used = 37
R-squared = 0.979525
Q= 0.42 ml/min



Fit 1: 50-1530 h
Equation Y = -0.00010705 * X - 0.3605
Number of data points used = 90
R-squared = 0.793939
Q= 0.03 ml/min



Fit 1: 10-100 h
Y = -0.00557254 * X - 1.096
Number of data points used = 6
R-squared = 0.958856
Q= 2.9 ml/min

Fit 2: 110-490 h
Y = -0.00118108 * X - 1.552
Number of data points used = 24
R-squared = 0.976314
Q= 0.56 ml/min

Fit 3: 495-820 h
Y = -0.00067082 * X - 1.734
Number of data points used = 21
R-squared = 0.957513
Q= 0.29 ml/min

Fit 4: 830-1340 h
Y = -0.00042636 * X - 1.905
Number of data points used = 32
R-squared = 0.915384
Q= 0.16 ml/min

Appendix 2

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

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

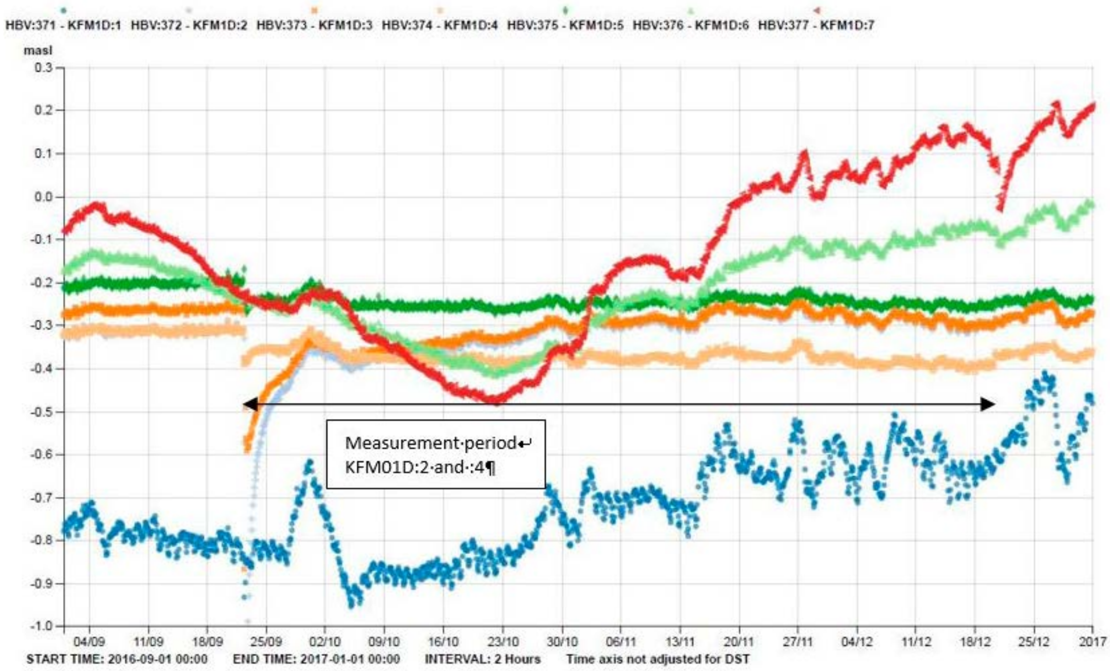
The deepest section = section 1
section 2
section 3
section 4
section 5
section 6
section 7
section 8
section 9
section 10

