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Monitoring Forsmark

Groundwater flow measurements in permanently installed boreholes

Test campaign no. 6, 2010

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April 2011

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Keywords: Groundwater flow, dilution test, tracer test, AP PF 400-09-014.

Abstract

This report describes the performance and evaluation of groundwater flow measurements in 31 borehole sections in permanently installed boreholes within the Forsmark site investigation area. The objective was to determine groundwater flow rates in all, at the time available, borehole sections instrumented for this purpose. This is the sixth test campaign performed within the monitoring program and measurements are planned to be repeated once every year.

The groundwater flow rates were determined through dilution measurements during natural conditions. Measured flow rates ranged from 0.04 to 55 ml/min with calculated Darcy velocities from $2.8 \cdot 10^{-10}$ to $3.0 \cdot 10^{-7}$ m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.0007 and 30.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i 31 borrhålssektioner i permanent installerade borrhål inom Forsmarks plats- undersökningsområde. Syftet var att bestämma grundvattenflödet i samtliga, vid denna tidpunkt och för detta ändamål, instrumenterade sektioner. Detta är den sjätte mätkampanjen som genomförts i moniteringsprogrammet och mätningarna är planerade att återupprepas en gång per år.

Grundvattenflödet mättes med utspädningsmetoden under naturliga förhållanden i utvalda borrhålssektioner. Uppmätta grundvattenflöden låg i intervallet 0,04–55 ml/min med beräknade Darcy hastigheter mellan $2{,}8 \cdot 10^{-10}$ och $3{,}0 \cdot 10^{-7}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,0007 och 30.

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1 Introduction

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 6, 2010, which is part of the programme for monitoring of geoscientific parameters and biological objects within the Forsmark site investigation area /1/. 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 plan AP PF 400-09-014 and the field work was conducted during November–December 2010 and March 2011. In Table 1-1 controlling documents for performing this activity are listed. The activity plan and the method description are SKB's internal controlling documents.

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

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

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

Activity plan	**Number**	**Version**
Monitering av grundvattenflöde 2010	AP PF 400-09-014	1.0
Method description	**Number**	**Version**
System för hydrologisk och meteorologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål.	SKB MD 368.010	1.0

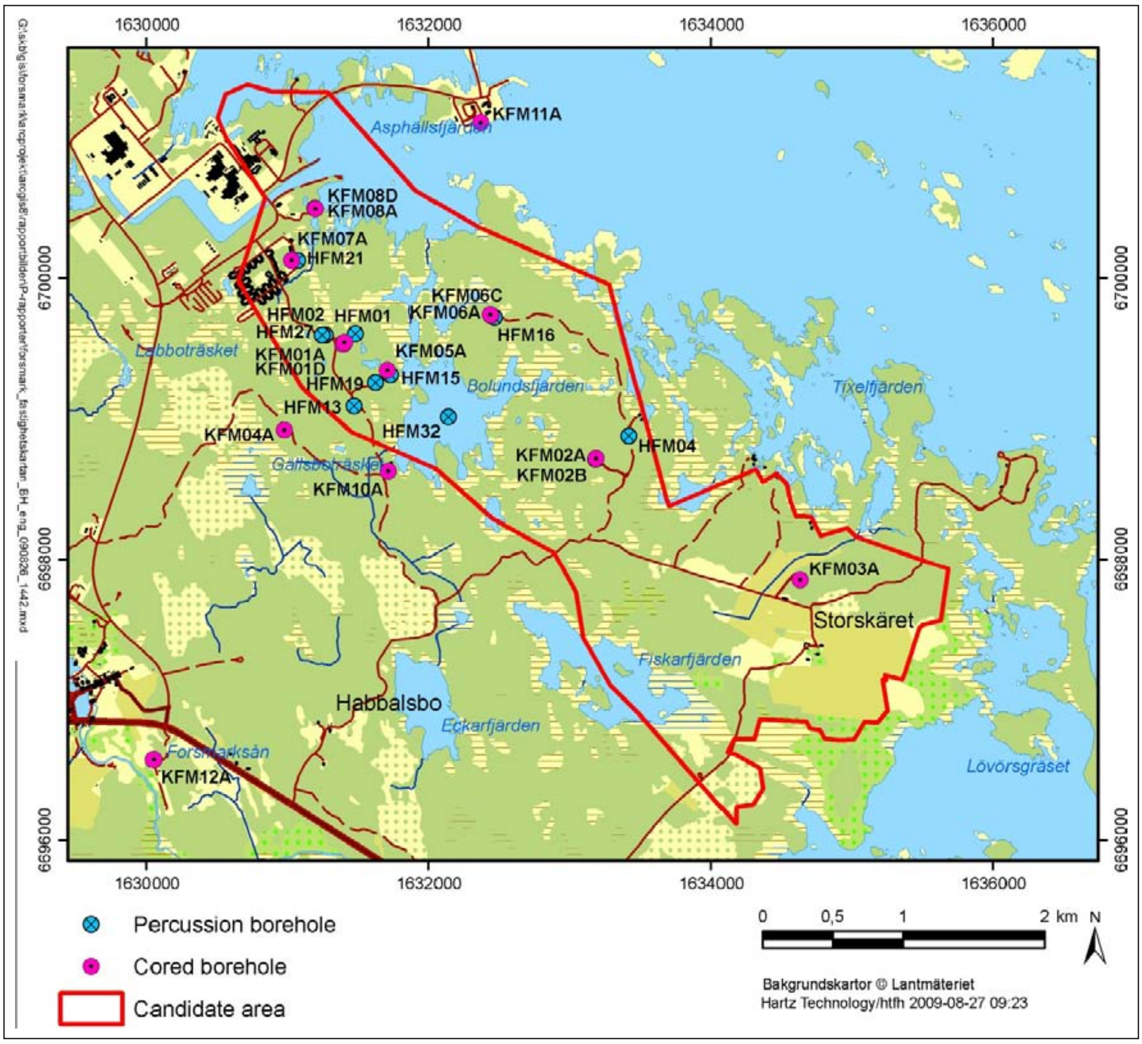

Figure 1-1. *Overview over the Forsmark site investigation area, showing locations of boreholes included in this activity.*

2 Objective and scope

The objective of this activity was to determine the groundwater flow in permanently installed borehole sections at Forsmark. A total of 31 borehole sections instrumented for this purpose were measured, cf. Table 4-1. This was the sixth test campaign performed within the monitoring programme and measurements are planned to be repeated once every year. The measurements will serve as a basis to study undisturbed groundwater flow as well as to monitor changes caused by future activities in the area such as underground construction and drilling.

The groundwater flow in the selected borehole sections was determined through tracer dilution measurements. No other major investigations were in progress during the measurement campaign, and 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 HMS-system 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 five identical equipment set-ups, allowing five 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 tracer used was a fluorescent dye tracer, Amino-G Acid from Aldrich (techn. quality).

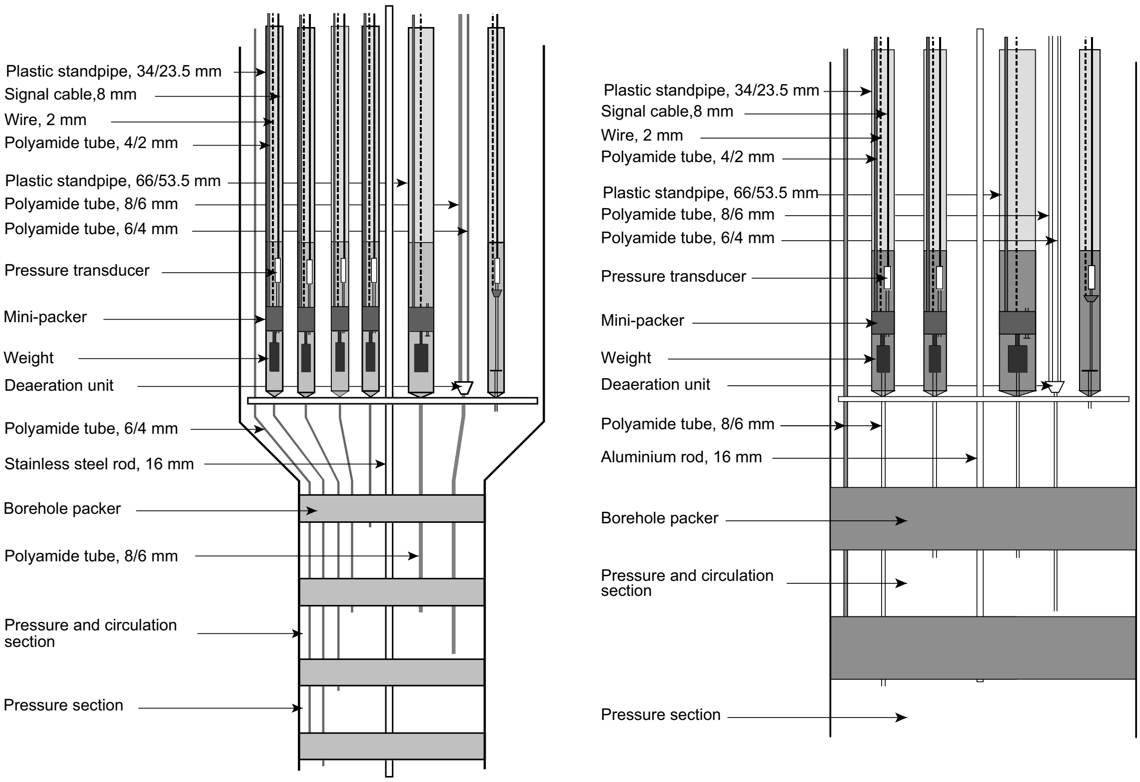

Figure 3-1. *Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.*

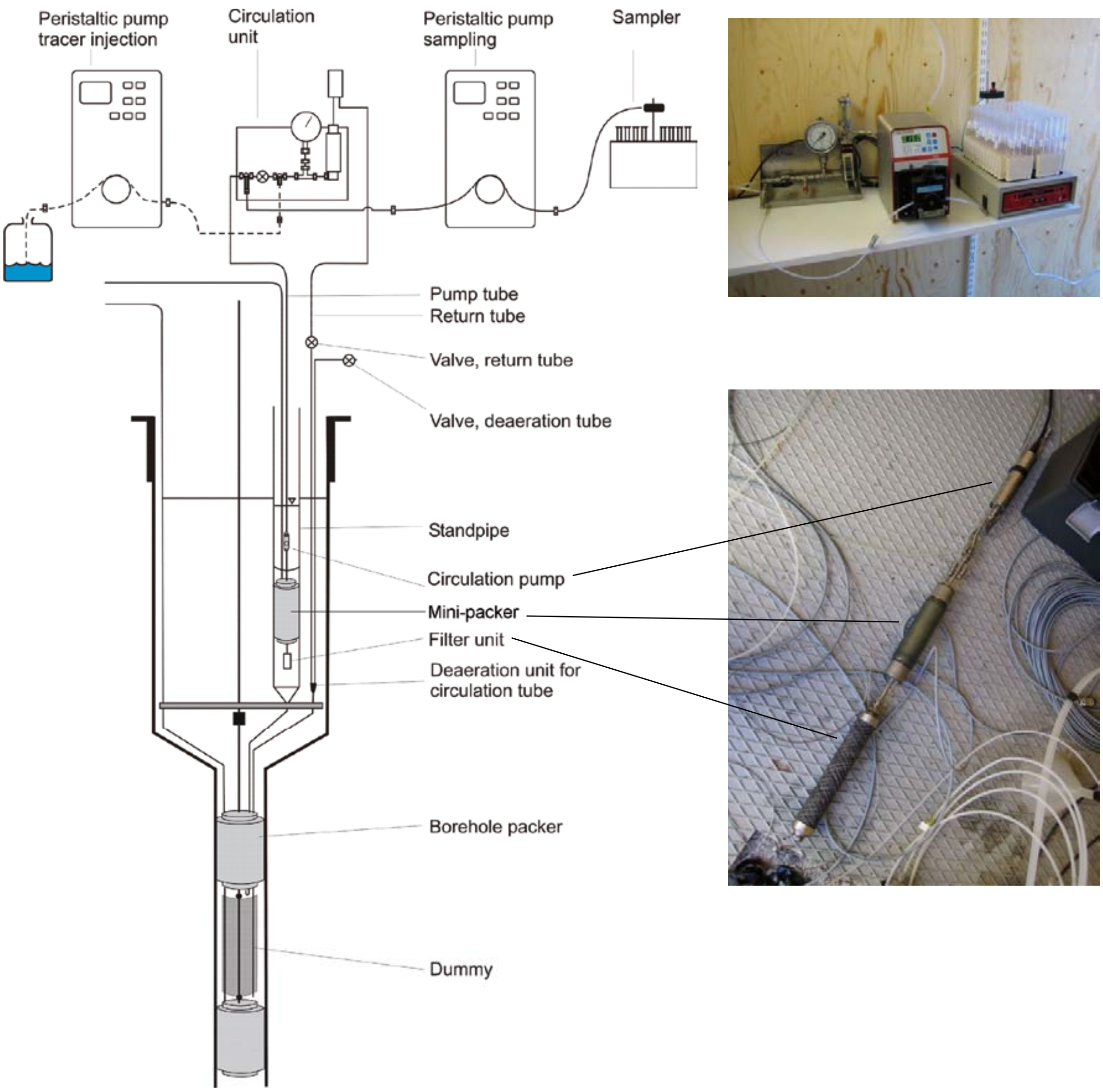

***Figure 3-2.** Schematic drawing of the equipment used in tracer dilution measurements.*

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.

4.2 Preparations

The preparations included mixing of the tracer stock solution, function checks of the equipment and calibration of the peristaltic pumps used for sampling and tracer injections.

4.3 Execution of field work

The borehole sections included in the monitoring program during the autumn 2010 are listed in Table 4-1.

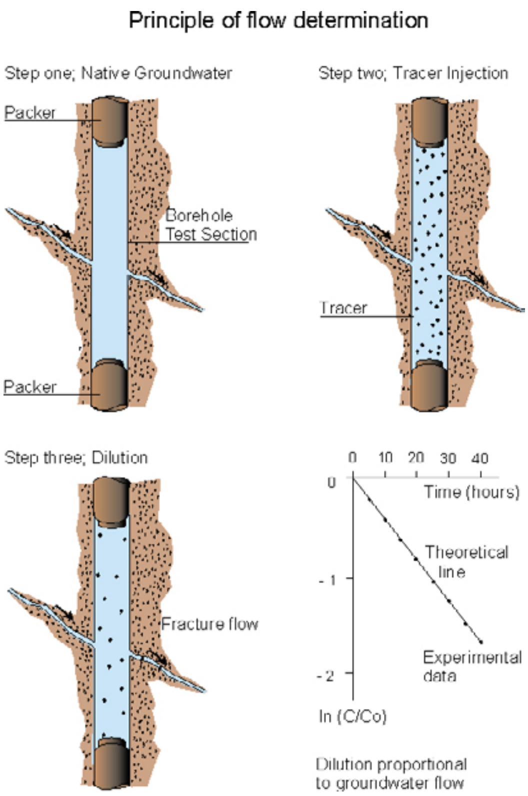

Figure 4-1. *General principles of dilution and flow determination.*

Table 4-1. Borehole sections included in the monitoring program, autumn 2010.

Borehole:section	Depth (m)	T (m^2/s)	Geologic character***	Test period (yymmdd)
KFM01A:5	109–130	1.0 E–7*	Single fracture, Fracture domain FFM02	101117–101122
KFM01D:2	429–438	8.0 E–7*	Single fracture, Fracture domain FFM01	101117–101122
KFM01D:4	311–321	2.0 E–7*	Single fracture, Fracture domain FFM01	101117–101122
KFM02A:3	490–518	2.1 E–6*	Zone ZFMF1	101201–101206
KFM02A:5	411–442	2.5 E–6*	Zone ZFMA2	101201–101206
KFM02B:2	491–506	3.0 E–5*	Not included in /27/	101129–101203
KFM02B:4	410–431	2.0 E–5*	Not included in /27/	101129–101203
KFM03A:1	969.5–994.5	5.5 E–7*	Single fracture, Fracture domain FFM03	Not measured
KFM03A:4	633.5–650	2.4 E–6*	Zone ZFMB1	101119–101124
KFM04A:4	230–245	2.0 E–5*	Zone ZFMA2	101115–101119
KFM05A:4	254–272	1.4 E–8*	Single fracture, Fracture domain FFM01	101126–101201
KFM06A:3	738–748	1.2 E–7*	Zone ZFMNNE0725	101203–101208
KFM06A:5	341–362	3.5 E–6*	Zone ZFMB7, Zone ZFMENE0060A	101203–101208
KFM06C:3	647–666	5.3 E–8*	Possible DZ (S-NNE/WNW)	110316–110321
KFM06C:5	531–540	1.1 E–6*	Zone ZFMWNW044	110316–110321
KFM07A:2	962–972	5.0 E–7*	Zone ZFMB8, Zone ZFMNNW0100	Not measured
KFM08A:2	684–694	1.0 E–6*	Possible DZ (S-WNW)	101215–101220
KFM08A:6	265–280	1.0 E–6*	Zone ZFMENE1061A	101215–101221
KFM08D:2	825–835	2.0 E–8*	Not included in /27/	101213–101217
KFM08D:4	660–680	2.0 E–7*	Not included in /27/	101217–101220
KFM10A:2	430–440	3.0 E–5*	Zone ZFMA2	101115–101119
KFM11A:2	690–710	1.0 E–6*	Not included in /27/	101124–101129
KFM11A:4	446–456	6.0 E–7*	Not included in /27/	101124–101129
KFM12A:3	270–280	1.0 E–6*	Not included in /27/	110316–110321
HFM01:2	33.5–45.5	4.0 E–5**	Zone ZFMA2	101122–101126
HFM02:2	38–48	5.9 E–4**	Zone ZFM1203	101210–101213
HFM04:2	58–66	7.9 E–5**	Zone ZFM866	101122–101126
HFM13:1	159–173	2.9 E–4**	Zone ZFMENE0401A	101208–101213
HFM15:1	85–95	1.0 E–4**	Zone ZFMA2	101126–101201
HFM16:2	54–67	3.5 E–4**	Zone ZFMA8	101203–101208
HFM19:1	168–182	2.7 E–4**	Zone ZFMA2	101206–101210
HFM21:3	22–32	4.0 E–5**	Single fracture, Fracture domain FFM02	101210–101215
HFM27:2	46–58	4.0 E–5**	Zone ZFM1203	101119–101124
HFM32:3	26–31	2.3 E–4**	Single fracture, Fracture domain FFM03	Not measured

* From PSS (Pipe String System) or PFL (Posiva Flow Logging) measurements, /2/–/18/.
** From HTHB (HydroTester HammarBorrhål) measurements, /19/–/26/.
*** Deformation zones according to Forsmark modelling, stage 2.2, /27/.

