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PROJECT:

Well Test Honselersdijk GT 2

Documentation of well test analysis

Technical report

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1. Summary

The civil engineer bureau Dr. Ch. Schmid has received from DI K. Gollob on 7th of May and 10th of May, 2012 the basic data for the interpretation of the short pumping tests (step 1: 26.04 – 27.04.2012; step 2: 28.04.2012; step 3: 02.05.2012; step 4: 02.05.2012) in the geothermal well Honselersdijk HON GT2 (NL) with the demand to process these data.

These data served as input data for the hydrological interpretation of the pumping test, which was executed in four steps. Therefore several different methods have been used, to achieve the best results for the hydraulic conductivity and transmissivity of the aquifer. Besides these interpretations, it was first of all also necessary, to evaluate the basic data and to implement a correction for the water level in the well during the pumping test, taking account of the temperature and pressure anomalies.

As a result of the pumping tests, by using different methods for interpretation, for correlation and validation, **the transmissibility ranges from 1.22 to 4.2*10^{-4} m²/s**. The highest temperature, measured in the depth of the ESP (Electrical Submersible Pump), was 86.5 °C. Compared to well GT 1 is in the well GT2 the temperature lowered by 1.70 °C at the position of the ESP.

2. Input material

The following data served as input data for the hydrological interpretation of the pumping test and the correction of the water level due to the temperature and pressure correction:

- ESP test data from well tests in GT2 from 26th April to 2nd May 2012
- Data for the injection test 1 to 3 from 5th May 2012
- Graphics for the data of the memory gauge from Schulze
- General geometric information of the borehole GT2 and geological overview of the formations
- Information of the deviation of the drilling for GT2

The received in-put data set is similar to the data set from Honselersdijk HON GT1 (NL). The data acquisition does not follow the standard condition for pumping tests in water wells, especially concerning the duration of the pumping time for each pumping sequence.

In this case a log analysis is not available. According the information from DI K. Gollob, also this reservoir consists mainly of an unconsolidated sandstone section, named Delft sandstone. It has to be assumed that certain parts of Ablasserdam sandstone section were drilled by the well GT2. Only the Pijnacker sandstone section was not drilled in this well.

Both well tests was planned and designed without input from the pumping test evaluation group, therefore the data set are not matched with the available software packages. The well logging evaluation in the aquifer was done by a third group of specialists.

3. Data Acquisition

Pressure and temperature on the submersible pump (ESP) are registered with a down hole sensor provided by Centrilift, which was situated in a depth of 515.44 m (intake at 498.58 m). These data were measured in different intervals. (maximum time span 20 minutes). Furthermore a documentation of the data from “Schulze” with very short interval exists in another data format. For analysing this data set a transformation and filtering of the data would be necessary. The recording period between the single data points is partially very long, especially for pumping tests, where rapid drawdown and recovery of the water level due to the small well diameter occurs. This fact causes some troubles for the hydrological interpretations of the pumping test, since an exact and detailed recording is the key factor for the correct evaluation of the hydraulic conductivity and transmissivity of an aquifer.

Another difficulty for the hydrological interpretation of the pumping test was the very short duration of the tests, especially the third and fourth pumping step run not more than 6 hours. For this situation only the recovery data sets provide sufficient information to calculate the transmissivity of the aquifer, the drawdown of the water level was just used for validation.

The third point, which has to be taken in account for the interpretations of the results from these “short-term pumping tests”, was the fact, that during the pumping steps the static water level never could be achieved.

3.1 Pressure

For the adaption of the measured pressure on the ESP to the real pressure and therefore for the calculation of the water level during the pumping test, the general barometric altitude equation has been used. The barometric formula, sometimes called the exponential atmosphere or isothermal atmosphere, is a formula used to model how the pressure (or density) of the air changes with altitude:

$$P = P_b \cdot exp\left[\frac{-g_0 \cdot M \cdot (h - h_b)}{R^* \cdot T_b}\right]$$

where

P_b = Static pressure (Pascal)
T_b = Standard temperature (K)
L_b = Standard temperature lapse rate -0.0065 (K/m)
H = Height above sea level (meters)
H_b = Height at bottom of layer b (meters; e.g.,h_1= 11,000 meters)
$R*$ = Universal gas constant for air: 8.31432 N·m /(mol·K)
g_0 = Gravitational acceleration (9.80665 m/s^2)
M = Molar mass of Earth's air (0.0289644 kg/mol)

In a simplified approach the pressure decrease by 1 hectopascal for each 8 meters of altitude. In addition had to be taken into account the formation pressure (which is not really known), and the pressure of the production fluid between the ESP sensor and the depth of the reservoir. But for the interpretation of the pumping tests and therefore the calculated water level, the difference in measured and calculated pressure is not so important, as the absolute water level, because the absolute values for the drawdown and recovery are the basics for the interpretation.

3.2 Temperature

One of the main differences in the evaluation of pumping tests between deep and shallow aquifers is the impact of the water temperature. This is because the volume of a certain amount of water depends on its temperature. I.e., the density of water increases with decreasing temperature and reaches its maximum value of 1,000 cm³/g at 3.98 °C. The specific volume follows the inverse trend. This is caused by the common behavior of liquids, that as a result of the increased motion of the molecules at elevated temperatures the effective volume per molecule increases. Thus they expand with increasing temperature and their density decreases.

From the change of the specific volume [v] or density [p] with temperature, the thermal expansion for a temperature change [*dT*] can be calculated:

$$\alpha = \frac{1}{dT}\, lnv = \frac{1}{dT}\ln\frac{1}{p}$$

This equation is based on a constant temperature depending expansion coefficient. The following table provides information of the temperature dependence on the specific volume and the density of water.

Table 1: Physical parameters for Density and Volume corrections

T [°C]	Specific volume *v* [cm³/g]		Density *ρ* [g/cm³]	
	Water solid (Ice)	Water liquid	Water solid (Ice)	Water liquid
- 20	1.08696	1.006580	0.920000	0.994390
0	1.09051	1.000160	0.917899	0.999868
4	-	1.000028	-	0.999972
20	-	1.001797	-	0.998234
40	-	1.007842	-	0.992247
60	-	1.017089	-	0.983226
80	-	1.029027	-	0.971819
100	-	1.043453	-	0.958382

As the temperature expansion coefficient of water does not increase linearly with temperature, it is useful to fit a quadratic or cubic polynomial to the above table, which then allows determining the change in the specific volume of water for pumping tests at deep aquifers by means of interpolation. This allows the determination of the expansion coefficient at every temperature. The difference between the quadratic and cubic interpolation is negligible.

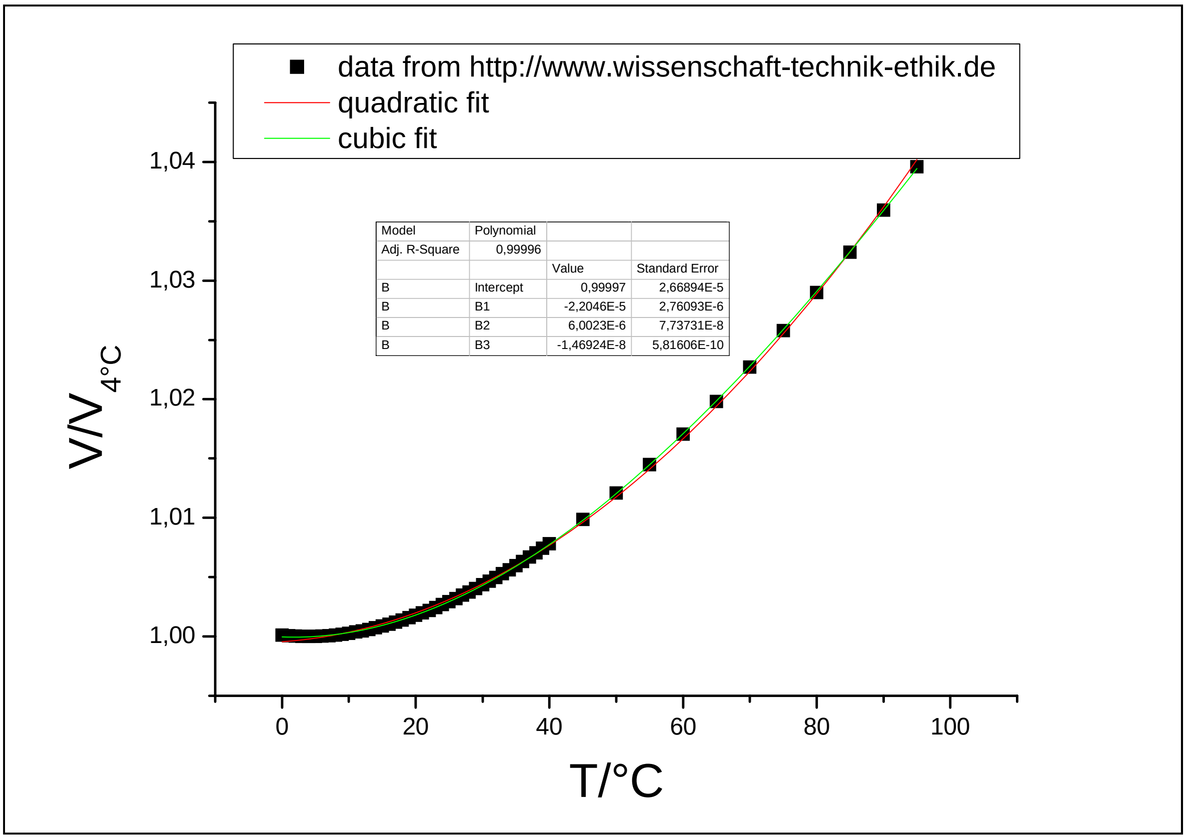
When considering the thermal expansion of water in boreholes one has to keep in mind that the above described effect only changes the water level in the borehole, as its cross section is not affected. For the evaluation of pumping tests at borehole Honselersdijk GT2 three reference temperatures were considered (36 °C, 60 °C and 90 °C) and the change in temperature compared to the original data was corrected using the following equations:

Quadratic fit:

$$\frac{V(8°C)}{V(T)} = \frac{h(8°C)}{h(T)} = \frac{1{,}00007}{0{,}99956 + 4{,}01953 * 10^{-5} * T + 4{,}07872 * 10^{-6} * T^{2}}$$

Cubic fit:

$$\frac{V(90°C)}{V(T)} = \frac{1{,}0359}{0{,}99997 - 2{,}2046 * 10^{-5} * T + 6{,}0023 * 10^{-6} * T^{2} - 1{,}46924 * 10^{-8} * T^{3}}$$



Model	Polynomial		
Adj. R-Square	0,99996		
		Value	Standard Error
B	Intercept	0,99997	2,66894E-5
B	B1	-2,2046E-5	2,76093E-6
B	B2	6,0023E-6	7,73731E-8
B	B3	-1,46924E-8	5,81606E-10

Fig. 1: Graphic determination of thermal expansion coefficient for water

For the evaluation of the pumping test all available data (original data, volumes at 36°C, 60°C and 90°C), have been used and compared with each other.

3.3 Flow Rate

This well test was done by different service crews directly after finishing the drilling and a temporary completion process. The flow rate for the different well test steps are summarized for a quick over view in table 2. In general are these listed test times for a comprehensive aquifer evaluation extremely short.

Table 2: Well test parameters

Pumping steps	Date	Time	Hours	Pumping rate
Step 1	26.04.2012 – 27.04.2012	14:00 - 05:50	15.50	32,0 l/s
Step 2	28.04.2012	08:35 - 17:15	8.40	37,5 l/s
Step 3	02.05.2012	09:25 - 13:50	4.25	42,5 l/s
Step 4	02.05.2012	16:20 - 22:20	6.00	47,5 l/s

3.4 Summary of the registered parameters

A selection of the most important parameters is summarized in table 3. The characteristic of the performed well test on the well Honseleresdijk GT2 is illustrated on the graphs in the appendices.

Table 3: Synoptically table of the well test 1 to 4 on the Honselersdijk GT2

Honselersdijk GT2	from	to	Database	
1. well test	26.04.2012 14:00	27.04.2012 05:50	Length of time for the test (t_{ges}):	15.5 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Max Temperature on the ESP (T_{TKP}):	87.01 °C
			Production volume (V_{ges}):	1,850 m³
			Static water table (p_{TKP}):	46.3 bar at 47.2 °C
			Drawdown in reservoir (dp_{Res}):	6.01 bar at 32 l/s
1. built up (recovery)	27.04.2012 05:50	28.04.2012 08:35	Length of time:	27.75 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Pressure on the ESP after built up (p_{TKP}):	46.85 bar at 46.5 °C
2. well test	28.04.2012 08:35	28.04.2012 17:15	Length of time for the test (t_{ges}):	8.4 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Max Temperature on the ESP (T_{TKP}):	88,02 °C
			Production volume (V_{ges}):	1,250 m³
			Static water table (p_{TKP}):	46.85 bar at 46.5 °C
			Drawdown in reservoir (dp_{Res}):	8.98 bar at 37.5 l/s
2. built up (recovery)	28.04.2012 17:15	02.05.2012 09:25	Length of time:	88.15 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Pressure on the ESP after built up (p_{TKP}):	50.37 bar at 36.7 °C
3. well test	02.05.2012 09:25	02.05.2012 13:50	Length of time for the test (t_{ges}):	4.25 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Max Temperature on the ESP (T_{TKP}):	87.41 °C
			Production volume (V_{ges}):	690 m³
			Static water table (p_{TKP}):	50.37 bar at 36.7 °C
			Drawdown in reservoir (dp_{Res}):	13.3 bar at 42.5 l/s
3. built up (recovery)	02.05.2012 13:50	02.05.2012 16:20	Length of time:	2,5 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Pressure on the ESP after built up (p_{TKP}):	47.07 bar at 74.18°C
4. well test	02.05.2012 16:20	02.05.2012 22:20	Length of time for the test (t_{ges}):	6 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Max Temperature on the ESP (T_{TKP}):	88.7 °C
			Production volume (V_{ges}):	1,050 m³
			Static water table (p_{TKP}):	47.07 bar at 74.18°C
			Drawdown in reservoir (dp_{Res}):	12.33 bar at 47.5 l/s
4. built up (recovery)	02.05.2012 22:20	03.05.2012 07:01	Length of time:	8.6 h
			Depths of the pressure sensor (ESP h_{TKP}):	515.44 m
			Pressure on the ESP after built up (p_{TKP}):	46.45 bar at 63.2 °C

4. Hydraulic Interpretation

4.1 Methodology

For the present work the methodology for the pumping test evaluation is different in some steps to the well GT1. In this case a software package focused on a gas bearing fluid was used. The pumping test from the well GT1 was done after water density correction (after Kestin, Khelifa & Correia, 1981) according to Dougherty Babu, 1984 for in stationary conditions. The experience from the evaluation of the pumping test on the well GT1 have shown that this special condition for the water well GT1 is not justified and gives also results with some uncertainties.

The exploited reservoir in the whole project is represented by unconsolidated sandstones containing a saline fluid, low in gas and also low in initial pressure. For this reason the hydraulic interpretation was done with different standard methods common in confined porous aquifers.

For the determination of the hydraulic conductivity and Transmissivity of the thermal water drilling of Honselersdijk GT2 a pumping test was performed from 26.04.2012 to 02.05.2012, which should give information about the productivity of this well. Therefore three pumping steps with a delivery rate of 32 l/s, 37.5 l/s and 42.5 (47.77) were elaborated.

For the interpretation of these pumping test results there are several methods, which can be used. In our case the following methods have been applied:

- Theis Method
- Cooper Jacob Time – Drawdown Method
- Theis Forward Solution
- Gringarten - Bourdet Forward Solution
- Theis Recovery Test
- Theis Step test
- Cooper Jacob Step test

In order to achieve the best results for the interpretation of the hydraulic Transmissivity, the results of all these methods have been compared to each other. The step tests dealing with the whole well test (including all three pumping steps) and the recovery tests have been used as a validation of the other methods.

Theis Method:

Theis (1935) developed an analytical solution for the interpretation of pumping tests with the following equation:

$$s(r,t) = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-u}du}{u}$$

$$u = \frac{r^2 S}{4Tt}$$

For the specific definition of u given above, the integral is known as the well function, W (u) and can be represented by an infinite Talor series. Using this function, the equation becomes:

$$s = \frac{Q}{4\pi T} W(u)$$

The line on a log-log plot with W (u) along the y-axis and 1/u along the x-axis is commonly called the Theis curve. The field measurements are plotted das t or t/r² along the x-aces and s along the y-axis. The data analysis is done by matching the line drawn through the plotted observed data to the Theis curve.

The Theis forward solution and the Gringarten forward solution are single well solutions that follow the same theory and assumptions as the standard Theis method. They can be better applied for single well solutions.

Cooper Jacob Method:

The Cooper Jacob (1946) method is a simplification of the Theis method valid for greater time values and decreasing distance from the pumping well (smaller values of u). This method involves truncation of the infinite Taylor series, which is used to estimate the well function W (u). The resulting equation is:

$$s = \left(\frac{2.3Q}{4\pi T}\right) log10 \left(\frac{2.25Tt}{Sr^2}\right)$$

This equation plots a straight line on a semi-logarithmic paper if the limiting condition is met. Thus, straight line plots of drawdown versus time can occur after sufficient time has elapsed. Transmissivity and storage are calculated as follows:

$$T = \frac{2.3Q}{4\pi \Delta s} \qquad S = \frac{2.25Tt0}{r^2}$$

Theis Recovery Test

When the pump is shut down after a pumping test, the water level inside the observation well will start to rise. This rise in water level is known as residual time (s`). Recovery test measurements allow calculating the Transmissivity of the aquifer, thereby providing an independent check on the results of the pumping test.

Using the approximation of the well function, W (u), shown in the Cooper Jacob method, the equation becomes:

$$s' = \frac{Q}{4\pi T}\left(ln\frac{4Tt}{r^2S} - ln\frac{4Tt'}{r^2S}\right)$$

To analyze the data, s' is plotted on the logarithmic y-axis and time is plotted on the linear x-axis as the ratio of t/t' (total time since pumping began divided by the time since the pumping ceased).

4.2 Interpretation of the Well Tests

Like mentioned in the previous chapters the well test for Honselersdijk GT2 was performed in four steps with a flow rate of 32 l/s, 37.5 l/s, 42.5 and 47.5 l/s. The initial water level has been adopted due to the thermal expansion at 36°C, 60°C and 90°C and according to the pressure correction. Because of the big water volume in the borehole the change of the water level was clearly recognizable as shown in the figures 2 and 3.