2016-09-01–2017-01-01

KFM01A

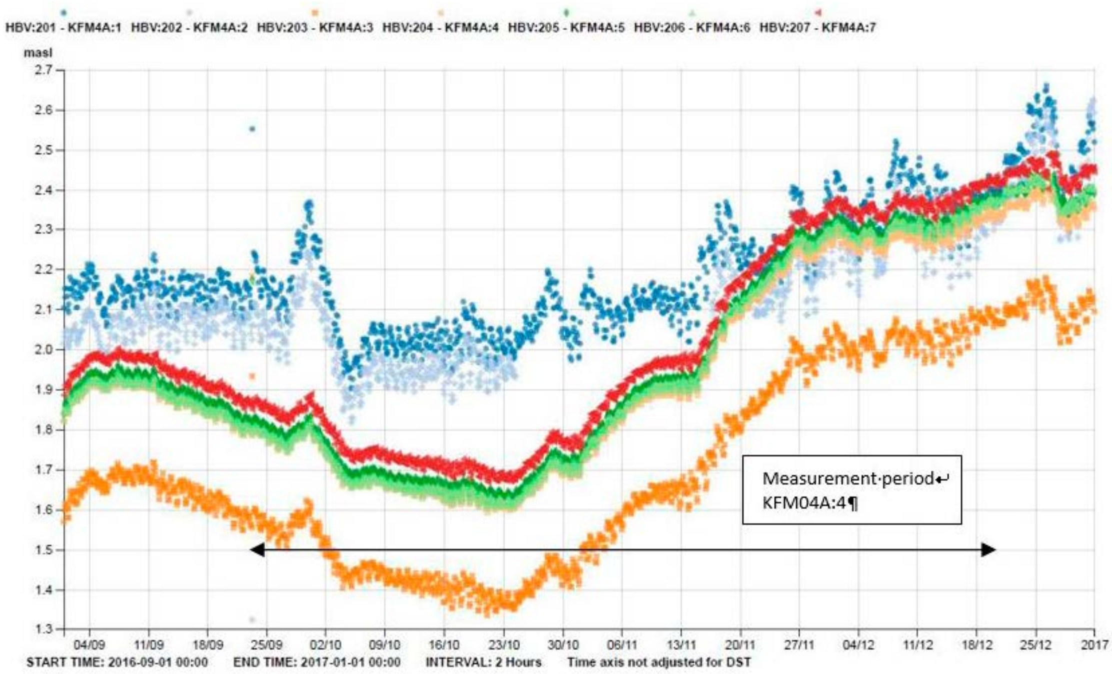
Measured section: KFM01A:5, dark green

KFM01D



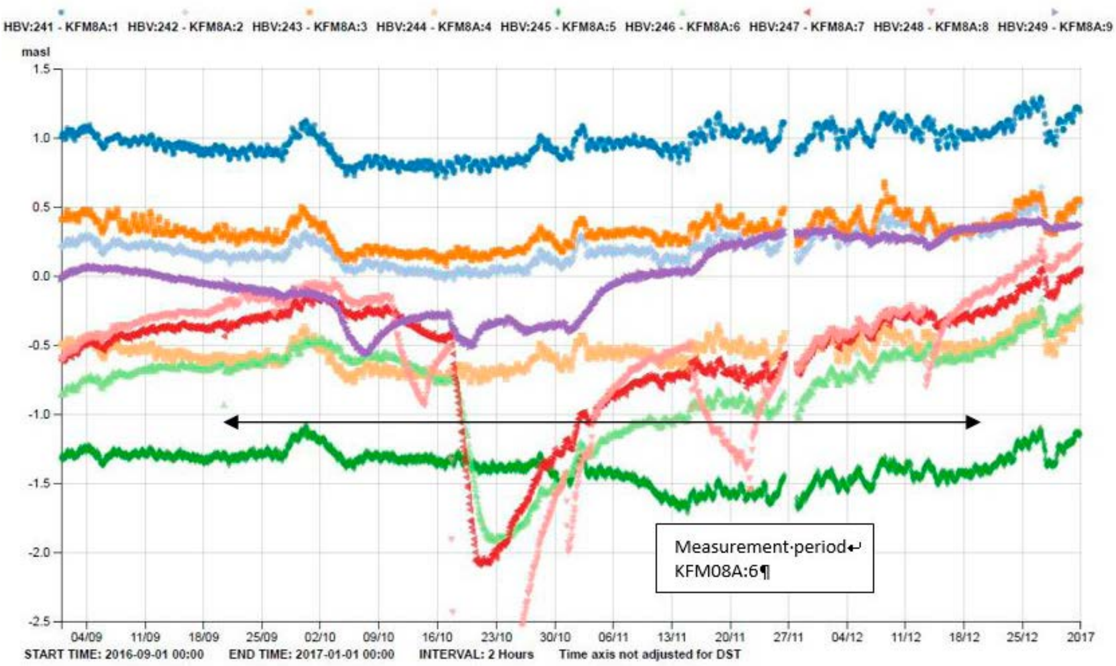
Measured sections: KFM01D:2, pale blue (behind section 3, dark orange), and KFM01D:4, pale orange