Groundwater flow measurements were made in 31 of the 34 sections. Sections KFM03A:1, KFM07A:2 and HFM32:3 were omitted for technical reasons. The duration of each test varied from 72 to 140 hours.

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. Five sections were measured simultaneously. The tracer solution was continuously circulated and sampled using the equipment described in Section 3.1.

After completion of each test, at least three section volumes were pumped from the measured section in order to remove the remaining tracer.

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. /28/. 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):

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

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.

The sampling procedure with a constant flow rate of approximately 0.1 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 90º angle between the borehole axis and the flow direction is assumed and the relation between the flow in the rock, the Darcy velocity, v (m/s), and the measured flow through the borehole section, Q_{bh}, can be expressed as:

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

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):

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

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

4.5 Nonconformities

After the measurement had been performed in borehole section HFM21:3 in November 2010, it was discovered that the down-hole circulation pump had been leaking. This can be seen in Appendix 2 as an increased groundwater level in the neighbouring section 4. The pump was later changed and the measurement successfully remade. No data is presented from the first, unsuccessful measurement.

The measurements in boreholes KFM06C and KFM12A had to be postponed until March 2011, due to other activities in the boreholes.

5 Results

5.1 General

Original data from the reported activity are stored in the primary database Sicada. Data are traceable in Sicada by the Activity Plan number (AP PF 400-09-14). 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 P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

5.2 Test campaign 6, 2010

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 injected tracer solution used.

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.

Table 5-1. Results from groundwater flow measurements, test campaign 6, 2010.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Vol. (l)	Measured flow, Q (ml/min)	Darcy velocity, v (m/s)	Hydraulic gradient, I (m/m)
KFM01A:5	109–130	1.0E–7*	33.21	0.05	2.8E–10	0.06
KFM01D:2	429–438	8.0E–7*	38.33	0.04	4.3E–10	0.005
KFM01D:4	311–321	2.0E–7*	31.27	0.1	1.2E–09	0.06
KFM02A:3	490–518	2.1E–6*	66.33	1.4	5.3E–09	0.07
KFM02A:5	411–442	2.5E–6*	60.78	0.8	3.0E–09	0.04
KFM02B:2	491–506	3.0E–5*	48.63	9.1	6.7E–08	0.03
KFM02B:4	410–431	2.0E–5*	47.58	27	1.4E–07	0.1
KFM03A:4	633.5–650	2.4E–6*	58.04	0.4	2.4E–09	0.02
KFM04A:4	230–245	2.0E–5*	35.00	6.1	4.4E–08	0.03
KFM05A:4	254–272	1.4E–8*	40.62	0.1	8.0E–10	1
KFM06A:3	738–748	1.2E–7*	58.25	0.5	5.9E–09	0.5
KFM06A:5	341–362	3.5E–6*	46.64	0.3	1.4E–09	0.008
KFM06C:3	647–666	5.3E–8*	64.00	0.1	6.8E–10	0.2
KFM06C:5	531–540	1.1E–6*	43.61	0.2	2.3E–09	0.02
KFM08A:2	684–694	1.0E–6*	55.15	0.8	8.3E–09	0.08
KFM08A:6	265–280	1.0E–6*	34.67	0.1	9.0E–10	0.01
KFM08D:2	825–835	2.0E–8*	63.44	0.9	9.7E–09	5
KFM08D:4	660–680	2.0E–7*	64.13	55	3.0E–07	30
KFM10A:2	430–440	3.0E–5*	39.52	1.4	1.6E–08	0.005
KFM11A:2	690–710	1.0E–6*	68.91	0.9	4.6E–09	0.09
KFM11A:4	446–456	6.0E–7*	40.47	0.2	2.2E–09	0.04
KFM12A:3	270–280	1.0E–6*	31.76	0.4	3.8E–09	0.04
HFM01:2	33.5–45.5	4.0E–5**	39.83	5.8	2.9E–08	0.009
HFM02:2	38–48	5.9E–4**	28.53	13	7.7E–08	0.001
HFM04:2	58–66	7.9E–5**	27.52	1.8	1.4E–08	0.001
HFM13:1	159–173	2.9E–4**	39.28	12	5.3E–08	0.003
HFM15:1	85–95	1.0E–4**	35.74	1.3	8.0E–09	0.0008
HFM16:2	54–67	3.5E–4**	43.61	4.4	2.0E–08	0.0007
HFM19:1	168–182	2.7E–4**	44.65	15	6.5E–08	0.003
HFM21:3	22–32	4.0E–5**	31.39	1.0	6.3E–09	0.002
HFM27:2	46–58	4.0E–5**	40.29	0.7	3.7E–09	0.001

* From PSS (Pipe String System) or PFL (Posiva Flow Logging) measurements, /2/–/11/, /13/–/18/.
** From HTHB (HydroTester HammarBorrhål) measurements, /19/–/25/.

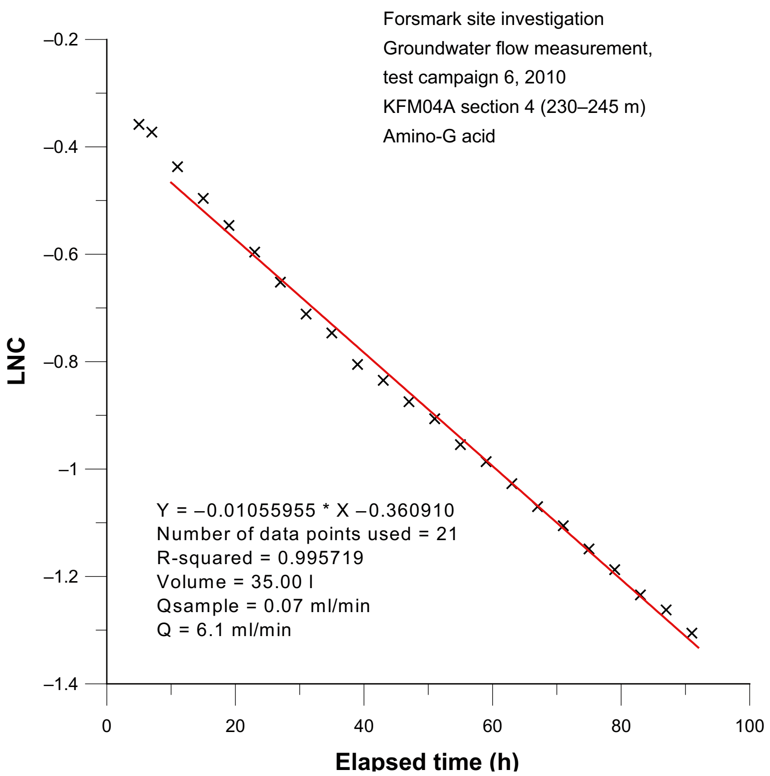

Figure 5-1. *Example of a tracer dilution graph (logarithm of concentration versus time) for borehole KFM04A, section 4, including straight-line fit.*

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 period for each section.

The results show that the groundwater flow during natural conditions varies from 0.04 to 55 ml/min in the measured sections with Darcy velocities ranging from $2.8 \cdot 10^{-10}$ to $3.0 \cdot 10^{-7}$ 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. In borehole sections KFM02B:4, KFM05A:4, KFM06A:3, KFM06C:3, KFM08D:2 and KFM08D:4 the hydraulic gradient is very large. In both sections in KFM08D the measured flow rates are higher than expected considering the transmissivity of the sections. Also, as for KFM05A:4, the groundwater levels in both sections were strongly affected during the measurements, as seen in Appendix 2, which may have influenced the flow rate and calculated hydraulic gradient. The large gradients may be due to rough estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. KFM05A:4 also represents a single fracture (cf. Table 4-1) where the Darcy concept may be questioned.

In general, the equipment has worked well and no major hydraulic disturbance has occurred during the tests, cf. Appendix 2. However, in borehole KFM05A and KFM08D the groundwater levels in the measured sections were apparently strongly affected during the measurements. This was probably caused by the circulation of section water. The unusual pressure responses previously noticed in borehole KFM08D were not seen this year. The two sections were, as usual, measured at different times, but this year the groundwater level in section 2 was not affected by the measurement in section 4.

In several of the measured borehole sections, early data are believed to be influenced by the mixing procedure, see Appendix 1. Consequently, the late time slope of the dilution curve is judged to represent the most reliable data.

5.3 Flow rate comparison

A comparison with flow rates obtained from previously performed test campaigns is compiled in Table 5-2 and graphically shown in Figures 5-2 to 5-5.

The comparison between years 2009 and 2010 shows relatively small changes in most of the 31 sections. However, six sections, KFM02A:5, KFM04A:4, KFM08D:4, KFM11A:4, HFM16:2 and HFM27:2 , demonstrate significantly increased flow (about a factor 2) for 2010 compared with the previous year, whereas five sections, KFM01D:4, KFM05A:4, KFM06C:3, KFM06C:5 and KFM08D:2 display significantly decreased flow. In some of these sections, KFM01D:4, KFM04A:4, KFM05A:4 and KFM08D:2 the flow rate measured in 2010 is more consistent with the results from 2007–2008 instead of the rather diverging result from 2009. Also, as mentioned earlier, the groundwater levels in KFM05A:4 and KFM08D:4 were strongly influenced during the measurements, probably caused by the circulation of section water. This behavior has occurred during all test campaigns performed, but in 2009 the groundwater level in KFM05A:4 was decreased by about 7 m compared to 0.5–1 m during both previous measurements and the present one. This could explain the higher flow rate measured in 2009. In KFM08D:4 on the other hand, the decrease during the measurement 2009 was about 1 m compared to around 7 m during previous measurements and a lower flow rate was measured in 2009. In 2010 the decrease in groundwater level was about 3.5 m and hence, the flow rate was measured to be somewhere in between the results from 2009 and the previous ones.

Table 5-2. Results from groundwater flow measurements in November–December 2010 / March 2011 compared with results from previously performed test campaigns.

Borehole: sec	Depth (m)	T (m^2/s)	Nov–Dec 2005 /29/ (ml/min)	Nov 2006 /30/ (ml/min)	Nov/Jan 2007–08 /31/ (ml/min)	Nov–Dec 2008 /32/ (ml/min)	Nov–Dec 2009 /33/ (ml/min)	Nov–Dec 2010 / Mar 2011 (ml/min)
KFM01A:5	109–130	1.0 E–7*	–	0.1	0.2	0.1	0.06	0.05
KFM01D:2	429–438	8.0 E–7*	–	–	0.3	0.04	0.06	0.04
KFM01D:4	311–321	2.0 E–7*	–	–	0.2	0.2	0.7	0.1
KFM02A:3	490–518	2.1 E–6*	2.1	0.8	0.8	1.2	1.6	1.4
KFM02A:5	411–442	2.5 E–6*	1.0	0.4	0.7	0.1	0.5	0.8
KFM02B:2	491–506	3.0 E–5*	–	–	4.6	12	8.9	9.1
KFM02B:4	410–431	2.0 E–5*	–	–	23	35	30	27
KFM03A:1	969.5–994.5	5.5 E–7*	1.7	–	–	–	–	
KFM03A:4	633.5–650	2.4 E–6*	0.5	0.5	0.6	1.1	0.4	0.4
KFM04A:4	230–245	2.0 E–5*	–	–	16.4	8.0	2.5	6.1
KFM05A:4	254–272	1.4 E–8*	0.5	1.4	0.1	0.1	2.3	0.1
KFM06A:3	738–748	1.2 E–7*	0.3	0.6	0.2	0.05	0.4	0.5
KFM06A:5	341–362	3.5 E–6*	0.5	0.6	5.7	0.2	0.2	0.3
KFM06C:3	647–666	5.3 E–8*	–	0.4	0.05	0.03	0.3	0.1
KFM06C:5	531–540	1.1 E–6*	–	0.3	0.2	0.4	0.4	0.2
KFM08A:2	684–694	1.0 E–6*	–	–	0.8	0.7	0.7	0.8
KFM08A:6	265–280	1.0 E–6*	–	–	0.2	0.06	0.1	0.1
KFM08D:2	825–835	2.0 E–8*	–	–	2.6	1.8	4.1	0.9
KFM08D:4	660–680	2.0 E–7*	–	–	91	123	21	55
KFM10A:2	430–440	3.0 E–5*	–	–	2.7	1.6	1.2	1.4
KFM11A:2	690–710	1.0 E–6*	–	–	0.2	0.3	0.5	0.9
KFM11A:4	446–456	6.0 E–7*	–	–	0.04	0.01	0.03	0.2
KFM12A:3	270–280	1.0 E–6*	–	–	0.3	1.8	0.3	0.4
HFM01:2	33.5–45.5	4.0 E–5**	–	–	7.8	6.3	5.7	5.8
HFM02:2	38–48	5.9 E–4**	38	8.9–38	33	23	22	13
HFM04:2	58–66	7.9 E–5**	2.2	10.4	0.8	2.6	1.4	1.8
HFM13:1	159–173	2.9 E–4**	24	4.3	12.6	17	8.2	12
HFM15:1	85–95	1.0 E–4**	0.8	5.2	8.5	4.0	1.8	1.3
HFM16:2	54–67	3.5 E–4**	–	1.6–6.6	1.0	2.8	2.4	4.4
HFM19:1	168–182	2.7 E–4**	9.7	3.4	24	18	9.9	15
HFM21:3	22–32	4.0 E–5**	–	–	1.9	2.1	1.0	1.0
HFM27:2	46–58	4.0 E–5**	–	0.4	0.5	0.8	0.4	0.7
HFM32:3	26–31	2.3 E–4**	–	0.5	–	1.2	–	–

* From PSS (Pipe String System) or PFL (Posiva Flow Logging) measurements, /2/–/11/, /13/–/18/.
** From HTHB (HydroTester HammarBorrhål) measurements, /19/–/26/.

