P-09-30

Forsmark site investigation

Groundwater flow measurements in permanently installed boreholes

Test campaign no. 4, 2008

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August 2009

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Keywords: Groundwater flow, Dilution test, Tracer test, AP PF 400-07-053.

Abstract

This report describes the performance and evaluation of groundwater flow measurements in 32 borehole sections in permanently installed boreholes within the Forsmark site investigation area. The objective was to determine the groundwater flow in all, at the time available, borehole sections instrumented for this purpose. This is the fourth test campaign performed within the monitoring program and it is planned to be repeated once every year.

The groundwater flow in the selected borehole sections was determined through dilution measurements during natural conditions. Measured flow rates ranged from 0.01 to 123 ml/min with calculated Darcy velocities from $6.7 \cdot 10^{-11}$ to $6.6 \cdot 10^{-7}$ m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.0003 and 66.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödesmätningar i 32 borrhålssektioner i permanent installerade borrhål inom Forsmarks platsundersökningsområde. Syftet var att bestämma grundvattenflödet i samtliga, vid denna tidpunkt och för detta ändamål, instrumenterade sektioner. Detta är den fjärde 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 0,01–123 ml/min med beräknade Darcy hastigheter mellan $6{,}7\cdot10^{-11}$ och $6{,}6\cdot10^{-7}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,0003 och 66.

Contents

1 Introduction

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 4, 2008, 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 stipulated to continue as an independent project starting in July 2007, after completion of Project Forsmark Site investigation in June 2007.

The work was carried out in accordance with activity plan AP PF 400-07-053 and the field work was conducted during November–December 2008 and March 2009. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions 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.

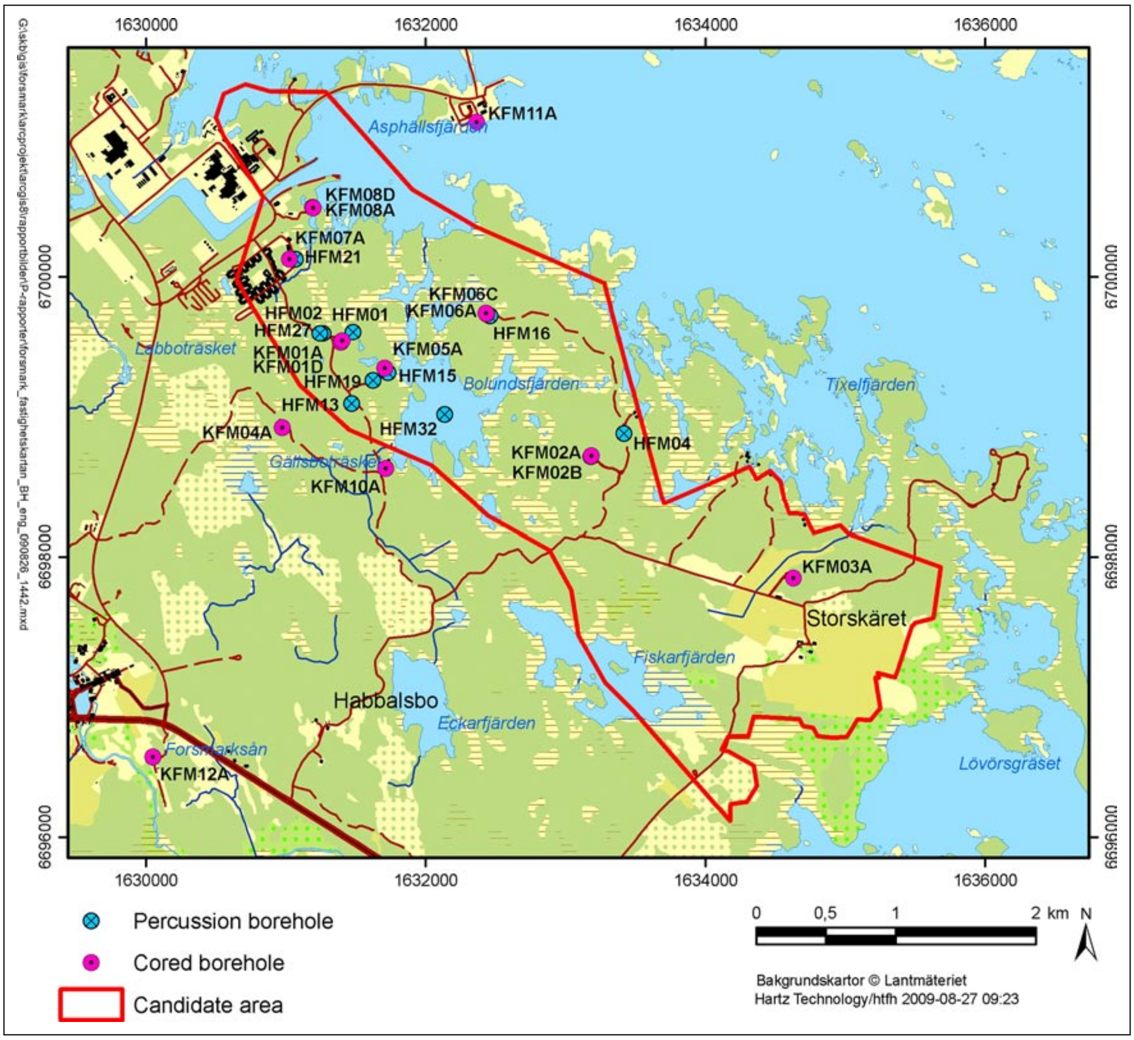

***Figure 1-1.** Overview over Forsmark site investigation area, showing locations of boreholes included in this activity.*

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

Activity plan	Number	Version
Monitering av grundvattenflöde 2008.	AP PF 400-07-053	1.0
Method description	**Number**	**Version**
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 borehole sections in permanently installed boreholes at Forsmark. Thirty-two borehole sections instrumented for this purpose (circulation sections) were measured, cf. Table 4-1. This was the fourth test campaign performed within the monitoring programme and it is 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 in the hydraulic gradients caused by 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 major investigation activities 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 Description of equipment and tracers used

The boreholes involved in the tests are instrumented with 1–9 inflatable packers isolating 2–10 borehole sections each. 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 planned to be used for tracer tests are equipped with three polyamide tubes. Two are used for injection, sampling and circulation in the borehole section and one is used for pressure monitoring.

The tracer dilution tests were performed using five identical equipment setups, i.e. 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 by a down-hole pump with variable speed and measured by a flow meter. Tracer injections are made 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).

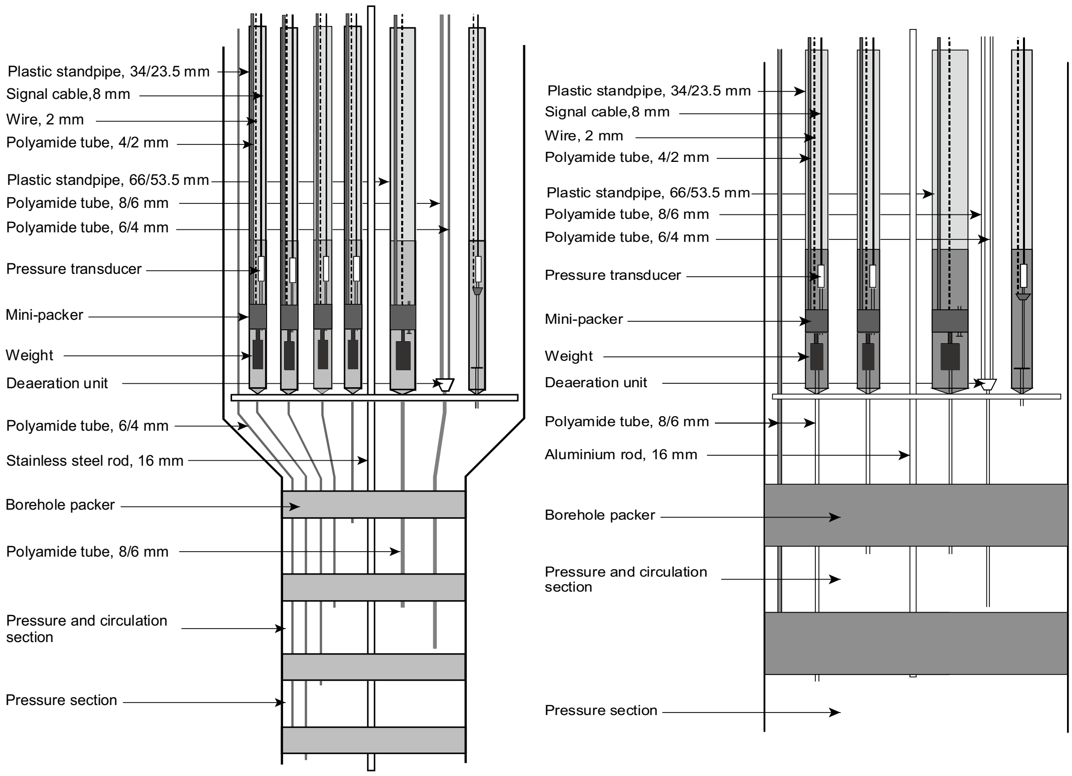

Figure 3-1. *Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.*

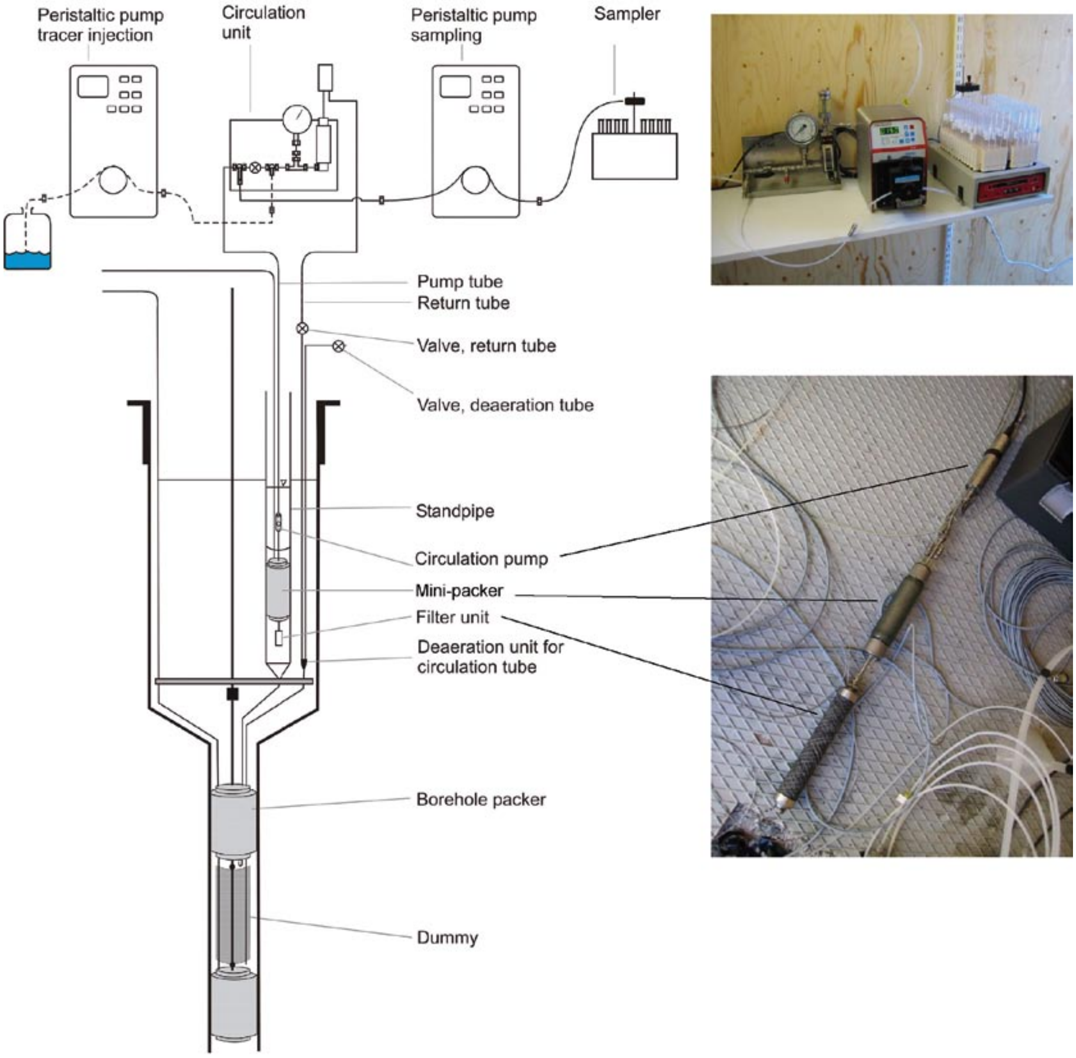

Figure 3-2. *Schematic drawing of the equipment used in tracer dilution measurements.*

4 Execution

4.1 General

In the dilution method a tracer is introduced and homogeneously distributed into a borehole test section. The tracer is subsequently diluted by the ambient groundwater, flowing through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section and the groundwater flow 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, functionality 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 2008 are listed in Table 4-1.

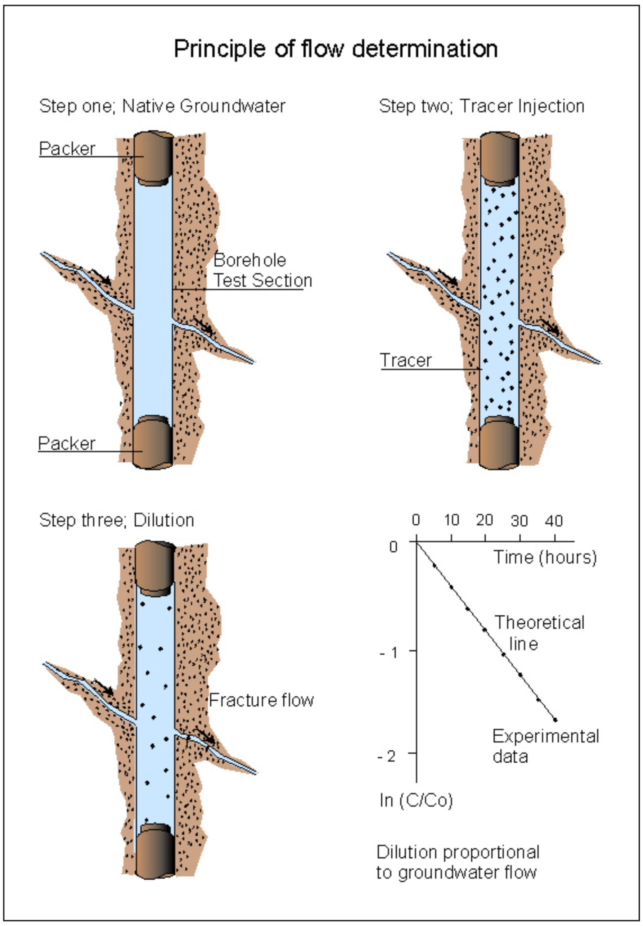

Figure 4-1. *General principles of dilution and flow determination.*

Table 4-1. Borehole sections included in the monitoring program, autumn 2008.

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	081128–081203
KFM01D:2	429–438	8.0 E–7*	Single fracture, Fracture domain FFM01	081128–081203
KFM01D:4	311–321	2.0 E–7*	Single fracture, Fracture domain FFM01	081128–081203
KFM02A:3	490–518	2.1 E–6*	Zone ZFMF1	081117–081121
KFM02A:5	411–442	2.5 E–6*	Zone ZFMA2	081117–081121
KFM02B:2	491–506	3.0 E–5*	Not included in /27/	081117–081121
KFM02B:4	410–431	2.0 E–5*	Not included in /27/	081117–081121
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	081203–081208
KFM04A:4	230–245	2.0 E–5*	Zone ZFMA2	081121–081125
KFM05A:4	254–272	1.4 E–8*	Single fracture, Fracture domain FFM01	081205–081210
KFM06A:3	738–748	1.2 E–7*	Zone ZFMNNE0725	081210–081215
KFM06A:5	341–362	3.5 E–6*	Zone ZFMB7, Zone ZFMENE0060A	081210–081215
KFM06C:3	647–666	5.3 E–8*	Possible DZ (S-NNE/WNW)	081212–081217
KFM06C:5	531–540	1.1 E–6*	Zone ZFMWNW044	081212–081217
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)	081215–081219
KFM08A:6	265–280	1.0 E–6*	Zone ZFMENE1061A	081215–081219
KFM08D:2	825–835	2.0 E–8*	Not included in /27/	081212–081217
KFM08D:4	660–680	2.0 E–7*	Not included in /27/	081217–081222
KFM10A:2	430–440	3.0 E–5*	Zone ZFMA2	081208–081212
KFM11A:2	690–710	1.0 E–6*	Not included in /27/	081125–081201
KFM11A:4	446–456	6.0 E–7*	Not included in /27/	081125–081201
KFM12A:3	270–280	1.0 E–6*	Not included in /27/	081203–081208
HFM01:2	33.5–45.5	4.0 E–5**	Zone ZFMA2	081208–081212
HFM02:2	38–48	5.9 E–4**	Zone ZFM1203	081208–081212
HFM04:2	58–66	7.9 E–5**	Zone ZFM866	081117–081121
HFM13:1	159–173	2.9 E–4**	Zone ZFMENE0401A	081121–081125
HFM15:1	85–95	1.0 E–4**	Zone ZFMA2	081201–081205
HFM16:2	54–67	3.5 E–4**	Zone ZFMA8	081205–081210
HFM19:1	168–182	2.7 E–4**	Zone ZFMA2	081201–081205
HFM21:3	22–32	4.0 E–5**	Single fracture, Fracture domain FFM02	081121–081125
HFM27:2	46–58	4.0 E–5**	Zone ZFM1203	081203–081208
HFM32:3	26–31	2.3 E–4**	Single fracture, Fracture domain FFM03	090316–090320

* 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, stage 2.2, /27/.

