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Forsmark site investigation

Pumping test in well SFM0074

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Abstract

The performance, results and analysis of a pumping test in well SFM0074 in the Forsmark area during May 2004 are presented. The screen of the pumping well, located in the vicinity of Lake Bolundsfjärden, is installed across the soil-rock interface. The monitoring wells are located both on land and below Lake Bolundsfjärden. The pumping test is designed to provide data for the estimation of the transmissivity (T), the storativity (S) of the investigated area, and the hydraulic contact between groundwater and surface water.

The drawdown and recovery data from the pumping test were evaluated by the Theis method, the Jacob method, and the Theis recovery method. Further, in order to investigate potential leakage of lake water into the pumped aquifer during the pumping test, drawdown data from two of the monitoring wells were analysed using the Walton (Hantush & Jacob) method for leaky aquifers.

The evaluation gave values of T in the interval $2.18 \cdot 10^{-4} – 3.30 \cdot 10^{-3}$ m^2/s, whereas the interval for S is $2.23 \cdot 10^{-4}–2.28 \cdot 10^{-3}$ (–). Compared to data from the pumping well, somewhat higher values of T were obtained from evaluation of data from the monitoring wells. The higher T-values may be more representative for the actual aquifer properties. The results indicate a hydraulic contact in the form of leakage from Lake Bolundsfjärden into the pumped aquifer, but that this contact is limited by low-permeable bottom sediments. A (partly) alternative interpretation is that during the pumping test, the cone of influence reached Bolundsfjärden, which hence acted as a positive hydraulic boundary.

Sammanfattning

I föreliggande rapport presenteras genomförande, resultat och analys av ett pumpförsök i filterbrunn SFM0074 i Forsmarksområdet under maj 2004. Brunnsfiltret i pumpbrunnen, belägen i närheten av Bolundsfjärden, är installerat över gränsskiktet mellan jord och berg. Observationsrören är belägna både på land och under Bolundsfjärden. Pumpförsöket är utformat för att ge data för bedömning av transmissivitet (T),storativitet (S) och den hydrauliska kontakten mellan grund- och ytvatten i det undersökta området.

Avsänknings- och återhämtningsdata från pumpförsöket utvärderades med Theis metod, Jacobs method samt med Theis metod för återhämtning. För att undersöka potentiellt läckage av ytvatten till akviferen under testet, analyserades avsänkningsdata från ett av observationsrören i Bolundsfjärden med Waltons (Hantush & Jacob) metod för läckande akviferer.

Utvärderingen gav värden på T i intervallet $2{,}18 \cdot 10^{-4}$–$3{,}30 \cdot 10^{-3}$ m^2/s, och intervallet för S är $2{,}23 \cdot 10^{-4}$–$2{,}28 \cdot 10^{-3}$ (–). Jämfört med data från pumpbrunnen, erhölls något högre T-värden från utvärderingen av data från observationsrören. Resultaten indikerar att det finns en hydraulisk kontakt i form av läckage från Bolundsfjärden till akviferen, men att denna kontakt begränsas av låg-permeabla bottensdiment. En (delvis) alternativ tolkning är att avsänkningstratten under pumptestet nådde Bolundsfjärden, som på så sätt kom att utgöra en positiv hydraulisk gräns.

Contents

1 Introduction

This report presents the methodology, results and analysis of a pumping test performed in well SFM0074 in the Forsmark area during the period May 11–24, 2004. The work was carried in accordance with activity plan AP PF 400-04-50, and is part of the site investigation at Forsmark. After the pumping was terminated, the recovery of the groundwater level was monitored for 8 days (until June 1).

The pumping well SFM0074 and the monitoring wells SFM0062–0063 were installed during spring 2004 /1/, whereas the monitoring wells SFM0031–0032 were installed and subjected to slug tests during spring 2003 /2, 3/. Moreover, slug tests were performed in monitoring wells SFM0062–0063 during spring 2004 /4/. No previous tests have been made in the pumping well SFM0074. Simultaneously as the pumping test, the water level was also monitored in the bedrock boreholes HFM13–15 (data provided by SKB). The locations of the pumping well, the monitoring wells, and the bedrock boreholes are shown in Figure 1-1.

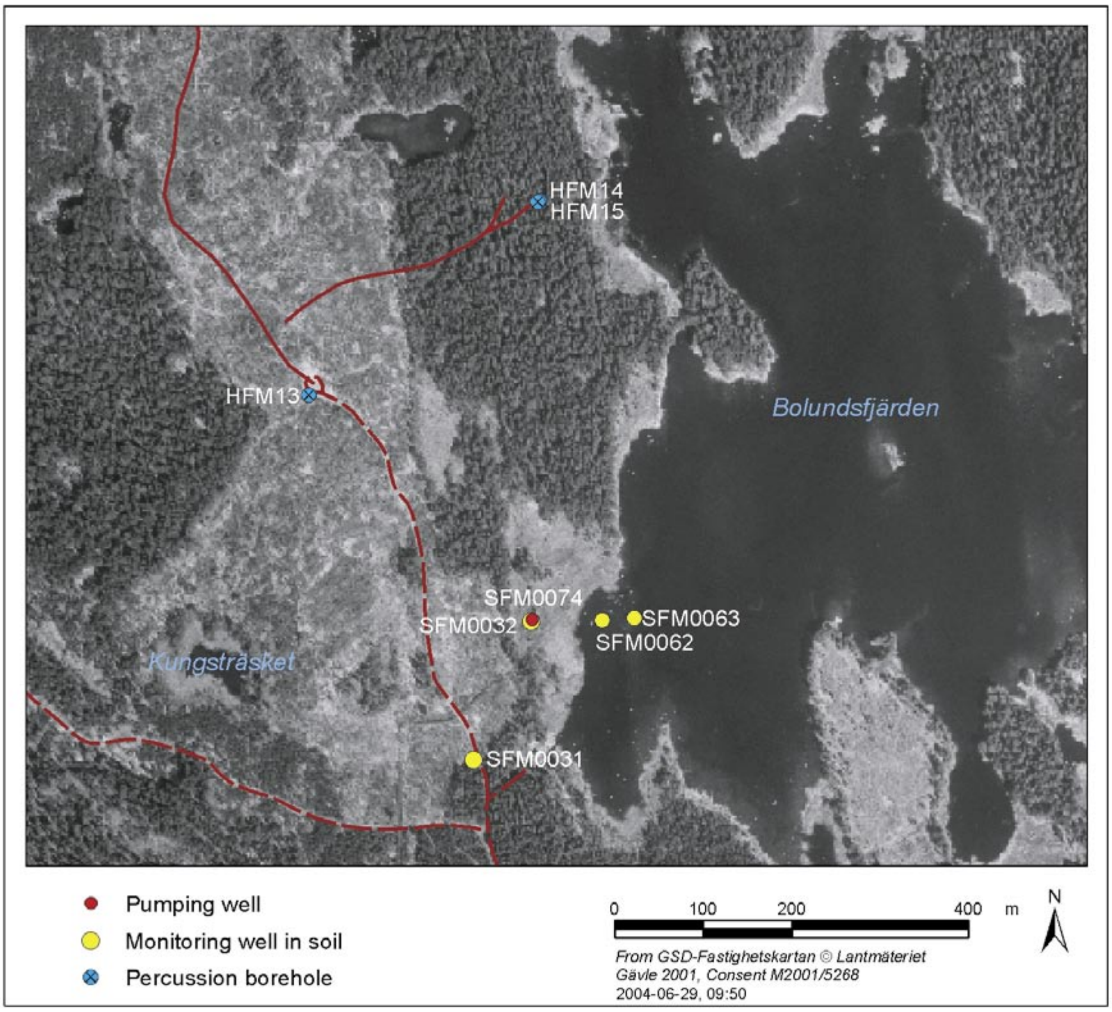

Figure 1-1. *Map showing the locations of the pumping well SFM0074, and the monitoring wells installed in soil (SFM0031–0032) and below open water (SFM0062–0063). The map also shows the locations of the bedrock boreholes HFM13–15.*

In the pumping well SFM0074, a custom-made drill casing (outer Ø 103 mm) was installed and used as a combined screen and pipe. The filter screen (open area 2.3 dm^2) is perforated by openings (c/c 30 mm, length 40 mm and width 3 mm) at a length of 2.70 m, of which 2.40 m are installed in rock below the soil-rock interface. The open borehole (Ø 57 mm) continues approximately 10 m further down into the bedrock.

In Table 1-1 controlling documents for performing the activities are listed. Both activity plans and method descriptions are SKB´s internal controlling documents. The data from the activity are stored in SKB´s database SICADA, field note no Forsmark 342.

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

Activity plan	Number	Version
Provpumpning av jord-bergbrunn SFM0074	AP PF 400-04-50	1.0
Method descriptions	**Number**	**Version**
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

2 Objective and scope

The overall objectives of the hydrogeological investigations in the Forsmark area are described in /5/ and /6/. The specific objective of the performed pumping test is to obtain data for estimation of the transmissivity (T) and the storativity (S) of the integrated soil-rock in the investigated area. Another objective is to provide information concerning the hydraulic contact between the investigated aquifer and Lake Bolundsfjärden.

The investigation involves a hydraulic (pumping) test in the filter well SFM0074, applying a discharge rate of ~2 m^3/h. The pumping test was terminated after approximately 13 days, and the recovery of the water level in the pumping well and seven other wells was observed for approximately 8 days after pump stop.

Basic technical data of the well SFM0074, in which the pumping test was performed, are given in Table 2-1. In the table, the reference level is the top of the stand pipe. The table also provides data of the four monitoring wells (SFM0031–0032 and SFM0062–0063). Table 2-2 gives the coordinates of the wells.

Table 2-1. Technical data of the filter well SFM0074, and the monitoring wells SFM0031–0032 and SFM0062–0063 (data from /1, 2/).

Filter (pumping) well		**Stand pipe**		**Screen (test section)**		
	Borehole diameter, d_w (mm)	Inner diameter, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[2] (m)	Depth to borehole seclow[2] (m)	Screen length (m)
SFM0074	1031	101	0	2.00	4.70	2.70
Monitoring well		**Stand pipe**		**Screen (test section)**		
	Borehole diameter, d_w (mm)	Inner diameter, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[2] (m)	Depth to borehole seclow[2] (m)	Screen length (m)
SFM0031	103	50	0	3.50	4.50	1.00
SFM0032	103	50	0	3.00	4.00	1.00
SFM0062	60.3	51.3	0	3.25	3.65	0.40
SFM0063	60.3	51.3	0	3.22	3.72	0.50

1 2.40 m from the soil-rock interface, the open borehole (Ø 57 mm) continues approximately 8 m further down into the bedrock. The screen of the pumping well SFM0074 has an outer and inner diameter of 114 and 101 mm, respectively, and a slot size of 3*40 mm.

