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Forsmark site investigation

Drilling and pumping test of wells at Börstilåsen

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Abstract

This report describes the drilling of one borehole in soil (PFM002565), and the drilling and installation of a pumping well (SFM0061) and two groundwater monitoring wells (SFM0059 and SFM0060) in the Forsmark area in November 2003. The specific objectives of the performed drilling and installation of wells are to obtain data on soil depth, soil composition and to enable a pumping test for determination of the hydraulic properties of the Börstil esker.

The thickness of the overburden varied between 2.2 and 7.0 m in the four boreholes. Gravel and sand are the dominating grain sizes and boulders are frequent.

The data from the pumping test were evaluated using three separate methods: the Theis method, the Jacob method, and the Theis recovery method. Due to the relatively limited pumping period (approximately 48 hours), the drawdown in a monitoring well located 170 m from the pumping well (parallel to the estimated direction of the esker) was not large enough to use the so-called "channel model" for the evaluation.

The evaluation gave values of T in the interval $3.39\text{-}6.85 \cdot 10^{-4}$ m^2/s (K varying from $1.24 \cdot 10^{-4}$ to $2.50 \cdot 10^{-4}$ m/s), whereas the interval for S is $1.99\text{-}3.95 \cdot 10^{-3}$. Compared to data from the pumping well, lower values of T were obtained from evaluation of data from the monitoring well located approximately 3 m from the pumping well. These lower T-values may be more representative for the actual aquifer properties.

A comparison between drawdown data for the wells and relative sea level data indicates a hydraulic contact between the Börstil esker and the sea. Other factors, such as variations of the barometric pressure, may also have influenced the water-level response during the test. However, air-pressure changes are likely to have a small effect on the water level in the investigated type of geological formation.

Sammanfattning

Denna rapport beskriver borrningen av ett jordhål (PFM002565) och installationen av en pumpbrunn (SFM0061) och två grundvattenrör (SFM0059 och SFM0060) i Börstilåsen i Forsmarksområdet under November 2003. Målsättningen med borrningarna och installationen av pumpbrunnen och observationsrören var att erhålla information gällande jorddjup och jordartssammansättning samt att möjliggöra en bestämning av Börstilåsens hydrauliska egenskaper genom en provpumpning.

Jordtäckets tjocklek varierade mellan 2,2 och 7,0 m i de fyra borrhålen. Grus och sand var de dominerande jordarterna och förekomsten av block var riklig.

Data från provpumpningen utvärderades med tre separata metoder: Theis metod, Jacobs metod och Theis metod för återhämtning. På grund av den relativt begränsade pumpperioden (ca 48 timmar), var avsänkningen från ett grundvattenrör beläget ca 170 m från pumpbrunnen (parallellt med åsens bedömda sträckning) inte tillräckligt stor för att den så kallade "kanalmodellen" skulle kunna tillämpas vid utvärderingen.

Utvärderingen gav T-värden i intervallet $3.39\text{-}6.85\cdot10^{-4}$ m^2/s (motsvarande K-värden mellan $1.24\cdot10^{-4}$ och $6.85\cdot10^{-4}$ m/s), medan intervallet för S är $1.99\text{-}3.95\cdot10^{-3}$. Jämfört med data från pumpbrunnen, erhölls lägre T-värden vid utvärderingen av data från ett grundvattenrör beläget ca 3 m från pumpbrunnen. Dessa lägre T-värden bör vara mer representativa för åsens egenskaper.

En jämförelse mellan avsänkningsdata från pumpbrunnen/grundvattenrören och den relativa havsnivån tyder på att det finns en hydraulisk kontakt mellan Börstilåsen och havet. Andra faktorer, till exempel lufttrycksvariationer, kan också ha påverkat vattennivåns respons under försöket. Lufttrycksvariationer bör dock ha en relativt liten effekt på vattennivåerna i den undersökta typen av geologisk formation.

Contents

1 Introduction

This report presents the drilling and installation of two groundwater monitoring wells (SFM0059-60) and one pumping well (SFM0061) at Börstilåsen in the Forsmark area. In a first borehole (PFM002565), bedrock was met already at 2.2 m below the ground surface. As no groundwater was present, no groundwater monitoring well was installed. The drilling and installations were performed during November 2003. The locations of the wells and the borehole are shown in Figures 1-1 and 1-2. Börstilåsen is a glaciofluvial deposit, an esker. A geological map of the Forsmark area is shown in Figure 1-3.

The pumping well SFM0061 and the two monitoring wells SFM0059-0060 were installed according to SKB AP PF 400-03-83 (SKB´s internal controlling document). The pumping test in pumping well SFM0061 was performed during the period December 2-4, 2003. The pumping was terminated December 4, and the recovery of the groundwater level was monitored until December 11. The test was performed according to the Activity Plan AP PF 400-03-81 (SKB´s internal controlling document).

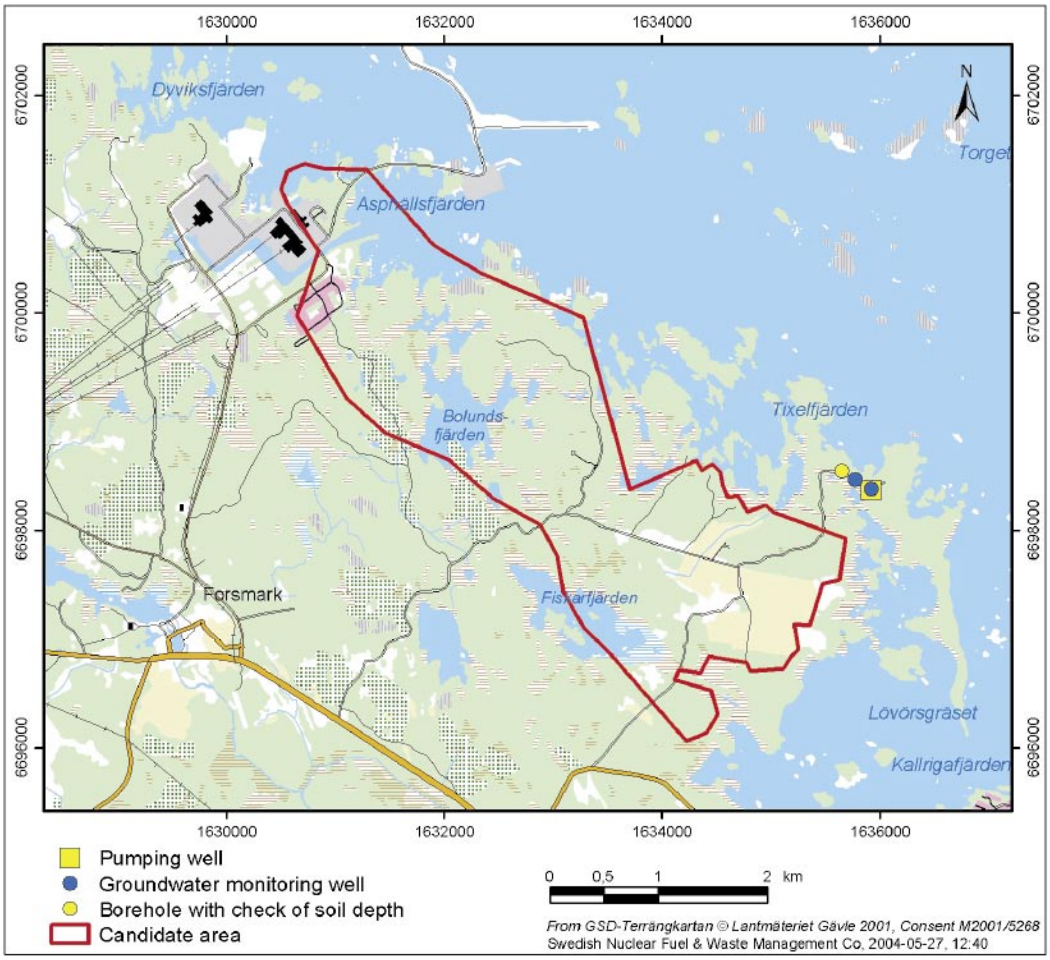


Figure 1-1. *Map showing the location of the pumping test.*

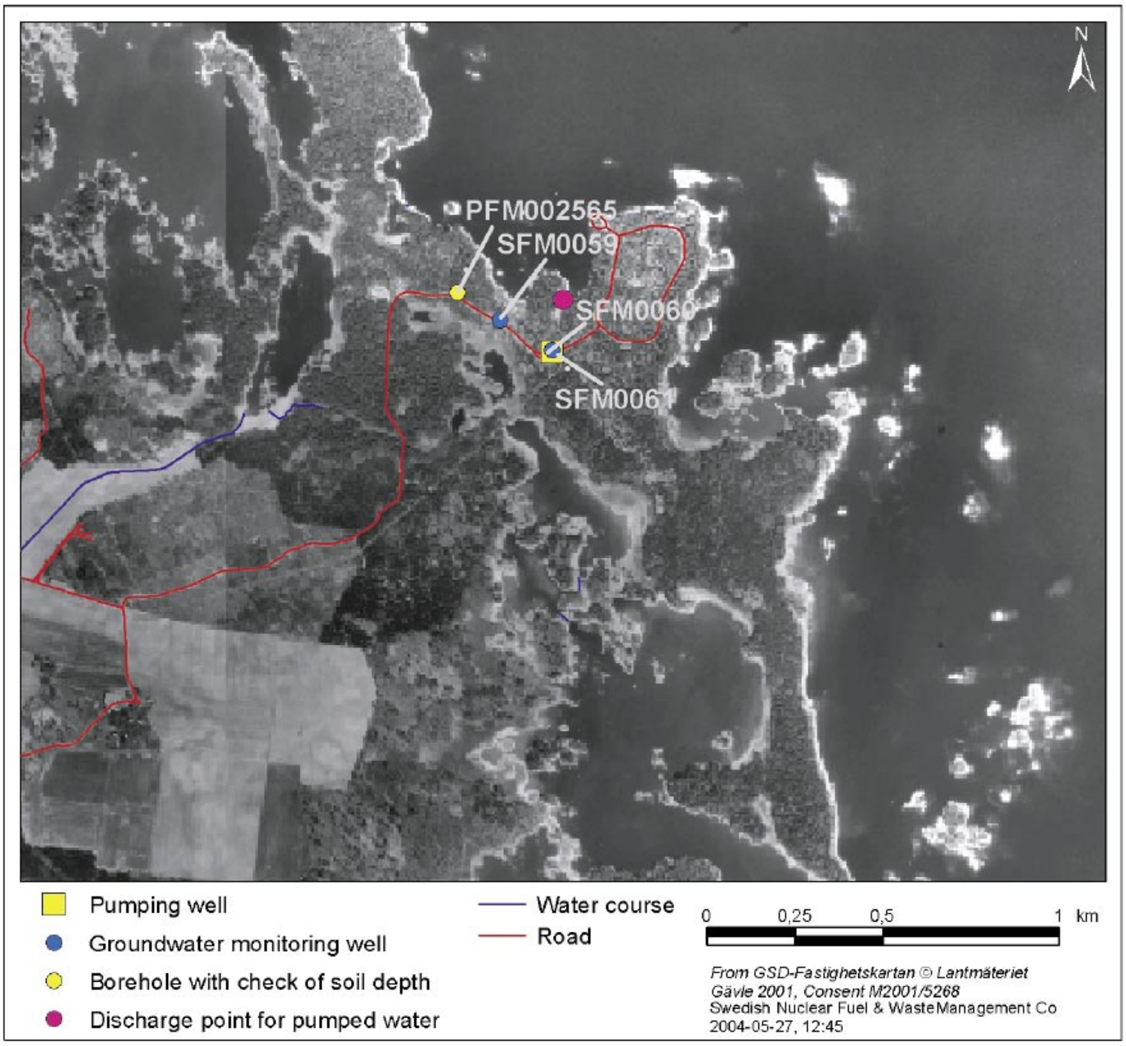


Figure 1-2. *Detailed map showing the location of the pumping well SFM0061, the two monitoring wells SFM0059-0060, and the borehole PFM002565.*