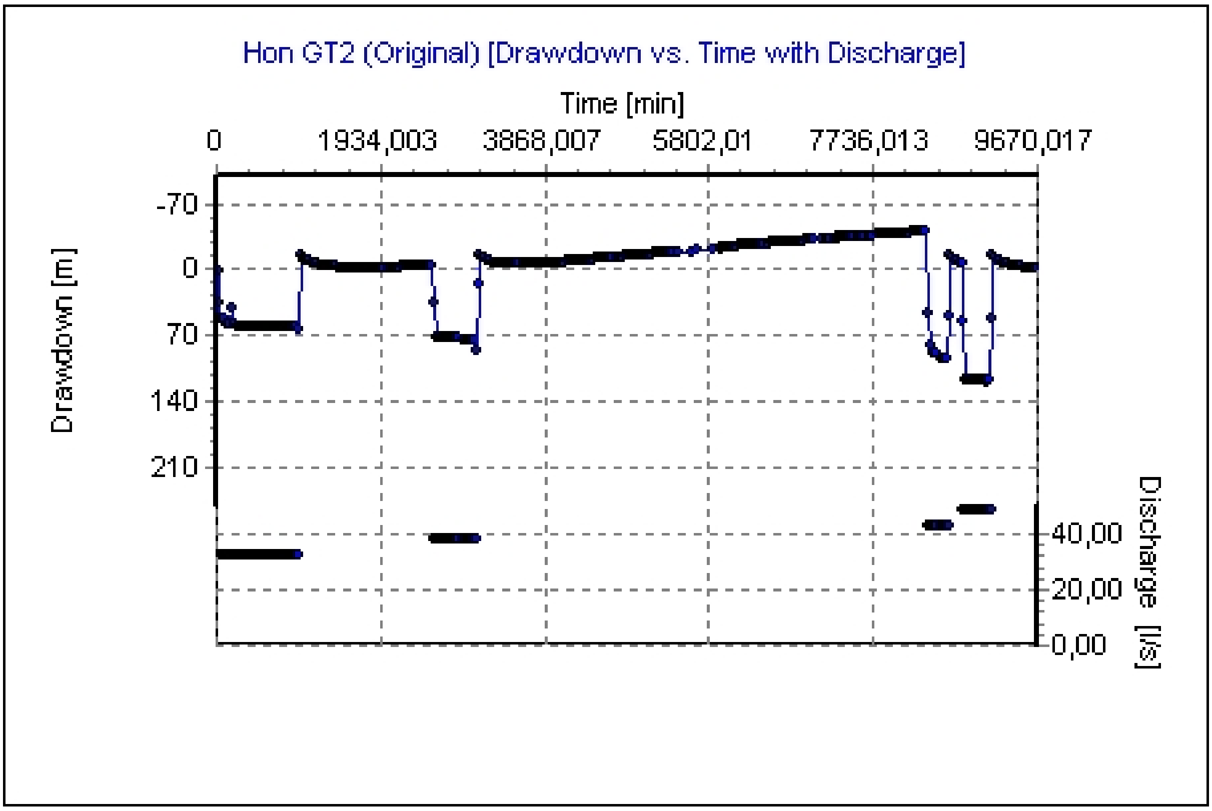


Fig. 2: Drawdown versus time diagram with the original data for the well test of Honselersdijk GT2

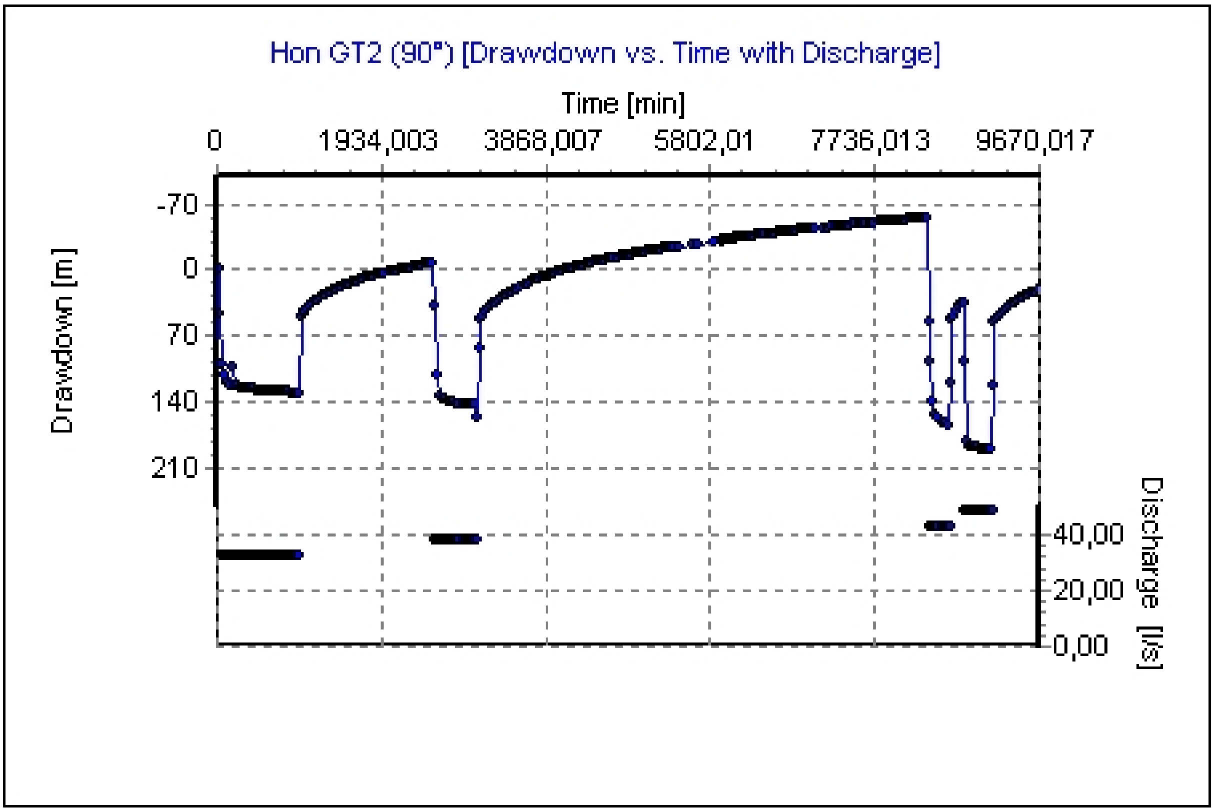


Fig. 3: Drawdown versus time diagram of the with the adopted data for 90°C for the well test of Honselersdijk GT2

It is also good visible in figure 2 and 3, that stationary condition during each pumping step had not been achieved. Also the time span of 20 minutes between two recorded measurements is quite high. To have a better performance of the drawdown and recovery curve the “Schulz” should be implemented (because of the urgent need of results it was not possible to transfer and check the plausibility of all this data). For better results these facts are essential. For a long term pumping test it will also be suggested, that temperature and pressure are measured in several different depths.

Table 3: Comparison of the well test results based on different evaluation methods

Pumping	Temperature	Method	Transmissivity	Comment
Step 1-4 *	36°C	Cooper-Jacob Step test	4,83*10^{-4} m²/s	validation
	36°C	Theis Step test	2,34*10^{-4} m²/s	validation
	60°C	Cooper-Jacob Step test	4,74*10^{-4} m²/s	validation
	60°C	Theis Step test	2,77*10^{-4} m²/s	validation
	90°C	Cooper-Jacob Step test	4,77*10^{-4} m²/s	validation
	90°C	Theis Step test	2,71*10^{-4} m²/s	validation
Step 1	36°C	Cooper-Jacob	3,30*10^{-4} m²/s	
	36°C	Gringarten Forward	1,80*10^{-4} m²/s	
	36°C	Theis	2,21*10^{-4} m²/s	validation
	36°C	Theis Forward	1,22*10^{-4} m²/s	
	90°C	Cooper-Jacob	2,43*10^{-4} m²/s	
	90°C	Gringarten Forward	2,30*10^{-4} m²/s	
	90°C	Theis	2,15*10^{-4} m²/s	validation
	90°C	Theis Forward	2,30*10^{-4} m²/s	
	90°C	Theis Recovery	1,00*10^{-4} m²/s	validation
Step 2	60°C	Cooper-Jacob	2,45*10^{-4} m²/s	
	60°C	Gringarten Forward	2,40*10^{-4} m²/s	
	60°C	Theis	2,41*10^{-4} m²/s	validation
	60°C	Theis Forward	2,53*10^{-4} m²/s	
	90°C	Cooper-Jacob	3,42*10^{-4} m²/s	
	90°C	Gringarten Forward	4,20*10^{-4} m²/s	
	90°C	Theis	4,06*10^{-4} m²/s	validation
	90°C	Theis Forward	4,00*10^{-4} m²/s	
	90°C	Theis Recovery	6,31*10^{-5} m²/s	validation
Step 3+4 **	90°C	Cooper-Jacob	1,46*10^{-4} m²/s	
	90°C	Theis	1,58*10^{-4} m²/s	validation

* Step 1-4 combines all pumping steps

** The pumping test step 3 could not be evaluated alone because the test duration was to short, therefore step 3 and 4 has been combined to step 3+4

For the interpretation of the well test and the calculation of the Transmissivity of the aquifer, as mentioned in the previous chapter, several methods for different temperatures (36°C, 60°C and 90°C) have been applied. Pumping step 2 and the combination 3+4 has only been calculated at 60°C and 90°C because the real production will be mostly at the actual temperature condition (approx. > 80°C).

In the appendix all results are shown in the diagrams, in the following table an overview of these achievements are listed with the comment, which method was abducted for validation.

In the table 3 results marked by “validation” represent reliable results calculated by different methods. Especially the calculation by the Cooper Jacob method, Theis method as well Theis Step test and Theis Recovery give comparable results.

4.3 Interpretation of the Productivity

The productivity of the well Honselersdijk GT2 has been calculated by the Hantush – Bierschenk Method. This approach is used to analyze the results of a variable pumping rate “step test” pumping test, to determine both the linear and non-linear well loss coefficient B and C. These coefficients can be used to predict an estimate of the real water level drawdown inside the pumping well in response to pumping. Solution methods such as Theis permit an estimate of theoretical drawdown inside a pumping well in response to pumping, but do not account for linear and non-linear well losses, which result in an increase in drawdown inside the well.

Linear well losses are caused by damage to the aquifer during drilling and completion of the well. The non-linear well losses are the friction losses that occur inside the well screen and in the suction pipe and the head losses that occur in the zone adjacent to the well. Because the well losses are associated with turbulent flow, it may be indicated a proportional to an n_{th} power of discharge.

The general equation for calculating drawdown inside a pumping well that includes well losses is written as:

$$Sw = BQ + CQ^p$$

Sw = drawdown inside the well
B = linear well loss coefficient
C = non-linear well loss coefficient
Q = pumping rate
p = non-linear well loss fitting coefficient

The non-linear well loss fitting coefficient *p* typically varies between 1.5 and 3.5 depending on the value of Q; Jacob proposed a value of *p* = 2 for most pumping test.

With the Hantush – Bierschenk Method the values for the well loss coefficients C and B are calculated and these values are used to estimate the expected drawdown inside the pumping well for any realistic discharge Q at a certain time t. The relationship between drawdown and discharge can then be used to choose, empirically, an optimum yield for the well.

For the calculation with the Hantush – Bierschenk Method you need a well test, which is pumped step-wise at increased discharge rates with equal duration pumping sessions. Therefore by using the data of the Honselersdijk GT2 well test the time for the recovery has been eliminated for this interpretation (Fig 4).

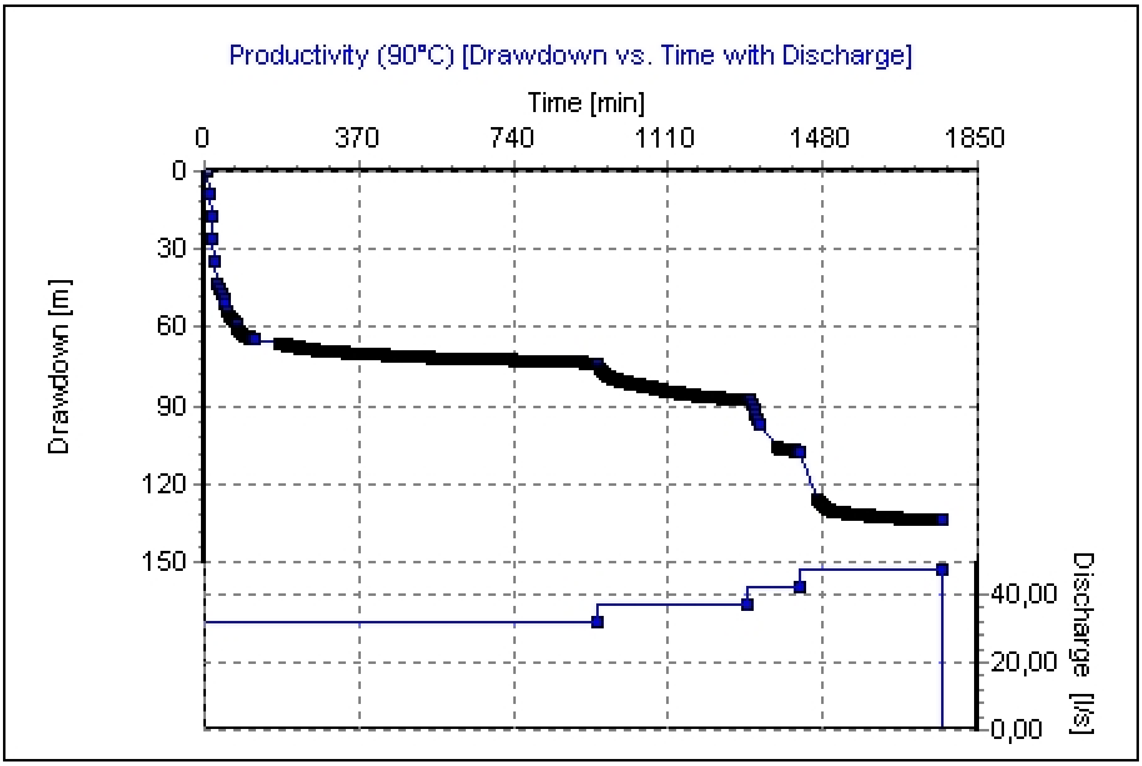


Fig 4: Corrected drawdown versus time diagram without recovery periods

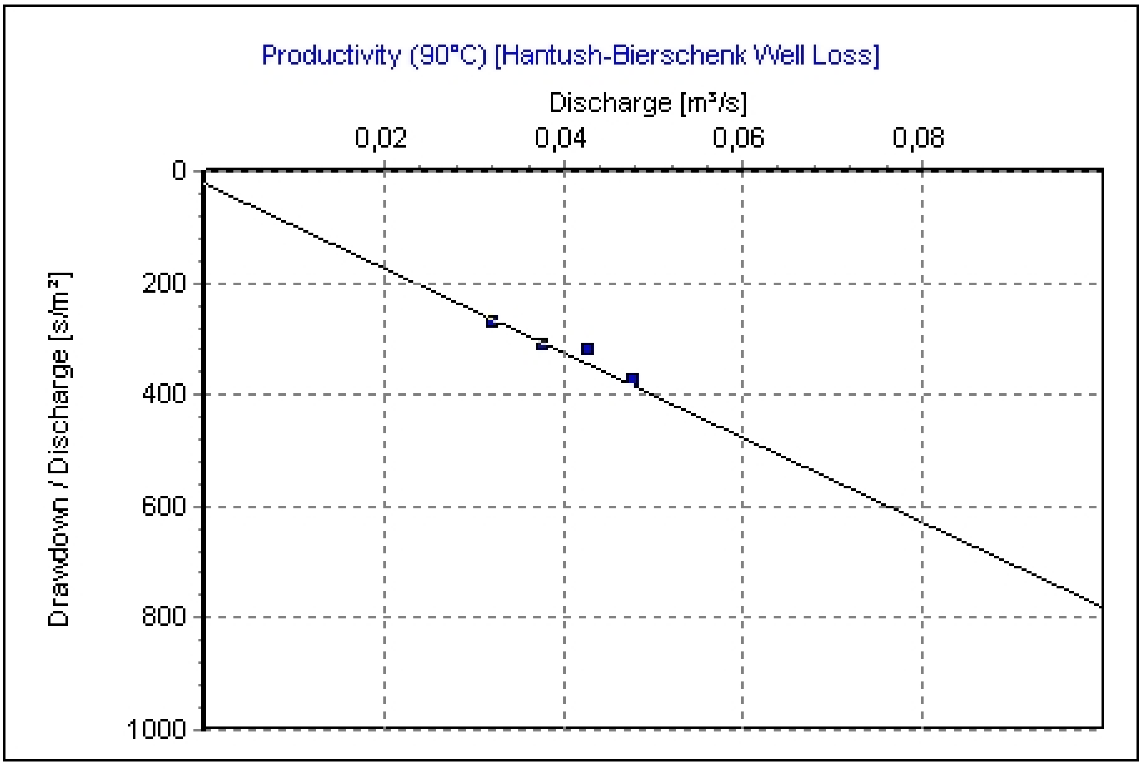


Fig.5: Diagram of the calculation from the productivity of the well, Honselersdijk GT2 after the Hantush-Bierschenk Method.

As the duration of the pumping steps had not been equal an interpolation was performed to solve this problem. Also the time for especially the pumping step 3 and 4 was far too short, the results of the interpretation of the prediction due to the Hantush-Bierschenk Method gives us just a rough overview. For a more detailed performance the input data should be more exactly, that means longer and equal durations of the pumping steps and measurements of the pressure respectively the water level within at least 5 minutes.

4.4 Hydraulic characteristic

To describe the hydraulic characteristic a more carefully and skill orientated data acquisition should be done. One of them is a denser recording interval of the pressure data during drawdown and built up phase of the pumping test. It is therefore not possible to get reliable results concerning these parameters. In addition to the length of the pumping test should be expanded.

Another factor influencing the productivity of a well is the skin factor who describes the hydraulic conductivity between formation and the well. In hydrogeology is the calculation of the skin factor based on an additional observation well. Single well solutions are described in the literature (A. Reinike "Veränderung hydraulischer Eigenschaften nach Stimmulations-experimenten im Rotliegenden der Geothermie-Forschungsbohrung Groß Schönbeck", Master Thesis TU Berlin, 2003). Therefore close data recording intervals during the built up phase of the pumping test are necessary. The available data set does not fulfill these requirements and therefore an interpretation of the reservoir characteristics in detail like the calculation of the skin effect, fracture geometry and connection within the aquifer system is not possible. See also report GT1 (Schmid GZ.:454-04/2012).

A carefully planned long term pumping test based on the till to now existing data set adapted to the expected results will help to solve these open questions.

5. Compilation of the Well Test Honselersdijk GT1 and GT2

The following table and figures shows a summary from all up to now calculated and interpreted hydraulic thermal parameters.

Table 4: Compilation of the hydraulic parameters in the well Honselersdijk GT2

Well test	Time	Q	max. drawdown		Production temperature (EPS)	PI	average Transmissivity *
	[hours]	[l/s]	[m]**	[bara]	[°C]	[l/s·bar]	[m²/s]
step 1-4	34.15	-		-	-		$3.74*10^{-4}$
step 1	15.5	32.0	130.6	6.01	87.01	5.3	$2.34*10^{-4}$
step 2	8.40	37.5	157.4	8.98	88.02	4.2	$3.87*10^{-4}$
step 3	4.25	42.5	163.8	13.30	87.41	3.2	$1.46*10^{-4}$
step 4	6.00	47.5	190.6	12.33	88.70	3.9	

* calculated for a water temperature of 90°C
** maximal drawdown corrected to a water temperature of 90°C

Figure 6 shows the transmissivity data of well GT1 and GT2. By comparing the results it has to be considered that the data from the well GT1 (diamond symbols) are evaluated under stationary and in stationary conditions using a software package applied in hydrocarbon exploration. The application of the stationary analysis method to the given data set gives transmissivity values in the range of 4.31 to 7.64*10^{-4} m²/s. Pumping test evaluation using the in stationary analysis method gives transmissivity values from 1.25 to 1.47*10^{-3} m²/s. The latter values seem to be unrealistic and will be discussed later.

The transmissivity data from well GT2 calculated at various temperatures (see table 3) are shown in figure 6 as filled circles. According to the small variance within the data not all points are visible.

