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Abstract

This report documents the results from the interference test performed in HLX33 together with dilution measurements in soil wells SSM000228 and SSM000229 and the tracer test between soil well SSM000228 and HLX33. The percussion borehole and the soil wells are located in the Laxemar subarea and the tests were performed between June and August 2006. HLX33 was used as pumping borehole and the pressure responses were observed in the soil wells SSM000228 and SSM000229.

The main purpose of the combined interference test in HLX33 together with the tracer test and dilution measurements was to study the hydraulic connection between soil and rock.

The flow period during the interference test lasted for 9 days. No pressure response due to the pumping was observed in neither SSM000228 nor SSM000229.

Dilution measurements were performed at natural and induced flow conditions, i.e. during pumping in HLX33. The dilution measurements in the soil wells indicated a reversed flow during pumping in HLX33 in both soil wells compared to natural flow conditions. During the tracer test tracer was injected in the soil well SSM000228. Tracer breakthrough was observed in the pumping borehole HLX33.

The dilution measurements in both soil wells showed a decreased flow during pumping in HLX33 compared to natural flow conditions. This is interpreted as significant flow response and a change in the flow direction.

Sammanfattning

Denna rapport dokumenterar resultaten från interferenstesten i HLX33 tillsammans med utspädningsmätningar i jordrören SSM000228 och SSM000229 samt spårförsöket mellan jordrör SSM000228 och HLX33. Hammarborrhålet och jordrören är belägna i Laxemarområdet och testerna utfördes från juni till augusti 2006. HLX33 användes som pumphål och tryckresponserna observerades i jordrören SSM000228 och SSM000229.

Huvudsyftet med den kombinerade interferenstesten i HLX33 tillsammans med spårförsöket och utspädningsmätningarna var att studera den hydrauliska kommunikationen mellan jord och berg.

Flödesperioden under interferenstesten varade 9 dagar. Ingen tryckrespons från pumpningen kunde konstateras i vare sig SSM000228 eller SSM000229.

Utspädningsmätningar utfördes under naturliga och under inducerade flödesförhållanden, dvs under pumpning i HLX33. Utspädningsmätningarna i båda jordrören indikerade ett minskat flöde under pumpning i HLX33 jämfört med naturliga förhållanden. Detta tolkas som tydlig påverkan med en riktningsförändring av flödet. Under spårförsöket injicerades spårämne i jordröret SSM000228. Genombrott av spårämne observerades i pumpborrhålet HLX33.

Contents

1 Introduction

A general program for site investigations presenting survey methods has been prepared /1/, as well as a site-specific program for the investigations in the Simpevarp area /2/. The interference and tracer testing form part of the site characterization program under item 1.1.5.9 and 1.1.7.4 in the work breakdown structure of the execution programme, /3/.

This document reports the results gained by the hydraulic interference test, dilution tests and tracer test in borehole HLX33 and the soil wells SSM000228 and SSM000229 performed within the site investigation in the subarea Laxemar at Oskarshamn.

The locations of the boreholes involved in the interference test are shown in Figure 1-1.
The tests were carried out between June and August 2006.

The interference- and tracer test and evaluations have been made according to the activity plan and method descriptions listed in Table 1-1. Both the activity plan and method descriptions are internal controlling documents of SKB.

Borehole HLX33, used as pumping borehole, and the surrounding soil wells that served as observation wells are listed in Table 1-2. The times referred to in this table are the chosen start and stop times of the flow period.

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 the performance of the interference test activity.

Pumping borehole	Activity Plan number	Version
Interferens- och spårämnestester mellan HLX33 och SSM000228 och SSM000229.	AP PS 400-06-36 (execution)	1.0
Utvärdering och rapportering av interferenstester och borr-resposner, December 2007.	AP PS 400-06-115 (evaluation)	1.0
Method documents	**Number**	**Version**
Instruktion för analys av injektions- och enhålspumptester.	SKB MD 320.004	1.0
Metodbeskrivning för interferenstester.	SKB MD 330.003	1.0
Metodbeskrivning för flerhålsspårförsök.	SKB MD 530.006	1.0
System för hydrologisk och meteorologisk datainsamling. Vattenprovtagning och utspädningsmätning i observationshål.	SKB MD 368.010	1.0

Table 1-2. Boreholes and soil pipes involved in the test together with start and stop times of the test.

Pumping borehole	Observation soil wells	Test start date and time (YYYY-MM-DD tt:mm)	Test stop date and time (YYYY-MM-DD tt:mm)
HLX33	SSM000228, SSM000229	2006-06-28 14:37:50	2006-08-07 15:19:15

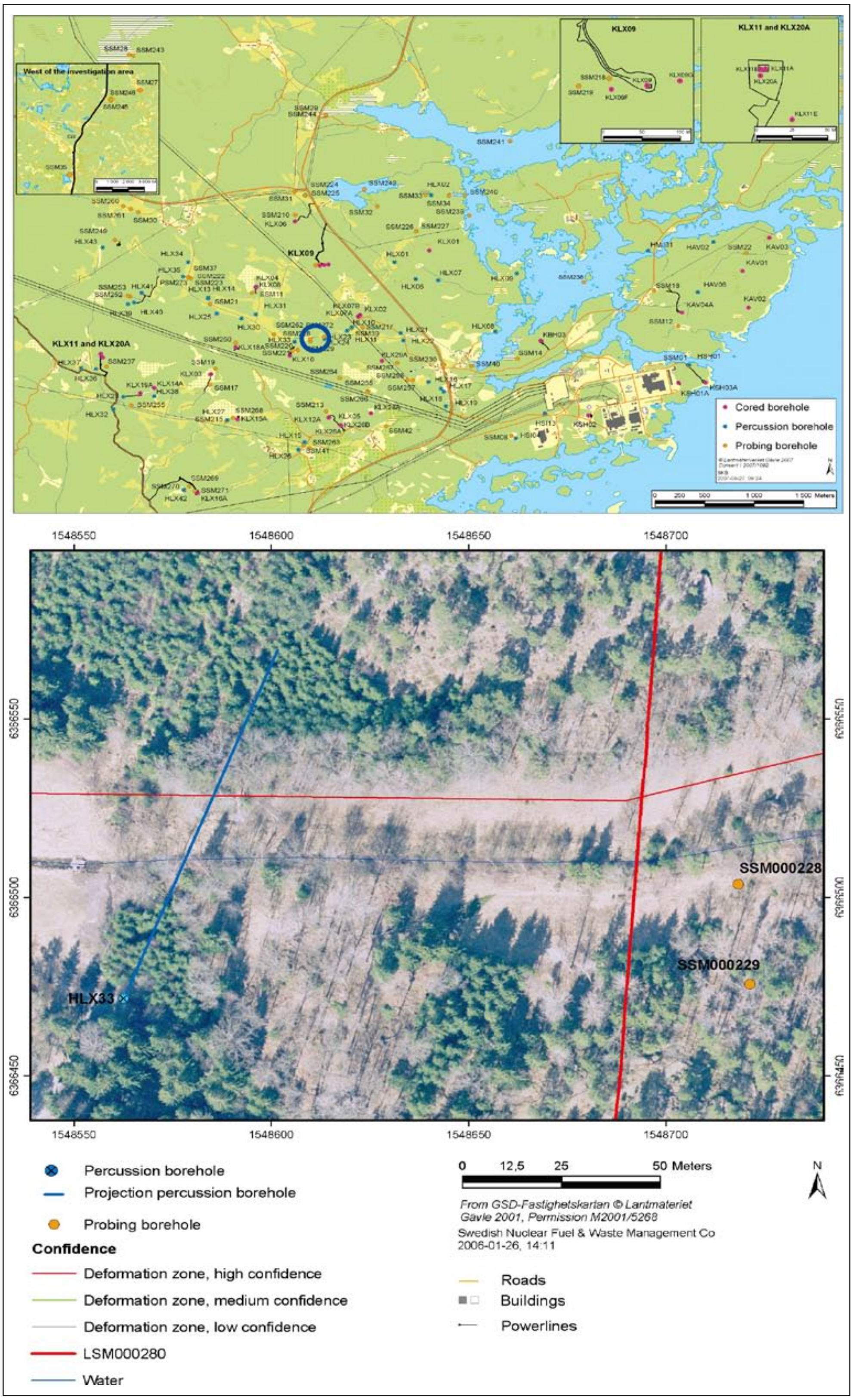

Figure 1-1. *The investigation area at Oskarshamn including part of the candidate area Laxemar selected for more detailed investigations. The positions of the boreholes included in the interference and tracer tests are displayed.*

2 Objectives

The main aim of hydraulic interference tests in the rock is to get support for interpretations of geologic structures in regard to their hydraulic and geometric properties deduced from single-hole tests. Furthermore, interference tests may provide information about the hydraulic connectivity and hydraulic boundary conditions within the tested area. Finally, interference tests make up the basis for calibration of numerical models of the area. In this case, the main purpose of the interference test together with the tracer test and dilution measurements was to study the hydraulic connection between soil and rock.

The interference test in conjunction with dilution measurements and tracer test was performed by pumping in borehole HLX33 and monitoring pressure responses in the soil wells SSM000228 and SSM000229. The borehole and soil wells are part of HMS, the Hydro Monitoring System at Oskarshamn.

3 Scope

3.1 Boreholes tested

Technical data of the boreholes tested are presented in Table 3-1.

The reference point in the boreholes is always top of casing (ToC) and top of the soil wells, respectively. The Swedish National coordinate system (RT90 2.5 gon V 0:-15) is used in the x-y-direction together with RHB70 in the z-direction. The coordinates of the boreholes at ground surface are shown in Table 3-2. All section positions are given as length along the borehole (not vertical distance from ToC). All times presented are Swedish summer times i.e. when appropriate, adjustment for daylight saving time has been made for all reported times.

Borehole logs are presented in Appendix 4.

Table 3-1. Pertinent technical data of the boreholes included in the interference test. (From Sicada).

Borehole data							
Bh ID	**Elevation of top of casing (ToC) (m.a.s.l.)**	**Borehole interval from ToC (m)**	**Casing/ Bh-diam. (m)**	**Inclination-top of bh (from horizontal plane) (°)**	**Dip-direction-top of borehole (from local N) (°)**	**Remarks**	**Drilling finished Date (YYYY-MM-DD)**
HLX33	12.20	0.00–9.10	0.190	–58.76	21.77	Borehole	2004-12-20
		9.10–202.10	0.139			Borehole	
		0.00–8.94	0.160			Casing ID	
		8.94–9.03	0.143			Casing ID	
SSM000228	13.09	1.00–7.10	0.120	–87.92	119.34	Borehole	2005-09-19
		7.10–13.00	0.054			Borehole	
		0.00–6.00	0.050			Casing ID	
		6.00–7.00	0.050			Casing ID, screen 0.3 mm	
		7.00–7.10	0.050			Casing ID	
SSM000229	13.68	0.30–4.10	0.120	–88.60	118.94	Borehole	2005-09-20
		4.10–7.30	0.054			Borehole	
		0.00–3.00	0.050			Casing ID	
		3.00–4.00	0.050			Casing ID, screen 0.3 mm	
		4.00–4.10	0.050			Casing ID	

Table 3-2. Coordinates of the boreholes and soil wells included in the interference test. (From Sicada).

Borehole data		
Bh ID	**Northing (m)**	**Easting (m)**
HLX33	6366471.74	1548562.71
SSM000228	6366503.70	1548718.36
SSM000229	6366475.65	1548721.34

3.2 Tests performed

A hydraulic interference test in conjunction with dilution measurements and a tracer test were performed. The results are presented in this report. The tracer test was preceded by dilution tests in two soil wells. The dilution tests were performed during undisturbed groundwater flow conditions and during pumping in borehole HLX33, respectively. The test sections of the borehole and soil pipes involved in the tests are listed in Table 3-3. The data extracted from HMS, the Hydro Monitoring System, from the observation soil wells was chosen so as to receive an appropriate amount of data from an appropriate time period providing information about the pressure conditions prior to as well as during and after the interference test. HMS is registering pressure continuously.

The column "Test section" in the tables below reports the hydraulically active section length. The upper part of the upper section in percussion boreholes is cased to some depth. The length of the casing is not included in the "Test section" unless there is a screened interval. The screened intervals in the soil wells and the casing length in borehole HLX33 can be found in Table 3-1.

The interpreted points of application, calculated as explained below, and lengths of the borehole sections involved in the interference test together with the distances between the pumping borehole and the observation sections are shown in Tables 3-3 and 3-4 below. The distances are calculated as the distance between the points of application in the pumping borehole and the points of application in respective observation section using a routine in the Sicada database. The estimations of the points of application in the observation sections were selected as the midpoint of the sections. In the pumping borehole, HLX33, the point of application is an estimation of the position of the anomaly that contributed to the major part of the transmissivity in the section.

Table 3-3. Borehole sections involved in the interference and tracer test in HLX33, see Figure 1-1.

Bh ID	Test section (m)	Test type1	Test configuration
HLX33	9.0–202.1	1B	Open borehole
SSM000228	6.0–7.0	2	Open borehole
SSM000229	3.0–4.0	2	Open borehole

[1)] 1B: Pumping test-submersible pump, 2: Interference test.

Table 3-4. Points of application and lengths of the test sections for the interference test in HLX33.

Bh ID	Test section (m)	Point of application (m below TOC)	Section length (m)	Distance to HLX33 (m)
HLX33	9.0–202.1	181.0	193.1	–
SSM000228	6.0–7.0	6.50	1.0	200.6
SSM000229	3.0–4.0	3.5	1.0	213.1

4 Description of equipment

4.1 Interference test

The pumping and interference test was performed with an integrated field unit consisting of a container at HLX33 housing a

- submersible pump: Grundfoss SPE5-70, range is about 5–100 L/min,
- absolute pressure transducer: Druck PTX1830, 10bar range and ± 0.1% accuracy,
- water level dipper,
- flow gauge: Krohne IFM1010 electromagnetic, 0–150 L/min.

The observation wells were equipped with absolute pressure gauges data logger as follows

- SSM000228: 30 PSIA LevelTroll integrated gauge and logger 7.0 m below TOC with accuracy of ± 0.2% of full scale and resolution of ± 0.01% of full scale.
- SSM000229: 30 PSIA LevelTroll integrated gauge and logger 4.0 m below TOC with accuracy of ± 0.2% of full scale and resolution of ± 0.01% of full scale.

All pressure gauges were set to log data every 10 seconds and event trigger of 0.1 kPa during the test.

Gauges were calibrated from the factory. During the test the pressure gauge reading are compared to those from a water level dipper for the purpose of checking sensibility of readout.

All the observation sections included in the interference test are part of the SKB hydro monitoring system (HMS), where pressure is recorded continuously.