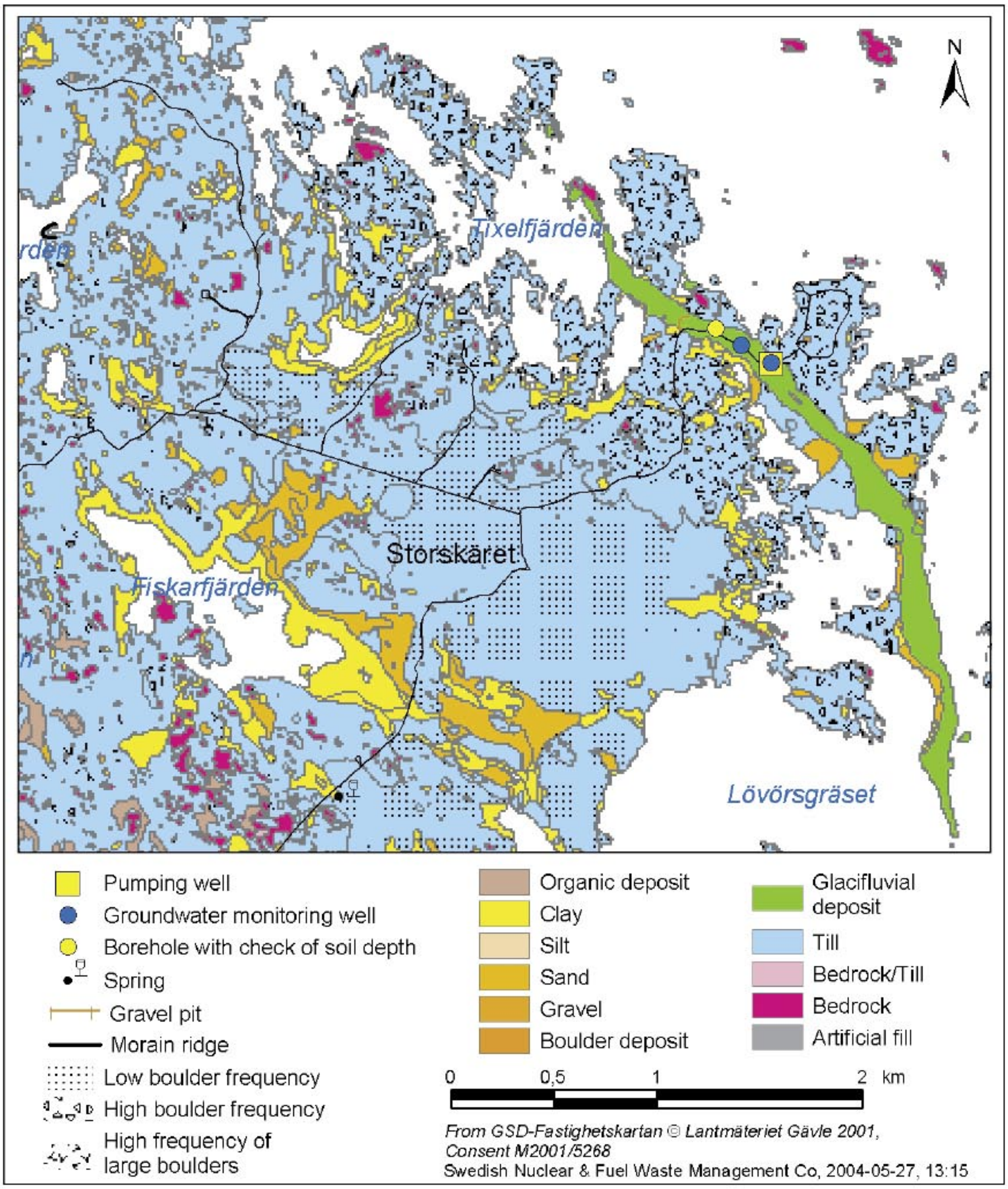


Figure 1-3. *Geological map including the location of the hydraulic test. The green area indicates the extent of the Börstil esker.*

In Table 1-1 controlling documents for performing the activities are listed. Activity plans for sub-activities reported in separate P-reports are not included in the table, but are mentioned in the text. Both activity plans and method descriptions are SKB´s internal controlling documents. Table 1-2 presents data references to the present activity.

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

Activity plans	Number	Version
Hydrauliskt test I filterbrunn på Börstilåsen	AP PF 400-03-81	1.0
Borrning och installation av SFM0059, SFM0060 och SFM0061 samt borrning av PFM002565 vid Börstilåsen. Jorddjupsbestämning, grundvattenrör i jord samt en filterbrunn	AP PF 400-03-83	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för jordborrning	SKB MD 630.003	1.0
Metodbeskrivning för slugtester i öppna grundvattenrör	SKB MD 325.100	1.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Instruktion för användning av kemiska produkter och material vid borrning och undersökningar	SKB MD 600.006	1.0
Inmätning och avvägning av objekt	SKB MD 110.001	1.0

Table 1-2. Data references.

Activity	Database	Identity number
AP PF 400-04-81	SICADA	Field Note No. Forsmark 339
AP PF 400-04-83	SICADA	Field Note Nos. Forsmark 264, 272-274
Surveying	SICADA	Field Note No. 215

2 Objective and scope

The overall objectives of the hydrogeological investigations in the Forsmark area are described in /1/ and /2/. The specific objectives of the performed drilling, installation of wells, and pumping test are to obtain data on soil depth, soil composition and hydraulic properties of the Börstil esker.

One pumping well and two groundwater monitoring wells were installed in the Börstil esker. Subsequent to the installation, a pumping test was performed in the pumping well SFM0061, applying a discharge rate of approximately 2 m^3/h (0.55 L/s). In order to determine the proper discharge rate to be used, a step-drawdown pumping test was performed in the pumping well prior to the actual pumping test. The pumping test was terminated after 48 hours, and the recovery of the water level in the three wells was observed.

3 Equipment

3.1 Drilling and soil sampling equipment

Drilling of the three monitoring wells was performed using a Nemek 407 RE DTH (Down The Hole-equipment) percussion drilling machine (Figure 3-1) supplied with various accessory equipment, see Figure 3-1.

The drilling machine was equipped with separate engines for transportation and power supplies. For discharging water and drill cuttings from the borehole, a 27 bars diesel air-compressor, type Atlas-Copco XRVS 455 Md was used. The DTH drill hammer was of type Secoroc 5", operated in the borehole by a Driconeq 76 mm pipe string. Drilling was performed with the Ejector-Tubex technique, whereby a 168/160 mm steel tube was driven through the soil layer.

Cleaning of all DTH-equipment was carried out with a high-capacity steam cleaner of type Kärcher HDS 1195.

Flow measurements during drilling were performed using measuring vessels of different sizes and a stop watch. Measurements of drilling penetration rate were accomplished with a carpenter's rule and a stop watch. Samples of soil and drill cuttings were collected in sampling pots, see Figure 3-1.

Figure 3-1. *Drilling for the pumping well SFM0061 at the Börstil esker.*

3.2 Pumping test equipment

For the pumping test, the following equipment was used:

1. Van Essen Instruments Diver® with built-in pressure transducer, temperature and electrical conductivity sensor, with connecting cable.
2. Portable PC.
3. Folding rule.
4. Elwa PLS 50A water-level meter, with light- and sound indicator.
5. WTW LF 320 conductivity meter with TetraCon® Standard-conductivity cell.
6. Grundfos SP 5A-17 multi-stage submersible pump, connected via a water-flow meter and pipes to a hose for discharge of pumped water.
7. Grundfos MP 1 two-stage submersible pump for water sampling.
8. Electronic stop watch and a plastic 10 L bucket.

The type of Van Essen Instruments Diver® used is illustrated in Figure 3-2 below.

Figure 3-2. *Close-up photograph of a Van Essen Instruments TD-Diver®, used for measurement of pressure and temperature in each well. Another Diver® model (CDT-Diver®), which was used in SFM0061, has an additional capability to measure the electrical conductivity.*

3.2.1 Sensors

Basic sensor data of the Diver® are given in Table 3-1. The Diver® has a built-in pressure transducer with a resistor bridge for pressure measurements, a semiconductor sensor for temperature measurements, and an electrode sensor for measurements of electrical conductivity. Temperature is used to automatically compensate the depth measurements for temperature effects.

Table 3-1. Sensor data of the Diver®.

	Name	Unit	Value/range
Pressure	Measurement range	cm wc[1]	0 to 1000[2]
	Resolution	cm wc	0.2[2]
	Accuracy	% of measurement range	0.1
Temperature	Measurement range	°C	-20 to +80
	Resolution	°C	0.01
	Accuracy	°C	±0.1
Electrical conductivity[3]	Measurement range	mS/m	0 to 500
	Resolution	mS/m	0.1[4]
	Accuracy	% of measurement range	1

[1] Centimetres water column.
[2] One of the two Divers® used in the filter well SFM0061 is a CDT-Diver®, with a measurement range of 0 to 3000 cm wc and a resolution of 0.6 cm wc.
[3] CDT-Diver® used in the filter well SFM0061.
[4] Resolution for the indicated measurement range.

Table 3-2 shows the position of the pressure transducer in the Diver® in each well during the pumping test. Positions are given in metres from the top of the stand pipe.

Table 3-2. Position (from top of the stand pipe) of pressure transducer in Diver® during the pumping test.

Well	Pressure transducer depth of Diver® during test (m)
SFM0059	5.85
SFM0060	7.60
SFM0061	7.25

4 Execution

4.1 Drilling, soil sampling and installation of wells

The performance of the work followed SKB MD 630.003 (Method Description for Soil Drilling) and included the following parts:

- preparations
- mobilisation, including lining up the machine and measuring the position
- drilling, measurements, and sampling during drilling
- installation of well screens and screen filters
- finishing off work
- data handling
- environmental control

4.1.1 Preparations

The preparation stage included the Contractor's service and function control of his equipment. The machinery was obliged to be supplied with fuel, oil and grease exclusively of the types stated in SKB MD 600.006 (Method Instruction for Chemical Products and Materials). Finally, the equipment was cleaned in accordance with SKB MD 600.004 (Method Instruction for Cleaning of Borehole Equipment and certain Ground-based Equipment) at the level used for boreholes prioritized for hydro-geochemical investigations (level 2).

Well screens and riser pipes were delivered in tight-fitting packages. Before delivery to the drilling site, the HDPE-pipes etc had been treated by acid leaching followed by rinsing with deionized water. At the drilling site, the screens and pipes aimed for boreholes SFM0059-61 were prepared by steam-cleaning.

4.1.2 Mobilisation

Mobilisation onto and at the site included first of all transport of drilling equipment, well screens and well pipes, sand, bentonite, sampling pots for soil and drill cuttings, hand tools and other necessary equipment. Furthermore, the mobilisation comprised cleaning of all DTH-equipment, preparation of the drill site, lining up the machine, and final function control.

4.1.3 Drilling, measurements, and sampling during drilling

Drilling was performed using a variant of the Tubex system, called Ejector-Tubex. Tubex is a system for simultaneous drilling and casing driving. The method is based on a pilot bit and an eccentric reamer, which together produce a borehole slightly larger than the external diameter of the casing tube. This enables the casing tube to follow the drill bit down the hole.

In the Ejector-Tubex system, the design of the discharge channels for the flushing medium, in this case compressed air, is such that the oxygen and oil contamination of the penetrated soil layers is reduced compared to conventional systems. During drilling, a temporary steel casing with the dimension 168.3 mm external and 160 mm internal diameter was simultaneously driven through the soil. When solid rock was indicated, drilling was continued approximately 0.3-1.5 m, to ensure that the bedrock surface had been reached and not only compact till or a large boulder.

During drilling, soil samples were taken every 0.5 m as well as samples of drill cuttings from the bedrock. The soil composition was determined in the field and the samples were stored for possible future analyses. The stratigraphy at SFM0060 was observed according to AP PF 400-02-12, Version 2.0 and is reported to the SKB´s SICADA database, Field Note No. Forsmark 153 and in a P-report in progress /3/.

4.1.4 Installation of the wells

The results observed during drilling regarding soil depth and type, groundwater inflow etc were analysed on-site and a decision was made about the design of the borehole installation. The well screen and well casing was then installed and the installation documented. The installation was performed uniquely for each well, according to the designs illustrated in Appendix 1.

The first part of the installation was to fill up a suitable amount of filter sand into the borehole, in order to cover the bedrock. The screen, connected to the riser pipes, was then lowered into the borehole, all the way down to the sand bed and was centralized in the borehole. During simultaneous lifting of the steel casing, the space between the plastic pipe and the inner casing wall was filled up with filter sand. In order to prevent surface water to infiltrate along the borehole, a bentonite sealing was installed at an appropriate level in the borehole, see Appendix 1.

4.1.5 Finishing off work

After installation of the screen and casing, and sand filter and sealing, the temporary casing was removed. The monitoring wells were secured with stainless steel protective casings, which were driven a short distance into the ground around the upper part of the HDPE casing. The casing was moulded firmly to the ground. Supplied with a lockable stainless steel cap, this construction offers an effective protection against damage of the monitoring wells.

