Constant head pumping tests
in oxidized glacial till

by

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INTRODUCTION

Accurate determination of flow parameters in porous media, notably, hydraulic conductivity (K), and specific yield (S_y) is necessary for a quantitative understanding of most problems in hydrogeology. In central Iowa it is not uncommon to find a soil profile which consists of an oxidized glacial till deposit underlain by an unoxidized layer. Recently, the fate and transport of water and chemicals in glacial till has become of concern. In the glaciated regions of Iowa, groundwater flow and contaminant transport in glacial till impacts agricultural chemicals, landfills, and underground storage tanks.

Bail tests and laboratory permeameter tests have been widely applied to investigate the hydrogeologic parameters of glacial till. Due to the low permeability, glacial tills are not commonly used for water supply and pumping tests are seldom done in glacial till. There are a wealth of data on flow parameters of glacial tills generated by bail tests or laboratory permeameter tests, but, to the author's knowledge, there are no published results for pumping tests in glacial till.

While many field studies have been done using constant discharge rate pumping tests, there is little literature relating to constant head pumping tests. A constant head pumping test is a pumping test in which the drawdown is held constant in the pumped well and the discharge varies with time. In a low conductivity medium with a small saturated thickness, selecting a constant pumping rate can be difficult. The constant pumping rate must be high enough to create a sufficient drawdown in the surrounding area for the data analysis, while avoiding pumping the well dry before the desired pumping duration is reached. Under such circumstances, a constant head pumping test may be a better choice.

The objectives of the research are to:

1. Study whether the constant-head pumping test is suitable in glacial till.
2. Determine the hydraulic conductivity and the specific yield of oxidized glacial till in central Iowa using constant-head pumping tests.
3. Compare the results of pumping tests and slug tests.

Two constant-head pumping tests were performed in an oxidized glacial till layer. The super-position of the Theis solution was fit to drawdown data modified by the Jacob correction to estimate the hydraulic conductivity and the specific yield of oxidized till. Also, the hydraulic conductivity estimated by the pumping tests were compared with that estimated by the slug tests performed by Lemar(1990).

LITERATURE REVIEW

General Description of Glacial Till

Glacial till is the most abundant material that was deposited on the land surface during Pleistocene time. In the regions in Northern America, glacial erosion produced till that generally has considerable silt and clay and therefore has low permeability. The glacial environment is one of the most complicated of all geologic environments, having a wide variety of sedimentational processes and resulting deposits. Goldthwait (1971) remarked: "Till has more variations than any other sediment with a single name." Most glacial till deposits can be classified into two general categories: supraglacial till and subglacial till (or basal till) based on the environments of deposition. Due to the effect of weathering, glacial till also can be separated into two kinds of glacial till: weathered (or oxidized) glacial till and unweathered (or unoxidized) glacial till (Lutenegger et al., 1983).

Subglacial till was formed at the glacier base while the supraglacial till was formed on the upper surface of the ice. Generally, subglacial till is more uniform in texture and has higher bulk densities in contrast to supraglacial till. Extensive discussion of glacial deposits can be found in Lutenegger et al., (1983), Kemmis et al., (1981), and Boulton and Paul, (1976).

Due to the effect of the weathering process, the original deposition properties of glacial till may be significantly changed. The most obvious and recognizable change is the iron oxidation compound in soils producing yellowish brown, or reddish brown color from initially unoxidized, dark gray glacial till. It is not uncommon to find fractures and root penetration in the oxidized zone, particularly at shallow depth. The change of deposition properties can alter hydrogeological properties (Lutenegger et al., 1983). Especially, fractures are recognized as an important factor which dramatically increase the bulk hydraulic conductivity. It has been found that the bulk hydraulic conductivity of fractured glacial till determined by field tests is commonly between 1 to 3 orders of magnitude larger than values of intergranular hydraulic conductivity determined by laboratory tests on unfractured samples. (Freeze and Cherry, 1979)

Hydraulic conductivity and specific yield

A number of studies have investigated the hydraulic conductivity of glacial till. Lutenegger (1990) performed a comprehensive literature review to identify technical papers related to the hydraulic conductivity of glacial materials, in particular, tills. Lutenegger suggested that the results of the hydraulic conductivity investigation appear to be related to the scale effect of the test technique used and illustrates the wide range of values (10^{-5} cm/s to 10^{-9} cm/s) encountered in these materials. Table 1, which is summarized from Lutenegger's review, shows the type of test methods used since 1975. The review indicates that most researchers tend to investigate the hydraulic conductivity of glacial till by slug tests in situ, or by laboratory methods, including falling head and constant head tests, and consolidation tests. The pumping test method was employed only by Grisak & Cherry (1975). Grisak & Cherry performed the pumping tests in a basal sand confined aquifer and monitored the response in the till confining layer. Since laboratory permeameter methods can only be used to investigate hydraulic conductivity, and the specific yield generated by the slug tests are not reliable (Freeze & Cherry, 1979), information on the specific yield of glacial till is very limited.