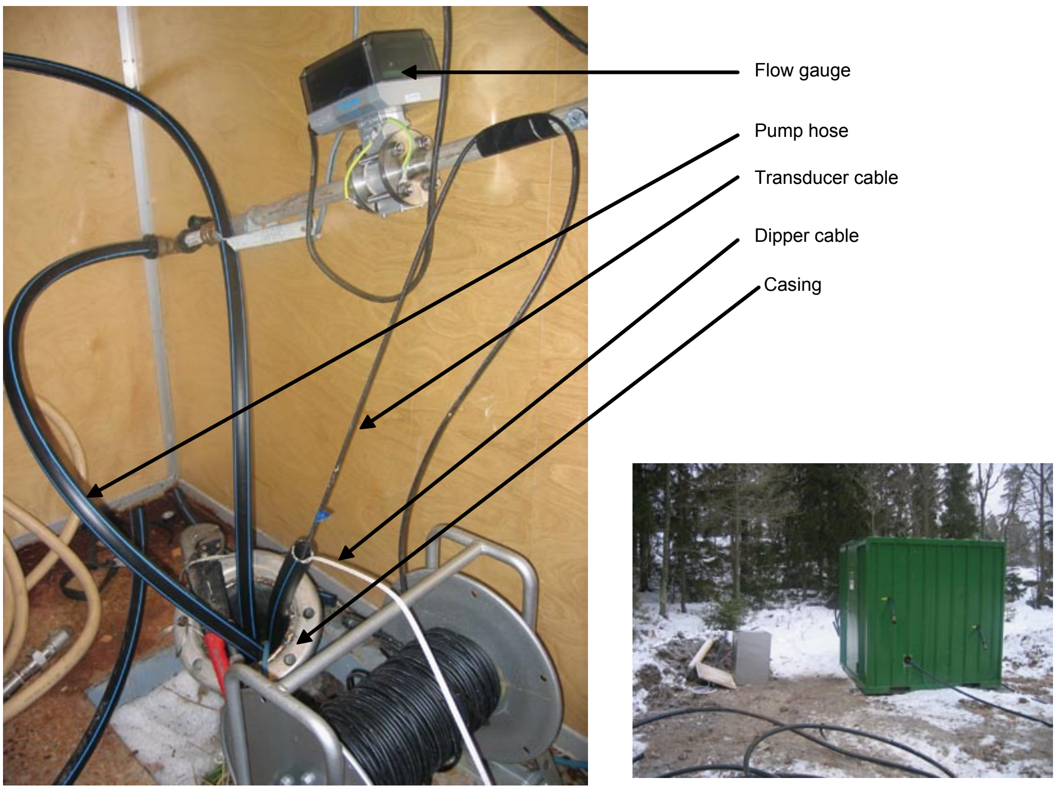

Figure 4-1. *Container housing the testing equipment (right) and instrumentation inside (left) in borehole HLX33.*

4.2 Tracer test

In the injection boreholes for the tracer dilution tests and the tracer test, identical equipment set-ups were used, allowing two sections to be measured simultaneously. A schematic drawing of the tracer test equipment used in the injection boreholes is shown in Figure 4-2. The basic idea is to have an internal circulation in the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to retrieve samples of the tracer concentration from the borehole section by means of a sampler outside the borehole and thus be able to monitor the dilution of the tracer with regard to time.

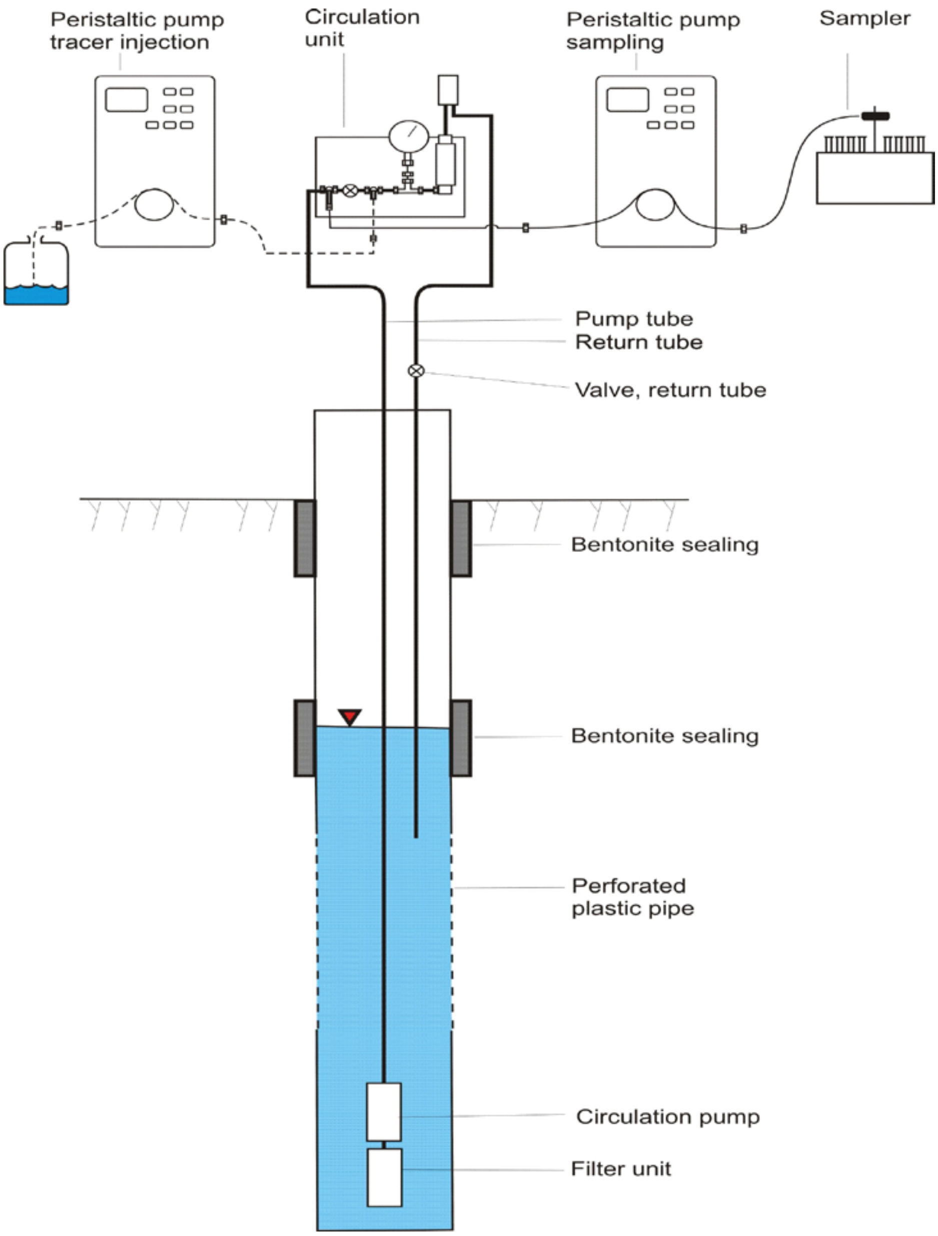

Figure 4-2. *Schematic drawing of the equipment used in tracer dilution measurements (not identical to the actual set-up).*

Circulation is controlled by a down-hole pump with variable speed and measured by a flow meter. Tracer injections are made using 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.

In the withdrawal borehole, another type of equipment was used for sampling. Samples from the outgoing pumped water were taken by an automatic programmable 24-valve sampler, producing discrete 1 litre samples, see Figure 4-3. In the original plan, a tube sampler was supposed to be used for manual sampling at different depths in the borehole. However, since only one large anomaly in the pumping borehole had been identified this part of the sampling process was omitted in agreement with the activity leader.

The tracer used in both the dilution tests and the tracer test, was a fluorescent dye tracer, Uranine (Sodium Fluorescein) from Merck (purum quality). Since only one of the injected boreholes was included in the tracer test, only one type of tracer had to be used.

Figure 4-3. *The automatic programmable sampler; magnetic valves (left) and control unit (right) (previous version to the one used in the test).*

5 Execution

5.1 Interference test

5.1.1 Preparations

The pumping test equipment was calibrated according to 3.1.1 and data loggers were set to log data every 10 seconds.

5.1.2 Procedure

Pumping from HLX33 was kept constant at 98 L/min during the test and pressure interference was recorded in soil wells SSM000228 and SSM000229 using the HMS (Hydro Monitoring System). The borehole and soil wells connected to the HMS are fitted with stationary equipment for measuring pressure in the different test sections.

Pumped water from HLX33 was discharged about 400 m downstream.

The water level of the stream Ekereumsån was also monitored 300 m downstream of HLX33.

5.1.3 Data handling

For the observation sections, quality controlled data from HMS were collected from the SKB database Sicada. The pressure and flow data from the pumping borehole were collected from HMS.

5.1.4 Transient analysis and interpretation

General

When possible, both qualitative and quantitative analyses have been carried out in accordance with the methodology descriptions for interference tests, SKB MD 330.003. Standard methods for constant-flow rate tests in an equivalent porous medium were used by the transient analyses and interpretation of the test.

Transient evaluation of all responding observation sections was performed, both for the flow and recovery period, respectively. All responding observation sections are also included in the response analysis. In the transient evaluation of the responses in the pumping borehole and selected observation sections the models described in /4/, /5/ and /6/ respectively was used. The responses in the pumping boreholes were evaluated as single-hole pumping tests according to the methods described in /7/.

In the primary qualitative analyses, data from the observation sections included in the interference test were studied in linear time versus pressure diagrams to deduce the responding sections. Linear diagrams of pressure versus time are presented in Chapter 6 for the boreholes included in the interference test.

The qualitative evaluation of the dominating transient flow regimes (pseudo-linear, pseudo-radial and pseudo-spherical flow, respectively) and possible outer boundary conditions was mainly based on the drawdown and recovery responses in logarithmic diagrams. In particular, pseudo-radial flow is reflected by a constant (horizontal) derivative in the diagrams, whereas no-flow- and constant head boundaries are characterized by a rapid increase and decrease of the derivative, respectively. Based on the qualitative evaluation relevant models were selected for the quantitative transient evaluation.

In the drawdown and recovery diagrams different values of the filter coefficient (step length) by the calculation of the pressure derivative were applied to investigate the effect on the pressure derivative. It is desired to achieve maximum smoothing of the derivative without altering the original shape of the test data.

The quantitative transient analysis was performed by the test analysis software AQTESOLV that enables both visual and automatic type curve matching. The transient evaluation was carried out as an iterative process of type curve matching and automatic non-linear regression. The transient interpretation of the hydraulic test parameters is in most cases based on the identified pseudo-radial flow regime appearing during the tests and plotted in log-log and lin-log data diagrams.

Hydraulic parameters

For the single-hole pumping tests the storativity was calculated using, Equation (5-1) from /8/. Firstly, the transmissivity and skin factor were obtained by type curve matching using a fixed storativity value of 10^{-6}. The storativity was then re-calculated from an empirical regression relationship between storativity and transmissivity according to Equation (5-1). The type curve matching was then repeated. In most cases the change of storativity does not significantly alter the transmissivity value in the new type curve matching, but only the estimated skin factor is altered correspondingly.

$$S = 0.0007 \cdot T^{0.5} \qquad (5\text{-}1)$$

S = storativity (–)
T = transmissivity (m^2/s)

In addition to the transient analysis, an interpretation based on the assumption of stationary conditions in the pumping boreholes was performed as described in /7/.

The wellbore storage coefficient (C) in the pumping borehole section can be obtained from the parameter estimation of a fictive casing radius, *r(c)* in an equivalent open test system according to Equation, (5-2).

$$C = \frac{\pi \cdot r(c)^2}{\rho \cdot g} \qquad (5\text{-}2)$$

The radius of influence at a certain time during the test may be estimated from Jacob's approximation of the Theis' well function according to Equation (5-3):

$$r_i = \sqrt{\frac{2.25 \cdot T \cdot t}{S}} \qquad (5\text{-}3)$$

T = representative transmissivity from the test (m^2/s)
S = storativity estimated from Equation 5-1
r_i = radius of influence at time t (m)
t = time after start of pumping (s)

Furthermore, a r_i-index (–1, 0 or 1) is defined to characterize the hydraulic conditions by the end of the test. The r_i-index is defined as shown below. It is assumed that a certain time interval of PRF can be identified between t_1 and t_2 during the test.

- r_i-index = 0: The transient response indicates that the size of the hydraulic feature tested is greater than the radius of influence based on the actual test time ($t_2 = t_p$), i.e. the PRF is continuing at stop of the test. This fact is reflected by a flat derivative at this time.
- r_i-index = 1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with lower transmissivity or an apparent barrier boundary (NFB). This fact is reflected by an increase of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2.
- r_i-index = –1: The transient response indicates that the hydraulic feature tested is connected to a hydraulic feature with higher transmissivity or an apparent constant head boundary (CHB). This fact is reflected by a decrease of the derivative. The size of the hydraulic feature tested is estimated as the radius of influence based on t_2.

If a certain time interval of PRF cannot be identified during the test, the r_i-indices –1 and 1 are defined as above. In such cases the radius of influence is estimated using the flow time t_p in Equation 5-3.

5.1.5 Response analysis and estimation of the hydraulic diffusivity

Response analysis

In responding observation sections the response time (dt_L) and the maximum drawdown (s_p) were calculated. The response time is generally defined as the time lag after start of pumping until a drawdown response of 0.1 m was observed in the actual observation section. The maximum drawdown does not always occur at stop of pumping, e.g. due to heavy precipitation by the end of the flow period. In such cases the transient analysis is based on the response prior to the precipitation.

The 3D distances between the point of application in the pumping borehole and all the observation borehole sections (r_s) were calculated. These parameters combined with the pumping flow rate (Q_p) are the variables used to calculate the response indices, which characterize the hydraulic connectivity between the pumping and the observed section. The parameters and the calculated hydraulic connectivity parameters are shown in the tables in Chapter 6. The response indices are calculated as follows:

Index 1:

$\mathbf{r_s^2/dt_L}$ = normalised distance r_s with respect to the response time (dp = 0.1 m) [m²/s]

Index 2:

$\mathbf{s_p/Q_p}$ = normalised drawdown s_p with respect to the pumping rate [s/m²]

Additionally, a third index was calculated including drawdown and distance. This index is calculated as follows:

Index 2 new:

$\mathbf{(s_p/Q_p) \cdot \ln(r_s/r_0)}$ As index 2 and assuming $r_0 = 1$. For the pumped borehole $r_s = e^1$ (i.e. a fictive borehole radius of 2.718.)

The classification based on the indices is given as follows:

Index 1 (r_s^2/dt_L)

		Colour code
$r_s^2/dt_L > 100$ m²/s	Excellent	
$10 < r_s^2/dt_L \leq 100$ m²/s	High	
$1 < r_s^2/dt_L \leq 10$ m²/s	Medium	
$r_s^2/dt_L \leq 1$ m²/s	Low	

Index 2 (s_p/Q_p)

		Colour code
$s_p/Q_p > 1 \cdot 10^5$ s/m²	Excellent	
$3 \cdot 10^4 < s_p/Q_p \leq 1 \cdot 10^5$ s/m²	High	
$1 \cdot 10^4 < s_p/Q_p \leq 3 \cdot 10^4$ s/m²	Medium	
$s_p/Q_p \leq 1 \cdot 10^4$ s/m²	Low	
$s_p < 0.1$ m	No response	

Index 2 new (s_p/Q_p) · ln(r_s/r_0)

		Colour code
$(s_p/Q_p) \cdot \ln(r_s/r_0) > 5 \cdot 10^5$ s/m²	Excellent	
$5 \cdot 10^4 < (s_p/Q_p) \cdot \ln(r_s/r_0) \leq 5 \cdot 10^5$ s/m²	High	
$5 \cdot 10^3 < (s_p/Q_p) \cdot \ln(r_s/r_0) \leq 5 \cdot 10^4$ s/m²	Medium	
$(s_p/Q_p) \cdot \ln(r_s/r_0) \leq 5 \cdot 10^3$ s/m²	Low	
$s_p < 0.1$ m	No response	

In some cases it is not clear if the section responds to the pumping or if the drawdown is based on natural processes solely. In uncertain cases, the data sets were regarded all together to better differentiate between these effects. By looking at the pressure responses before and after the pumping period, it may be possible to distinguish between natural fluctuations and those induced by pumping.