Finally, the drilling machine was removed, the site cleaned, and a joint inspection of the drilling site made by SKB and the Contractor.

4.1.6 Data handling

Minutes for the following items: Activities, Cleaning of equipment, Drilling, Drillhole, Deliverance of field material, and Discrepancy report were collected by the Activity Leader, who made a control of the information and had it stored in the SKB database SICADA, Field Note Nos. 264 and 272-74.

4.1.7 Environmental control

A program according to SKB's routine for environmental control was followed throughout the activity. A checklist was filled in and signed by the Activity Leader, and was filed in the SKB archive.

4.2 Pumping test

4.2.1 Preparation

Prior to the tests, the Divers® were tested at SWECO's office in Marieberg, Stockholm. The test procedure is described in SKB MD 325.100 (Method Instruction for Slug Tests in Open Groundwater Wells). The tests showed that the water pressure head measured by the Divers® was equal (with a resolution of 0.01 m) to the height of the water column above the pressure transducer when the Divers® were lowered to two known depths into a water-filled plastic bucket.

In addition, prior to the tests, the Divers® were lowered to known depths in the wells for measurement of the undisturbed water pressure head. These data, combined with the measured depth to the water level in the wells, were used as part of the evaluation of the tests for data checking. For all Divers® used in the hydraulic test, these checks gave satisfying results.

4.2.2 Execution of tests

The principle of a pumping test is to abstract groundwater from a pumping well, and to observe the decline of the water level in the pumping well and in surrounding groundwater monitoring wells as a function of time. The recovery of the water level in the wells can also be observed following termination of the pumping /4/.

The decline (or recovery) of the water level as function of time depends on the hydraulic contact between the well and the surrounding geological material, the hydraulic properties (hydraulic conductivity and storativity) of the geological formation, the boundary conditions for groundwater flow, the pumping rate, and the design of the well screen. According to the criteria given in AP PF 400-03-81, the pumping was terminated after 48 hours, and the recovery of the water level was observed more than 24 hours after pump stop.

A step-drawdown pumping test was performed prior to the pumping test. The purpose of a step-drawdown test is to determine the proper abstraction rate during the following pumping test. The step-drawdown pumping test and the pumping test are summarized in Tables 4-1 and 4-2. Water sampling was performed in wells SFM0059 and SFM0061 prior to and during (SFM0061) the pumping test. The water sampling is summarized in Table 4-3. The analyses of the water samples are performed according to AP PF-400-03-33 and are presented in a P-report in progress /4/.

Table 4-1. Step-drawdown pumping test performed in pumping well SFM0061.

Pumping step no.	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[2] (min)	Depth to water level in well prior to test[3] (m)	Qp[4] (m^3/s)
1	2003-12-02 13:35:00	20	5.30	$2.27 \cdot 10^{-4}$
2	2003-12-02 13:55:00	20	5.46	$2.86 \cdot 10^{-4}$
3	2003-12-02 14:15:00	20	5.55	$5.56 \cdot 10^{-4}$

[1] Swedish Standard Time.
[2] tp denotes duration of the phase of the test. tp is from pump start/start of pumping step with certain Qp, to a step with a higher Qp/pump stop.
[3] The reference point is the top of the stand pipe.
[4] Qp denotes abstraction rate during the pumping step.

Table 4-2. Pumping test performed in pumping well SFM0061.

Well	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[2] (min)	tF[2] (min)	Depth to water level in well prior to test[3] (m)	Qp[4] (m^3/s)
SFM0059	-		10 049	4.41	-
SFM0060	-		10 037	4.83	-
SFM0061	2003-12-02 15:30:00	2 790	10 041	5.32	$5.56 \cdot 10^{-4}$

[1] Swedish Standard Time.
[2] tp denotes duration of pumping phase of the test, and tF duration of recovery phase of the test. tp is from pump start to pump stop, whereas tF is from pump stop to when the Diver® was lifted out from the particular well.
[3] The reference point is the top of the stand pipe.
[4] Qp denotes abstraction rate during the test. Qp varied between 5.30^{-4} m^3/s (10 L/18.75 s) and 5.8810^{-4} m^3/s (10 L/17 s) for the manual flow-rate measurements performed during the test (using a plastic bucket and a stop watch). The value of Qp given in the table is the average value of Qp from these measurements.

Table 4-3. Water sampling performed in wells SFM0059-0061.

Well	Sample no.	Sampling date and time[2] (YYYY-MM-DD hh:mm:ss)	Sampling depth[3] (m)	Qp[5] (m^3/s)
SFM0059	8165	2003-12-02 14:45:00	5.85	
SFM0060[1]	-	-	-	-
SFM0061	8167	2003-12-02 14:35:00	-	$5.56 \cdot 10^{-4}$
	8168	2003-12-03 15:00:00		
	8166	2003-12-04 13:30:00		

[1] It was agreed by the Activity Leader to omit water sampling in monitoring well SFM0060, as it is located very close to the filter well SFM0061, which was sampled.
[2] Swedish Standard Time.
[2] tp denotes duration of flowing phase of the test, and tF duration of recovery phase of the test. tp is from pump start to pump stop, whereas tF is from pump stop to when the last Diver® is lifted out from the particular well.
[3] The reference point is the top of the stand pipe for well SFM0059 (water was sampled from the bottom of the well). For well SFM0061, the pumped water was sampled.
[4] Qp denotes flow rate during the sampling.

Prior to the test, all equipment that was lowered into the wells was cleaned according to SKB MD 600.004, Version 1.0 (Method Instruction for Cleaning of Borehole Equipment and certain Ground-based Equipment), level 2. Subsequently, the depth to the water level and the depth to the bottom of all wells were measured. In order to observe the displacement of the water level in the wells during the test, besides the continuous recording by pressure transducers, the water level in the wells was also measured with a manual water-level meter several times during the test.

Figure 4-1 illustrates the pumping test arrangement.

Figure 4-1. *Pumping test arrangement. The red hose is used for discharge of pumped water from the pumping well SFM0061. Monitoring well SFM0060 is seen in the background.*

Test procedure

The test procedure given in AP PF 400-04-81 is briefly described below:

1. Function checks and cleaning of Divers® and all other equipment that is lowered into the wells according to SKB MD 600.004 , level one.
2. Installation of the pump in the pumping well and connection to a water-flow meter.
3. Connection of pump to stationary electrical supply and installation of a plastic hose for discharge of pumped water.
4. Emptying of the water in the monitoring wells (SFM0059 and SFM0060) followed by water sampling.
5. Installation of Divers® in the wells.
6. Performance of step-drawdown pumping test. Manual measurements of the water level in the pumping well (i) prior to the test, and (ii) immediately prior to the termination of each pumping step.
7. Termination of step-drawdown pumping test, recovery of the water level in the pumping well. Determination of proper pumping rate during the pumping test in consultation with the Activity Leader.
8. Performance of pumping test. Manual measurements of the water level in the pumping well and the observation wells at 0.5, 1, 2, 3, 20 and 48 hours after initiation of the pumping test.
9. Sampling of pumped water from the pumping well at 1, 24 and 48 hours after initiation of the pumping test.

At several occasions during the pumping test, the discharge rate from the pumping well was checked (i) at the pumping well using the water-flow meter and a stop watch, and (ii) at the discharge point using a plastic 10 L bucket and a stop watch.

10. Termination of pumping test (pump stop) after approximately 48 hours.
11. Continued measurements of pressure, temperature and electrical conductivity in the pumping well and the observation wells for approximately 7 days after pump stop.

The sampling intervals of the Diver® during the step-drawdown pumping test and the pumping test are given in Table 4-4. Before changing the sampling frequency, the Diver® is stopped with the PC, and data are saved in a separate raw data file (cf. Appendix 2).

Table 4-4. Sampling intervals for pressure, temperature and electrical conductivity measurements during the step-pumping test and the pumping test.

Time from start of test (min)	Sampling interval (s)
Step-drawdown pumping test	
-10 to 0	1
0 to 20	1
20 to 40	1
40 to 60	1
Pumping test	
-10 to 0	1
0 to 10	1
10 to 2 880 (48 hrs)	60
2 880 to 10 080 (7 d)	60

4.2.3 Data handling

Raw data from the Divers® (internal *.mon format) was saved on a portable PC, using the computer programme EnviroMon Ver. 1.45. After the test, the saved *.mon files were exported from EnviroMon to *.csv (comma-separated format).

Prior to the data evaluation for the generation of primary data files, all files in *.csv format were imported to MS Excel and saved in *.xls format. Data processing was performed in MS Excel, in order to produce data files for the estimation of transmissivity and storativity. The data processing performed in MS Excel involved

(1) correction of the pressure data for the barometric pressure (obtained by keeping a Diver®, designed for measurement of the barometric pressure) in open air during the test,

(2) identification of the exact starting and termination times of (i) the individual steps in the step-drawdown pumping test and (ii) the pumping test, and

(3) correction for the small differences in the depth of the two Divers®, having different sampling intervals.

A list of all generated raw and primary data files is given in Appendix 2. The raw data files (*.mon and *.csv) were delivered in digital form to the Activity Leader as well as the results of the evaluation (HY640 - PLU Interference test - CRwr_borstil_2004.xls and HY645 - PLU_Interference test-obs.holes_borstil_2004.xls) for quality control and storage in the SICADA database, Field Note No. Forsmark 339.

4.2.4 Analyses and interpretation

The following sections provide a short overview of the methods used for analysis and interpretation of the data obtained during the pumping test. For a more detailed description of the used methods, see /5/.

Theis method

The Theis method is designed to estimate the transmissivity (T) and storativity (S) of an aquifer /4/. The method was originally developed for fully penetrating wells in confined aquifers. In the method, the measured data of the drawdown s(t) = ho-h(t), where s is the drawdown and t denotes time, are plotted in a diagramme with a logarithmic scale on both axes. Subsequently, a so-called type curve of W(1/u) versus 1/u is plotted in the same diagramme, and the measured data curve is fitted to the type curve. In the type curve, the parameter u is defined as $u = \frac{r^2 S}{4Tt}$, where r is the distance from the observation well to the pumping well, and the well function W(u) is defined as $W(u) = \int_u^\infty \frac{\exp(-x)}{x} dx$. After the two curves are fitted against each other, the coordinates of a so-called match point are used to obtain T and S. Commonly, the point (W(1/u), 1/u) = (1, 1) is chosen as the match point. The theory of the method and practical recommendations for its application are given in /5/.

For the present analysis according to the Theis method, the computer program Aquifer Test Ver 3.0 was used /6/. The program allows for both automatic and manual fitting of the type curve to the measured data.

Jacob method

The Jacob method utilizes the fact that the well function W(u) can be developed as the series $W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{2 \cdot 3!} - \frac{u^4}{2 \cdot 4!} + \ldots$. According to the definition of the parameter u (see above), the approximation is valid for u < 0.01 (i.e., for a small distance r from the observation well to the pumping well and/or for large times, t). The theory of the Jacob method and practical recommendations for its application are given in /5/.

For the present analysis according to the Jacob method, the computer program Aquifer Test Ver 3.0 was used /6/. The program allows for both automatic and manual fitting of a the type curve to the measured data.

Theis recovery method

The Theis recovery method is designed to estimate the transmissivity T of an aquifer based on data from the recovery phase following pump stop /5/. The method can be used to analyse recovery data from both monitoring wells and pumping wells, but it is most suited for cases where stationary conditions have been attained during pumping. In the method, the measured data of the residual drawdown s(t'/t) = h_0-h(t'/t), where s is the residual drawdown and t'/t denotes dimensionless time, are plotted in a diagramme with a logarithmic scale on the time axis. The dimensionless time t'/t is the elapsed time since pump stop (t') divided by the time since pump start (t). Subsequently, a straight line is fitted to the measured data in order to provide T. The theory of the method and practical recommendations for its application are given in /5/.

For the present analysis according to the Theis recovery method, the computer program Aquifer Test Ver. 3.0 was used /6/. The program allows for both automatic and manual fitting of a straight line to the measured data.

4.3 Nonconformities

It was planned to use data from monitoring well SFM0059 to evaluate T and S, using the so-called channel model (AP PF 400-04-81). The channel model can be used in situations where the groundwater flow takes place in a geologic formation with parallel (no-flow or leaking) boundaries, and may for instance be applicable to analyse pumping tests in eskers /5/. The monitoring well(s) must be located in areas where the groundwater flow towards the pumping well is parallel to the boundaries. In the present case, monitoring well SFM0059 is located approximately 170 m from the pumping well (SFM0061), in the direction of the Börstil esker (see Figure 1-3). However, the drawdown obtained in monitoring well SFM0059 during the 48-hour pumping test ($s < 0.1$ m; see Appendix 3) does not provide a sufficient basis for a channel-model evaluation.