Groundwater flow measurements were made in 32 of the 34 sections. Sections KFM03A:1 and KFM07A:2 were omitted for technical reasons, cf. Section 4.5. The duration of each test varied from 91 to 141 hours.

The tests were made by injecting a slug of tracer (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 start concentration in the borehole section would 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):

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

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) versus t, and by knowing the borehole volume V, Q_{bh} may then be obtained from the straight-line slope. If c_0 is constant, it is sufficient to use ln c in the plot.

The sampling procedure with a constant flow of 5-11 ml/h 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:

$$Q_{bh} = v \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha \tag{4-2}$$

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):

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

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 the angles in the sections not always 90º, the calculation of the hydraulic gradient is a rough estimation.

4.5 Nonconformities

Borehole sections KFM03A:1 (969.5–994.5 m) and KFM07A:2 (962–972 m), included in the monitoring programme and listed in the Activity Plan (AP PF 400-07-053), were not measured.

Previous test campaigns have shown that borehole sections KFM03A:1 and KFM07A:2 are very difficult or even impossible to circulate. The reason for this may be the large depth and gasification combined with quite low transmissivity. Also, both sections have large volumes (about 90 and 70 litres, respectively) and long tubing which decreases the circulation capacity of the pump. It was therefore decided to exclude these two sections from the test campaign this time.

5 Results

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 400-07-053). 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.

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 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 4, 2008.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Vol. (l)	Measured flow (ml/min)	Darcy velocity (m/s)	Hydraulic gradient (m/m)
KFM01A:5	109–130	1.0 E–7*	33.21	0.1	6.9E–10	0.15
KFM01D:2	429–438	8.0 E–7*	38.33	0.04	5.1E–10	0.0057
KFM01D:4	311–321	2.0 E–7*	31.21	0.2	1.8E–09	0.091
KFM02A:3	490–518	2.1 E–6*	66.33	1.2	4.7E–09	0.063
KFM02A:5	411–442	2.5 E–6*	60.78	0.1	3.5E–10	0.0043
KFM02B:2	491–506	3.0 E–5*	48.63	12	8.8E–08	0.044
KFM02B:4	410–431	2.0 E–5*	47.58	35	1.8E–07	0.19
KFM03A:4	633.5–650	2.4 E–6*	58.04	1.1	7.3E–09	0.050
KFM04A:4	230–245	2.0 E–5*	35.00	8.0	5.8E–08	0.043
KFM05A:4	254–272	1.4 E–8*	40.62	0.1	8.0E–10	1.0
KFM06A:3	738–748	1.2 E–7*	58.25	0.05	5.6E–10	0.046
KFM06A:5	341–362	3.5 E–6*	46.64	0.2	1.0E–09	0.0063
KFM06C:3	647–666	5.3 E–8*	64.00	0.03	2.0E–10	0.071
KFM06C:5	531–540	1.1 E–6*	43.61	0.4	5.4E–09	0.044
KFM08A:2	684–694	1.0 E–6*	55.15	0.7	7.4E–09	0.074
KFM08A:6	265–280	1.0 E–6*	34.67	0.06	4.1E–10	0.0061
KFM08D:2	825–835	2.0 E–8*	63.44	1.8	1.9E–08	9
				(5.2)	(5.6E–08)	(28)
KFM08D:4	660–680	2.0 E–7*	64.13	123	6.6E–07	66
KFM10A:2	430–440	3.0 E–5*	39.52	1.6	1.8E–08	0.0059
KFM11A:2	690–710	1.0 E–6*	68.91	0.3	1.7E–09	0.033
KFM11A:4	446–456	6.0 E–7*	40.47	0.01	6.7E–11	0.0011
KFM12A:3	270–280	1.0 E–6*	31.76	1.8	2.0E–08	0.20
HFM01:2	33.5–45.5	4.0 E–5**	39.83	6.3	3.1E–08	0.0093
HFM02:2	38–48	5.9 E–4**	28.53	23	1.4E–07	0.0024
HFM04:2	58–66	7.9 E–5**	27.52	2.6	2.0E–08	0.0020
HFM13:1	159–173	2.9 E–4**	39.28	17	7.5E–08	0.0036
HFM15:1	85–95	1.0 E–4**	35.74	4.0	2.4E–08	0.0024
HFM16:2	54–67	3.5 E–4**	43.61	2.8	1.3E–08	0.0005
HFM19:1	168–182	2.7 E–4**	44.65	18	8.0E–08	0.0041
HFM21:3	22–32	4.0 E–5**	31.39	2.1	1.3E–08	0.0032
HFM27:2	46–58	4.0 E–5**	40.29	0.8	4.0E–09	0.0012
HFM32:3	26–31	2.3 E–4**	20.06	1.2	1.4E–08	0.0003

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

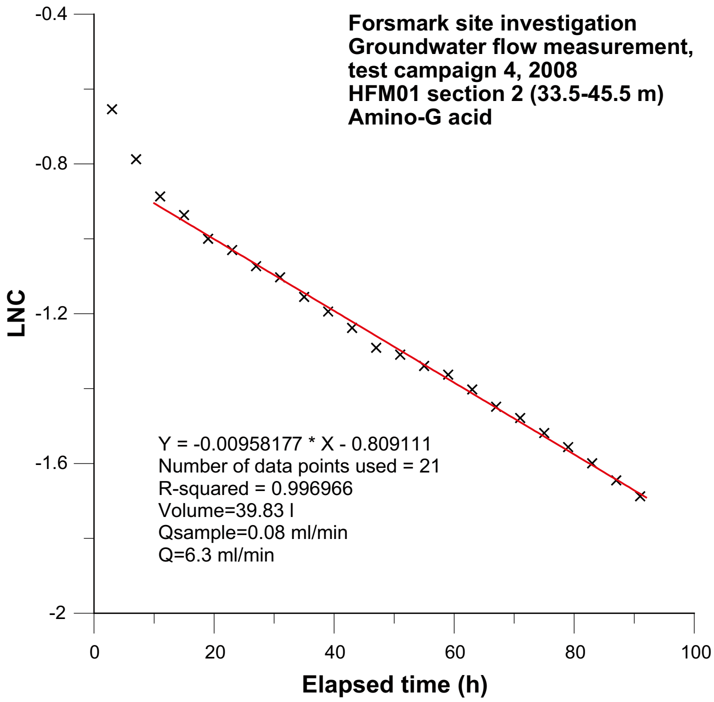

Figure 5-1. *Example of a tracer dilution graph (logarithm of concentration versus time) for borehole HFM01, section 2, including straight-line fit.*

In Appendix 2 the groundwater level during the entire test period is shown 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 0.01 to 123 ml/min in the measured sections with Darcy velocities ranging from $6.7 \cdot 10^{-11}$ to $6.6 \cdot 10^{-7}$ 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 fractures should therefore be treated with great care. In borehole sections KFM01A:5, KFM02B:4, KFM05A:4, KFM08D:2, KFM08D:4 and KFM12A:3, the hydraulic gradient is considered to be very large. In KFM05A:4 the groundwater level decreased about 0.7 m during the test, as seen in Appendix 2, which may have affected the flow rate and calculated hydraulic gradient. In both sections in KFM08D the measured flow rates are much higher than expected from the transmissivities. Also, as for KFM05A:4, the groundwater levels in both sections were strongly affected during the measurements (Appendix 2). The large gradients may also be due to wrong estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. KFM05A:4 and KFM01A:5 also represent single fractures (cf. Table 4-1) where the Darcy concept may be questioned.

The tracer dilution graph for KFM08D:2 gives two different flow rates (Appendix 1). Due to the increased pressure, especially during the first part of the measurement (Appendix 2), the last part of the dilution curve is probably the most representative of natural conditions.

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 considerably influenced during the measurements. This was probably caused by the circulation of section water. A somewhat strange behavior was also noticed in borehole KFM08D. Even though the two sections were measured separately in time, the measurement in section 4 also strongly affected the groundwater level in section 2. This indicates that there is some kind of connection between the sections which could also explain the unexpectedly high flow rates measured in the sections.

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

A comparison with flow rates obtained from previously performed test campaigns is compiled in Table 5-2 and is also graphically shown in Figures 5-2 to 5-5. The comparison shows relatively small changes in most of the 32 sections. However, four sections, KFM02B:2, KFM12A:3, HFM04:2 and HFM16:2, demonstrate significantly increased flow compared with previous year, whereas six sections, KFM01D:2, KFM02A:5, KFM06A:3, KFM06A:5, KFM08A:6 and KFM11A:4 display significantly decreased flow (more than a factor 2).

Table 5-2. Results from groundwater flow measurements in November–December 2008 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 (ml/min)
KFM01A:5	109–130	1.0 E–7*	–	0.1	0.2	0.1
KFM01D:2	429–438	8.0 E–7*	–	–	0.3	0.04
KFM01D:4	311–321	2.0 E–7*	–	–	0.2	0.2
KFM02A:3	490–518	2.1 E–6*	2.1	0.8	0.8	1.2
KFM02A:5	411–442	2.5 E–6*	1.0	0.4	0.7	0.1
KFM02B:2	491–506	3.0 E–5*	–	–	4.6	12
KFM02B:4	410–431	2.0 E–5*	–	–	23	35
KFM03A:4	633.5–650	2.4 E–6*	0.5	0.5	0.6	1.1
KFM04A:4	230–245	2.0 E–5*	–	–	16.4	8.0
KFM05A:4	254–272	1.4 E–8*	0.5	1.4	0.1	0.1
KFM06A:3	738–748	1.2 E–7*	0.3	0.6	0.2	0.05
KFM06A:5	341–362	3.5 E–6*	0.5	0.6	5.7	0.2
KFM06C:3	647–666	5.3 E–8*	–	0.4	0.05	0.03
KFM06C:5	531–540	1.1 E–6*	–	0.3	0.2	0.4
KFM08A:2	684–694	1.0 E–6*	–	–	0.8	0.7
KFM08A:6	265–280	1.0 E–6*	–	–	0.2	0.06
KFM08D:2	825–835	2.0 E–8*	–	–	2.6	1.8
KFM08D:4	660–680	2.0 E–7*	–	–	91	123
KFM10A:2	430–440	3.0 E–5*	–	–	2.7	1.6
KFM11A:2	690–710	1.0 E–6*	–	–	0.2	0.3
KFM11A:4	446–456	6.0 E–7*	–	–	0.04	0.01
KFM12A:3	270–280	1.0 E–6*	–	–	0.3	1.8
HFM01:2	33.5–45.5	4.0 E–5**	–	–	7.8	6.3
HFM02:2	38–48	5.9 E–4**	38	8.9–38	33	23
HFM04:2	58–66	7.9 E–5**	2.2	10.4	0.8	2.6
HFM13:1	159–173	2.9 E–4**	24	4.3	12.6	17
HFM15:1	85–95	1.0 E–4**	0.8	5.2	8.5	4.0
HFM16:2	54–67	3.5 E–4**	–	1.6–6.6	1.0	2.8
HFM19:1	168–182	2.7 E–4**	9.7	3.4	24	18
HFM21:3	22–32	4.0 E–5**	–	–	1.9	2.1
HFM27:2	46–58	4.0 E–5**	–	0.4	0.5	0.8
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/.

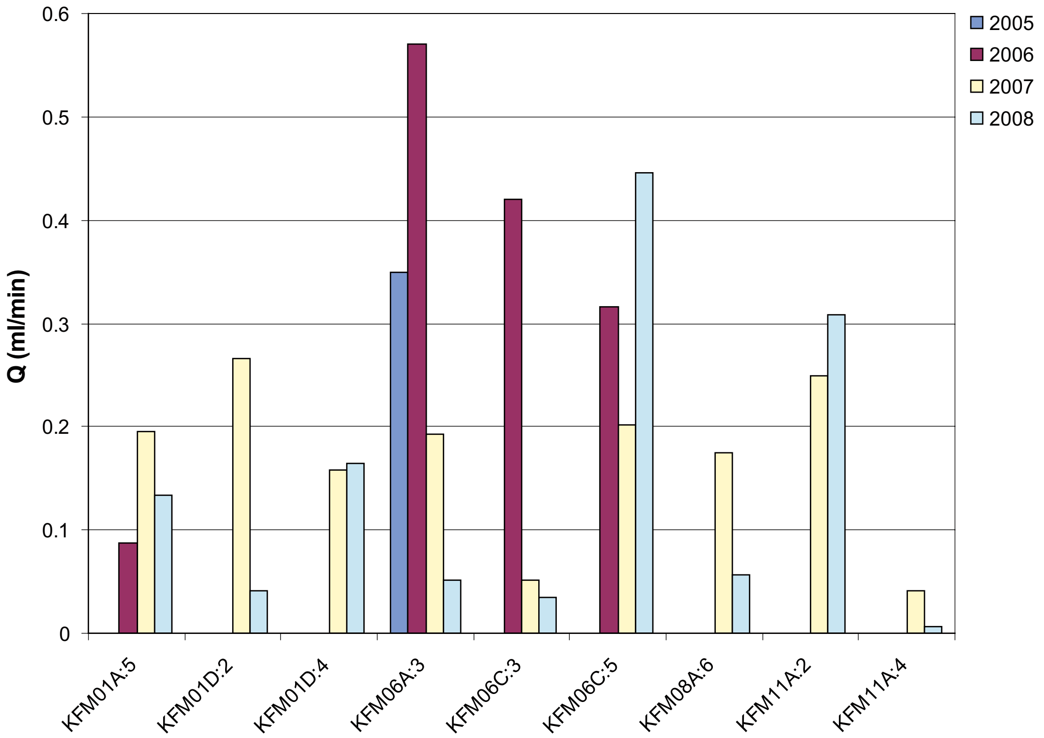

Figure 5-2. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 0.05–0.6 ml/min.*

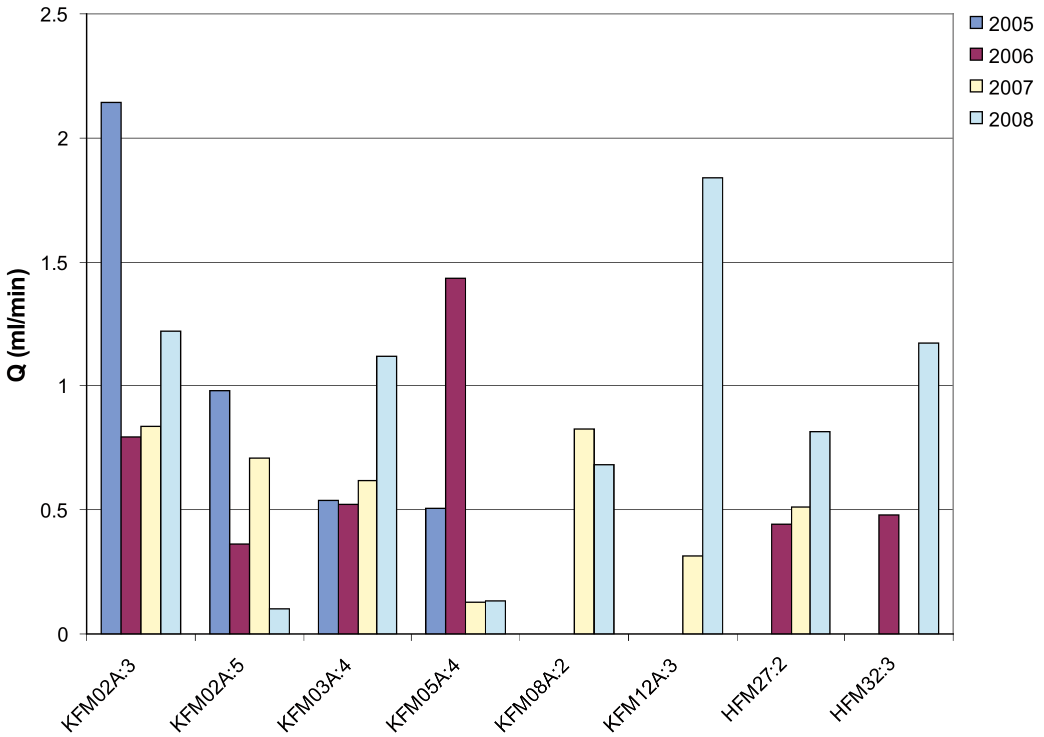

Figure 5-3. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 0.1–2.5 ml/min.*