All observation data are influenced by natural fluctuations of the groundwater level such as tidal effects, long term trends together with precipitation. The pressure changes due to tidal effects are different for the observation boreholes.

Estimation of hydraulic diffusivity

The distances, r_s, between different borehole sections have been calculated as the spherical distance using the co-ordinates for the points of application presented in Table 3-4. The calculation of the hydraulic diffusivity is based on radial flow according to /9/.

$$T / S = r_s^2 / [4 \cdot dt_L \cdot (1 + dt_L / tp) \cdot \ln(1 + tp / dt_L)] \qquad (5\text{-}4)$$

The time lag dt_L is here defined as the time when the pressure response in an observation section is 0.01 m. The pumping time is included as tp. The estimates of the hydraulic diffusivity according to above should be seen as approximate values.

5.2 Tracer and dilution tests

5.2.1 General

In order to measure the groundwater flow and transport properties of the aquifer, tracer injections were made in soil wells nearby the pumping borehole HLX33. Initially, before the pumping started, tracer dilution tests were performed in the two soil wells SSM000228 and SSM000229 for measurement of the undisturbed groundwater flow. After sufficient amount of data were retrieved from the undisturbed dilution tests, tracer was injected once again in the two soil wells but this time while pumping in HLX33. Analysis of the dilution tests performed under natural and induced ground water flow respectively showed that pumping in HLX33 affected the groundwater flow in both soil wells. A stronger tracer solution was injected in that pipe and the pumping borehole HLX33 was continuously sampled for tracer breakthrough.

5.2.2 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.

5.2.3 Procedure

Tracer dilution tests

The dilution tests were made by injecting a slug of tracer in the wells and allowing the natural groundwater flow to dilute the injected tracer. Soil wells SSM000228 and SSM000229 were injected approximately one hour apart. The tracer solution was continuously circulated and sampled using the equipment described above. Due to a rather rapid dilution in SSM000229, an extra injection, using a slightly stronger tracer solution was performed approximately three hours after the first injection. After eight days, new injections in both soil pipes were performed to measure the dilution under pumped conditions. The new injections were necessary due to the fast dilution in the soil wells under natural conditions.

Tracer test

Soil well SSM000228 was chosen for tracer injection for the tracer test since the dilution tests showed that the groundwater flow in SSM000228 was significantly affected by pumping in HLX33. In this case the borehole tracer was injected by an "exchange" procedure, i.e. water was also withdrawn from the section during the tracer injection. The same volume of water was withdrawn as was added by the injection. The tracer injection was performed as a decaying pulse injection, i.e. injection of a tracer pulse in a circulating system without excess pressure. A simple and reasonable assumption is that the amount of tracer that leaves the injection section (and into the transport path) is proportional to the tracer concentration in the injection section. Samples were continuously withdrawn from the injection section to monitor the tracer injection, or rather the tracer concentration in the injection borehole, versus time.

Pumping was performed in HLX33 with a mean flow rate of approximately 97 L/min and samples were taken and analysed for tracer breakthrough in this borehole.

The samples were analysed for dye tracer content at the Geosigma Laboratory using a Jasco FP 777 Spectrofluorometer or alternatively at the "Baslab"-laboratory at Clab, using a Turner Biosystems TD-700 fluorometer.

5.2.4 Analyses and interpretations

Tracer dilution tests

Flow rates were calculated from the decay of tracer concentration versus time through dilution with natural unlabelled groundwater, c.f. /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/c0) and time, t (s):

$$\ln (c/c_0) = -(Q_{bh}/V) \cdot \Delta t \qquad (5\text{-}5)$$

In Equation 5-5, 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/c0) versus t, knowing the borehole volume V, Q_{bh} may be obtained from the straight-line slope. If c0 is constant, it is sufficient to use ln c in the plot.

The sampling procedure with a constant flow of 4–6 mL/h also creates a dilution of the tracer. The sampling flow rate is therefore subtracted from the value obtained from Equation 5-5.

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 practise, 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, q_w (m/s), and the measured flow through the borehole section, Q_{bh}, can be expressed as:

$$Q_{bh} = q_w \cdot L_{bh} \cdot 2r_{bh} \cdot \alpha \qquad (5\text{-}6)$$

In Equation 5-6, 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.

The factor α is commonly given the value 2 in the calculations, which is the theoretical value for a homogeneous porous media.

Tracer test

Tracer mass recovery was calculated for the flow path SSM000228 → HLX33. Before the injection a sample of the stock solution was taken and the tracer concentration of the sample was measured. The injected volume together with the tracer concentration of the stock solution was used to determine the injected mass. The tracer mass recovered in the pumping borehole section was determined by integration of the breakthrough curves for mass flux (mg/h) versus time (h).

The evaluation of the tracer test has also involved computer modelling using a simple one-dimensional advection-dispersion model /11/. From the computer modelling, dispersivity and mean travel times were determined using an automated parameter estimation program, PAREST /12/. PAREST uses a non-linear least square regression where regression statistics (correlation, standard errors and correlation between parameters) also is obtained.

The chosen one-dimensional model assumes a constant fluid velocity and negligible transverse dispersion, cf. Equation 5-7.

$$\partial C/\partial t = D(\partial^2 C/\partial x^2) - v \cdot \partial C/\partial x \qquad (5\text{-}7)$$

where: D = Dispersion coefficient
v = fluid velocity (m/s)
C = concentration of solute
x = distance from injection point (m)
t = time (s)

According to /13/, the dispersion in a radially converging flow field can be calculated with good approximation by equations valid for one-dimensional flow. Although a linear flow model (constant velocity) is used for a converging flow field, it can be demonstrated that breakthrough curves and parameter estimates are similar for Peclet numbers (= distance/dispersivity) of about 10 and higher.

/14/ gives a solution for step input with dispersion over the injection boundary. The solution of Equation 5-7 then is:

$$C/C_o = \tfrac{1}{2}\,\mathrm{erfc}\,[(x-v\cdot t)\,/\,Z] + (V/\pi)^{1/2}\exp\,[(x-v\cdot t)^2\,/\,(4D\cdot t)] - \tfrac{1}{2}\,[1+v\cdot x/D+V]\exp\,[v\cdot x/D]\,\mathrm{erfc}[(x+v\cdot t)\,/\,Z] \qquad (5\text{-}8)$$

where: $Z = 2(D\cdot t)^{1/2}$

$V = v^2 t/D$

Variable injection schemes were simulated by superposition of the solution given in Equation 5-8.

The fit of the breakthrough curves using a three-parameter fit included velocity, v, dispersion coefficient, D, and the so called F-factor which corresponds to injected mass divided by fracture volume, M_{inj}/V_f.

6 Results

6.1 General comments and assumptions

It is assumed that the flow rate is constant from one data point of flow rate to the next. It is also assumed that the start and stop of pumping is defined as the time of the first and last flow value, respectively in the flow rate data file. The drawdown data files in the observation sections are terminated at stop of pumping although the drawdown might continue.

All pressure data for the observation sections presented in this report have been corrected for atmospheric pressure changes by subtraction from the measured (absolute) pressure. The pressure in some of the sections included in the interference test was displaying an oscillating behaviour. This is naturally caused by so called tidal fluctuations or earth tides in combination with changes of the sea water level. These phenomena have, to some extent, been investigated previously in /15/. Further corrections of the measured drawdown have been made, e.g. due to the superimposed natural trend, see Appendix 3. In this case observed oscillating behaviour did not complicate the interpretation of responses in the observation sections.

The transient evaluation of the test was analysed as variable flow rate tests. The nomenclature and symbols used for the results of the single-hole and interference test are according to the *Instruction for analysis of single-hole injection- and pumping tests* (SKB MD 320.004) and the methodology description for interference tests (SKB MD 330.003), respectively (both are SKB internal controlling documents). Additional symbols used are explained in the text.

Linear plots of pressure versus time for the pumping and observation sections are presented in Figures 6-1 through 6-4. Transient evaluation of the drawdown and recovery period is shown in log-log and lin-log diagrams in Appendix 2. The results are also summarized in Table 6-10. The locations of all boreholes are shown in Figure 1-1. Abbreviations of flow regimes and hydraulic boundaries that may appear in the text are listed below.

WBS = Wellbore storage

PRF = Pseudo-radial Flow regime

PLF = Pseudo-linear flow regime

PSF = Pseudo-spherical flow regime

PSS = Pseudo-stationary flow regime

NFB = No-flow boundary

CHB = Constant –head boundary

6.2 Interference test in HLX33

6.2.1 Pumping borehole HLX33

General test data for the pumping test in HLX33 are presented in Table 6-1. The borehole is cased to 9.0 m. The uncased interval of the borehole is thus 9.0–202.1 m.

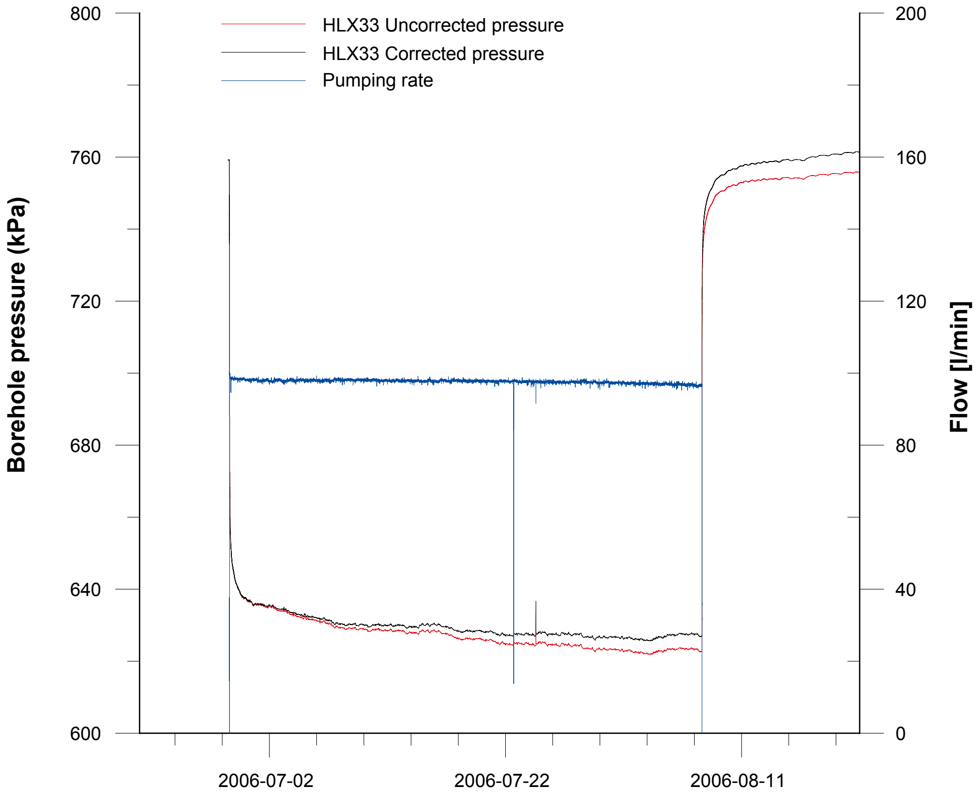

Figure 6-1. *Linear plot of flow rate and uncorrected (red) and corrected pressure (black) versus time in the pumping borehole HLX33.*

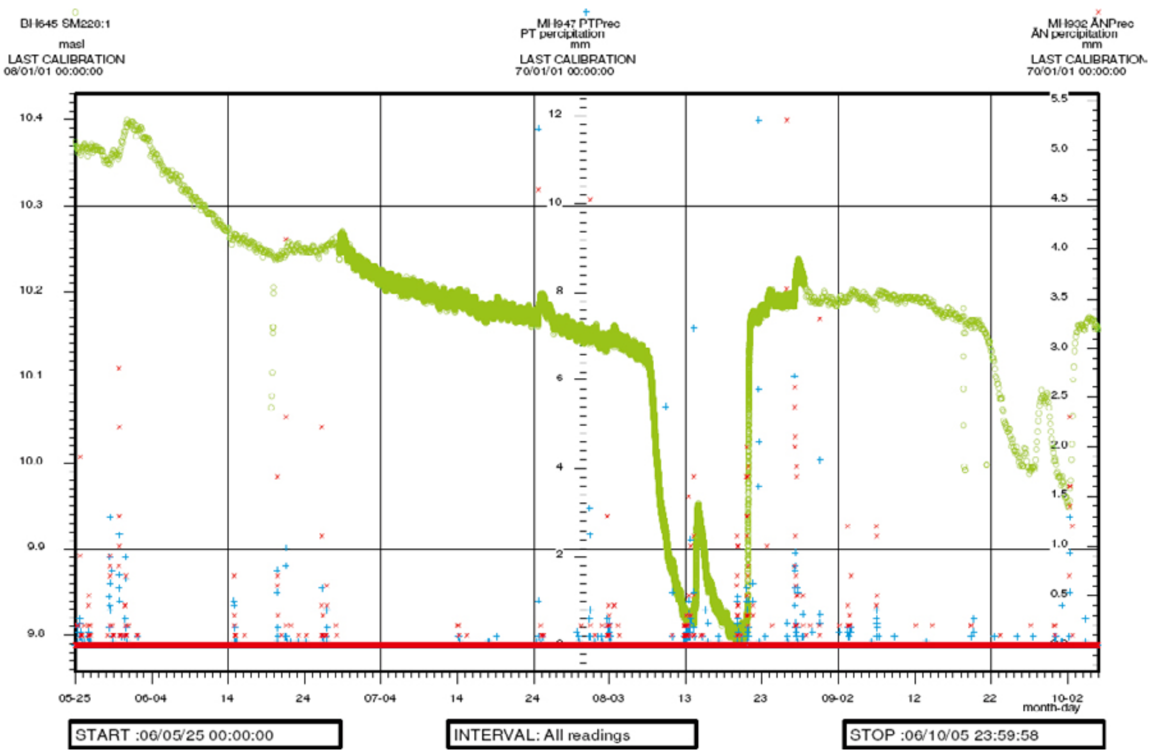

Figure 6-2. *Linear plot of ground water level (green) in the observation soil well SSM000228 together with precipitation at northern part of Äspö island (red) and Plittorp (blue) during the interference test in borehole HLX33.*

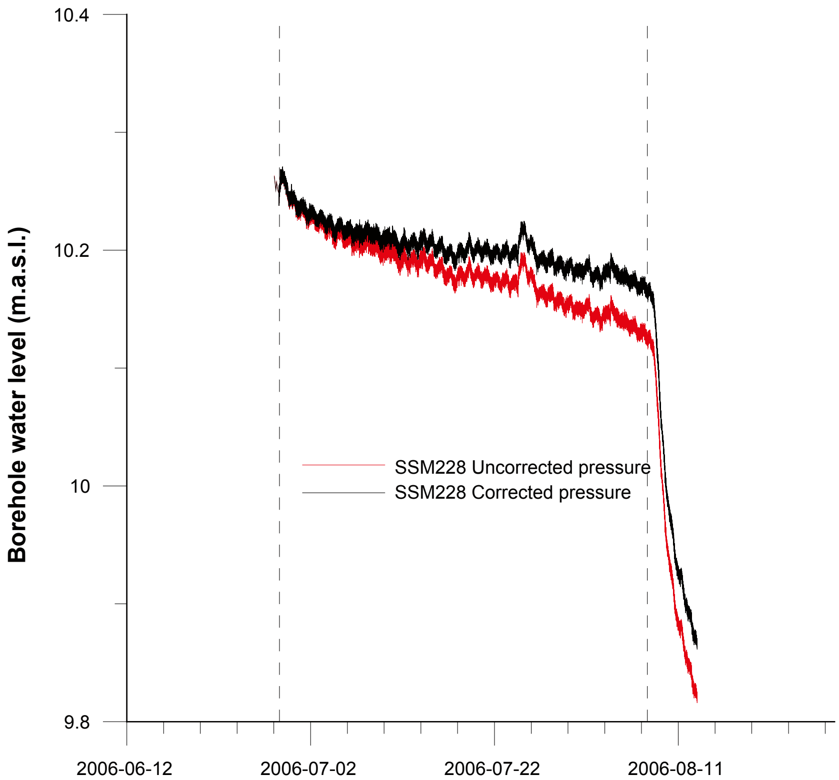

Figure 6-3. *Linear plot of uncorrected (red) and corrected pressure (black) versus time in the observation well SSM000228.*