Since stationary conditions during the run of the pumping test has not been reached the evaluation of the pumping test data on GT2 has only been done by in stationary analysis methods. Especially suitable for single well solutions of pumping tests are the methods of “Gringarten Forward” and ”Theis Forward”. The results of these methods are summarized in table 4 and figure 6. Additional different hydraulic models have been adopted for the validation of the results (see table 3).

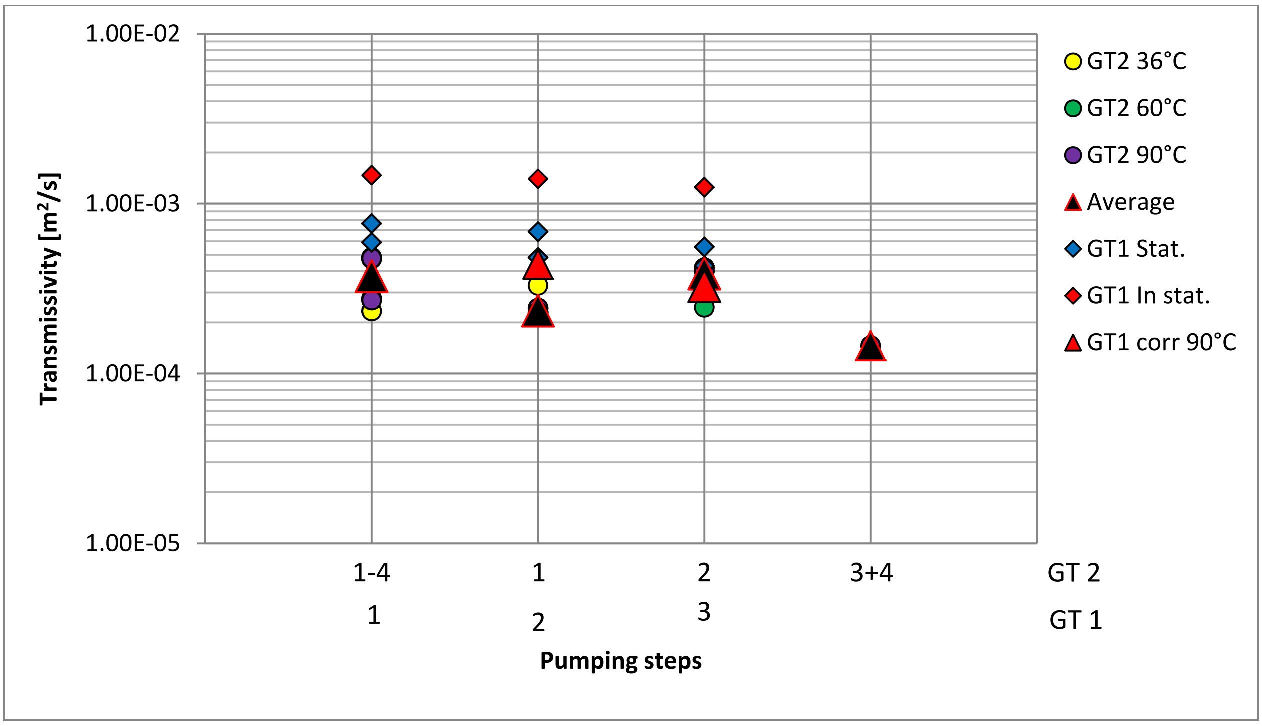


Fig.6: Plot of validated Transmissivity data from well, Honselersdijk GT2 calculated at various temperatures compared to results of well GT1. Triangles represent the average values of the Transmissivity. Data from the well GT1 are corrected to 90 °C for comparison.

To elucidate the differences in the transmissivity calculation of well GT1 and GT2 selected steps of the pumping test on GT1 has been re-evaluated (table 5). Figure 7 demonstrate the results and show that the raw data, marked as GT1 origin, gives unrealistic high transmissibility values. These values fall accidentally in the same range as transmissivity data reported from the in stationary evaluation method. The same data sets give after temperature correction to 90 °C more realistic values and agree well with the results of well GT2. In summary the differing transmissivity data of well GT1 and GT2 are induced by comparing results obtained from raw data and temperature corrected data.

Table 5: Results from the re-evaluation of the data from well GT1 by the “in house” software

	Transmissivity from data corrected to 90°C	Transmissivity from origin data set	Transmissivity in stationary report GT1
Well test 2 (Step 2a)	4.27E-04 m²/s	1.72E-03 m²/s	1.43E-03 m²/s
	4.51E-04 m²/s	1.73E-03 m²/s	
	4.43E-04 m²/s	1.74E-03 m²/s	
Well test 3 (Step 3)	3.20E-04 m²/s	1.52E-03 m²/s	1.25E-03 m²/s
	3.39E-04 m²/s	1.08E-03 m²/s	
	3.34E-04 m²/s	1.08E-03 m²/s	

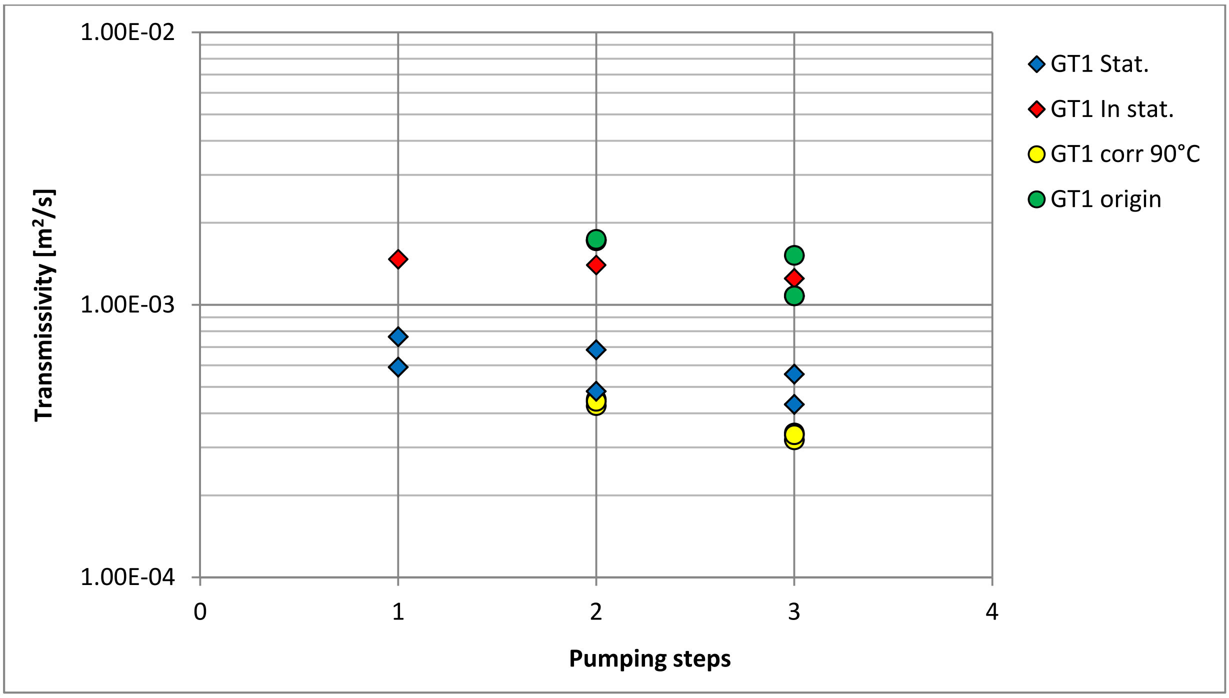


Fig.7: Plot of Transmissivity data from well Honselersdijk GT1 calculated at stationary and in stationary conditions (see Report GT1) compared to results obtained by the “in house software” on the same data set (origin) and after temperature correction.

Summarizing the hydraulic parameters from the well GT2 the transmissibility values range from $4.83*10^{-4}$ to $6.31*10^{-5}$ m²/s (see table 3). This variability is restricted from 3.74 to $1.46*10^{-4}$ (average values) if only temperature corrected results (90 °C) will be considered. Compared to well GT1 (transmissibility range from 4.31 to $7.64*10^{-4}$) coincide this data very well (see figure 6). The transmissibility difference between these two wells in the same sedimentary system varies within realistic boundaries. Also has to be taken into account that in the short time of the well tests stationary conditions could not be achieved and relatively large extrapolation had been necessary by the use of the different evaluation methods respectively hydraulic models. Another reason is to see in the different screen lengths from GT1 and GT2 (table 6).

Table 6: Table of screen positions and screen lengths in the well Honselersdijk GT1 and GT2

GT 1	MD [m]	length [m]
Screen 1	2550 – 2720	170
Screen 2	2880 – 3003	123
Screen 2	3032 - 3154	122
total		415

GT 2	MD [m]	length [m]
Screen 1	2403 - 2682	279
		279

Comparing the regression line GT1 and GT2 in figure 8 the influence of the run time of the pumping test becomes obvious. In the case of GT1 the pumping steps (drawdown period) run in the middle more than 13 hours and quasi stationary conditions could approximately been reached resulting in a sufficient fit of the regression line. The pumping test of well GT2 run in most of the steps only half the time compared to GT1. Therefore the data points show more scattering and to get a sufficient regression pumping step 3 (only 4.25 h) has to be excluded.

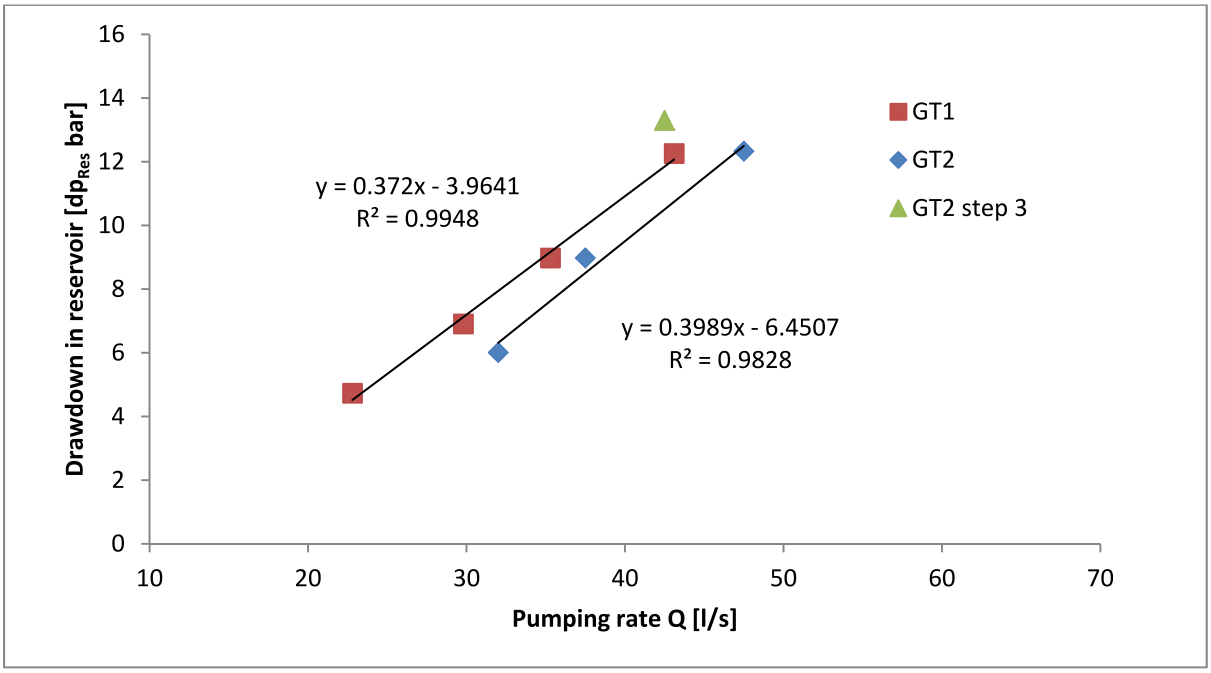


Fig.8: Plot of drawdown in reservoir [dp$_{Res}$] versus pumping rate [l/s] for well Honselersdijk GT1 and GT2. The data point of the well test GT2 step 3 was excluded from calculation of the regression line.

At the moment considering the whole data sets from the well Honselersdijk GT1 and GT 2 it looks that the storage capacity and therefore the productivity of the well GT1 is a little bit better or quite similar compared to the well GT2. Whereas the quality of the input data on GT1 is quite better compared to GT2 (see the different correlation graphs). Therefore results are weaker on GT2.

For a final evaluation it has to be considered that both wells maybe not enough developed. Therefore it is possible that over an extended production period the development of the wells respectively the “near well zone” to the aquifer will improve the transmissibility conditions.

6. Additional Questions

For a detailed calculation of the depression cone different formulas exists. The main input parameters are the conductivity and the drawdown in the well. The pumping test evaluation gives as results the transmissivity. The transmissivity can with the knowledge of the real aquifer thickness be converted to conductivity. In our case the actual productive aquifer thickness is not well known. A rough method after Kusakin (in Strzodka, 1977) uses the transmissivity data corrected by a constant and the actual drawdown at each pumping step to calculate the depression cone.

$$R = 575 \cdot s \cdot \sqrt{T}$$

R=Radius of depression cone
s =drawdown
T = Transmissivity

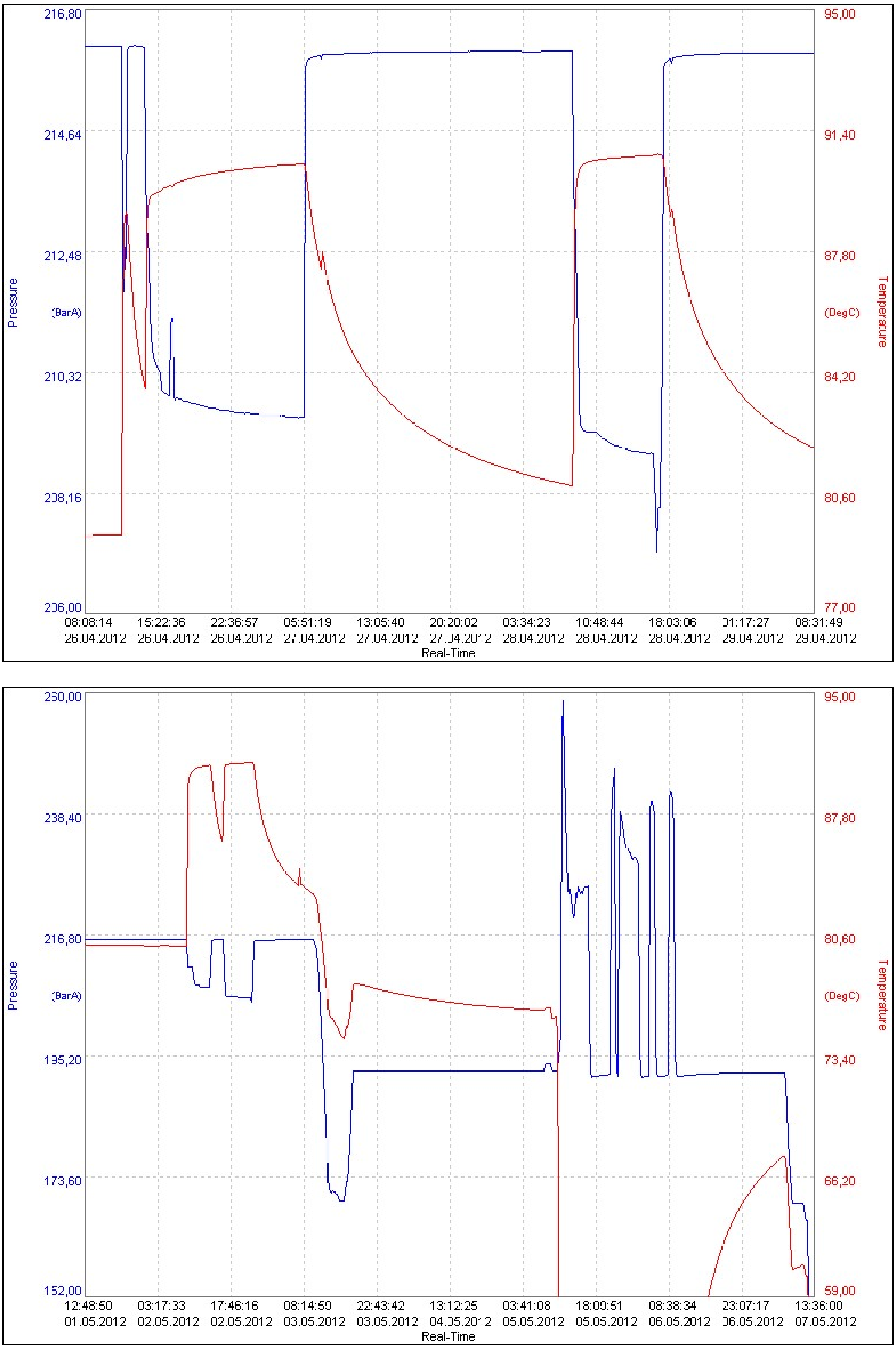
In the following table 7 these estimations are summarized and compared to well GT1.

GT2	Pumping rate [l/s]	Drawdown [m] *	Transmissivity [m²/s)	Depression cone [m]
Step 1	32.0	130.6	2.34E-04	1,149
Step 2	37.5	157.4	3.87E-04	1,780
Step 3	42.5	163.8	1.46E-04	1,138
Step 4	47.5	190.6	1.46E-04	1,324
GT1				
Step 2a	29,8	127	4.40E-04	1,532
Step 3	43.1	174	3.31E-04	1,820

* Drawdown data corrected to reservoir conditions (temperature 90 °C).

As seen in the table above and as discussed in the chapters before gives good data qualities a good agreement within the results (see well GT1). Data on GT 2 varies during the very short pumping test runs (quasi stationary conditions could not been reached).

Appendix 1: Pressure, Temperature Real-Time-Plots



Pressure and temperature Real-Time-Plot fom the well tests Honselersdijk GT2

Appendix 2: Injection test

After the well test also three short injection tests was done on the well Honselersdijk GT2. Data sets from the “mud pressure” (pump pressure), “pressure on the choke manifold” (annulus pressure) and the “injection rate” was produced over the testing time. Furthermore screen shots from these three test intervals were also available (Fig. 1, 3 and 4). The data sets are represented as Excel files, but not split up in different rows, therefore a detailed processing and examination as example by a Horner plot was not offered. Similar to the report for the well GT1 only a short analyze of the injection test will be done to compare the actual date to the well GT1.

Injection test 1 (Fig. 1) was done from 05.05.2012 at 11:05 to 05.05.2012 at 16:00. The injection rate was approximately 20 l/sec (1,200 l/min).