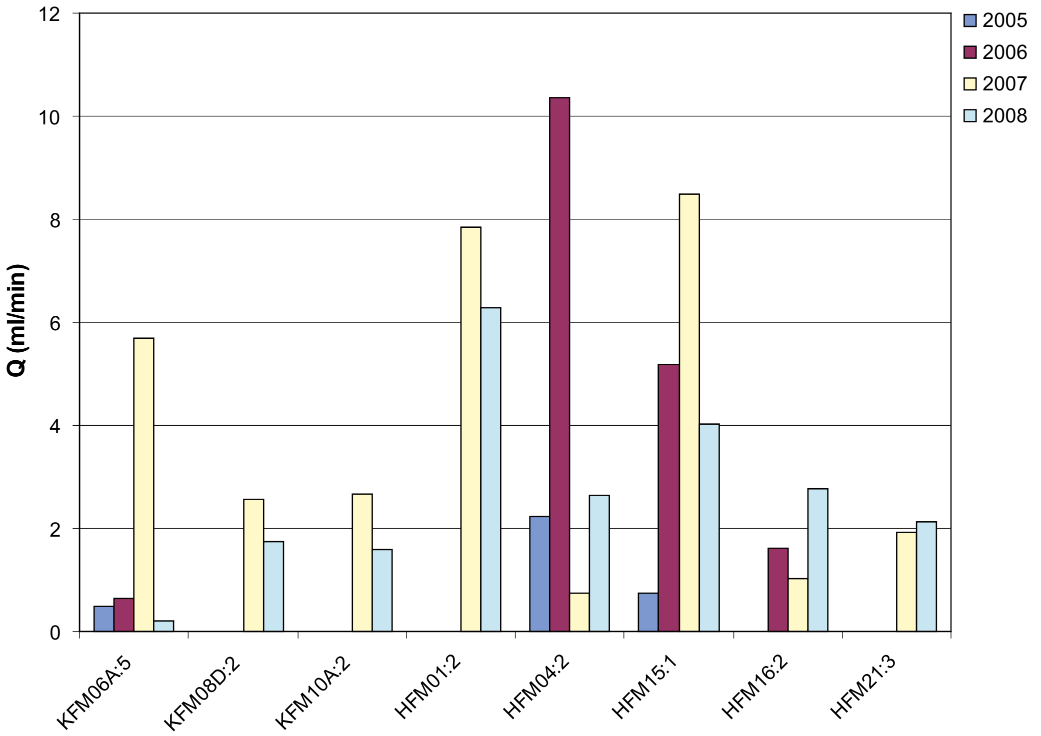

Figure 5-4. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 1–12 ml/min.*

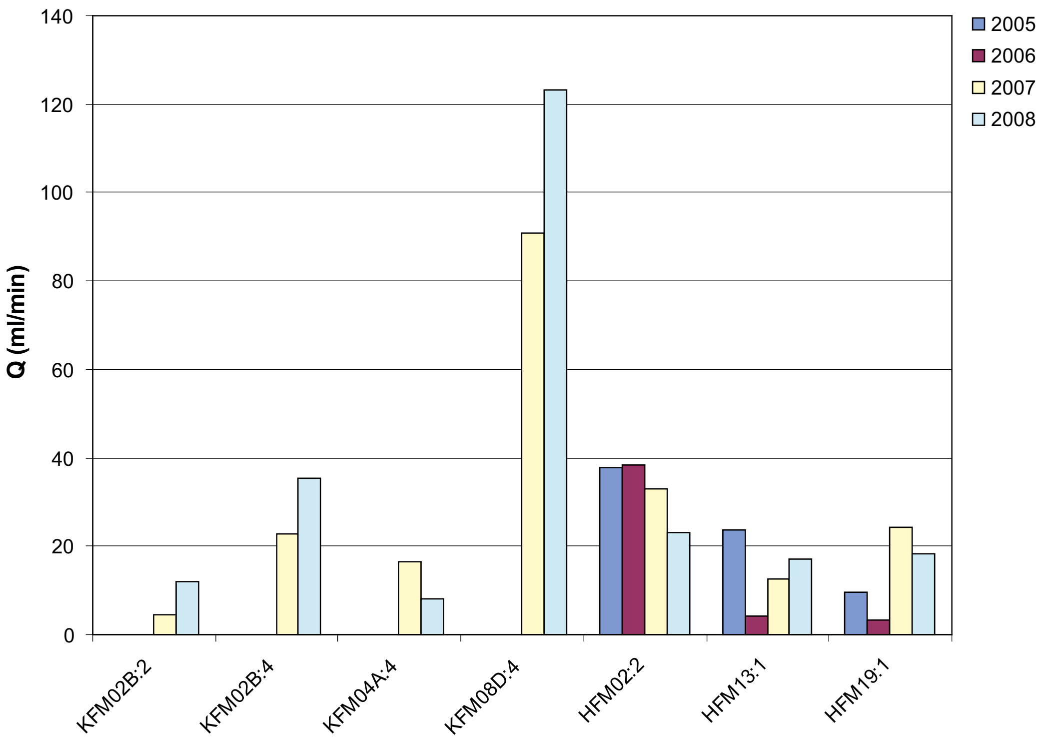

Figure 5-5. *Comparison of flow rates determined from all measurement campaigns performed for borehole sections having flow rates in the range 10–140 ml/min.*

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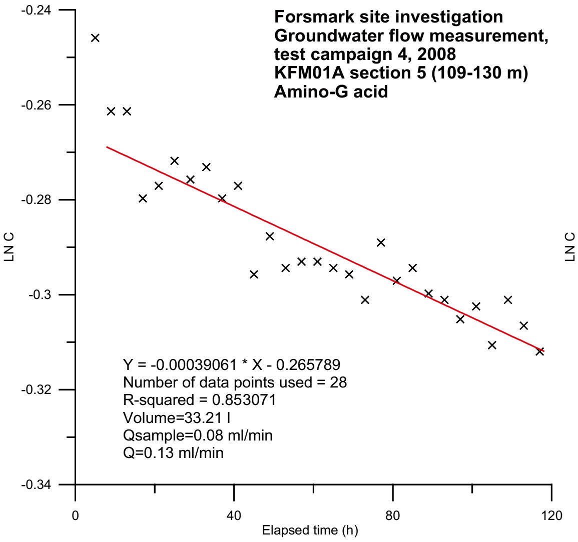
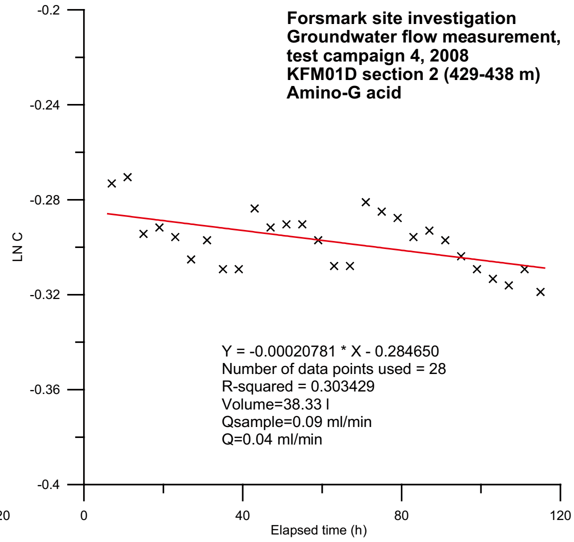
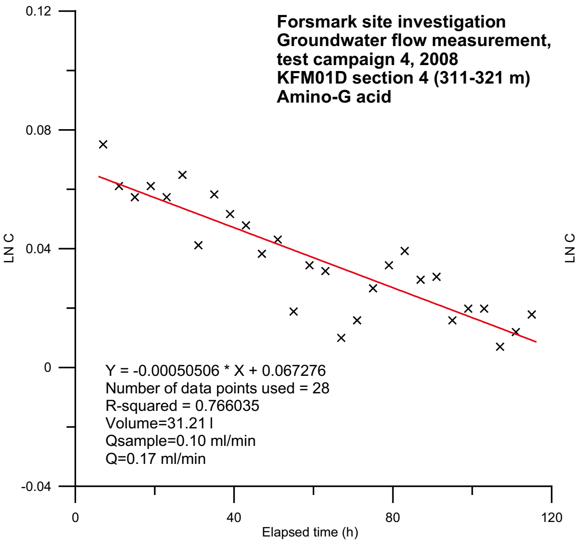
Appendix 1