KFM04A



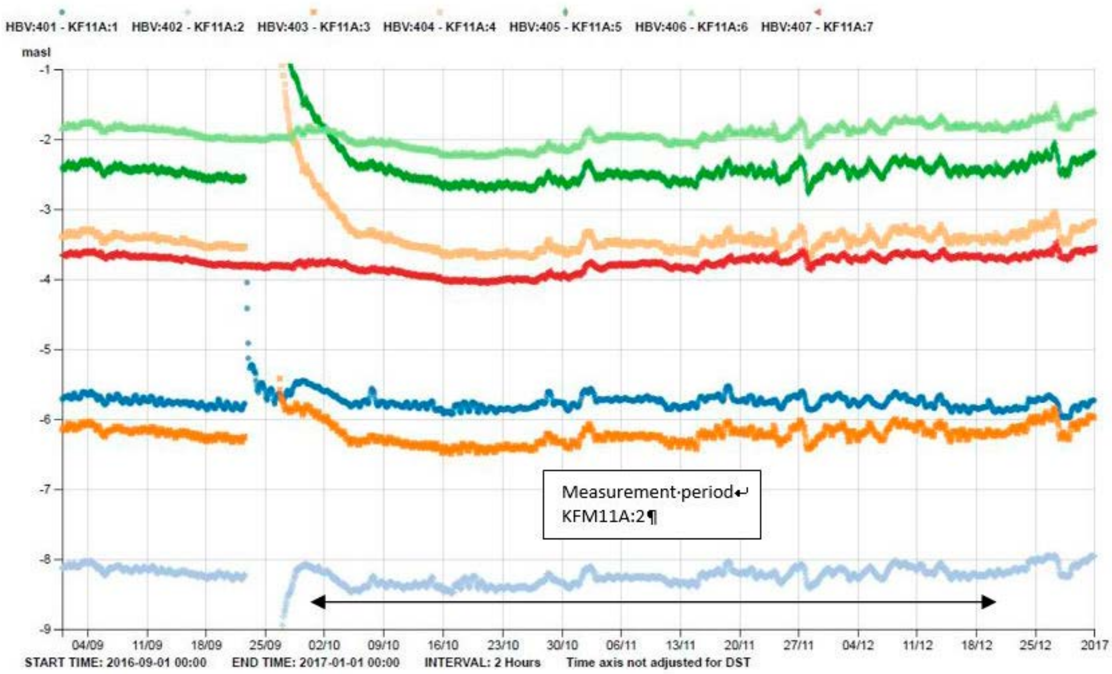
Measured section: KFM04A:4, pale orange

KFM08A



Measured section: KFM08A:6, pale green