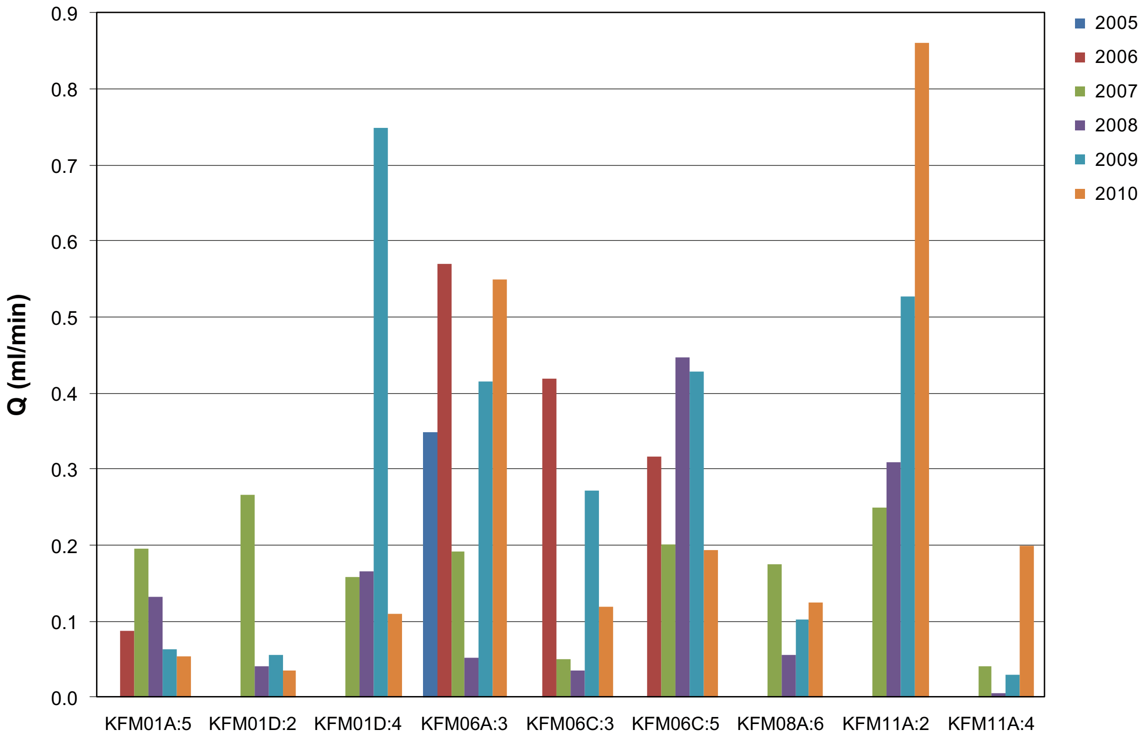

Figure 5-2. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 0.03–0.9 ml/min.*

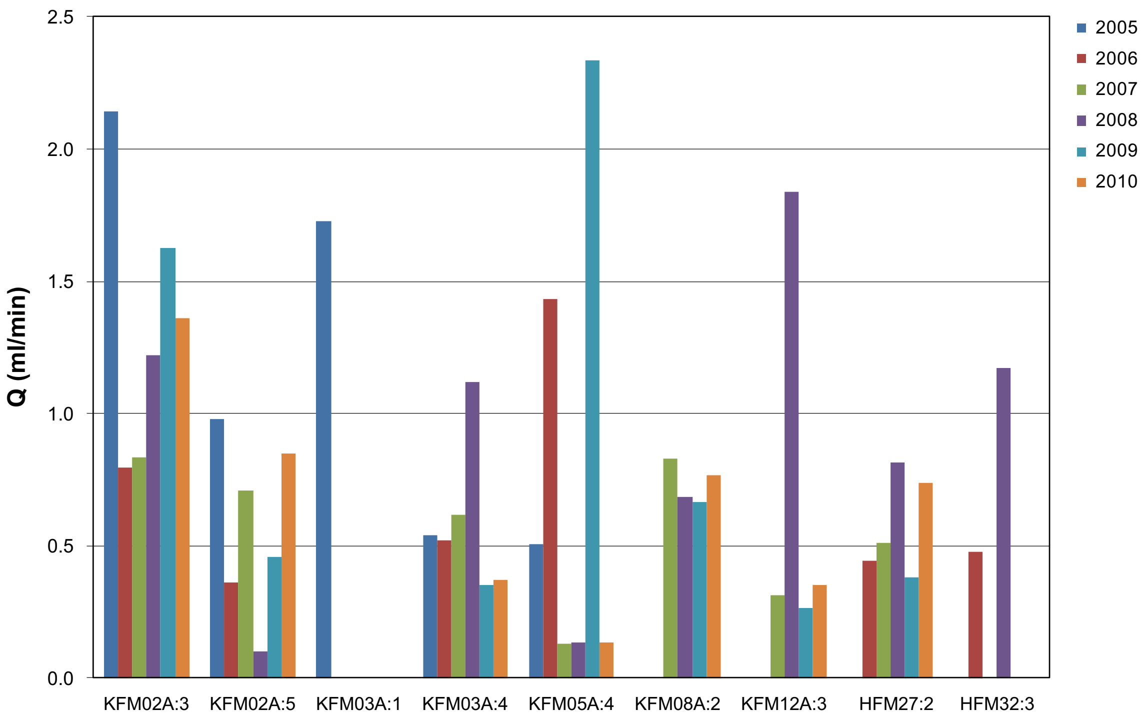

Figure 5-3. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 0.1–2.5 ml/min.*

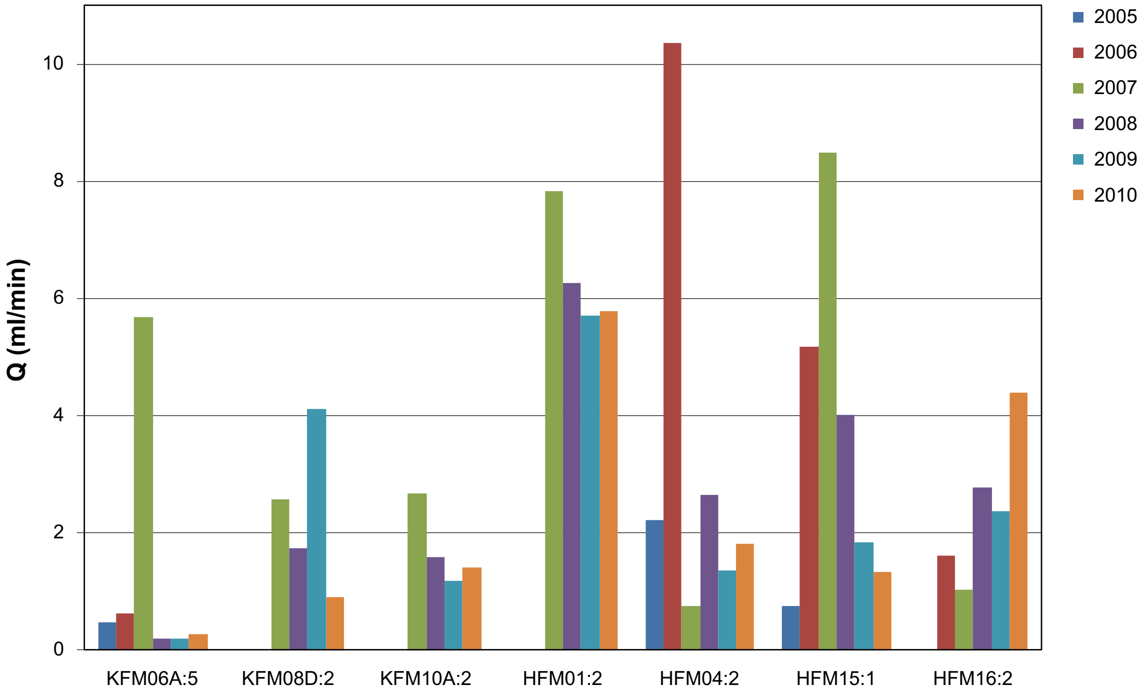

Figure 5-4. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 0.2–11 ml/min.*

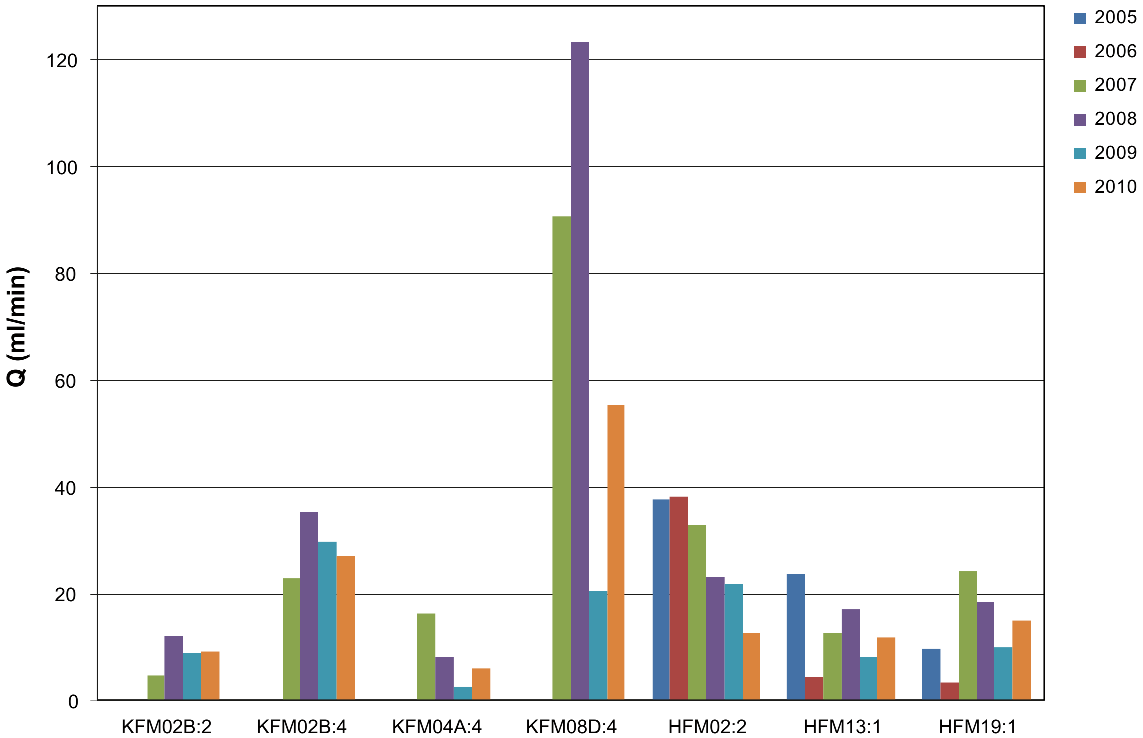

Figure 5-5. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 2.5–123 ml/min.*

Some major investigation activities that most likely caused more or less pronounced hydraulic disturbances in the area and thus may have affected the ongoing groundwater flow measurements are compiled in Table 5-3. In most cases though, the activities have probably not had any considerable influence on the flow rate measurements. In 2006 however, the measurement in HFM04:2 was strongly affected by the rock stress measurements with the overcoring method performed in KFM02B. As a result the measured flow rate was probably overestimated, cf. Figure 5-4. In addition, other events performed between the test campaigns, such as drilling and pumping tests, may have caused changes in the hydraulic gradients and flow distribution. For example, two major pumping tests were performed in borehole HFM14 during July 2006 and also during June–October 2007. Pressure responses were seen in many of the borehole sections included in the monitoring program.

Table 5-3. Various activities performed in the Forsmark area during the test campaigns with groundwater flow measurements, 2005–2011 (excerpt from Sicada).

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

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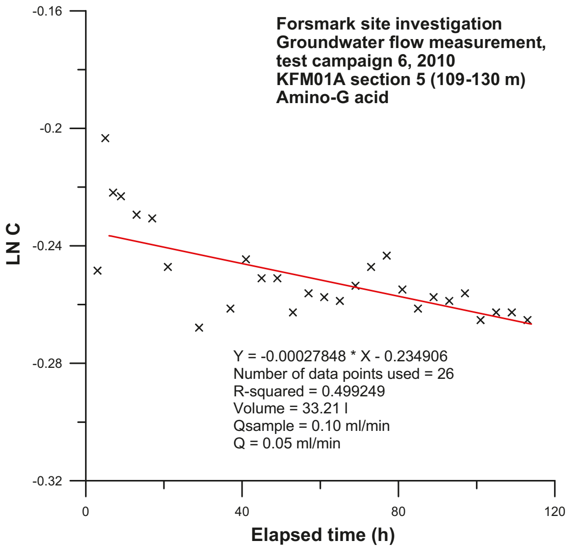
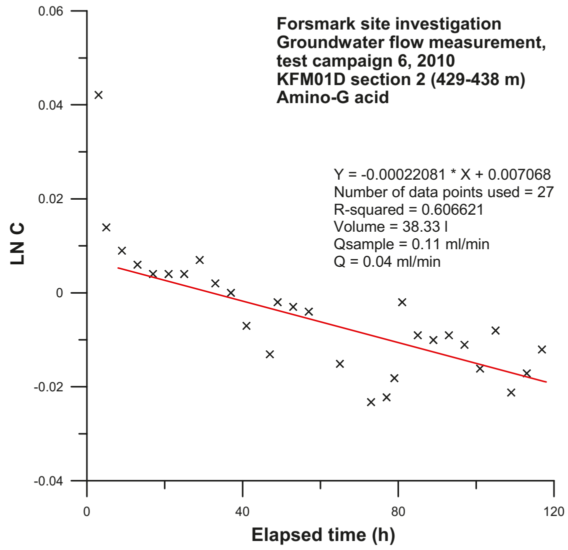
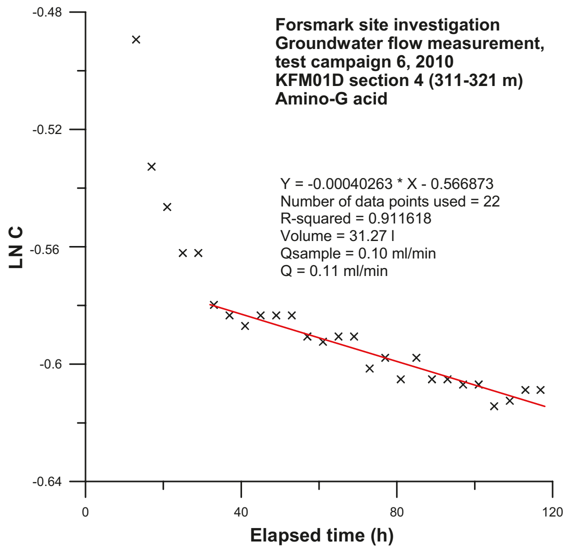
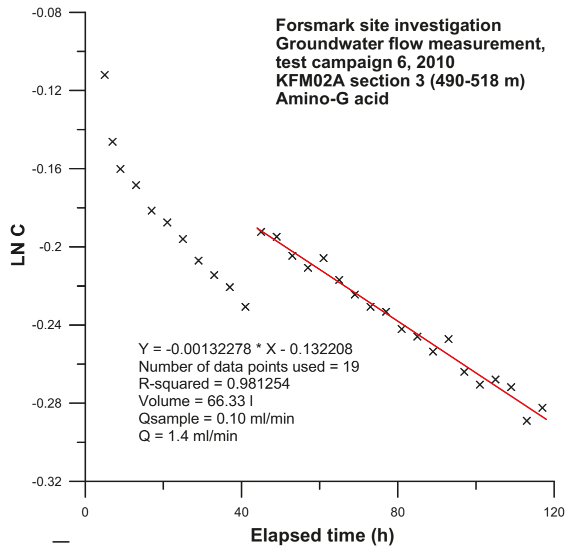
Tracer dilution graphs

