P-06-59

Forsmark site investigation

Groundwater flow measurements in permanently installed boreholes

Test campaign no. 1, 2005

Eva Wass, Geosigma AB

September 2006

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ISSN 1651-4416
SKB P-06-59

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Keywords: Groundwater flow, Dilution test, Tracer test, AP PF 400-05-093.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

Abstract

This report describes the performance and evaluation of groundwater flow measurements in twelve 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 first 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 17 to 1,800 ml/h with calculated Darcy velocities from $1.7 \cdot 10^{-9}$ to $1.9 \cdot 10^{-7}$ m/s. Hydraulic gradients were calculated according to the Darcy concept and varied between 0.0004 and 2.3.

Sammanfattning

Denna rapport beskriver genomförandet och utvärderingen av grundvattenflödes-mätningar i tolv borrhålssektioner i permanent installerade borrhål i Forsmarks platsundersökningsområde. Syftet var att bestämma grundvattenflödet i samtliga, vid denna tidpunkt och för detta ändamål, instrumenterade sektioner. Detta är den första 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. De uppmätta grundvattenflödena låg i intervallet 17–1 800 ml/h med beräknade Darcy hastigheter mellan $1{,}7 \cdot 10^{-9}$ och $1{,}9 \cdot 10^{-7}$ m/s. Hydrauliska gradienter beräknades enligt Darcy-konceptet och varierade mellan 0,0004 och 2,3.

Contents

1 Introduction

This document reports the results gained from the groundwater flow measurements in permanently installed boreholes, test campaign no. 1, 2005, which is one of the activities performed within the Forsmark site investigation. The work was carried out in accordance with activity plan AP PF 400-05-093 and the field work was conducted during November and December 2005. 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 boreholes and drill sites 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 i permanent installerade borrhål, mätkampanj 1, 2005	AP PF 400-05-093	1.0
Method description	**Number**	**Version**
System för hydrologisk och metrologisk datainsamling Vattenprovtagning och utspädningsmätning i observationshål	SKB MD 368.010	1.0

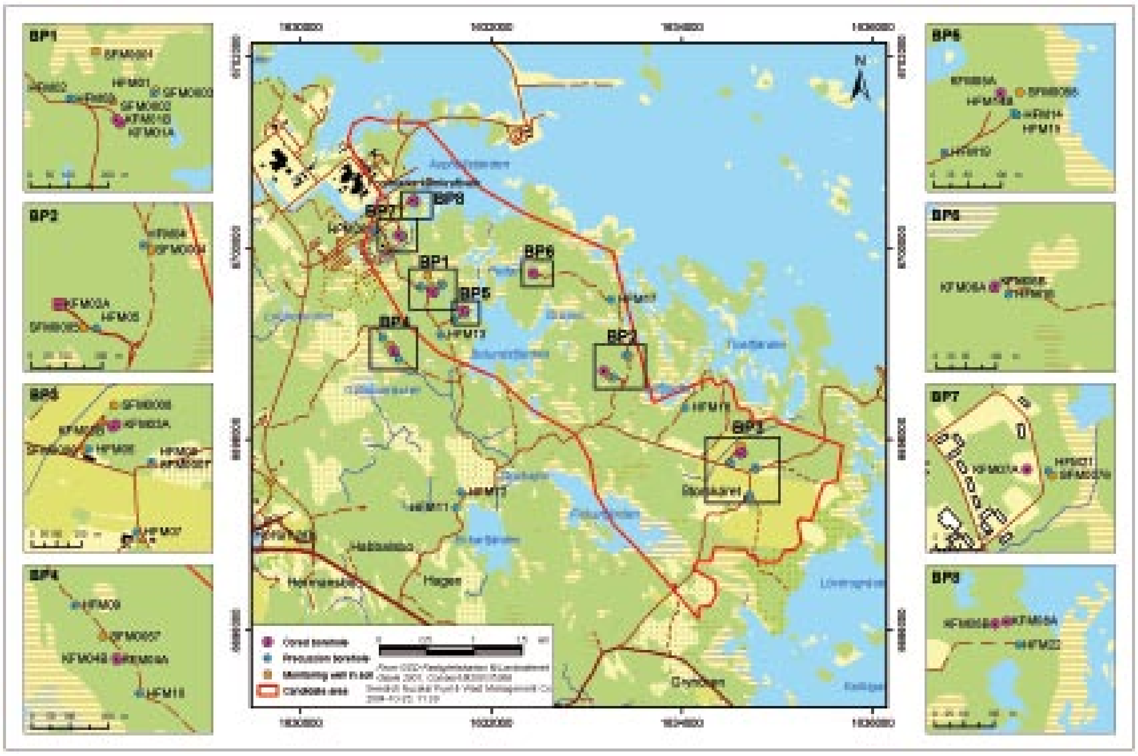

Figure 1-1. Overview over Forsmark site investigation area, showing borehole locations and drill sites in detail.

2 Objective and scope

The objective of this activity was to determine the groundwater flow in borehole sections in permanently installed boreholes at Forsmark. Twelve borehole sections instrumented for this purpose (circulation sections) were measured, cf Table 4-1. This was the first 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 undisturbed conditions.

3 Equipment

3.1 Description of equipment and tracers used

The boreholes involved in the tests are instrumented with 1–7 inflatable packers isolating 2–8 borehole sections each. In Figure 3-1 drawings of the instrumentation in core and percussion boreholes are presented.

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 four identical equipment set-ups, i.e. allowing four sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-2. The basic idea is to cause 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.

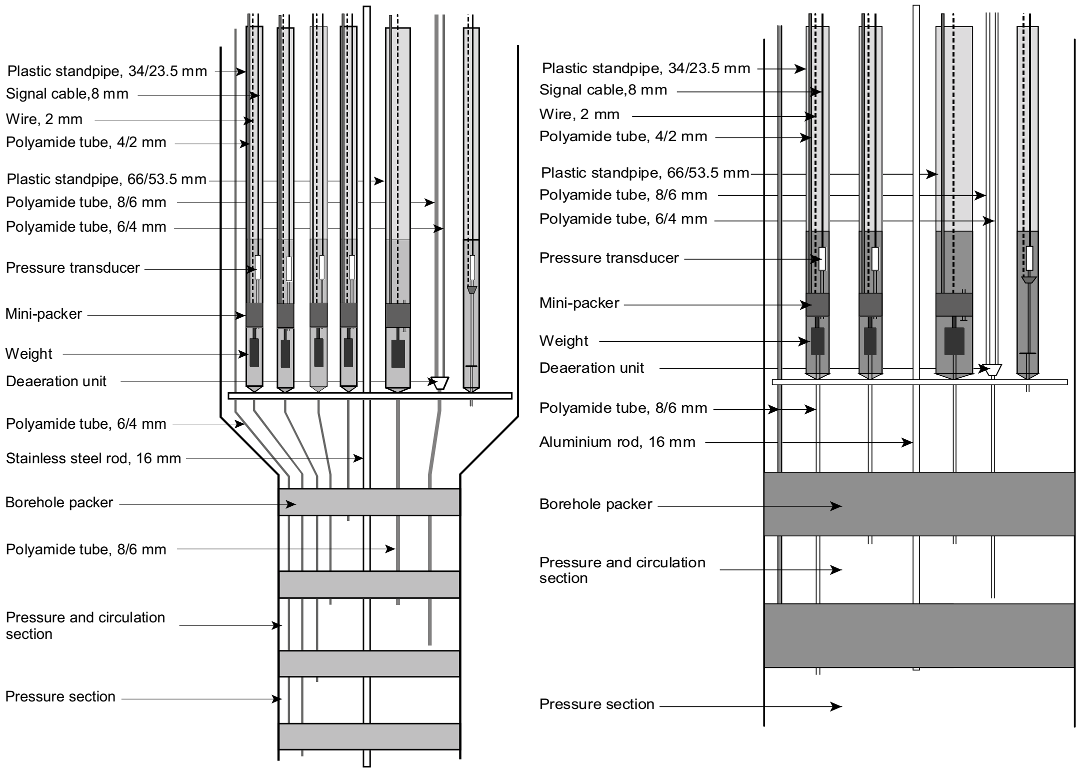

Figure 3-1. *Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.*

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, SKB internal document, see Table 1-1.

The tracer used was a fluorescent dye tracer, Uranine (Sodium Fluorescein), from Merck (purum quality).