2 Secup and seclow are upper and lower limits of the well screen, respectively.

Table 2-2. Coordinates (coordinate system RT 90 2.5 gon W 0: –15 for X and Y, and RHB70 for Z) and type for the filter well SFM0074 and the monitoring wells.

Borehole	Northing (m)	Easting (m)	Elevation[1] m.a.s.l.	Type	Distance from the pumping well SFM0074 (m)
SFM0074	6698839.08	1631738.02	0.82	Pumping well, not at core drill site	–
SFM0031	6698681.55	1631661.09	2.63	Groundwater monitoring well, not at core drill site	175.31
SFM0032	6698838.26	1631725.79	1.63	Groundwater monitoring well, not at core drill site	12.26
SFM0062	6698838.72	1631807.99	1.18	Groundwater monitoring well below open water	69.97
SFM0063	6698839.05	1631851.41	1.28	Groundwater monitoring well below open water	113.39

[1]Top of the stand pipe.

3 Equipment

3.1 Description of equipment

For the 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 COND 315i conductivity meter with TetraCon® 325 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.

3.2 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	
	Resolution	mS/m	
	Accuracy	% of measurement range	0 to 141.3
			0.1[4]
			1

[1] Centimetres water column.

[2] One of the two Divers® used in pumping well SFM0074 and monitoring well SFM0062 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 filter well SFM0074 and monitoring well SFM0062.

[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)
SFM0074	3.3; 10.0[1]
SFM0031	4.0
SFM0032	4.0
SFM0062	3.0
SFM0063	3.0

[1]Two Divers® were installed at two different depths.

4 Execution

4.1 Preparations

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, Version 1.0 (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 test, 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 Execution of field work

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 the 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 /7/.

Figure 4-1 illustrates the pumping test arrangement.

Figure 4-1. *Pumping well SFM0074, flow meter, and hose for discharge of water from the well to Lake Bolundsfjärden.*

The decline (or recovery) of the water level as function of time depends on the pumping rate, hydraulic contact between the well and the surrounding geological material, the hydraulic properties (hydraulic conductivity and storativity) of the geological formation, and the boundary conditions for groundwater flow. The pumping was terminated after approximately 13 days, and the recovery of the water level was observed for approximately 8 days after pump stop**.**

A step-drawdown pumping test was performed prior to the pumping test. The purpose of a step-drawdown pumping test is to determine the proper abstraction rate for the subsequent pumping test.

The test procedure is briefly described below:

1. Function checks and cleaning of pumps, Divers® and all other equipment that is lowered into the wells according to SKB MD 600.004, Version 1.0 (Method Instruction for Cleaning of Borehole Equipment and certain Ground-based Equipment) at level one.

2. Installation of the pump in the pumping well and connection to a water-flow meter.

3. Connection of the pump to stationary electrical supply and installation of a plastic hose for discharge of pumped water to Lake Bolundsfjärden.

4. Manual measurements of the water levels in the pumping well, the monitoring wells and Lake Bolundsfjärden. Measurements of the depth of the wells.

5. Emptying of the water in the monitoring wells (SFM0032, SFM0062–0063, and SFM0074) followed by water sampling.

6. Installation of Divers® in the wells.

7. 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.

8. Termination of step-drawdown pumping test, recovery of the water level in the pumping well. Determination of proper abstraction rate during the pumping test in consultation with the Activity Leader.

9. Performance of the pumping test. Manual measurements of the water level in the pumping well and the monitoring wells as a back up and check of the automatic recordings.

10. Sampling of water from the pumping well during the pumping test. Water sampling in the monitoring wells after the stop of recovery measurements.

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

12. Termination of pumping test (pump stop) after approximately 13 days.

13. Continued measurements of pressure, temperature and electrical conductivity in the pumping well and the monitoring wells for approximately 8 days after pump stop.

The sampling intervals of the Divers® during the pumping test are given in Table 4-1. Note that the exact lengths of the periods with certain sampling intervals vary between the individual wells. Before changing the sampling interval, the Diver® is stopped with the PC, and data are saved in a separate raw data file (cf Appendix 1).

Table 4-1. Sampling intervals for pressure-, temperature- and electrical conductivity measurements during the pumping test.

Time from start of test (min)	Sampling interval (s)
–10 to 0	1
0 to 180	1
180 to 10 080 (1 week)	30
10 080 to 30 237 (21 days)	60 (120 and 300 for SFM0062 and 0063)

The pumping test is summarized in Table 4-2. Water sampling was performed prior to and during the pumping test. The water sampling is summarized in Table 4-3.

Table 4-2. Summary of pumping test performed in filter well SFM0074.

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)
SFM0074	2004-05-11 16:00:00	18 425	1363 (upper Diver®)	0.26	$5.57 \cdot 10^{-4}$
SFM0031	–	–	1402	1.21	
SFM0032	–	–	1390	1.07	
SFM0062	–	–	11 812	0.51	
SFM0063	–	–	11 810	0.80	

1 Swedish Summer Time (Swedish Standard Time + 1 h).

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 Diver® is lifted out from the particular well.

3 The reference point is the top of the stand pipe.

4 Qp denotes flow rate during the test. Qp varied between $4.70 \cdot 10^{-4}$ m^3/s and $6.10 \cdot 10^{-4}$ m^3/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 SFM0074, SFM0032, SFM0062–0063, and in Bolundsfjärden.

Well	Sample no.	Sampling date and time[1] (YYYY-MM-DD hh:mm)
SFM0074[2]	8471	2004-05-11 10:45
	8467	2004-05-11 19:15
	8470	2004-05-12 15:00
	8464	2004-05-13 15:04
	8462	2004-05-14 14:05
	8465	2004-05-16 11:25
	8463	2004-05-17 11:05
	8461	2004-05-18 10:35
	8494	2004-05-19 15:07
	8495	2004-05-21 15:55
	8496	2004-05-24 10:55
SFM0032	8469	2004-05-11 10:30
SFM0062	8468	2004-05-11 11:05
	8498	2004-05-28 14:05
SFM0063	8466	2004-05-11 11:30
Bolundsfjärden	8460	2004-05-11 11:50

1Swedish Summer Time (Swedish Standard Time + 1 h).

2The flow rate during the sampling was on average $5.57 \cdot 10^{-4}$ m^3/s.

4.3 Data handling

Raw data from the Divers® (internal *.mon format) were 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 in open air during the test (obtained from a Diver® designed for measurement of the barometric pressure), (2) identification of the exact starting and termination times of the pumping test, and (3) correction for the small differences in depth for cases where either two Divers® were used (SFM0074) or when the Diver® was raised and lowered during the test. During the pumping test, the pre-test air-pressure data from the Diver® were adjusted, using air-pressure data (available from www.skb.se) from one of the on-site meteorological stations; this station measures the atmospheric air pressure twice per hour.

A list of all generated raw and primary data files is given in Appendix 1. 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_bolundsfjarden_2004.xls and HY645 - PLU_Interference test-obs.holes_bolundsfjarden_2004.xls) for quality control and storage in SKB´s SICADA database, field note no Forsmark 342.

4.4 Analyses and interpretations

The following sections provide a short description of the methods used for analysis and interpretation of the data obtained during the pumping test. For a more detailed description of the methods used, see /7/ and /8/.

4.4.1 Theis method

The Theis method is designed to estimate the transmissivity (T) and storativity (S) of an aquifer /7/. 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 logaritmic scale on both axes. Subsequently, a so-called type curve of W(1/u) (or W(u)) versus 1/u is plotted in the same diagramme, and the mesasured 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 radial distance from the pumping well to the observation 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. The theory of the method and practical recommendations for its application are given in /7/.

For the present analysis according to the Theis method, the computer program Aquifer Test Ver 3.0 was used /9/. The program allows for both automatic and manual fitting of the type curve to the measured data.

4.4.2 Jacob method

The Jacob method utilizes the fact that the well function W(u) in Section 4.4.1 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 Section 4.4.1), 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 /7/.

For the present analysis according to the Jacob method, the computer program Aquifer Test Ver 3.0 was used /9/. The program allows for both automatic and manual fitting of the type curve to the measured data.

4.4.3 Theis recovery method

The Theis recovery method is designed to estimate the transmissivity T of an aquifer, using data from the recovery phase following the pump stop /7/. The method can be used to analyse recovery data from both monitoring wells and pumping wells, but it is best suited for cases where stationary conditions have been attained during pumping. In the method, the measured data of the residual drawdown s(t’/t) = h0-h(t’/t) is plotted in a diagram with a logarithmic scale on the time axis. s is the residual drawdown and h0 is the water level at pump start. For the ratio t’/t (dimensionless time), t’ is the sum of elapsed times from pump start and pump stop; the latter is denoted 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 /7/.

For the present analysis according to the Theis recovery method, the computer program Aquifer Test Ver 3.0 was used /9/. The program allows for both automatic and manual fitting of a straight line to the measured data.

4.4.4 The Walton (Hantush & Jacob) method for leaky aquifers

In order to investigate possible leakage of lake water into the pumped aquifer during the pumping test, the Walton (Hantush & Jacob) method was used./10/, taking into account leakage from an upper to a lower aquifer. In particular, the method was used to analyse drawdown data from monitoring well SFM0032, installed on land close to Lake Bolundsfjärden, and SFM0062, installed below open water in Lake Bolundsfjärden.

Similar to the Theis method (see section 4.4.1), the method involves fitting of measured drawdown data to a type curve. However, the type curve is now plotted as W(1/u, r/L) (or W(u, r/L), where the parameters u and r have the same definitions as in the Theis method. The parameter L is defined as

$$L = \sqrt{Kb\frac{b'}{K'}}$$

where b is the saturated aquifer thickness, and b'/K' denotes the thickness of the low-permeable layer divided by its hydraulic conductivity. The well function W(u, r/L) is given as

$$W(u,r/L) = \int_u^\infty \frac{\exp(-xr^2)}{4L^2x}\,dx$$

The theory of the method and practical recommendations for its application are given in /7, 10/. For the present analysis according to the Walton method, the computer program Aquifer Test Ver 3.0 was used /9/. The program allows for both automatic and manual fitting of the type curve to the measured data.

4.5 Nonconformities

According to activity plan AP PF 400-04-50, pump stop was planned 72 hours after pump start. Based on the observed drawdown in the wells at that point, it was agreed by the Activity Leader to extend the pumping test to obtain more data for evaluation of the hydraulic contact between the aquifer and the lake. The pumping was prolonged to approximately 13 days.

5 Results

5.1 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 (m²/s) Transmissivity.

K (m/s) Hydraulic conductivity.

S (–) Storativity.

5.2 Results

5.2.1 Drawdown and recovery

Figures 5-1 to 5-5 below show manual measurements of the water level (m.a.s.l.) in the pumping well (SFM0074) and the monitoring wells (SFM0031–0032, and SFM0062–0063; for the latter two wells, the lake water level is also shown) as function of time from pump start. The pumping was stopped 18 425 minutes from pump start.