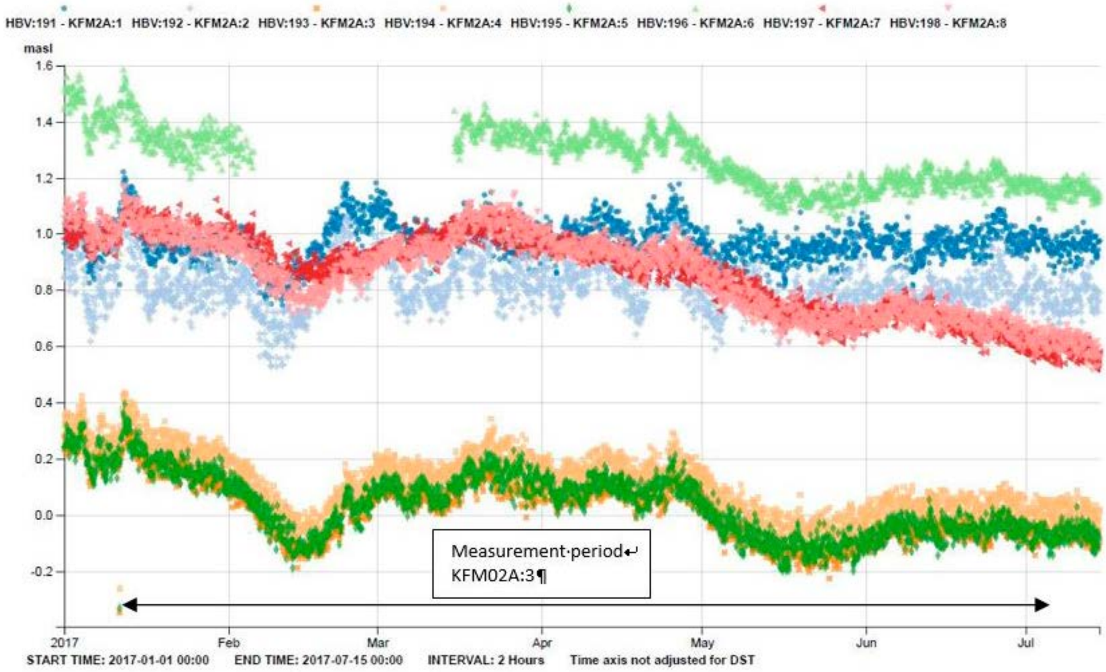
KFM11A



Measured section: KFM11A:2, pale blue

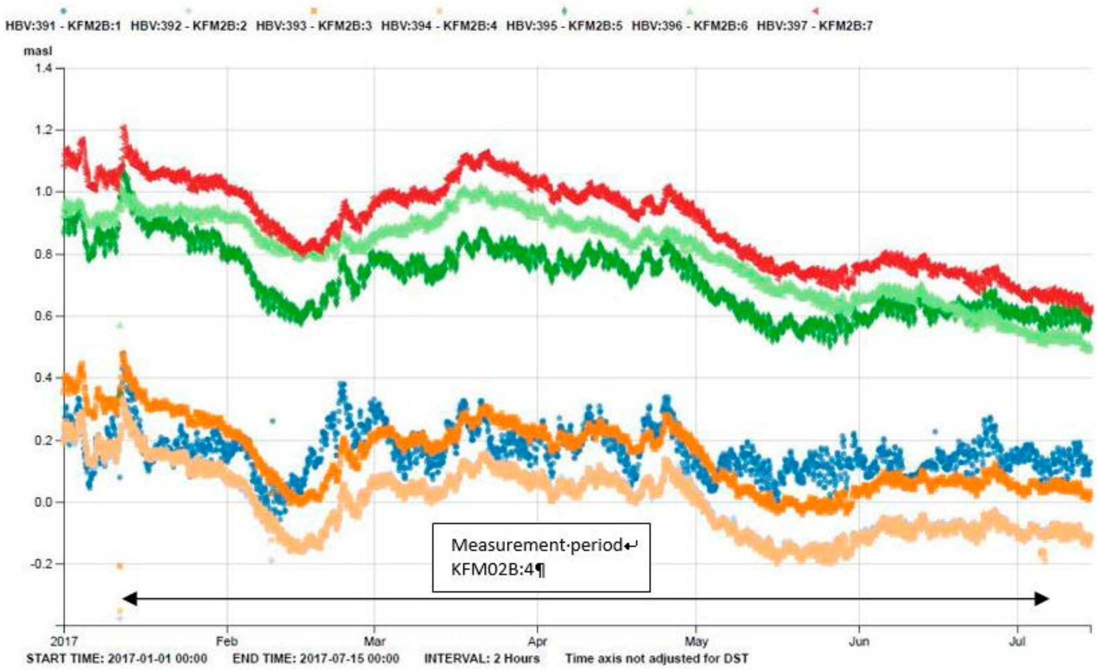