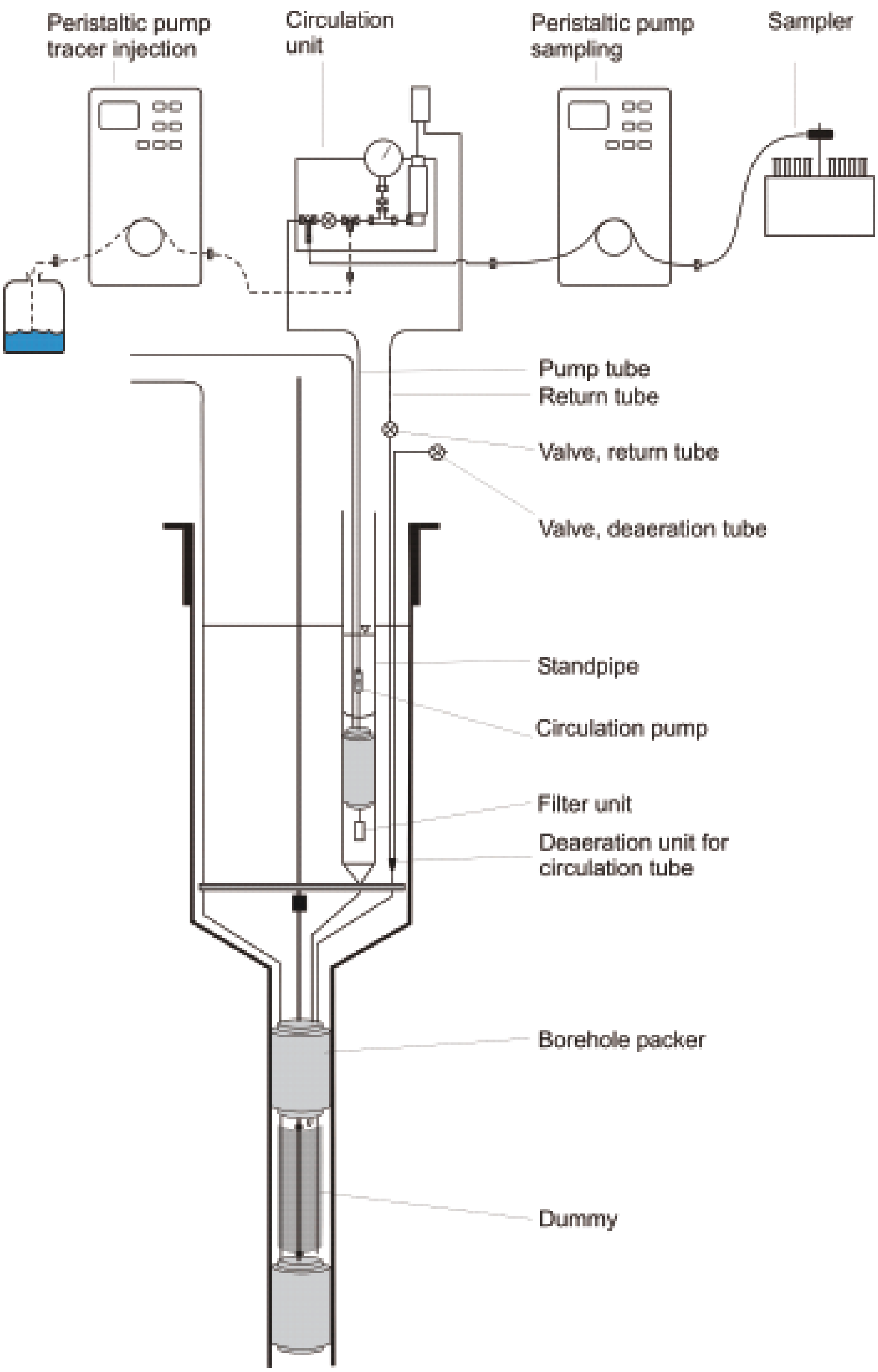

Figure 3-2. *Schematic drawing of the equipment used in tracer dilution measurements.*

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 metrologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål." (SKB MD 368.010, SKB internal document), cf Table 1-1.

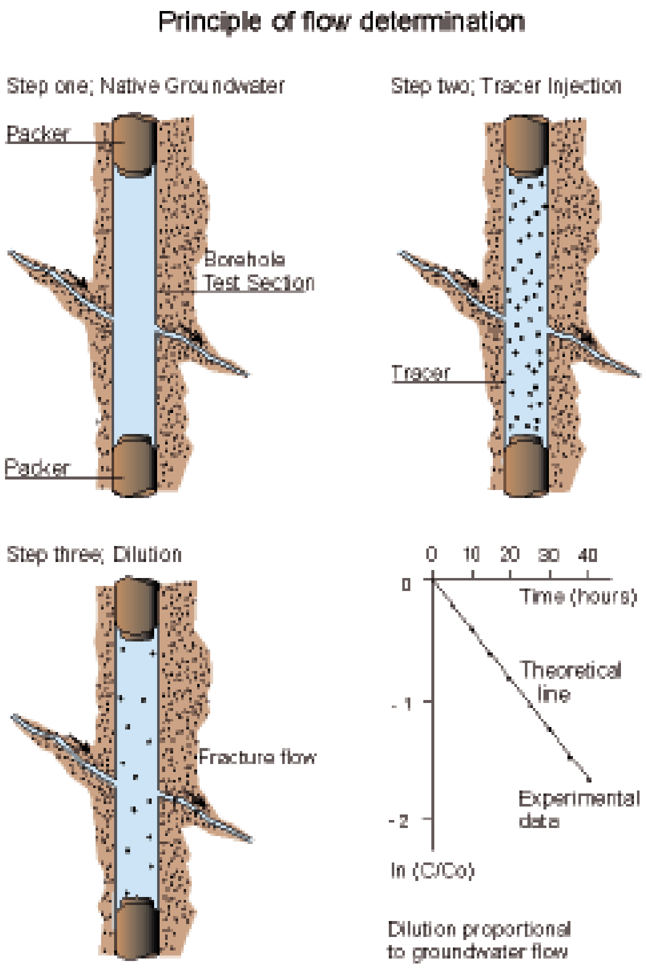

Figure 4-1. *General principles of dilution and flow determination.*

4.2 Preparations

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

4.3 Execution of field work

The test campaign involved 12 different borehole sections listed in Table 4-1. The duration of each test varied from 80 to 290 hours.

The tests were made by injecting a slug of tracer (Uranine, 500 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 it takes 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 0.5 mg/l. Four sections were injected simultaneously. The tracer solution was continuously circulated and sampled using the equipment described in Section 3.1.

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

Table 4-1. Borehole sections used for groundwater flow measurements, autumn 2005.

Borehole: section	Depth (m)	Transmissivity (m^2/s)	Geologic character***	Test period (yymmdd)
KFM02A:3	490–518	2.1 E–6*	Zone ZFMNE00A2	051122–051128
KFM02A:5	411–442	2.5 E–6*	Zone ZFMNE00A2	051116–051122
KFM03A:1	969.5–994.5	5.5 E–7*	5–6 flowing fractures, no deformation zone	051123–051205
KFM03A:4	633.5–650	2.4 E–6*	Zone ZFMNE00B1	051118–051123
KFM05A:4	254–272	1.4 E–8*	Single fracture	051123–051128
KFM06A:3	738–748	1.2 E–7*	Single flow anomaly, Zone ZFMNE061	051129–051205
KFM06A:5	341–362	3.5 E–6*	2 flowing fractures, Zone ZFMNE060	051117–051124
HFM02:2	38–48	5.9 E–4**	Zone ZFMNE00A2	051209–051212
HFM04:2	58–66	7.9 E–5**	Zone ZFMNE0866	051117–051122
HFM13:1	159–173	2.9 E–4**	Zone ZFMNE0401	051206–051212
HFM15:1	85–95	1.0 E–4**	Zone ZFMNE00A2	051205–051212
HFM19:1	168–182	2.7 E–4**	Zone ZFMNE00A2	051205–051212

* From PSS measurements, transient evaluation, /1/, /2/, /3/ and /4/.
** From HTHB measurements, transient evaluation, /5/, /6/, /7/ and /8/.
*** Deformation zones according to Forsmark 2.1 site descriptive model /9/.

4.4 Analyses and interpretations

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural unlabelled groundwater, cf /10/. 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):

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

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) 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 5–9 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 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:

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

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 mostly is heterogeneous and the angles in the sections not always 90°, the calculation of the hydraulic gradient is a rough estimation.

4.5 Nonconformities

There are no nonconformities with respect to the activity plan or the method descriptions.

5 Results

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.

In Figure 5-1 an example of a typical tracer dilution curve is shown, in this case borehole section KFM02A:3. 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. 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 17 to 1,800 ml/h in the measured sections with Darcy velocities ranging from $1.7 \cdot 10^{-9}$ to $1.9 \cdot 10^{-7}$ 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 KFM05A:4, KFM03A:1 and KFM06A:3 the hydraulic gradient is considered to be very large. However, in KFM03A:1 the result from the dilution measurement is uncertain, as further discussed below. In KFM05A:4 the groundwater level is decreased about 0.5 m during the test, as seen in Appendix 2, which may have affected the flow rate and calculated hydraulic gradient. The large gradients may also be due to wrong estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. All three sections also represent single fractures (cf Table 4-1) or, as for KFM03A:1, a set of individual fractures (no fracture zone) 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, a major hydraulic event occurred about one week prior to the dilution measurements affecting percussion boreholes HFM02, HFM13, HFM15 and HFM19. In the three latter boreholes, a slight increase in the groundwater pressure can be seen during the first 2–3 days of the dilution measurements. This is also reflected in the tracer dilution graphs where higher flow rates are indicated during this period. These data were therefore omitted in the evaluation as not being representative of natural conditions, cf Appendix 1. In KFM06A:5 sampling was disturbed due to a malfunctioning sampler and data are missing for about 70 hours in the dilution graph. Also, in KFM03A:1 there was a problem maintaining the circulation rate in the section. The reason for this may be the large depth and gasification combined with quite low transmissivity. A very slow circulation rate (2–3 l/h) had to be used resulting in slow and poor mixing of the tracer in the borehole section. This is clearly seen in the dilution graph in Appendix 1 and the result from the measurement in KFM03A:1 is uncertain.