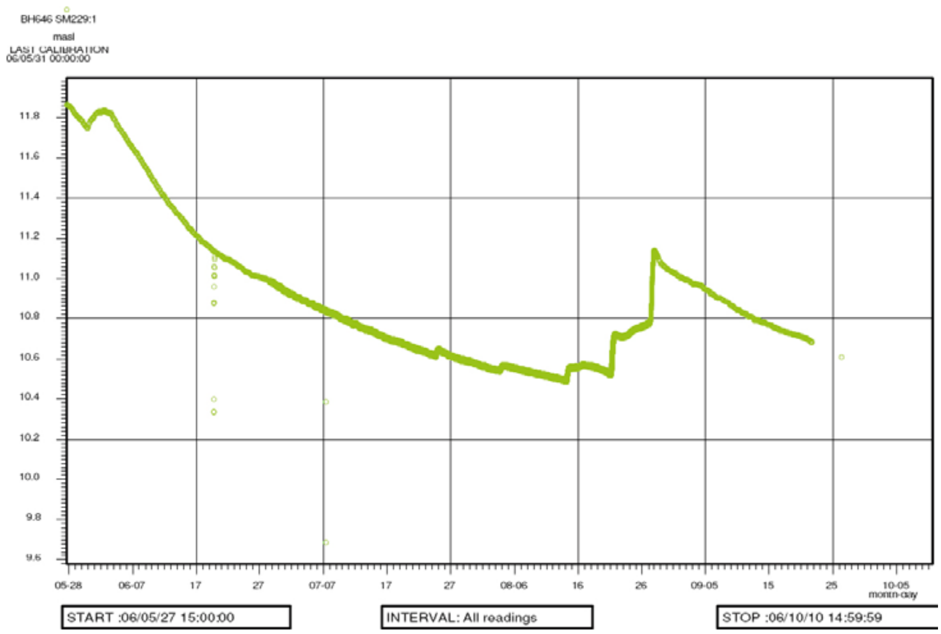

Figure 6-4. *Linear plot of ground water level in the observation soil well SSM000229 during the interference test in borehole HLX33.*

Table 6-1. General test data for the pumping test in HLX33: 9.0–202.1 m.

General test data			
Pumping borehole	HLX33		
Test type[1]	Constant Rate withdrawal and recovery test		
Test section (open borehole/packed-off section):	open borehole		
Test No	1		
Field crew	SKB		
Test equipment system			
General comment	Interference test		
	Nomenclature	**Unit**	**Value**
Borehole length	L	m	193.1
Casing length	L_c	m	9.0
Test section- secup	Secup	m	9.0
Test section- seclow	Seclow	m	202.1
Test section length	L_w	m	201.1
Test section diameter[2]	$2 \cdot r_w$	mm	139
Test start (start of flow period)		yymmdd hh:mm:ss	060628 14:34
Packer expanded		yymmdd hh:mm:ss	
Start of flow period		yymmdd hh:mm:ss	060628 14:34:36
Stop of flow period		yymmdd hh:mm:ss	060807 15:09:10
Test stop (stop of flow period)		yymmdd hh:mm	060807 15:09
Total flow time	t_p	min	57,642
Total recovery time	t_F	min	12,041

Pressure data			
Relative pressure in test section before start of flow period	p_i	m	77.4
Relative pressure in test section before stop of flow period	p_p	m	63.9
Relative pressure in test section at stop of recovery period	p_F	m	76.8
Pressure change during flow period ($p_i - p_p$)	dp_p	m	13.5
Flow data			
Flow rate from test section just before stop of flow period [3]	Q_p	m^3/s	0.00161
Mean (arithmetic) flow rate during flow period	Q_m	m^3/s	0.00163
Total volume discharged during flow period	V_p	m^3	5,630

[1] Constant Head injection and recovery, Constant Rate withdrawal and recovery or Constant Drawdown and recovery.

[2] Nominal diameter.

[3] The flow meter was out of order for the last days and the number given is an estimation of the actual flow.

Comments on the test

The test was performed as a constant rate pumping test. The mean flow rate was 97.8 L/min and the duration of the flow period was c. 9 days. A total drawdown during the flow period of 13.5 m and a total recovery at the end of the recovery period of 12.9 m was observed (cf. Figure 6-1).

Flow regime and calculated parameters

The measured data are corrected for the naturally decreasing pressure trend during the test period before the analysis, see Appendix 3 for correction procedure. The recovery period was truncated due to influence of precipitation by the end. After initial WBS, both the flow and recovery period are dominated by slightly pseudo-spherical (leaky) flow. The test was analyzed as a variable flow rate test.

Selected representative parameters

Evaluation was performed by applying the Moench' (Case 1) /6/ model for a leaky aquifer. Consistent results of evaluated hydraulic parameter values are obtained from the flow and recovery period respectively. The parameter values estimated from the flow period are selected as the most representative for the test. The selected representative transmissivity is $1.5 \cdot 10^{-4}$ m^2/s for an assumed storativity of $4.7 \cdot 10^{-4}$.

6.2.2 Observation soil well SSM000228

In Figure 6-2 an overview of the pressure response in observation soil well SSM000228 and precipitation data from northern part of Äspö Island and Plittorp, situated approximately 10 km east of Äspö island is shown. The screened interval of this monitoring soil well is 6.0–7.0 m. General test data from the observation section SSM000228: 6.0–7.0 m, are presented in Table 6-2.

Comments on the test

The water level variations in SSM000228 are strongly influenced by the natural, decreasing head trend and precipitation, see Figure 6-2. Furthermore, after the end of pumping in HLX33 a rapid decrease in hydraulic head occurred in SSM000228. The observed response is primarily not caused by the pumping but by the pumped borehole water being discharged in the stream as explained in Section 6.2.4.

Hence, due to the strong influences of external effects to observed hydraulic head in SSM000228 and the complicated correlation between the different effects in time and space as explained in 6.2.4, no transient evaluation is presented.

6.2.3 Observation soil well SSM000229

The water level variations in SSM000229 are assumed to be due to the natural, decreasing head trend in combination with precipitation and seem to be virtually unaffected, or very little affected, by the pumping in HLX33, Figure 6-4. The same trend can also be seen in other boreholes, unaffected by the pumping in HLX33 c.f. Figure 6-5. This is also indicated by the dilution test. Thus, no transient analysis was made in this soil well.

6.2.4 Water level in the stream Ekerumsån

The water level of the stream Ekerumsån was monitored during the test with the purpose to establish if any hydraulic contact could be detected between the rock aquifer and the stream.

In addition to the permanent gauging station in the stream PSM000365 which is located about 1,800 m downstream of HLX33, a temporary pressure gauge was installed 174 m downstream of HLX33. The gauge was fitted at 2.04 m length in a temporary PEM-hose, PSM000274 . The pumped water from HLX33, (98 L/min) was discharged in Ekerumsån about 125 m downstream of PSM000274. The two gauges show similar behaviour.

Table 6-2. General test data from the observation section SSM000228: 6.0–7.0 m during the interference test in HLX33.

Pressure data	Nomenclature	Unit	Value
Hydraulic head in test section before start of flow period	h_i	m.a.s.l.	10.25
Corrected hydraulic head in test section before stop of flow period	h_p	m.a.s.l.	10.17
Hydraulic head in test section at stop of recovery period	h_F	m.a.s.l.	–
Corrected hydraulic head change during flow period (h_i – h_p)	dh_p	m	0.08

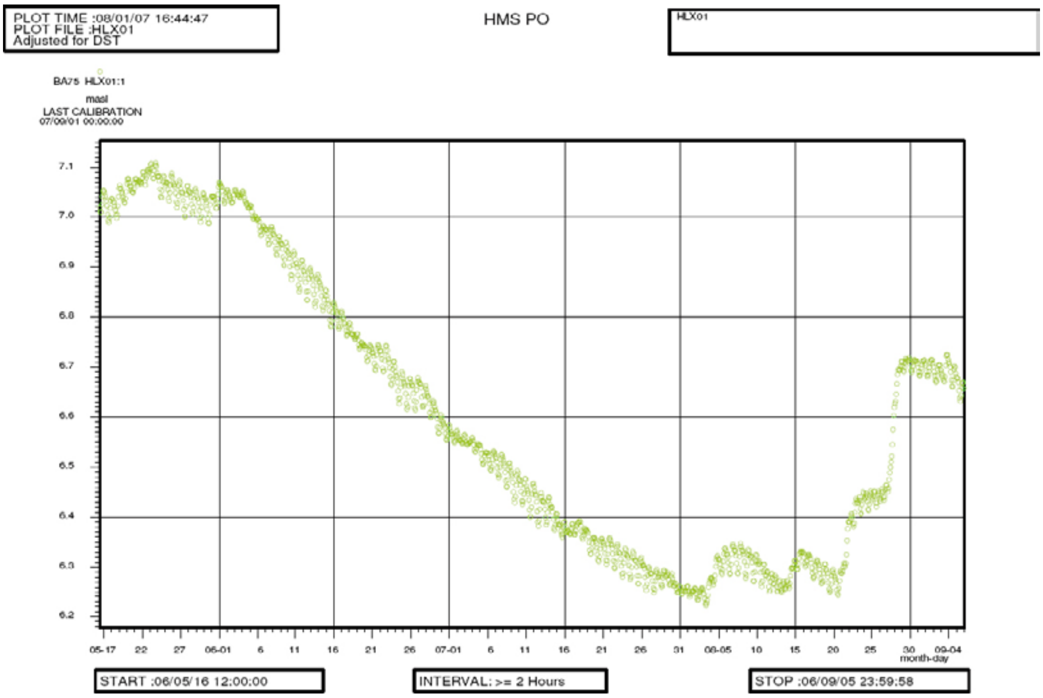

Figure 6-5. Linear plot of ground water level in the borehole HLX01:1 during the interference test in borehole HLX33. HLX01 is situated about 1.5 km north-east of the pumped HLX33.

From the monitored data it is evident that the stream level increase by 0.03 m at pump start over a period of about two hours and decreases by about 0.09 m at pump stop over a period of about one day, see Figure 6-6. At the same time it is also seen that at the water level in SSM000228 responds in a similar way with an increased water level at pump start of 0.02 m and decrease by about 0.3 m at pump stop, Figure 6-7.

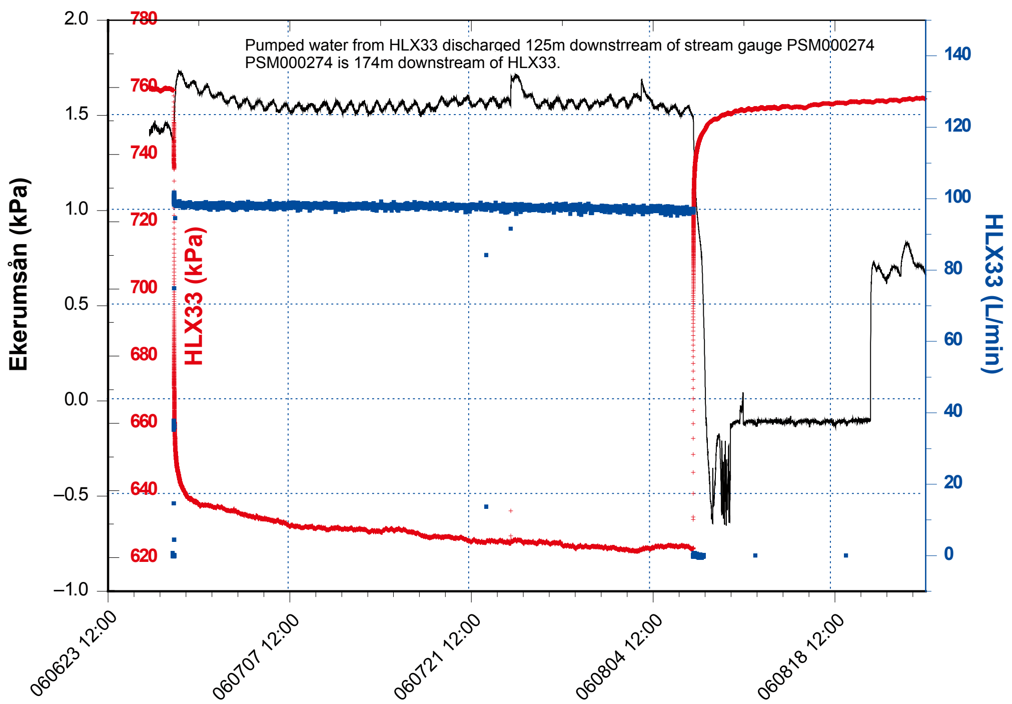

Figure 6-6. Water level in the Ekerumsån at PSM000274 and HLX33 data.

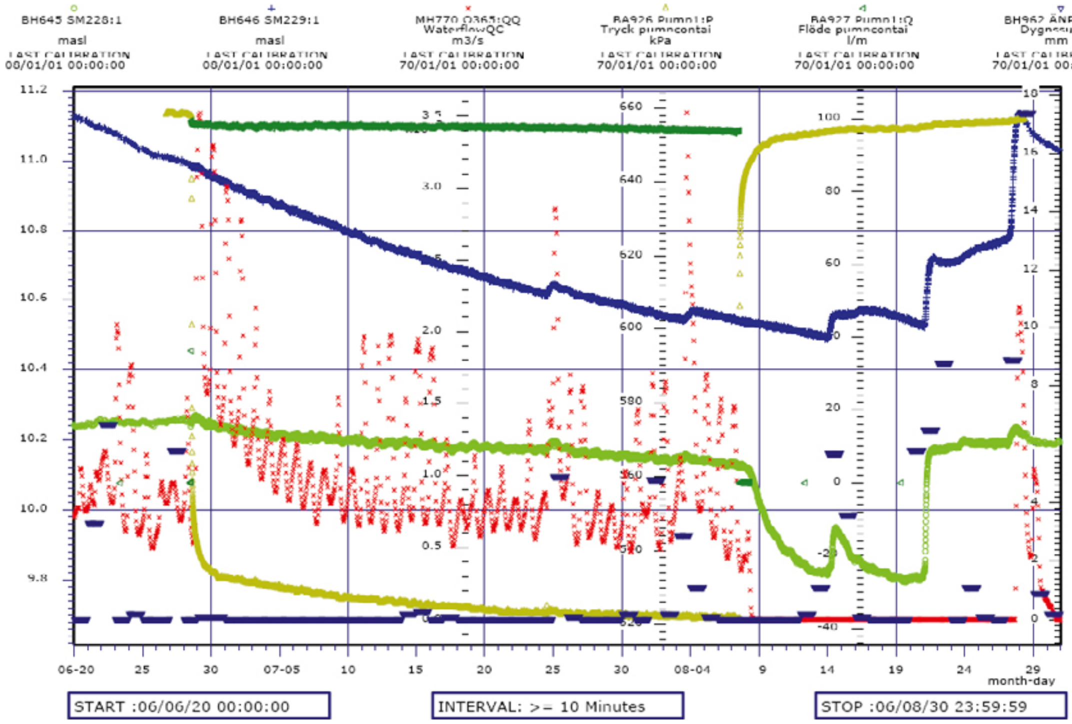

Figure 6-7. *Monitored data during the tests from HLX33, SSM000228, SSM000229, precipitation and stream flow of Ekerumsån at the gauging station PSM000365.*

The reason for this behaviour is believed to be caused by

a) the pumped water discharged into the stream and
b) generally decreasing water levels in the area.