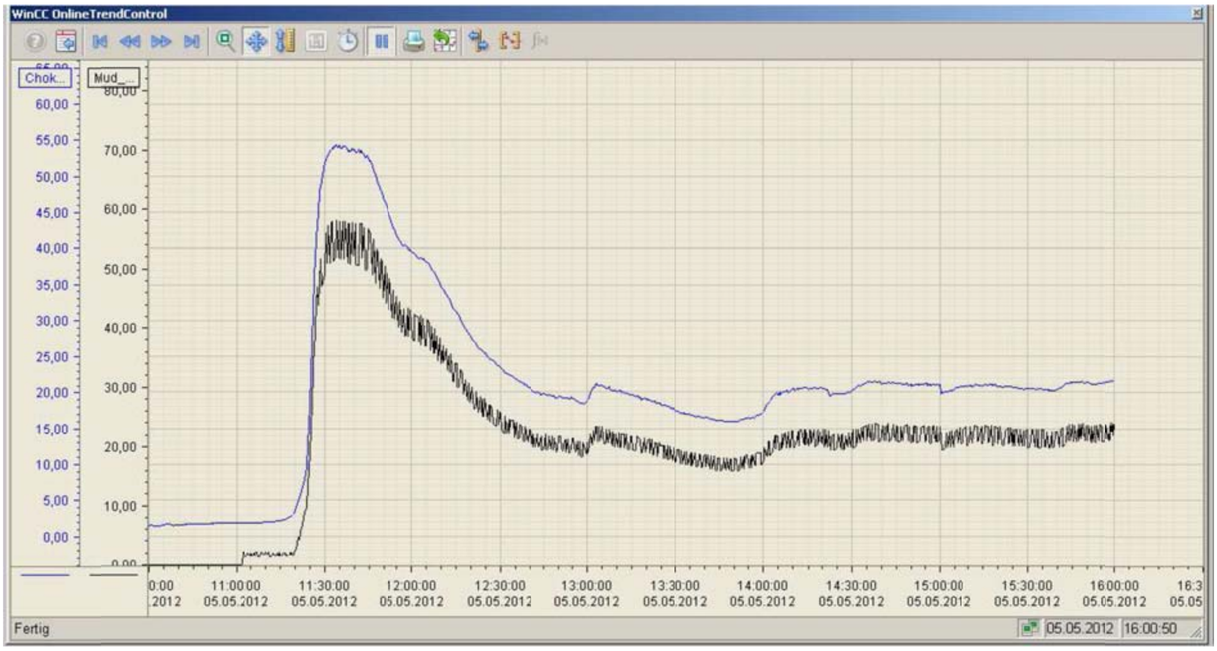


Fig. 1: Injection test 1 Honselersdijk GT2; 1,200 Ltr/min.

The end of the first step of this test is missing. The decay period of the pressure is in this figure (screen shot) not included. As example compare figure 2 with the similar first step of the injection test on GT1.

The maximum Choke pressure by the injection test on well GT2 was 54 bar (max.73 bar at GT1) and the maximum Mud pressure reach 68 bar on GT2 (max. 85 bar at GT1). As a first analyze this demonstrate better hydraulic conditions at the beginning of the reinjection on well GT2. After 160 minutes the Choke pressure decreases to approx. 20 bars, Mud pressure to approx. 25 bars. These values stay with a small variation constant up to end of this test step. This tendency also is quite different to the situation on well GT1 (Fig. 2).

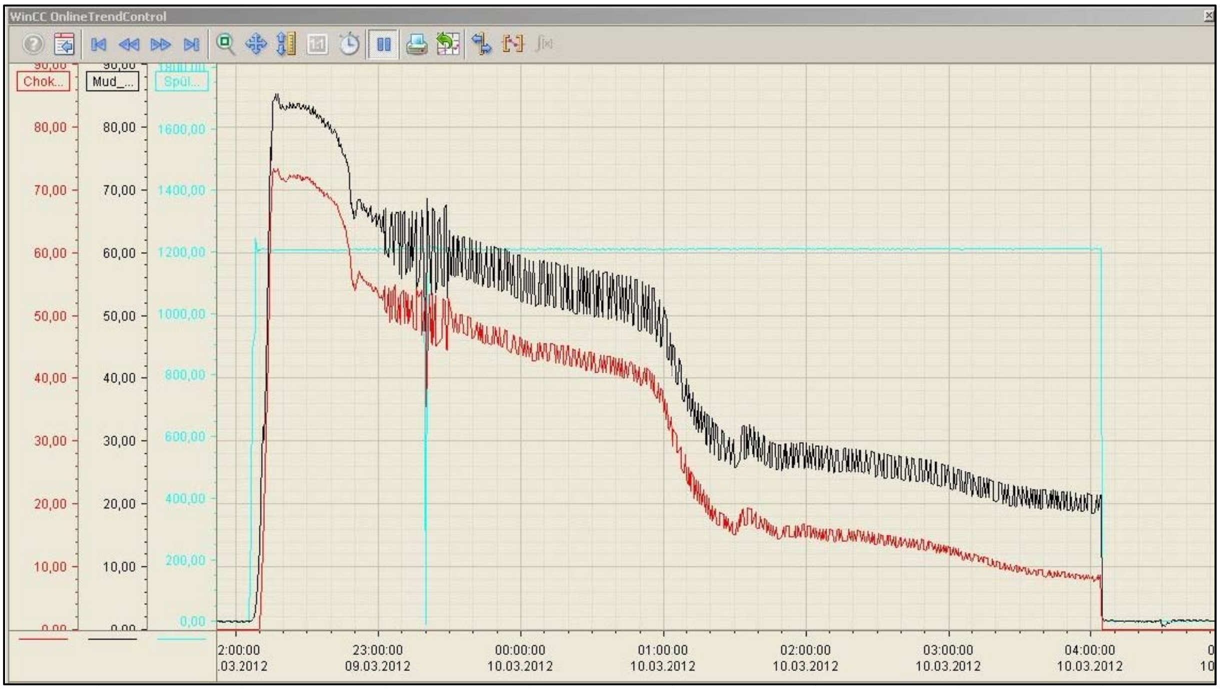


Fig. 2: Injection test 1 Honselersdijk GT1

The screen shot on fig. 1 shows also a typical curve progression at the beginning of a fluid injection with an extremely abrupt increase of the initiation pressure until to the breakdown pressure. A significant decrease at 20 bar (25 bar mud pressure) shows the beginning of the frictional pressure drop. In this case is significant difference to the following “pore pressure”.

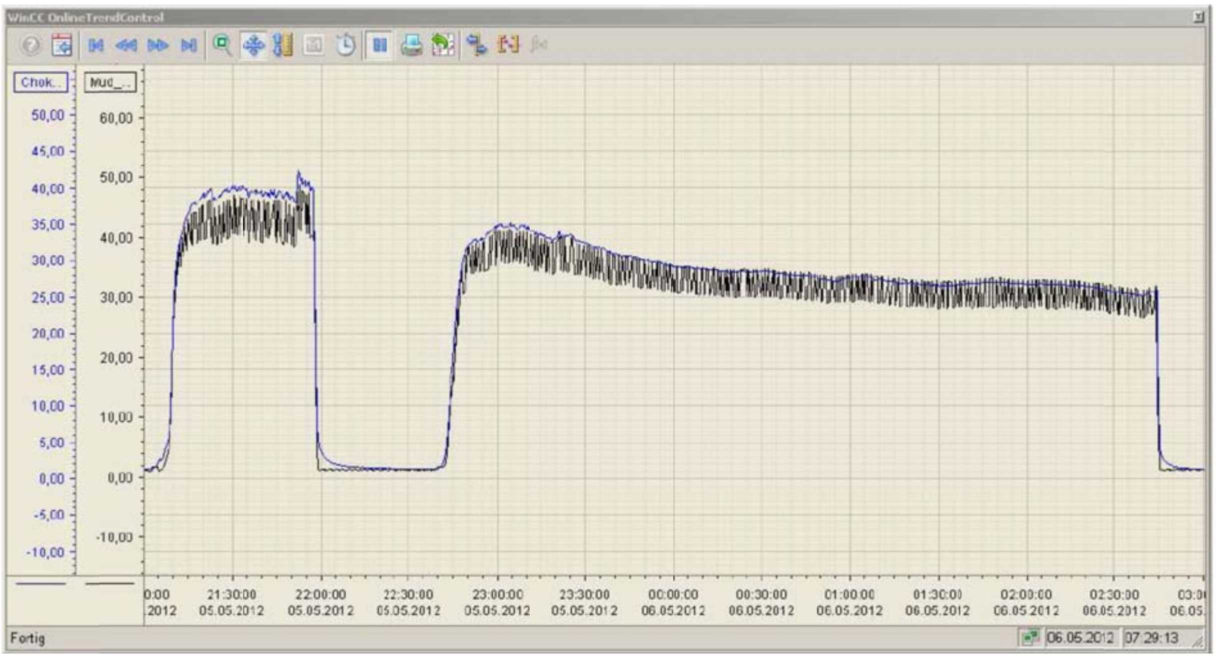


Fig. 3: Injection test 2 Honselersdijk GT2; 1,800 Ltr. /min

Injection test 2 (Fig. 3) was done from 05.05.2012 at 21:00 to 06.05.2012 at 02:45. The figure shows a break during the injection time on 05.05.2012 from 22:00 to 22:40. The injection rate was approximately 30 l/sec (1.800 l/min). This data set gives in spite of a higher injection rate a complete different picture compared to figure 1. One reason therefore is the opening of the reservoir by the first test step.

The screen shot show after both beginnings a strong curve progression. The typical breakdown pressure (wellbore pressure) could no more be noticed. The maximum mud pressure reaches a value of approx. 47 bar (40 bar Choke pressure). The minimum values at the end of this test step where approx. 35 bar (26 bar Choke pressure). For a comprehensive analysis of well GT2 more injection steps (Guidelines for produced water injection) must be done. In this case a monitoring of the test will be possible.

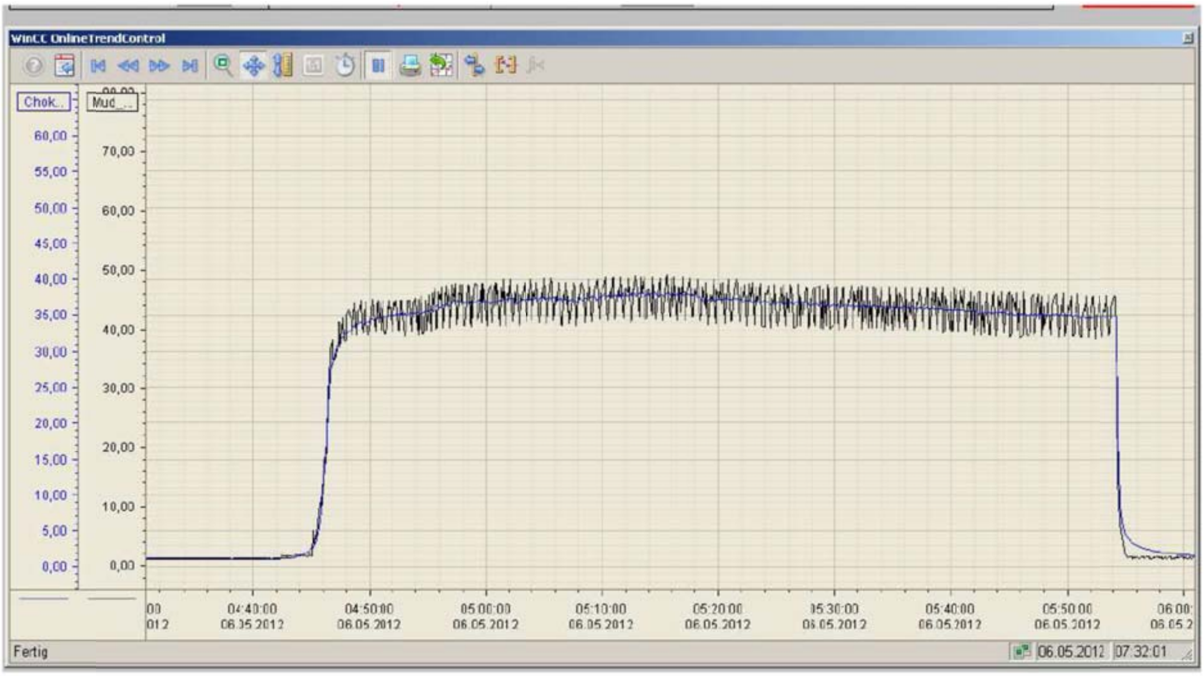


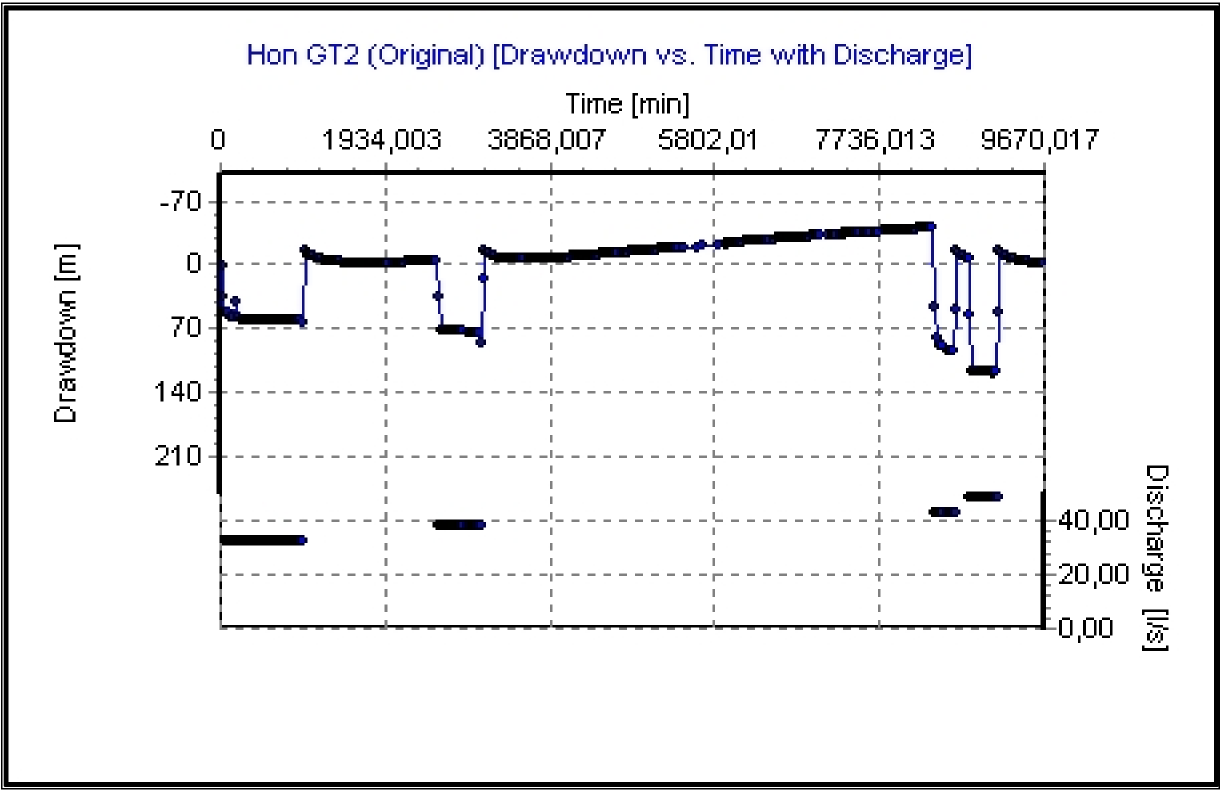
Fig. 4: Injection test 3 Honselersdijk GT2; 2,400 Ltr. /min

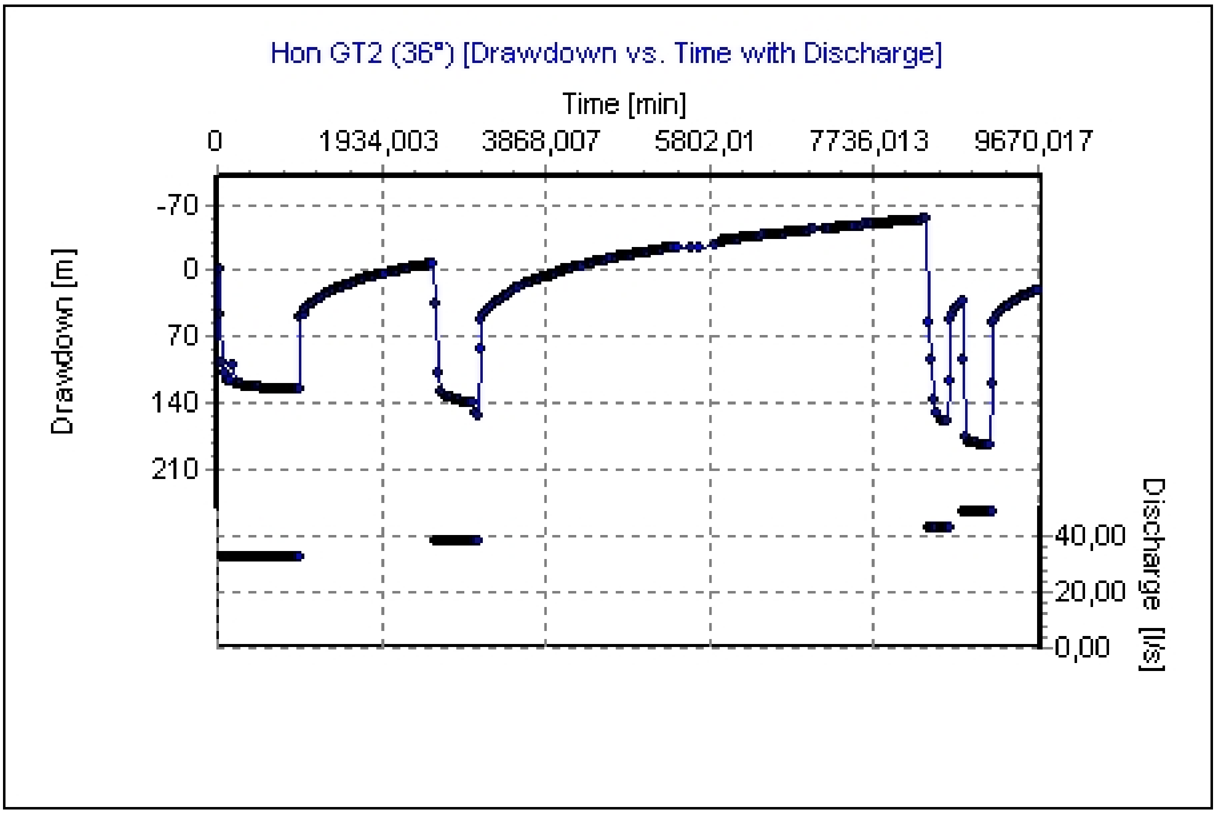
Injection test 3 (Fig. 4) was done from 06.05.2012 at 04:45 to 05:55. The injection rate was planned and started at approximately 2.400 ltr. / min. This short injection test reached a maximum value for the Mud pressure of about 48 bar (Choke pressure 37 bar). This screen shot demonstrate a quite open formation and allows a good prediction for the real operation conditions during the injection.