The original results are stored in the primary data base SICADA. These data are available for further interpretation and are traceable by the activity plan number (AP PF 400-05-093).

Table 5-1. Results from groundwater flow measurements, test campaign 1, 2005.

Borehole/ section	Depth (m)	Transmissivity (m^2/s)	Volume (l)	Measured flow (ml/h)	Darcy velocity (m/s)	Hydraulic gradient (m/m)
KFM02A:3	490–518	2.1 E–6*	44.63	84	5.41E–09	0.072
KFM02A:5	411–442	2.5 E–6*	41.57	38	2.21E–09	0.027
KFM03A:1	969.5–994.5	5.5 E–7*	70.33	78	5.63E–09	0.26
KFM03A:4	633.5–650	2.4 E–6*	47.32	25	2.73E–09	0.019
KFM05A:4	254–272	1.4 E–8*	27.18	18	1.80E–09	2.3
KFM06A:3	738–748	1.2 E–7*	50.48	17	3.05E–09	0.25
KFM06A:5	341–362	3.5 E–6*	33.62	20	1.71E–09	0.010
HFM02:2	38–48	5.9 E–4**	23.08	1,800	1.86E–07	0.0032
HFM04:2	58–66	7.9 E–5**	23.07	110	1.40E–08	0.0014
HFM13:1	159–173	2.9 E–4**	31.13	1,100	8.28E–08	0.0040
HFM15:1	85–95	1.0 E–4**	29.80	37	3.70E–09	0.0004
HFM19:1	168–182	2.7 E–4**	36.51	470	3.44E–08	0.0018

* From PSS measurements, transient evaluation, /1/, /2/, /3/ and /4/.
** From HTHB measurements, transient evaluation, /5/, /6/, /7/ and /8/.

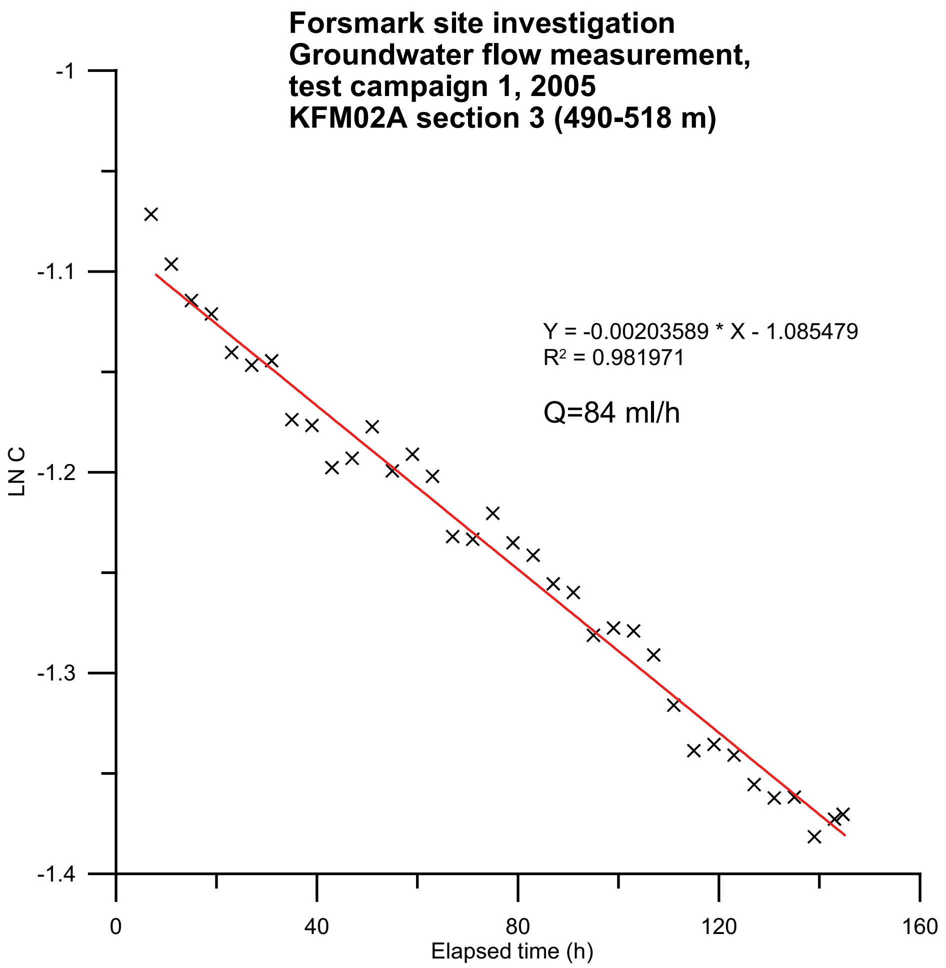

Figure 5-1. Example of a tracer dilution graph (Logarithm of concentration versus time) for borehole KFM02 section 3, including straight-line fit.

6 References

/1/ **Källgården J, Ludvigson J-E, Jönsson J, 2004.** Forsmark site investigation. Single-hole injection tests in borehole KFM02A. SKB P-04-100, Svensk Kärnbränslehantering AB.

/2/ **Källgården J, Ludvigson J-E, Hjerne C, 2004.** Forsmark site investigation. Single-hole injection tests in borehole KFM03A. SKB P-04-194, Svensk Kärnbränslehantering AB.

/3/ **Gokall-Norman K, Ludvigson J-E, Hjerne C, 2005.** Forsmark site investigation. Single-hole injection tests in borehole KFM05A. SKB P-05-56, Svensk Kärnbränslehantering AB.

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/5/ **Ludvigson J-E, Jönsson S, Levén J, 2003.** Forsmark site investigation. Pumping tests and flow logging - Boreholes KFM01A (0-100 m), HFM01, HFM02 and HFM03. SKB P-03-33, Svensk Kärnbränslehantering AB.

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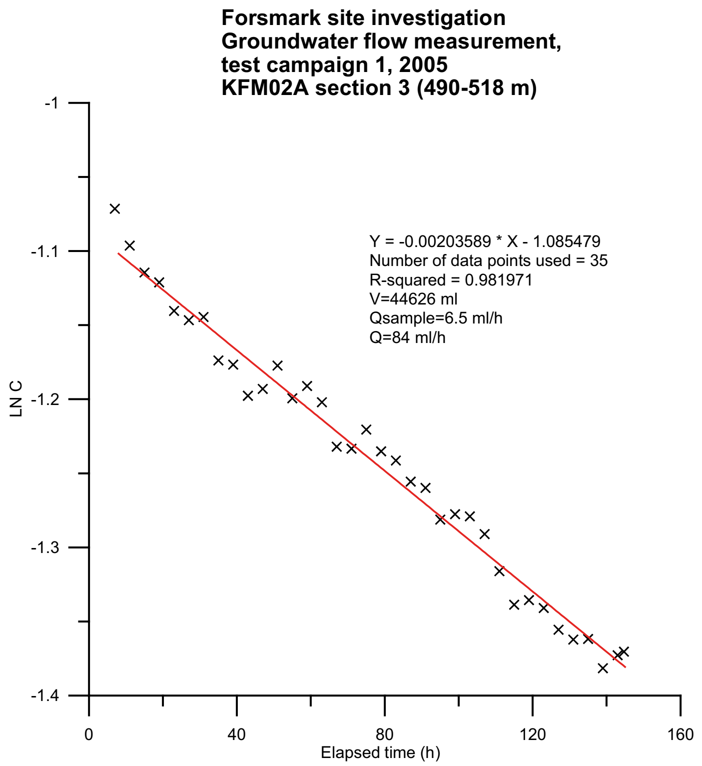
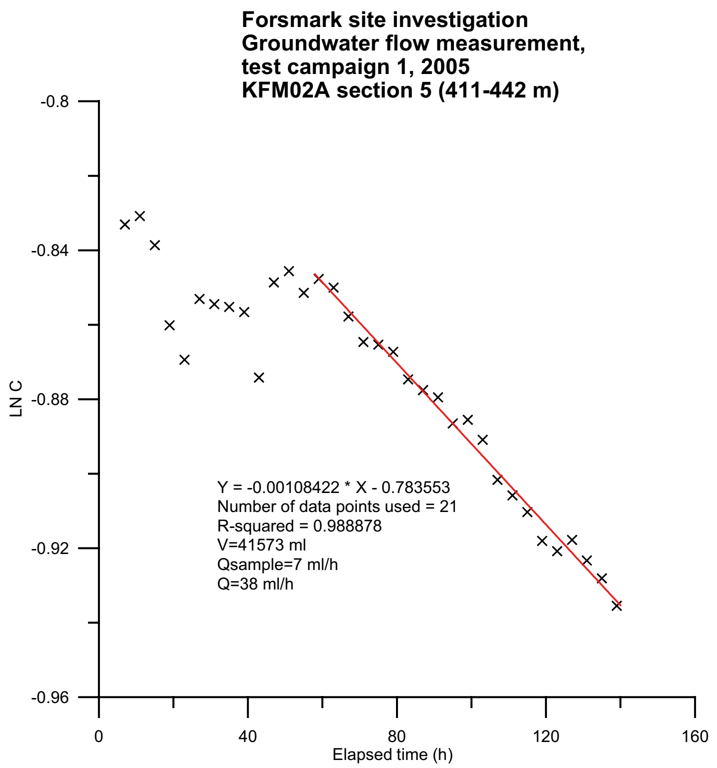
/9/ **SKB, 2006.** Site descriptive modelling Forsmark stage 2.1. SKB R-06-38, Svensk Kärnbränslehantering AB.