The flow rate in the stream prior to the test start (i.e. start of pump in HLX33) was about 60 L/min to be compared to the 98 L/min discharged in the stream from HLX33. This contribution of water from the aquifer maintains a higher water level in the stream and SSM000228 during the test which would otherwise have shown a similar decreasing trend as the area at large. When the pumping is stopped the water level in the stream equilibrates with the natural level which is a virtually a dry stream. This is also applicable for SSM000228 which apparently is in direct contact with the stream due to its close proximity (c. 5 m). The relatively sudden rises in water levels seen are all well correlated to precipitation events and hence groundwater recharge events.

6.2.5 Estimation of the hydraulic diffusivity

The hydraulic diffusivity of observation sections can be estimated from the observed response time lag in the sections according to Section 5.1.5. The time lag dt_L is here based on a draw-down s = 0.01 m in the observation section. The estimated time lag based on the drawdown in the observation section is shown in Table 6-3, no responses were however observed and no diffusivity calculated.

Table 6-3. Estimated response lag times and hydraulic diffusivity for the selected observation section from the interference test.

Pumping borehole	Observation soil well	Section (m)	measured $dt_{L[s=0.01\ m]}$ (s)	r_s (m)	T/S (m^2/s)
HLX33	SSM000228	6.0–7.0	No response	200.6	–
HLX33	SSM000229	3.0–4.0	No response	158.7	–

6.3 Dilution measurements

As mentioned above, tracer dilution measurements were performed in boreholes SSM000228 and SSM000229, both before (natural conditions) and during pumping (stressed conditions) in HLX33. The results are presented in Table 6-4 and in the dilution graphs in Figure 6-6.

Notable is that the hydraulic gradient seems to be reversed, or partly reversed, in both soil wells when pumping started in HLX33, i.e. the natural flow was directed away from HLX33. In both SSM000228 and SSM000229 the flow was decreased during the pumping period, which would indicate a change in gradient/flow direction. However, the change in flow rate in SSM000229 during natural and pumped conditions was relatively small. New injections of tracer were performed in both soil pipes prior to start of pumping in order to get well detectable tracer concentrations in the soil pipes. Therefore the graphs in Figure 6-8 do not show the actual change of slope.

6.4 Tracer test

Tracer injection was performed in borehole SSM000228. In Table 6-5 tracer injection data are presented.

HLX33 was pumped with a withdrawal rate of 98 L/min and the discharged water was continuously sampled for tracer breakthrough.

Tracer breakthrough in HLX33 was detected from the injection of Uranine in borehole SSM000228, see Figure 6-9. Unfortunately, a power failure stopped the automatic sampler from working after about 400 hours of sampling and breakthrough data are missing for approximately 200 hours. However, the peak of the breakthrough curve could still, just, be identified.

Manual water samples were also taken on a few occasions from a brook lying approximately 10 m to the north of SSM000228. Analysis shows that the Uranine concentrations in the samples correlate closely to the concentrations of Uranine in samples retrieved from the pumping borehole, HLX33, cf. Figure 6-9. This may possibly indicate that some part of the flow passing through SSM000228 end up in the brook. More likely, however, is that the discharged water from HLX33 flowed back upstream in the small brook which is connected to Ekerumsån. There was no flowing water in the brook at the time of the test, only standing water.

Tracer mass recovery for Uranine was 33% when sampling was stopped 760 hours after the injection.

The breakthrough curve was evaluated using the one-dimensional advection-dispersion model described in Section 5.2.4. The best-fit run is shown in Figure 6-10 (left). The somewhat edgy appearance of the model simulation is caused by the fact that about 200 hours of data is missing, as described above.

The parameters determined from the model run are presented in Table 6-6, where the mean velocity also is translated into a mean travel time, t_m. The regression statistics show quite low standard errors (2–6%). The parameters obtained were then used to simulate the breakthrough curve ahead, Figure 6-10 (right). After 2,400 hours the recovery would then be estimated at 49%.

Table 6-4. Results from the tracer dilution measurements.

Borehole	Volume (L)	Qnatural (mL/min)	Darcy velocity, natural (m/s)	Qstressed (mL/min)	Darcy velocity, stressed (m/s)
SSM000228	8.4	34	$1.3 \cdot 10^{-6}$	14	$5.4 \cdot 10^{-7}$
SSM000229	4.5	4.5	$4.9 \cdot 10^{-7}$	1.2	$1.3 \cdot 10^{-7}$

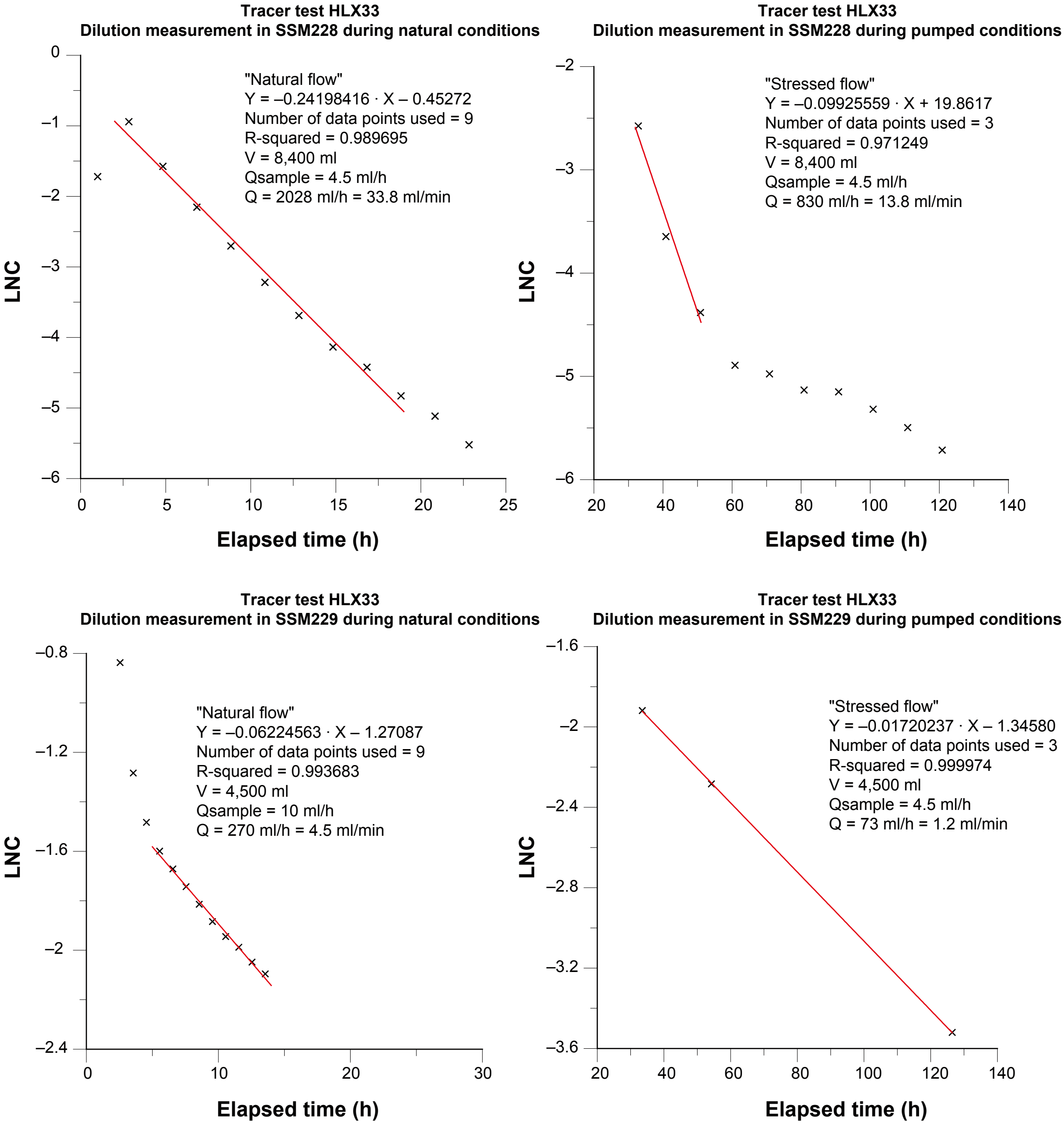

Figure 6-8. *Tracer dilution graphs (Logarithm of concentration versus time) for the measured soil wells SSM000228 and SSM000229 including straight-line fits. Note that the axis scales differ between the plots.*

Table 6-5. Tracer injection data (measured values).

Borehole	Section volume (L)	Injected volume (L)	Distance* to HLX33 (m)	Tracer used	Start conc., C0	Inj. mass (g)
SSM000228	8.4	8.0	204	Uranine	9,944	67

* Euclidian distance between the filter depth in the soil well and the estimated inflow point at 181 m borehole length in HLX33.

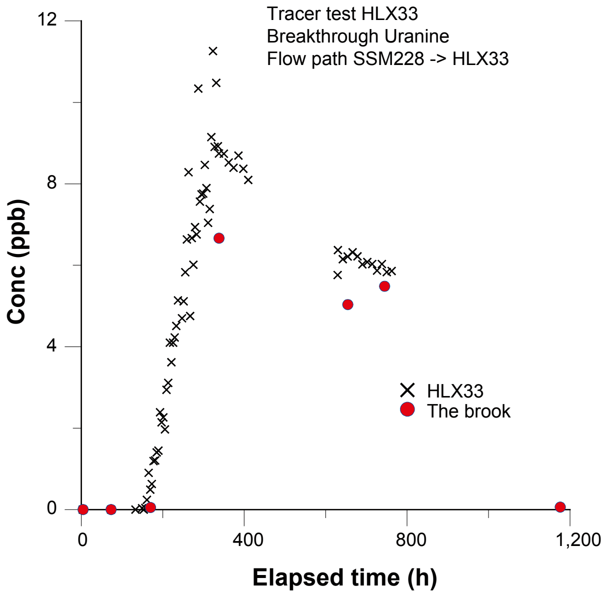

Figure 6-9. *Uranine concentrations in the discharged water from HLX33 and from the brook located just north of SSM000228.*

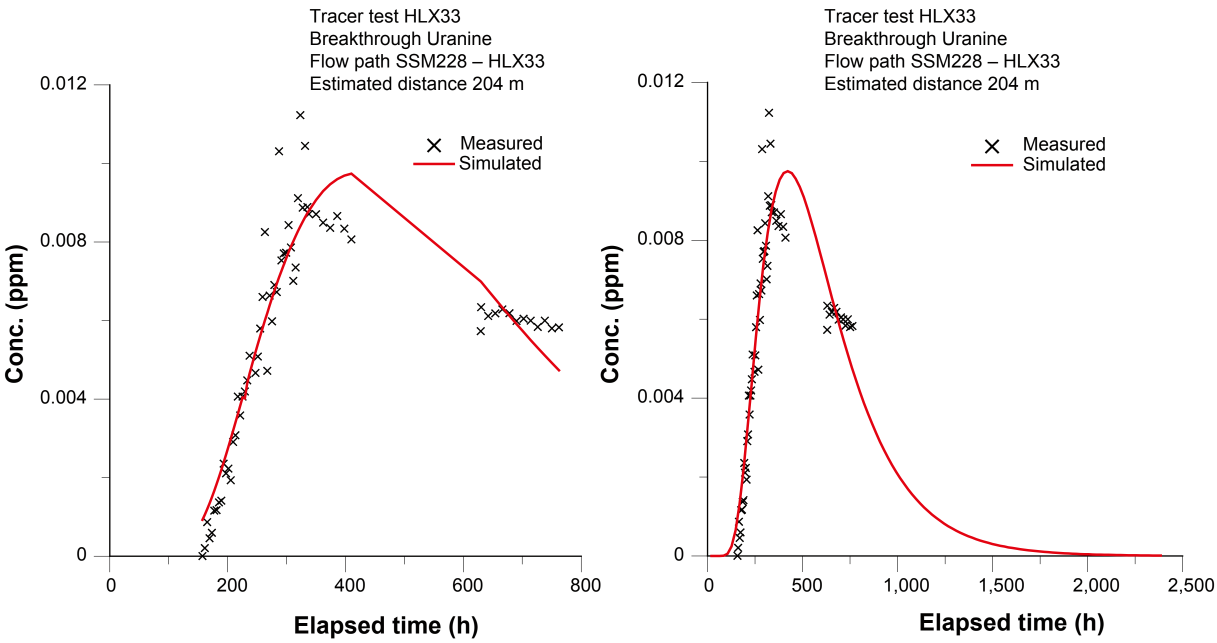

Figure 6-10. *Measured data and model simulations of tracer breakthrough (concentration versus time) in HLX33 from the injection of Uranine in SSM000228.*

Table 6-6. Evaluated parameters using PAREST (one-dimensional advection-dispersion model) for the flow path SSM000228 → HLX33. Values within brackets are standard errors in percent.

Injection borehole	Tracer	Distance	Mean velocity, v (m/s)	Mean travel time, tm (h)	Dispersivity, D/v (m)	F
SSM000228	Uranine	204[1/]	$1.07 \cdot 10^{-4}$ (2)	528	27 (6)	$2.04 \cdot 10^{-4}$ (4)

[1/] The Euclidian distance between the filter depth (5 m) in SSM000228 and the estimated inflow point at 181 m borehole length in HLX33.

6.5 Summary

6.5.1 Interference test

Compilations of measured test data from the interference test are shown in Table 6-7.
In Table 6-8 calculated hydraulic parameters for the pumping borehole are presented.

No unambiguous response to the pumping in HLX33 could be detected in SSM000228 or SSM000229. Observation well SSM000228 has a certain hydraulic connection to HLX33 but it is too disguised to be hydraulically evaluated. However, a vague pressure response is supported by the dilution tests and tracer test performed.

A transient analysis was made of the pumping borehole HLX33 after correction of the natural, decreasing trend of hydraulic head.

The normalized squared distance to the pumping borehole with respect to the time lag was calculated. This parameter is directly related to the hydraulic diffusivity (T/S) of the formation. In addition, the normalized drawdown with respect to the flow rate was calculated. From these parameters different response indices were calculated according to Section 5.1.5. The indexes for the observation sections included in the interference tests are presented in Table 6-9 but since no response was indicated, all indexes are 0.

Table 6-7. Summary of test data from the pumping borehole during the interference test in HLX33.

Pumping borehole ID	Section (m)	Test Type[1)]	h_i (m)	h_p (m)	h_F (m)	Q_p (m³/s)	Q_m (m³/s)	V_p (m³)
HLX33	9.00–133.20	1B	77.36	63.90	76.84	$1.61\cdot10^{-3}$	$1.63\cdot10^{-3}$	5,631.59

[1)] 1B: Pumping test-submersible pump, 2: Interference test (observation borehole during pumping in another borehole).

Table 6-8. Summary of calculated hydraulic parameters from the single-hole test in HLX33.