2017-01-01–2017-07-15

KFM02A



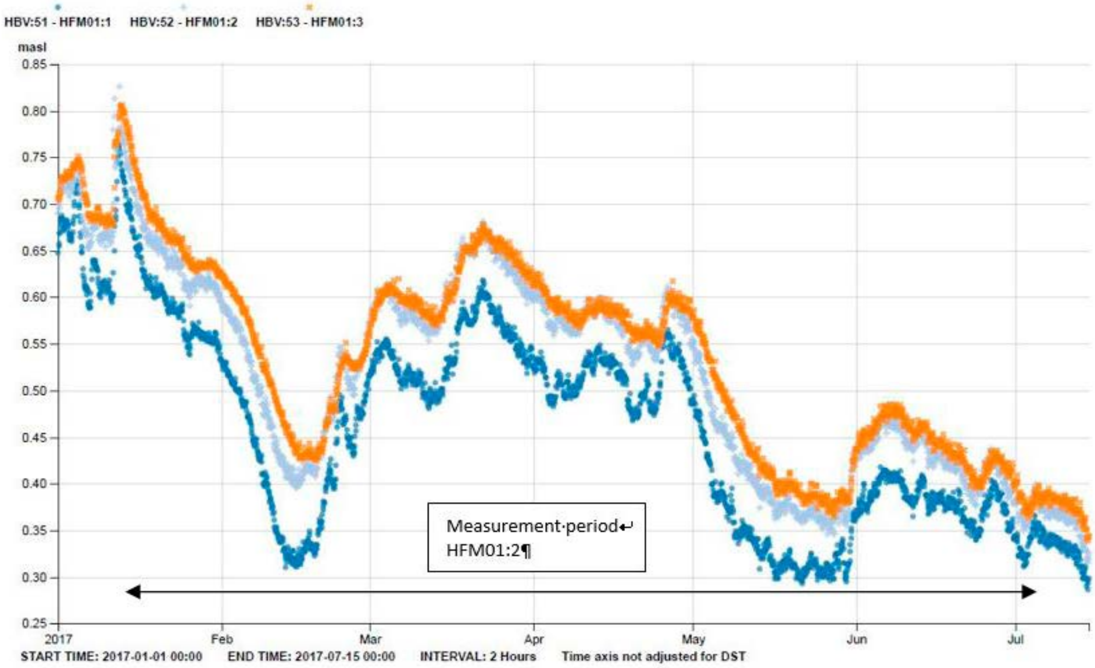
Measured section: KFM02A:3, dark orange (behind section 5, dark green)