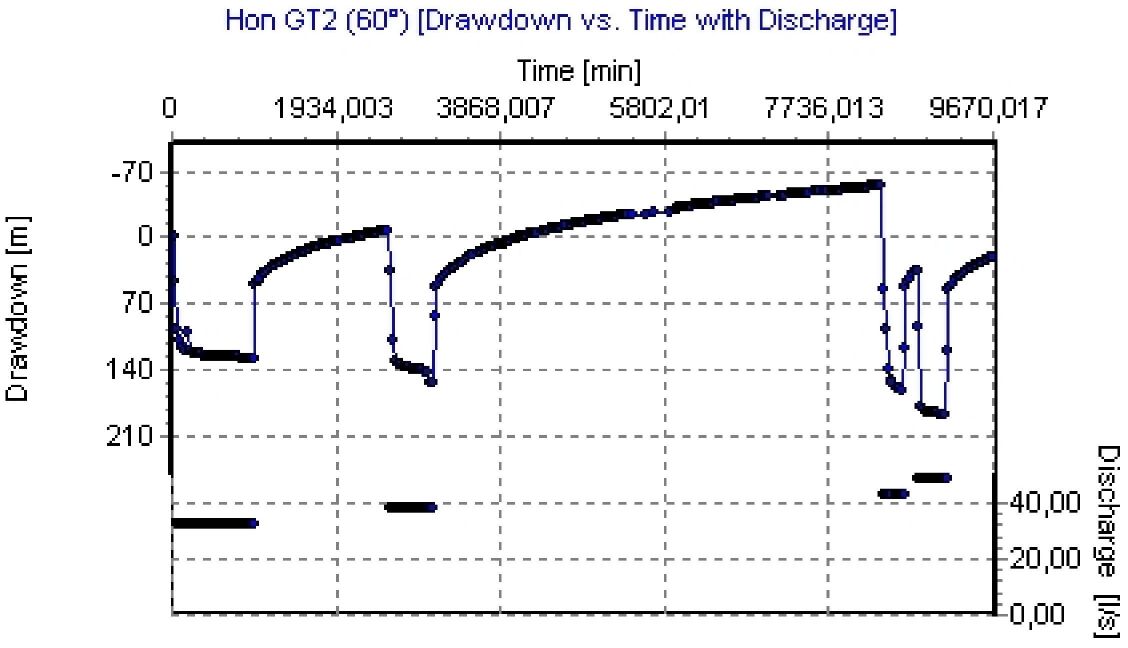
This short test analysis gives as result a realistic economic flow rate from about 2,400 Ltr./min (40 Ltr./sec). However for a long term injection the influenced of the water quality, rock water interaction, pore geometry etc. will be an essential for a the long term economical function of this system.

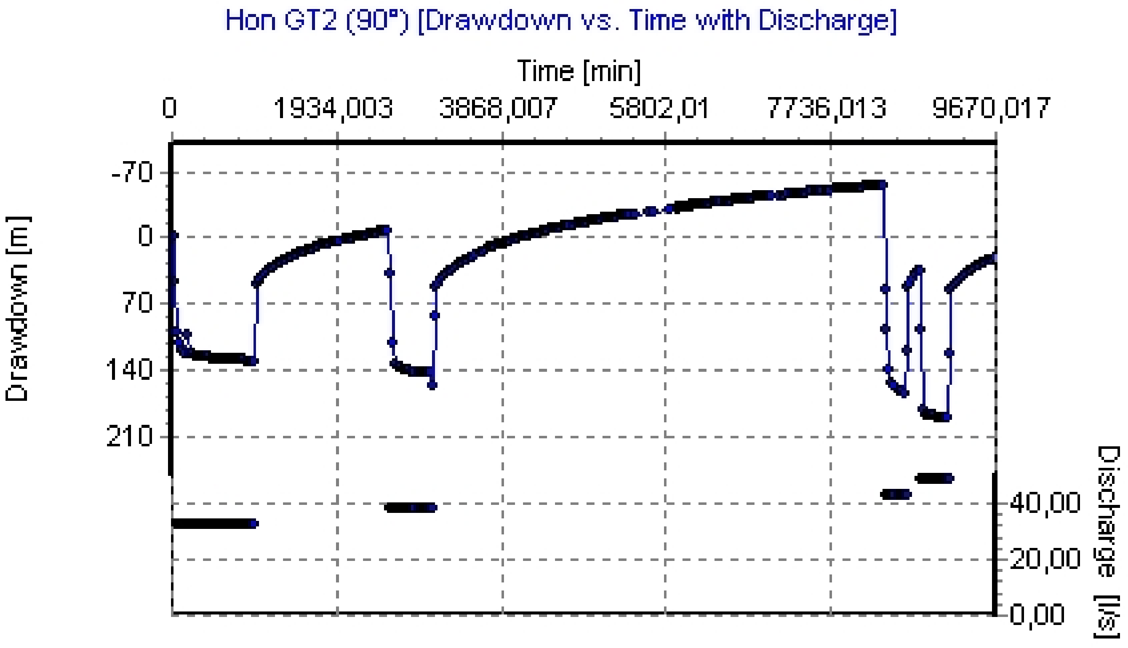
After this analysis it shows a significant better injectability for the aquifer explored by the well GT2. Otherwise the result from the production test give lower transmissibility values for this well compared to well GT1. The reason for these discrepancies could be the fact that the borehole respectively the aquifer was no enough developed at the beginning of these very short well tests.

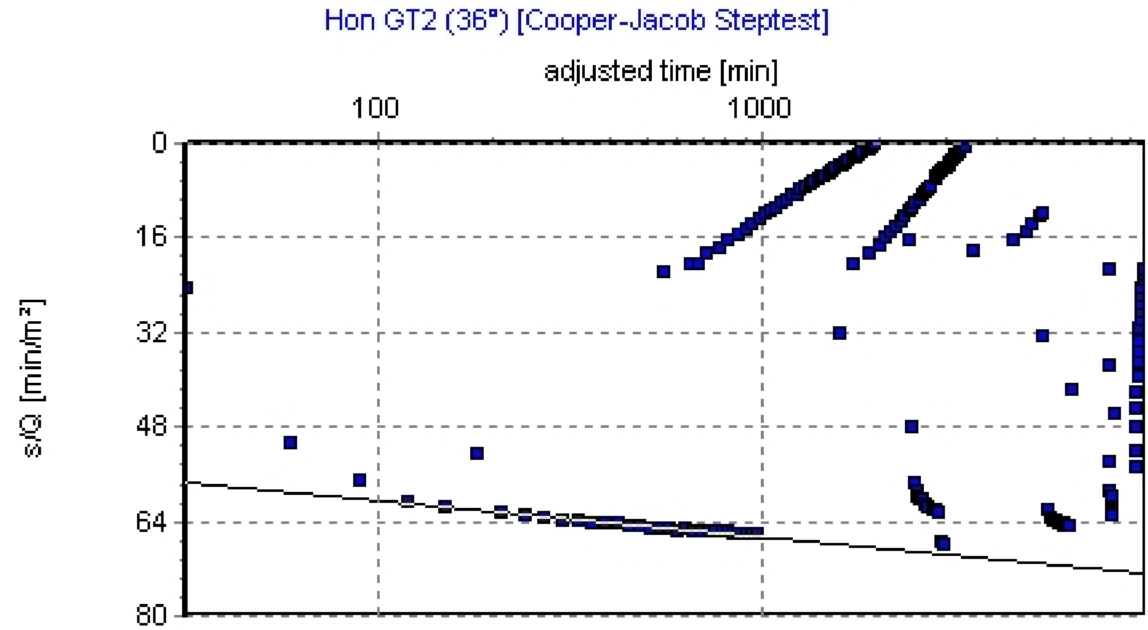
Appendix 3: Graphs to the well test evaluation



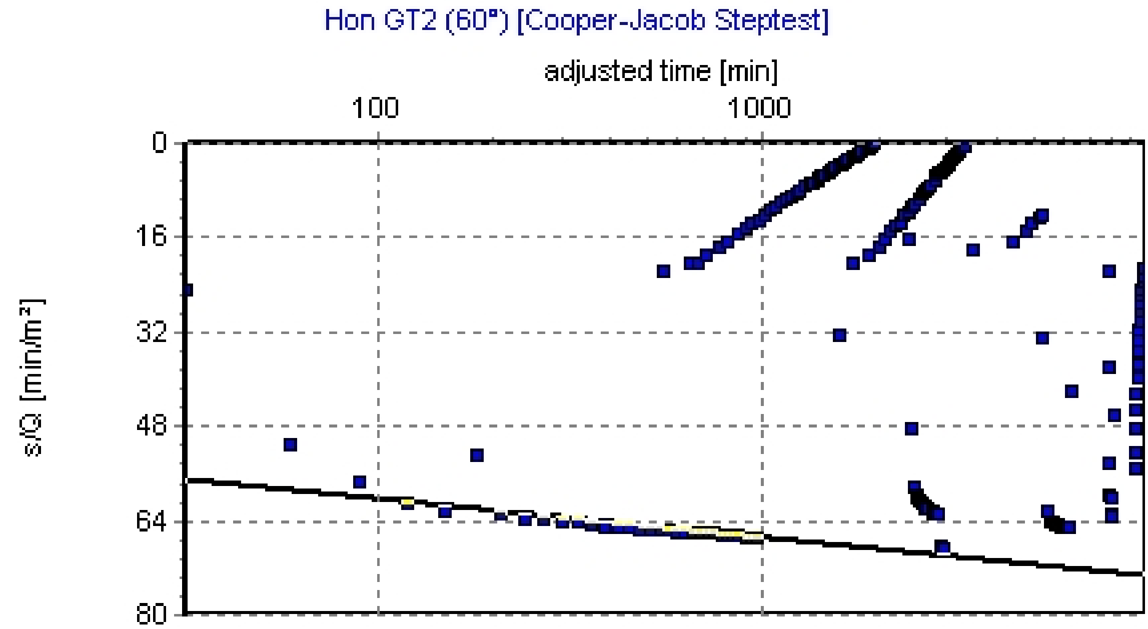



Hon GT2 (60°) [Drawdown vs. Time with Discharge]
Time [min]
0
1934,003
3868,007
5802,01
7736,013
9670,017
Drawdown [m]
-70
0
70
140
210
Discharge [l/s]
40,00
20,00
0,00

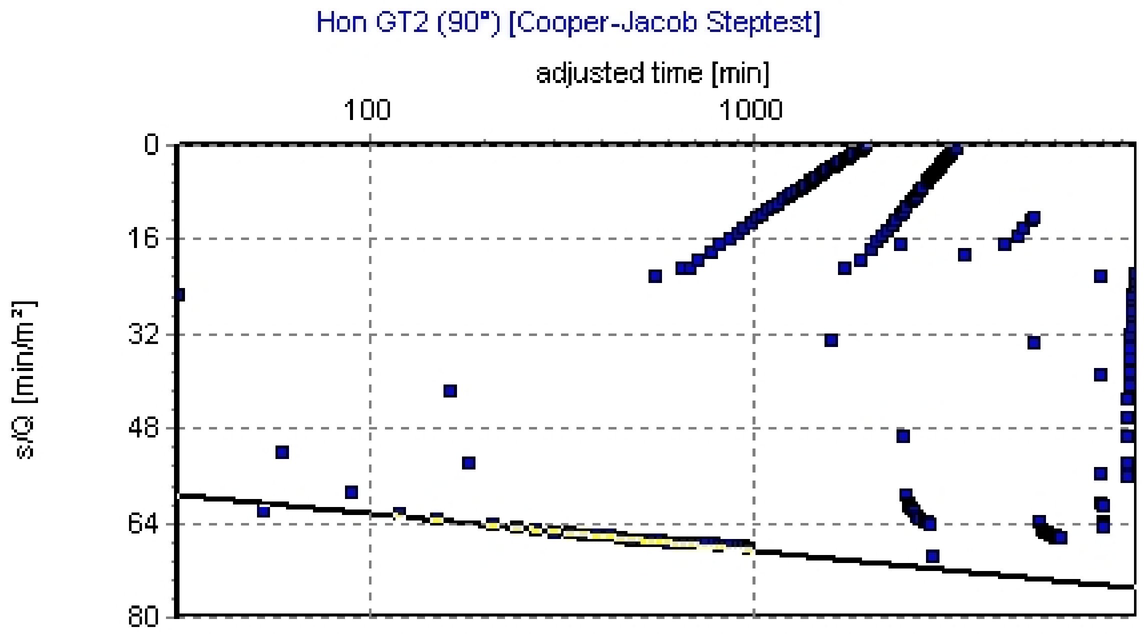

Hon GT2 (90°) [Drawdown vs. Time with Discharge]
Time [min]
0
1934,003
3868,007
5802,01
7736,013
9670,017
Drawdown [m]
-70
0
70
140
210
Discharge [l/s]
40,00
20,00
0,00



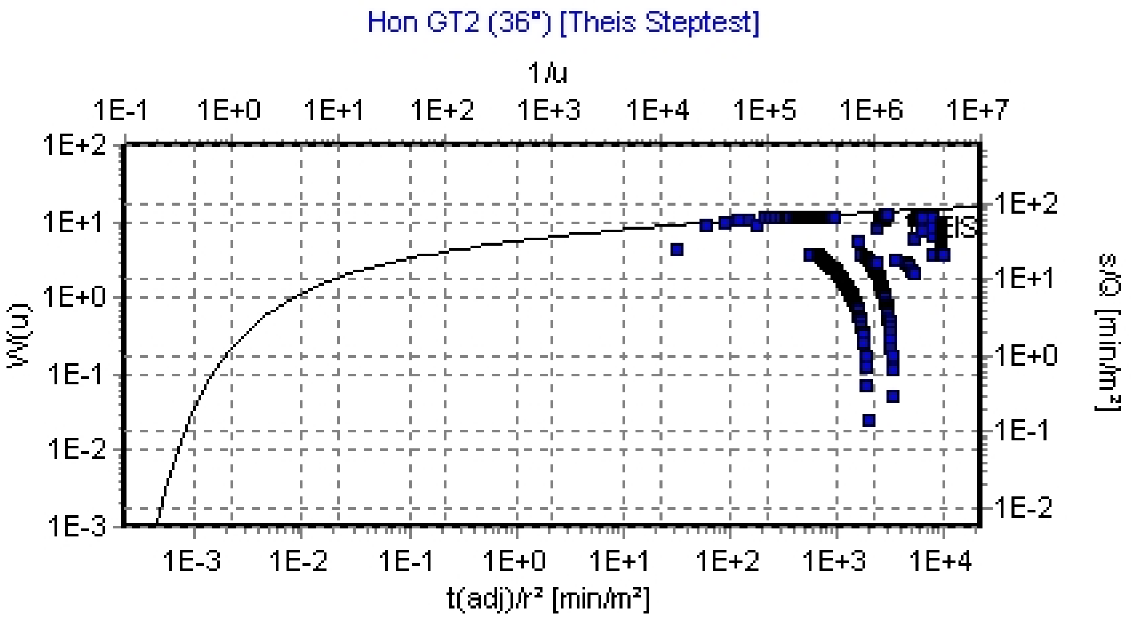
Transmissivity: 4,83E-4 m²/s
Conductivity: 2,20E-6 m/s



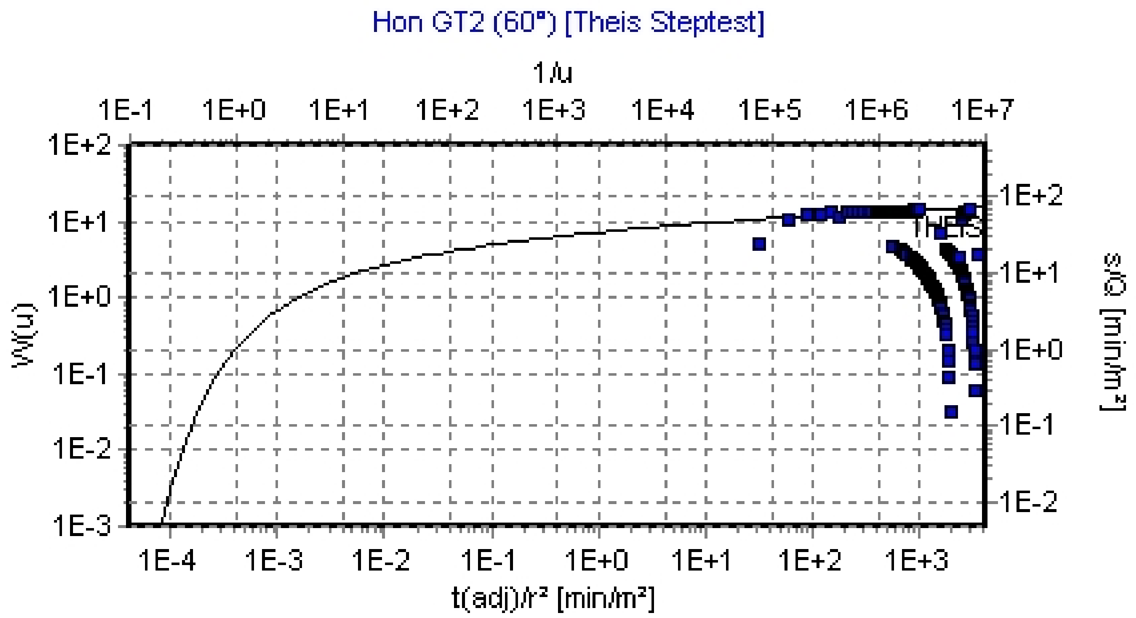
Transmissivity: 4,74E-4 m²/s
Conductivity: 2,16E-6 m/s


Hon GT2 (90°) [Cooper-Jacob Steptest]

Transmissivity: 4,77E-4 m²/s
Conductivity: 2,17E-6 m/s

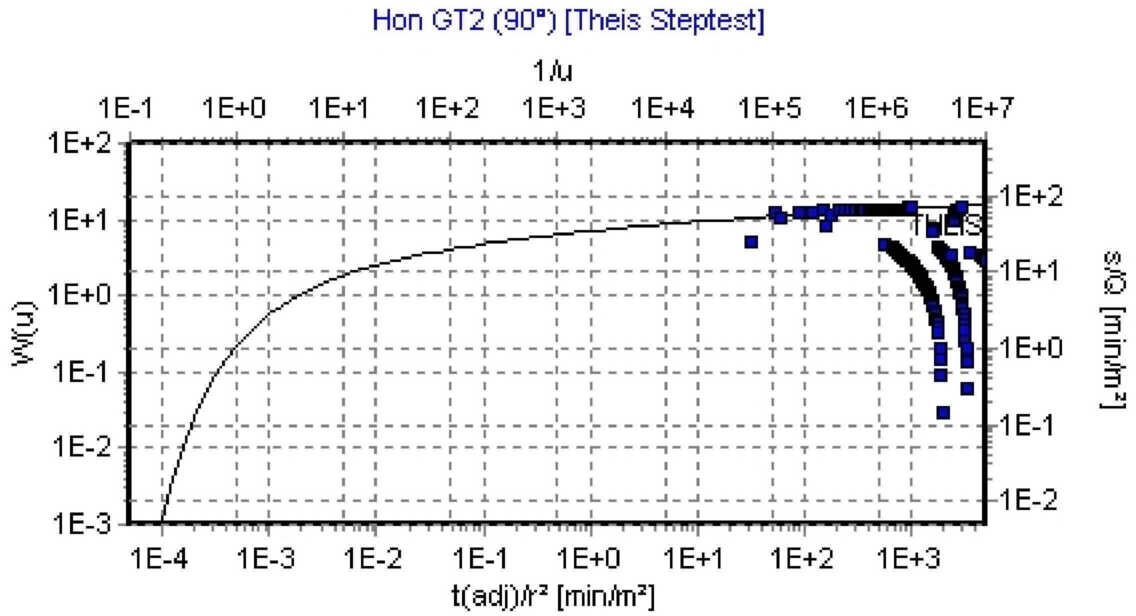

Hon GT2 (36°) [Theis Steptest]