5 Results

5.1 Drilling and installation of wells

The thickness of the overburden varied between 2.2 and 7.0 m in the four boreholes. Gravel and sand are the dominating grain sizes and boulders are frequent. Profiles of the four boreholes, including well design, are presented in Appendix 1. The presented soil compositions are determined in the field, for PFM002565, SFM0059 and SFM0061 by the drilling staff and for SFM0060 by the site Quaternary geologist. The stratigraphical description of SFM0060 was performed within the activity AP PF 400-02-12 and is presented in a P-report in progress /3/.

Location and geometric data for the wells are summarized in Table 5-1 and 5-2.

Table 5-1. Technical data of the monitoring wells SFM0059 and SFM0060 and the pumping well SFM0061; the stainless steel screen in pumping well SFM0061 has an outer and inner diameter of 162 and 148 mm, respectively, and a slot size of 0.25 mm.

Monitoring well		Stand pipe		Screen (test section)		
	Borehole diameter, d_w (mm)	Inner diameter of stand pipe, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[1] (m)	Depth to borehole seclow[1] (m)	Screen length, b (m)
SFM0059	193.7	72	0	4.85	5.85	1
SFM0060	193.7	72	0	6.60	7.60	1
Pumping well						
	Borehole diameter, d_w (mm)	Inner diameter of stand pipe, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[1] (m)	Depth to borehole seclow[1] (m)	Screen length, b (m)
SFM0061	193.7	150	0	6.02	8.06	2.04

[1] Depth from the top of the stand pipe.

Table 5-2. Coordinates (given in the coordinate system RT90 2.5 gon V 0:-15 and RHB70) of the wells (data supplied by SKB).

Well	Northing (m)	Easting (m)	Elevation (m.a.s.l.)	Distance from the pumping well SFM0061 (m)
SFM0059	6698464.478	1635777.324	4.532	170.787
SFM0060	6698379.807	1635923.865	4.909	3.138
SFM0061	6698376.669	1635923.809	5.398	-

Drilling, well installation and soil sampling data are stored in SKB´s SICADA database. Field Note Nos. are Forsmark 269 and 272-274. The surveying are stored in Field Note No. Forsmark 215.

5.2 Pumping test

5.2.1 Nomenclature and symbols

The nomenclature and symbols used for the results presented in the following sections are given below.

s (m): Drawdown (water level prior to pumping test minus present water level)

T (m^2/s): Transmissivity

K (m/s): Hydraulic conductivity

S (-): Storativity

5.2.2 Results

The results of the performed pumping test are shown in diagrammes in Appendix 3.

5.2.3 Interpreted parameters

Table 5-1 below shows the parameters (T and S) evaluated by the Theis method, the Jacob method and the Theis recovery method. Graphical output from the analysis is shown in diagrammes in Appendix 3.

Table 5-3. Parameters evaluated by the Theis method, the Jacob method, and the Theis recovery method.

Method	Well	T (m^2/s)	K (m/s)	S (-)
Theis	SFM0059[1]	-	-	-
	SFM0060	$6.11 \cdot 10^{-4}$	$2.23 \cdot 10^{-4}$	$1.99 \cdot 10^{-3}$
	SFM0061[2]	$6.85 \cdot 10^{-4}$	$2.50 \cdot 10^{-4}$	-
Jacob	SFM0059[1]	-	-	-
	SFM0060	$3.39 \cdot 10^{-4}$	$1.24 \cdot 10^{-4}$	[4]$3.95 \cdot 10^{-3}$
	SFM0061[2]	[4]$5.64 \cdot 10^{-4}$	$2.06 \cdot 10^{-4}$	-
Theis recovery[3]	SFM0059[1]	-	-	-
	SFM0060	[4]$3.46 \cdot 10^{-4}$	$1.26 \cdot 10^{-4}$	-
	SFM0061	$4.44 \cdot 10^{-4}$	$1.62 \cdot 10^{-4}$	-

[1] Due to limited drawdown during the 48-hour pumping test, data are not possible to evaluate.
[2] Using drawdown data from a pumping well, the method is only suited to estimate the transmissivity T and hydraulic conductivity K.
[3] The method only provides data on transmissivity T and hydraulic conductivity K.
[4] Transmissivity and storativity value delivered for storage in the SICADA database.

5.3 Discussion of results

The performed pumping test was evaluated according to Theis method, the Jacob method, and the Theis recovery method /5/. For monitoring well SFM0059, the drawdown (s < 0.1 m) obtained during the present 48-hour pumping test was too limited to provide a sufficient basis for an evaluation of T and/or S. On the other hand, it is possible to use drawdown and recovery data from monitoring well SFM0060 (located only a few metres from the pumping well) and the pumping well SFM0061 to estimate T and S of the Börstil esker, in an area close to the pumping well.

The drawdown data for wells SFM0060 and SFM0061 (Appendix 3) indicate that the drawdown rate decreases approximately 100 minutes after pump start. The behaviour may be due to delayed yield of water from the unsaturated zone, or it may indicate that there is a hydraulic contact between the esker and the Baltic sea (a so-called positive hydraulic boundary).

Approximately 16-17 hours (~1 000 minutes) after pump start, the water level in SFM0060 and SFM0061 actually increased during a few hours. Sea-level data for the Forsmark area indicate a rise of the sea level at this point (see Figure 5-1). The results indicate a hydraulic contact between the Börstil esker and the Baltic. Variations in the barometric pressure may also have had an impact of the water level in the wells and in the aquifer. However, the effects of air-pressure variations on the water levels should be relatively small for the investigated type of geological formation.

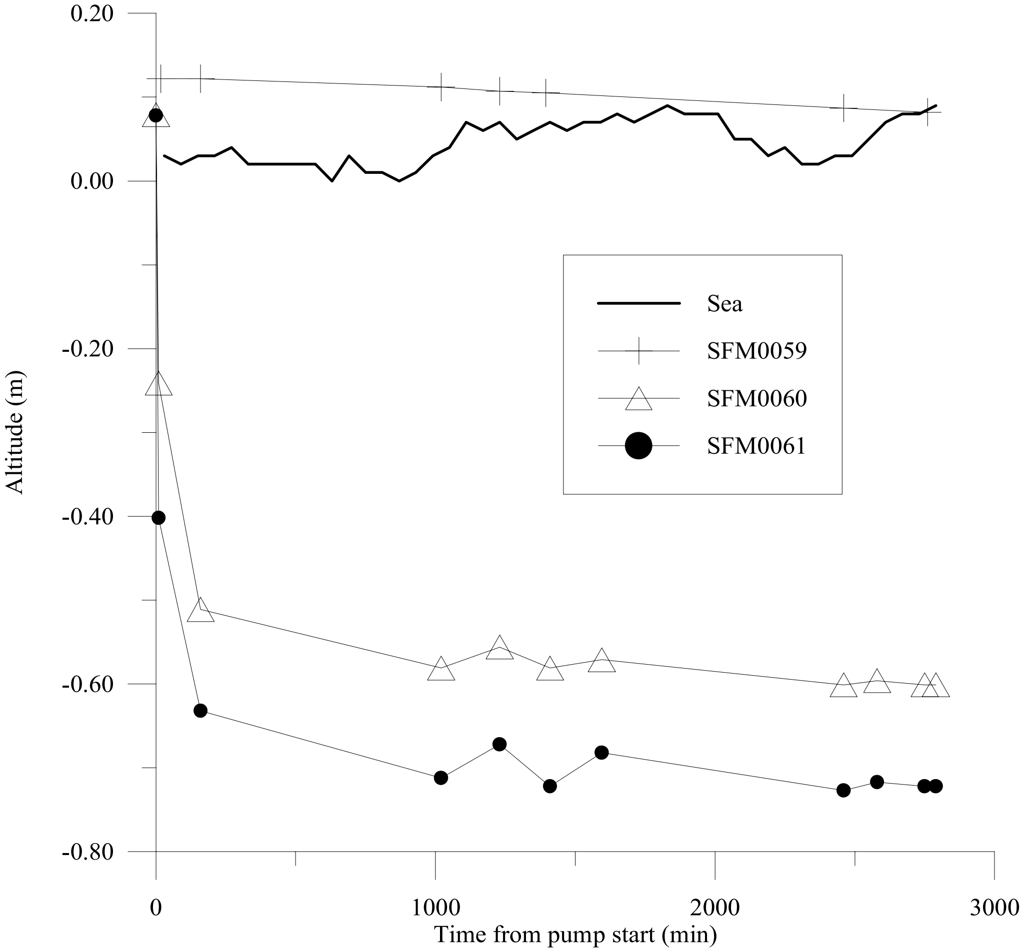


Figure 5-1. *Water level in the Baltic, monitoring wells SFM0059-0060, and the pumping well SFM0061. Altitudes are given in coordinate system RHB 70. (Sea-level data provided by SKB.)*

The evaluation of the drawdown and recovery data for wells SFM0060-0061 gives values of T in the interval $3.39\text{-}6.85 \cdot 10^{-4}$ m^2/s, whereas the interval for S is $1.99\text{-}3.95 \cdot 10^{-3}$. The value of T obtained from the data analysis for the pumping well (SFM0061) is higher compared to monitoring well SFM0060. The former case provides an estimate of T for a limited area around the pumping well (which may be affected by the installation and design of the well), whereas the latter (lower) value may be representative for a (somewhat) larger volume of the aquifer. Based on the data evaluation, the transmissivity values reported to the SICADA database are $T = 3.46 \cdot 10^{-4}$ and $T = 5.64 \cdot 10^{-4}$ m^2/s for well SFM0060 and SFM0061, respectively. The storativity value $S = 3.95 \cdot 10^{-3}$ (-) is reported for well SFM0060.

6 References

/1/ **SKB, 2001.** Platsundersökningar. Undersökningsmetoder och generellt genomförandeprogram. SKB R-01-10 (in Swedish).

/2/ **SKB, 2001.** Program för platsundersökning vid Forsmark. SKB R-01-42 (in Swedish).

/3/ **Hedenström A, 2004.** Forsmark site investigation. Stratigraphical and analytical data of Quaternary deposits. SKB P-report in progress.

/4/ **Borgiel M, Nilsson A-C, 2004.** Sampling and analyses of near surface groundwater. Results from shallow monitoring wells in soil, BAT filter tips, springs, and private wells, May 2003 to May 2004. SKB P-report in progress.

/5/ **Carlsson L, Gustafson G, 1984.** Provpumpning som geohydrologisk undersökningsmetodik. Rapport R41:1984, Statens råd för byggnadsforskning. (In Swedish.)

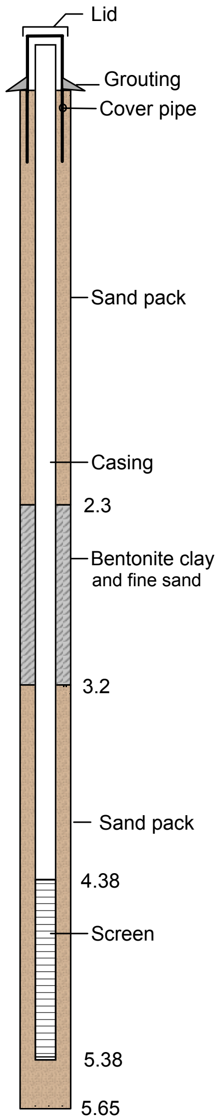
/6/ **Waterloo Hydrogeologic, Inc, 2000.** User's guide for Aquifer Test. Waterloo, Ont., Canada.