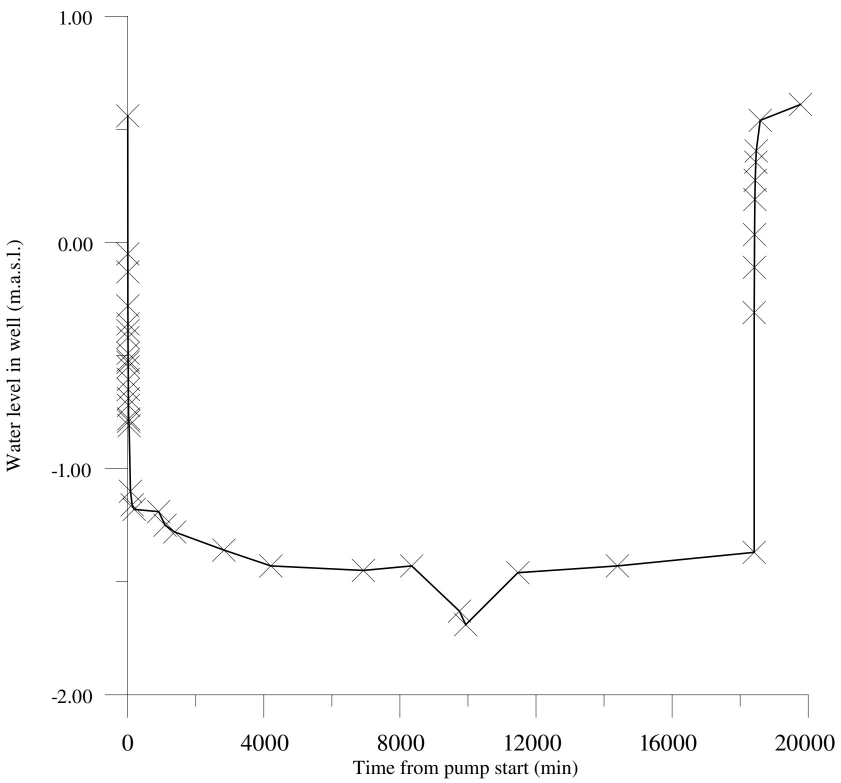

Figure 5-1. *Manual measurements of the water level in the pumping well SFM0074 as function of time after pump start.*

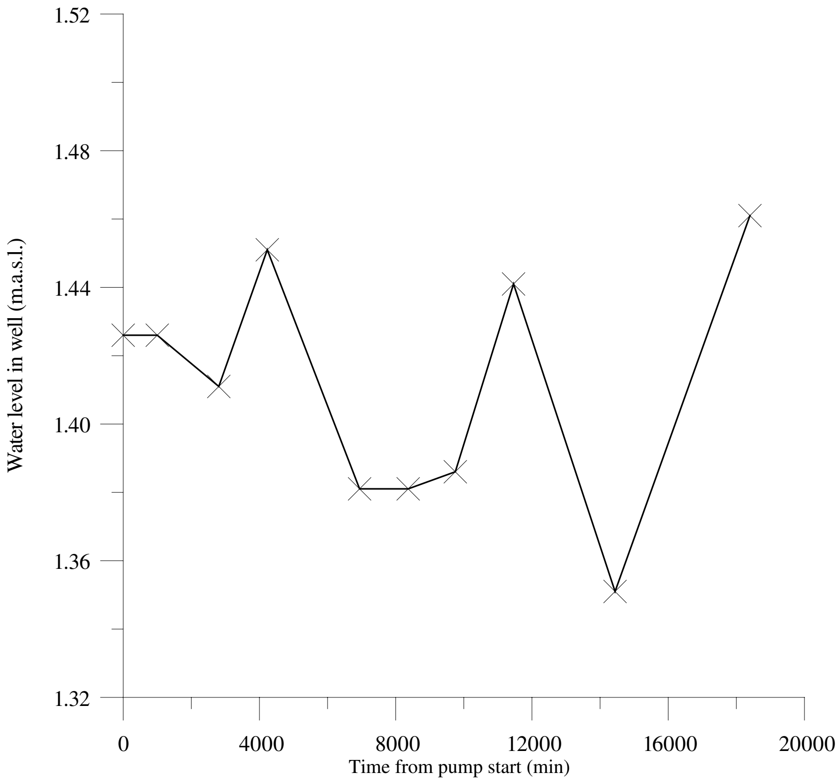

Figure 5-2. *Manual measurements of the water level in monitoring well SFM0031 as function of time after pump start.*

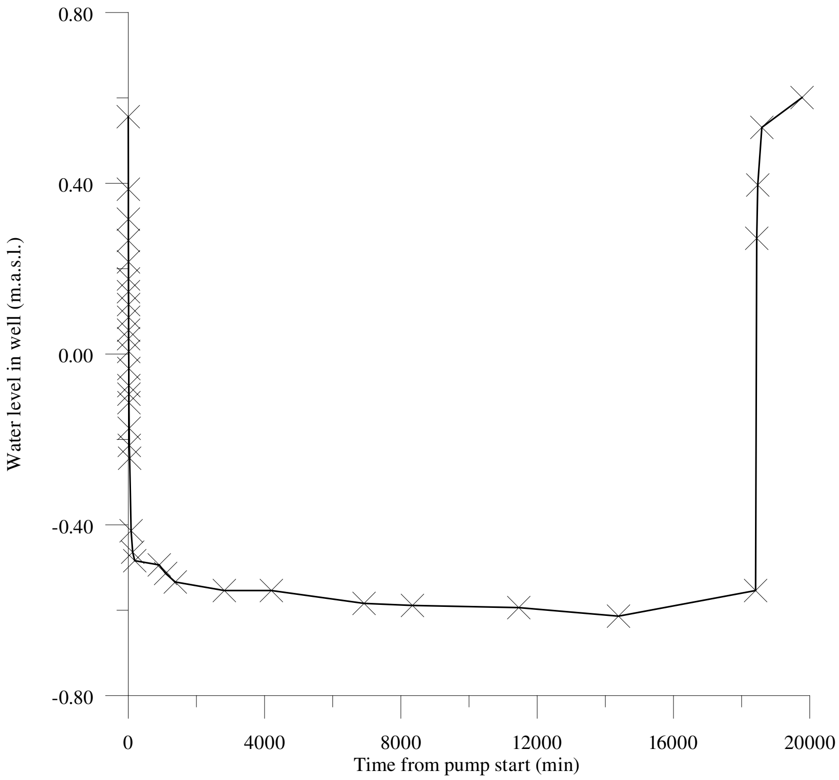

Figure 5-3. *Manual measurements of the water level in monitoring well SFM0032 as function of time after pump start.*

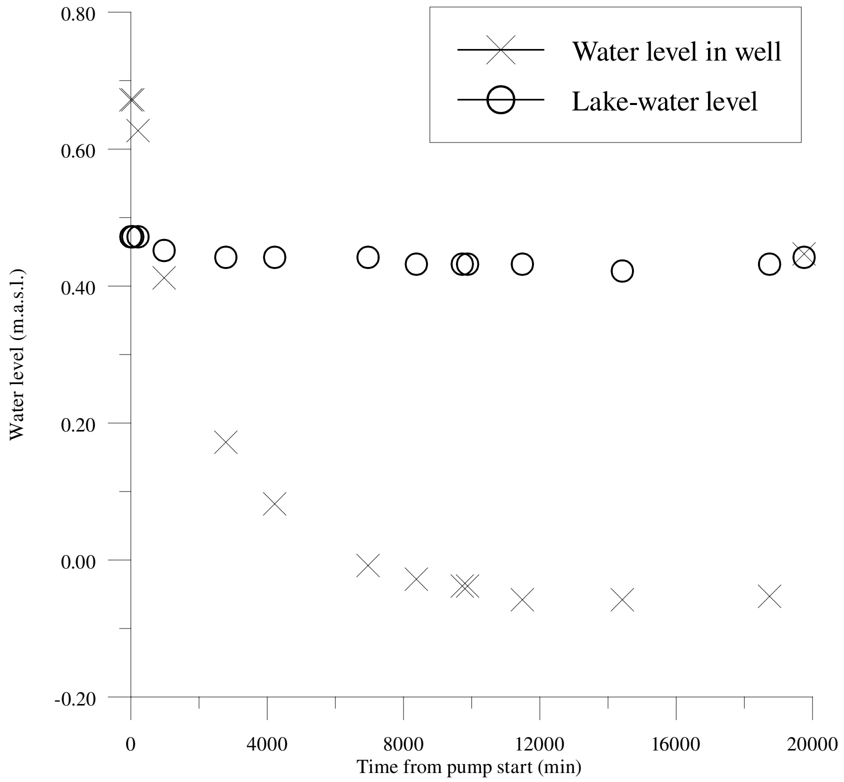

Figure 5-4. *Manual measurements of the water level in monitoring well SFM0062 and the lake-water level as function of time after pump start.*

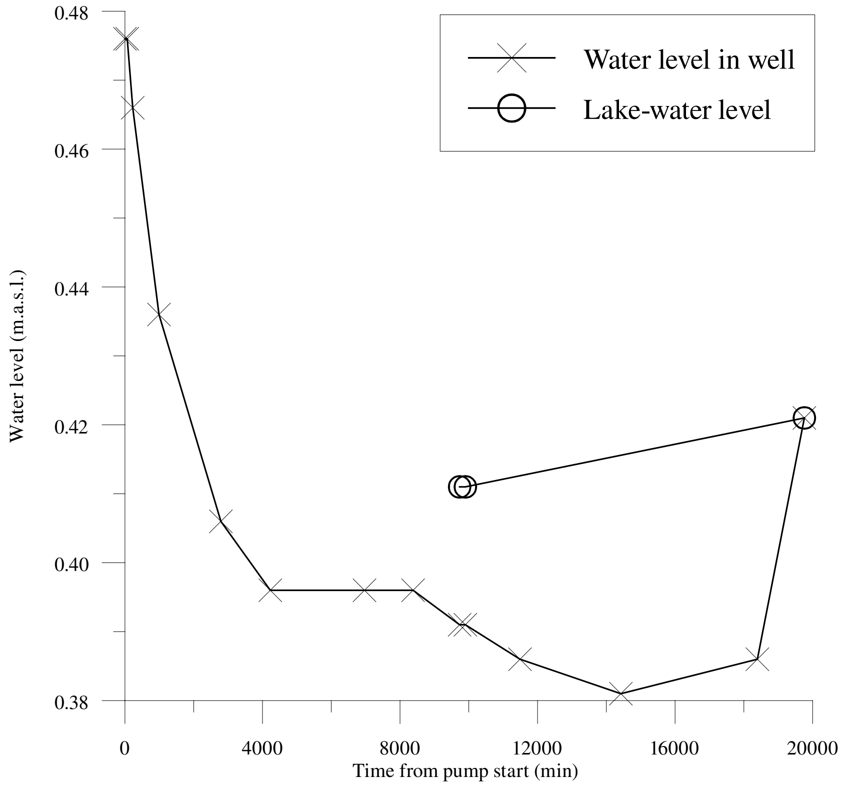

Figure 5-5. *Manual measurements of the water level in monitoring well SFM0063 and the lake-water level as function of time after pump start.*

The water level measurements show a relatively large drawdown soon after pump start in the pumping well SFM0074 (Figure 5-1) and in monitoring well SFM0032 (Figure 5-3). The water level in monitoring well SFM0031 (Figure 5-2) fluctuated during the pumping test, and these data hence provide a poor basis for parameter evaluation. The water level in monitoring well SFM0063 (Figure 5-5) decreased after pump start, but the drawdown was rather small. For monitoring well SFM0062 (Figure 5-4), the measurements show a gradual transition, rather than instant, to stationary conditions which may indicate local leakage of lake water into the pumped aquifer /8/. For monitoring well SFM0032 (Figure 5-3), the transition was of a more instant nature, in turn indicating that the cone of influence reached a hydraulic boundary /8/; see also the discussion on potential lake water leakage and impact of hydraulic boundaries in section 5.2.3.