KFM02B



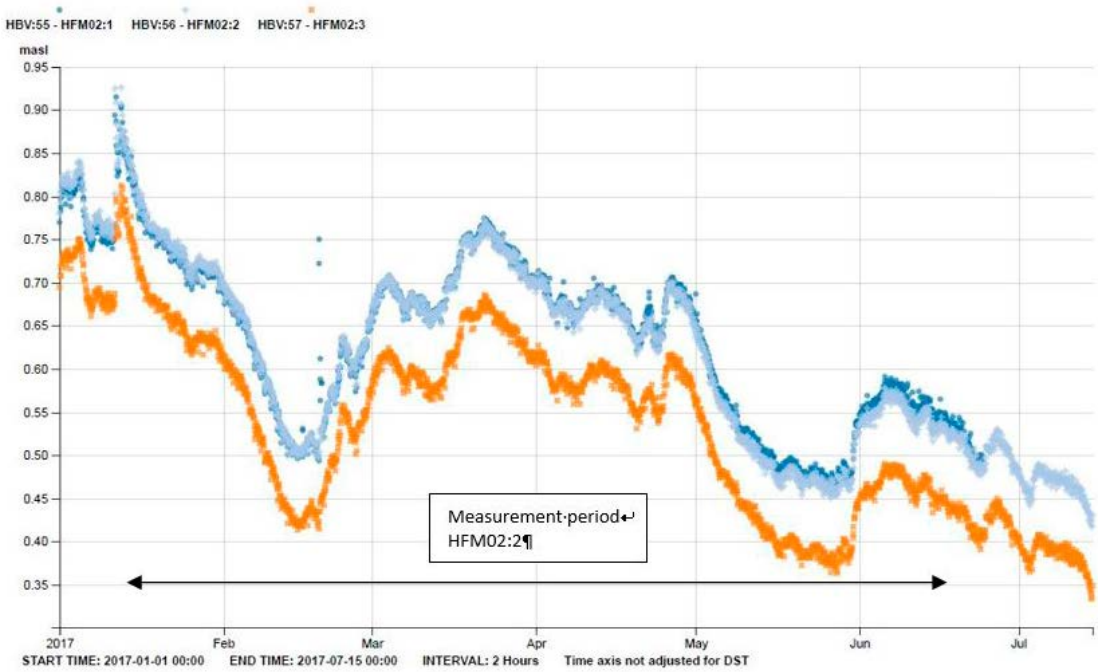
Measured section: KFM02A:4, pale orange

HFM01



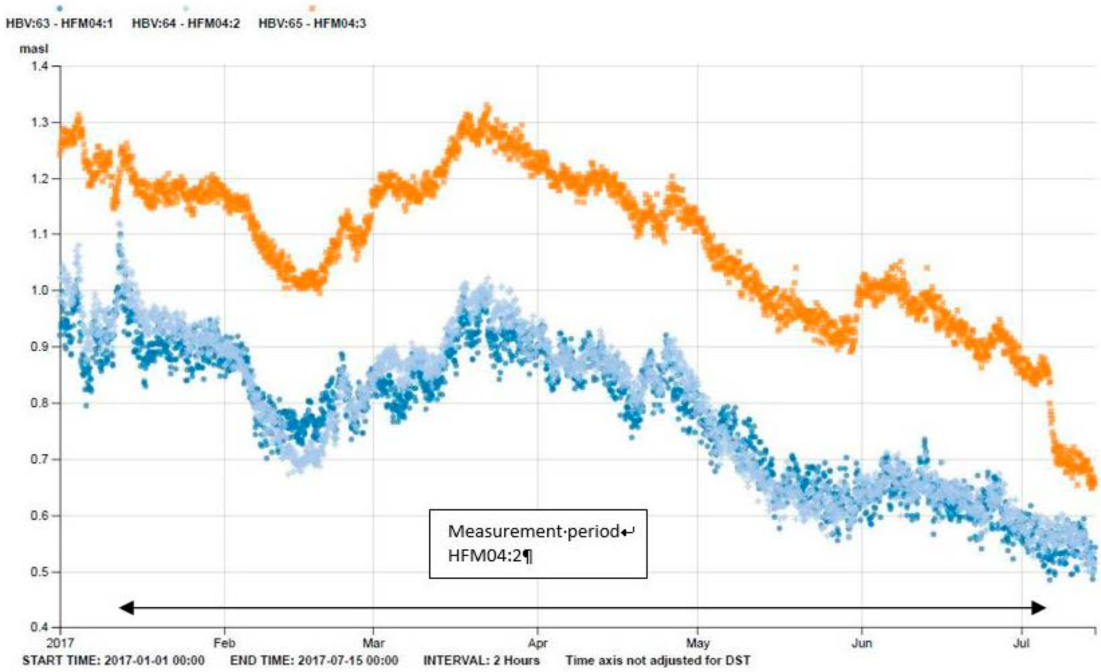
Measured section: HFM01:2, pale blue

HFM02



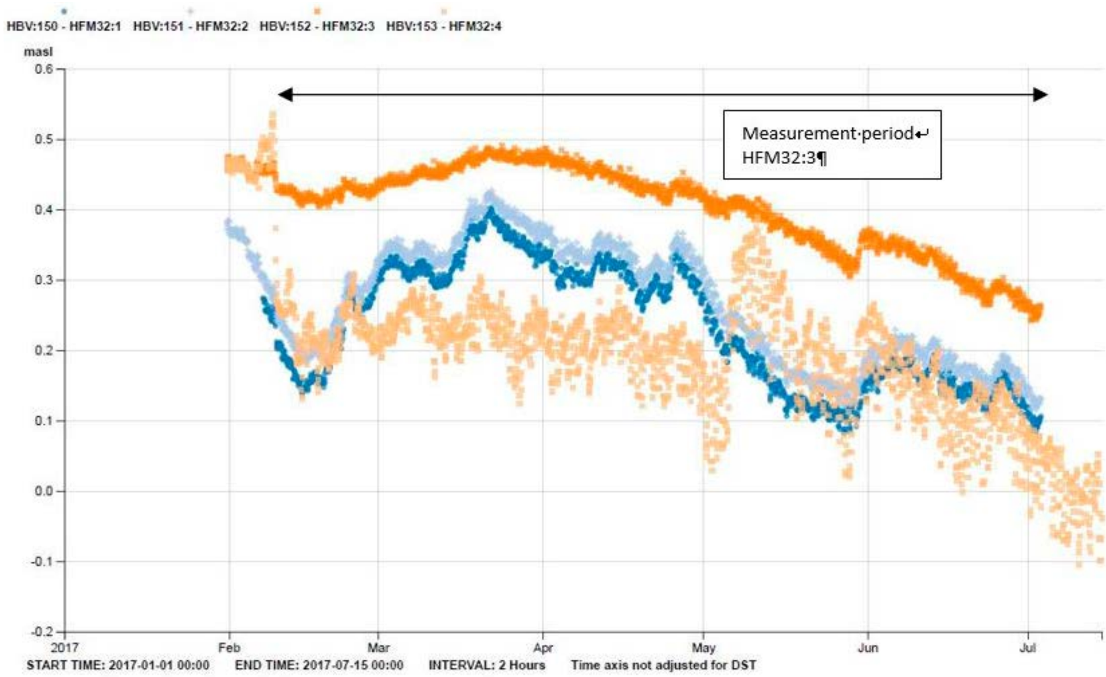