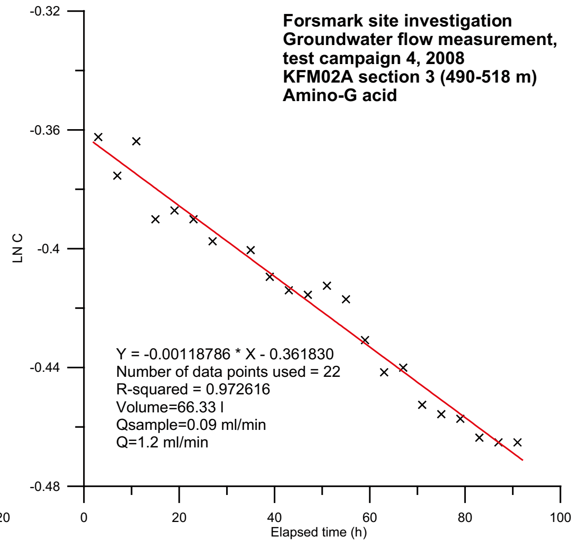
Tracer dilution graphs

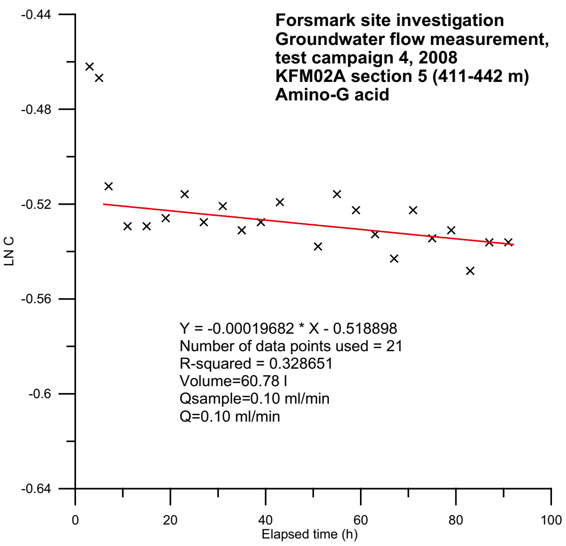
Core boreholes

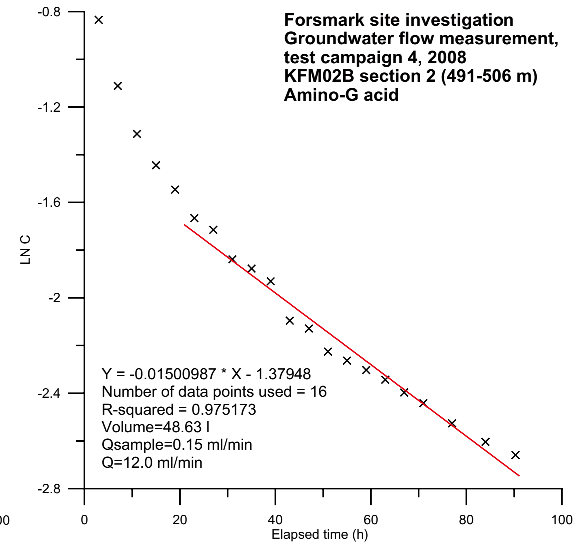


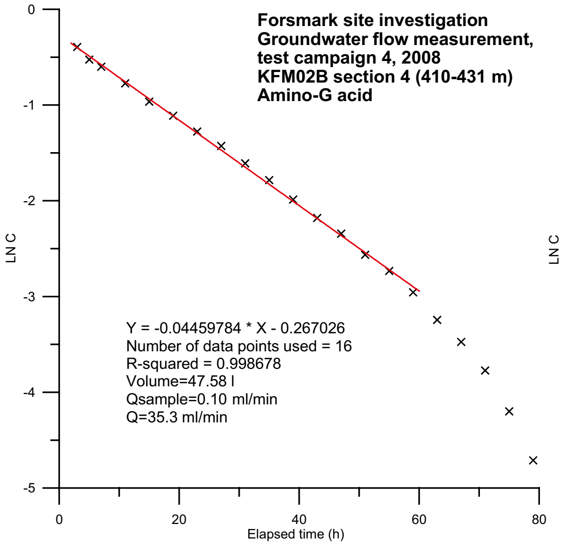








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Groundwater flow measurement,
test campaign 4, 2008
KFM02B section 4 (410-431 m)
Amino-G acid
Y = -0.04459784 * X - 0.267026
Number of data points used = 16
R-squared = 0.998678
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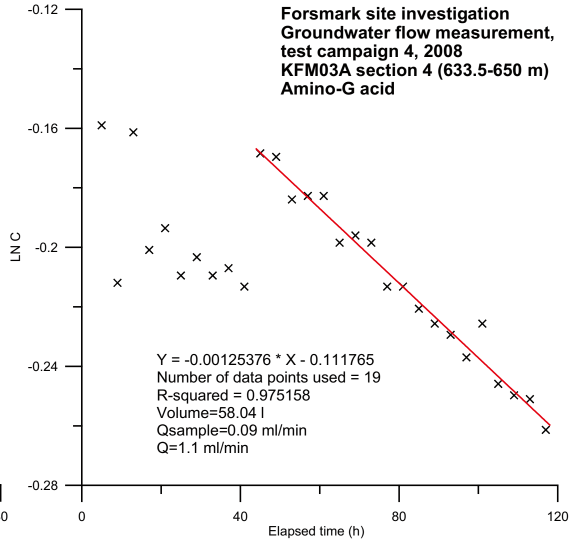
Qsample=0.10 ml/min
Q=35.3 ml/min
LN C
Elapsed time (h)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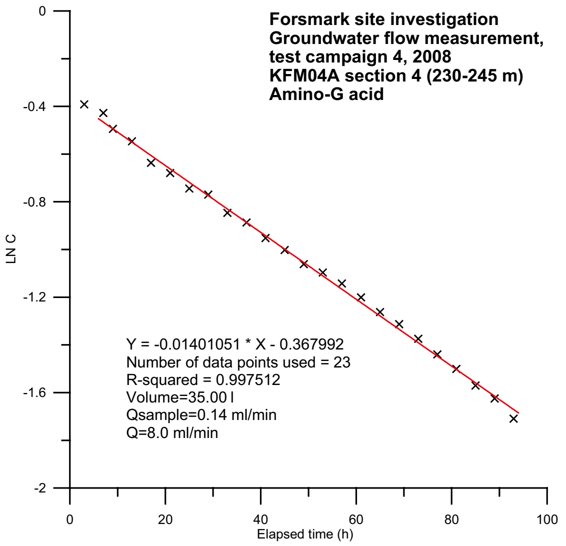
KFM03A section 4 (633.5-650 m)
Amino-G acid
Y = -0.00125376 * X - 0.111765
Number of data points used = 19
R-squared = 0.975158
Volume=58.04 l
Qsample=0.09 ml/min
Q=1.1 ml/min
LN C
Elapsed time (h)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Groundwater flow measurement,
test campaign 4, 2008
KFM04A section 4 (230-245 m)
Amino-G acid
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R-squared = 0.997512
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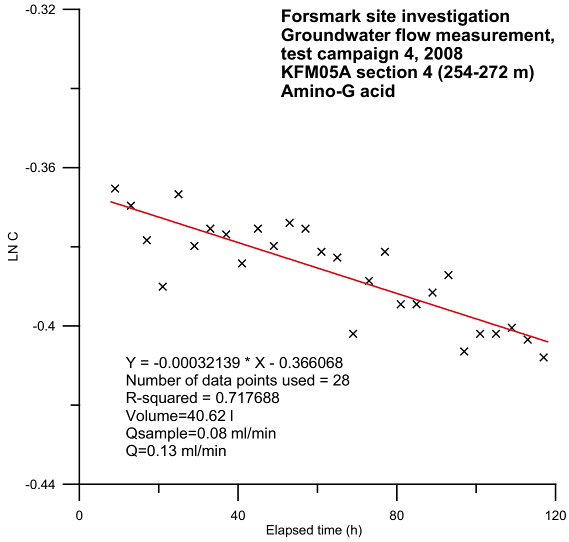
Q=8.0 ml/min
LN C
Elapsed time (h)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KFM05A section 4 (254-272 m)
Amino-G acid
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R-squared = 0.717688
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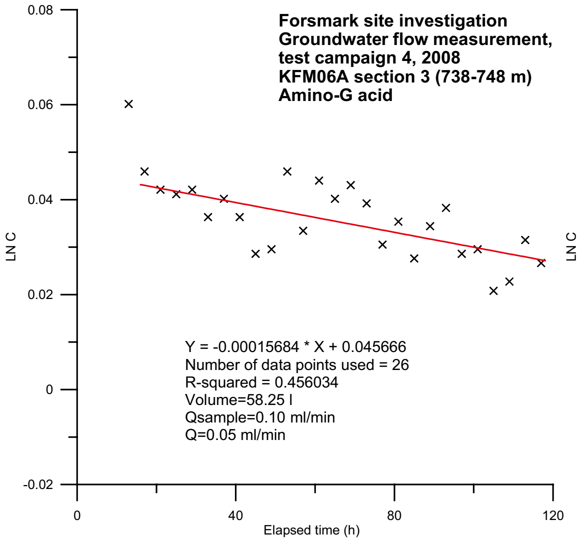
LN C
Elapsed time (h)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KFM06A section 3 (738-748 m)
Amino-G acid
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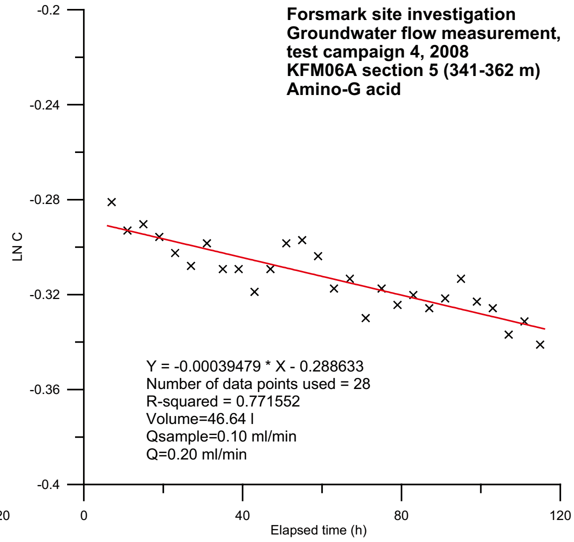
Volume=58.25 l
Qsample=0.10 ml/min
Q=0.05 ml/min
LN C
Elapsed time (h)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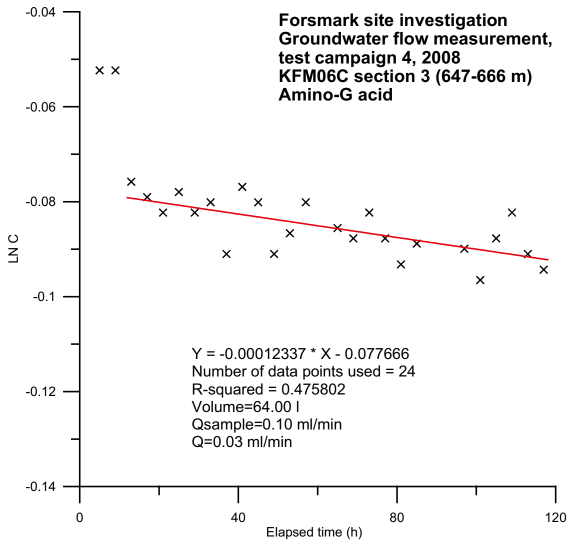
Q=0.20 ml/min
LN C
Elapsed time (h)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KFM06C section 3 (647-666 m)
Amino-G acid
Y = -0.00012337 * X - 0.077666
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R-squared = 0.475802
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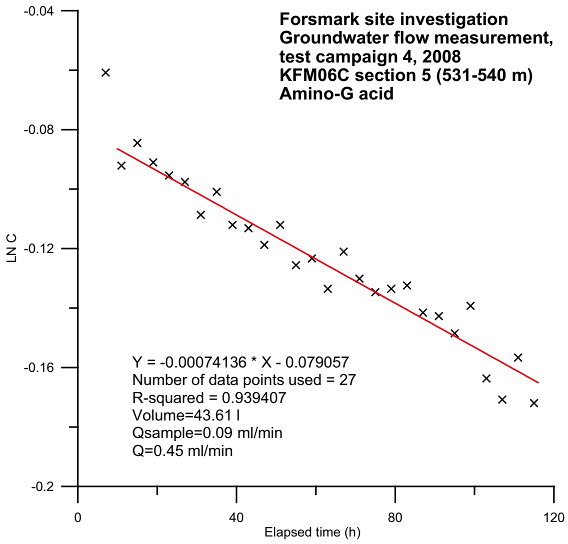
Qsample=0.10 ml/min
Q=0.03 ml/min
LN C
Elapsed time (h)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Groundwater flow measurement,
test campaign 4, 2008
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R-squared = 0.939407
Volume=43.61 l
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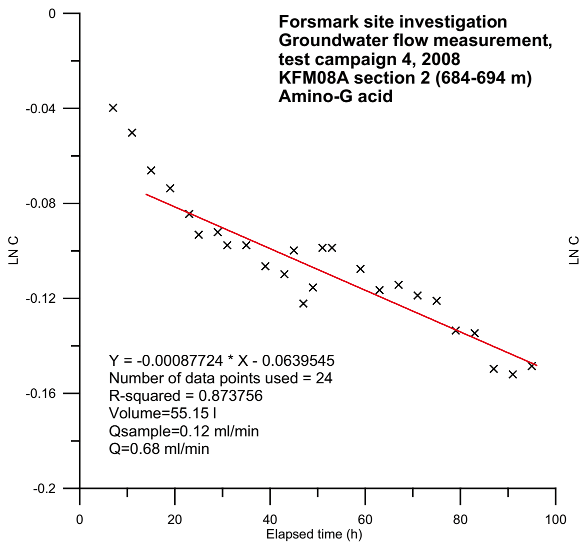
LN C
Elapsed time (h)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Groundwater flow measurement,
test campaign 4, 2008
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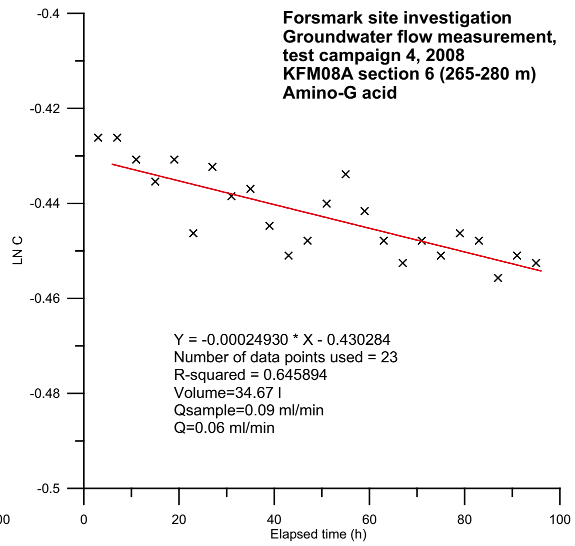
Amino-G acid
Y = -0.00087724 * X - 0.0639545
Number of data points used = 24
R-squared = 0.873756
Volume=55.15 l
Qsample=0.12 ml/min
Q=0.68 ml/min
LN C
Elapsed time (h)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Groundwater flow measurement,
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KFM08A section 6 (265-280 m)
Amino-G acid
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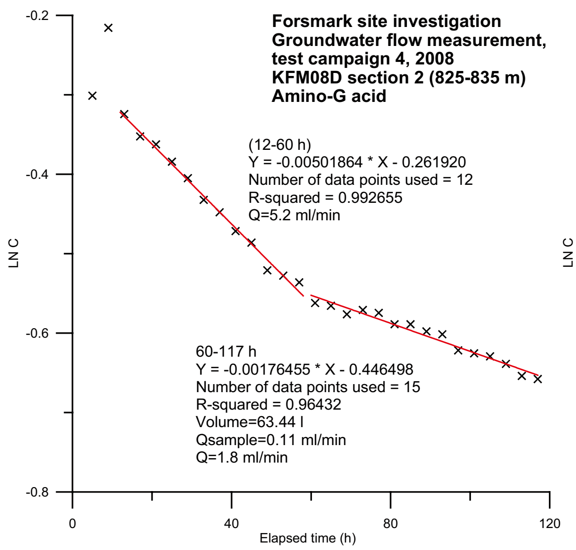
Number of data points used = 23
R-squared = 0.645894
Volume=34.67 l
Qsample=0.09 ml/min
Q=0.06 ml/min
LN C
Elapsed time (h)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Groundwater flow measurement,
test campaign 4, 2008
KFM08D section 2 (825-835 m)
Amino-G acid
(12-60 h)
Y = -0.00501864 * X - 0.261920
Number of data points used = 12
R-squared = 0.992655
Q=5.2 ml/min
60-117 h
Y = -0.00176455 * X - 0.446498
Number of data points used = 15
R-squared = 0.96432
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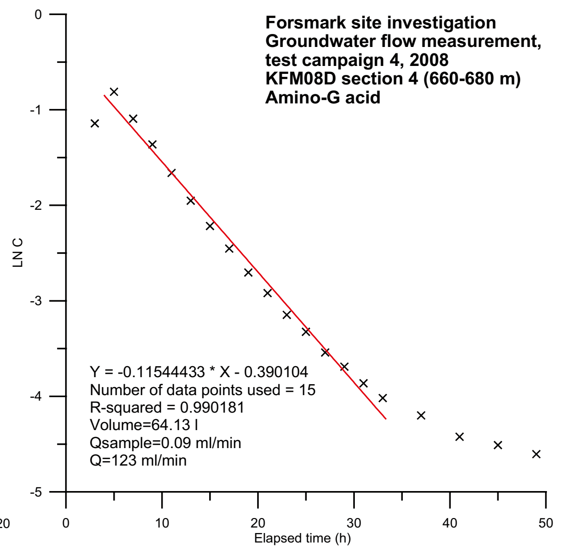
LN C
Elapsed time (h)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Amino-G acid
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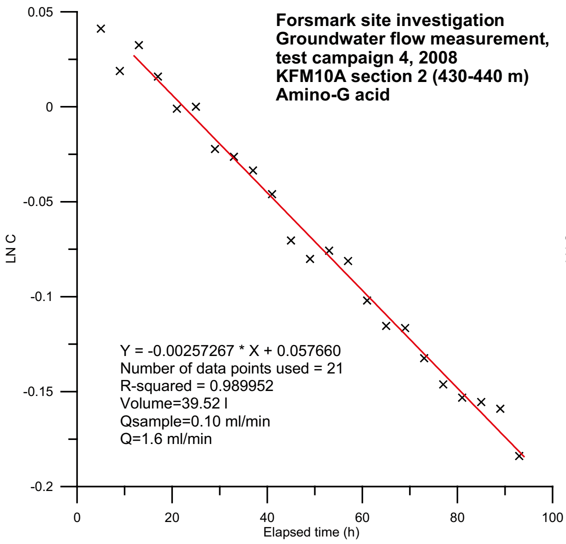
Q=123 ml/min
LN C
Elapsed time (h)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Amino-G acid
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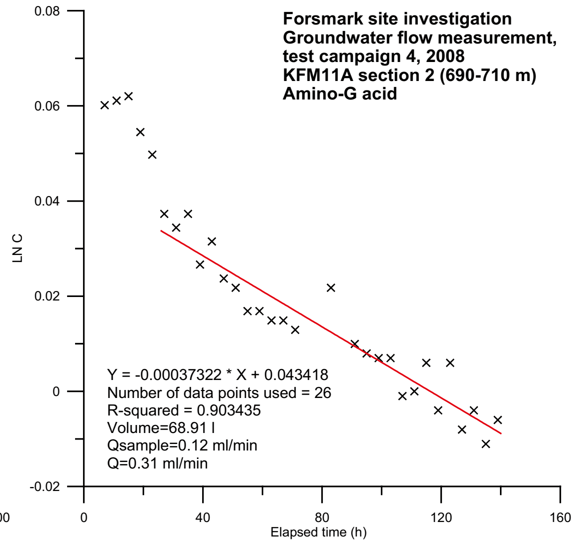
Elapsed time (h)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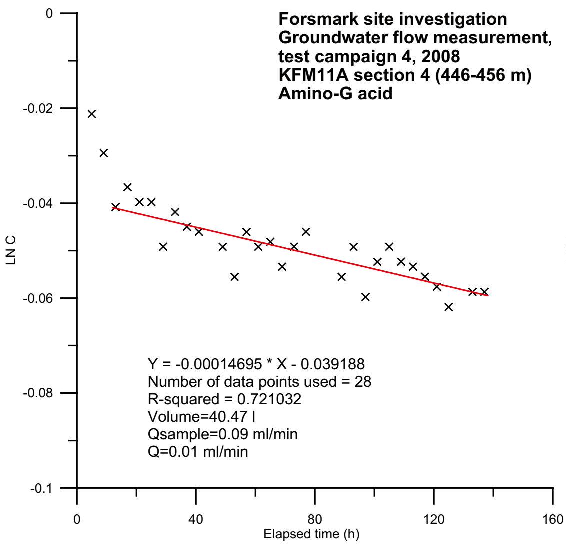
Elapsed time (h)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KFM11A section 4 (446-456 m)
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Volume=40.47 l
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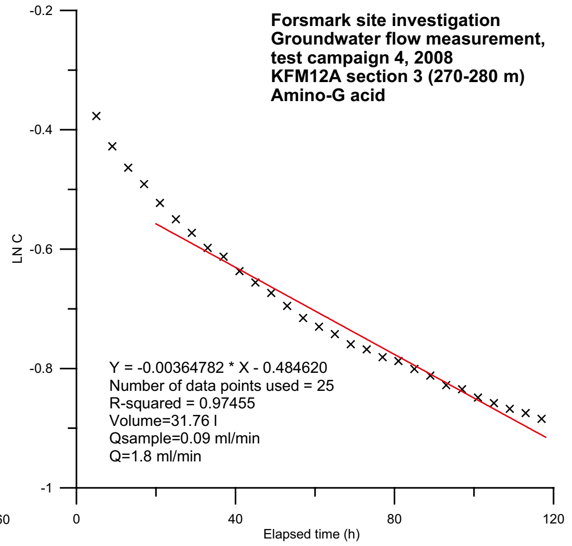
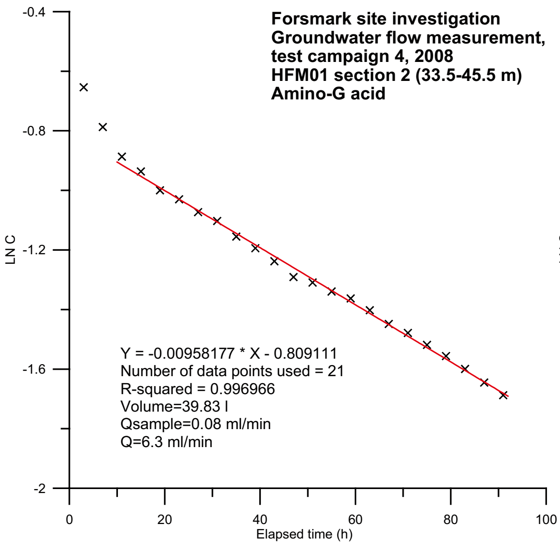
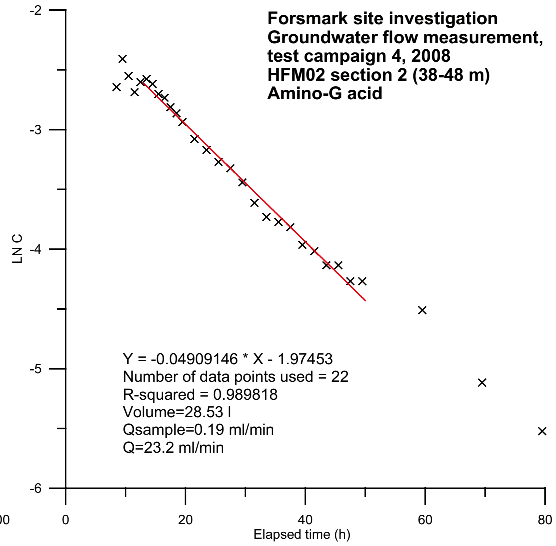
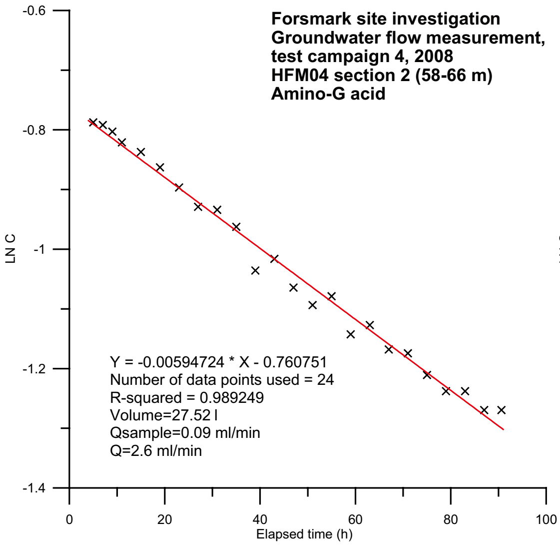
Q=0.01 ml/min
LN C
Elapsed time (h)

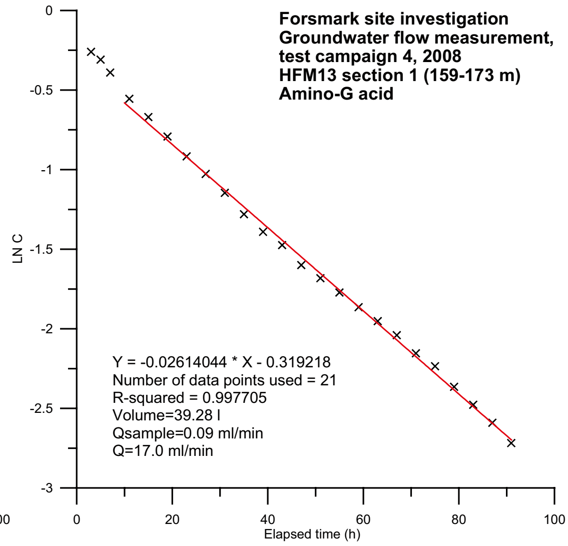

Forsmark site investigation
Groundwater flow measurement,
test campaign 4, 2008
KFM12A section 3 (270-280 m)
Amino-G acid
Y = -0.00364782 * X - 0.484620
Number of data points used = 25
R-squared = 0.97455
Volume=31.76 l
Qsample=0.09 ml/min
Q=1.8 ml/min
LN C
Elapsed time (h)