Even though the data have not been analysed in any detail in the present context, the groundwater levels measured in the bedrock boreholes HFM13–15 (data provided by SKB; not shown in the present report) did not demonstrate any drawdown and/or recovery that seem to be associated with the performed pumping test. Hence, it appears that the cone of influence did no reach these wells during the test, and the data from HFM13–15 are not discussed further.

5.2.2 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 diagram in Appendix 2.

Table 5-1. 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	SFM0074[1]	[3]$2.49\cdot10^{-4}$	$5.61\cdot10^{-5}$	–
	SFM0031	[3]$2.73\cdot10^{-3}$	$5.61\cdot10^{-4}$	[3]$9.97\cdot10^{-4}$
	SFM0032	$3.07\cdot10^{-4}$	$6.91\cdot10^{-5}$	$2.23\cdot10^{-4}$
	SFM0062	$2.93\cdot10^{-4}$	$6.60\cdot10^{-5}$	$1.44\cdot10^{-3}$
	SFM0063	[3]$1.65\cdot10^{-3}$	$3.71\cdot10^{-4}$	[3]$2.28\cdot10^{-3}$
Jacob	SFM0074[1]	$2.65\cdot10^{-4}$	$5.96\cdot10^{-5}$	–
	SFM0031	$3.30\cdot10^{-3}$	$7.44\cdot10^{-4}$	$8.40\cdot10^{-4}$
	SFM0032	[3]$2.47\cdot10^{-4}$	$5.57\cdot10^{-5}$	[3]$2.45\cdot10^{-4}$
	SFM0062	$2.43\cdot10^{-4}$	$5.47\cdot10^{-5}$	[3]$1.75\cdot10^{-3}$
	SFM0063	$2.17\cdot10^{-3}$	$4.89\cdot10^{-4}$	$1.60\cdot10^{-3}$
Theis recovery[2]	SFM0074	$2.30\cdot10^{-4}$	$5.17\cdot10^{-5}$	–
	SFM0031[4]	–	–	–
	SFM0032	$2.18\cdot10^{-4}$	$4.92\cdot10^{-5}$	–
	SFM0062	[3]$2.45\cdot10^{-4}$	$5.53\cdot10^{-5}$	–
	SFM0063	$1.41\cdot10^{-3}$	$3.18\cdot10^{-4}$	–

[1] Using drawdown data from a pumping well, the method is only suited to estimate the transmissivity T and hydraulic conductivity K.

[2] The method only provides data on transmissivity T and hydraulic conductivity K.

[3] Transmissivity and storativity value delivered for storage in the SICADA database.

[4] It was not possible to fit the recovery data.

5.2.3 Potential impact of hydraulic boundaries and lake-water leakage

In addition to estimation of the hydraulic aquifer parameters, indications of the possible hydraulic contact between the pumped aquifer and Lake Bolundsfjärden were analysed. In principle, this contact can be in the form of a distinct hydraulic boundary reached by the expanding cone of influence of the pumping test or as a leakage through the bottom sediments which increases as the difference in hydraulic head over the sediments increases. These two processes are usually manifested in rather similar ways in pumping test drawdown curves, and are therefore difficult to discern in practice.

Figure 5-6 illustrates the result of the curve-fitting procedure according to the Walton (Hantush & Jacob) method for monitoring well SFM0032. In cases where leakage takes place, the drawdown data typically level away too much in order to obtain a good fit to the standard type curve associated with the Theis method.

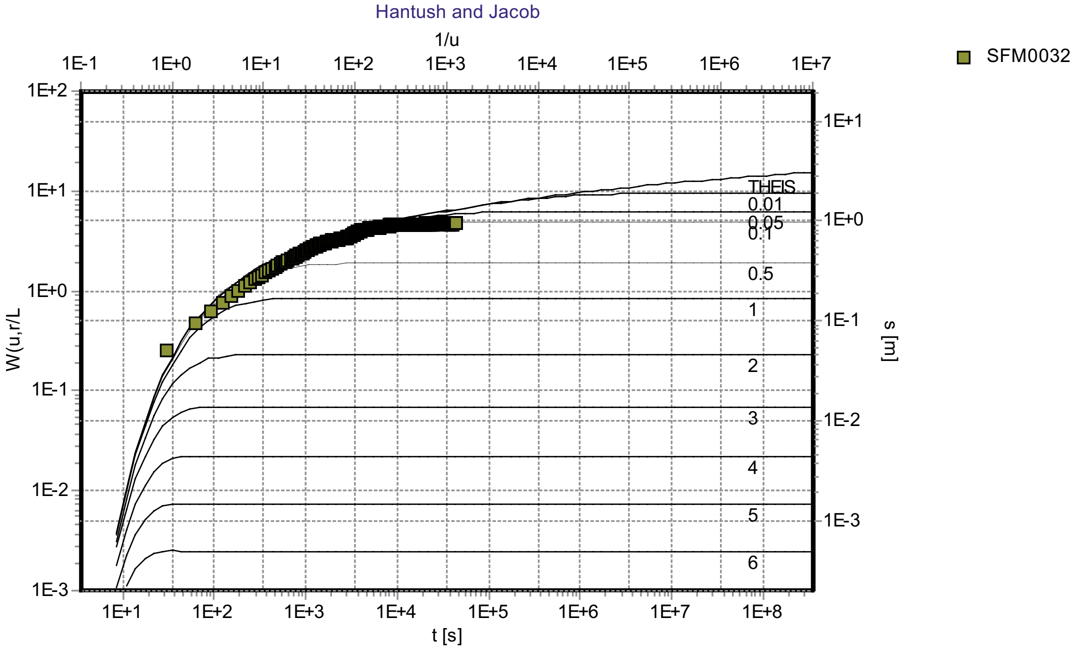

Figure 5-6. *Evaluation of the drawdown data from monitoring well SFM0032 using the Walton (Hantush & Jacob) method.*

In the Walton method (Figure 5-6), there is one type curve for each ratio r/L, and the type curve approaches the standard Theis curve as r/L decreases (i.e. for increasing b′ and/or decreasing K′). As seen in Figure 5-6, the best fit is obtained to the type curve associated with r/L = 0.1. Using r = 12.26 m (Table 2-2), b = 2.70 m (Table 2-1), and b′ = 0.5 m, we obtain a ratio r/L corresponding to a ratio K/K′ ≈ 10^4. It should be noted that the aquifer thickness (b) is approximated by the screen length of the pumping well, and that the value of b′ is assumed being equal to the thickness of the gyttja layer identified during drilling of monitoring well SFM0062 /1/. The definition of the parameter L (see above) shows that the sensitivity of the interpreted ratio K/K′ to the approximated parameters b and b′ is inverse and linear, so that a doubling of b or b′ implies a 50% reduction of the ratio K/K′.

Figure 5-7 (also shown in Figure A2-4 in Appendix 2) illustrates the corresponding results for monitoring well SFM0062. In this case a rather good fit is also obtained to the standard type curve (i.e. r/L = 0) associated with the Theis method.

As seen in Figure 5-7, the best fit is obtained to the type curve associated with r/L = 0.5. Using r = 69.97 m (Table 2-2), b = 2.70 m (Table 2-1), and assuming that b′= 0.5 m (see discussion after Figure 5-6), in this case we obtain a ratio r/L corresponding to a ratio K/K′ ≈ $1.5 \cdot 10^4$.

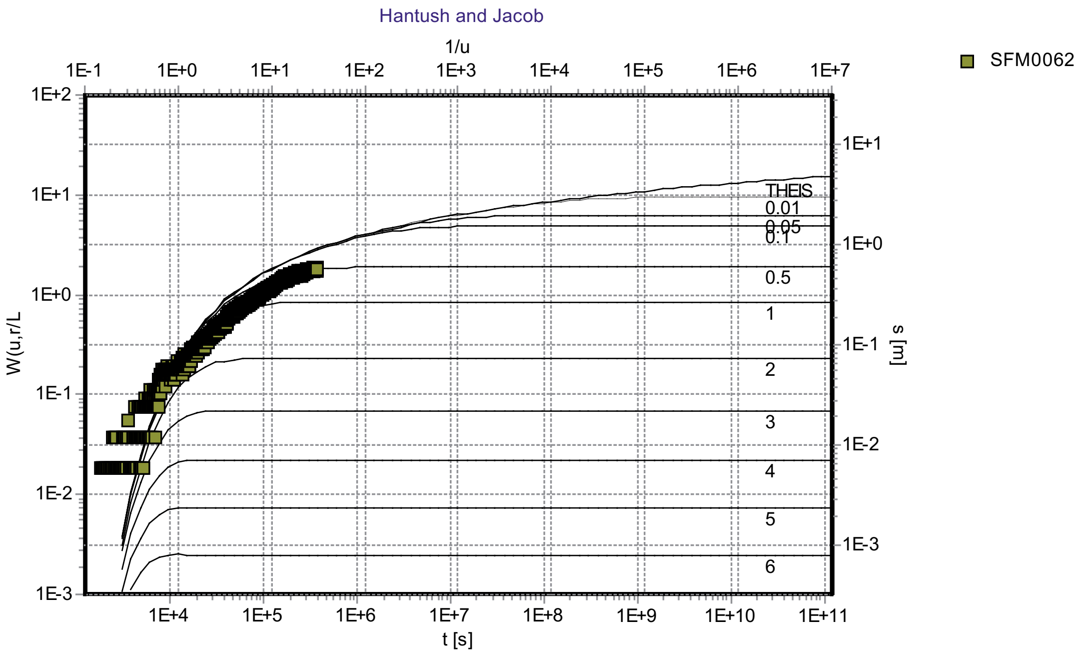

Figure 5-7. *Evaluation of the drawdown data from monitoring well SFM0062 using the Walton (Hantush & Jacob) method.*

Besides potential leakage of lake water, an alternative interpretation of a poor fit to the standard Theis curve is that the drawdown (the growth of the cone of influence) is affected by some hydraulic boundary. In particular, this may be the case for monitoring well SFM0032, for which the transition to stationary conditions was relatively instant /8/. The impact of and distance to hydraulic boundaries is here analysed by a so called mirror-well method combined with the Jacob method /10/ using drawdown data from monitoring well SFM0032, installed in the vicinity of the pumping well SFM0074.