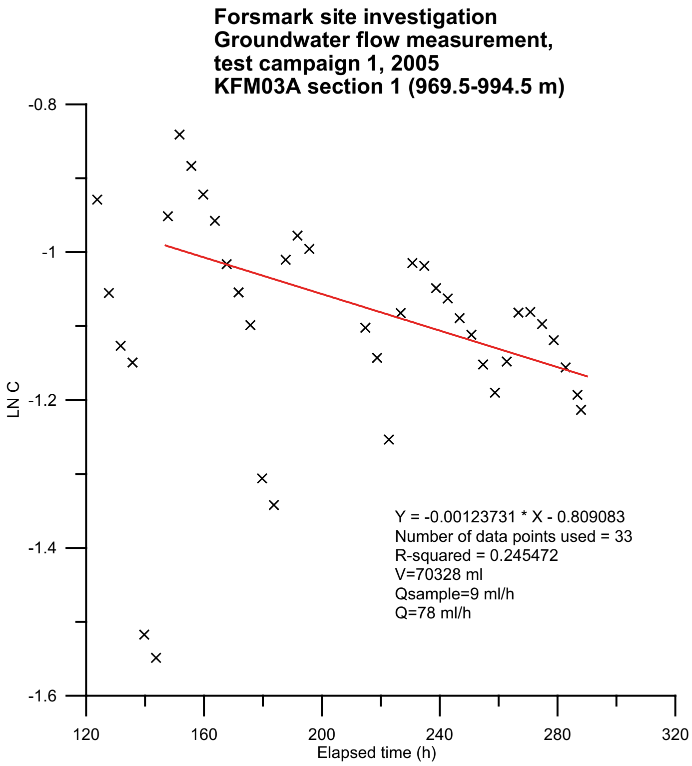
/10/ **Gustafsson E, 2002.** Bestämning av grundvattenflödet med utspädningsteknik – Modifiering av utrustning och kompletterande mätningar. SKB R-02-31 (in Swedish). Svensk Kärnbränslehantering AB.