Transmissivity: 2,34E-4 m²/s
Storativity: 1,24E-4
Conductivity: 1,06E-6 m/s



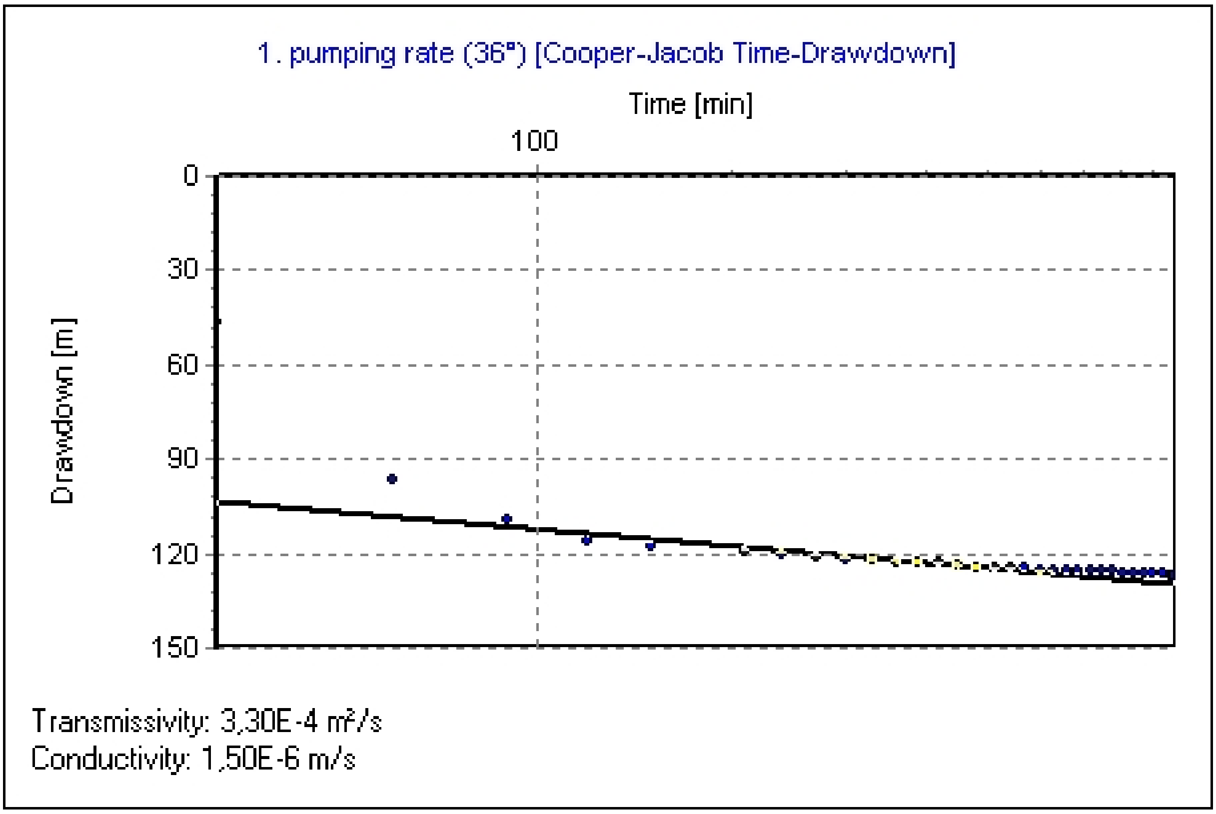
Transmissivity: 2,77E-4 m²/s
Conductivity: 1,26E-6 m/s

Storativity: 2,77E-5

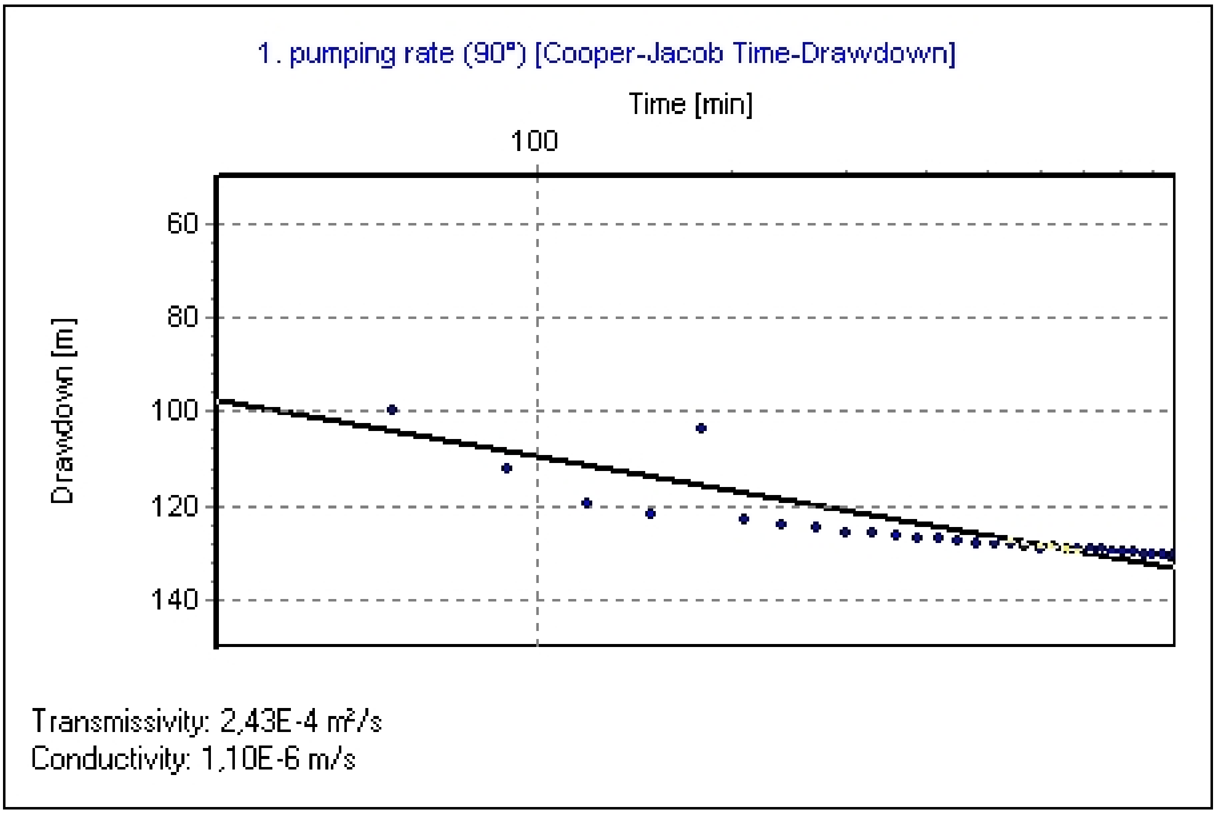


Transmissivity: 2,71E-4 m²/s
Conductivity: 1,23E-6 m/s

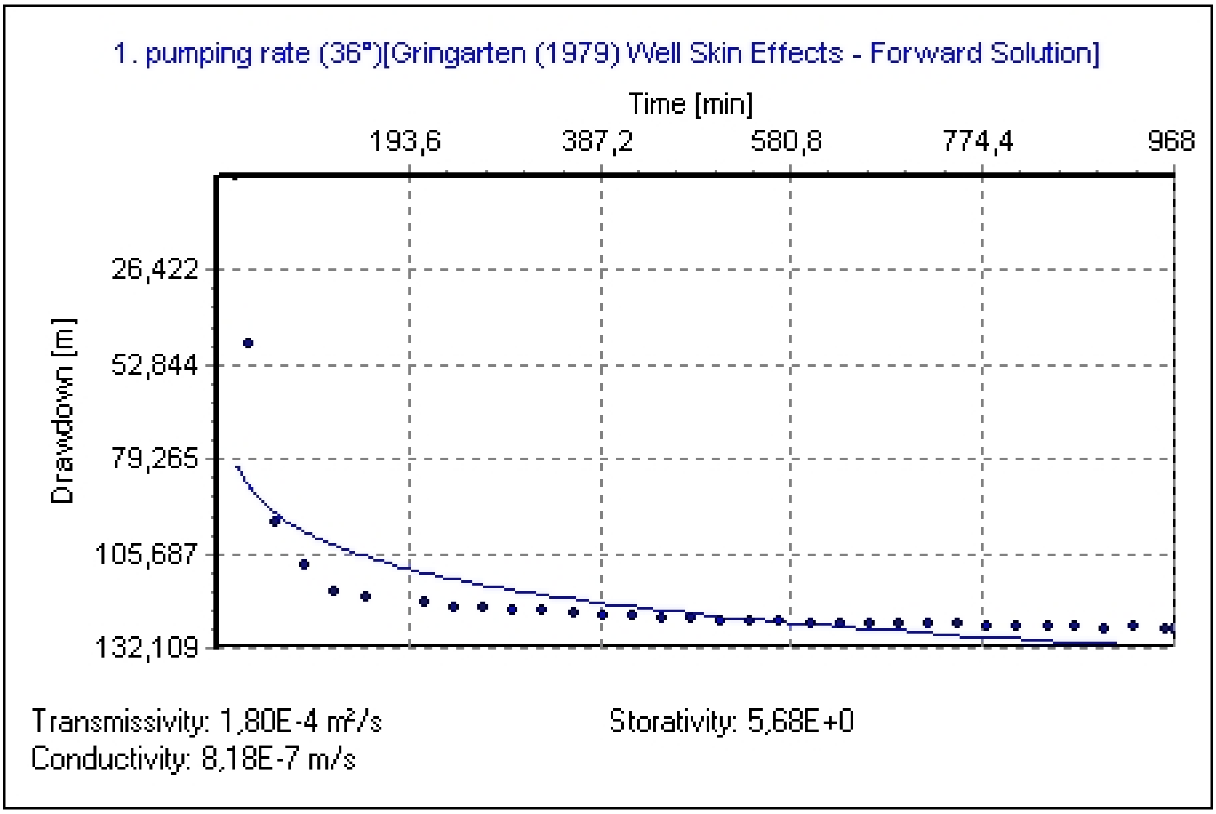
Storativity: 3,23E-5



Transmissivity: 3,30E-4 m²/s
Conductivity: 1,50E-6 m/s

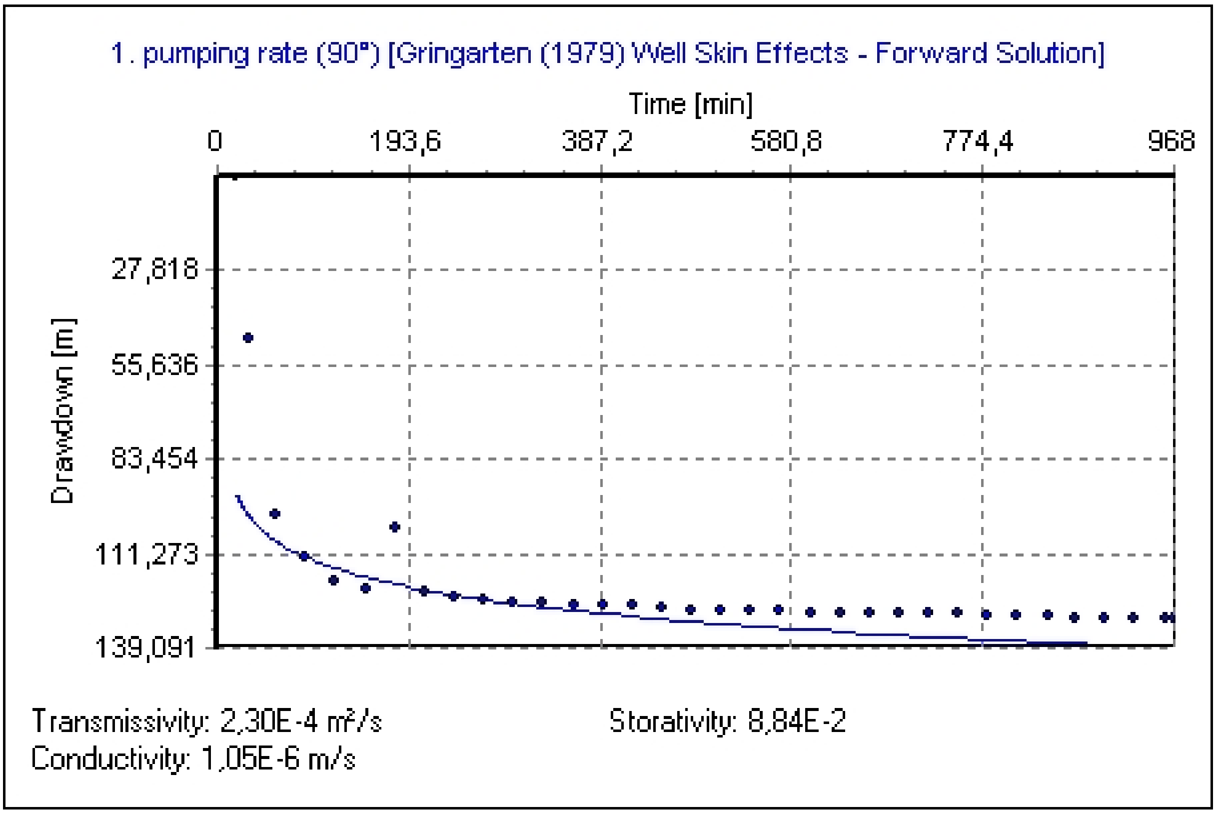


Transmissivity: 2,43E-4 m²/s
Conductivity: 1,10E-6 m/s



Transmissivity: 1,80E-4 m²/s
Conductivity: 8,18E-7 m/s

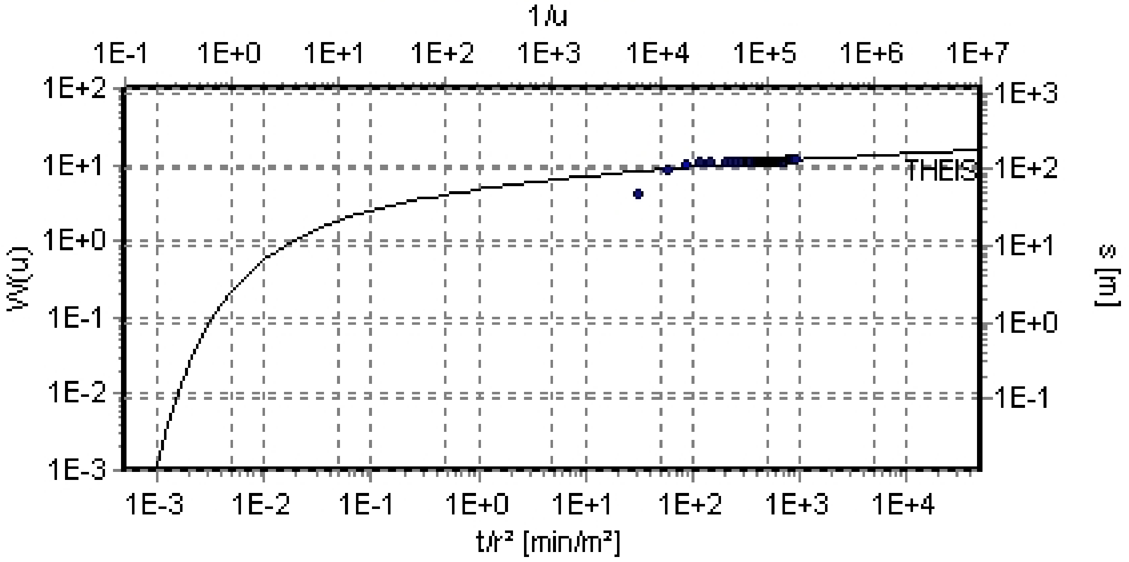
Storativity: 5,68E+0



Transmissivity: 2,30E-4 m²/s
Conductivity: 1,05E-6 m/s

Storativity: 8,84E-2

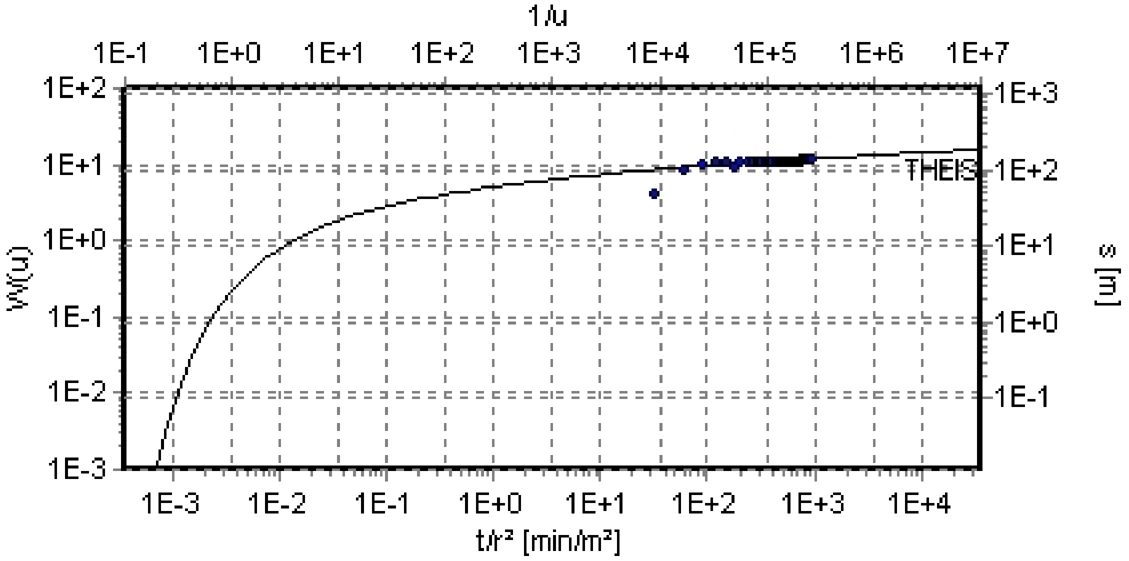
1 . pumping rate (36°) [Theis]