The (virtual) mirror well, having the same discharge rate as the (real) pumping well, is thought to be located on the ”opposite side” but at the same distance from a potential hydraulic boundary as the distance from the pumping well to the boundary. The distance r_{01} from the pumping well (SFM0074) to the mirror well can then be calculated according to

$$r_{01} = r_{00}\sqrt{\frac{t_1}{t_0}}$$

where r_{00} is the distance from the monitoring well (SFM0032) to the pumping well, and the definitions of t_0 and t_1 are shown in Figure 5-8 below (also shown in Figure A2-8 in Appendix 2).

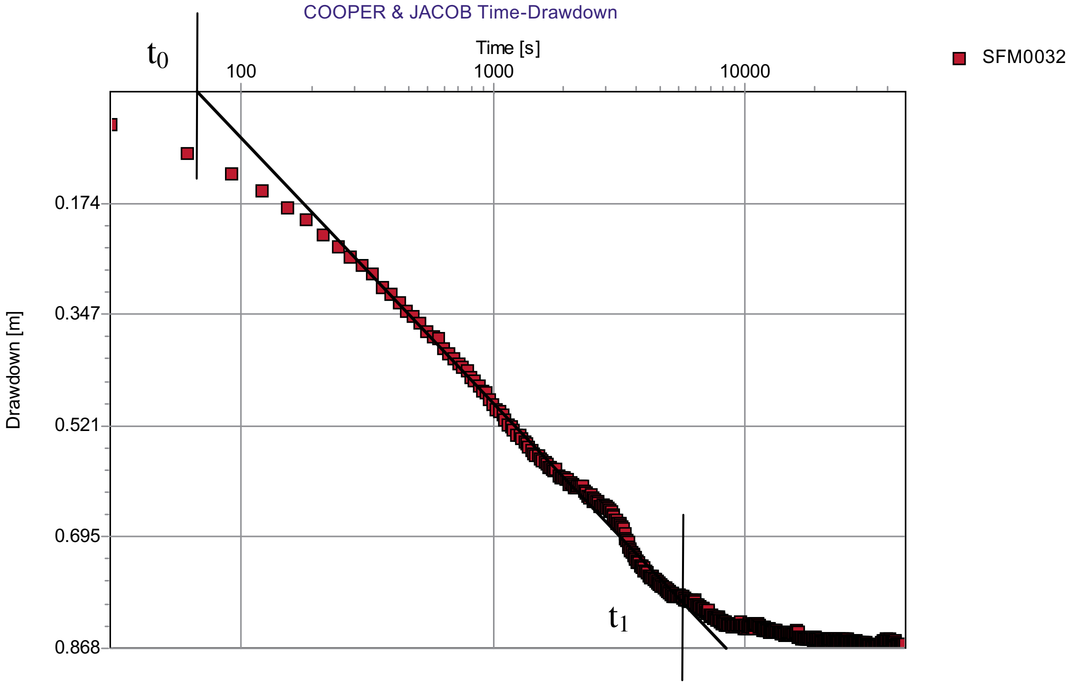

Figure 5-8. *Definition of the parameters t0 and t1, identified by means of the Jacob method, used in calculation of the distance from a pumping well (SFM0074) to a mirror well in a semi-log plot of drawdown versus time from pump start. The figure shows drawdown data from monitoring well SFM0032.*

As monitoring well SFM0032 is located close to the pumping well SFM0074, which in turn is located approximately 50 m from Bolundsfjärden (see air photograph in Figure 1-1), a mirror well should hence be located in Bolundsfjärden approximately 100 (50 + 50) m from the pumping well. Using the methodology described above, the parameter values r_{00} = 12.26 m (Table 2-2), $t_0 \approx 70$ s and $t_1 \approx 5\,500$ s (Figure 5-8) give the result $r_{01} \approx 109$ m. Hence, this result supports the alternative hypothesis that Lake Bolundsfjärden acted as a positive boundary during the pumping test.

In summary, the analysis of the drawdown data from SFM0032 and SFM0062 indicates that there most probably is a hydraulic contact between Lake Bolundsfjärden and the pumped aquifer. However, the results also indicate that the contact is limited by low-permeable bottom sediments. The analysis shows that a (partly) alternative interpretation is that Lake Bolundfjärden acted as a positive hydraulic boundary when the cone of influence reached the shoreline of the lake.

5.3 Summary of results

Performance, results and analysis of a pumping test in well SFM0074 in the Forsmark area were presented. The drawdown and recovery data from the pumping test were evaluated by three separate methods: the Theis method, the Jacob method, and the Theis recovery method. Potential leakage of lake water into the pumped aquifer during the pumping test was investigated by analysing drawdown data from monitoring wells SFM0032 and SFM0062, using the Walton (Hantush & Jacob) method for leaky aquifers. Moreover, the impact of and distance to hydraulic boundaries were analysed by a mirror-well method, using drawdown data from monitoring well SFM0032.

The evaluated transmissivity T was in the interval $2.18 \cdot 10^{-4}$–$3.30 \cdot 10^{-3}$ m^2/s, and the interval for S was $2.23 \cdot 10^{-4}$–$2.28 \cdot 10^{-3}$ (–). Slug tests /3, 4/ performed in the monitoring wells (SFM0031, 0032, 0062, and 0063), evaluated by the Cooper et al. method /11/ and reported to the SICADA database, gave the following T-values (m^2/s): $1.09 \cdot 10^{-6}$ (SFM0031), $7.68 \cdot 10^{-5}$ (SFM0032), $1.32 \cdot 10^{-7}$ (SFM0062), and $6.17 \cdot 10^{-8}$ (SFM0063); all these T-values were evaluated for $S = 1 \cdot 10^{-5}$. A comparison with the results reported to the SICADA database (Table 5-1) shows that the transmissivity values obtained from the present pumping test are 1-5 orders of magnitude higher. In particular, the evaluated T-values are 3–5 orders of magnitude higher for the monitoring wells installed below open water (SFM0062 and SFM0063). A possible explanation to the large differences are that the T-values of the pumping test mainly represent the properties of the contact zone between soil-rock and the uppermost part of the rock while the slug tests in SFM0062 and SFM0063 represent the properties of the till in the immediate vicinity of the monitoring wells. The screen of SFM0032 is placed in till in the contact zone with the rock and with a probable good contact with the uppermost one metre of the rock through the borehole.

The results indicate that there most probably is a hydraulic contact between the pumped aquifer and Lake Bolundsfjärden, but that this contact is limited by low-permeable bottom sediments. The analysis shows that a (partly) alternative interpretation is that Lake Bolundfjärden acted as a positive hydraulic boundary when the cone of influence reached the shoreline of the lake.

6 References

/1/ **Werner K, Lundholm L, 2004.** Forsmark site investigation. Supplementary drilling and soil sampling, installation of groundwater monitoring wells, a pumping well, and surface water level gauges. P-04-139. Svensk Kärnbränslehantering AB.

/2/ **Johansson P-O, 2003.** Forsmark site investigation. Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. SKB P-03-64. Svensk Kärnbränslehantering AB.

/3/ **Werner K, Johansson P-O, 2003.** Forsmark site investigation. Slug tests in groundwater monitoring wells in soil. SKB P-03-65. Svensk Kärnbränslehantering AB.

/4/ **Werner K, 2004.** Forsmark site investigation**.** Supplementary slug tests in groundwater monitoring wells in soil. P-04-140. Svensk Kärnbränslehantering AB.

/5/ **SKB, 2001.** Platsundersökningar. Undersökningsmetoder och generellt genomförande-program. SKB R-01-10 (in Swedish). Svensk Kärnbränslehantering AB.

/6/ **SKB, 2001.** Program för platsundersökning vid Forsmark. SKB R-01-42 (in Swedish). Svensk Kärnbränslehantering AB.

/7/ **Carlsson L, Gustafson G, 1984.** Provpumpning som geohydrologisk undersöknings-metodik. Rapport R41:1984, Statens råd för byggnadsforskning. (In Swedish.)

/8/ **Kruseman G P, de Ridder N A, 1990.** Analysis and evaluation of pumping test data. ILRI Publ. 47, International Inst For Land Reclamation and Improvement, The Netherlands.

/9/ **Waterloo Hydrogeologic, Inc, 2000.** User's guide for Aquifer Test. Waterloo Hydrogeologic, Inc., Waterloo, Ont., Canada.

/10/ **Hantush M S, Jacob C E, 1955.** Non-steady radial flow in an infinite leaky aquifer. Am Geophys Union Trans, vol 36, pp 95–100.

/11/ **Cooper H H Jr, Bredehoeft J D, Papadopoulos I S, 1967.** Response of a finite-diameter well to an instantaneous charge of water. Water Resour. Res 3 (1), 263–269.

Appendix 1

List of generated raw data files and primary data files

Table A1-1. 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
SFM0074	sfm0074,1 sfm0074,2 sfm0074,3 sfm0074,undre logger	SFM0074_ bearbetningsfil_ovre_logger SFM0074_ bearbetningsfil_undre_logger	SFM0074
SFM0031	sfm0031,1 sfm0031,2	SFM0031_bearbetningsfil	
SFM0032	sfm0032,1 sfm0032,2	SFM0032_bearbetningsfil	
SFM0062	sfm0062,1 sfm0062,2 sfm0062,3	SFM0062_bearbetningsfil	
SFM0063	sfm0063,1 sfm0063,2	SFM0063_bearbetningsfil	

Appendix 2

Diagrams

Appendix 2 contains diagrams of the analysis of the pumping test.

The analyses of the drawdown and recovery data, according to the Theis, Jacob and Theis recovery methods, are shown in Figures A2-1 to A2-14.