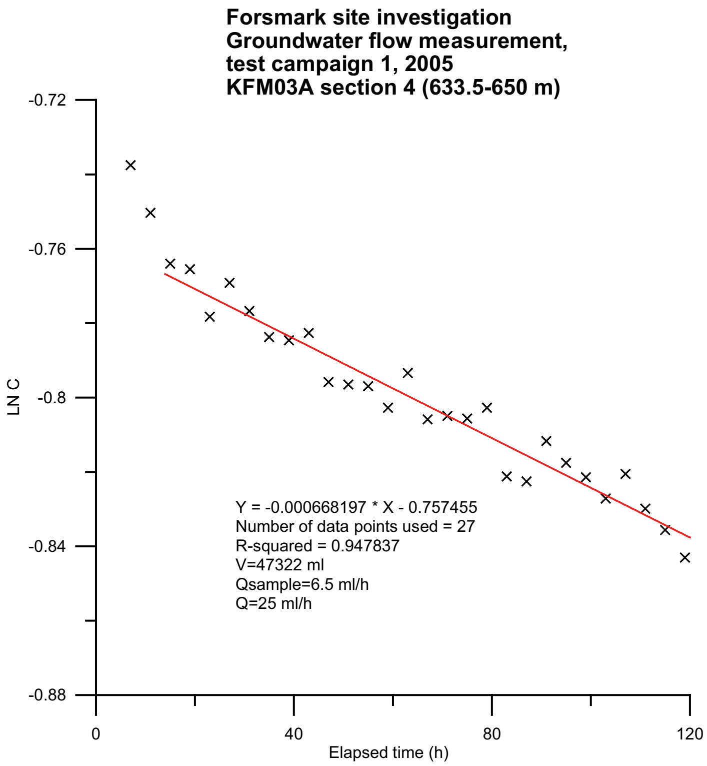
Appendix 1

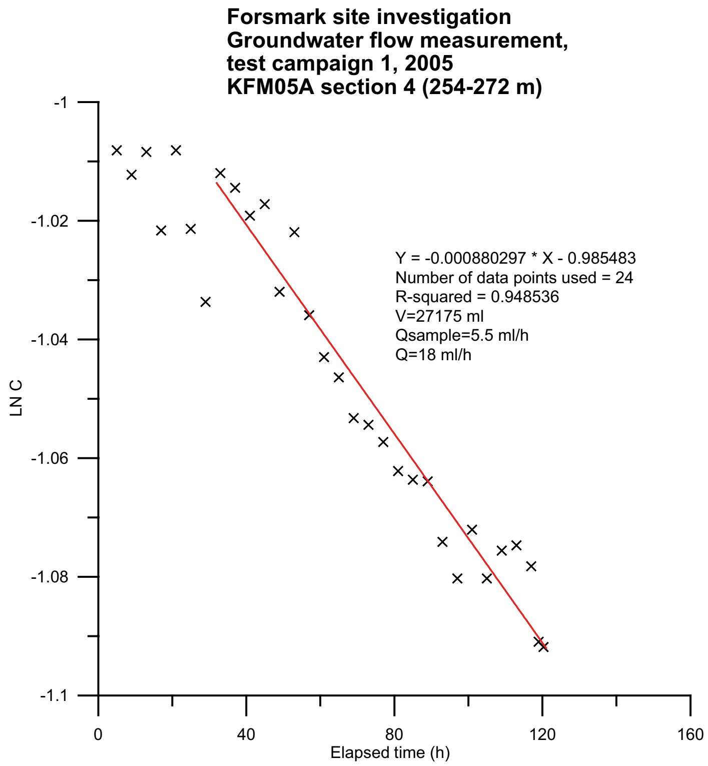
Tracer dilution graphs

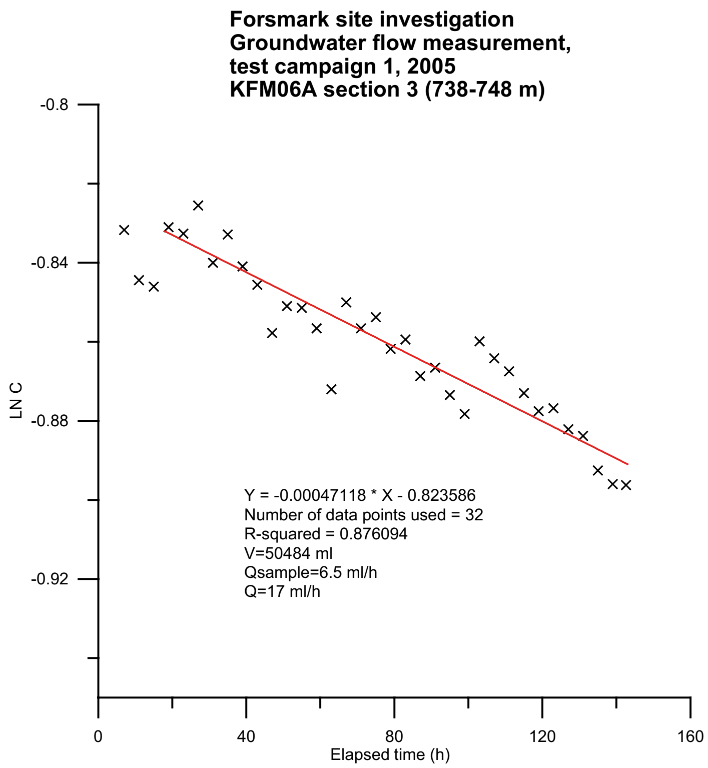


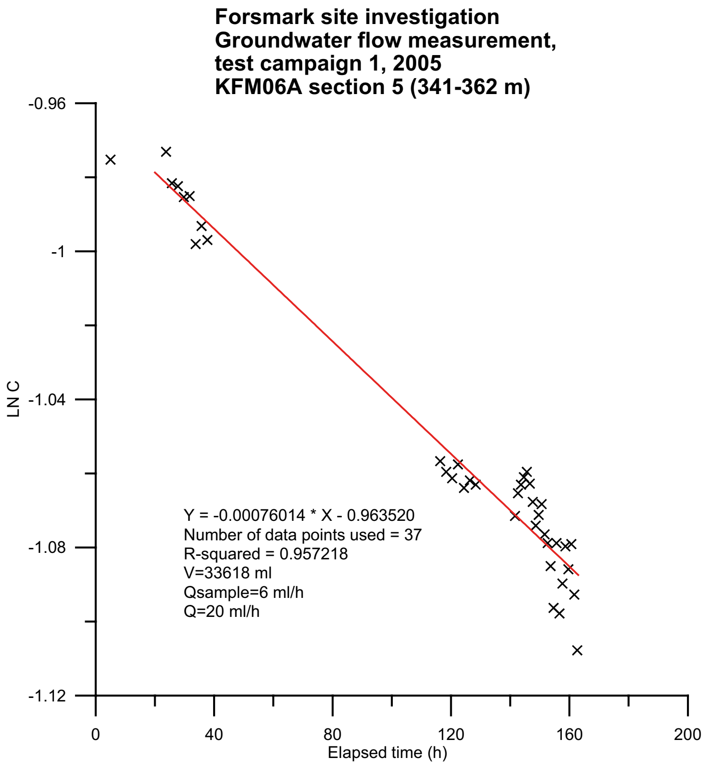


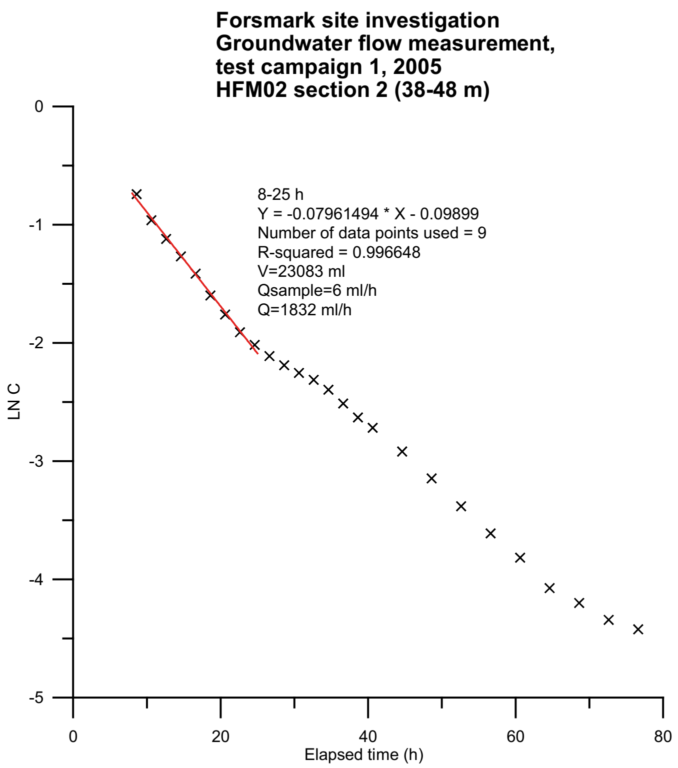

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
KFM03A section 1 (969.5-994.5 m)
LN C
Elapsed time (h)
Y = -0.00123731 * X - 0.809083
Number of data points used = 33
R-squared = 0.245472
V=70328 ml
Qsample=9 ml/h
Q=78 ml/h

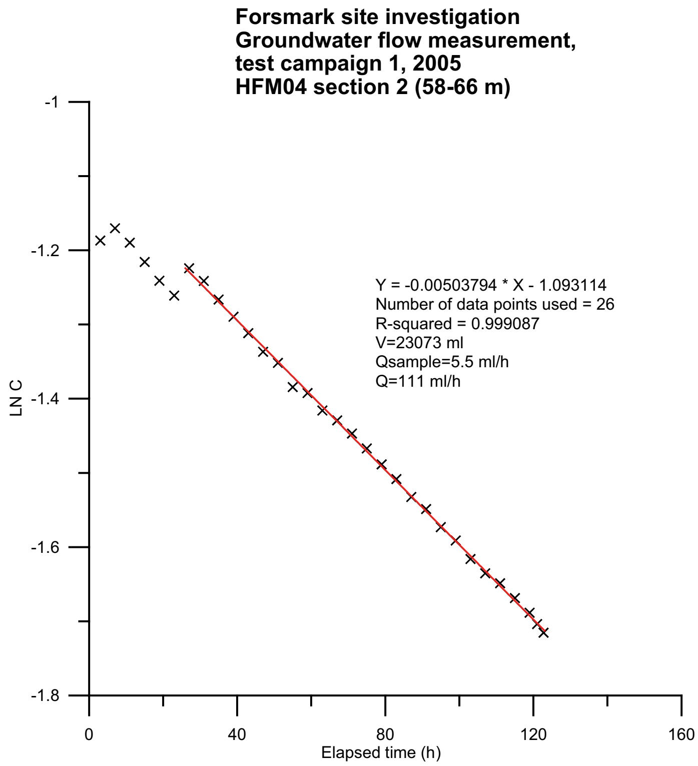

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
KFM03A section 4 (633.5-650 m)
LN C
Elapsed time (h)
Y = -0.000668197 * X - 0.757455
Number of data points used = 27
R-squared = 0.947837
V=47322 ml
Qsample=6.5 ml/h
Q=25 ml/h

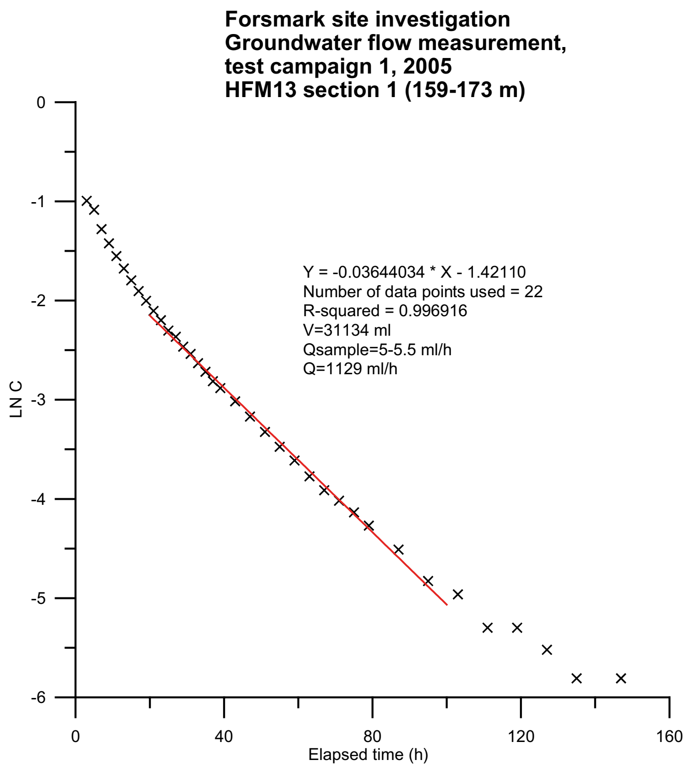

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
KFM05A section 4 (254-272 m)
Y = -0.000880297 * X - 0.985483
Number of data points used = 24
R-squared = 0.948536
V=27175 ml
Qsample=5.5 ml/h
Q=18 ml/h
LN C
Elapsed time (h)
-1
-1.02
-1.04
-1.06
-1.08
-1.1
0
40
80
120
160

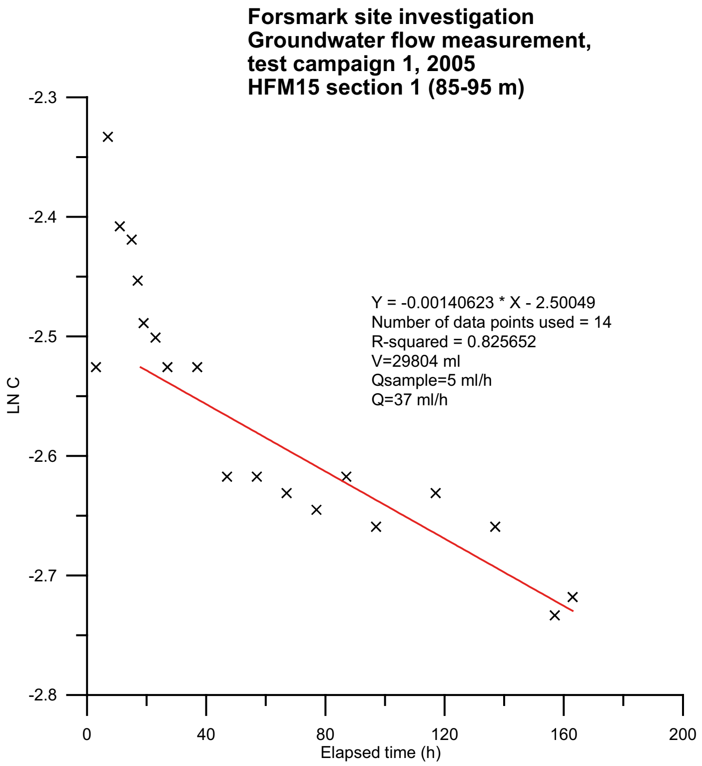

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
KFM06A section 3 (738-748 m)
Y = -0.00047118 * X - 0.823586
Number of data points used = 32
R-squared = 0.876094
V=50484 ml
Qsample=6.5 ml/h
Q=17 ml/h
LN C
Elapsed time (h)
-0.8
-0.84
-0.88
-0.92
0
40
80
120
160