Transmissivity: 2,21E-4 m²/s
Conductivity: 1,00E-6 m/s

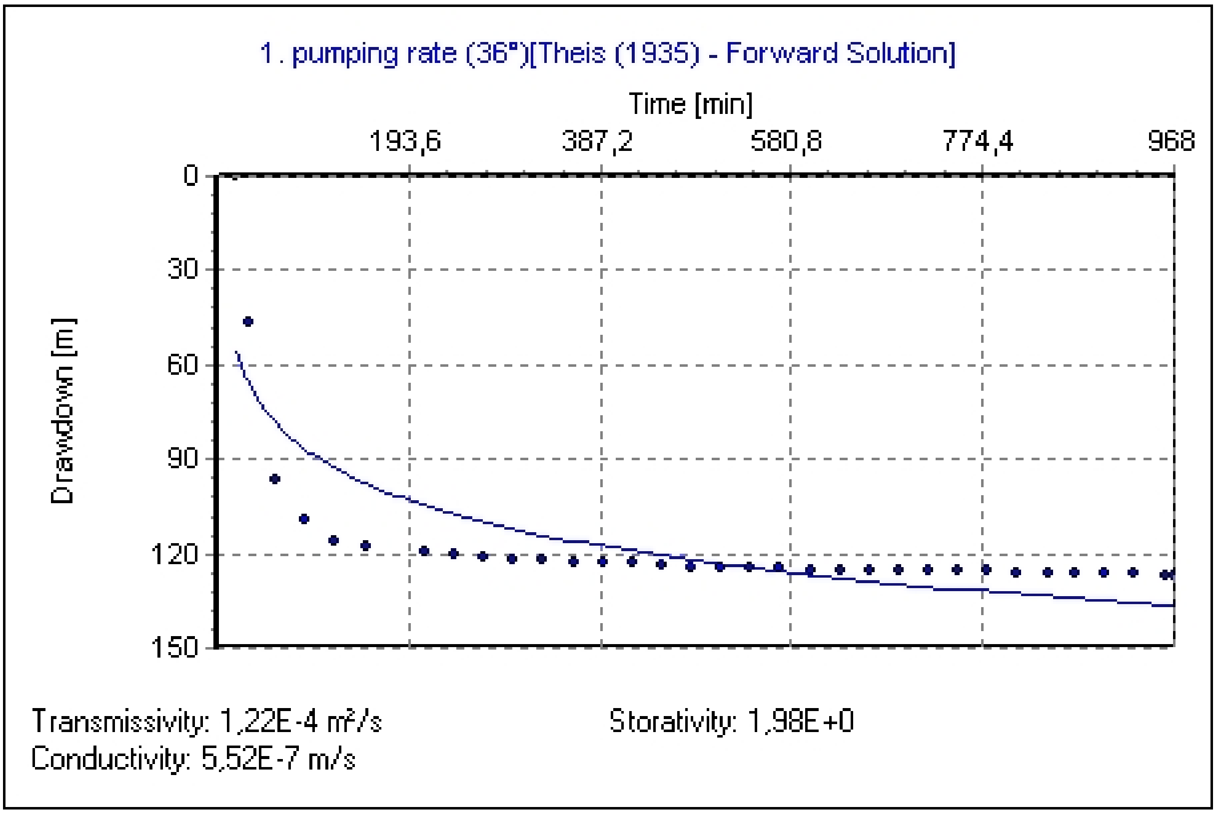
Storativity: 2,63E-4

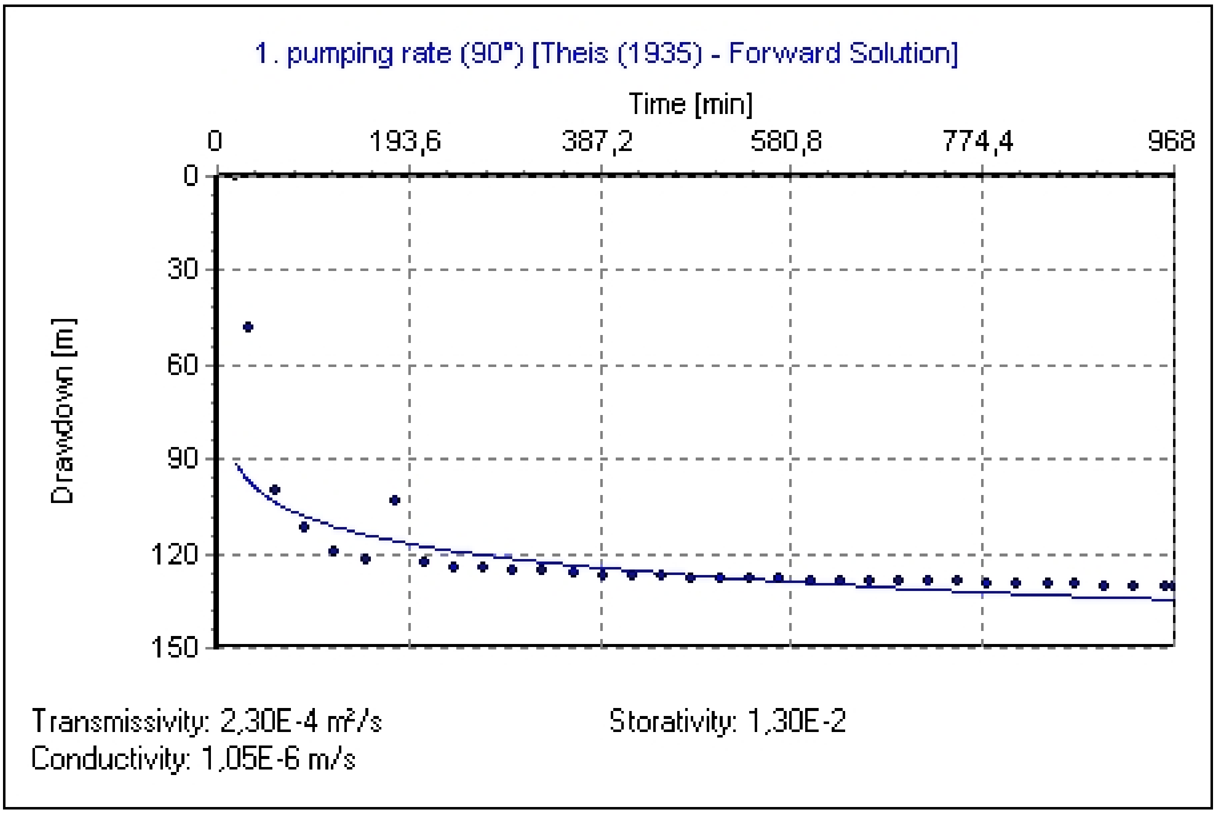
1 . pumping rate (90°) [Theis]

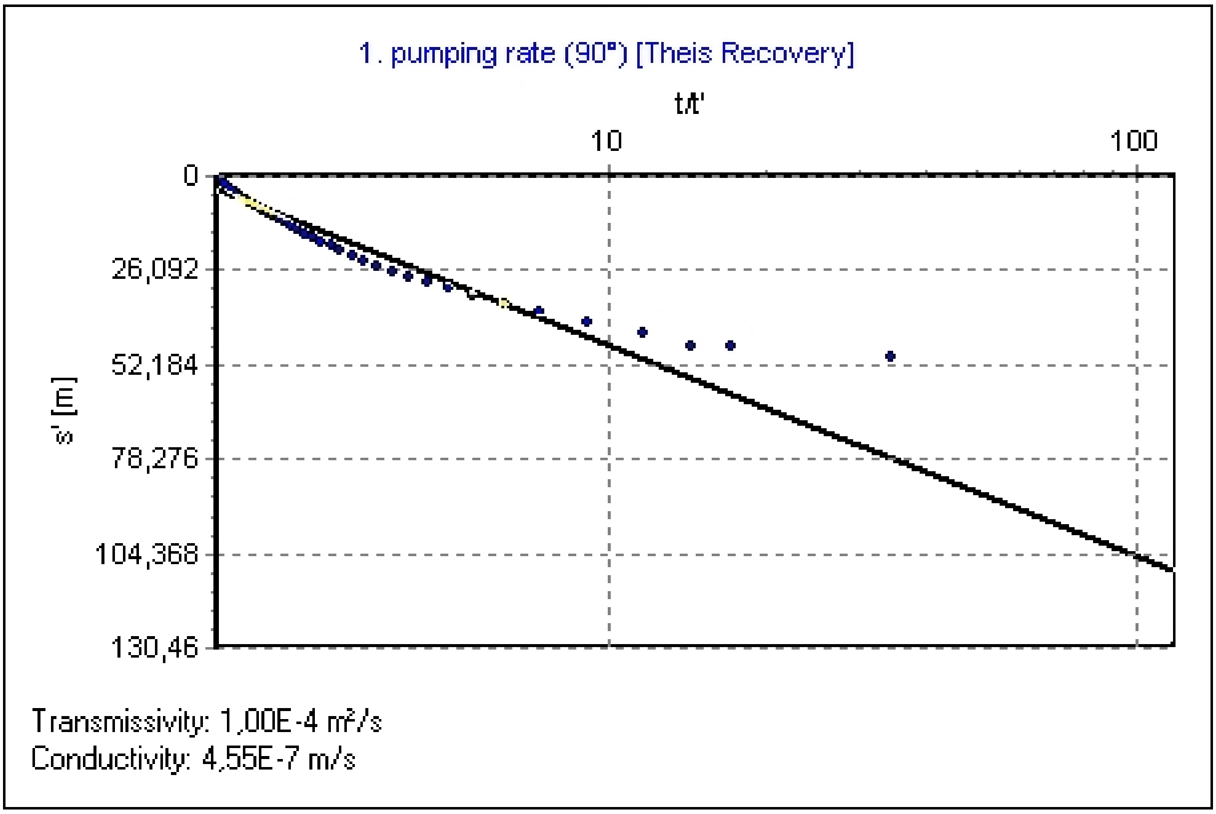


Transmissivity: 2,15E-4 m²/s
Conductivity: 9,76E-7 m/s

Storativity: 1,85E-4

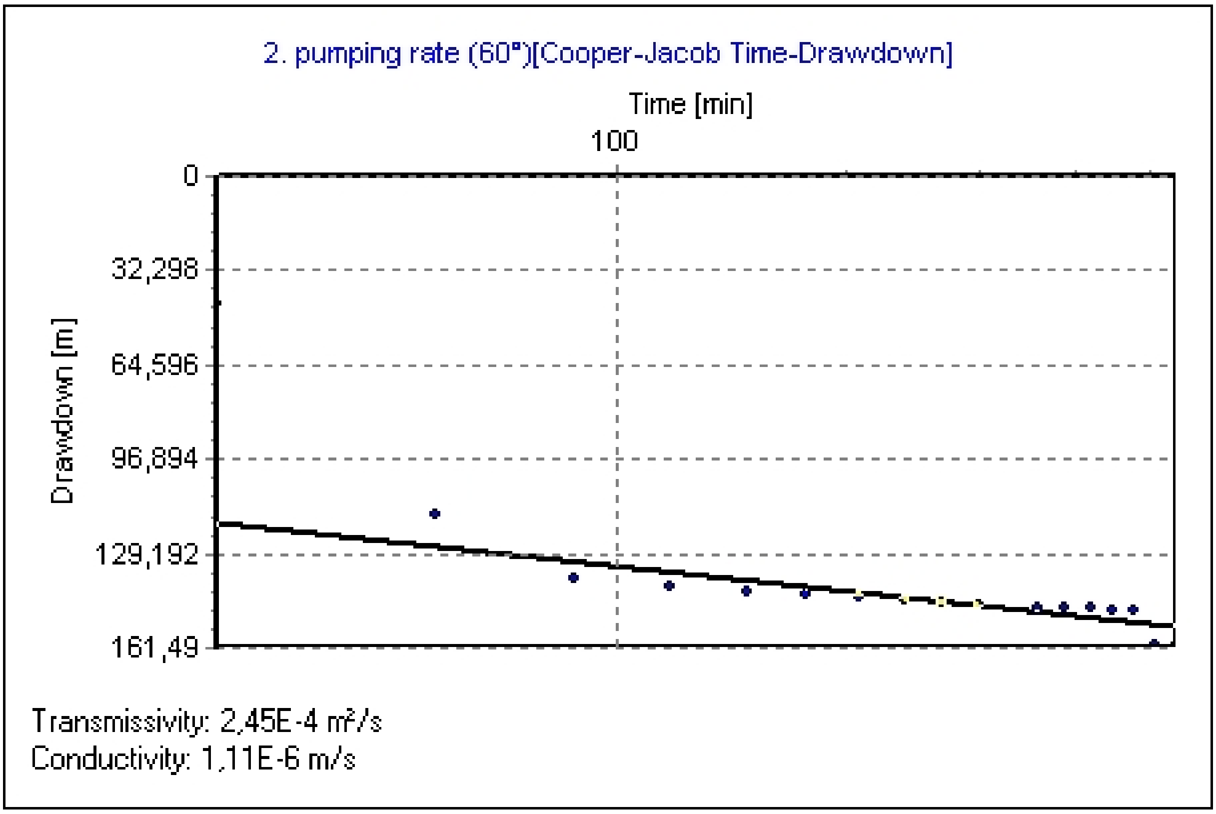

1. pumping rate (36°)[Theis (1935) - Forward Solution]
Time [min]
193,6
387,2
580,8
774,4
968
Drawdown [m]
0
30
60
90
120
150
Transmissivity: 1,22E-4 m²/s
Storativity: 1,98E+0
Conductivity: 5,52E-7 m/s


1. pumping rate (90°) [Theis (1935) - Forward Solution]
Time [min]
0
193,6
387,2
580,8
774,4
968
Drawdown [m]
0
30
60
90
120
150
Transmissivity: 2,30E-4 m²/s
Storativity: 1,30E-2
Conductivity: 1,05E-6 m/s



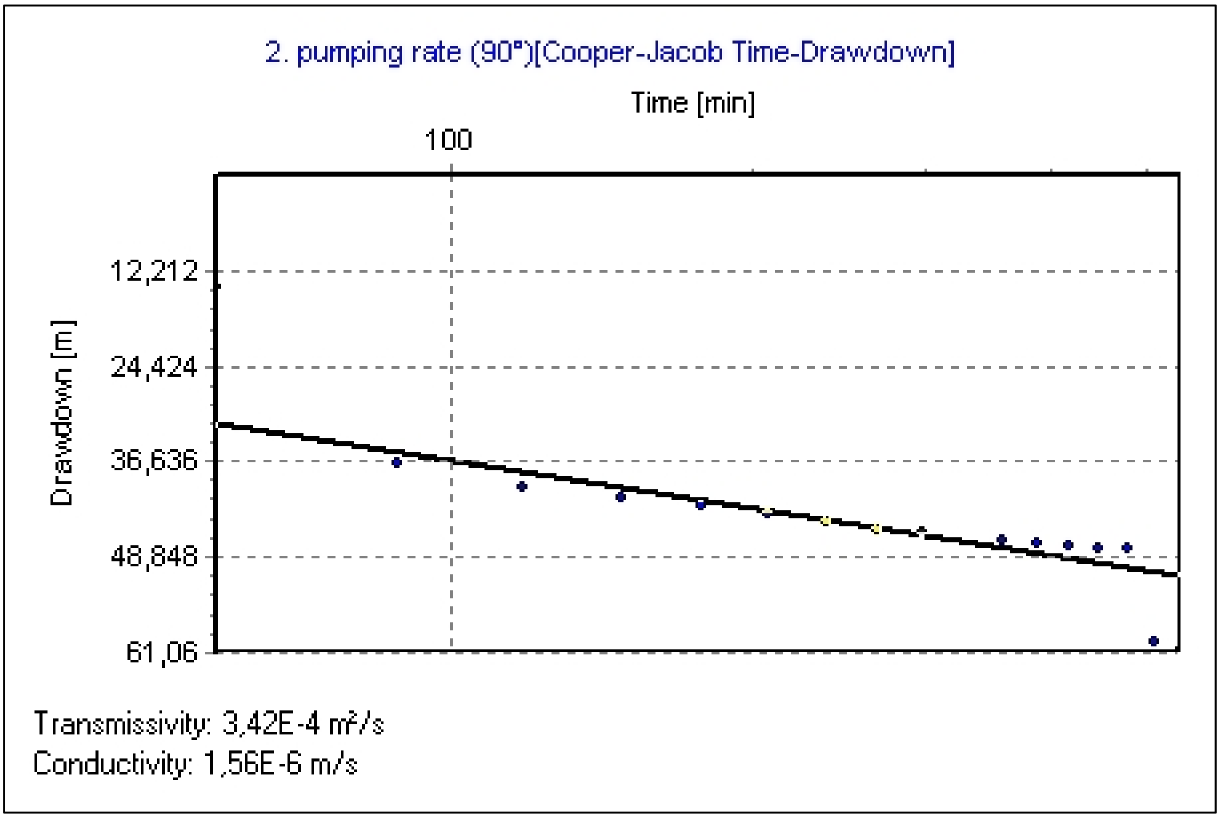
1. pumping rate (90°) [Theis Recovery]

Transmissivity: 1,00E-4 m²/s
Conductivity: 4,55E-7 m/s

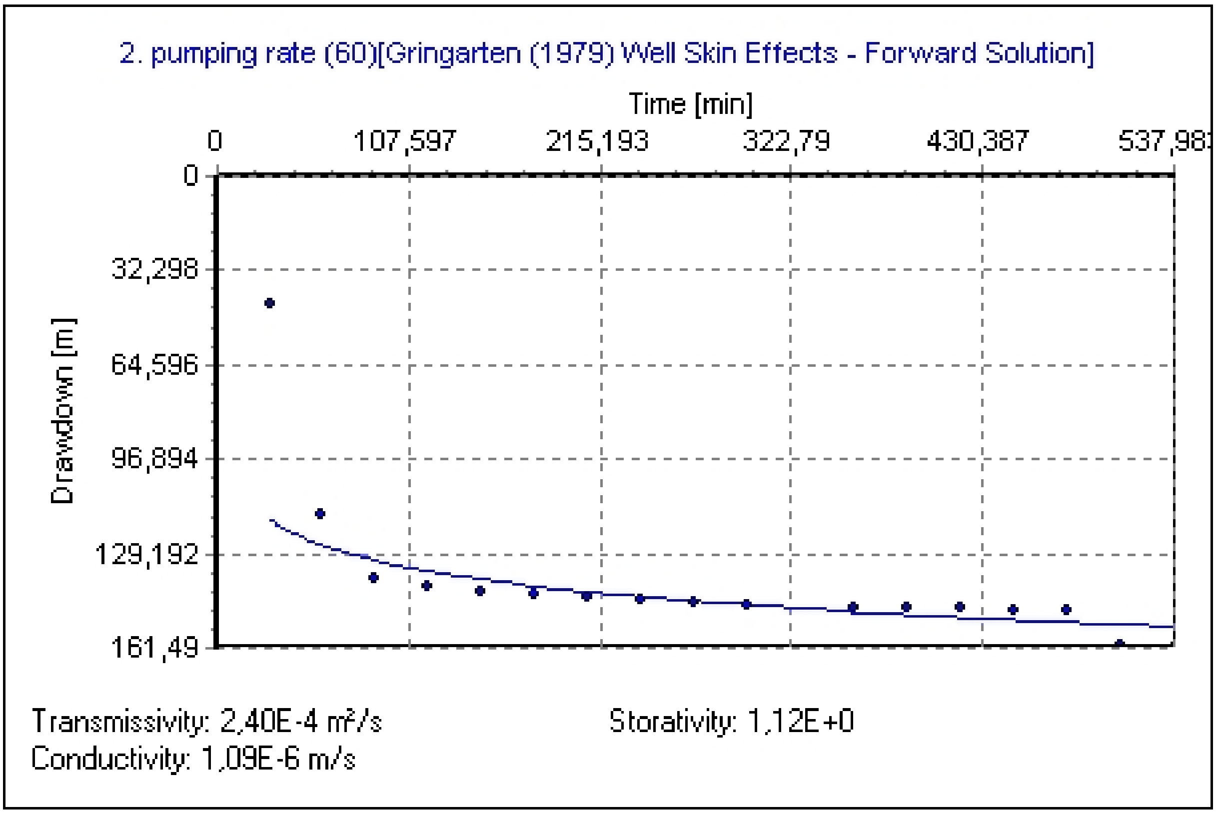


2. pumping rate (60°)[Cooper-Jacob Time-Drawdown]

Transmissivity: 2,45E-4 m²/s
Conductivity: 1,11E-6 m/s

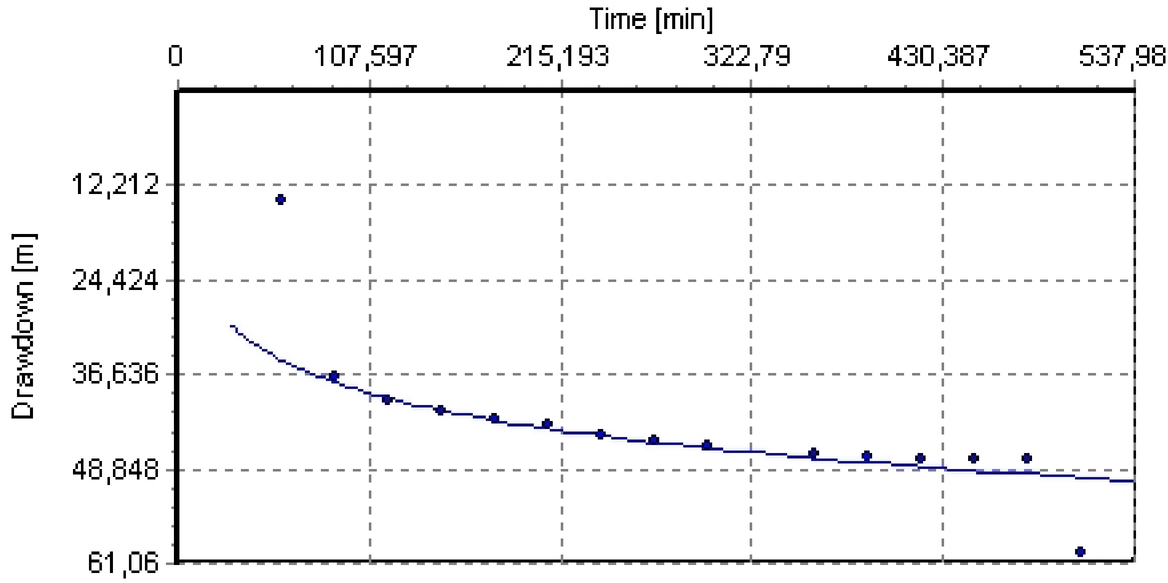


Transmissivity: 3,42E-4 m²/s
Conductivity: 1,56E-6 m/s



Transmissivity: 2,40E-4 m²/s
Conductivity: 1,09E-6 m/s
Storativity: 1,12E+0

2. pumping rate (90°) [Gringarten (1979) Well Skin Effects - Forward Solution]