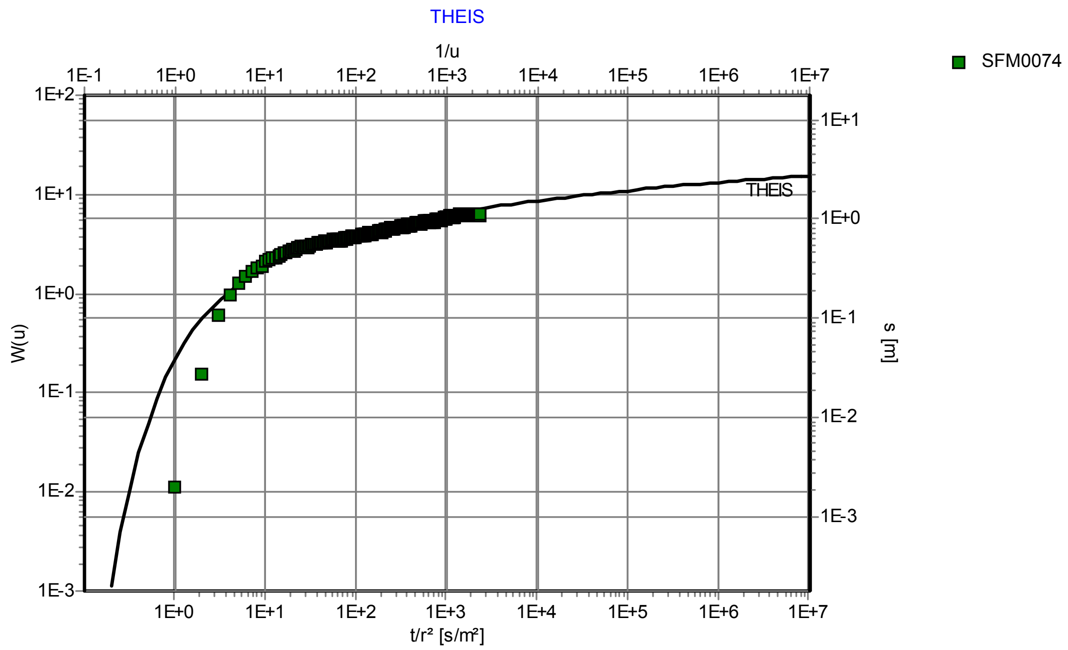

Figure A2-1. *Evaluation of the drawdown data from pumping well SFM0074 using the Theis method for pumping wells.*

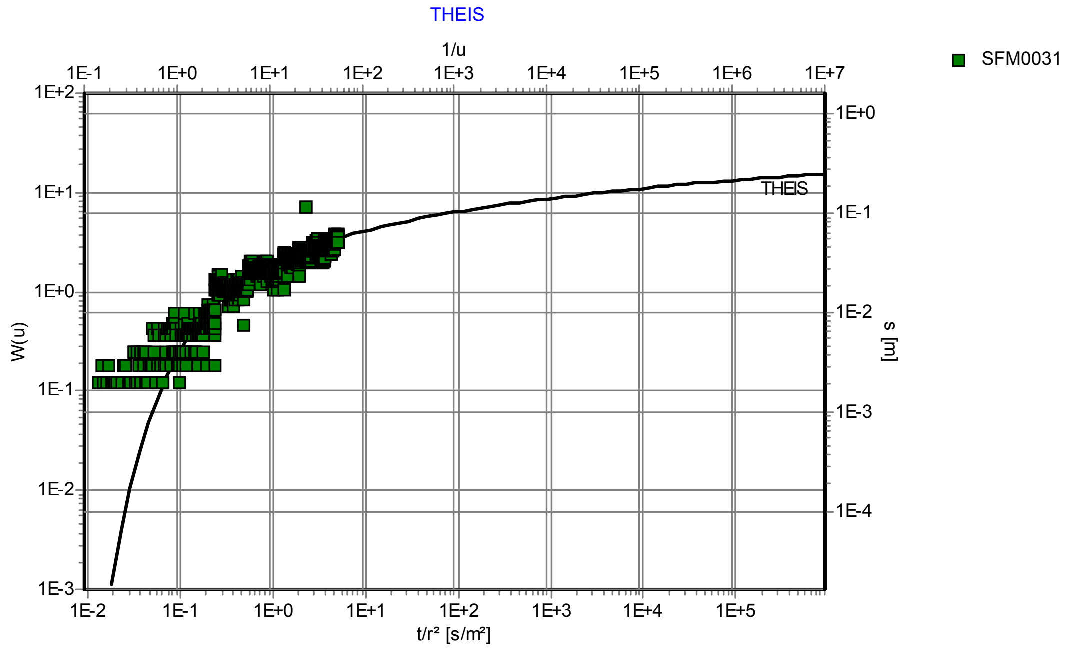

Figure A2-2. *Evaluation of the drawdown data from monitoring well SFM0031 using the Theis method.*

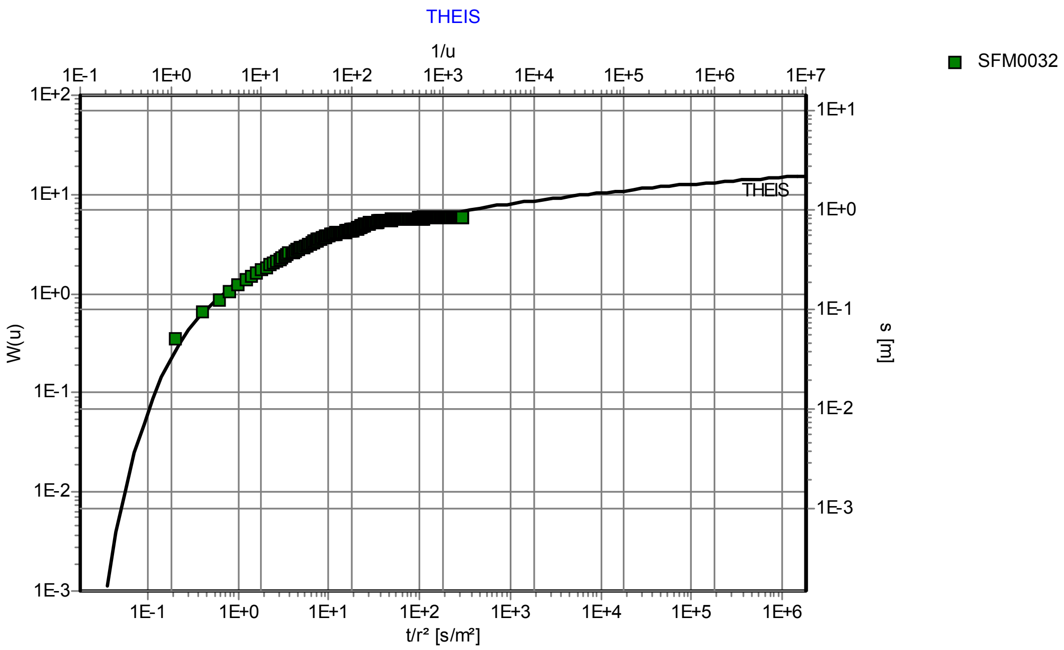

__Figure A2-3.__ Evaluation of the drawdown data from monitoring well SFM0032 using the Theis method.

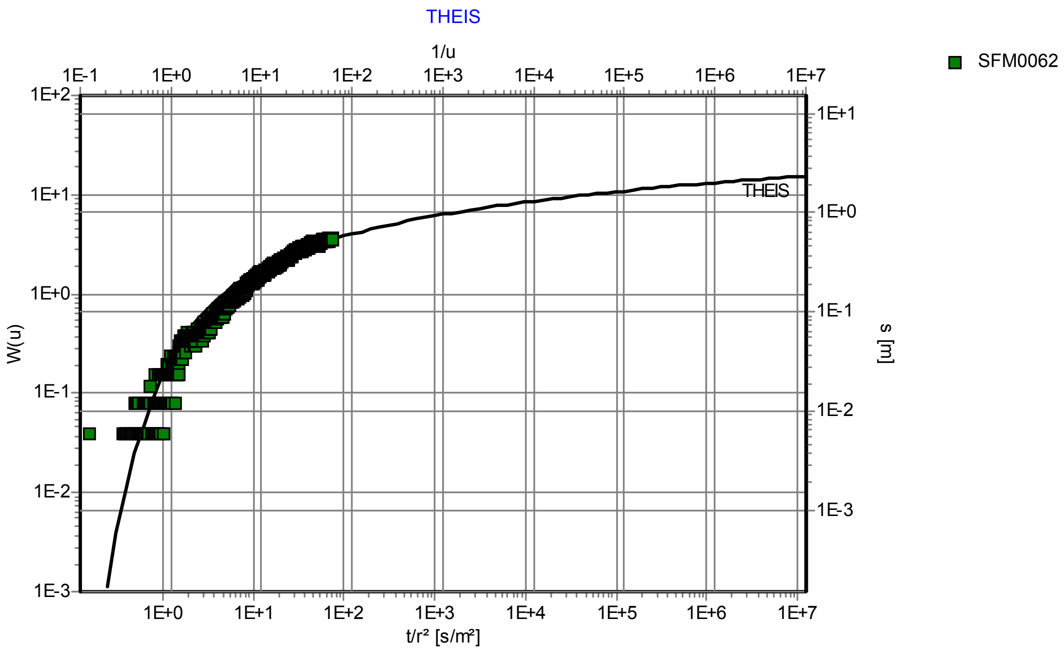

__Figure A2-4.__ Evaluation of the drawdown data from monitoring well SFM0062 using the Theis method.

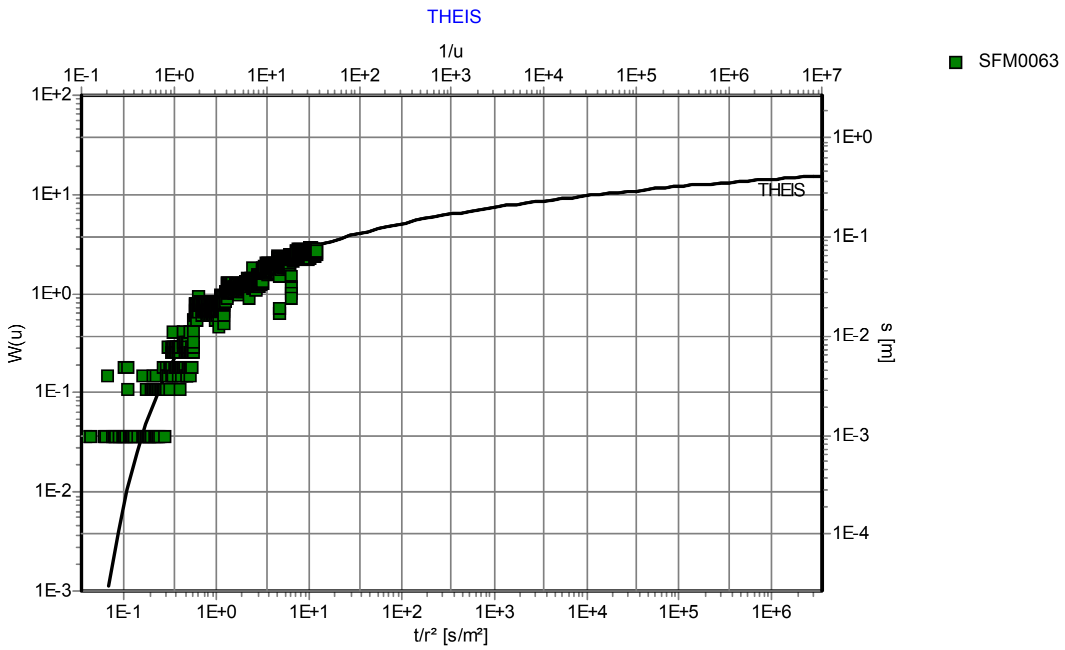

Figure A2-5. *Evaluation of the drawdown data from monitoring well SFM0063 using the Theis method.*