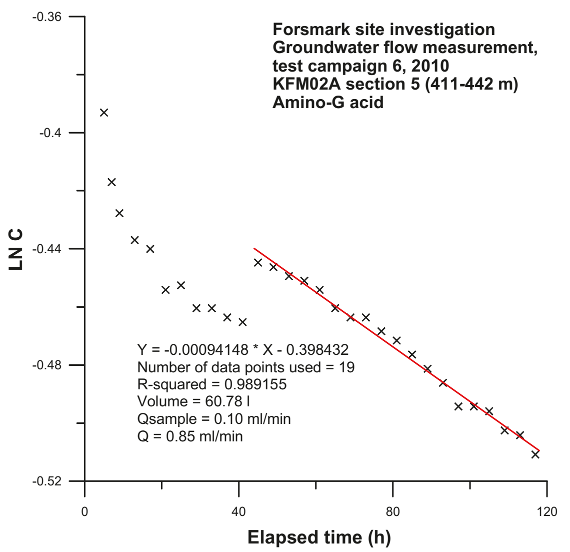
Core boreholes

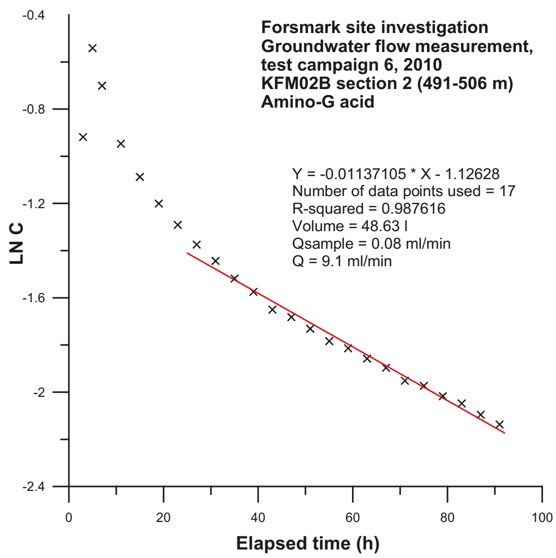


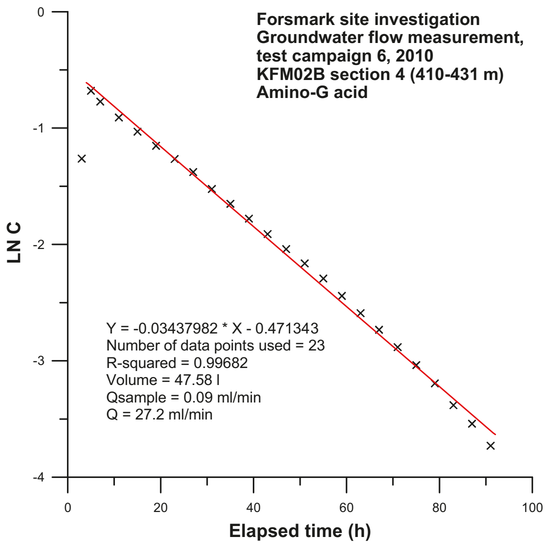








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Groundwater flow measurement,
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KFM02B section 4 (410-431 m)
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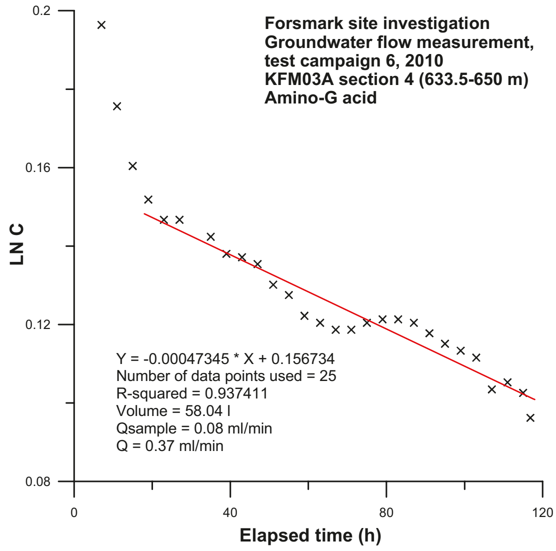
Number of data points used = 23
R-squared = 0.99682
Volume = 47.58 l
Qsample = 0.09 ml/min
Q = 27.2 ml/min
LN C
Elapsed time (h)
0
-1
-2
-3
-4
0
20
40
60
80
100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Number of data points used = 25
R-squared = 0.937411
Volume = 58.04 l
Qsample = 0.08 ml/min
Q = 0.37 ml/min
LN C
Elapsed time (h)
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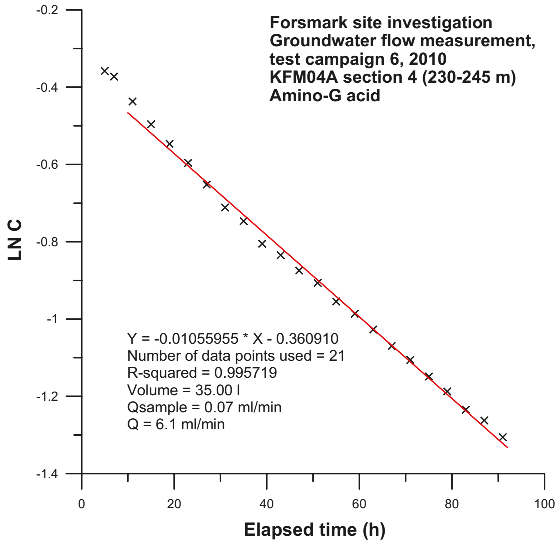
0.16
0.12
0.08
0
40
80
120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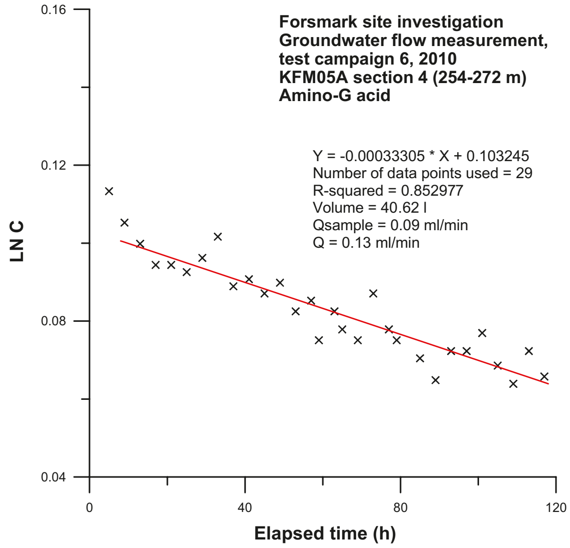
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R-squared = 0.852977
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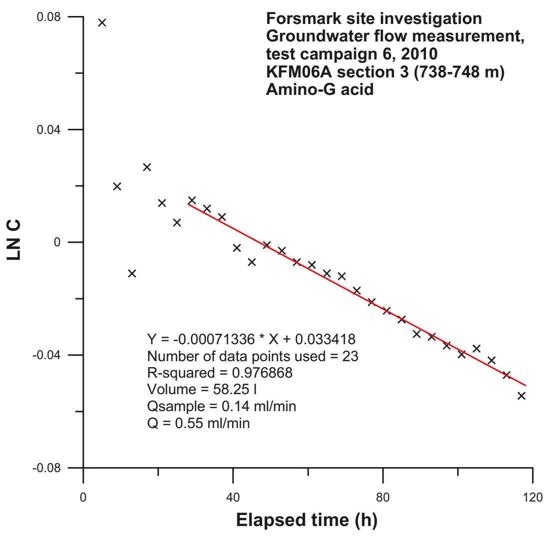
0.04
0
40
80
120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KFM06A section 3 (738-748 m)
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Number of data points used = 23
R-squared = 0.976868
Volume = 58.25 l
Qsample = 0.14 ml/min
Q = 0.55 ml/min
LN C
Elapsed time (h)
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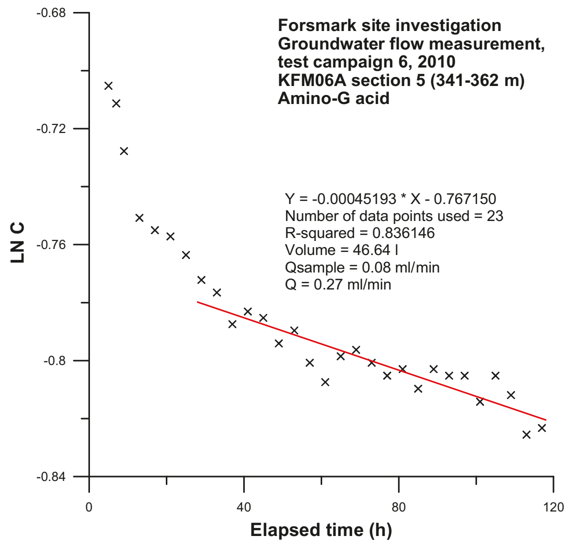
0.04
0
-0.04
-0.08
0
40
80
120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test campaign 6, 2010
KFM06A section 5 (341-362 m)
Amino-G acid
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Number of data points used = 23
R-squared = 0.836146
Volume = 46.64 l
Qsample = 0.08 ml/min
Q = 0.27 ml/min
LN C
Elapsed time (h)
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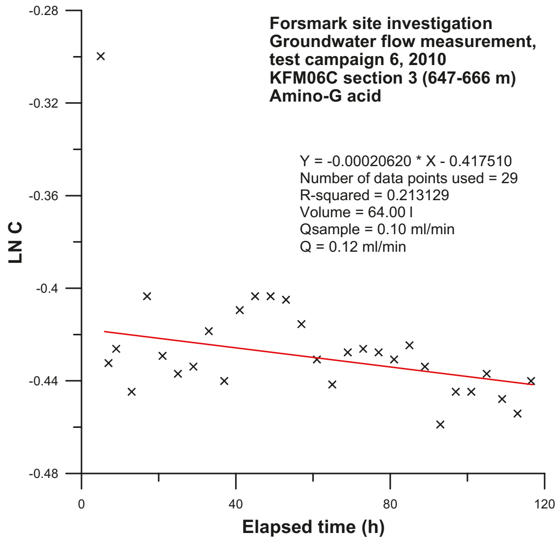
-0.76
-0.8
-0.84
0
40
80
120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KFM06C section 3 (647-666 m)
Amino-G acid
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Volume = 64.00 l
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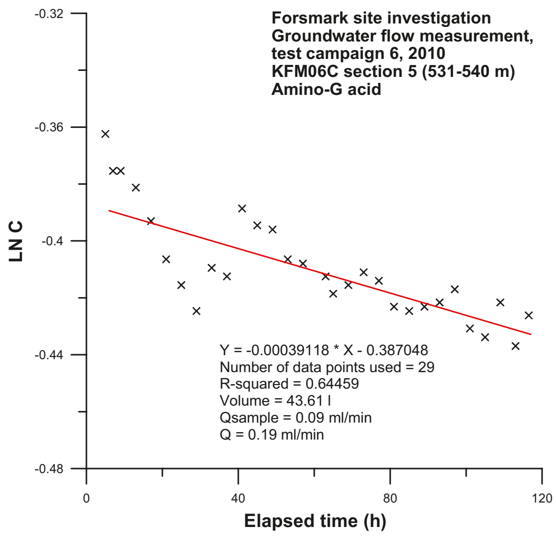
Q = 0.12 ml/min
LN C
Elapsed time (h)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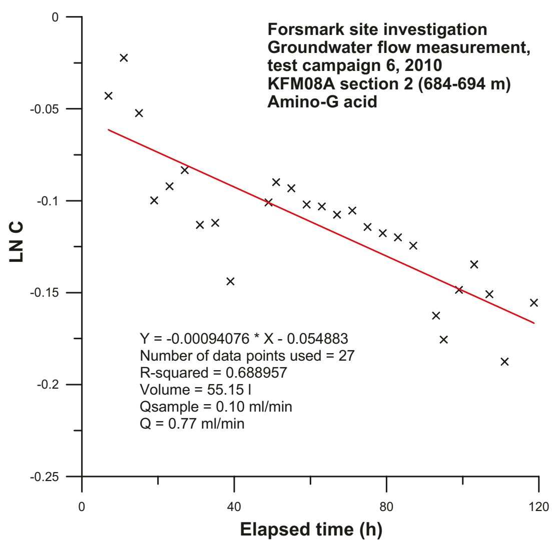
LN C
Elapsed time (h)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Volume = 55.15 l
Qsample = 0.10 ml/min
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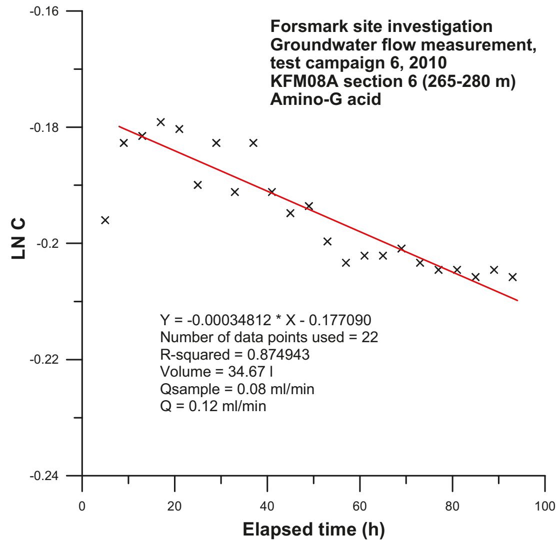
LN C
Elapsed time (h)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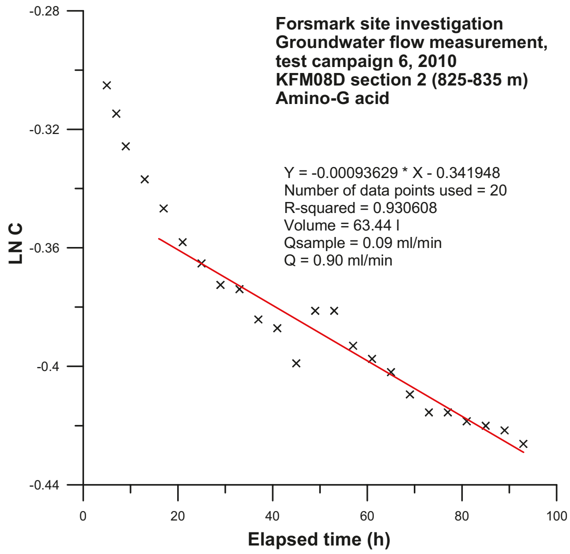
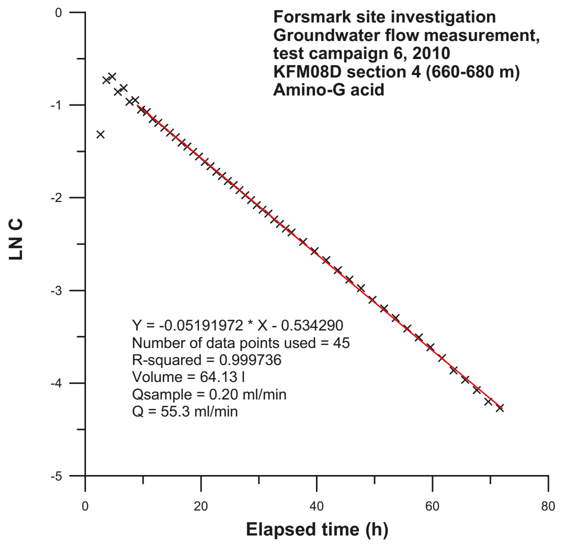
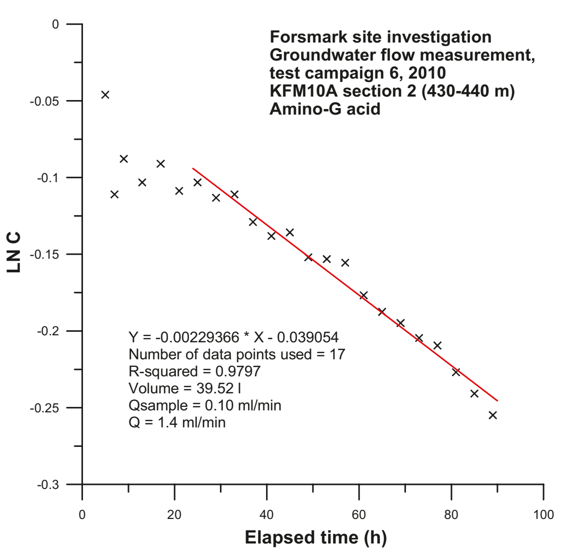
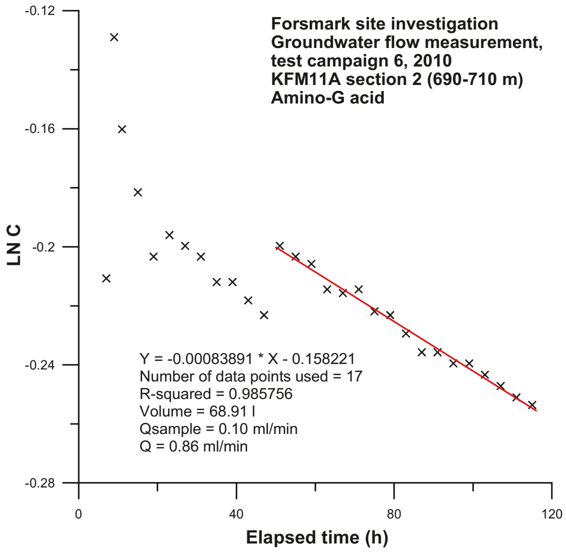
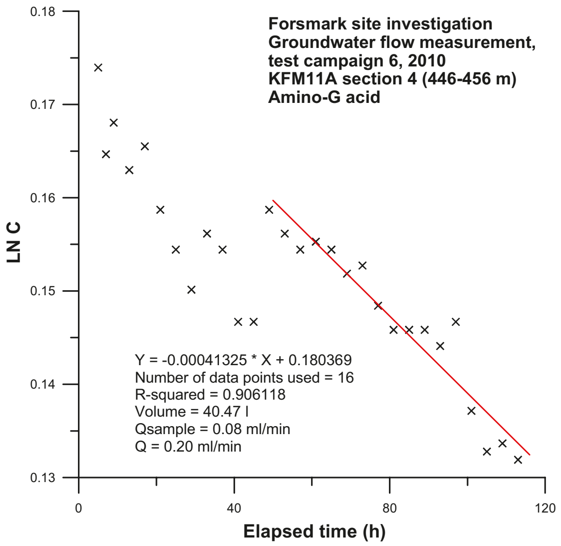
Number of data points used = 22
R-squared = 0.874943
Volume = 34.67 l
Qsample = 0.08 ml/min
Q = 0.12 ml/min
LN C
Elapsed time (h)

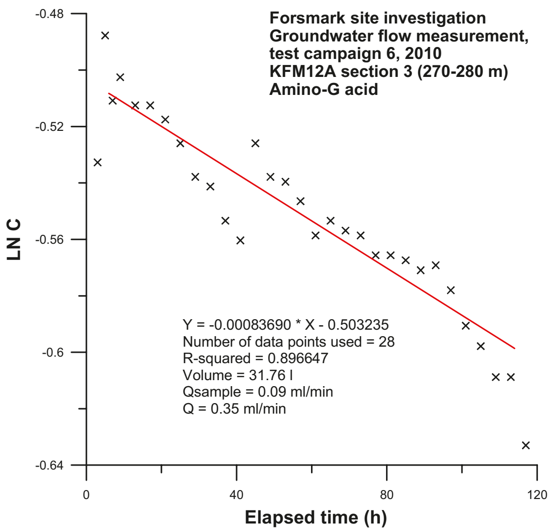

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM08D section 2 (825-835 m)
Amino-G acid
Y = -0.00093629 * X - 0.341948
Number of data points used = 20
R-squared = 0.930608
Volume = 63.44 l
Qsample = 0.09 ml/min
Q = 0.90 ml/min
LN C
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM08D section 4 (660-680 m)
Amino-G acid
Y = -0.05191972 * X - 0.534290
Number of data points used = 45
R-squared = 0.999736
Volume = 64.13 l
Qsample = 0.20 ml/min
Q = 55.3 ml/min
LN C
Elapsed time (h)