Pumping borehole ID	Section (m)	Test type[1)]	Q/s (m²/s)	T_M (m²/s)	T_T (m²/s)	ξ (–)	C (m³/Pa)	S* (–)
HLX33	9.00–202.10	1B	0.00012	$1.60\cdot10^{-4}$	$1.50\cdot10^{-4}$	–0.13	$2.30\cdot10^{-6}$	$4.70\cdot10^{-4}$

[1)] 1B: Pumping test-submersible pump, 2: Interference test (observation borehole during pumping in another borehole).

Table 6-9. Calculated normalized response time lags and normalized drawdown for the observation sections included in the interference tests.

Pumping borehole	Observation borehole	Section (m)	r_s^2/dt_L[s=0.1 m] (m²/s) Index 1	s_p/Q_p (s/m²) Index 2	$(s_p/Q_p)\cdot\ln(r_s/r_o)$ (s/m²) Index 2 new
HLX33	SSM000228	6.0–7.0	0	0	0
HLX33	SSM000229	3.0–4.0	0	0	0

Nomenclature used:

Q/s	=	specific flow for the pumping/injection borehole
T_M	=	steady state transmissivity from Moye's equation
T_T	=	transmissivity from transient evaluation of single-hole test
T_o	=	transmissivity from transient evaluation of interference test
S_o	=	storativity from transient evaluation of interference test
T_o/S_o	=	hydraulic diffusivity (m^2/s)
K'/b'	=	leakage coefficient from transient evaluation of interference test
S*	=	assumed storativity by the estimation of the skin factor in single hole tests
C	=	wellbore storage coefficient
ξ	=	skin factor

6.5.2 Tracer and dilution tests

The hydraulic gradient seemed to be reversed or partly reversed in the soil wells during pumping in HLX33. This is indicated by the reduction in flow during stressed conditions, see Table 6-10.

Tracer breakthrough was detected in HLX33 from the injection of Uranine in SSM000228. Selected parameters are presented in Table 6-11.

Recovery (Uranine) in SSM000228 was c. 33% after 760 hours of sampling.

From model simulations of the breakthrough curve (Uranine) a mean travel time of 528 hours and a dispersivity of 27 m was obtained in SSM000228 (using the distance 204 m). By simulating the breakthrough curve ahead a recovery of 49% was reached after 2,400 hours (= 100 d).

6.6 Nonconformities

6.6.1 Interference test

The pumped water from borehole HLX33 that was discharged in the Ekerumsån influenced the groundwater level in observation well SSM000228 to such extent that it masked any potential response to the pumping. Hence, the data from this well could not be utilised for interpretation as intended.

6.6.2 Tracer and dilution tests

- A tube sampler was supposed to be used for manual sampling at different depths in the pumping borehole. However, since only one large anomaly in the pumping borehole had been identified this part of the sampling process was omitted in agreement with the activity leader.
- On some occasions the sampler did not function properly. Sometimes only a few samples could be retrieved. It is believed that power failures may have affected the sampler. Additionally, larva had on two separate occasions built a nest inside the sampler causing it to fail. During the pumped conditions, only manual sampling was possible to conduct in SSM000229, why only three valid samples could be taken.
- The automatic, magnetic valve sampler used in HLX33 was stopped as a result of a power failure. When restarted, the appropriate measures were not taken. This caused a loss of sample data during approximately 200 hours. The peak of the breakthrough curve could still, just, be identified though.

Table 6-10. Results from the tracer dilution measurements.

Borehole	Volume (L)	$Q_{natural}$ (mL/min)	Darcy velocity, natural (m/s)	$Q_{stressed}$ (mL/min)	Darcy velocity, stressed (m/s)
SSM000228	8.4	34	$1.3 \cdot 10^{-6}$	14	$5.4 \cdot 10^{-7}$
SSM000229	4.5	4.5	$4.9 \cdot 10^{-7}$	1.2	$1.3 \cdot 10^{-7}$

Table 6-11. Evaluated parameters using PAREST (one-dimensional advection-dispersion model) for the flow path SSM000228 → HLX33. Values within brackets are standard errors in percent.

Injection borehole	Tracer	Distance	Mean velocity, v (m/s)	Mean travel time, t_m (h)	Dispersivity, D/v (m)	F
SSM000228	Uranine	204	$1.07 \cdot 10^{-4}$ (2)	528	27 (6)	$2.04 \cdot 10^{-4}$ (4)

7 References

/1/ **SKB 2001.** Platsundersökningar. Undersökningsmetoder och generellt genomförandeprogram. SKB R-01-10, Svensk Kärnbränslehantering AB.

/2/ **SKB 2006**. Program för platsundersökning vid Simpevarp. SKB R-05-37, Svensk Kärnbränslehantering AB.

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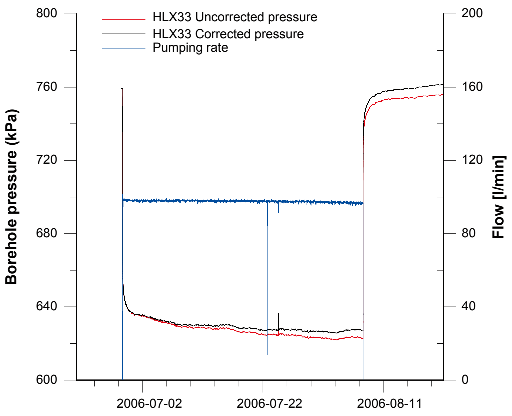
Test summary sheet HLX33

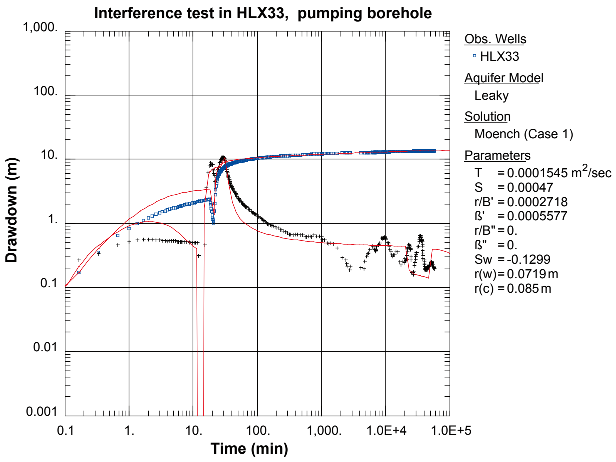
Test summary sheet – Pumping borehole HLX33

Project:	**PLU**	**Test type:**	**1B**
Area:	**Oskarshamn**	**Test no:**	**1**
Borehole ID:	**HLX33**	**Test start:**	**2006-06-28 14:37:36**
Test section (m):	**9.0–202.1**	**Responsible for test execution:**	**SKB field crew**
Section diameter, $2 \cdot r_w$ (m):	**0.139**	**Responsible for test evaluation:**	**GEOSIGMA AB Jan-Erik Ludvigson**

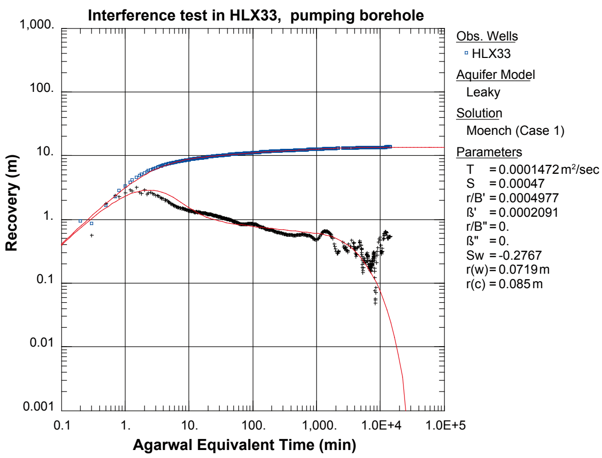
Linear plot Q and p



Log-Log plot incl. derivates- flow period



Log-Log plot incl. derivatives- recovery period



Flow period		**Recovery period**	
Indata		**Indata**	
p_0 (kPa)			
p_i (kPa)	759.2		
p_{p_corr} (kPa)	627.1	p_{F_corr} (kPa)	754.1
Q_p (m³/s)	$1.61 \cdot 10^{-3}$		
tp (min)	57,642	t_F (min)	12,041
S^* (–)	$4.7 \cdot 10^{-4}$	S^* (–)	$4.7 \cdot 10^{-4}$
EC_w (mS/m)			
$Temp_w$(gr C			
Derivative fact.	0.3	Derivative fact.	0.2
r (m)		r (m)	
Results		**Results**	
Q/s (m²/s)	$1.2 \cdot 10^{-4}$		
T_M (m²/s)	$1.6 \cdot 10^{-4}$		
Flow regime:	WBS->PSF	Flow regime:	WBS->PSF
dt_1 (min)		dt_1 (min)	
dt_2 (min)		dt_2 (min)	
T (m²/s)	$1.5 \cdot 10^{-4}$	T (m²/s)	$1.5 \cdot 10^{-4}$
S (–)		S (–)	
K_s (m/s)		K_s (m/s)	
S_s (1/m)		S_s (1/m)	
C (m³/Pa)	$2.3 \cdot 10^{-6}$	C (m³/Pa)	$2.3 \cdot 10^{-6}$
C_D (–)		C_D (–)	
ξ (–)	–0.13	ξ (–)	–0.28
T_{GRF}(m²/s)		T_{GRF}(m²/s)	
S_{GRF}(–)		S_{GRF}(–)	
D_{GRF} (–)		D_{GRF} (–)	

Selected representative parameters.

dt_1 (min)		C (m³/Pa)	$2.3 \cdot 10^{-6}$
dt_2 (min)		C_D (–)	
T_T (m²/s)	$1.5 \cdot 10^{-4}$	ξ (–)	–0.13
S* (–)	$4.7 \cdot 10^{-4}$		
K_s (m/s)			
S_s (1/m)			

Comments:

The measured data are corrected for the naturally decreasing pressure trend during the test period before the analysis. The recovery period was truncated due to influence of precipitation by the end. After initial WBS, both the flow and recovery period are dominated by slightly pseudo-spherical (leaky) flow. The test was analysed as a variable flow rate test.

Consistent results of evaluated hydraulic parameter values are obtained from the flow and recovery period respectively. The parameter values estimated from the flow period are selected as the most representative for the test.

Appendix 2

Test diagrams

Nomenclature for AQTESOLV:

T = transmissivity (m^2/s)

S = storativity (–)

K_Z/K_r = ratio of hydraulic conductivities in the vertical and radial direction (set to 1)

Sw = skin factor

r(w) = borehole radius (m)

r(c) = effective casing radius (m)

r/B = leakage coefficient (s^{-1})

b = thickness of formation (m)

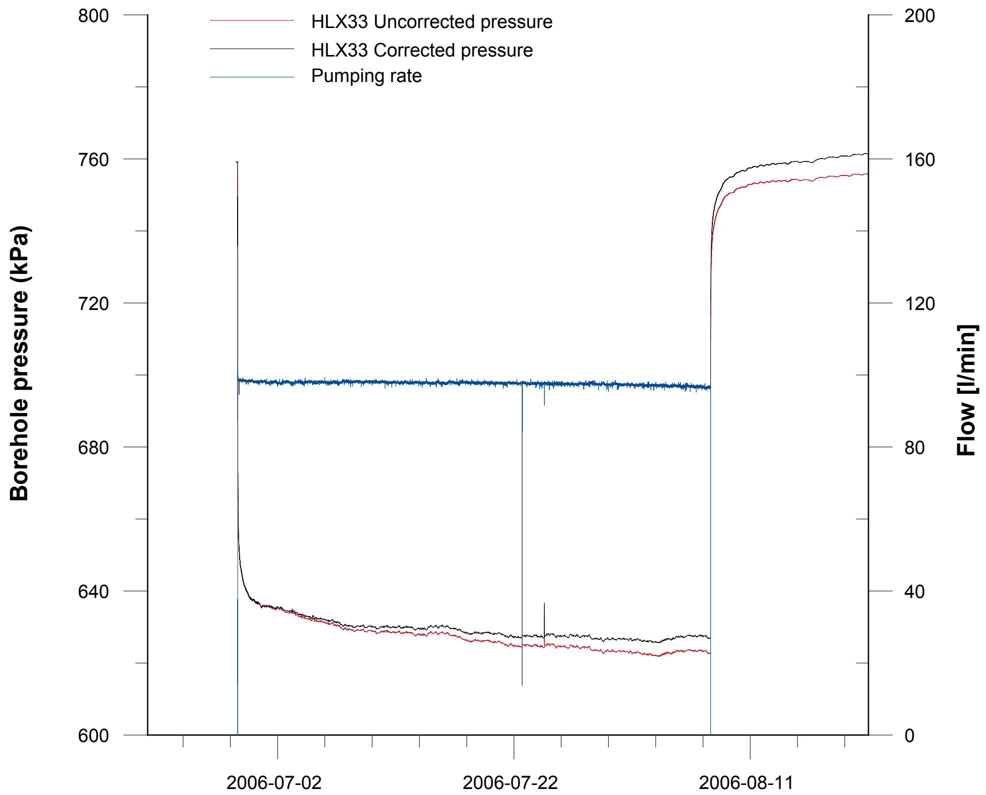


Figure A2-1. *Linear plot of flow rate, pressure and corrected pressure versus time in the pumping borehole HLX33.*

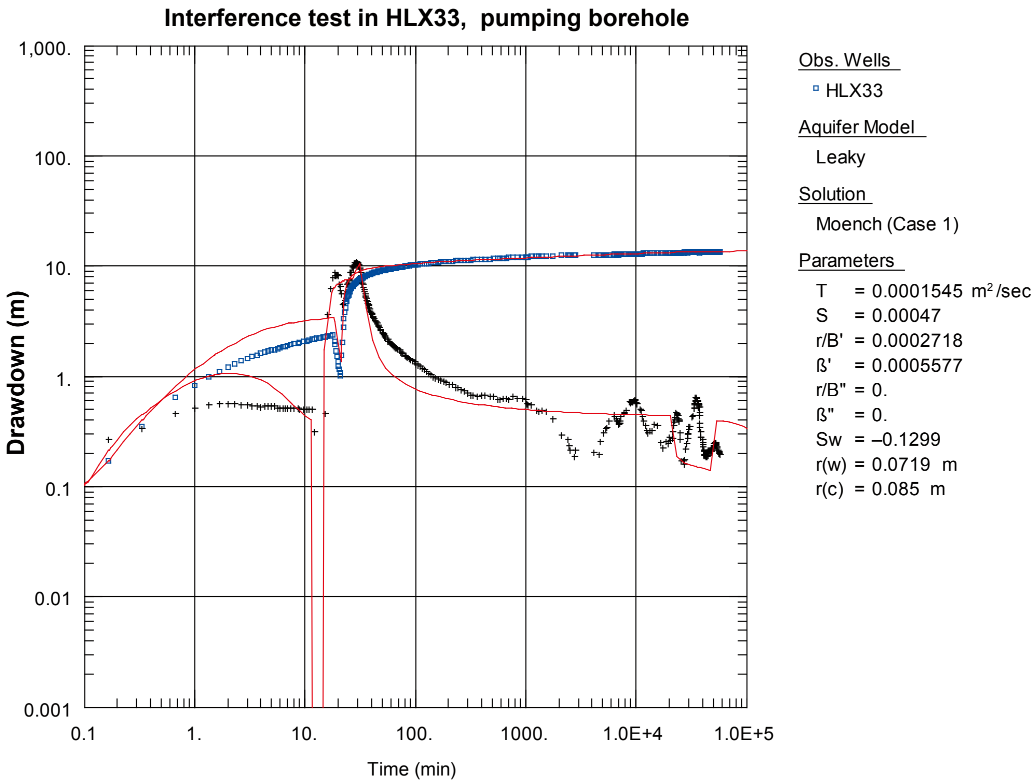


Figure A2-2. *Log-log plot of drawdown (blue □) and drawdown derivative (black +) versus time together with simulated curves (red) in the pumping borehole HLX33.*