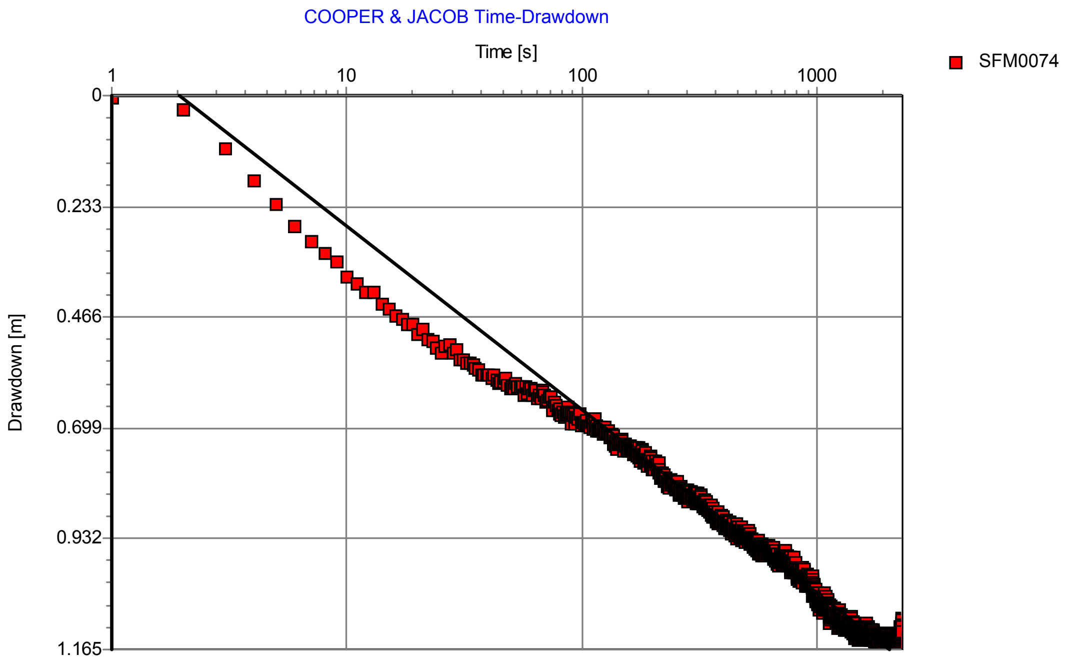

Figure A2-6. *Evaluation of the drawdown data from pumping well SFM0074 using the Jacob method for pumping wells.*

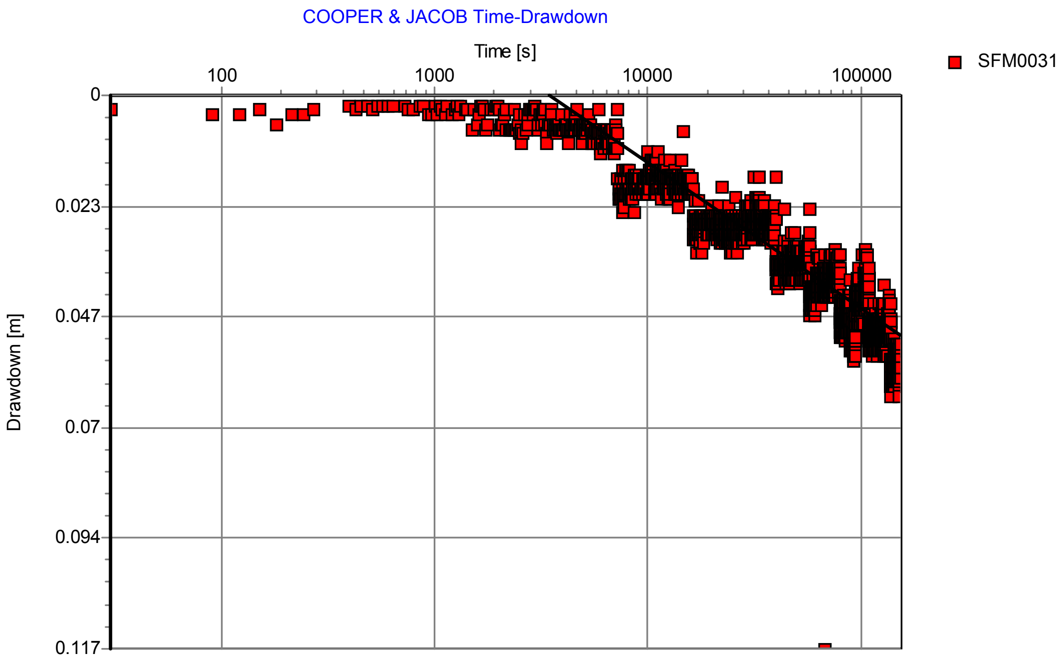

Figure A2-7. *Evaluation of the drawdown data from monitoring well SFM0031 using the Jacob method.*

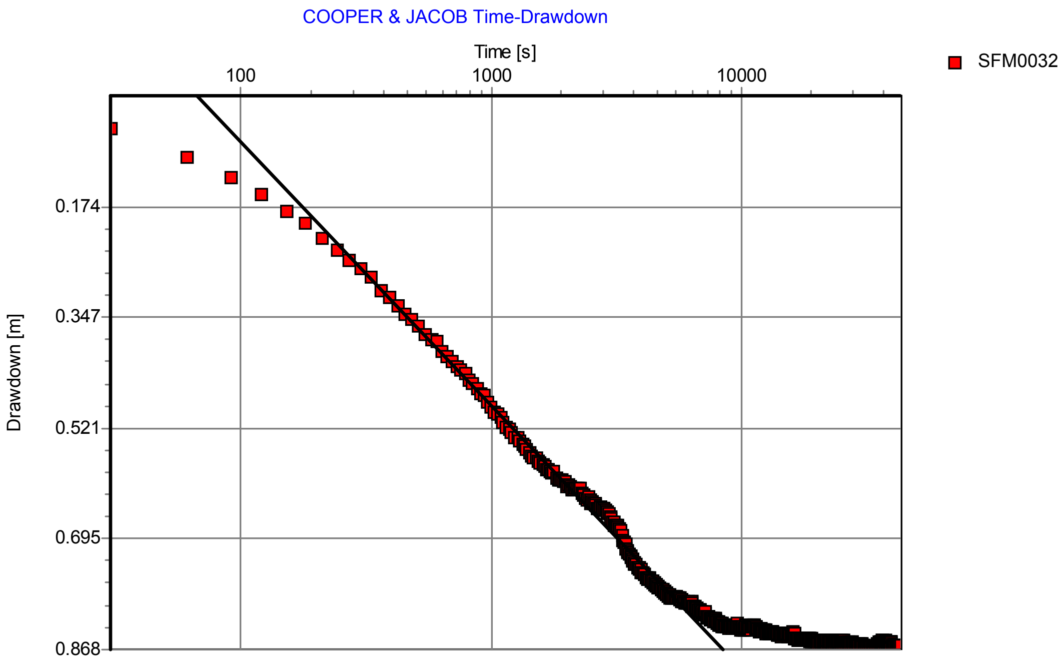

Figure A2-8. *Evaluation of the drawdown data from monitoring well SFM0032 using the Jacob method.*

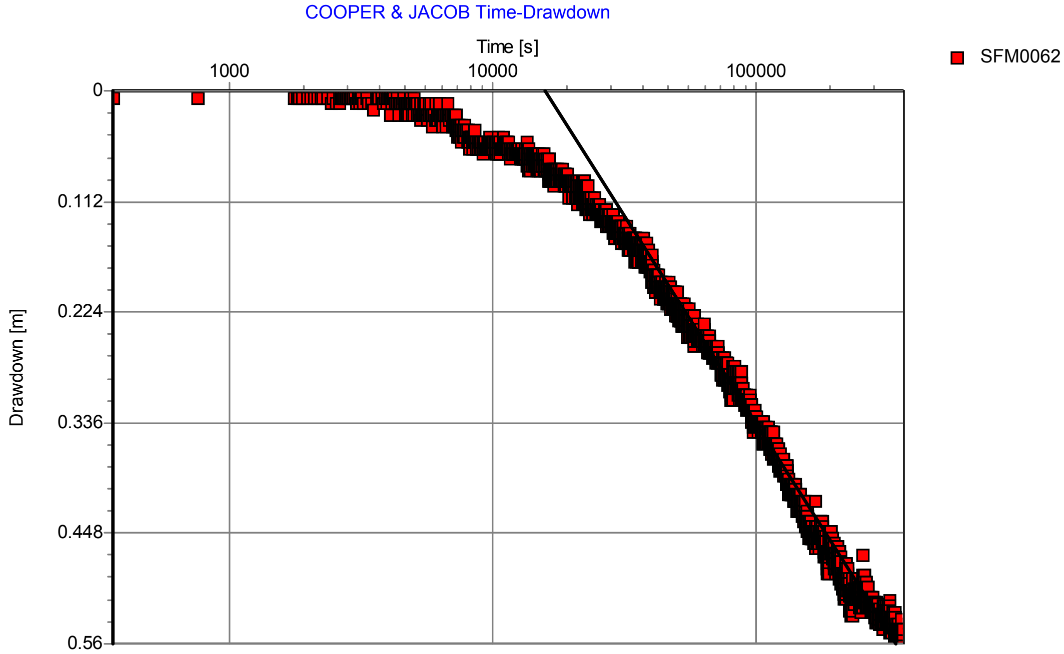

Figure A2-9. *Evaluation of the drawdown data from monitoring well SFM0062 using the Jacob method.*