Appendix 1

Borehole profiles and well design

SWECO VIAK	FORSMARK Borehole SFM0059
Company rep. Anders Månsson (Sven Andersson AB) and Kenneth Åkerström (MIRAB)	Coordinate system : RT 90 2.5 gon W 0:-15 : RHB 70 Northing : 6698464.478 Easting : 1635777.324
Client: Svensk Kärnbränslehantering AB	Top of stand pipe : 4.532 m.a.s.l Ground elevation : 4.03 m.a.s.l Total pipe length : 5.88 m Groundwater level : - Date of completion : 2003-11-19

Depth (m)	Elev. (m.a.s.l)	Description (determined in field)	Samples*
0	4	gravel, sand	
0.5		sand	sample
1	3		sample
1.5		sand, gravel	sample
2	2		sample
2.5		sand	sample
3	1		sample
3.5			sample
4	0	sand, gravel	sample
4.5			sample
5	-1		sample
5.3		bed rock	
5.65			sample
6			



Well Construction Information

Drilling method	: Percussion (Tubex)
Borehole diameter	: 193.7 mm
Sampling method	: Compressed air
COVER PIPE	
Material	: Stainless steel
Inner diameter	: -
Outer diameter	: 168 mm
Total length	: 1.06 m
CASING	
Material	: HDPE
Inner diameter	: 72 mm
Outer diameter	: 90 mm
Total length	: 4.88 m
SCREEN	
Material	: HDPE
Inner diameter	: 72 mm
Outer diameter	: 90 mm
Total length	: 1.00 m
Slot	: 0.30 mm
SAND PACK	
Grain size	: Coarse sand
Total length	: 4.6 m
ANNULUS SEAL	
Material	: Bentonite clay/Fine sand
Total length	: 1.0 m

*SICADA Field note 274

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SWECO VIAK

FORSMARK Borehole SFM0060

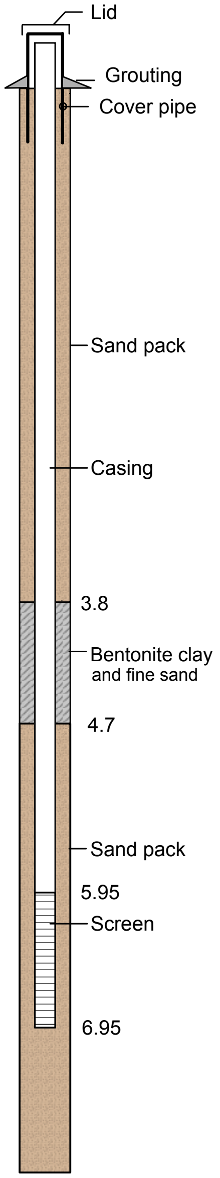
Company rep.
Anders Månsson (Sven Andersson AB)
and Kenneth Åkerström (MIRAB)

Client: Svensk Kärnbränslehantering AB

Coordinate system	: RT 90 2.5 gon W 0:-15
	: RHB 70
Northing	: 6698379.807
Easting	: 1635923.865

Top of stand pipe	: 4.909 m.a.s.l
Ground elevation	: 4.26 m.a.s.l
Total pipe length	: 7.60m
Groundwater level	: -
Date of completion	: 2003-11-13

Depth (m)	Elev. (m.a.s.l)	Description (determined in field)	Samples*
0–0.5		gravel, sand	
0.5–7		gravel, stone	
7–8		bed rock	



Well Construction Information

Drilling method	: Percussion (Tubex)
Borehole diameter	: 193.7 mm
Sampling method	: Compressed air
COVER PIPE	
Material	: Stainless steel
Inner diameter	: -
Outer diameter	: 168 mm
Total length	: 1.06 m
CASING	
Material	: HDPE
Inner diameter	: 72 mm
Outer diameter	: 90 mm
Total length	: 6.60 m
SCREEN	
Material	: HDPE
Inner diameter	: 72 mm
Outer diameter	: 90 mm
Total length	: 1.00 m
Slot	: 0.30 mm
SAND PACK	
Grain size	: Coarse sand
Total length	: 7.1 m
ANNULUS SEAL	
Material	: Bentonite clay/fine sand
Total length	: 0.9 m

*SICADA Field notes 272 and 153

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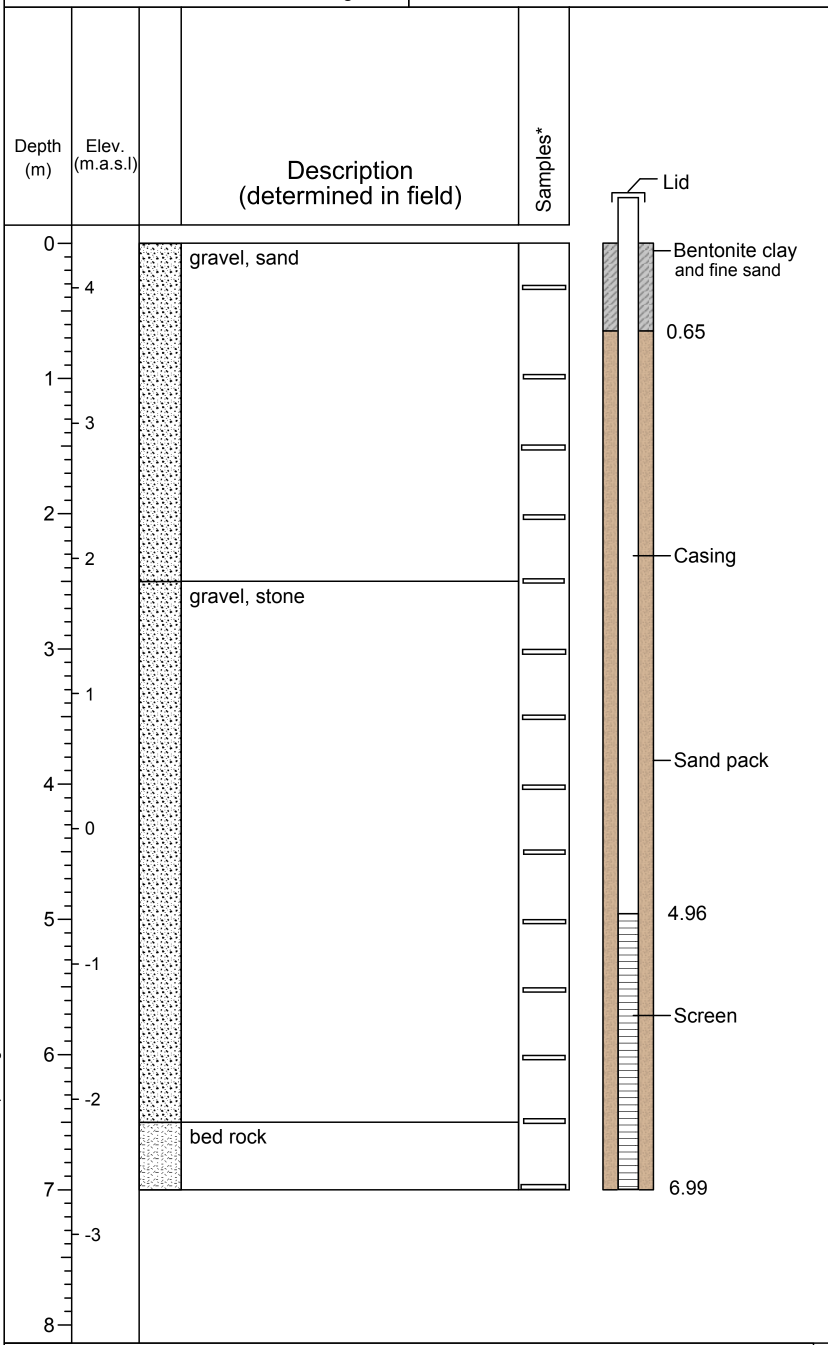
SWECO VIAK	FORSMARK Borehole SFM0061

Company rep.
Anders Månsson (Sven Andersson AB)
and Kenneth Åkerström (MIRAB)

Client: Svensk Kärnbränslehantering AB

Coordinate system	: RT 90 2.5 gon W 0:-15	Top of stand pipe	: 5.398 m.a.s.l
	: RHB 70	Ground elevation	: 4.33 m.a.s.l
Northing	: 6698376.669	Total pipe length	: 8.06 m
Easting	: 1635923.809	Groundwater level	: -
		Date of completion	: 2003-11-17



Well Construction Information

Drilling method	: Percussion (Tubex)
Borehole diameter	: 193.7 mm
Sampling method	: Compressed Air
CASING	
Material	: Stainless steel
Inner diameter	: 150 mm
Outer diameter	: 154 mm
Total length	: 6.02 m
SCREEN	
Material	: Stainless steel
Inner diameter	: 148 mm
Outer diameter	: 162 mm
Total length	: 2.04 m
Slot	: 0.25 mm
SAND PACK	
Grain size	: 0.4-0.8 mm
Total length	: 6.35 m
ANNULUS SEAL	
Material	: Bentonite clay/fine sand
Total length	: 0.65 m

*SICADA Field note 273

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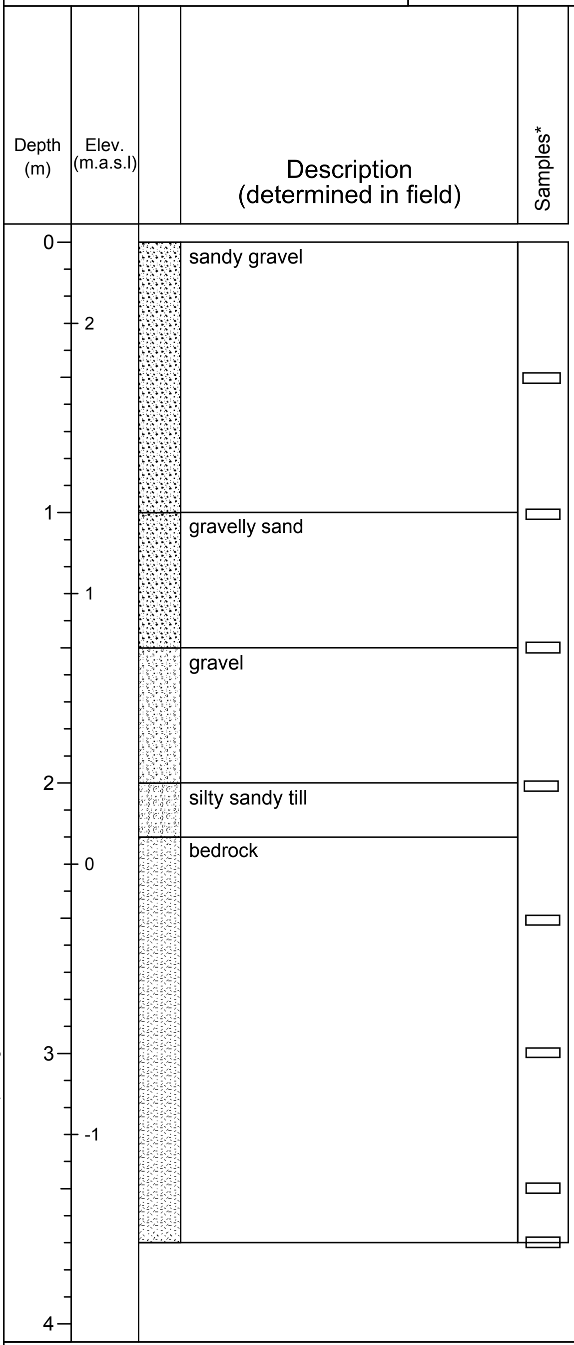
SWECO VIAK

FORSMARK PFM002565

Company rep. Anders Månsson (Sven Anderssons AB) Kenneth Åkerström (MIRAB), Keijo Huikuri (GNC) Tommy Karlberg (GNC)	
Client: Svensk Kärnbränslehantering AB	

Coordinate system	: RT 90 2.5 gon W 0:-15	Ground elevation	: 2.300 m.a.s.l
	: RHB 70	Drilling method	: Tubex 165
Northing	: 6698542.299	Sampling method	: Compressed air
Easting	: 1635656.092	Borehole diameter	: 193.3 mm
		Date of completion	: 2003-11-12



*SICADA Field note 269

Appendix 2

List of generated raw data files and primary data files

Table A2-1. List of generated raw data files and primary data files

Well	Raw data files: *.mon Parameters: Pressure and temperature	Data processing files: *.xls	Primary data files: *.mdb Parameters: Transmissivity and storativity
SFM0059	Diver_38235_sfm0059 Diver_38236_sfm0059	SFM0059_bearbetningsfil	SKB_Börstilåsen
SFM0060	Diver_38229_sfm0060 Diver_38231_sfm0060 Diver_38229_aterhamtn_sfm0060	SFM0060_återhämtning_bearbetningsfil	
SFM0061	Diver_38240_sfm0061 Diver_CTD-5_sfm0061[1] Diver_38240_aterhamtn_sfm0061	SFM0061_återhämtning_bearbetningsfil	

[1]Also including electrical conductivity.

Appendix 3

Diagrammes

Appendix 3 contains diagrammes of the results and the analysis of the pumping test.

Figures A3-1 to A3-8 show data on drawdown and recovery from monitoring wells SFM0059-0061 and pumping well SFM0061 in semi-logarithmic plots, as well as data on electrical conductivity and temperature.

The analyses of the drawdown and recovery data, according to the Theis, Jacob and Theis recovery methods, are shown in Figures A3-9 to A3-14.