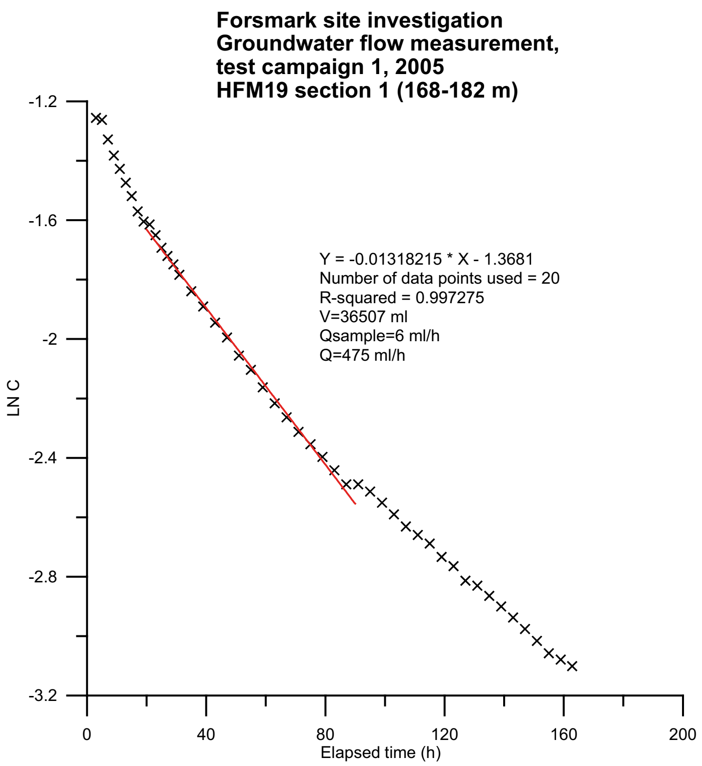

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
KFM06A section 5 (341-362 m)
Y = -0.00076014 * X - 0.963520
Number of data points used = 37
R-squared = 0.957218
V=33618 ml
Qsample=6 ml/h
Q=20 ml/h
LN C
Elapsed time (h)
-0.96
-1
-1.04
-1.08
-1.12
0
40
80
120
160
200


Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
HFM02 section 2 (38-48 m)
8-25 h
Y = -0.07961494 * X - 0.09899
Number of data points used = 9
R-squared = 0.996648
V=23083 ml
Qsample=6 ml/h
Q=1832 ml/h
LN C
Elapsed time (h)
0
-1
-2
-3
-4
-5
0
20
40
60
80


Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
HFM04 section 2 (58-66 m)
Y = -0.00503794 * X - 1.093114
Number of data points used = 26
R-squared = 0.999087
V=23073 ml
Qsample=5.5 ml/h
Q=111 ml/h
LN C
-1
-1.2
-1.4
-1.6
-1.8
0
40
80
120
160
Elapsed time (h)


Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
HFM13 section 1 (159-173 m)
Y = -0.03644034 * X - 1.42110
Number of data points used = 22
R-squared = 0.996916
V=31134 ml
Qsample=5-5.5 ml/h
Q=1129 ml/h
LN C
0
-1
-2
-3
-4
-5
-6
0
40
80
120
160
Elapsed time (h)

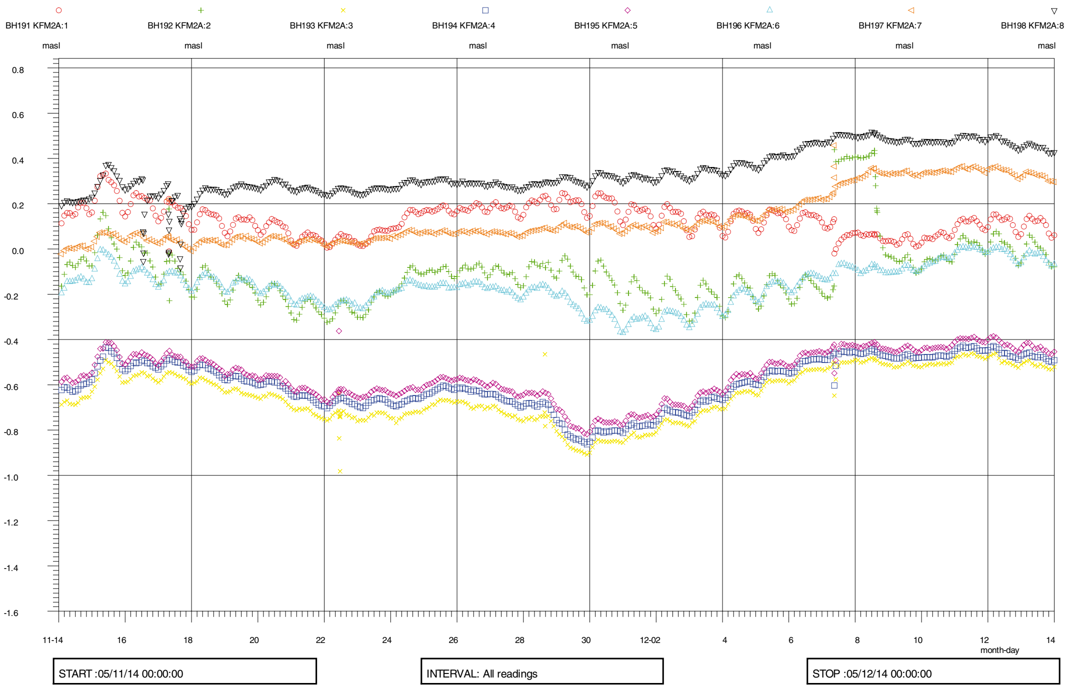

Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
HFM15 section 1 (85-95 m)
Y = -0.00140623 * X - 2.50049
Number of data points used = 14
R-squared = 0.825652
V=29804 ml
Qsample=5 ml/h
Q=37 ml/h
LN C
Elapsed time (h)
-2.3
-2.4
-2.5
-2.6
-2.7
-2.8
0
40
80
120
160
200


Forsmark site investigation
Groundwater flow measurement,
test campaign 1, 2005
HFM19 section 1 (168-182 m)
Y = -0.01318215 * X - 1.3681
Number of data points used = 20
R-squared = 0.997275
V=36507 ml
Qsample=6 ml/h
Q=475 ml/h
LN C
Elapsed time (h)
-1.2
-1.6
-2
-2.4
-2.8
-3.2
0
40
80
120
160
200

Groundwater levels (masl)