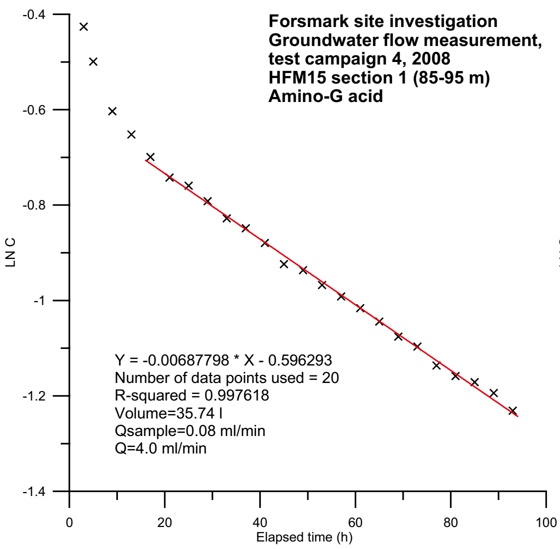
Percussion boreholes

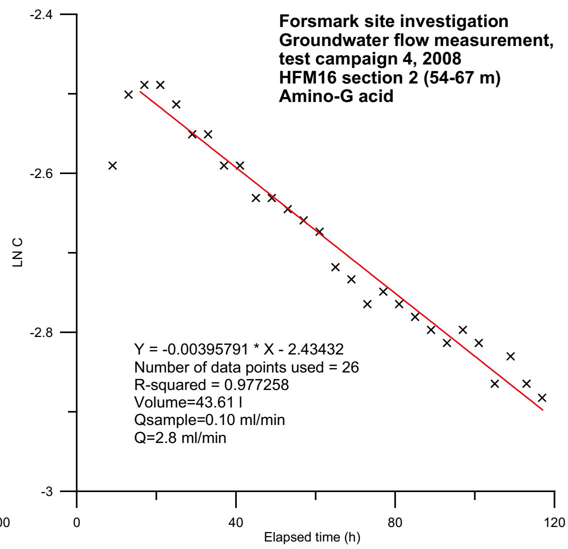


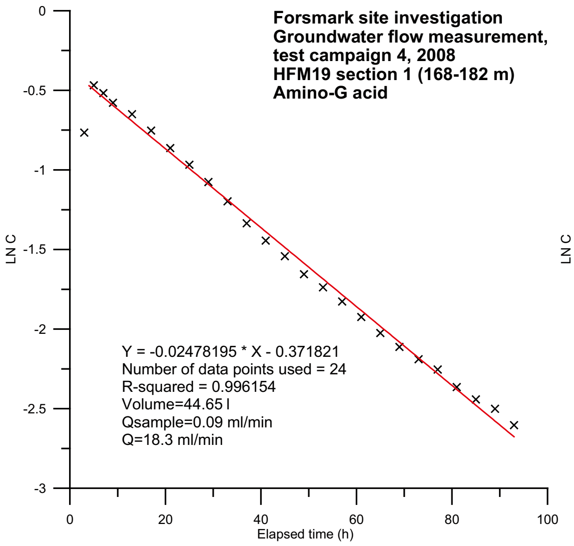








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Groundwater flow measurement,
test campaign 4, 2008
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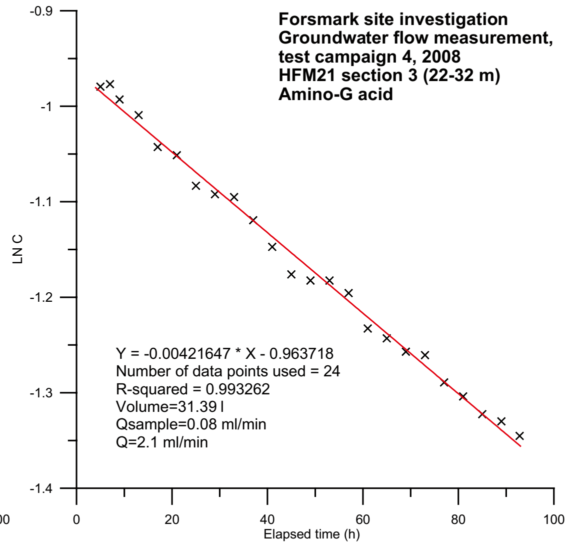
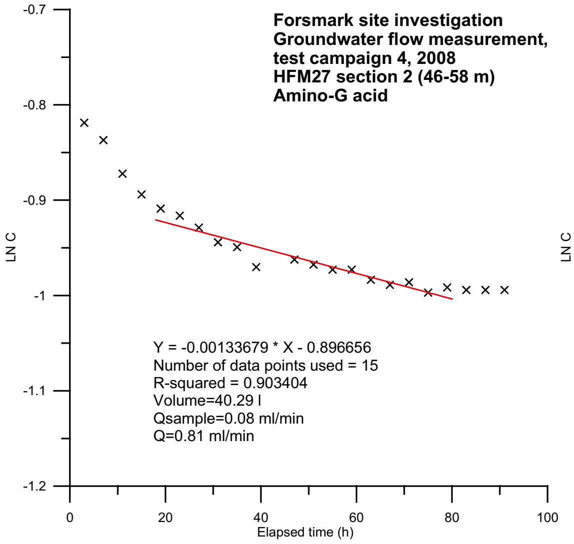
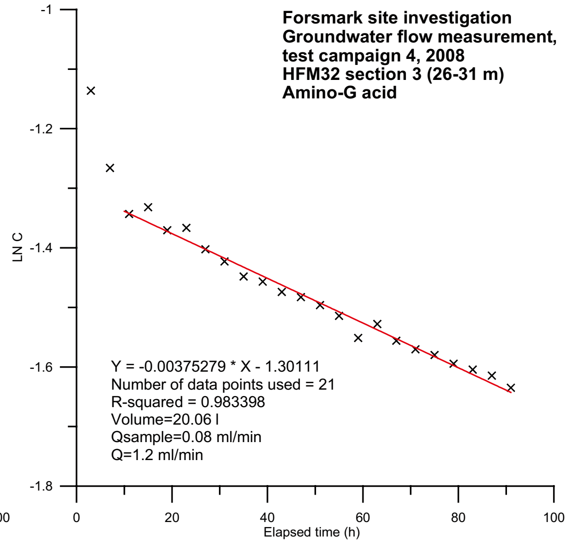
Number of data points used = 24
R-squared = 0.996154
Volume=44.65 l
Qsample=0.09 ml/min
Q=18.3 ml/min
LN C
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 4, 2008
HFM21 section 3 (22-32 m)
Amino-G acid
Y = -0.00421647 * X - 0.963718
Number of data points used = 24
R-squared = 0.993262
Volume=31.39 l
Qsample=0.08 ml/min
Q=2.1 ml/min
LN C
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 4, 2008
HFM27 section 2 (46-58 m)
Amino-G acid
Y = -0.00133679 * X - 0.896656
Number of data points used = 15
R-squared = 0.903404
Volume=40.29 l
Qsample=0.08 ml/min
Q=0.81 ml/min
LN C
Elapsed time (h)

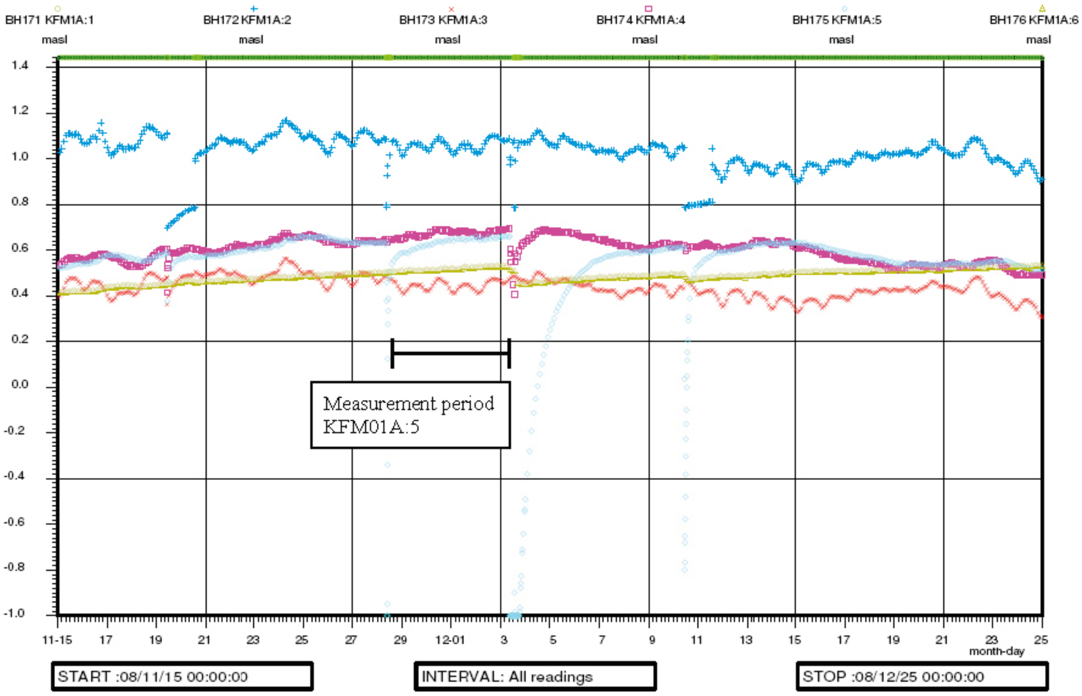

Forsmark site investigation
Groundwater flow measurement,
test campaign 4, 2008
HFM32 section 3 (26-31 m)
Amino-G acid
Y = -0.00375279 * X - 1.30111
Number of data points used = 21
R-squared = 0.983398
Volume=20.06 l
Qsample=0.08 ml/min
Q=1.2 ml/min
LN C
Elapsed time (h)

Groundwater levels (metres above sea level)

2008-11-15 – 2008-12-25 (All boreholes except HFM32)

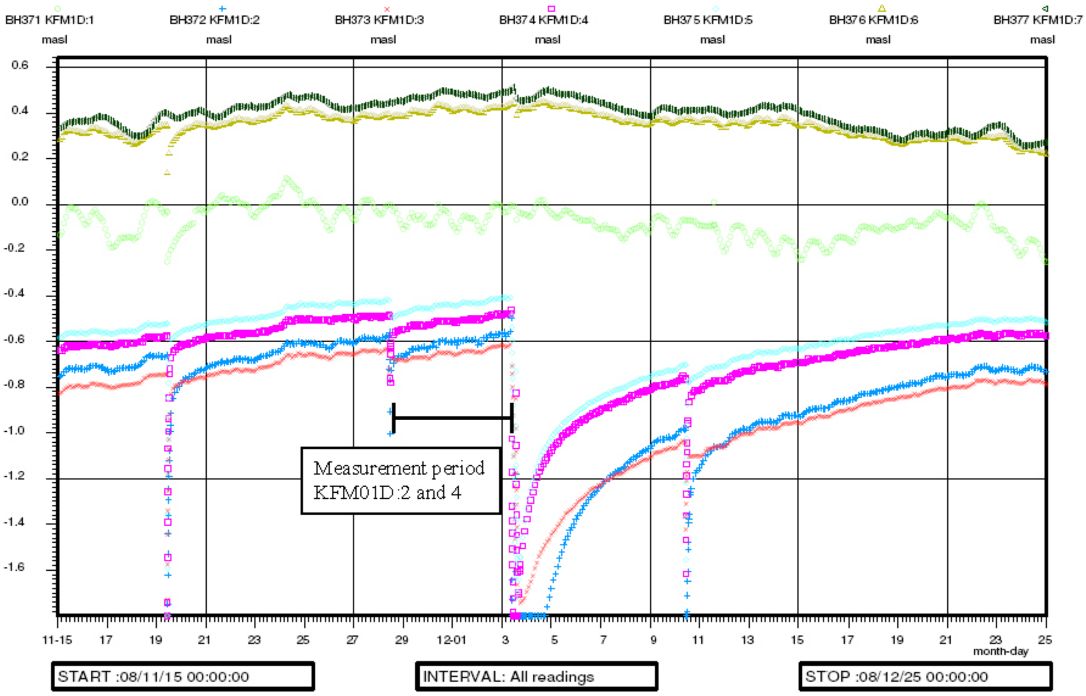
2009-03-01 – 2009-04-01 (Borehole HFM32)

KFM01A



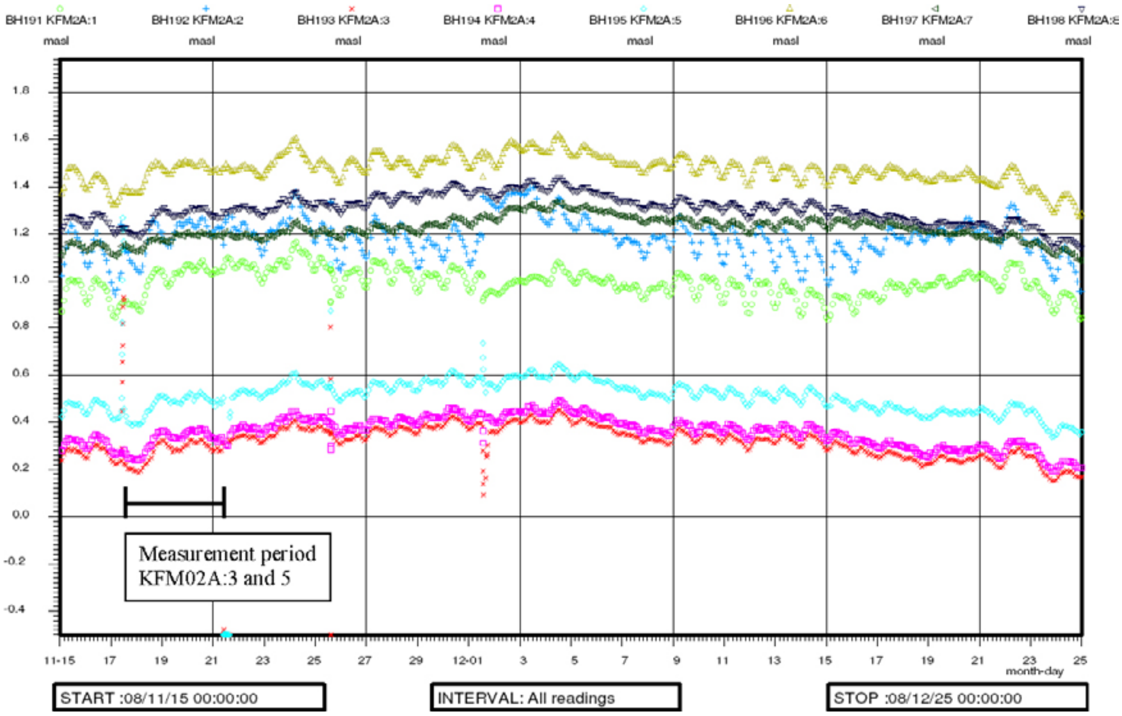
Measured section: KFM01A:5 (pale blue)

KFM01D



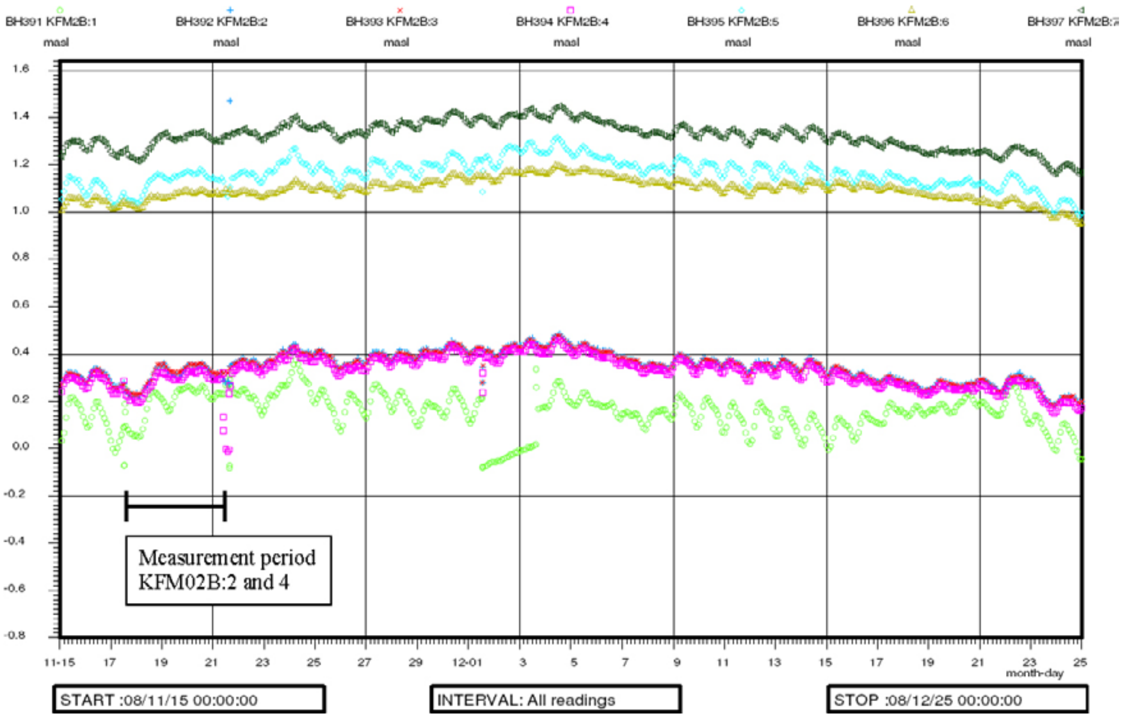
Measured sections: KFM01D:2 (blue) and KFM01D:4 (mauve)