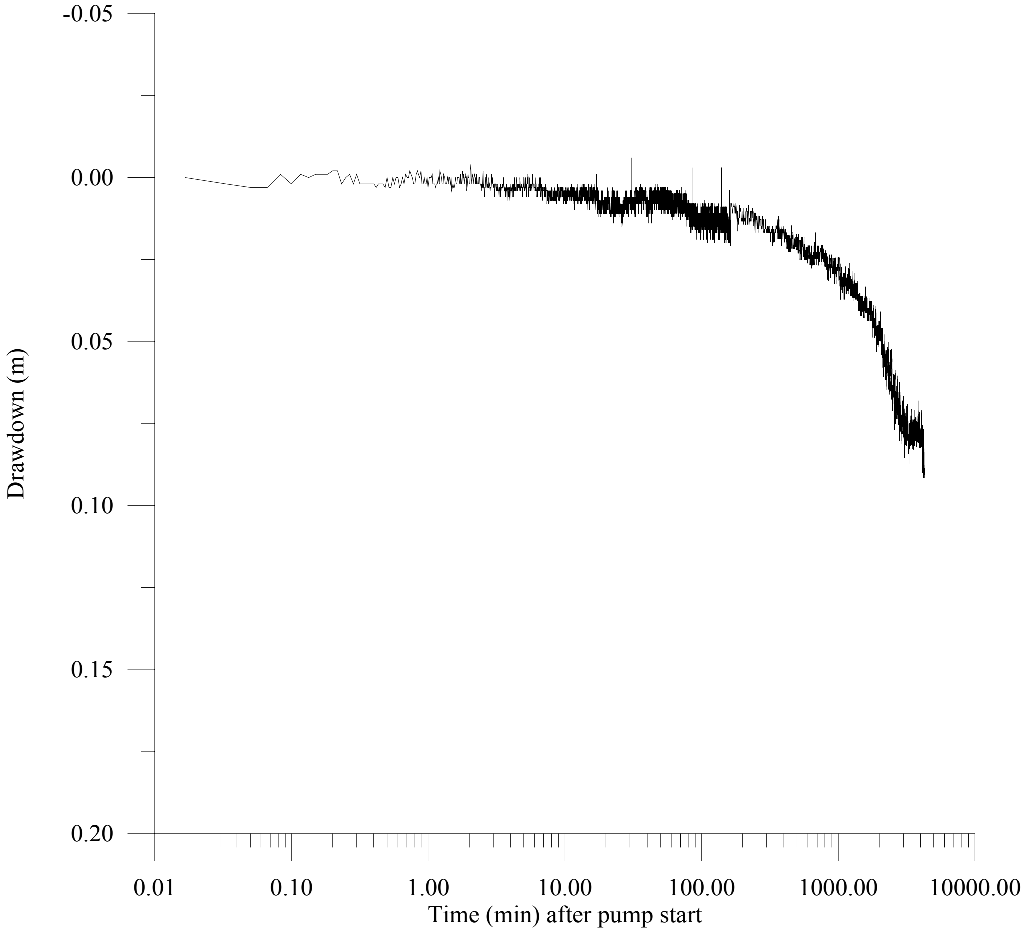


Figure A3-1. *Log-linear plot of drawdown versus time after pump start in monitoring well SFM0059. Pumping was terminated ~ 2 790 min after pump start.*

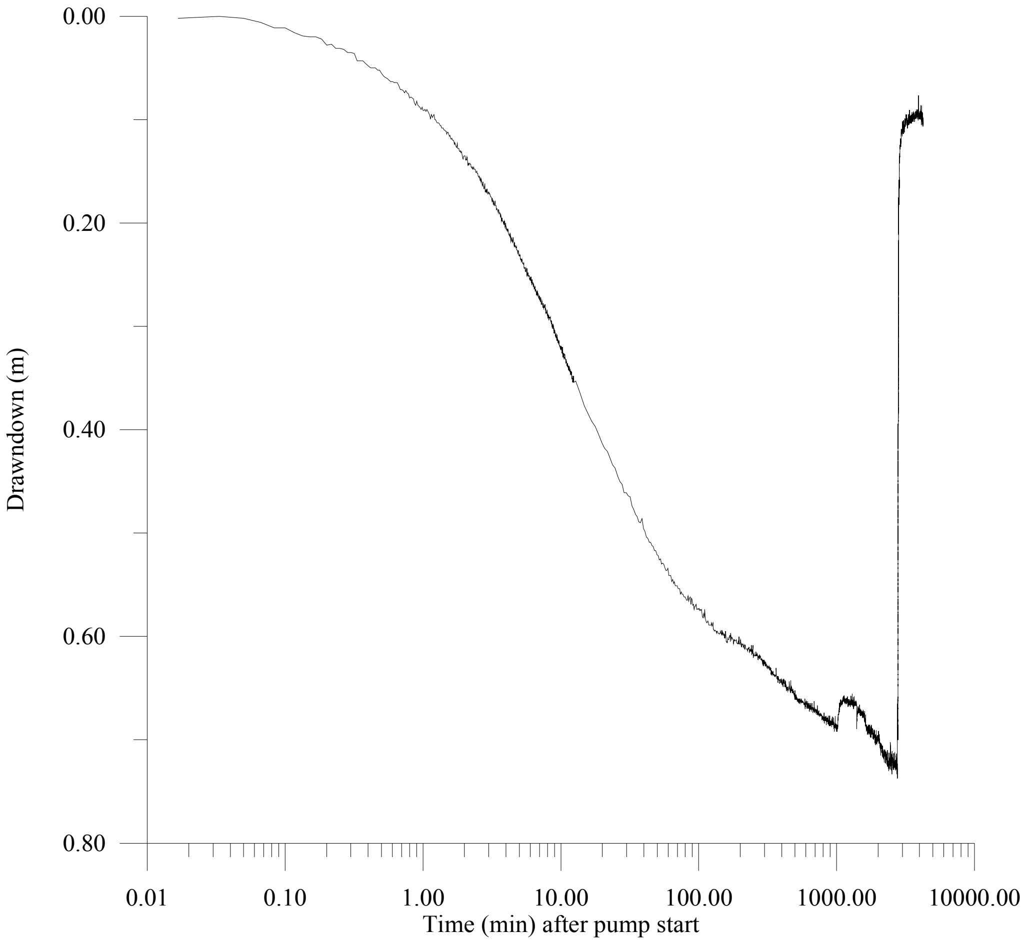


Figure A3-2. *Log-linear plot of drawdown versus time after pump start in monitoring well SFM0060. Pumping was terminated ~ 2 790 min after pump start.*

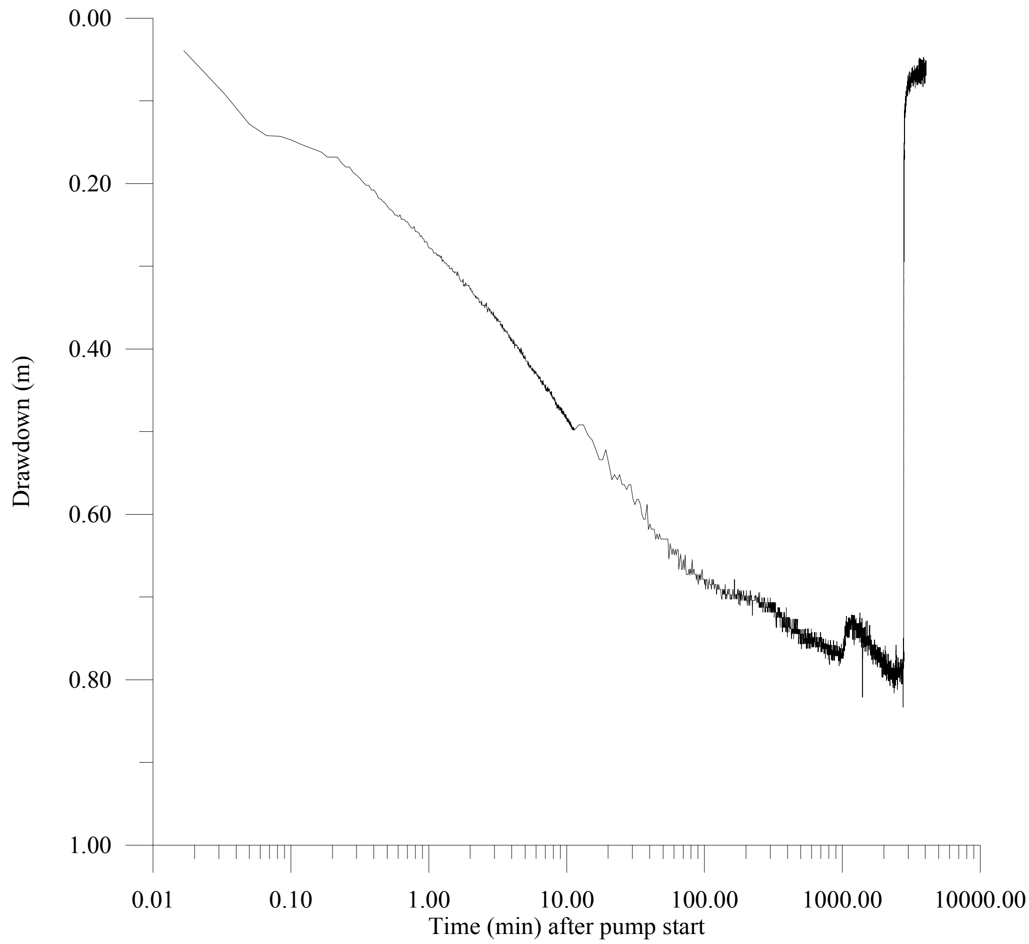


Figure A3-3. *Log-linear plot of drawdown versus time after pump start in pumping well SFM0061. Pumping was terminated ~ 2 790 min after pump start.*

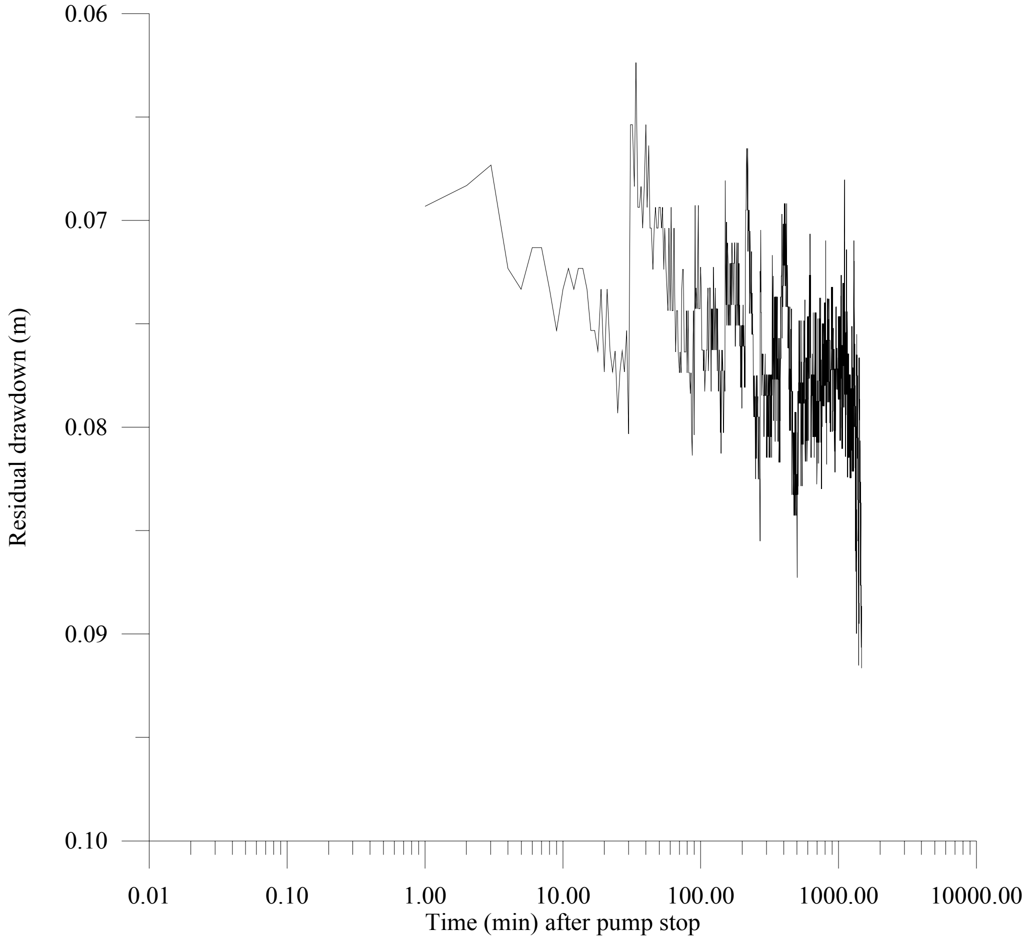


Figure A3-4. *Log-linear plot of residual drawdown versus time after pump stop in monitoring well SFM0059.*