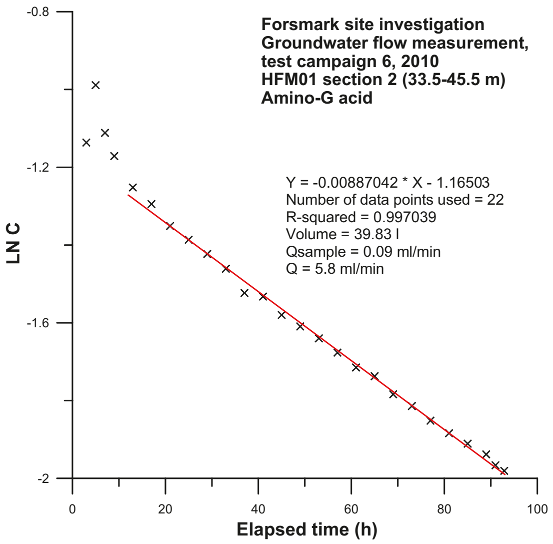

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM10A section 2 (430-440 m)
Amino-G acid
Y = -0.00229366 * X - 0.039054
Number of data points used = 17
R-squared = 0.9797
Volume = 39.52 l
Qsample = 0.10 ml/min
Q = 1.4 ml/min
LN C
Elapsed time (h)

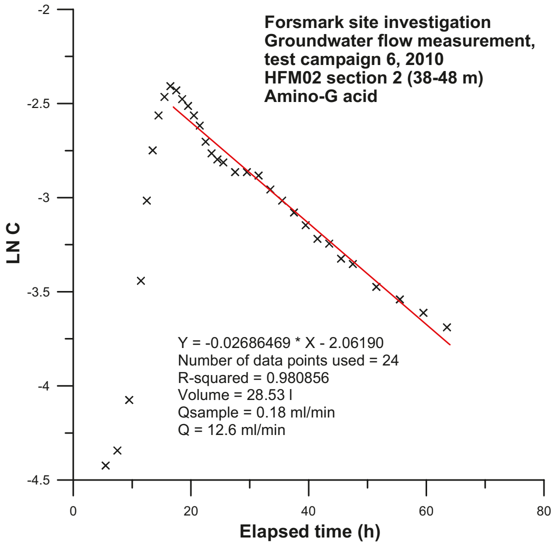

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM11A section 2 (690-710 m)
Amino-G acid
Y = -0.00083891 * X - 0.158221
Number of data points used = 17
R-squared = 0.985756
Volume = 68.91 l
Qsample = 0.10 ml/min
Q = 0.86 ml/min
LN C
Elapsed time (h)

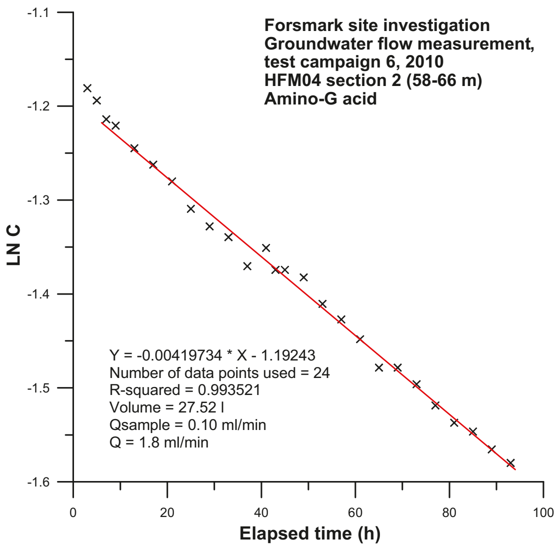

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM11A section 4 (446-456 m)
Amino-G acid
Y = -0.00041325 * X + 0.180369
Number of data points used = 16
R-squared = 0.906118
Volume = 40.47 l
Qsample = 0.08 ml/min
Q = 0.20 ml/min
LN C
Elapsed time (h)

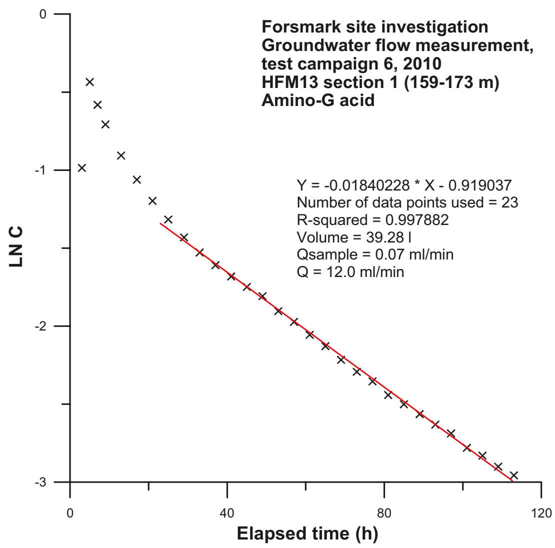

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
KFM12A section 3 (270-280 m)
Amino-G acid
Y = -0.00083690 * X - 0.503235
Number of data points used = 28
R-squared = 0.896647
Volume = 31.76 l
Qsample = 0.09 ml/min
Q = 0.35 ml/min
LN C
Elapsed time (h)

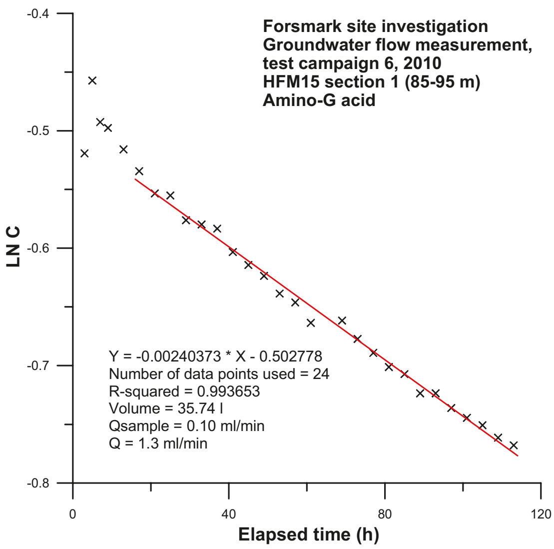
Percussion boreholes

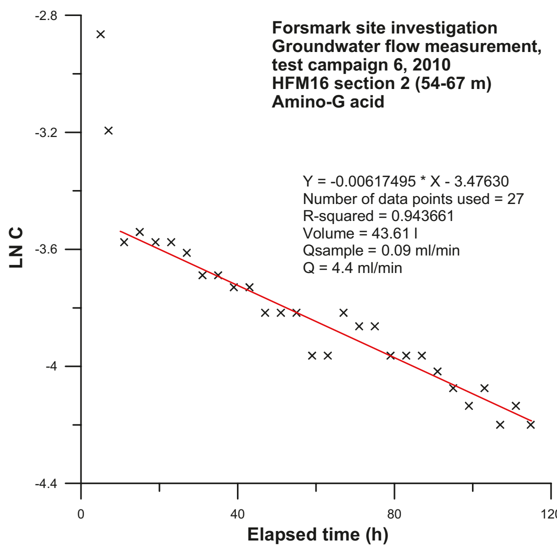


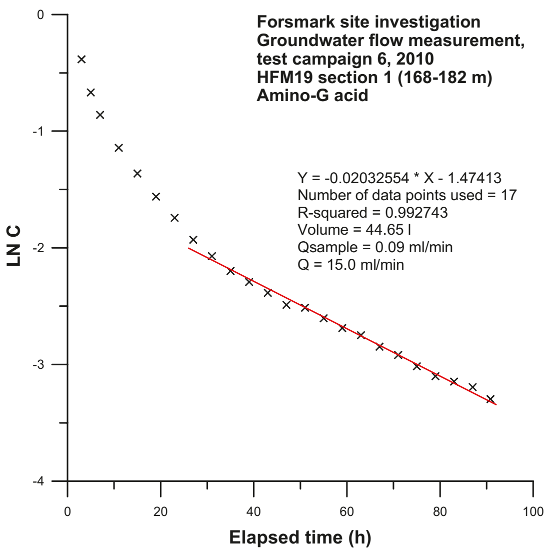


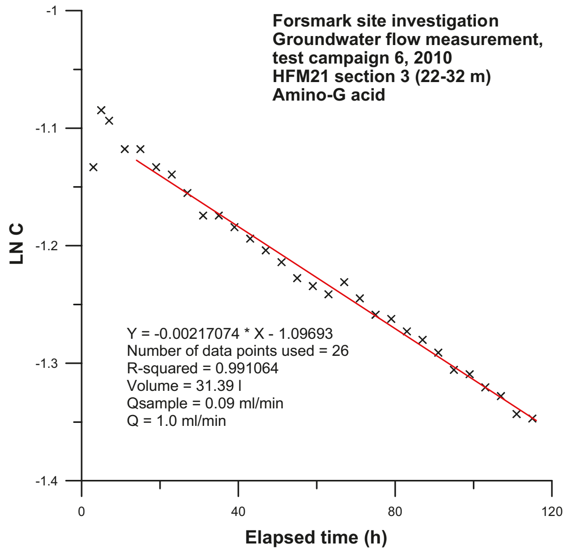


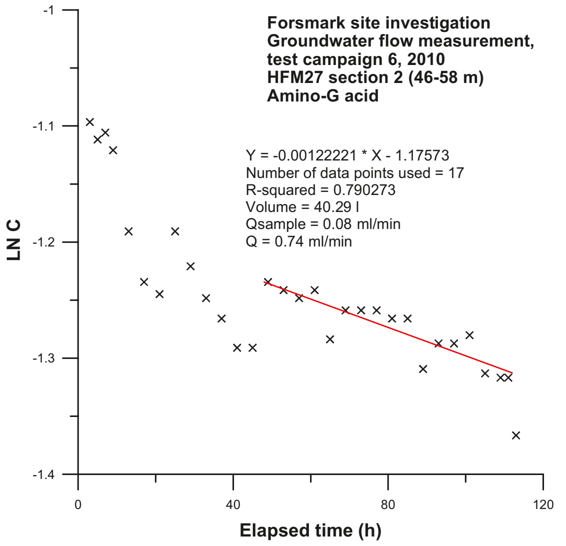







Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
HFM19 section 1 (168-182 m)
Amino-G acid
Y = -0.02032554 * X - 1.47413
Number of data points used = 17
R-squared = 0.992743
Volume = 44.65 l
Qsample = 0.09 ml/min
Q = 15.0 ml/min
LN C
Elapsed time (h)
0
-1
-2
-3
-4
0
20
40
60
80
100

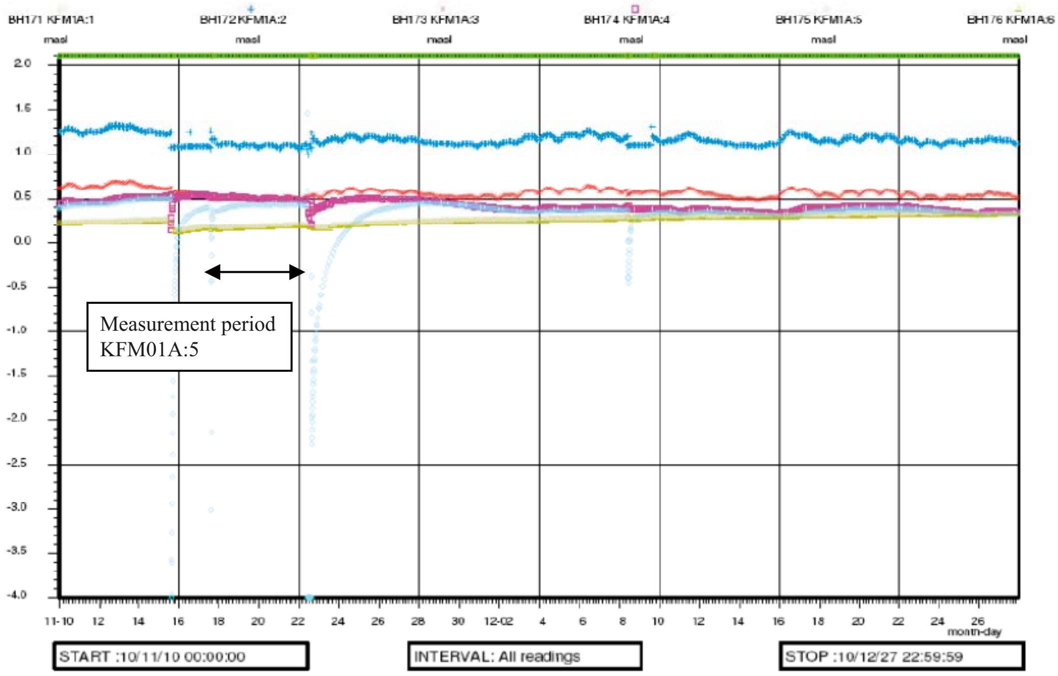

Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
HFM21 section 3 (22-32 m)
Amino-G acid
Y = -0.00217074 * X - 1.09693
Number of data points used = 26
R-squared = 0.991064
Volume = 31.39 l
Qsample = 0.09 ml/min
Q = 1.0 ml/min
LN C
Elapsed time (h)
-1
-1.1
-1.2
-1.3
-1.4
0
40
80
120


Forsmark site investigation
Groundwater flow measurement,
test campaign 6, 2010
HFM27 section 2 (46-58 m)
Amino-G acid
Y = -0.00122221 * X - 1.17573
Number of data points used = 17
R-squared = 0.790273
Volume = 40.29 l
Qsample = 0.08 ml/min
Q = 0.74 ml/min
LN C
Elapsed time (h)
-1
-1.1
-1.2
-1.3
-1.4
0
40
80
120

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

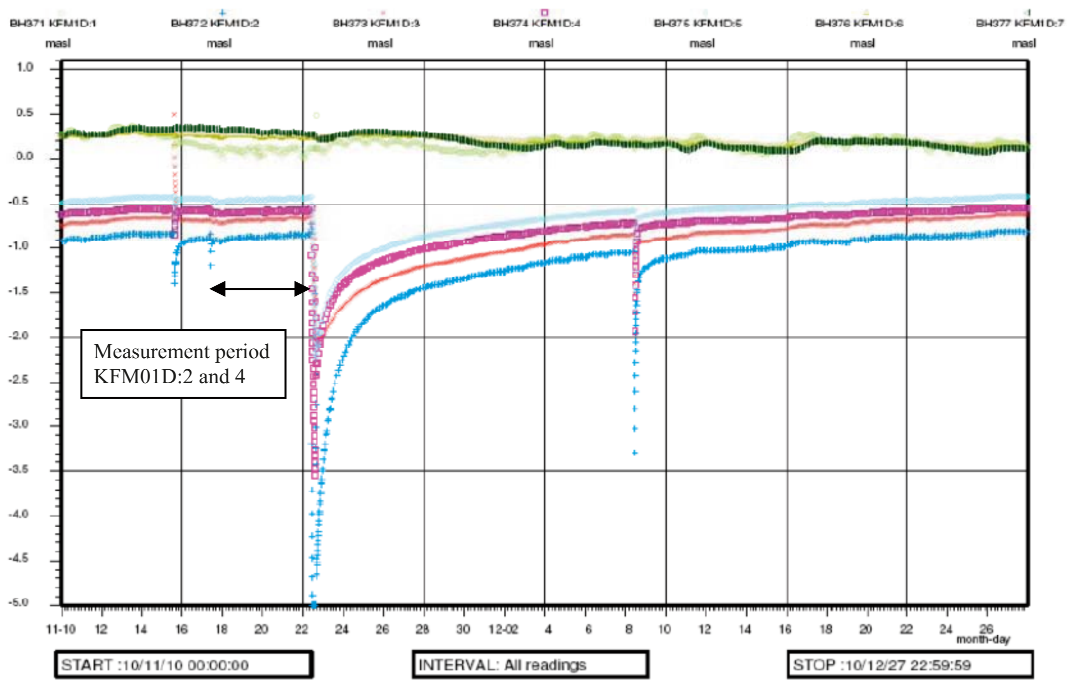
2010-11-10–2010-12-27 and 2011-03-11–2011-03-28