KFM02A



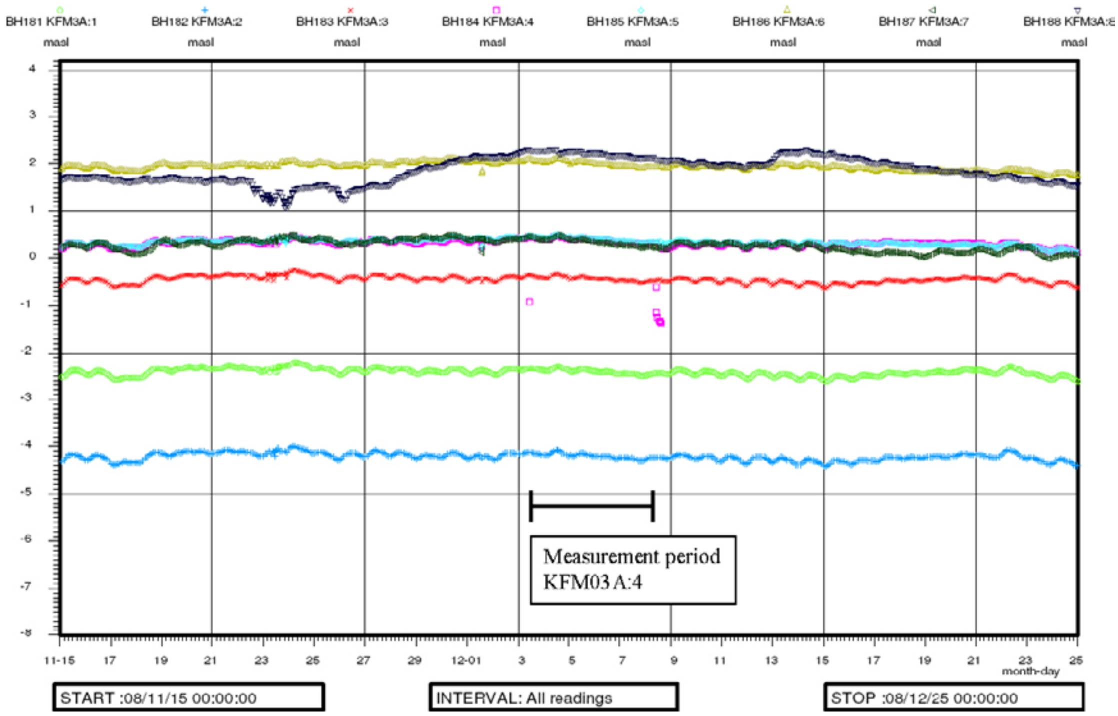
Measured sections: KFM02A:3 (red) and KFM02A:5 (pale blue)

KFM02B



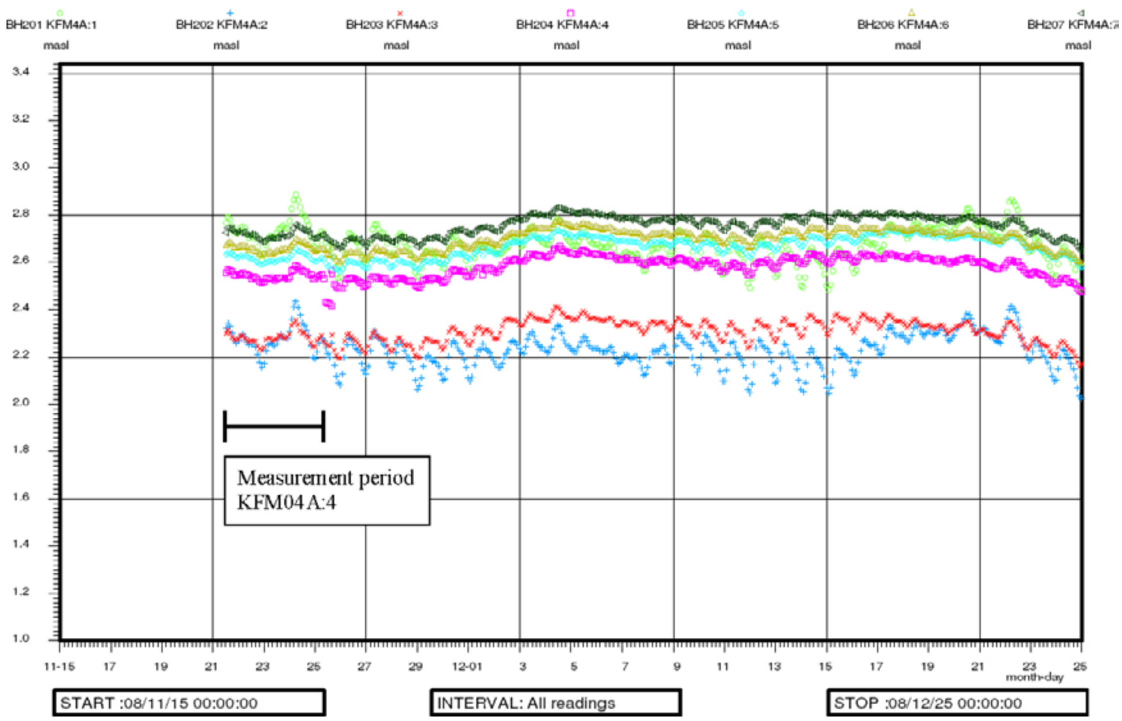
Measured sections: KFM02B:2 (blue) and KFM02B:4 (mauve)

KFM03A



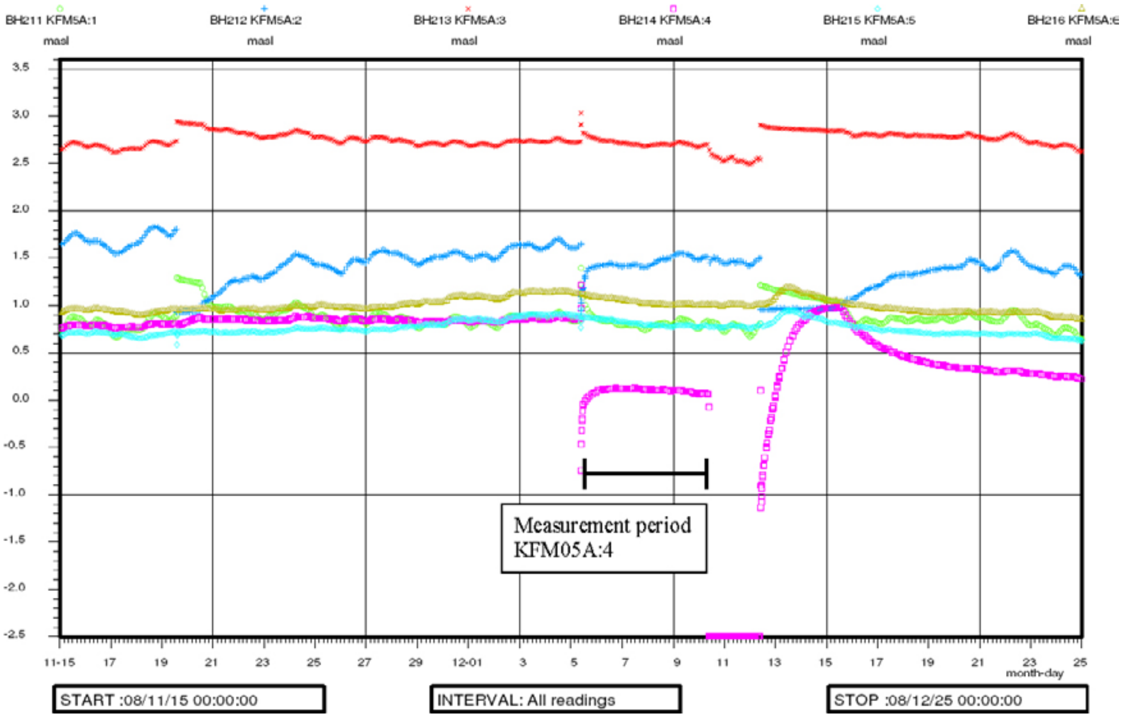
Measured section: KFM03A:4 (mauve)

KFM04A



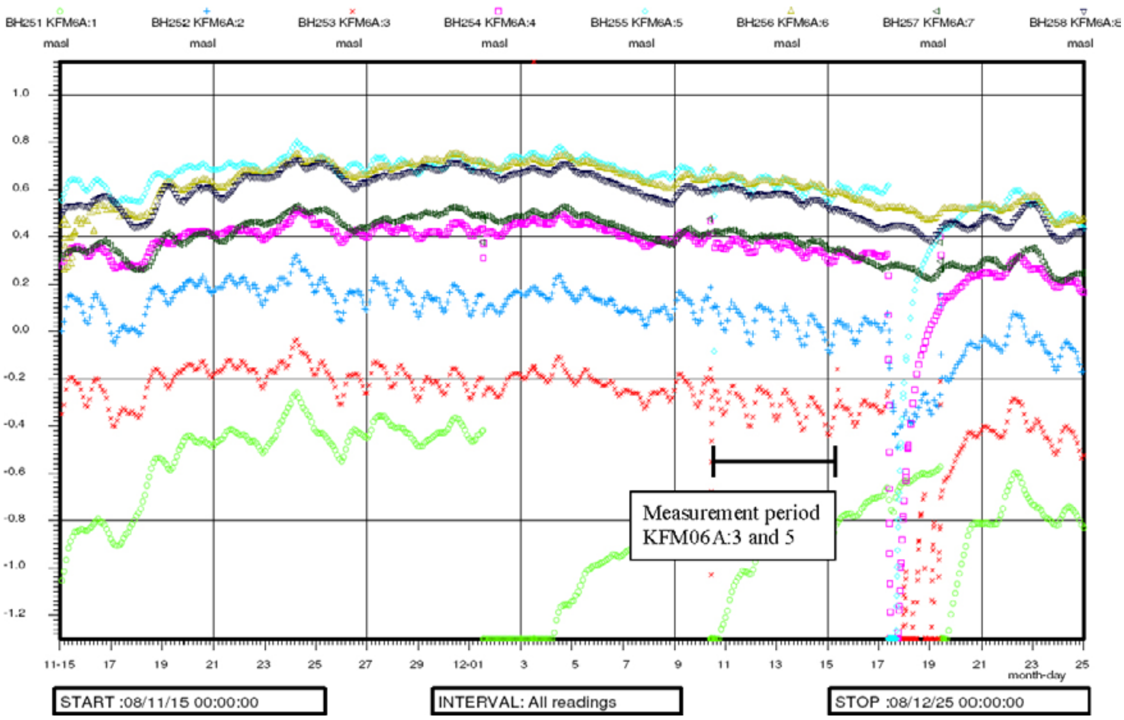
Measured section: KFM04A:4 (mauve)

KFM05A



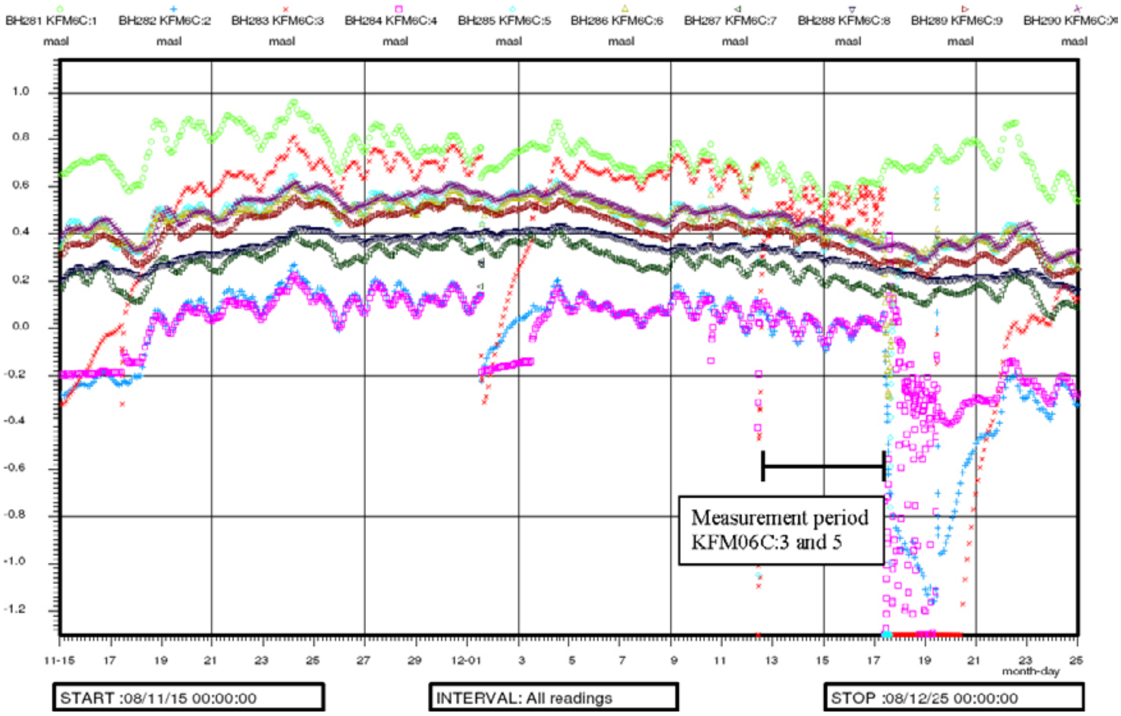
Measured section: KFM05A:4 (mauve)

KFM06A



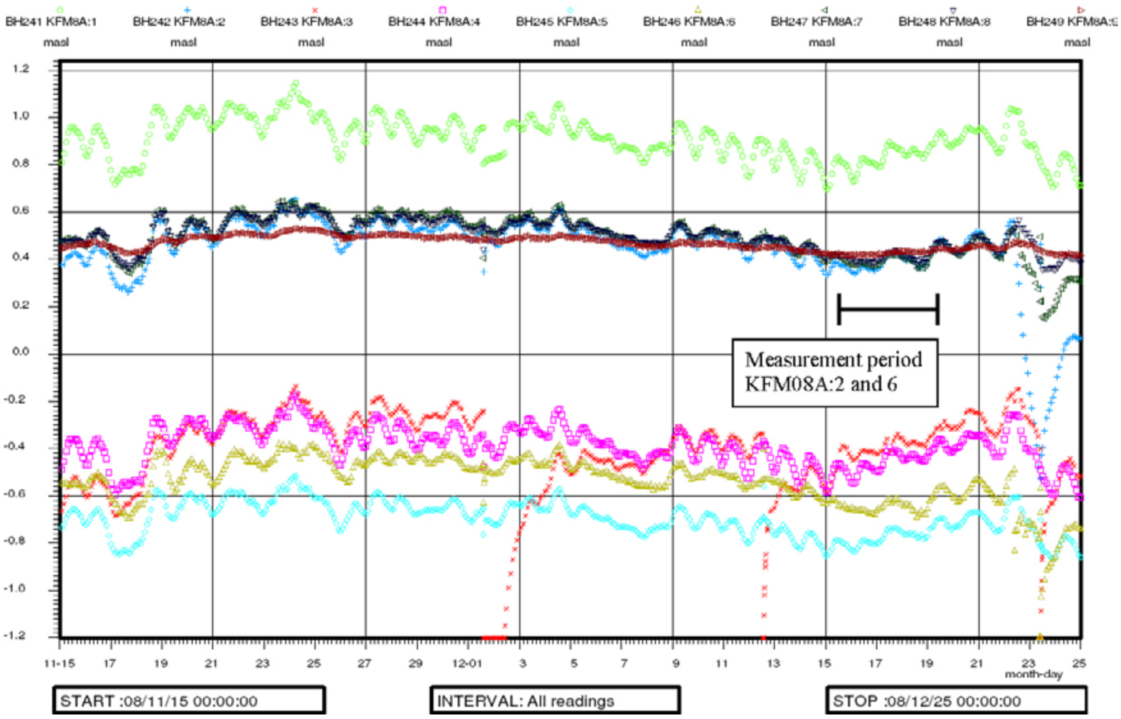
Measured sections: KFM06A:3 (red) and KFM06A:5 (pale blue)

KFM06C



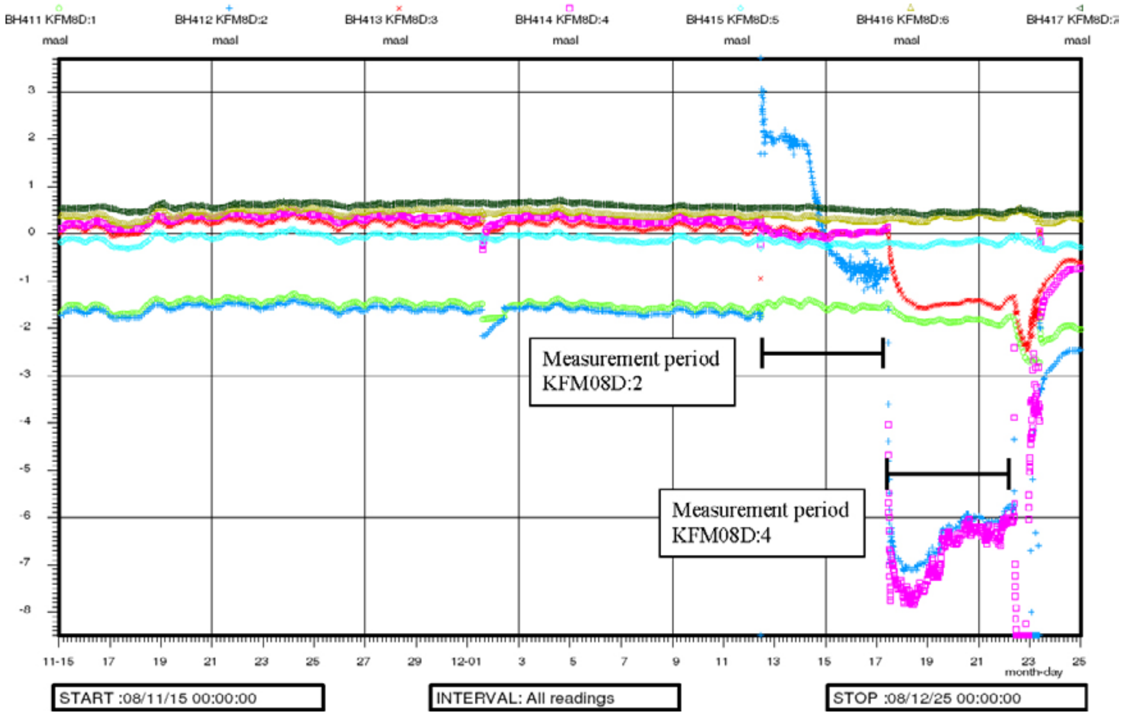
Measured sections: KFM06C:3 (red) and KFM06C:5 (pale blue)