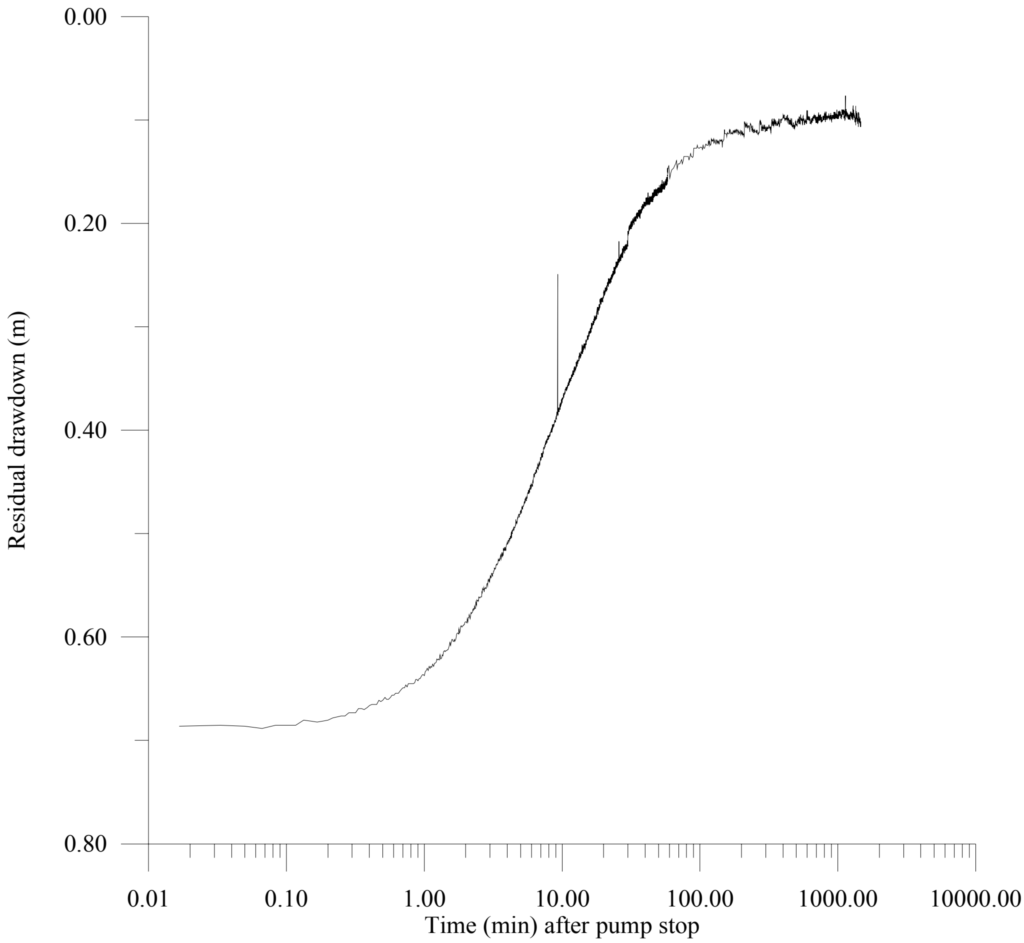


Figure A3-5. *Log-linear plot of residual drawdown versus time after pump stop in monitoring well SFM0060.*

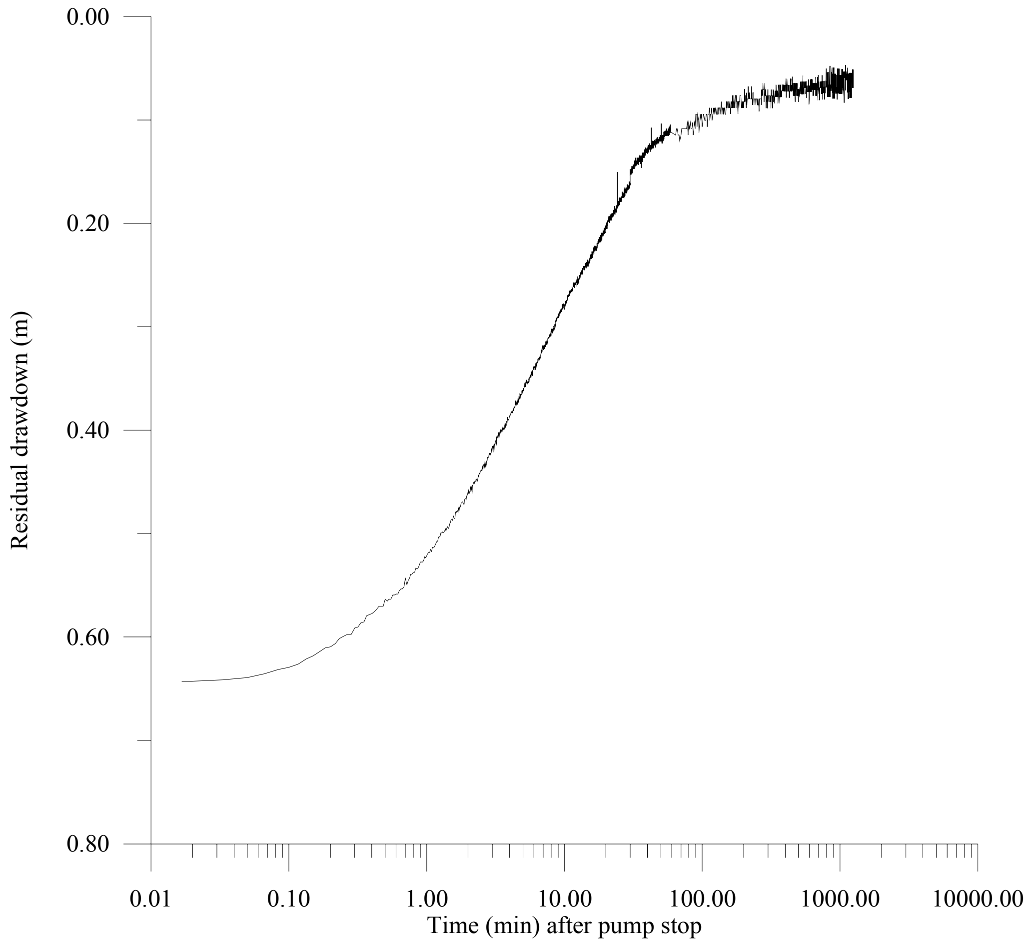


***Figure A3-6**. Log-linear plot of residual drawdown versus time after pump stop in pumping well SFM0061.*

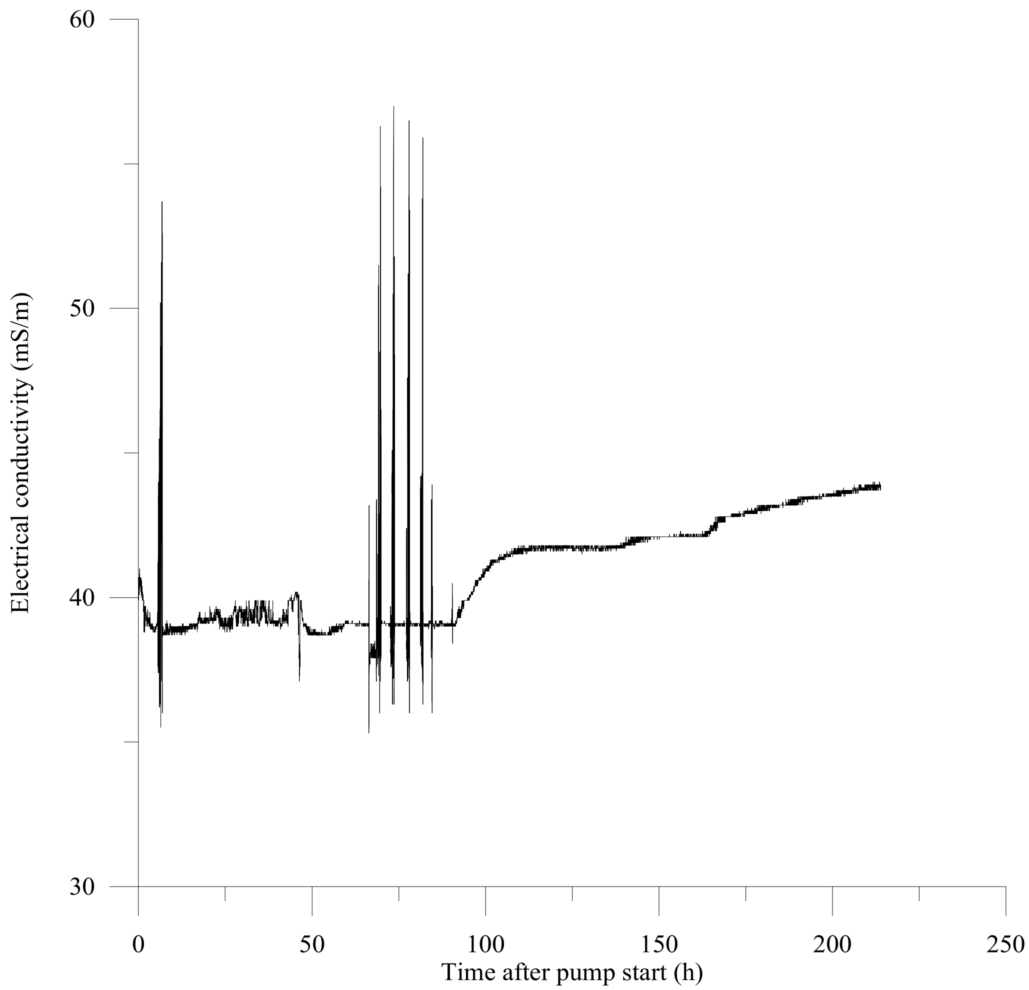


Figure A3-7. *Linear plot of electrical conductivity versus time after pump start in pumping well SFM0061. Pumping was terminated ~46.5 h after pump start. Indidual peak values have not been removed from the original data set.*

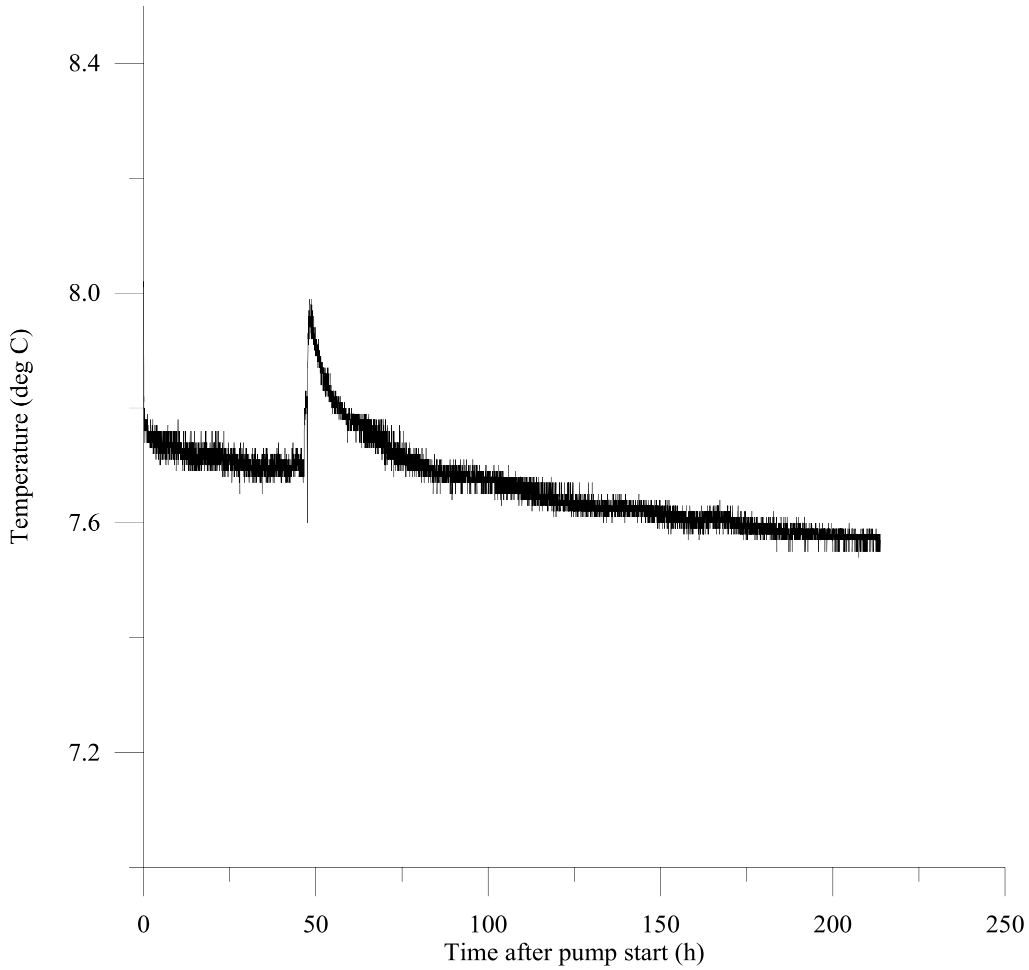


Figure A3-8. *Linear plot of temperature (° C) versus time after pump start in pumping well SFM0061. Pumping was terminated ~46.5 h after pump start.*