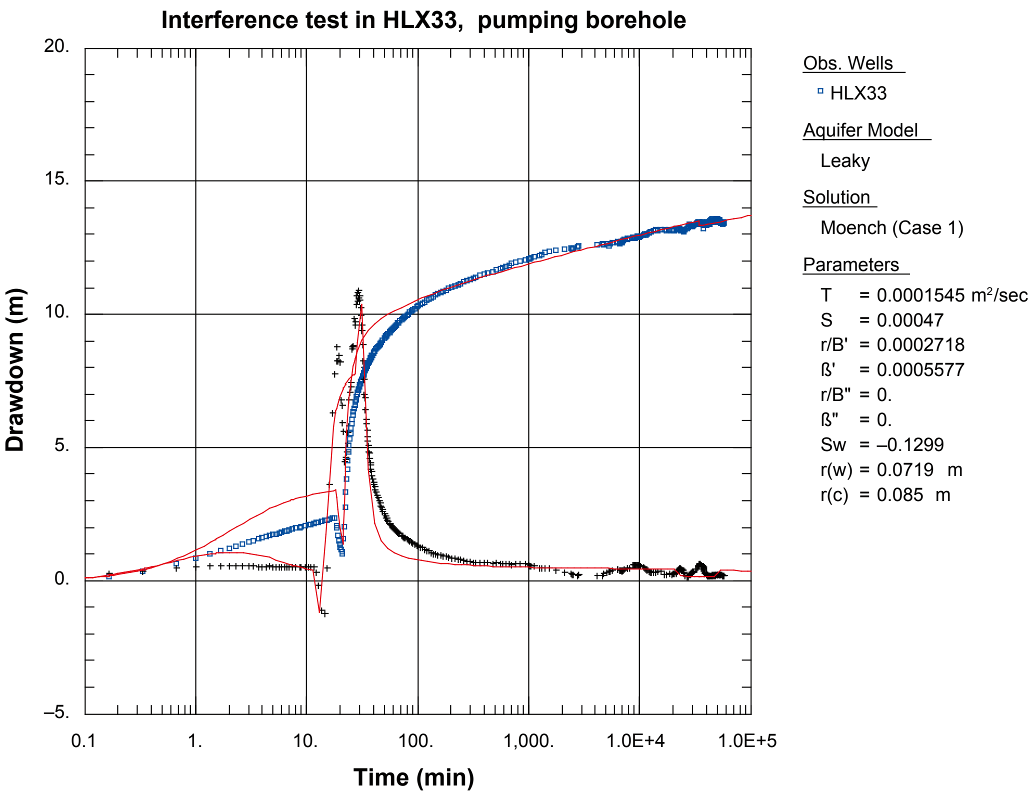


Figure A2-3. *Lin-log plot of drawdown (blue □) and drawdown derivative (black +) versus time together with simulated curves (red) in the pumping borehole HLX33.*

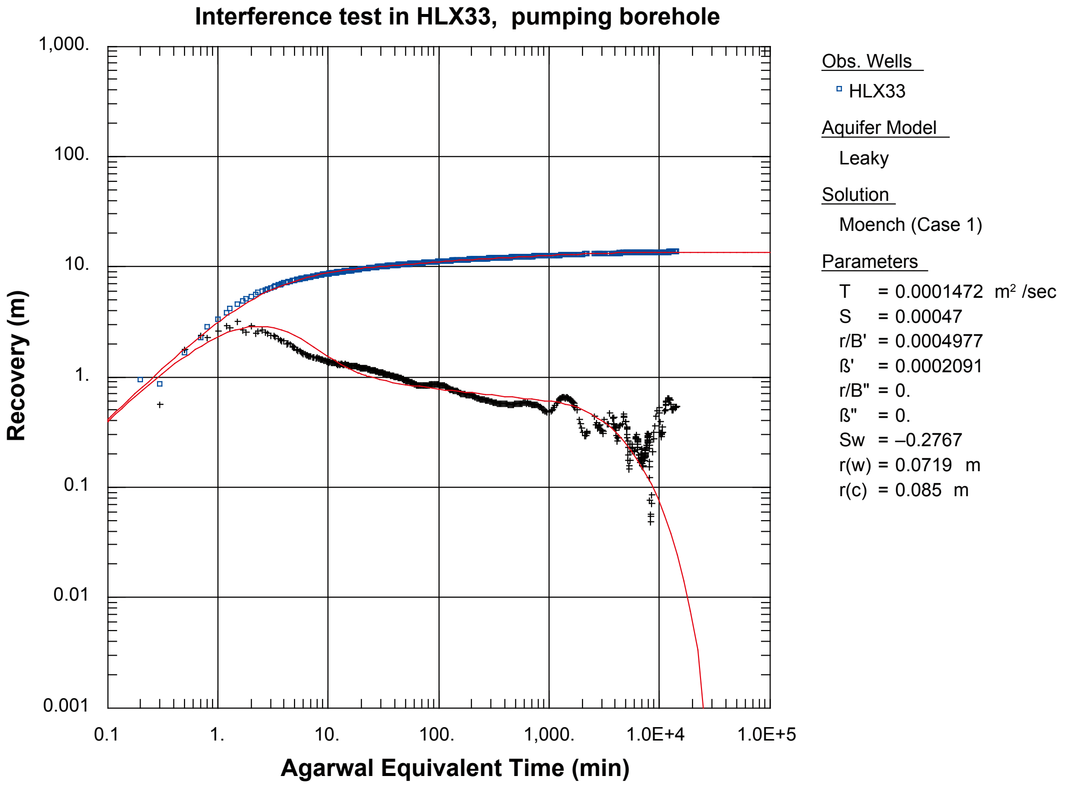


Figure A2-4. *Log-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) together with simulated curves (red) in the pumping borehole HLX33.*

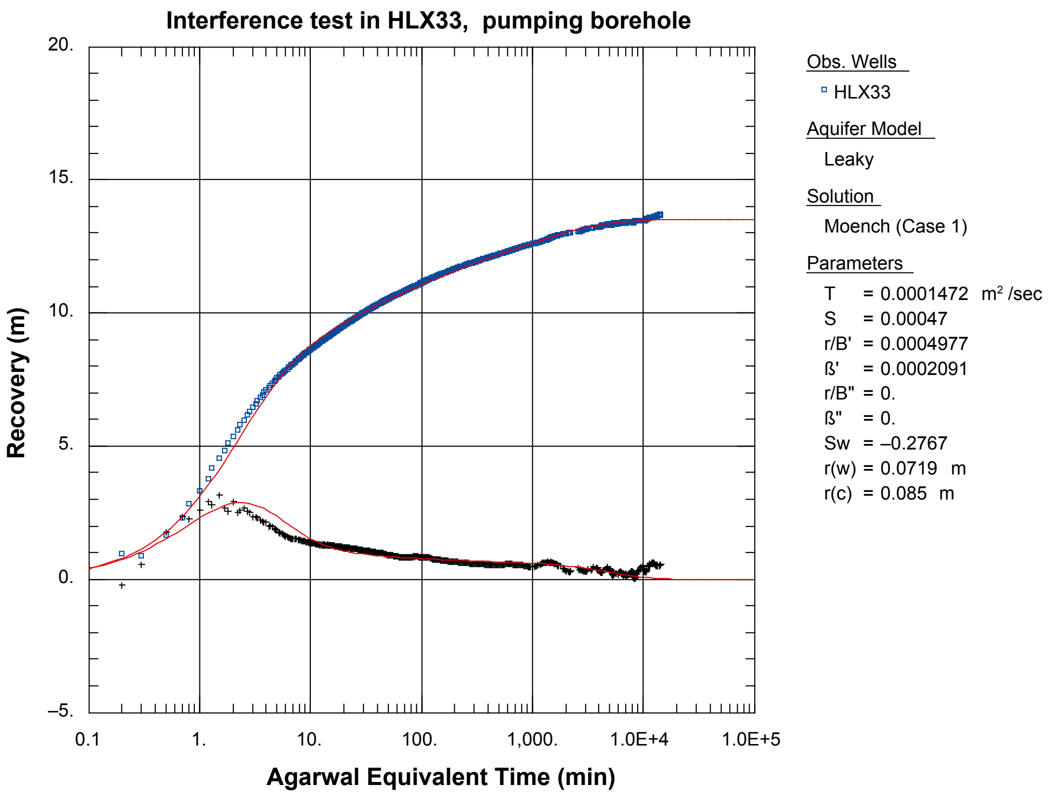


Figure A2-5. *Lin-log plot of pressure recovery (blue □) and -derivative (black +) versus equivalent time (dte) together with simulated curves (red) in the pumping borehole HLX33.*

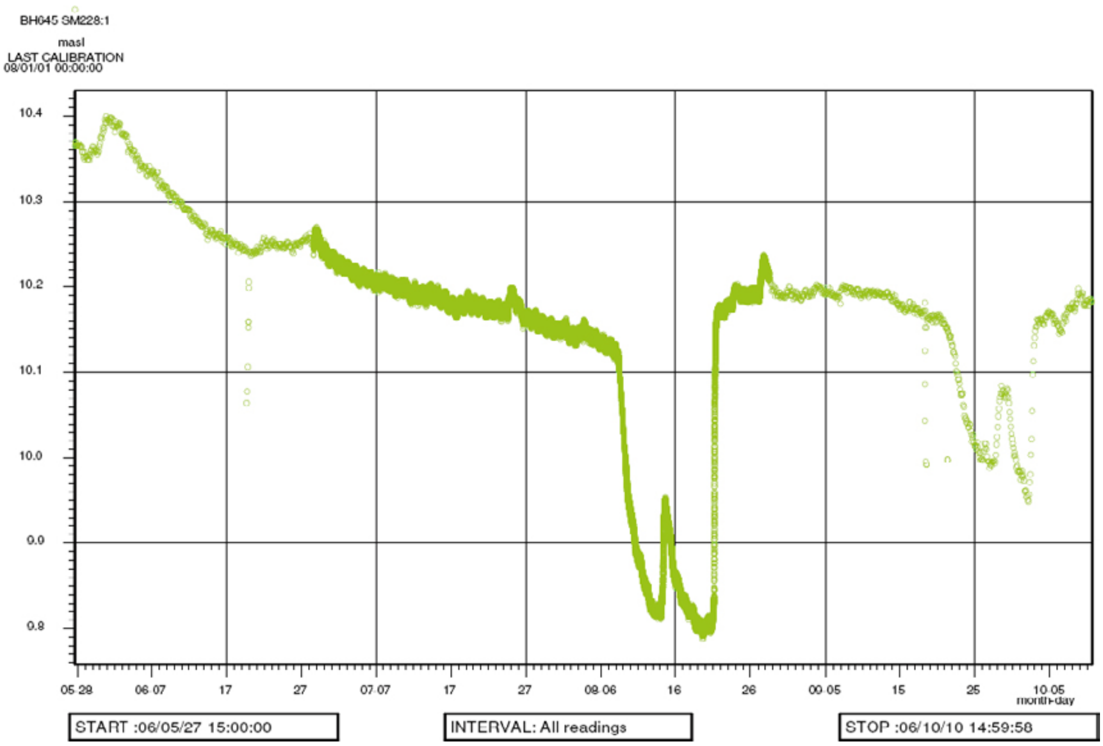


Figure A2-6. *Linear plot of ground water level in the observation borehole SSM000228 during pumping in borehole HLX33.*

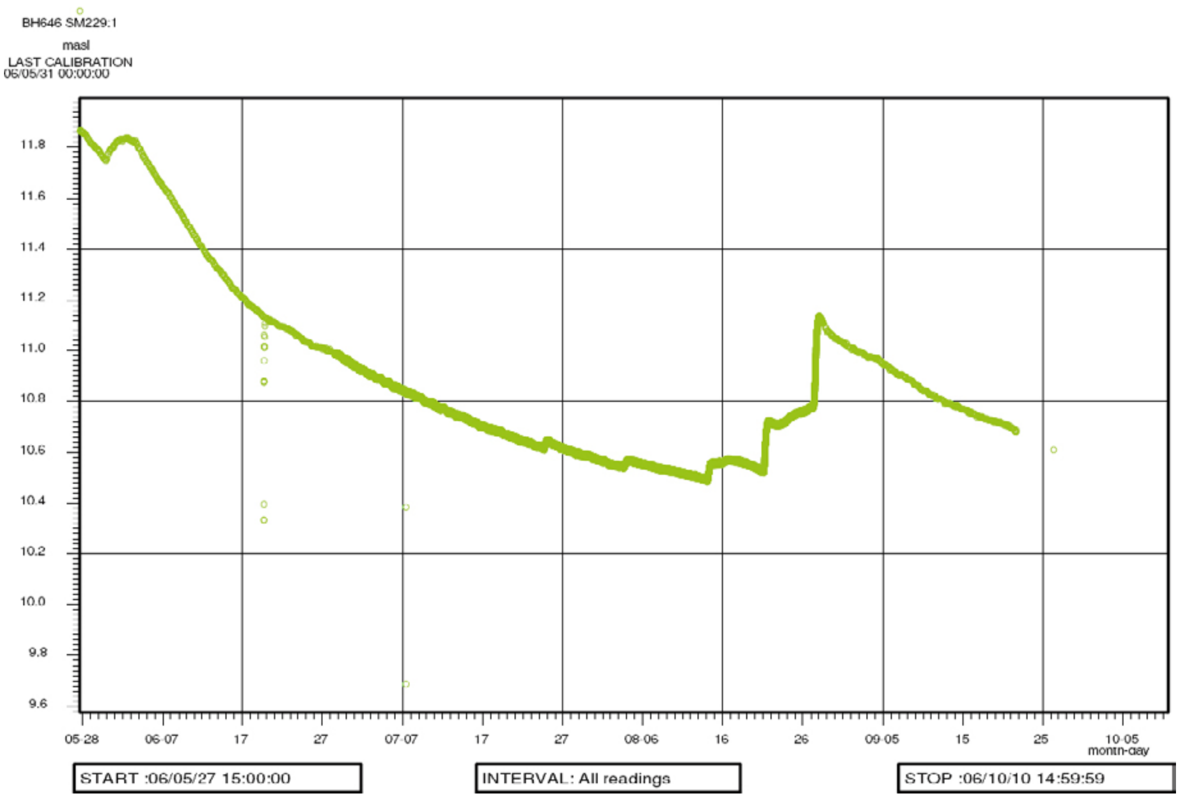


Figure A2-7. *Linear plot of ground water level in the observation borehole SSM000229 during pumping in borehole HLX33.*

Appendix 3

Correction of head and drawdown for natural decreasing trend

A natural, decreasing head trend was ongoing during the entire period of the interference test in HLX33, Figure 5-11. The head data from the test period were corrected for the natural trend using the graphical technique described in Figure 5-11 according to Equation (1). The assumed trend line may be calculated between two arbitrary points on the measured head curve. In this case, t_1 is chosen at start of pumping ($t_1 = 0$) and t_2 immediately before the head increase due to precipitation. The trend line coincides with the observed head trend before start of pumping. The slope of the assumed trend line (which is negative in this case) is calculated according to Equation (2).