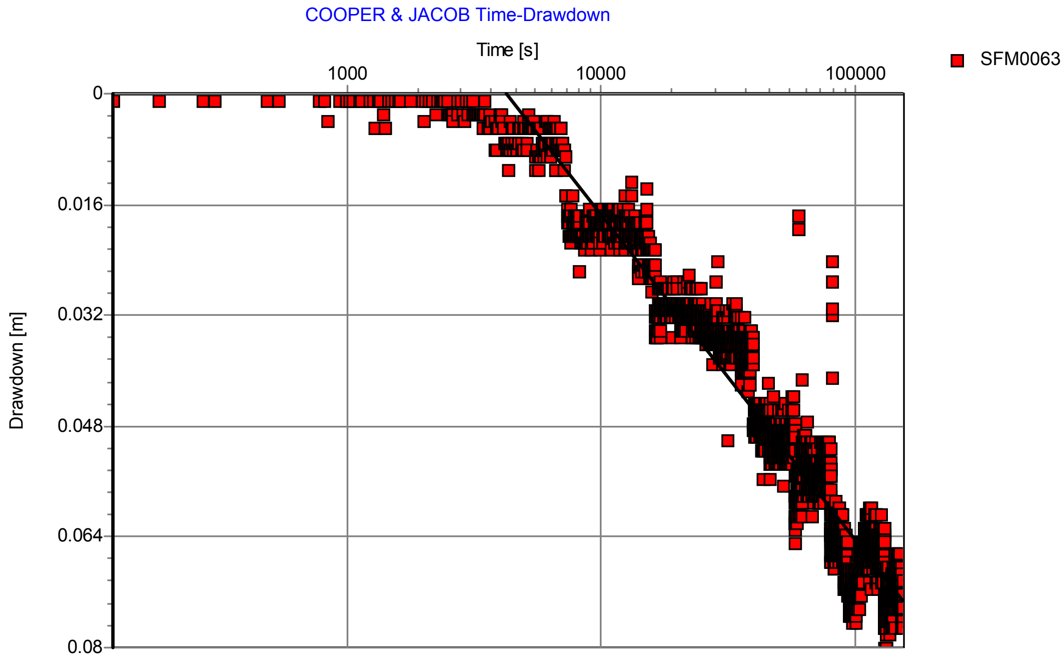

Figure A2-10. *Evaluation of the drawdown data from monitoring well SFM0063 using the Jacob method.*

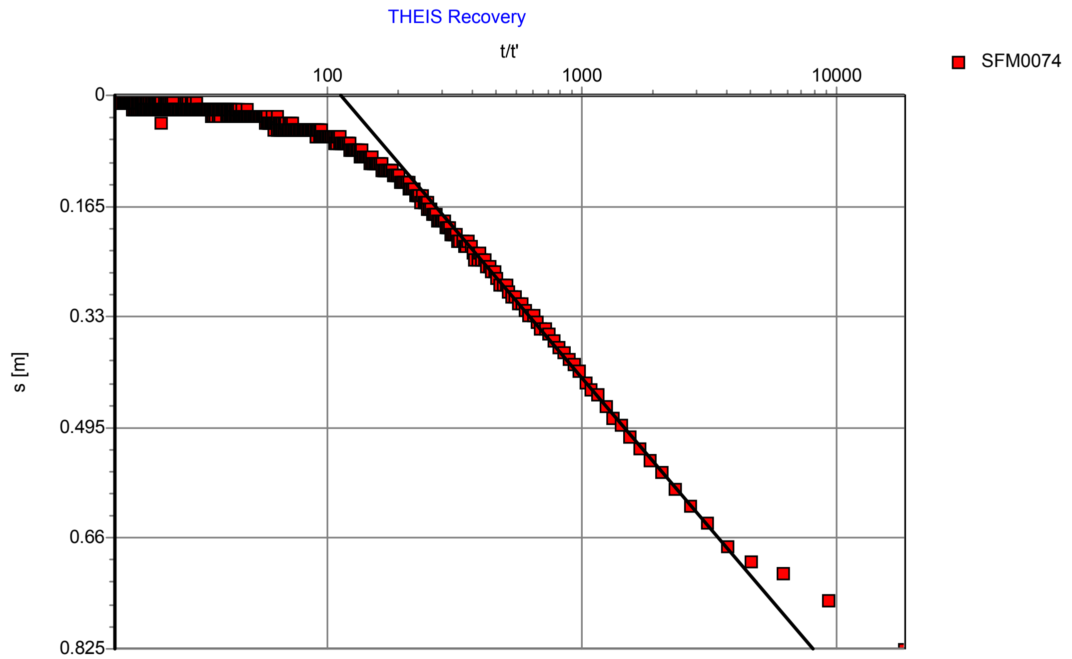

Figure A2-11. *Evaluation of the recovery data from pumping well SFM0074 using the Theis recovery method.*

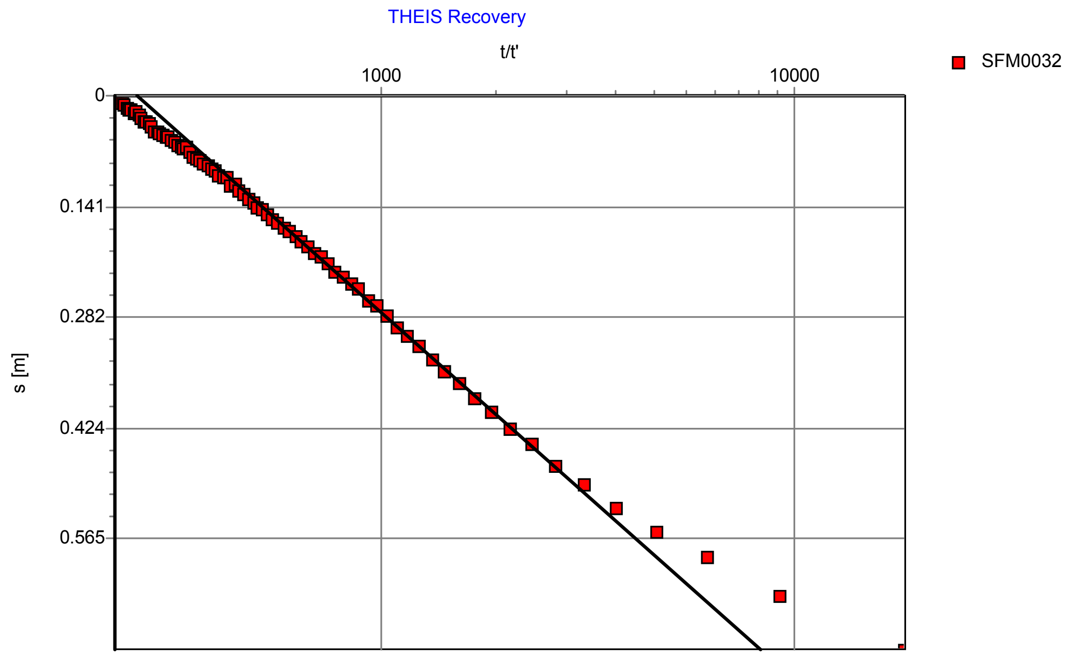

Figure A2-12. *Evaluation of the recovery data from monitoring well SFM0032 using the Theis recovery method.*

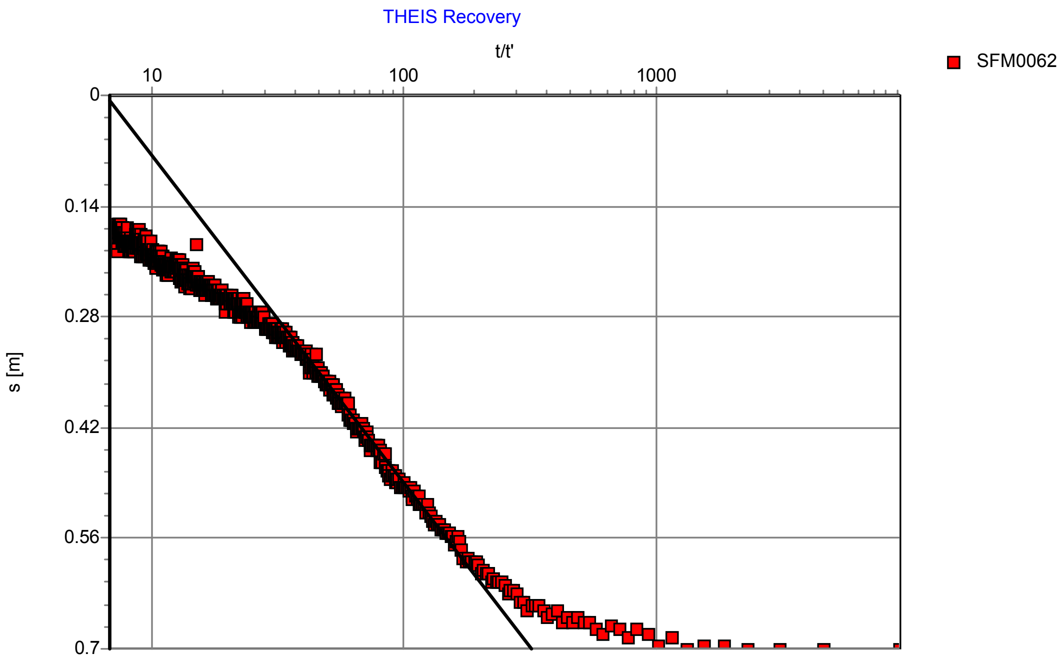

Figure A2-13. *Evaluation of the recovery data from monitoring well SFM0062 using the Theis recovery method.*

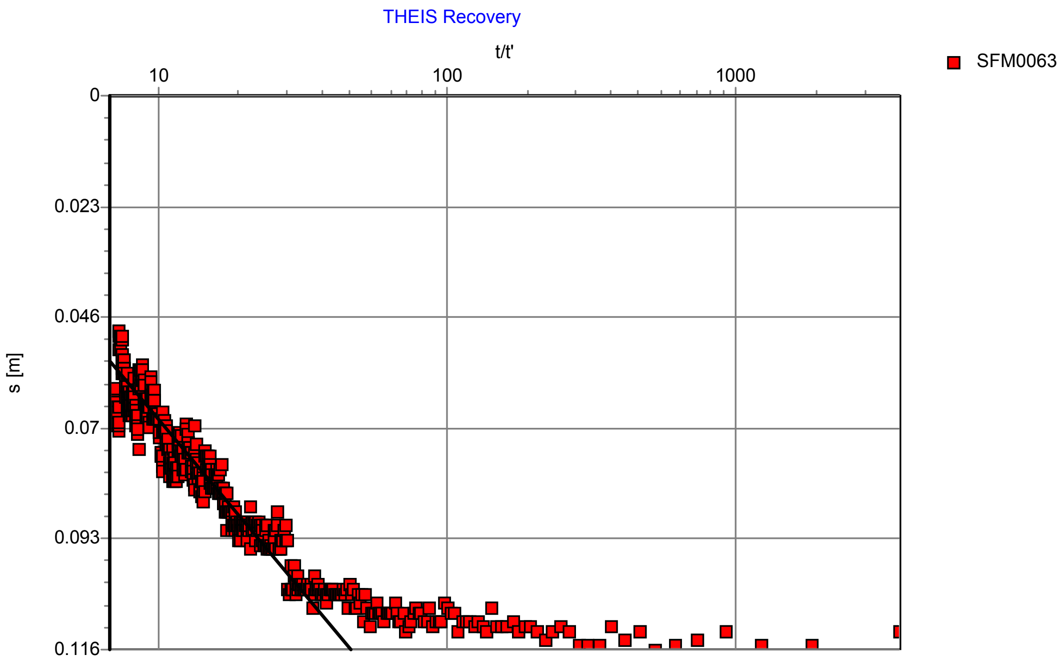

Figure A2-14. *Evaluation of the recovery data from monitoring well SFM0063 using the Theis recovery method.*