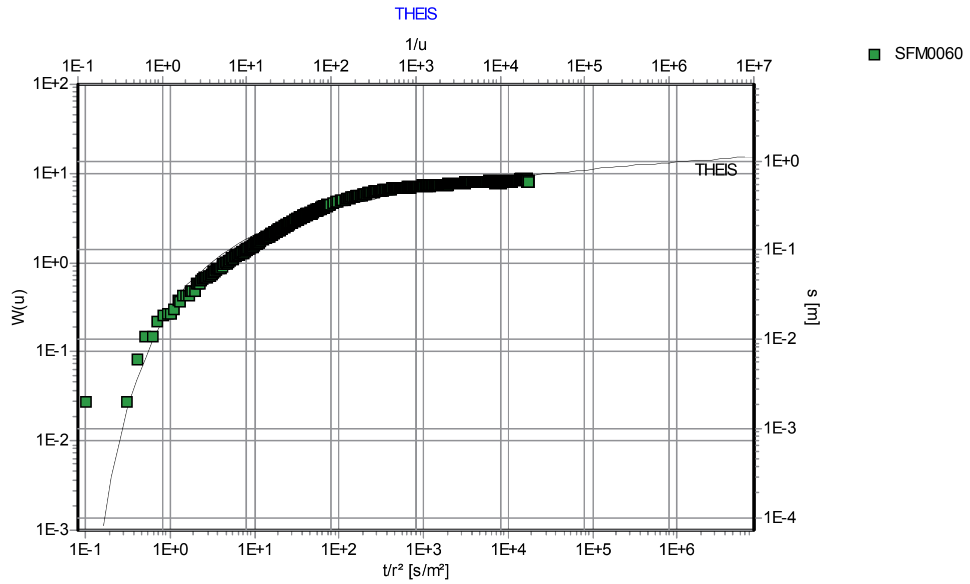


Figure A3-9. *Evaluation of the drawdown data from monitoring well SFM0060 using the Theis method.*

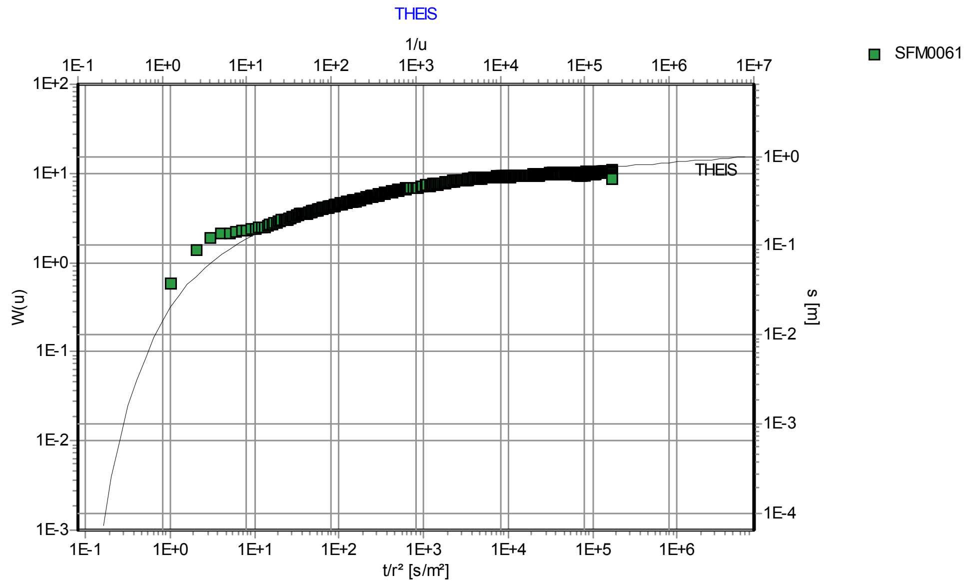


Figure A3-10. *Evaluation of the drawdown data from pumping well SFM0061 using the Theis method for pumping wells.*

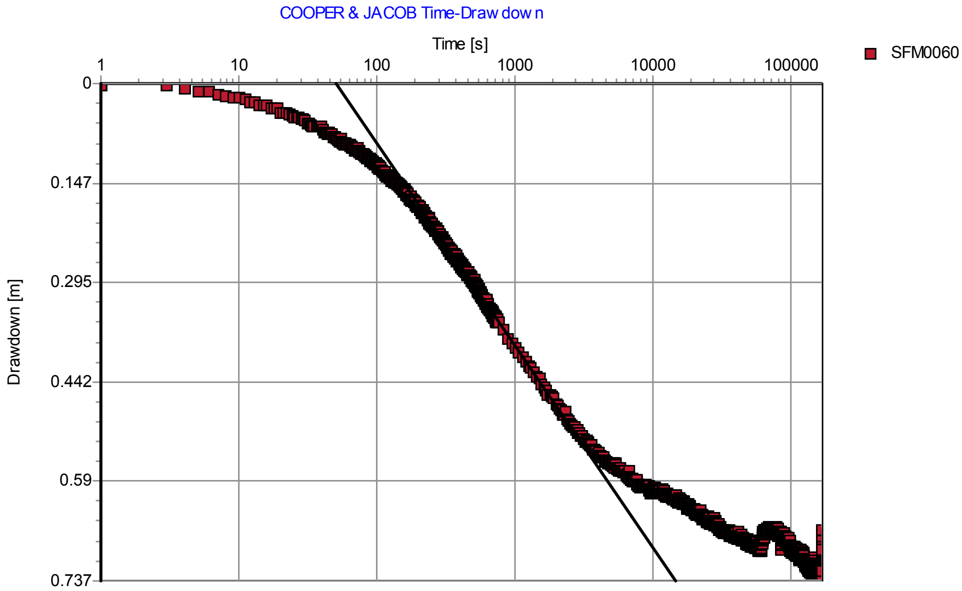


__Figure A3-11.__ Evaluation of the drawdown data from monitoring well SFM0060 using the Jacob method.

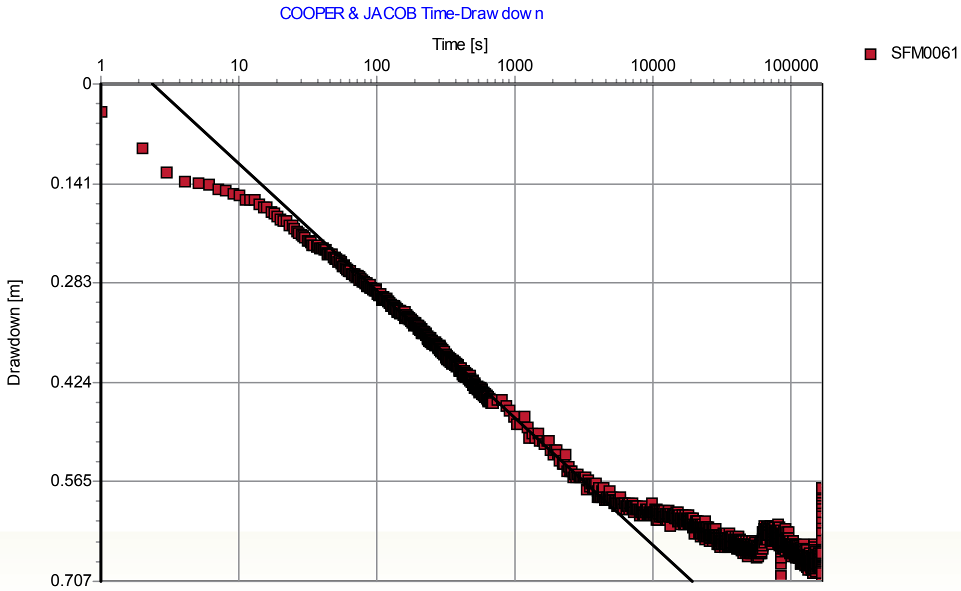


__Figure A3-12.__ Evaluation of the drawdown data from pumping well SFM0061 using the Jacob method for pumping wells.

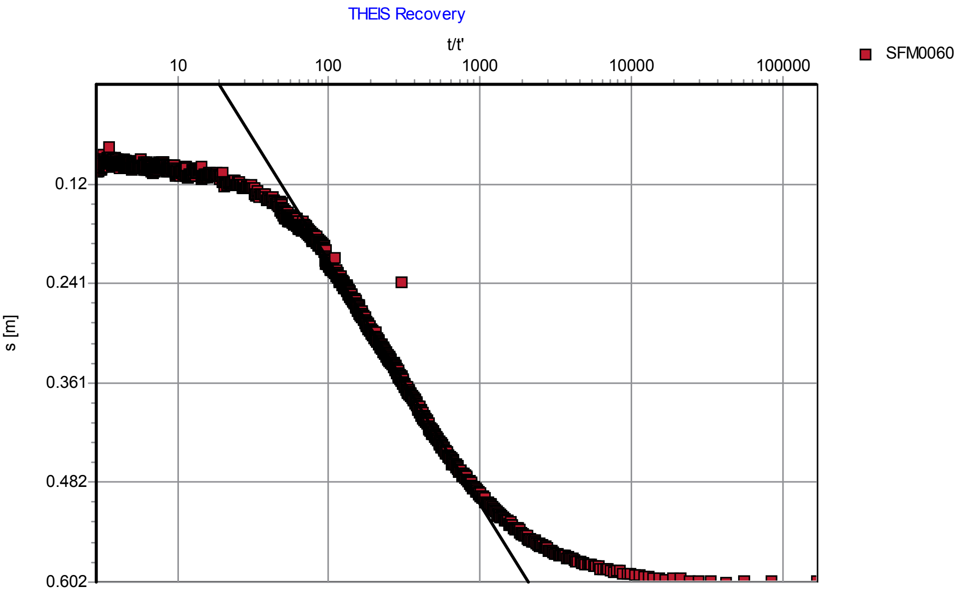


__Figure A3-13.__ Evaluation of the recovery data from monitoring well SFM0060 using the Theis recovery method.

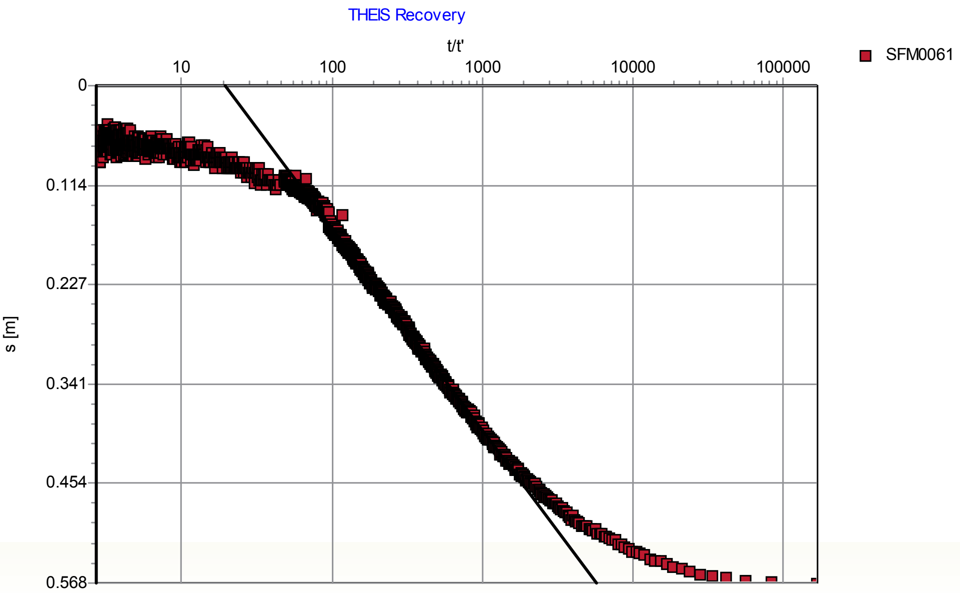


__Figure A3-14.__ Evaluation of the recovery data from pumping well SFM0061 using the Theis recovery method.