The linear trend is assumed to represent the existing natural head trend between the two points. However, as indicated in Figure 5-11, the natural trend may not be entirely linear during the whole time period between t_1 and t_2 which may cause a slight overcompensation of the head during time periods with a lower natural trend. To eliminate, or reduce this effect, the applied trend correction was not allowed to cause increasing heads at the end of the flow period in any observation section. In such cases a lower trend correction was applied. A linear trend correction with time was determined individually for all responding observation sections according to Equation (1) and applied to both the drawdown and recovery period.

$$h(t)_{corr} = h(t) - (dh/dt) \cdot t \quad (1)$$

$$dh/dt = (h_2 - h_1)/(t_2 - t_1) \quad (2)$$

$h(t)$ = measured head at time t (m)

$h(t)_{corr}$ = corrected head at time t (m)

dh/dt = slope of assumed trend line = $(h_2 - h_1)/(t_2 - t_1)$

h_1 and h_2 = measured head (m) at time t_1 and t_2 (s) after start of pumping, respectively

t = total elapsed time since start of pumping (s)

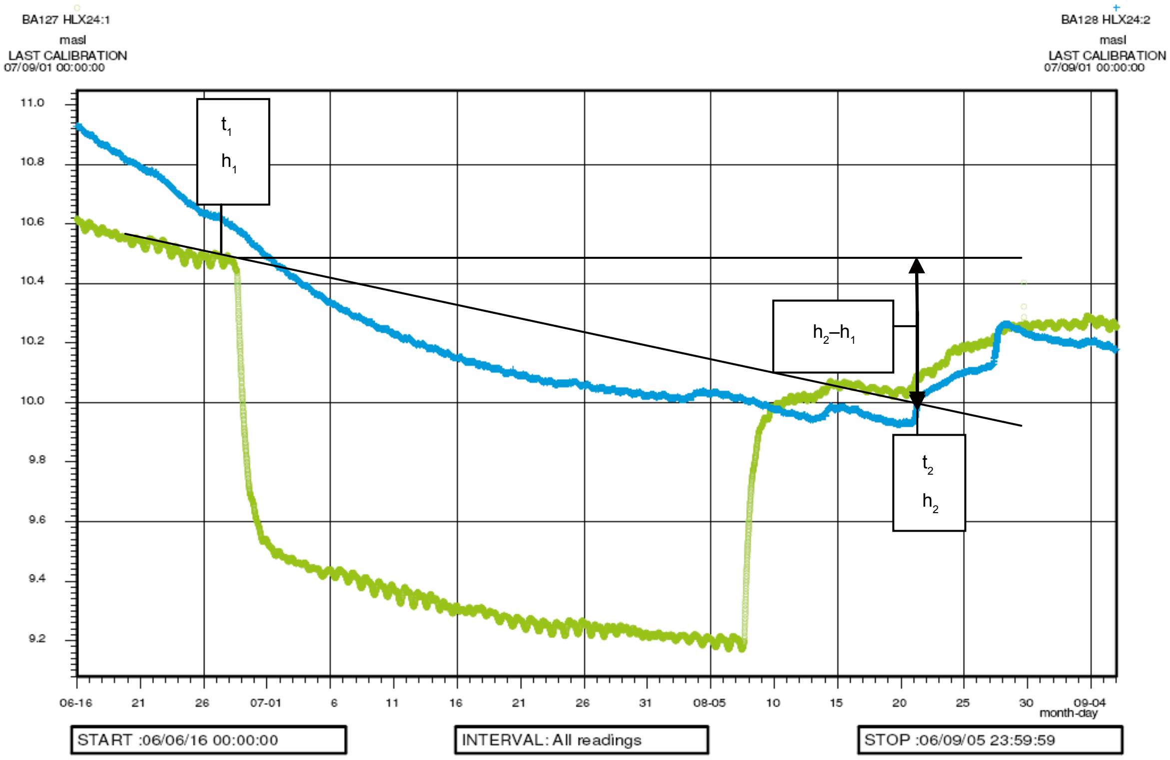
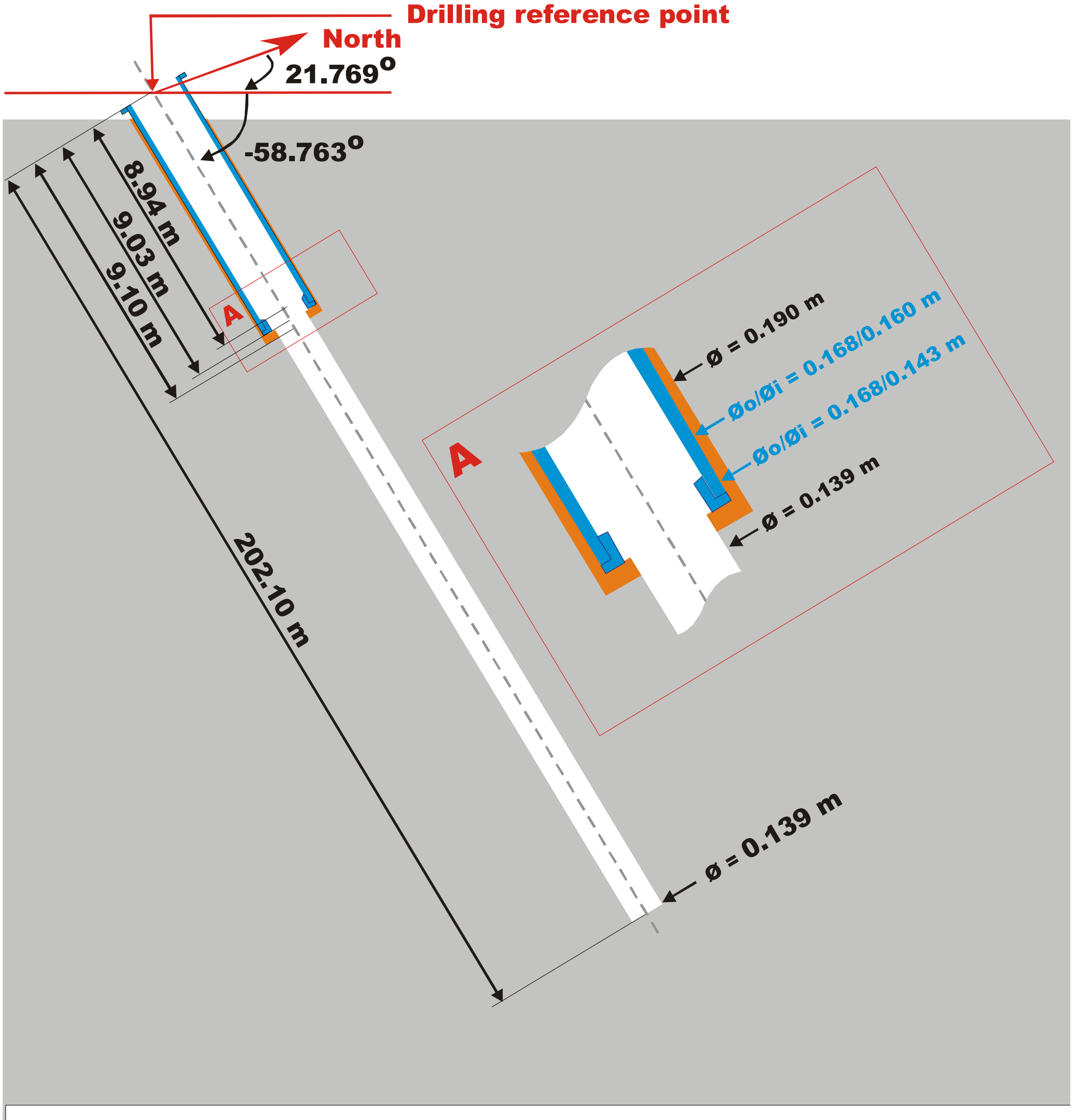


Figure A3-1. *Linear plot of head versus time in observation borehole sections HLX24:1 (green) and HLX24:2 (blue) during the interference test in HLX33. The figure shows the procedure for correction of the natural head trend.*

Borehole logs of HLX33, SSM000228, SSM000229

Technical data

Borehole HLX33



Drilling reference point

Northing:	**6366471.744 (m), RT90 2,5 gon V 0:-15**
Easting:	**1548562.705 (m), RT90 2,5 gon V 0:-15**
Elevation:	**12.201 (m), RHB 70**

Drilling period

Drilling start date: 2004-12-17
Drilling stop date: 2004-12-20

LAXEMAR BOREHOLE SSM000228

Company rep.
Torbjörn Johansson

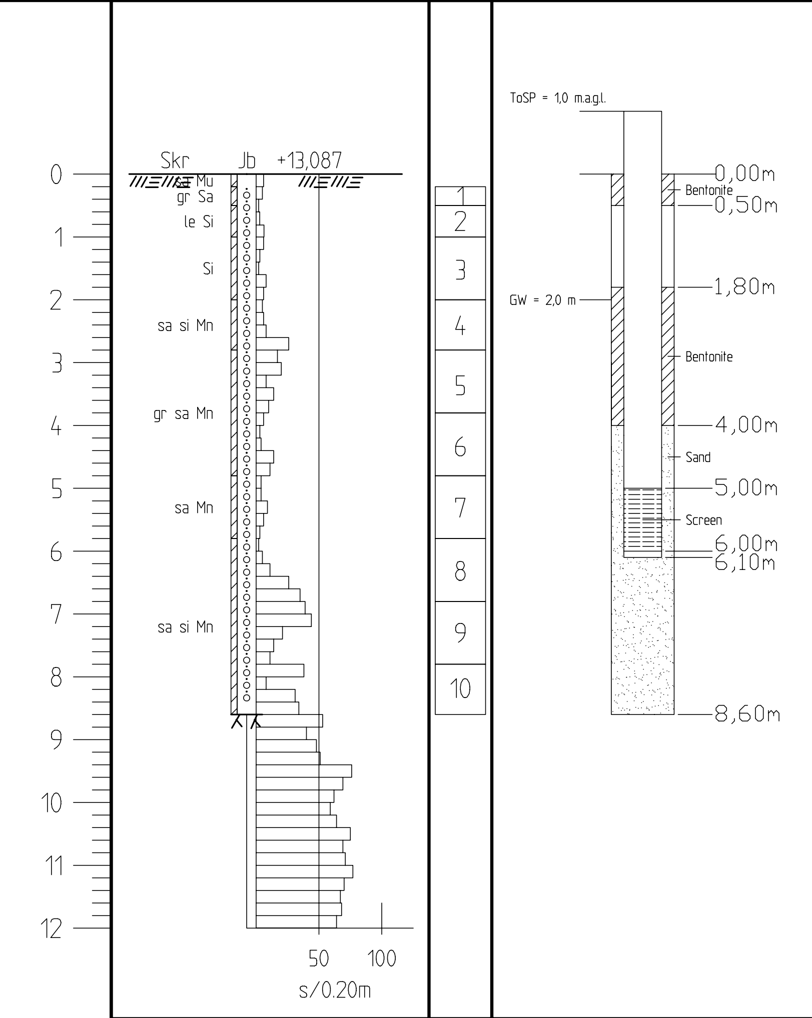
Client: Svensk Kärnbränslehantering AB

Northing :6366503,701
Easting :1548718,363

Coordinate system : RT90-RHB70

Top of stand pipe : 1,0 m.a.g.l.
Total pipe length : 7,10 m
Groundwater level : 2,0 m.b.g.l.
Date of completion : 2005-09-19

Depth (m)	Description	Samples	Groundwater monitoring well description	Borehole Construction Information



Drilling method : NOEK
Borehole diameter : 120 mm
sampling method : Auger

CASING
Material : PEH
Outer diameter : 63 mm
Inner diameter : 50 mm
Total length : 6,00 m

SCREEN
Material : PEH
Outer diameter : 63 mm
Inner diameter : 50 mm
Total length : 1,00 m
Slot : 0,3 mm

ANNULUS SEAL
Material : Bentonite clay
Total length : 2,70 m

SAND PACK
Grain size : 0,4-0,8 mm
Total length : 4,60 m

DRILLING EQUIPMENT
Drilling rig : GM 65 GTT
Drill hammer : Furukawa HB2G
Drill rod : Geostång Φ44
Drill bit : Stift Φ54

GEOLOGICAL LOG
0-0,2m sandy topsoil
0,2-0,5m gravelly sand
0,5-1,0m clayey silt
1,0-2,0m silt
2,0-2,8m sandy silty till
2,8-4,8m gravelly sandy till
4,8-5,8m sandy fill
5,8-8,6m sandy silty till
8,6m rock surface

ToSP : Top of Stand Pipe
m.a.g.l. : meters above ground level
m.b.g.l. : meters below ground level

LAXEMAR BOREHOLE SSM000229

Company rep.
Torbjörn Johansson

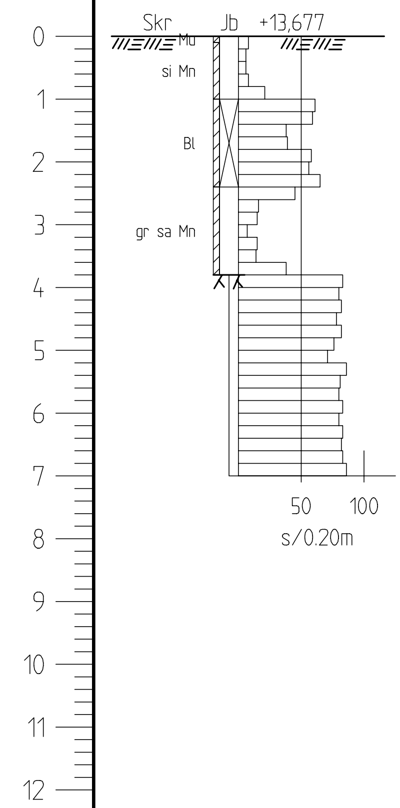
Client: Svensk Kärnbränslehantering AB

Northing : 6366475,650
Easting : 1548721,342

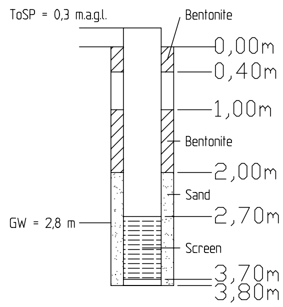
Coordinate system : RT90-RHB70

Top of stand pipe : 0,3 m.a.g.l.
Total pipe length : 4,10 m
Groundwater level : 2,8 m.b.g.l.
Date of completion : 2005-09-20

Depth (m)	Description	Samples	Groundwater monitoring well description	Borehole Construction Information



Samples: 1, 2, 3



Drilling method : NOEK
Borehole diameter : 120 mm
sampling method : Auger

CASING
Material : PEH
Outer diameter : 63 mm
Inner diameter : 50 mm
Total length : 3,00 m

SCREEN
Material : PEH
Outer diameter : 63 mm
Inner diameter : 50 mm
Total length : 1,00 m
Slot : 0,3 mm

ANNULUS SEAL
Material : Bentonite clay
Total length : 1,40 m

SAND PACK
Grain size : 0,4-0,8 mm
Total length : 1,80 m

DRILLING EQUIPMENT
Drilling rig : GM 65 GTT
Drill hammer : Furukawa HB2G
Drill rod : Geostång Φ44
Drill bit : Stift Φ54

GEOLOGICAL LOG
0-0,1m topsoil
0,1-1,0m silty till
1,0-2,4m boulders
2,4-3,8m gravelly sandy till
3,8m rock surface

ToSP : Top of Stand Pipe
m.a.g.l. : meters above ground level
m.b.g.l. : meters below ground level