Measured section: HFM02:2, pale blue

HFM04



Measured section: HFM04:2, pale blue

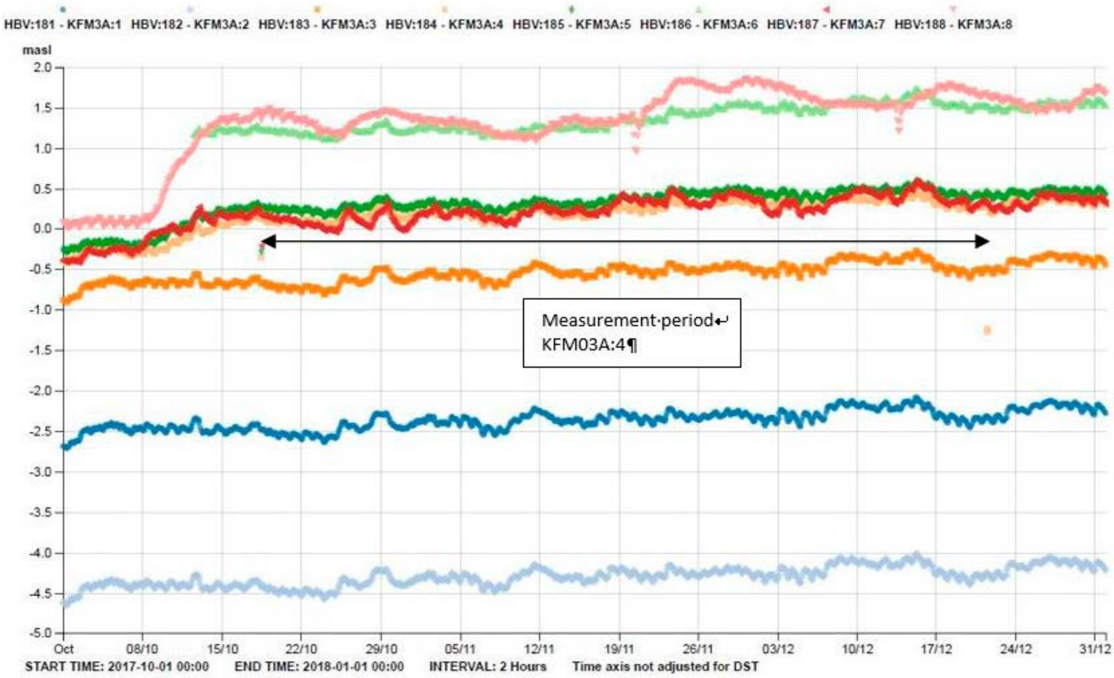
HFM32



Measured section: HFM32:3, dark orange

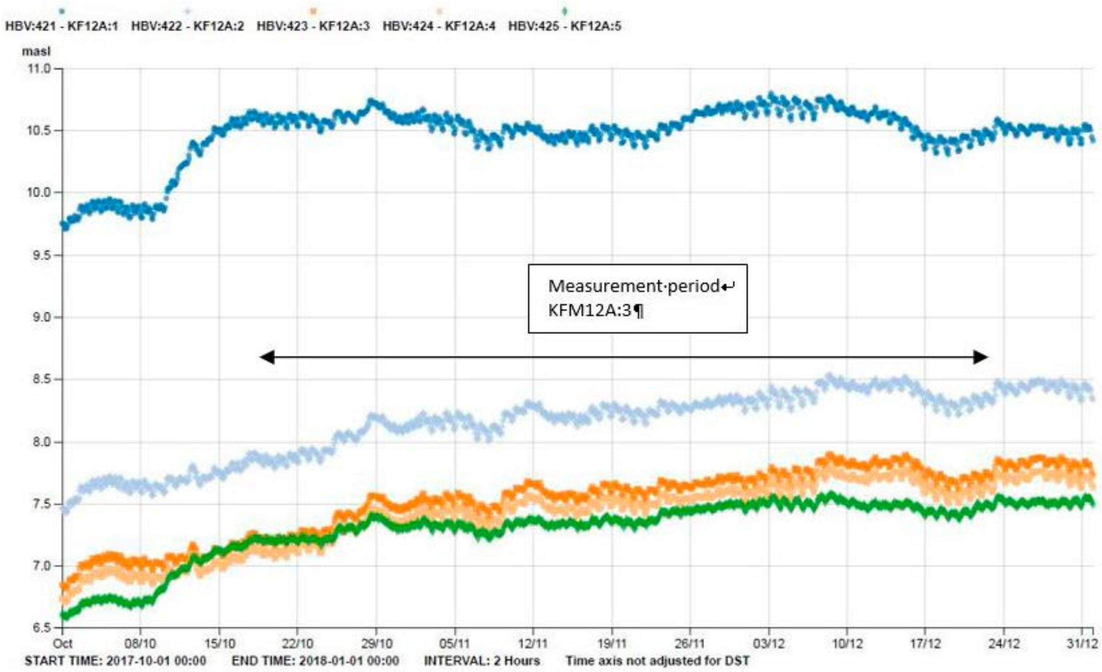
2017-10-01–2018-01-01

KFM03A



Measured section: KFM03A:4, pale orange

KFM12A



Measured section: KFM12A:3, dark orange

Arkitektkopia AB, Bromma, 2019

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