KFM01A



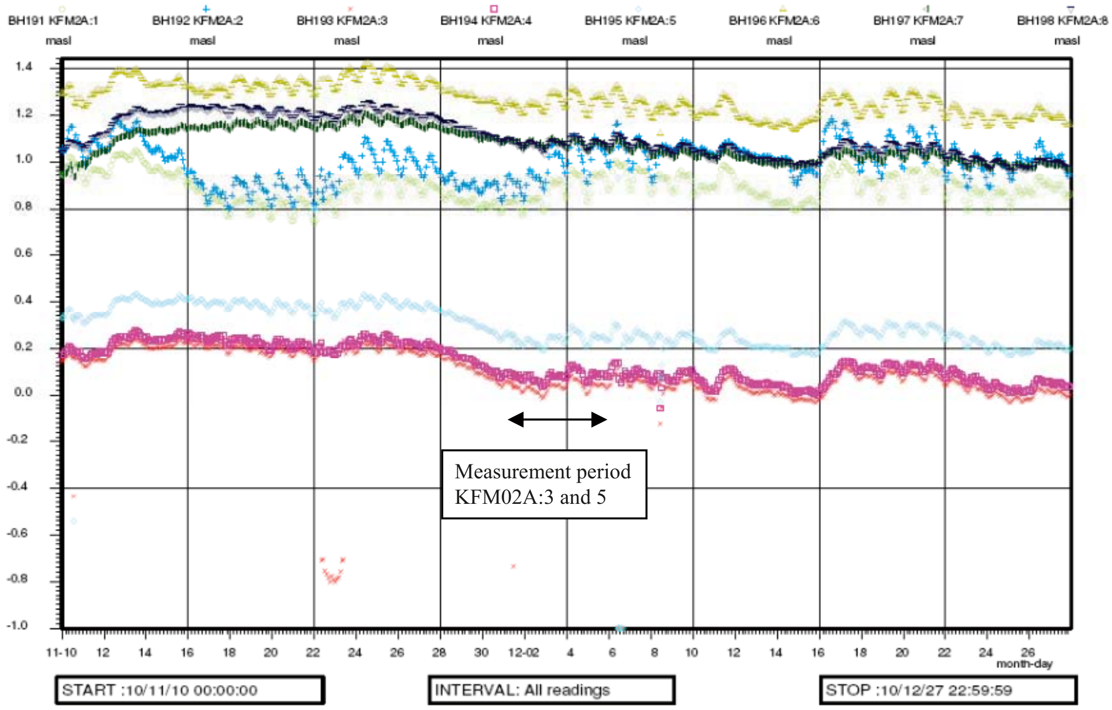
Measured section: KFM01A:5 (pale blue)

KFM01D



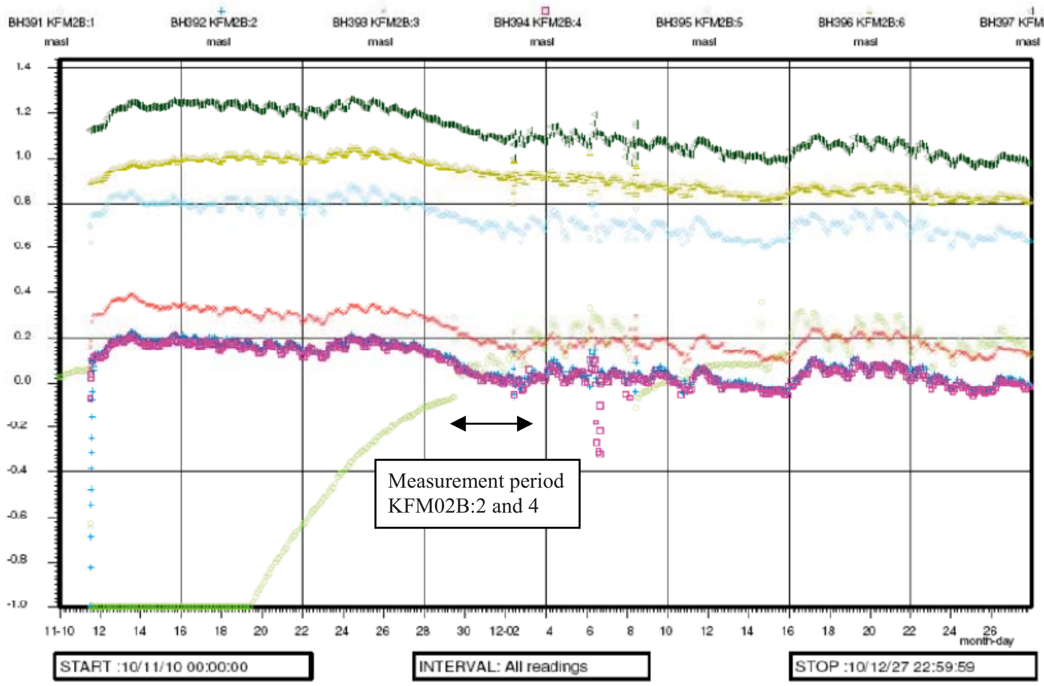
Measured sections: KFM01D:2 (blue) and KFM01D:4 (mauve)

KFM02A



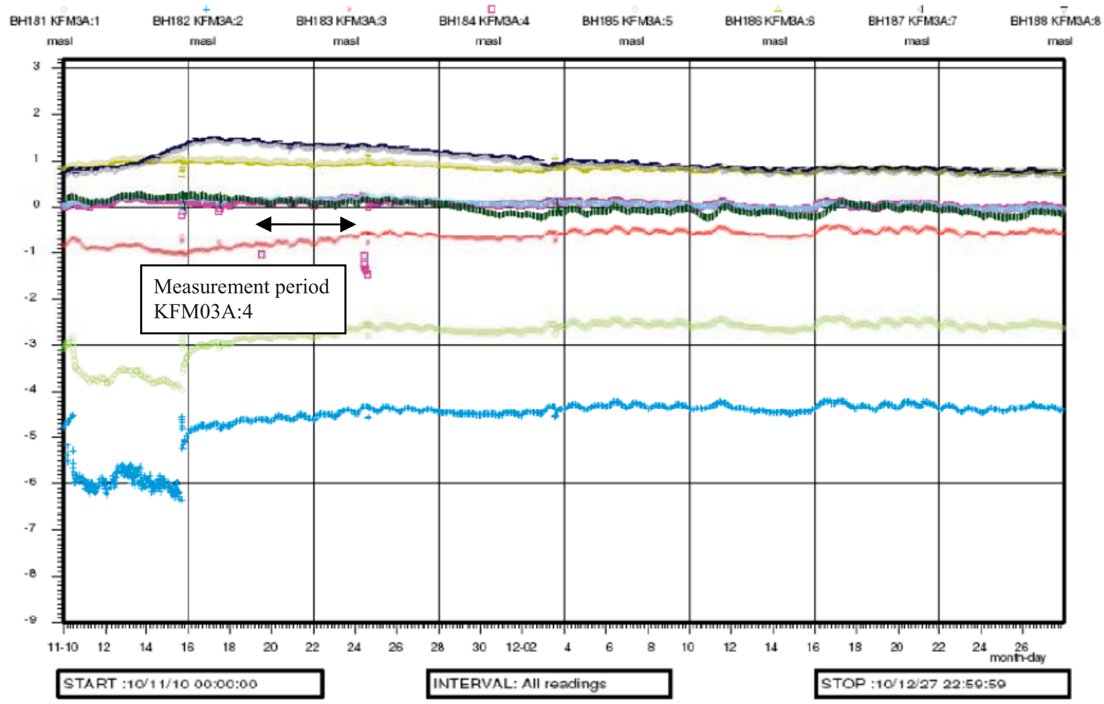
Measured sections: KFM02A:3 (red) and KFM02A:5 (pale blue)

KFM02B



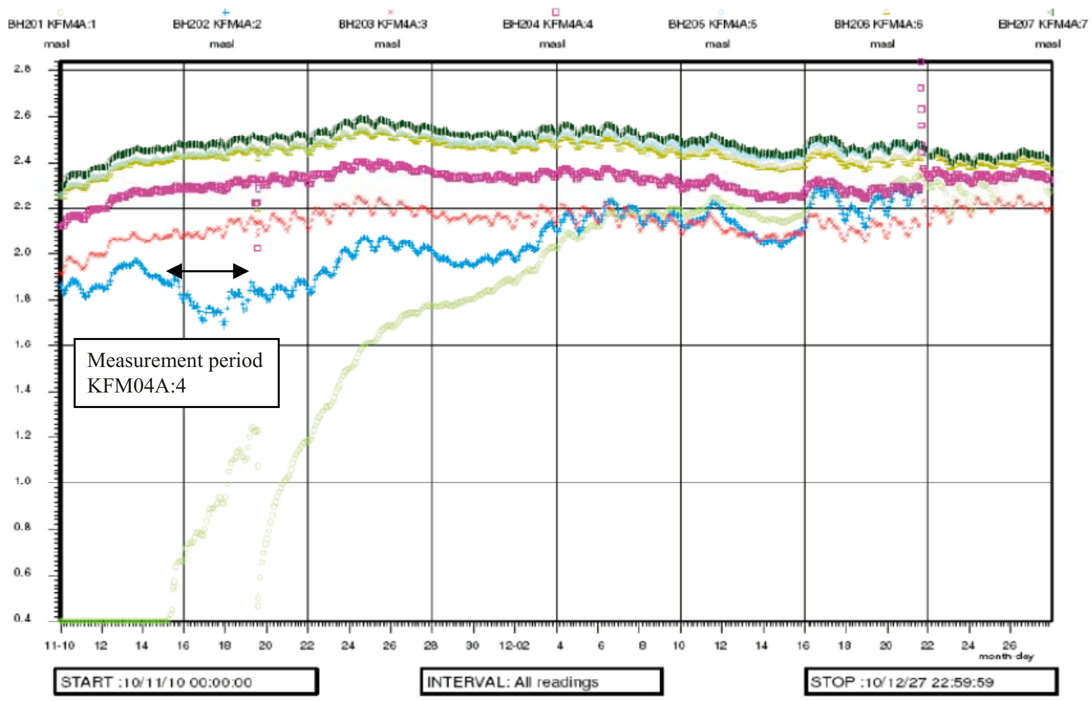
Measured sections: KFM02B:2 (blue) and KFM02B:4 (mauve)

KFM03A



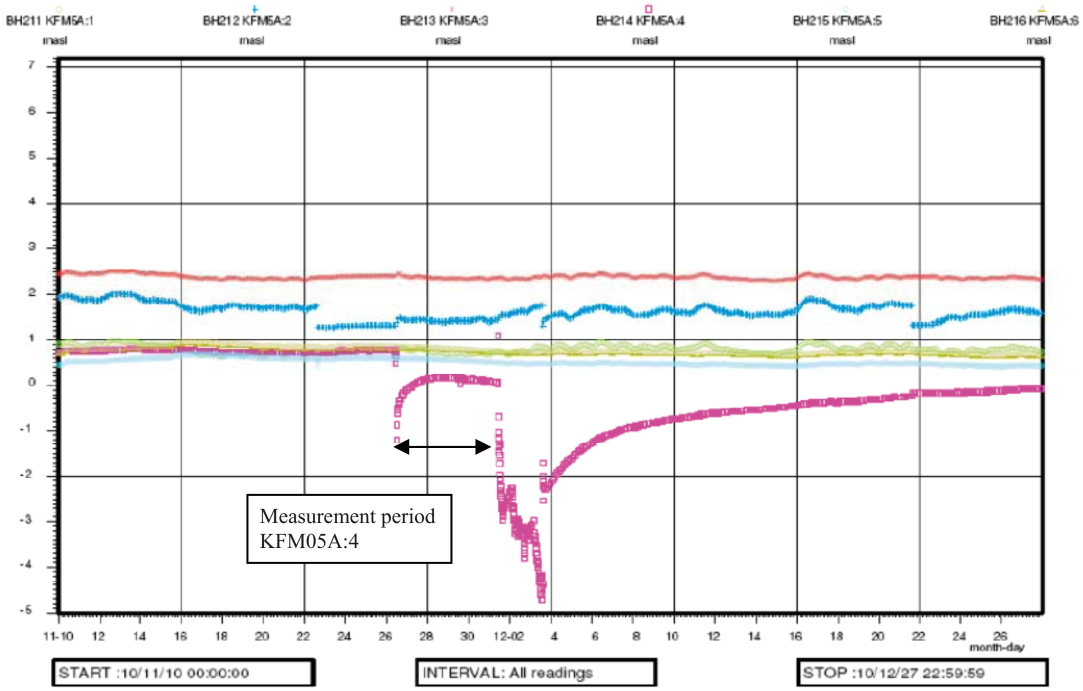
Measured section: KFM03A:4 (mauve)

KFM04A



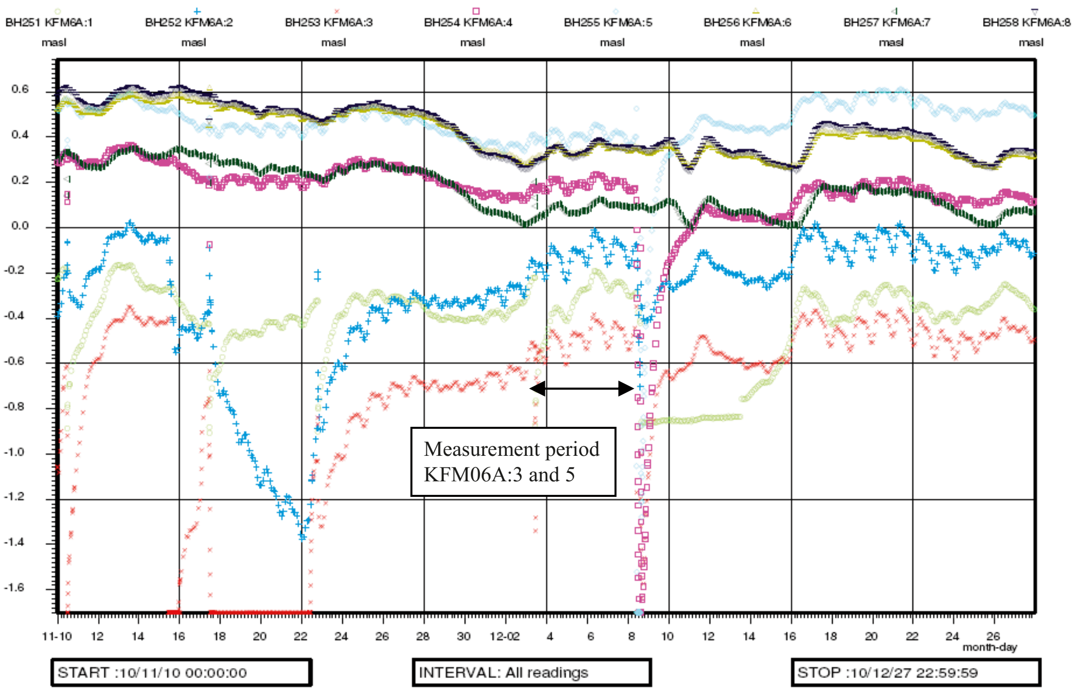
Measured section: KFM04A:4 (mauve)

KFM05A



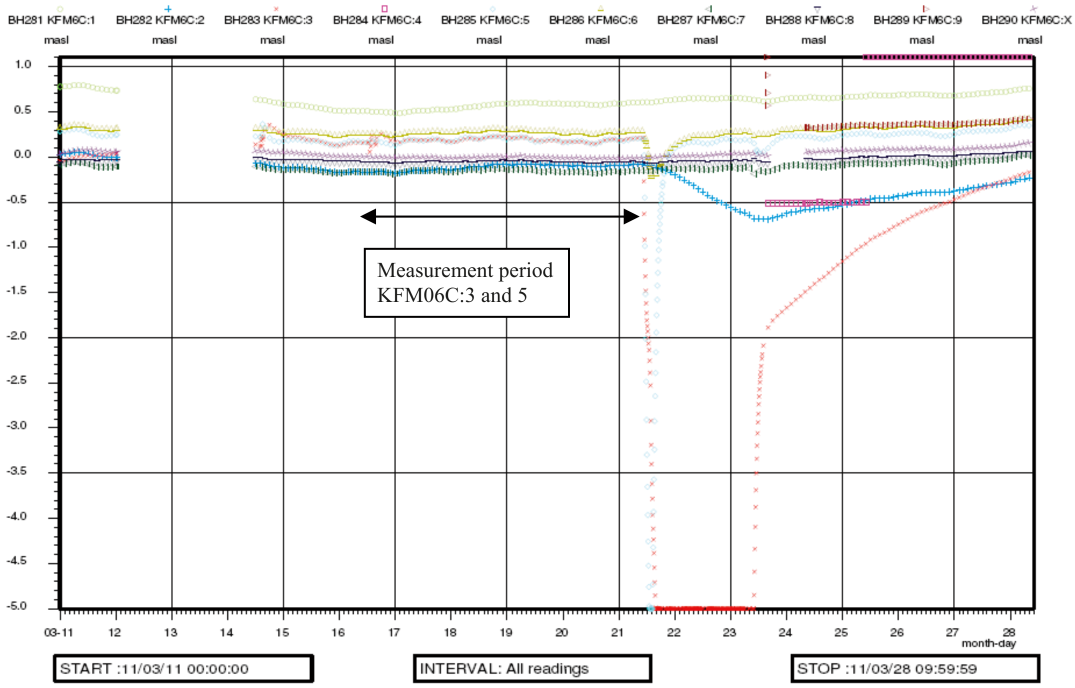
Measured section: KFM05A:4 (mauve)