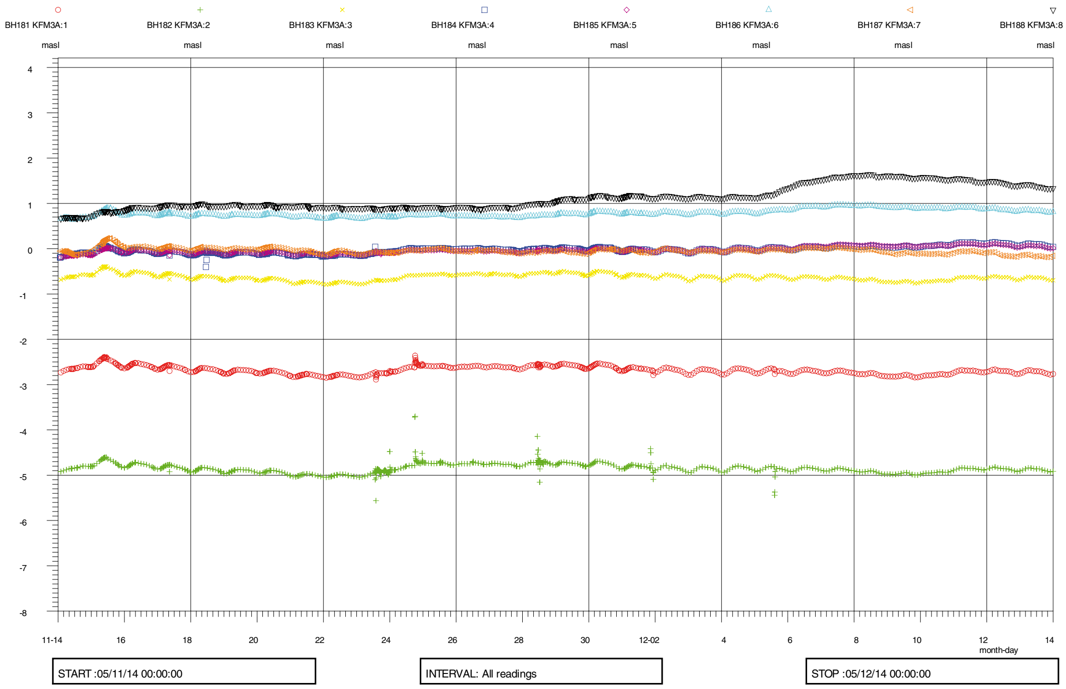
2005-11-14–2005-12-14

KFM02A



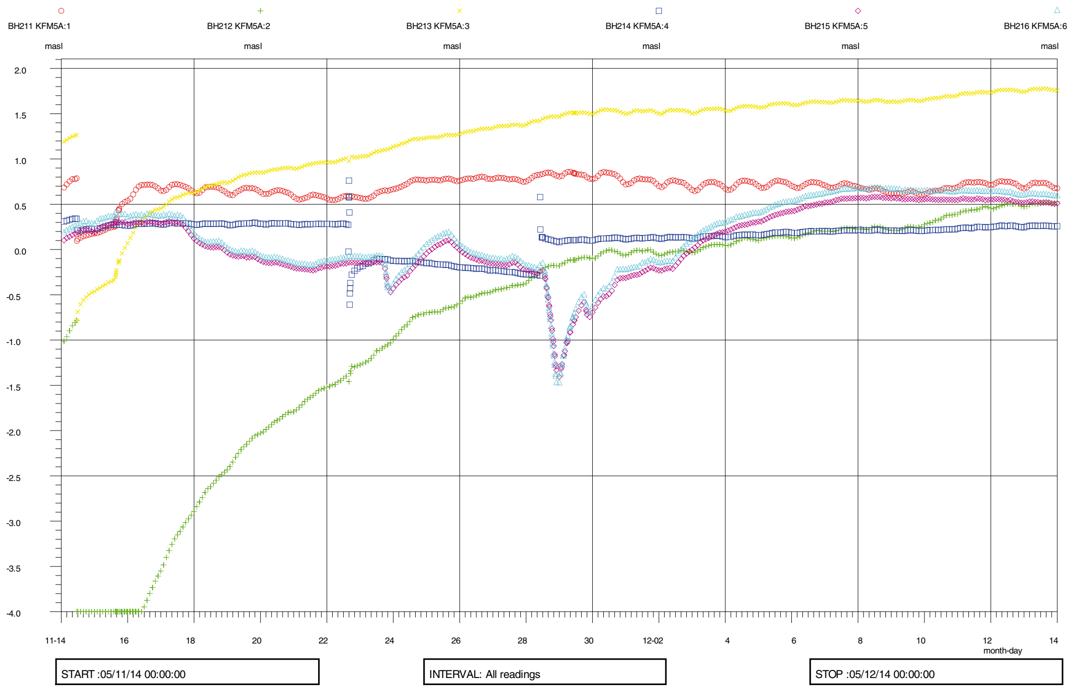
Measured sections: KFM02A:3 (yellow) and KFM02A:5 (dark red).

KFM03A



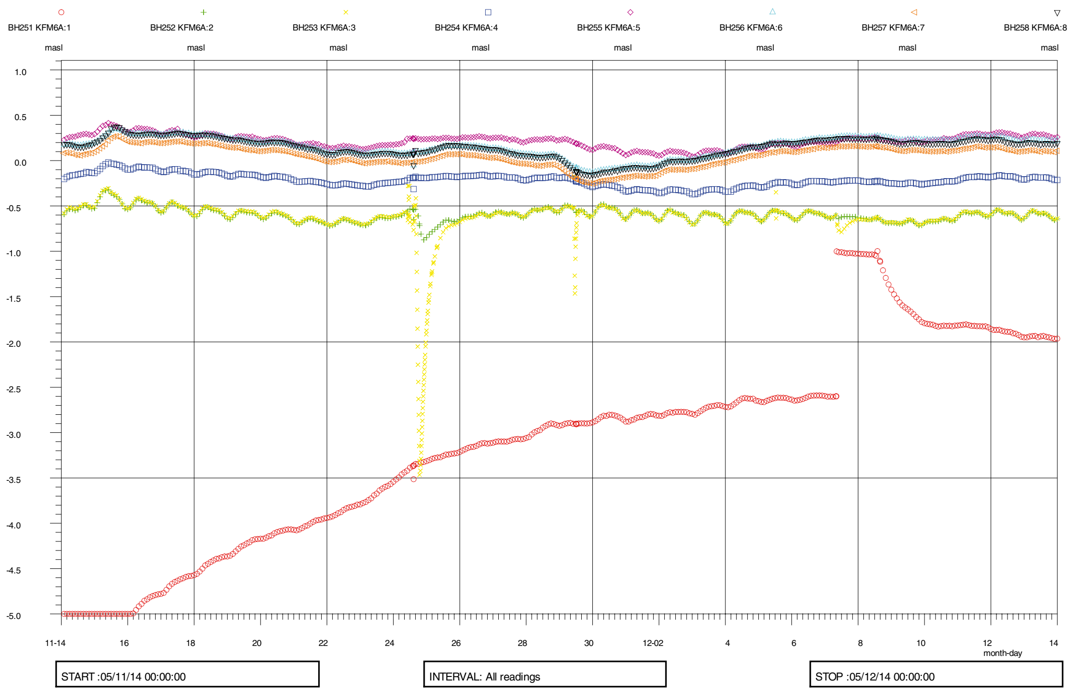
Measured sections: KFM03A:1 (red) and KFM03A:4 (dark blue).

KFM05A



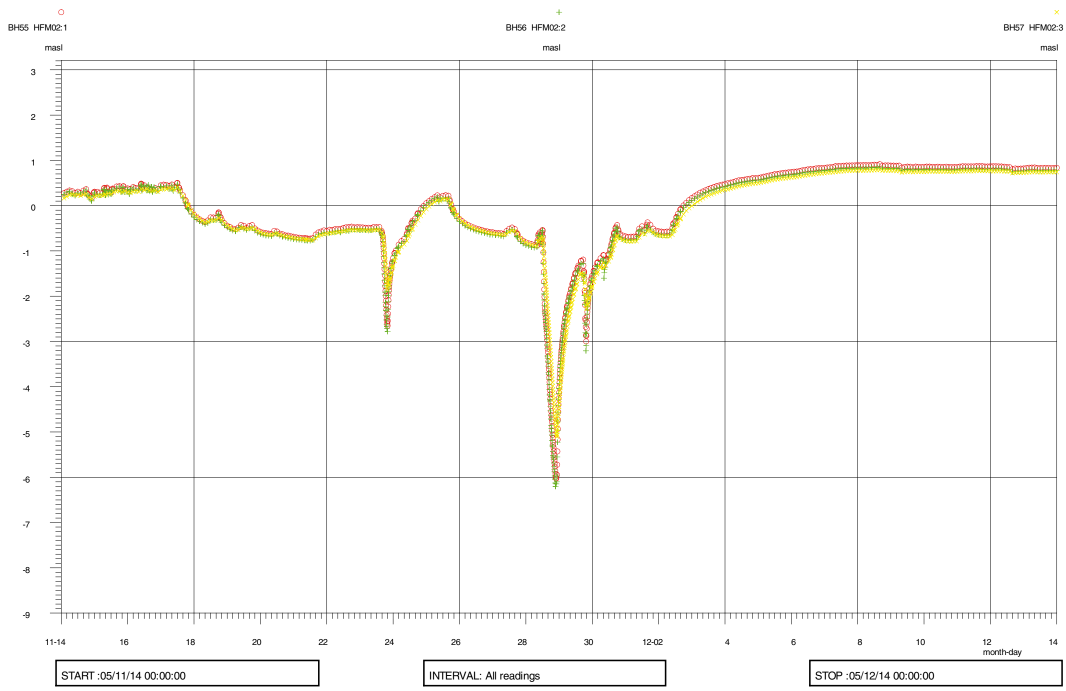
Measured section: KFM05A:4 (dark blue).