KFM08A



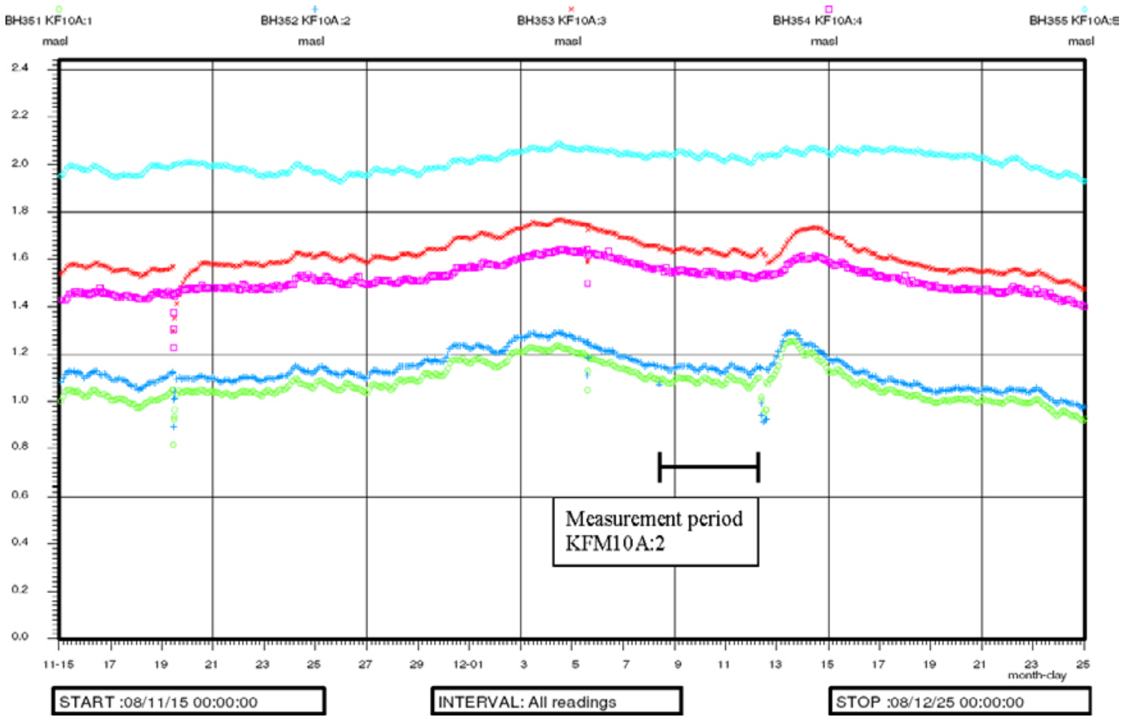
Measured sections: KFM08A:2 (blue) and KFM08A:6 (beige)

KFM08D



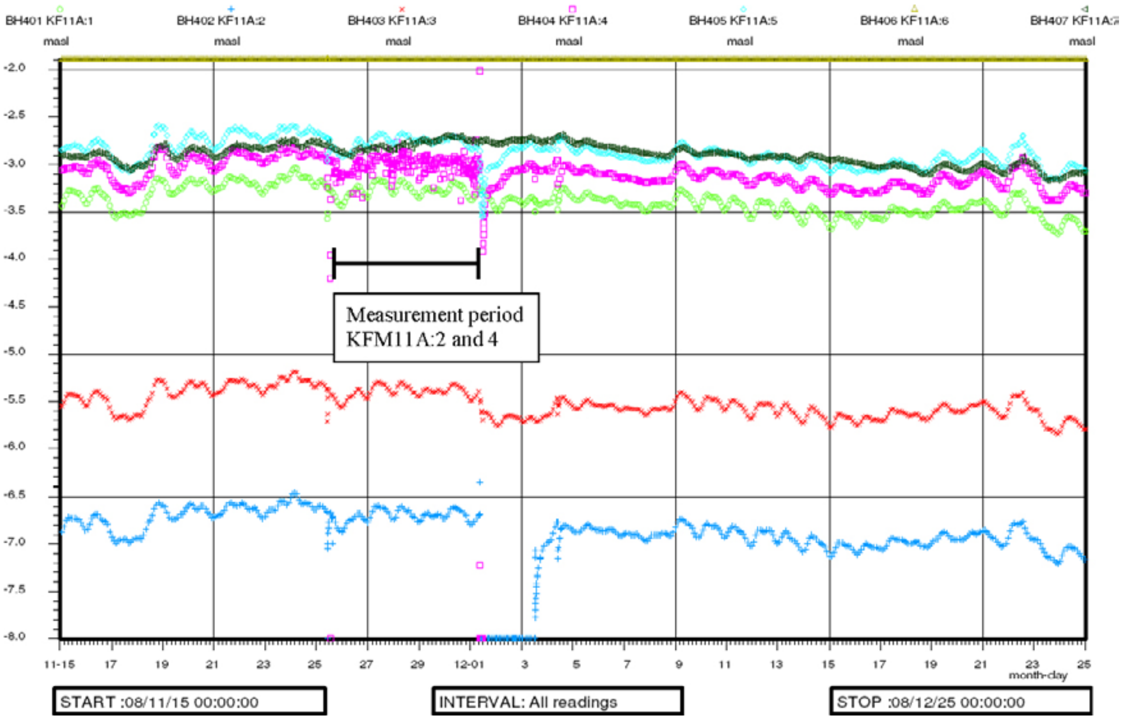
Measured sections: KFM08D:2 (blue) and KFM08D:4 (mauve)

KFM10A



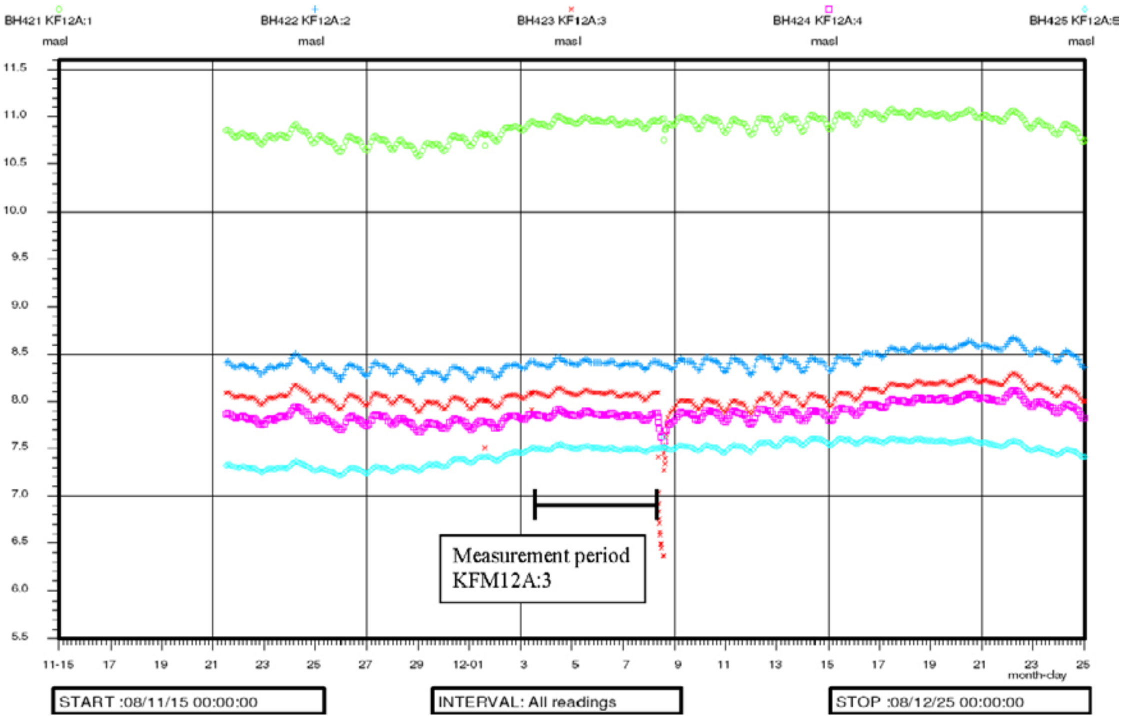
Measured section: KFM10A:2 (blue)

KFM11A



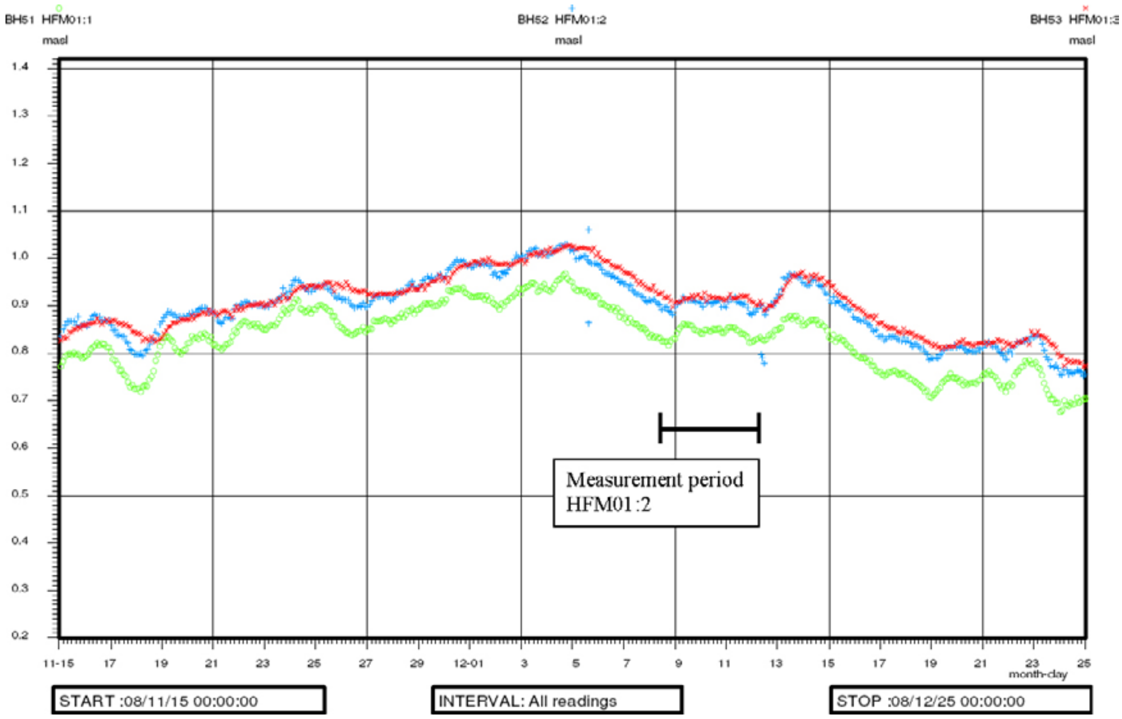
Measured sections: KFM11A:2 (blue) and KFM11A:4 (mauve)

KFM12A



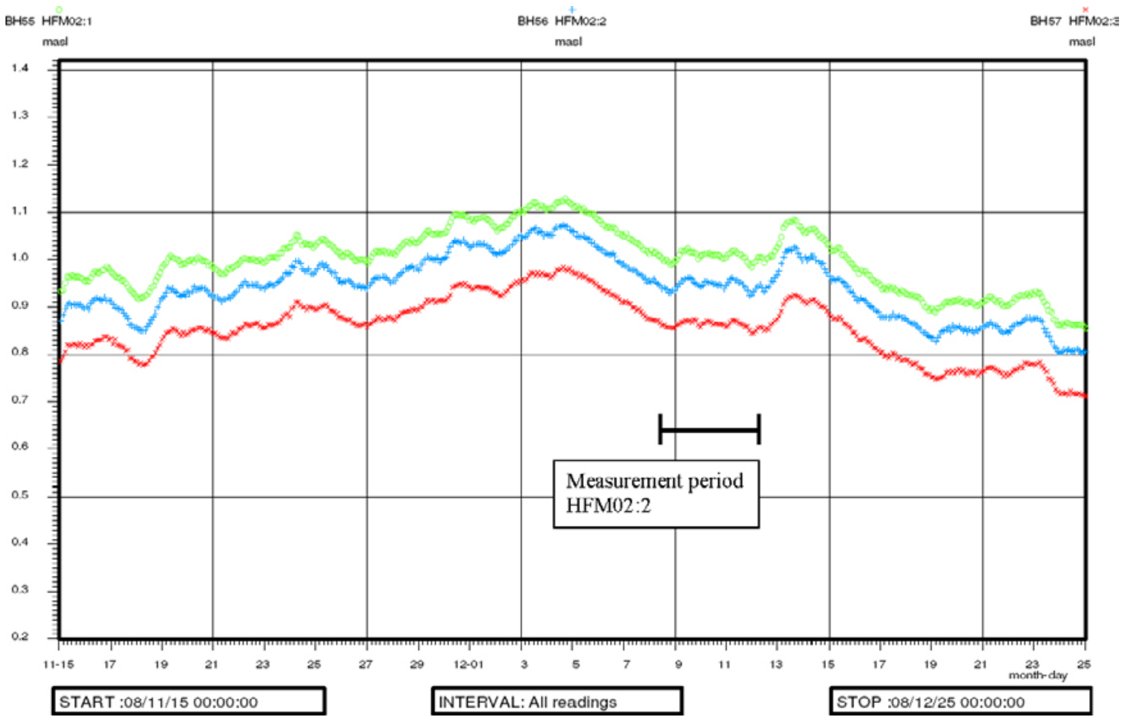
Measured section: KFM12A:3 (red)

HFM01



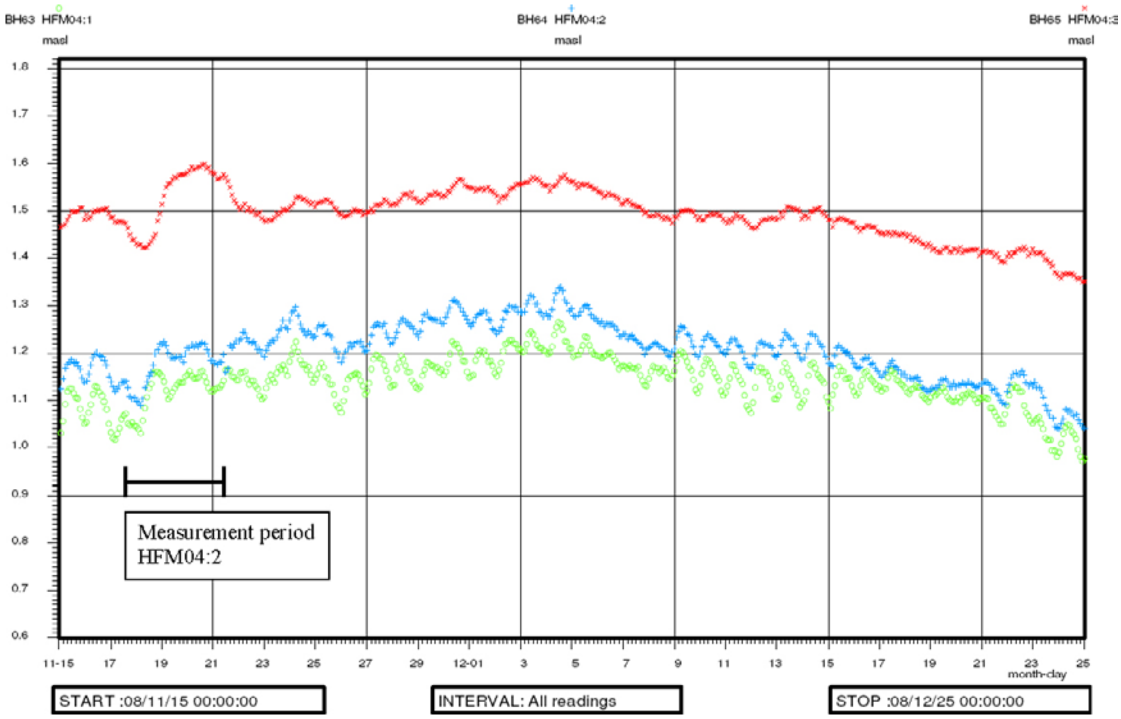
Measured section: HFM01:2 (blue)