KFM06A



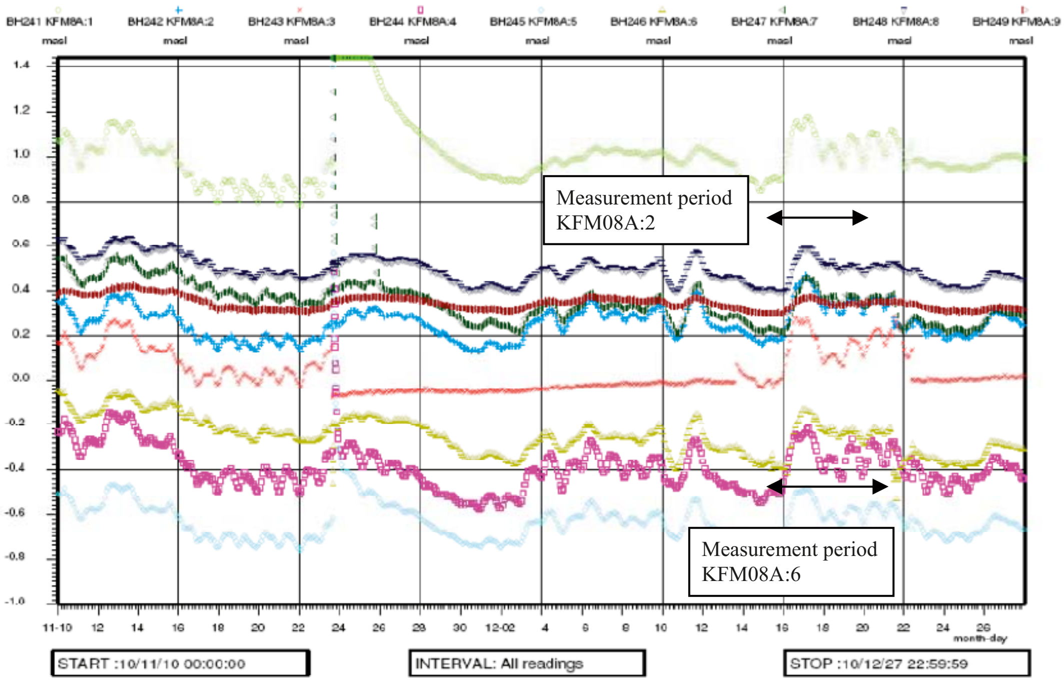
Measured sections: KFM06A:3 (red) and KFM06A:5 (pale blue)

KFM06C



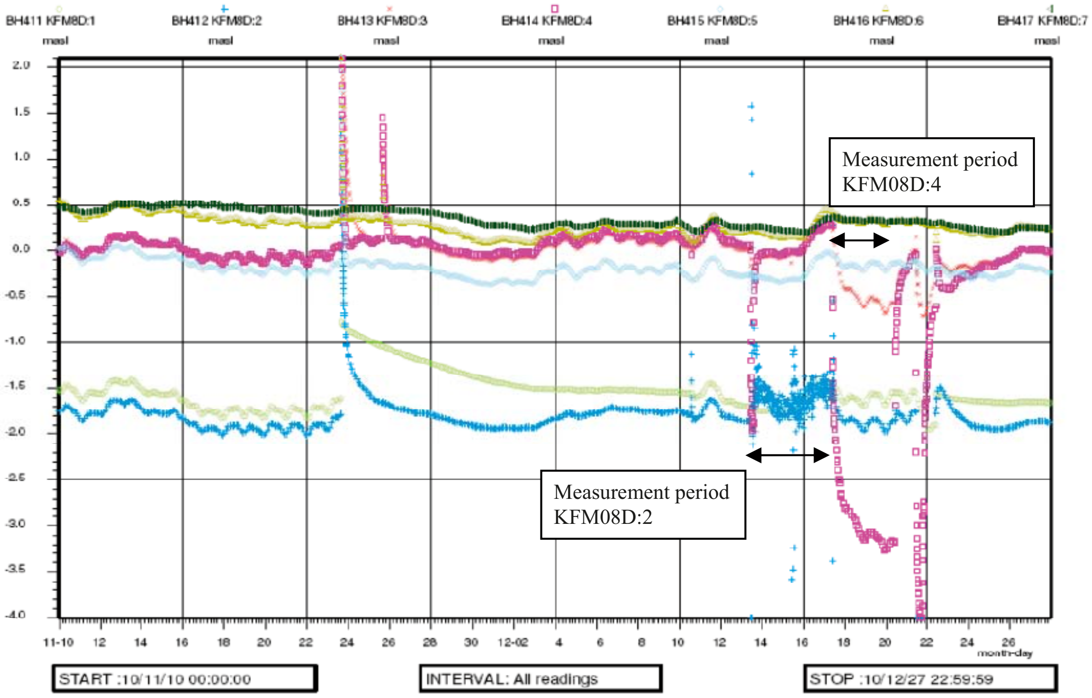
Measured sections: KFM06C:3 (red) and KFM06C:5 (pale blue)

KFM08A



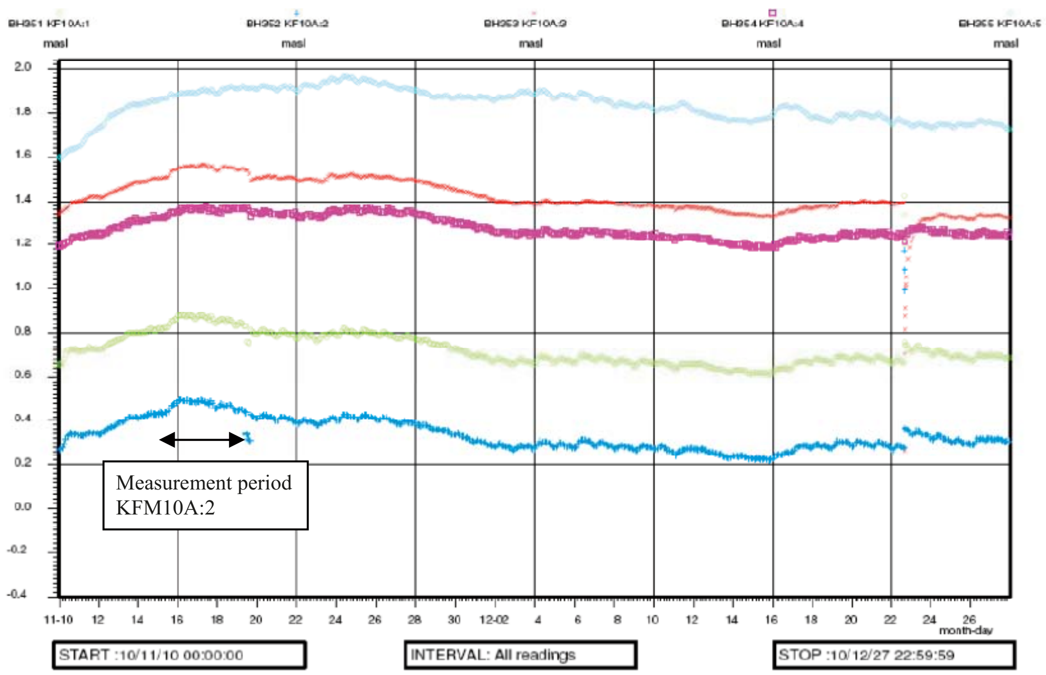
Measured sections: KFM08A:2 (blue) and KFM08A:6 (beige)

KFM08D



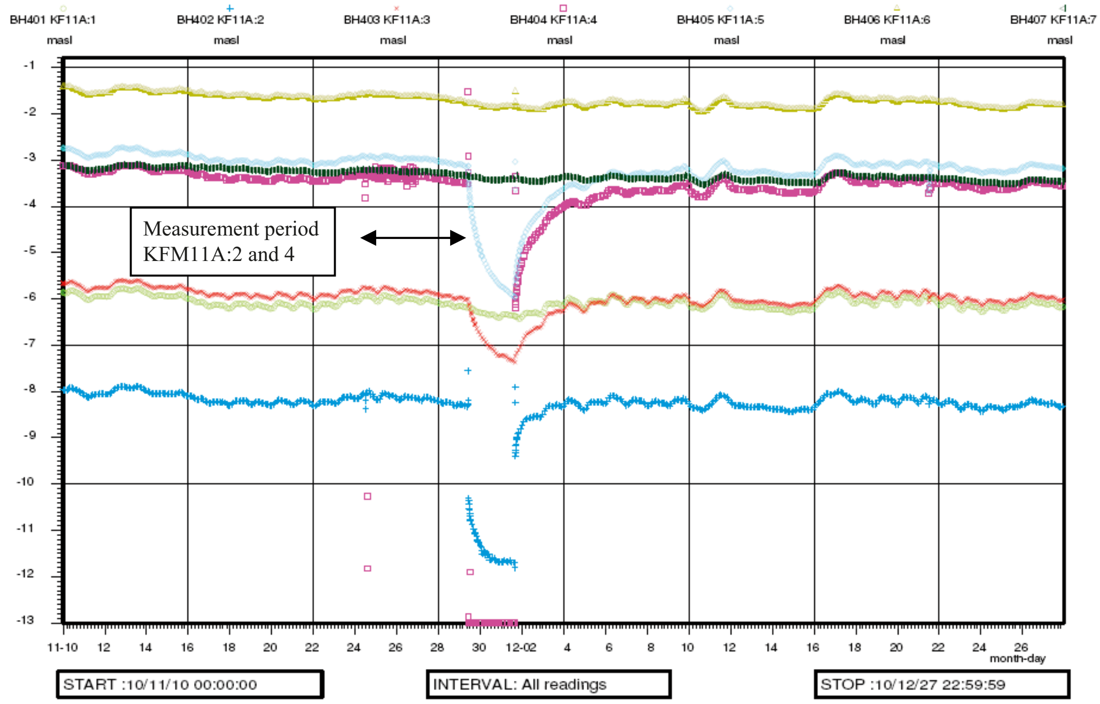
Measured sections: KFM08D:2 (blue) and KFM08D:4 (mauve)

KFM10A



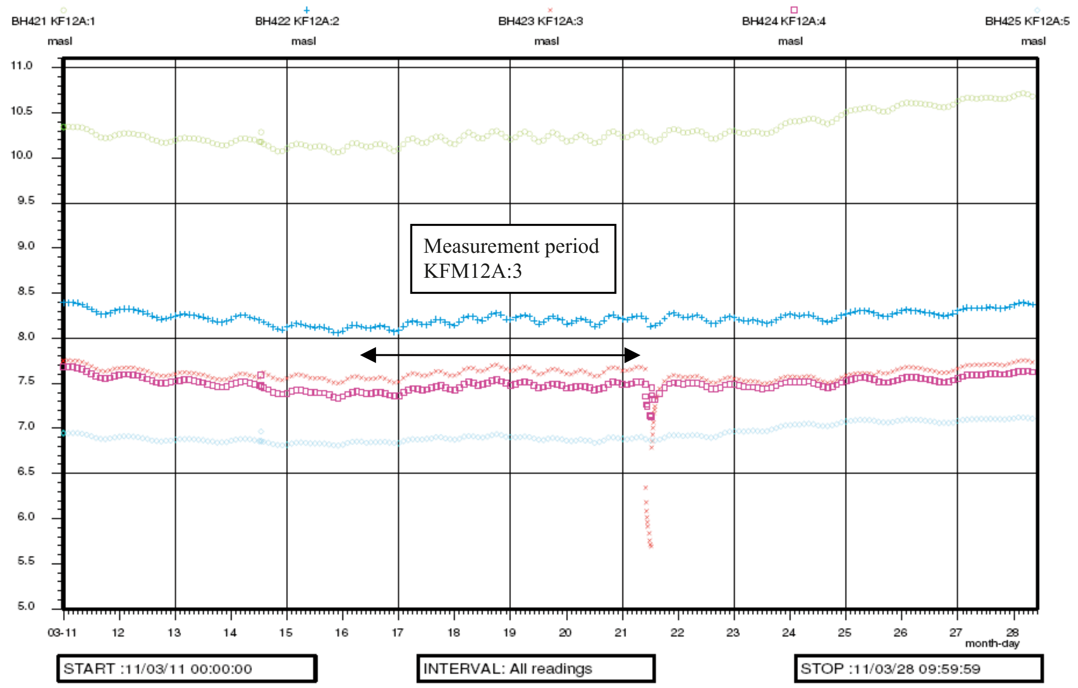
Measured section: KFM10A:2 (blue)

KFM11A



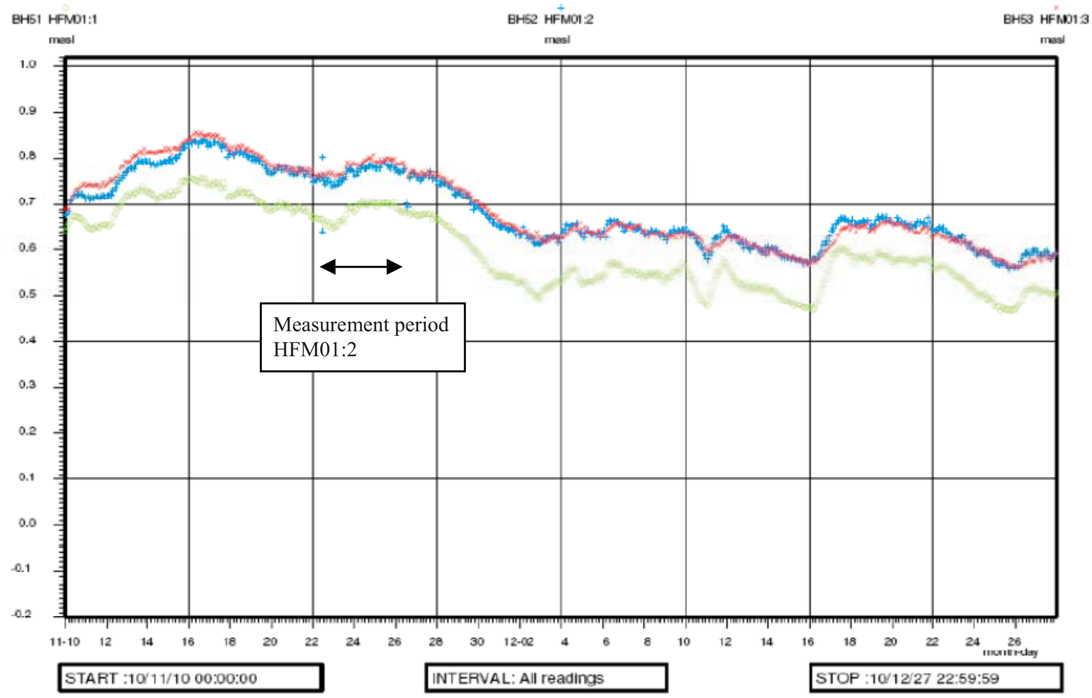
Measured sections: KFM11A:2 (blue) and KFM11A:4 (mauve)

KFM12A



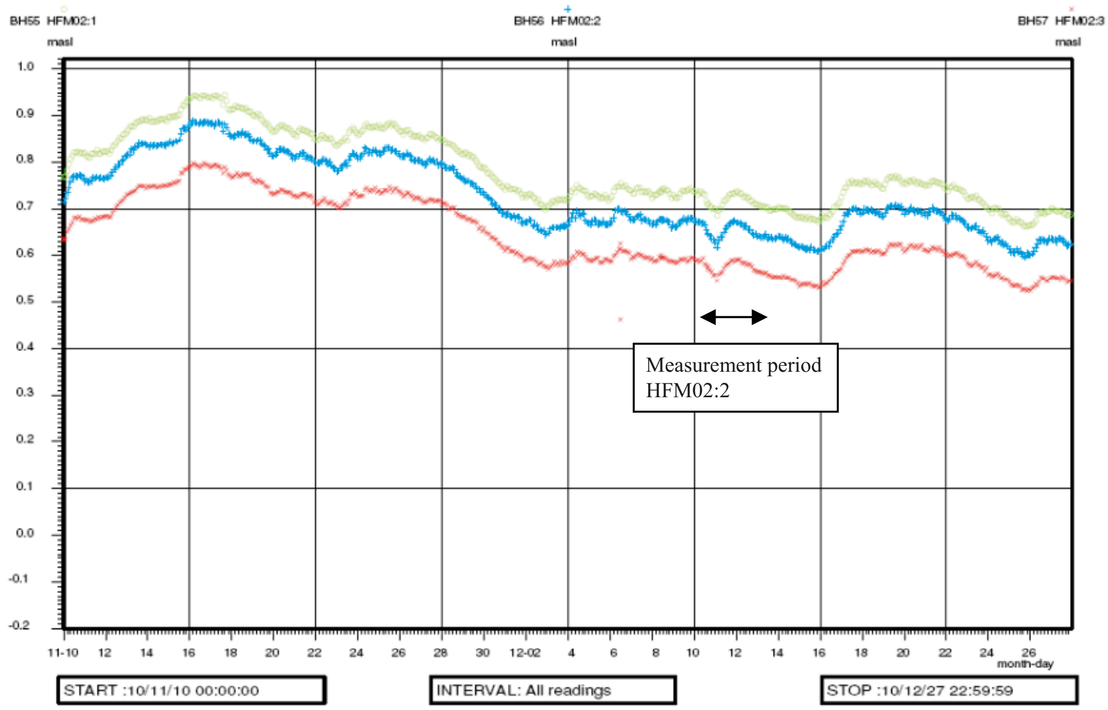
Measured section: KFM12A:3 (red)