KFM06A



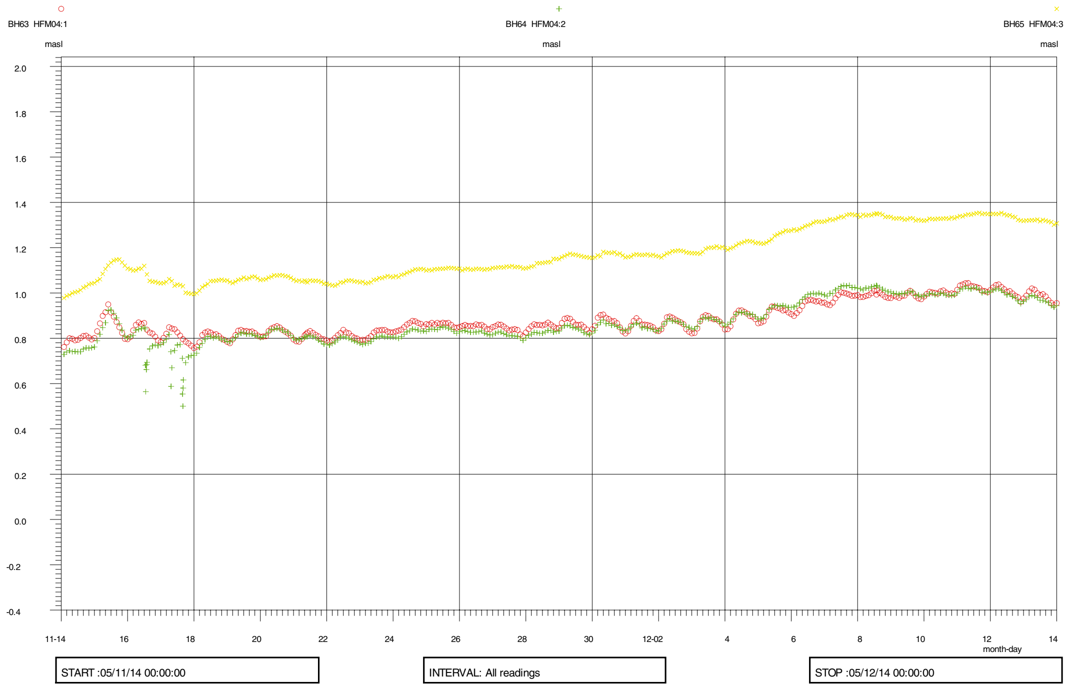
Measured sections: KFM06A:3 (yellow) and KFM06A:5 (dark red).

HFM02



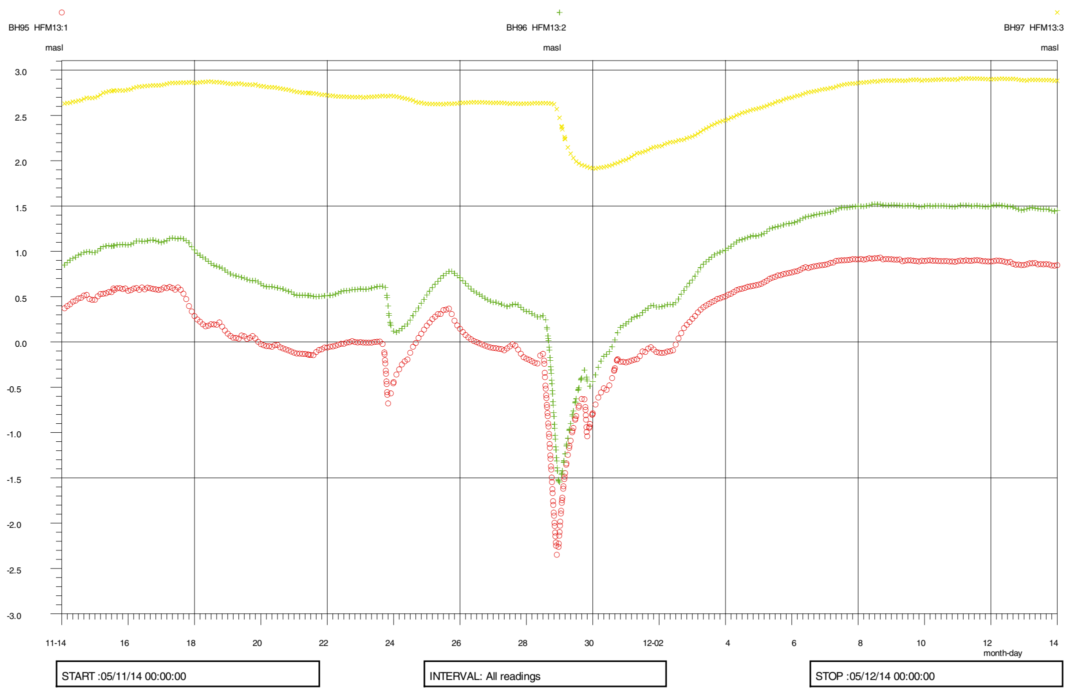
Measured section: HFM02:2 (green).

HFM04



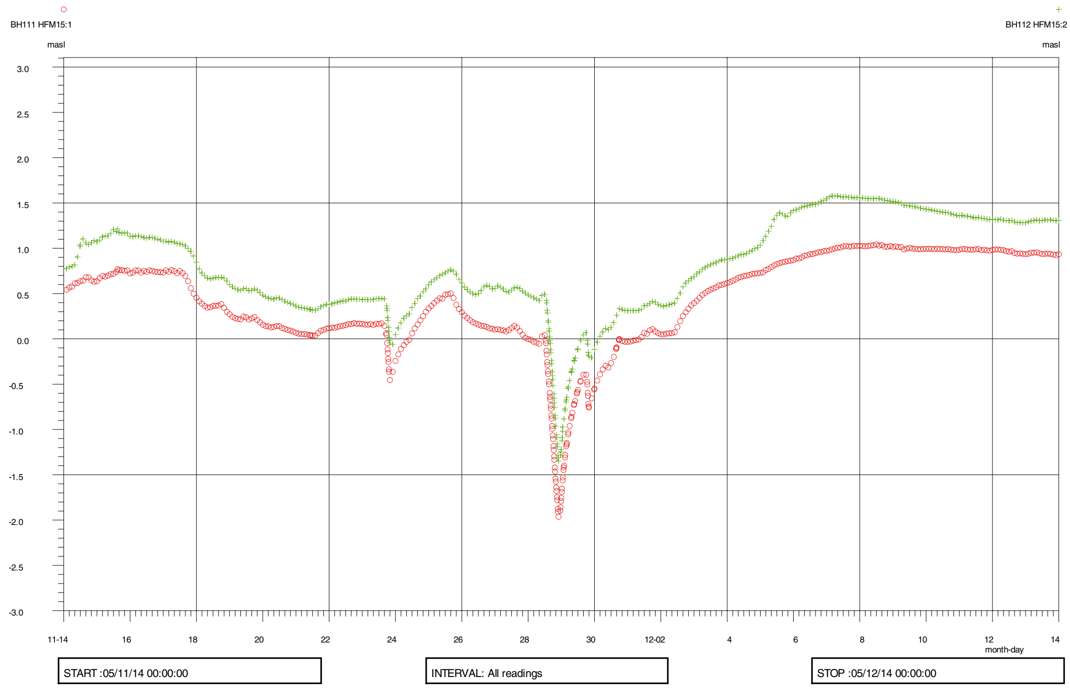
Measured section: HFM04:2 (green).

HFM13



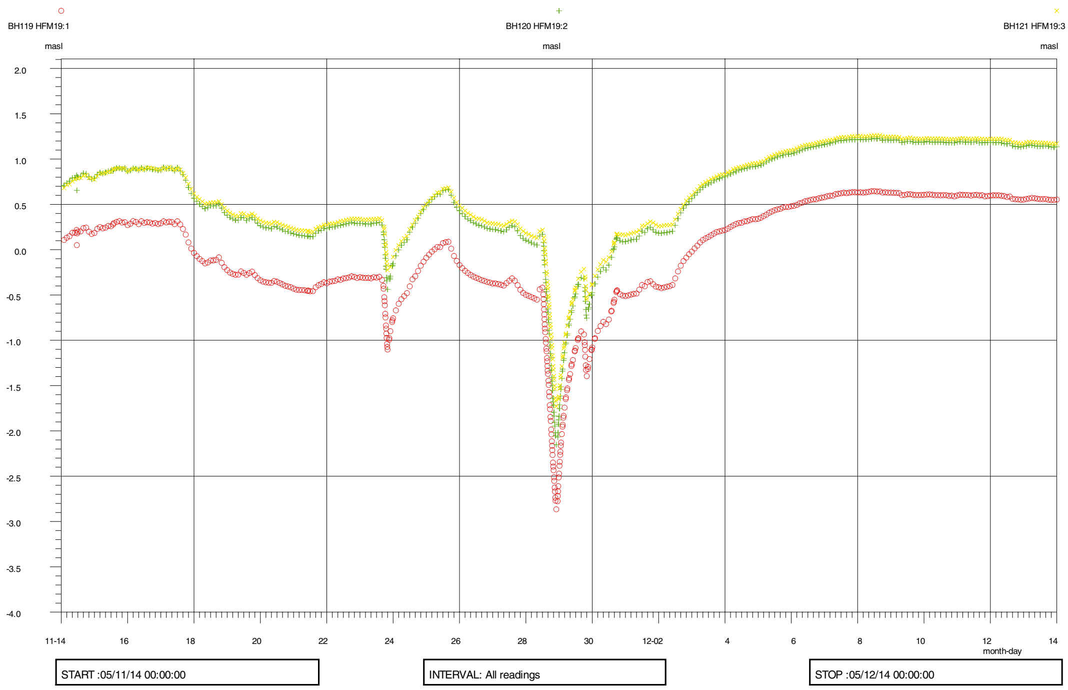
Measured section: HFM13:1 (red).

HFM15



Measured section: HFM15:1 (red).

HFM19



Measured section: HFM19:1 (red).