HFM02



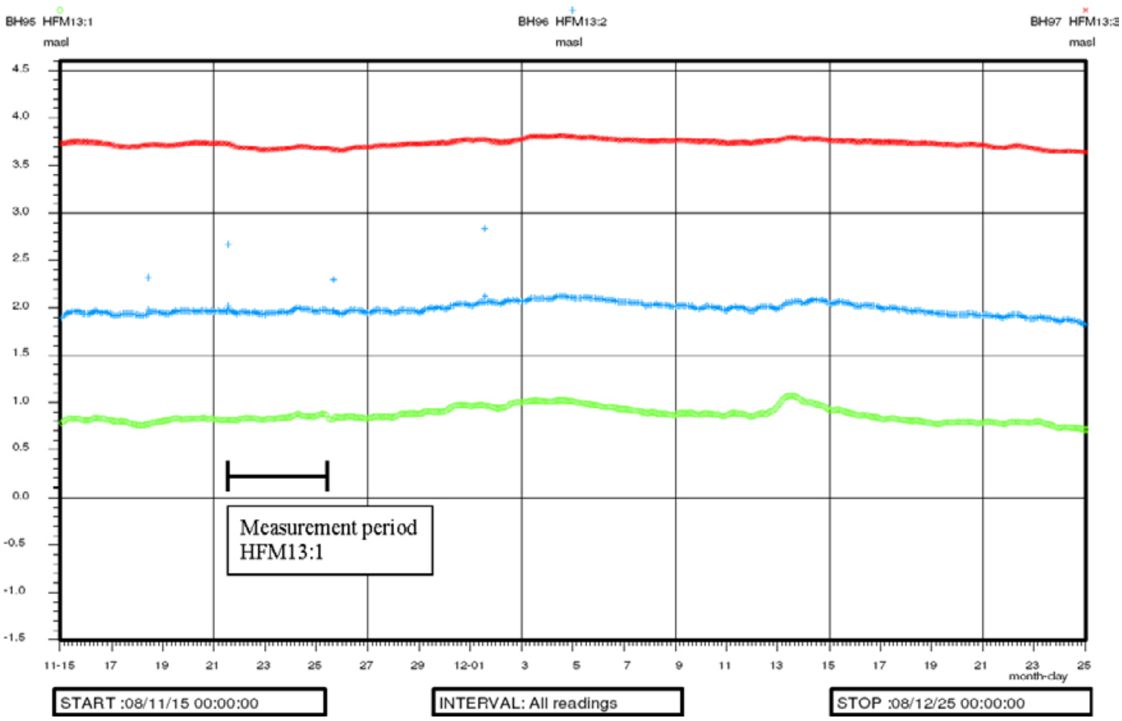
Measured section: HFM02:2 (blue)

HFM04



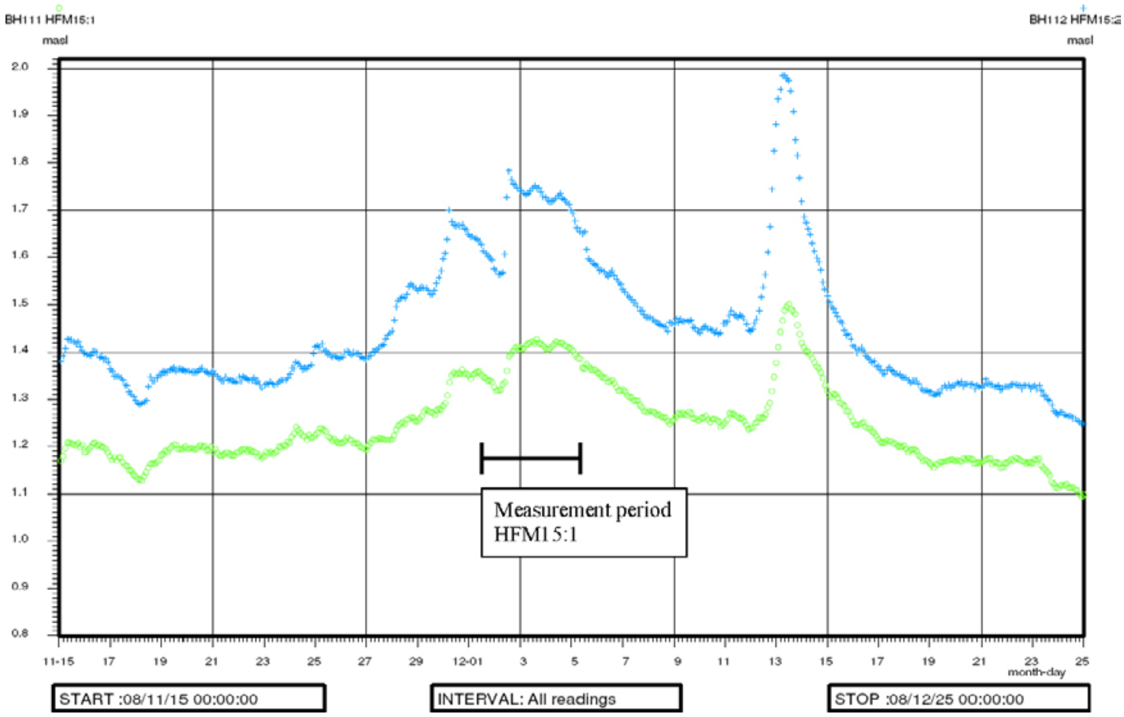
Measured section: HFM04:2 (blue)

HFM13



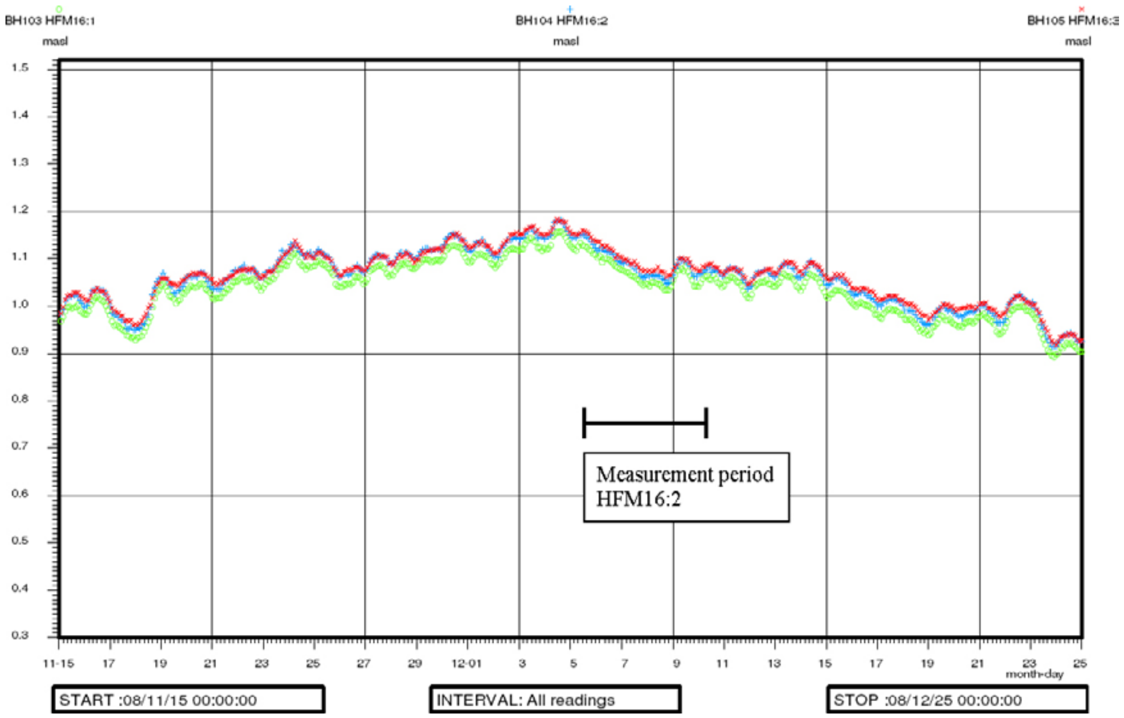
Measured section: HFM13:1 (green)

HFM15



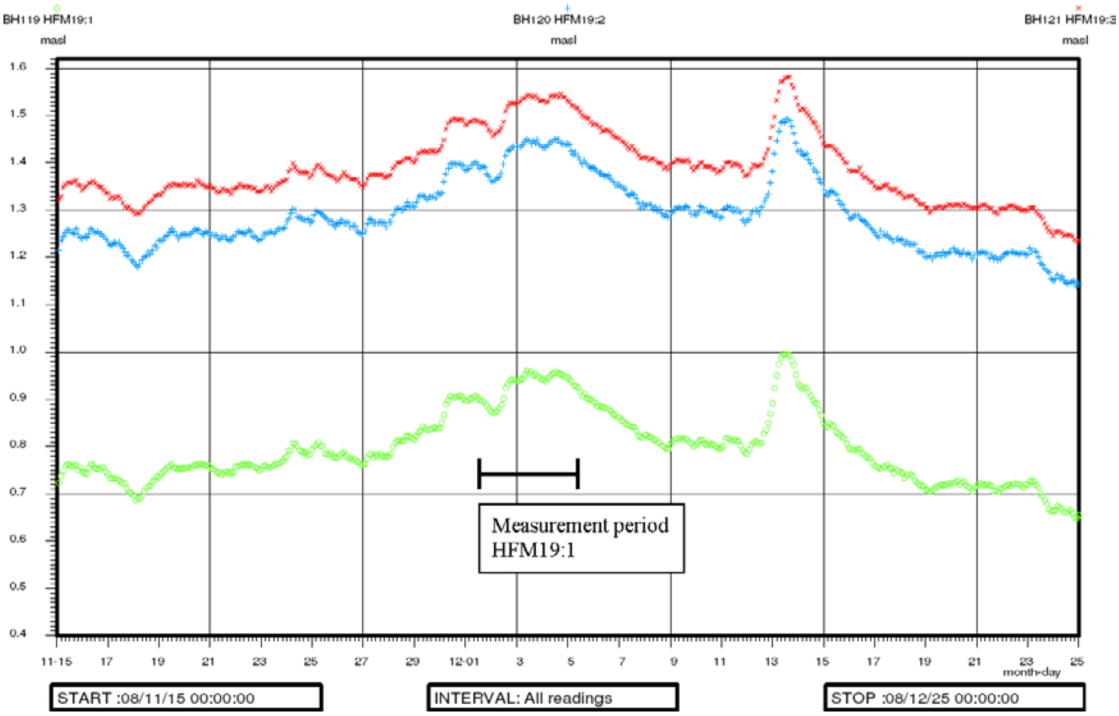
Measured section: HFM15:1 (green)

HFM16



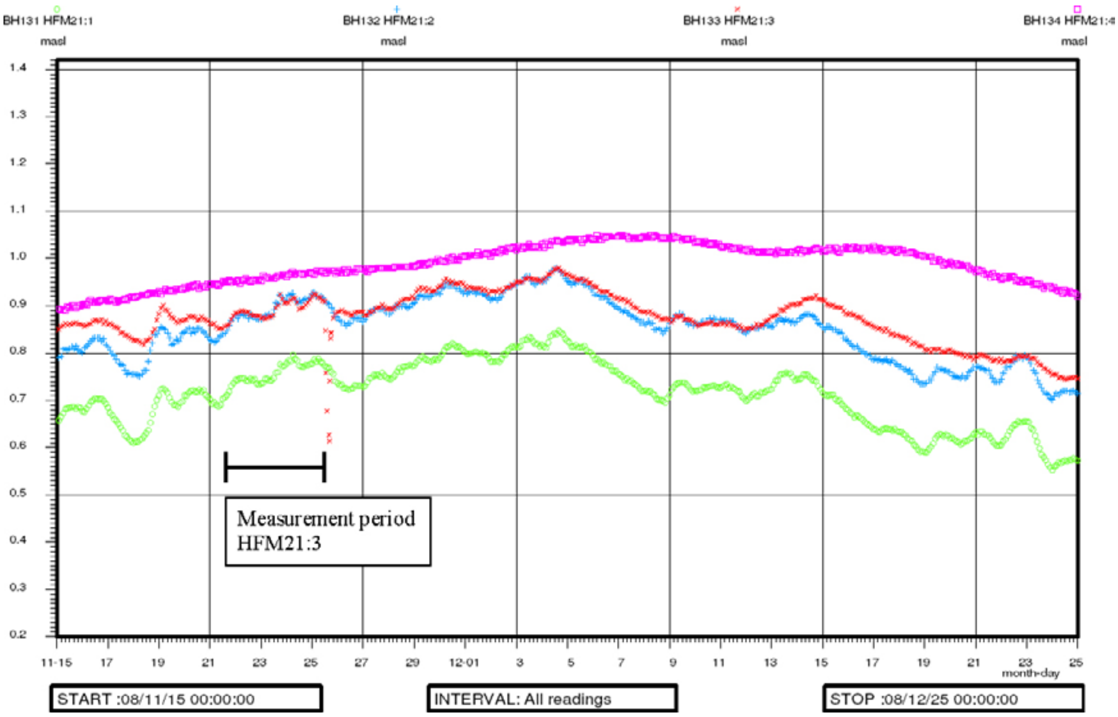
Measured section: HFM16:2 (blue)

HFM19



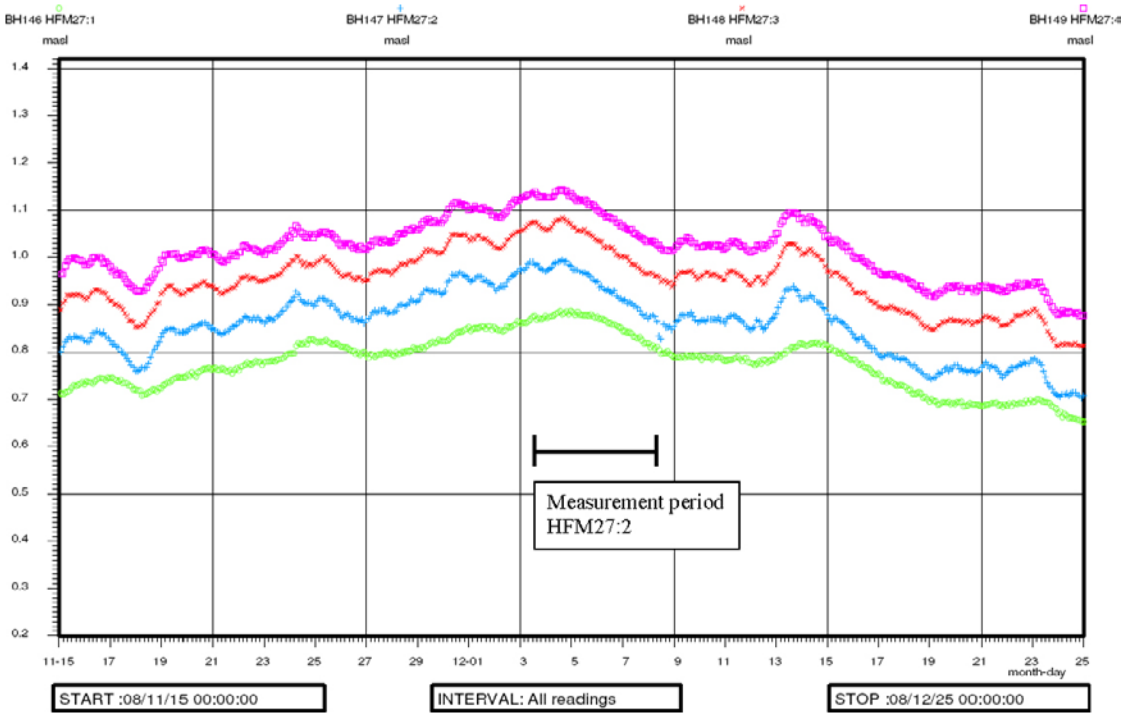
Measured section: HFM19:1 (green)

HFM21



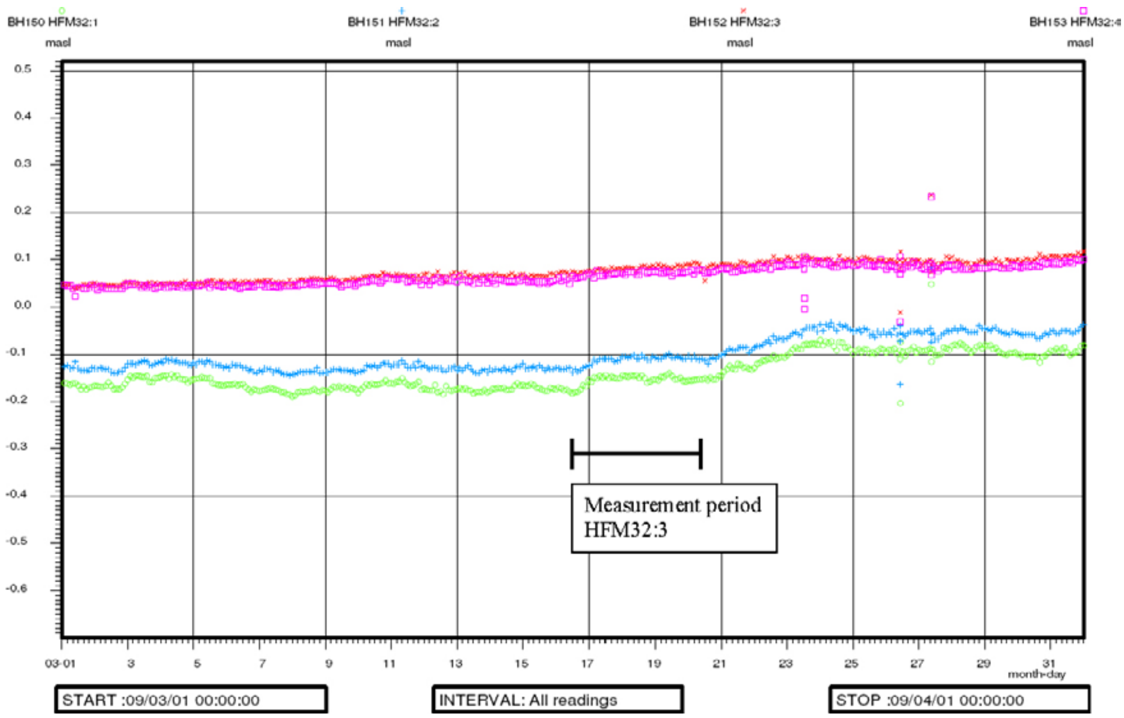
Measured section: HFM21:3 (red)

HFM27



Measured section: HFM27:2 (blue)

HFM32



Measured section: HFM32:3 (red)