HFM01



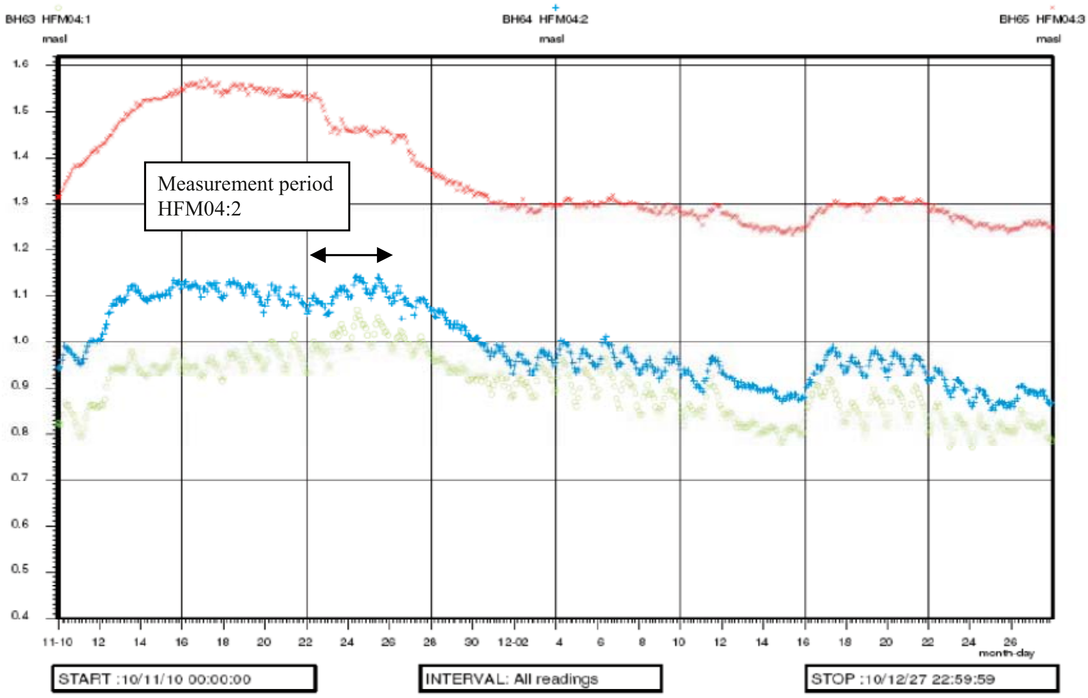
Measured section: HFM01:2 (blue)

HFM02



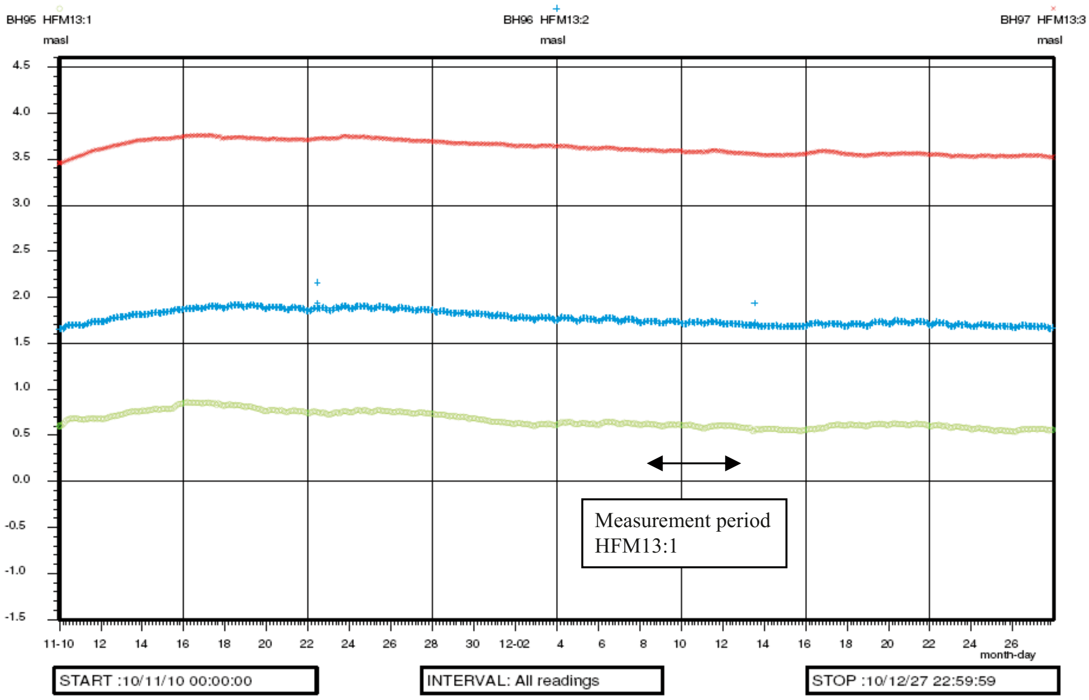
Measured section: HFM02:2 (blue)

HFM04



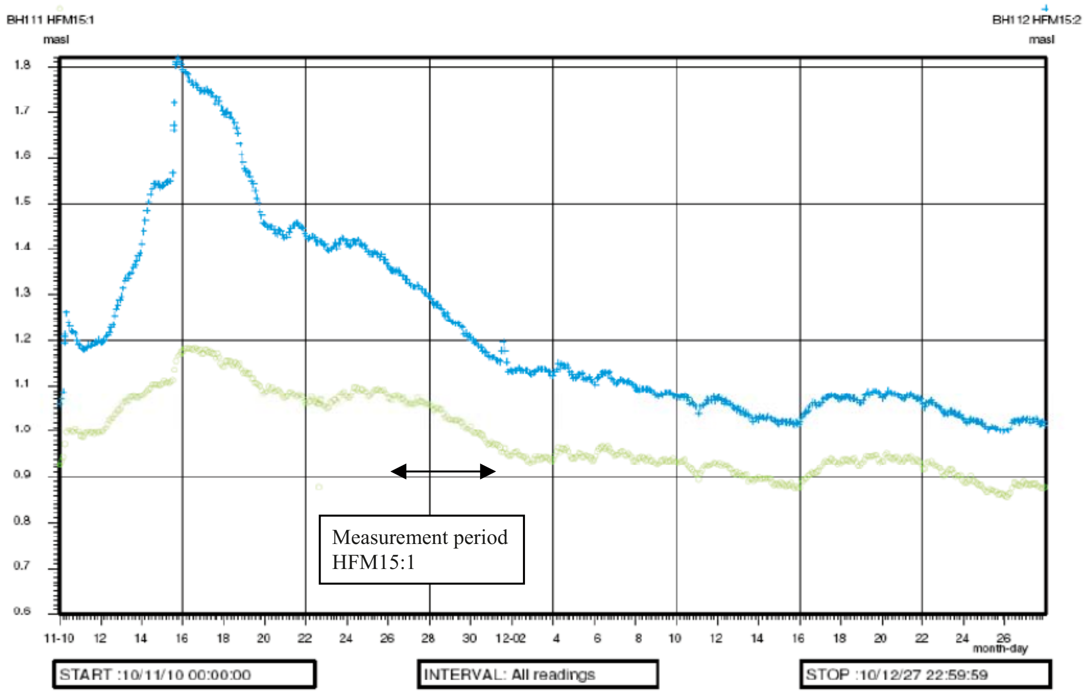
Measured section: HFM04:2 (blue)

HFM13



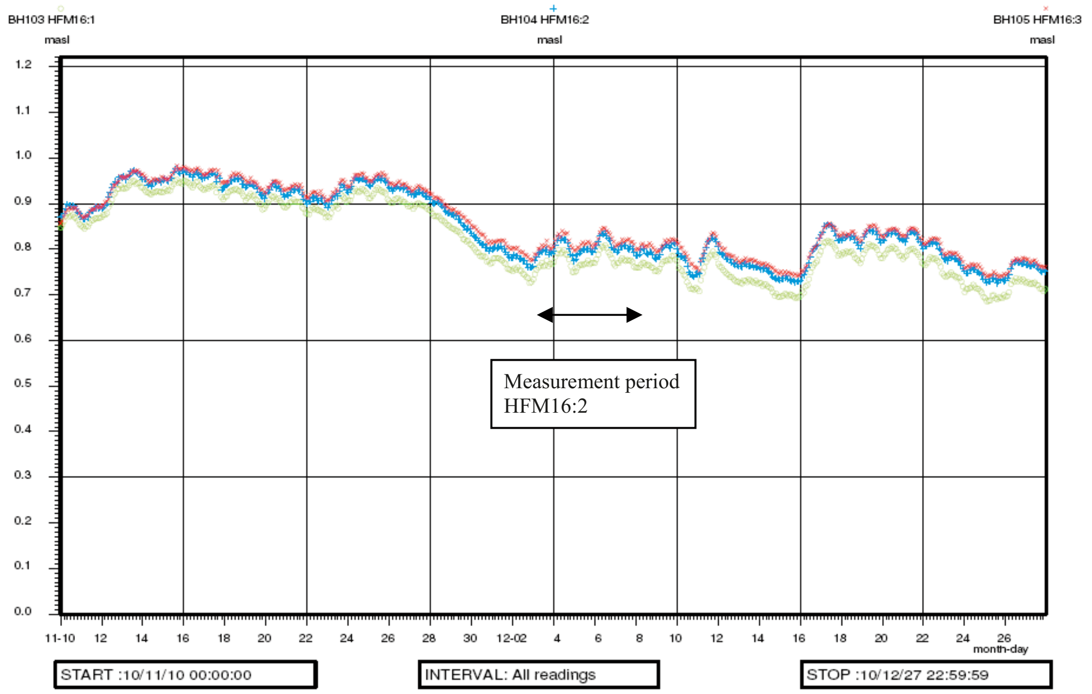
Measured section: HFM13:1 (green)

HFM15



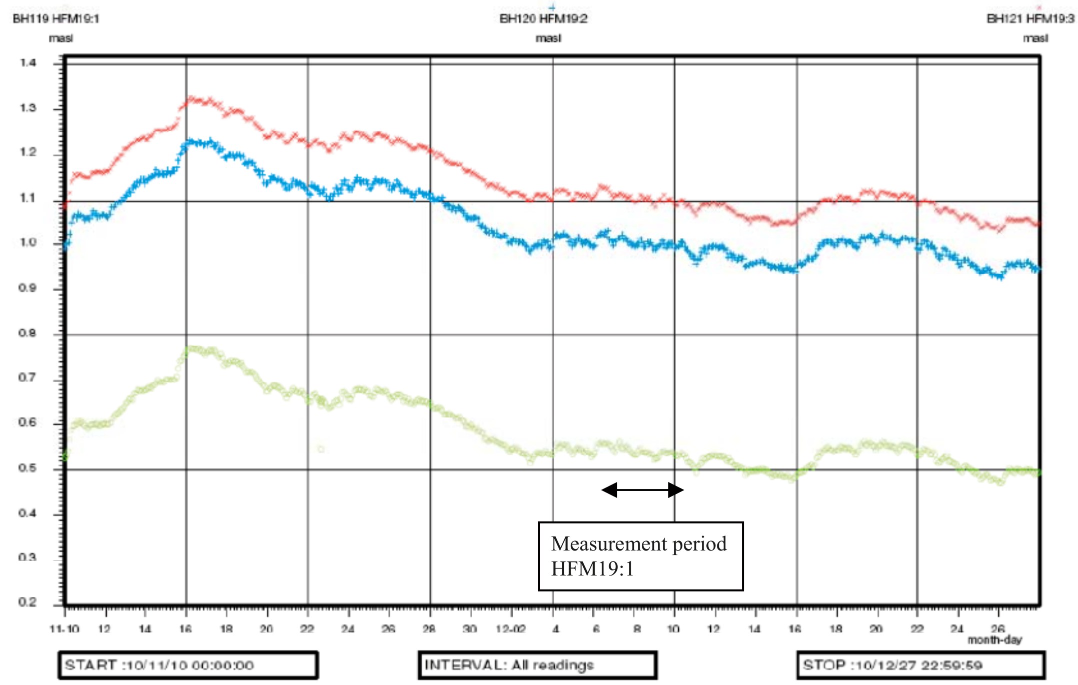
Measured section: HFM15:1 (green)

HFM16



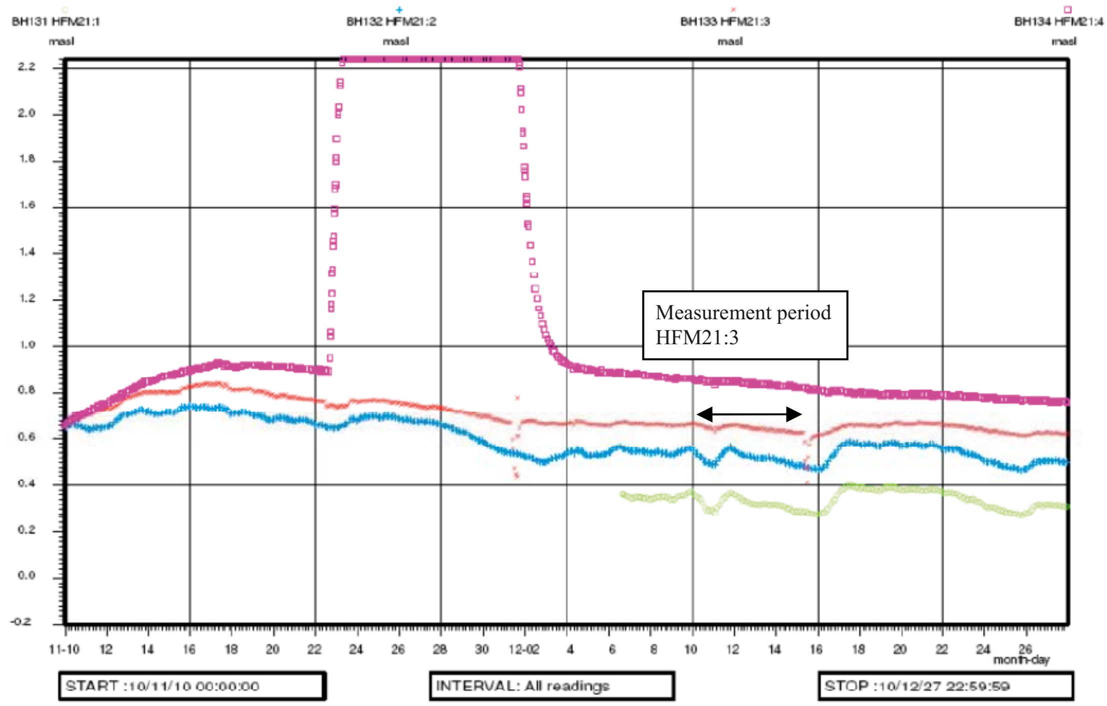
Measured section: HFM16:2 (blue)

HFM19



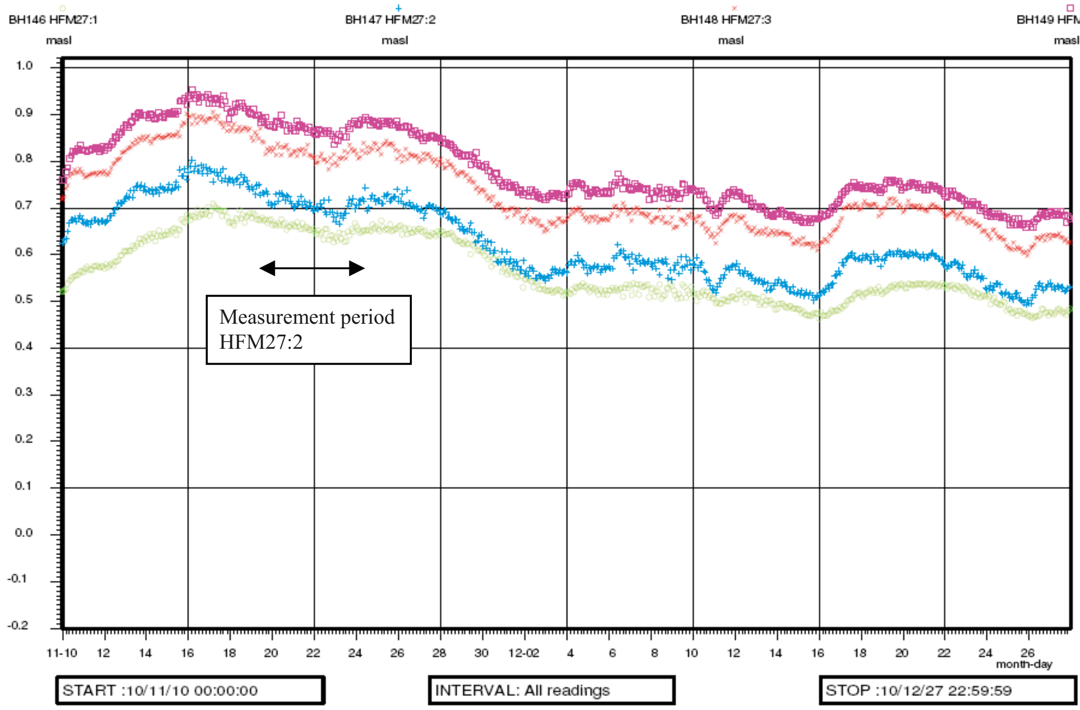
Measured section: HFM19:1 (green)

HFM21



Measured section: HFM21:3 (red)

HFM27



Measured section: HFM27:2 (blue)