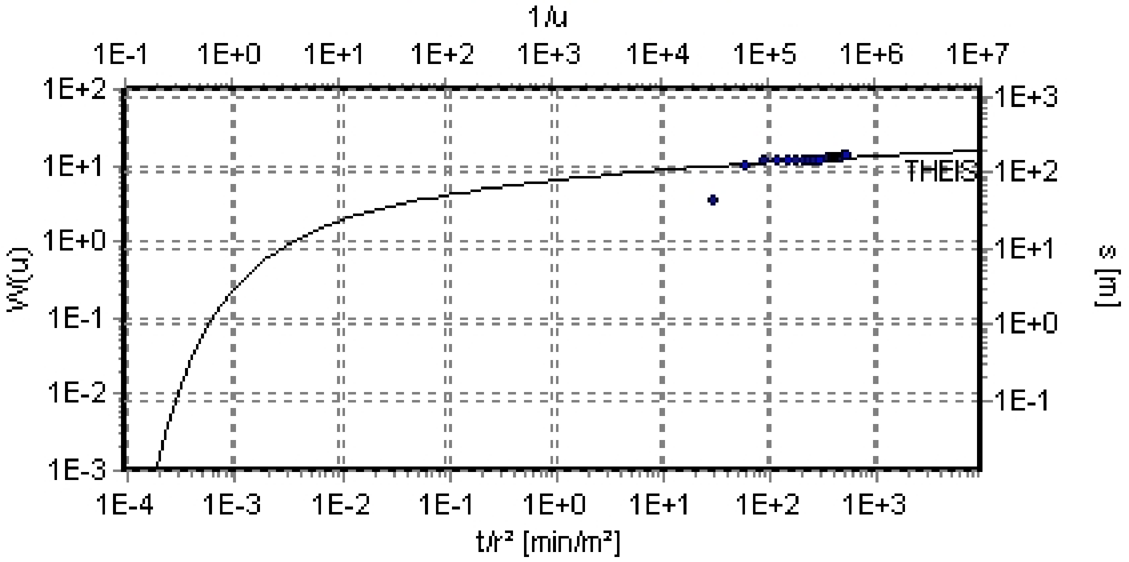


Transmissivity: 4,20E-4 m²/s

Storativity: 2,52E+0

Conductivity: 1,91E-6 m/s

2. pumping rate (60°)[Theis]

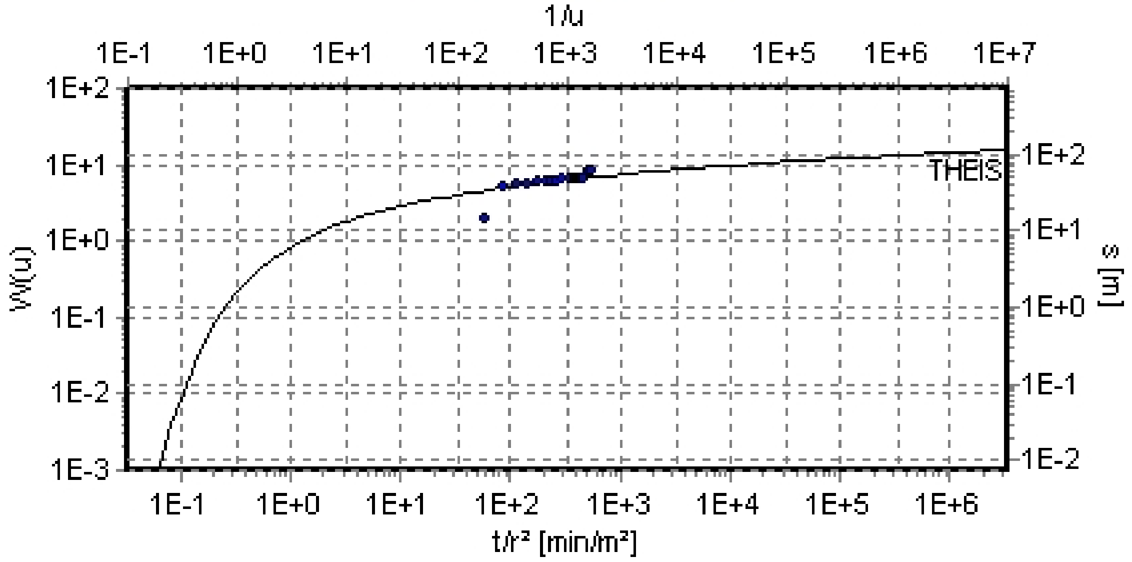


Transmissivity: 2,41E-4 m²/s

Storativity: 5,36E-5

Conductivity: 1,10E-6 m/s

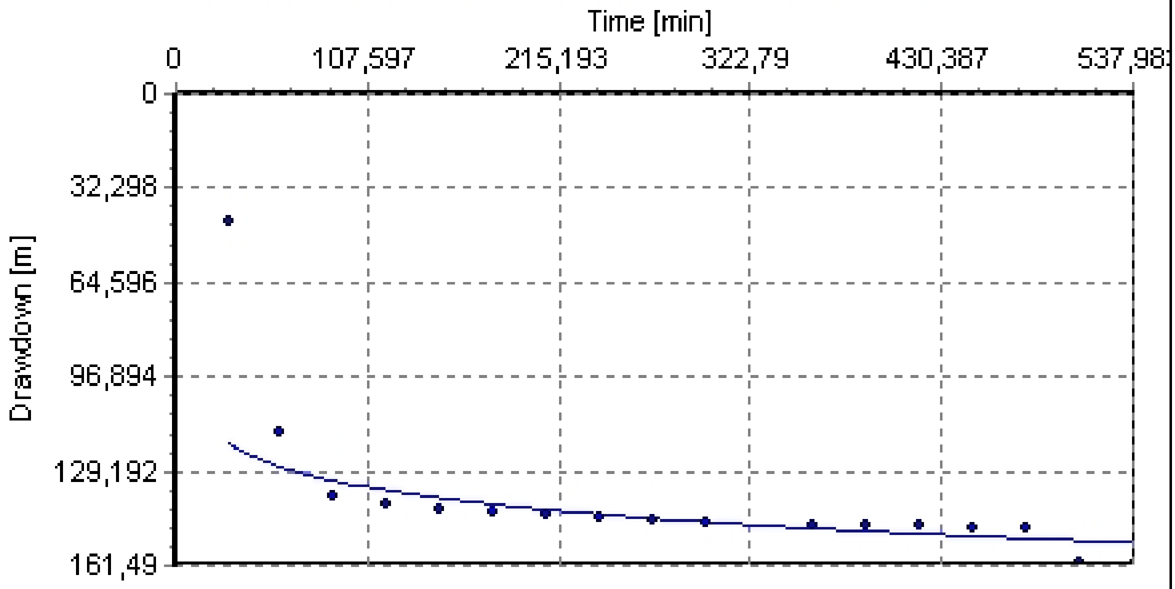
2. pumping rate (90°)[Theis]



Transmissivity: 4,06E-4 m²/s Storativity: 3,25E-2

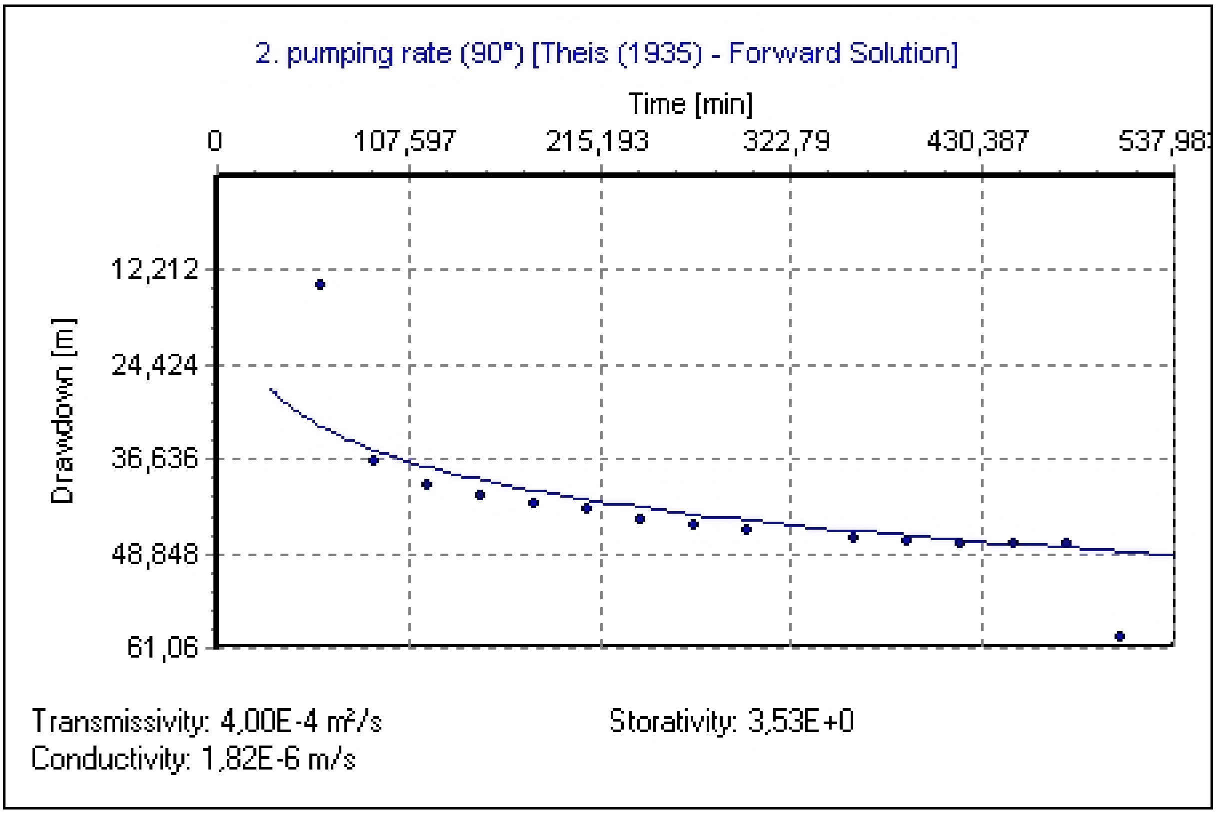
Conductivity: 1,85E-6 m/s

2. pumping rate (60°) [Theis (1935) - Forward Solution]

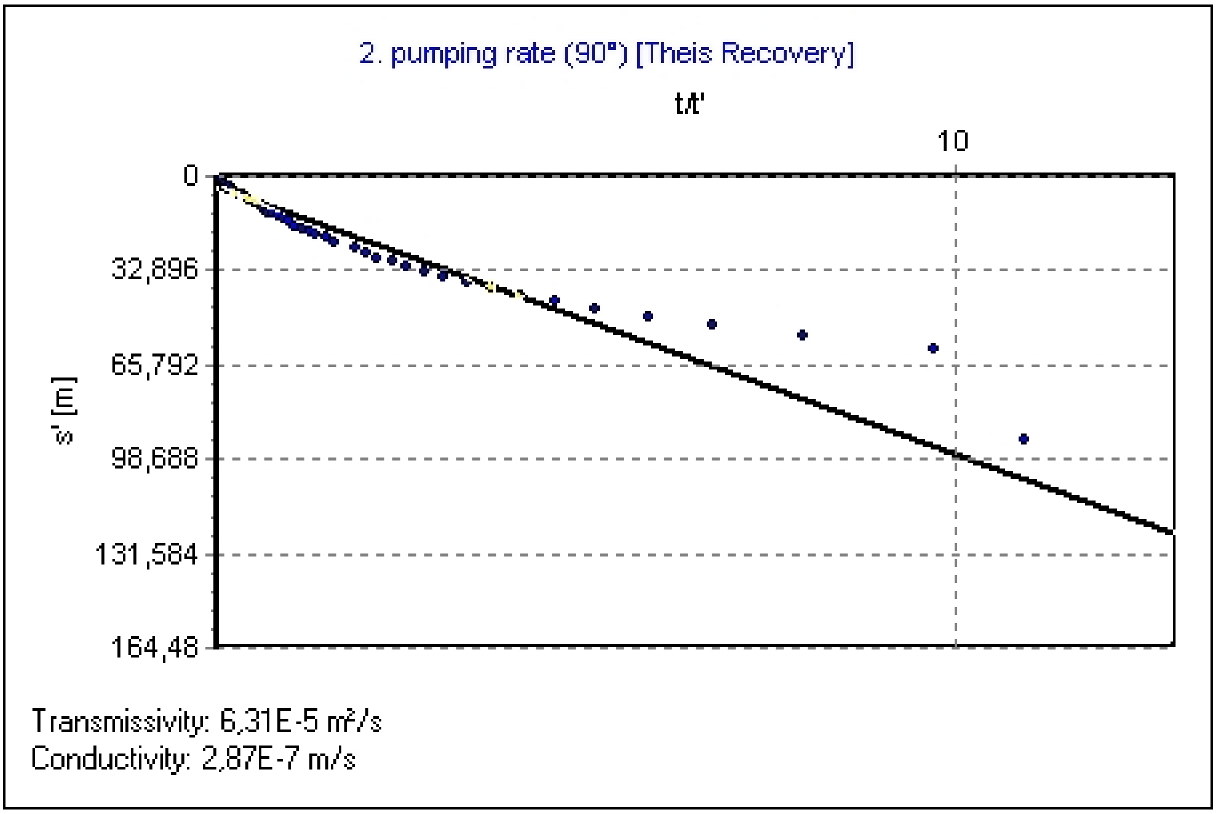


Transmissivity: 2,53E-4 m²/s Storativity: 3,45E-3

Conductivity: 1,15E-6 m/s

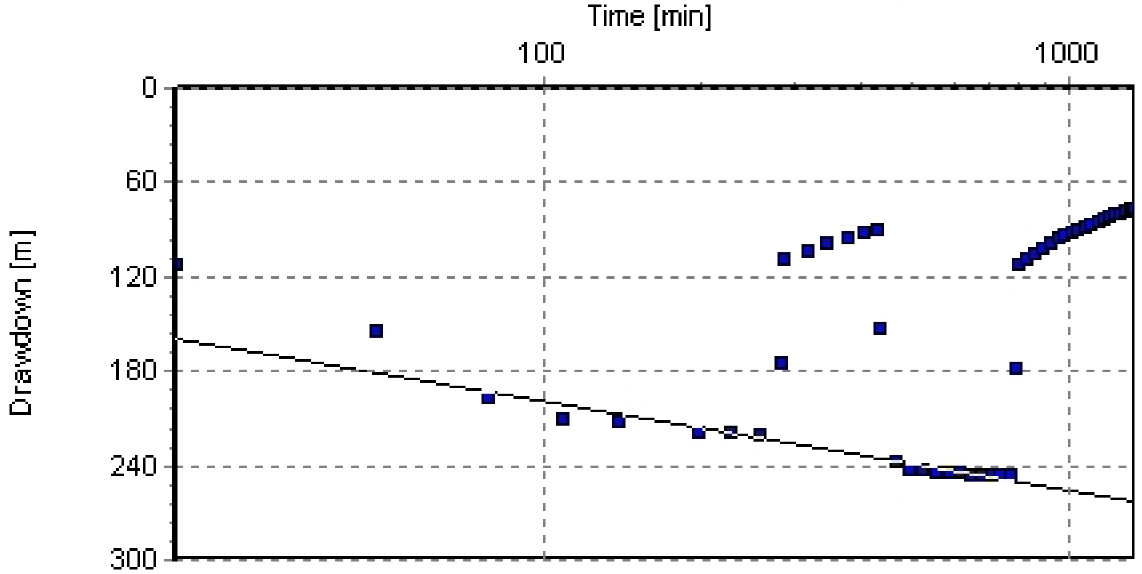

2. pumping rate (90°) [Theis (1935) - Forward Solution]

Transmissivity: 4,00E-4 m²/s
Storativity: 3,53E+0
Conductivity: 1,82E-6 m/s


2. pumping rate (90°) [Theis Recovery]

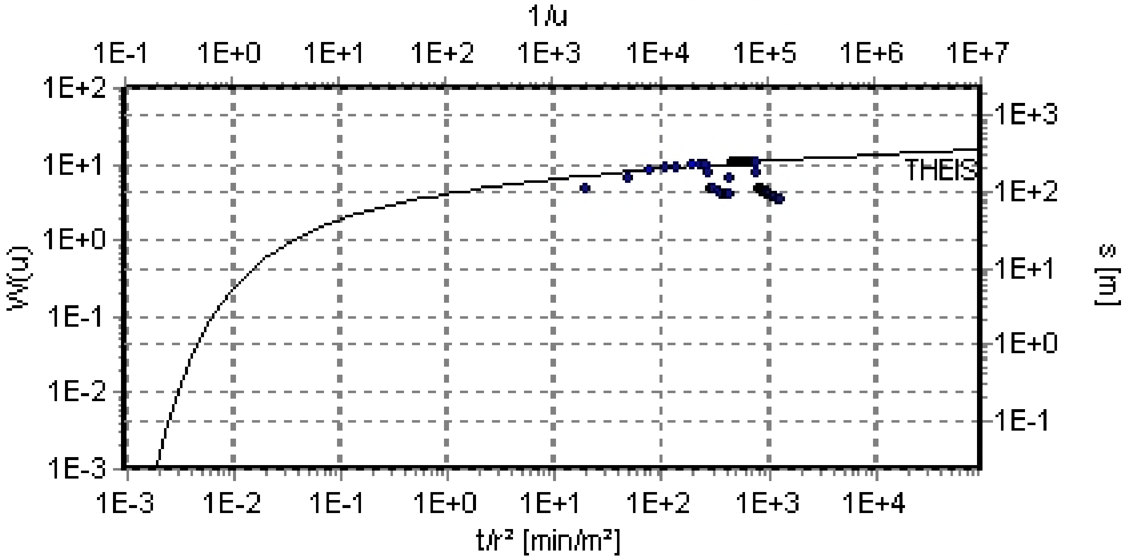
Transmissivity: 6,31E-5 m²/s
Conductivity: 2,87E-7 m/s

3.+4. pumping rate (90°)[Cooper-Jacob Time-Drawdown]



Transmissivity: 1,46E-4 m²/s
Conductivity: 6,65E-7 m/s

3.+4. pumping rate (90°) [Theis]



Transmissivity: 1,58E-4 m²/s
Conductivity: 7,17E-7 m/s

Storativity: 3,63E-4