Table 1. Methods used for investigating hydraulic conductivity of glacial till from 1975 to 1990, based on Lutenegger's literature review (1990)

	Methods		
Researchers	Laboratory tests	Slug Tests	Pumping tests
Prudic (1981)	*	*	
Little (1988)	*		
Desauliniers et al. (1981)	*	*	
Goodall & Quigley (1977)	*	*	
Keller et al. (1986)	*	*	
Grisak & Cherry (1975)	*		*
Law & Lee (1981)	*		
Hendry (1982)	*	*	
Craven & Ruedisll (1987)		*	
Starrett and Edil (1982)		*	
Sharp (1984)	*	*	
Bradbury & Muldoon (1990)		*	
Total:	9	9	1

Mathematical Model

To estimate the hydraulic conductivity and specific yield from a pumping test, a mathematical model is required in which the response of the aquifer to pumping is a function of the parameters. In this section, the information about the mathematical models which are relative to the analysis of a constant head pumping test in an unconfined aquifer will be provided.

The Theis solution (Theis, 1935) has been widely applied in analyzing constant rate pumping tests in aquifers. It is recognized that the Theis solution is also applicable to other boundary conditions with adjustment. The Theis solution, after being modified by the super-position method, may be used to analyze the drawdown response of a constant head pumping test which has continuously varying discharge (Stallman, 1962). For a pumping test in a homogeneous, isotropic, infinite unconfined aquifer, the drawdowns can be treated as that which would occur in an equivalent confined aquifer after they are corrected by the Jacob correction method and the early time drawdown data are ignored due to the effect of vertical flow.

Theis solution

In 1935, Theis utilized an analogy to the heat-flow equation given by H.S. Carslaw to arrive at an analytical solution to the motion of ground water flow in a confined aquifer due to well pumping. The governing equation which describes unsteady radial flow to a well in a confined aquifer due to well pumping is written in terms of drawdown (Bear, 1979)

$$\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r}=\frac{S}{T}\frac{\partial s}{\partial t} \tag{1}$$

with boundary conditions,

$$s(r,0)=0,\ r_w\leq r\leq\infty \tag{2}$$

$$s(\infty,t)=0,\ t\geq 0 \tag{3}$$

$$\lim_{r-r_w\to 0}2\pi T\frac{\partial s}{\partial r}=-Q=const.,\ t>0 \tag{4}$$

where s(r,t) = the drawdown, at radial distance r and time t, (L); r_w = the radius of the well, (L); Q = the discharge of the pumping well, (L^3/T); T = the coefficient of transmissibility of an aquifer, which is defined as the product of hydraulic conductivity and the thickness of the aquifer, (L^2/T); S = the coefficient of storage, (as a decimal, dimensionless). Equation (1) assumes the medium is homogeneous and isotropic, flow is horizontal, and T and S are constant. The solution of (1) to (4) is (Theis, 1935)

$$s(r,t)=(Q/4\pi T)\int_{r^2S/4Tt}^{\infty}(e^{-u}/u)\,du \tag{5}$$

The value of the integral in equation (5) is given by the exponential integral

$$\int_u^{\infty}\left(\frac{e^{-u}}{u}\right)du=-0.577216-\ln u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}+\ldots \tag{6}$$

where

$$u=\frac{r^2S}{4Tt} \tag{7}$$

In the groundwater literature, the integral (6) is known as the well function, W(u). With this notation, equation (5) can be rewritten as

$$s(r,t)=\frac{Q}{4\pi T}W(u) \tag{8}$$

Theis (1935) noted that theoretically, equation (8) applies rigorously only to water-bodies (i) being contained in entirely homogeneous sediments, (ii) of infinite areal extent, (iii) in which the well penetrates the entire thickness of the water-body, (iv) in which the coefficient of transmissibility is constant at all times and in all places, (v) in which the pumping well has an infinitesimal diameter, and (vi), applicable only to unconfined water-bodies in which the water in the volume of sediments through which the water-table has fallen is discharged instantaneously with the fall of the water-table. Also, the pumping rate should be uniform and continuous. An ideal well pumping system has the boundary conditions: (i) The system is located in a confined aquifer with horizontal impermeable layers on the top and bottom, (ii) The thickness of the aquifer is constant, (iii) The aquifer is homogeneous, isotropic, and infinite, (iv) The diameter of the pumped well is infinitesimal, (v) The pumping well penetrates the whole thickness of the aquifer, (vi) The pumping rate is uniform and continuous. The equation (8) gives the drawdown at any point and time for an ideal well pumping system when the pumping rate and the aquifer constants, coefficients of transmissibility and storage, are known. Inversely, the transmissibility and specific yield can be estimated by fitting equation (8) with data of the measured drawdown, whether at different places or at the same place at different times, and the pumping rate.

Super-position method

The pumping rate of a constant-head pumping test continuously decreases with time because of the decrease in the head gradient with time. If the pumping rate is plotted against time, the smooth curve will be similar to the example shown in Figure 1. This smooth curve may be approximated by a series of discrete pumping rates as shown in Figure 1. Applying the principle of super-position to the Theis solution (8), the drawdown caused by the simulated stepped pumping rates is given by

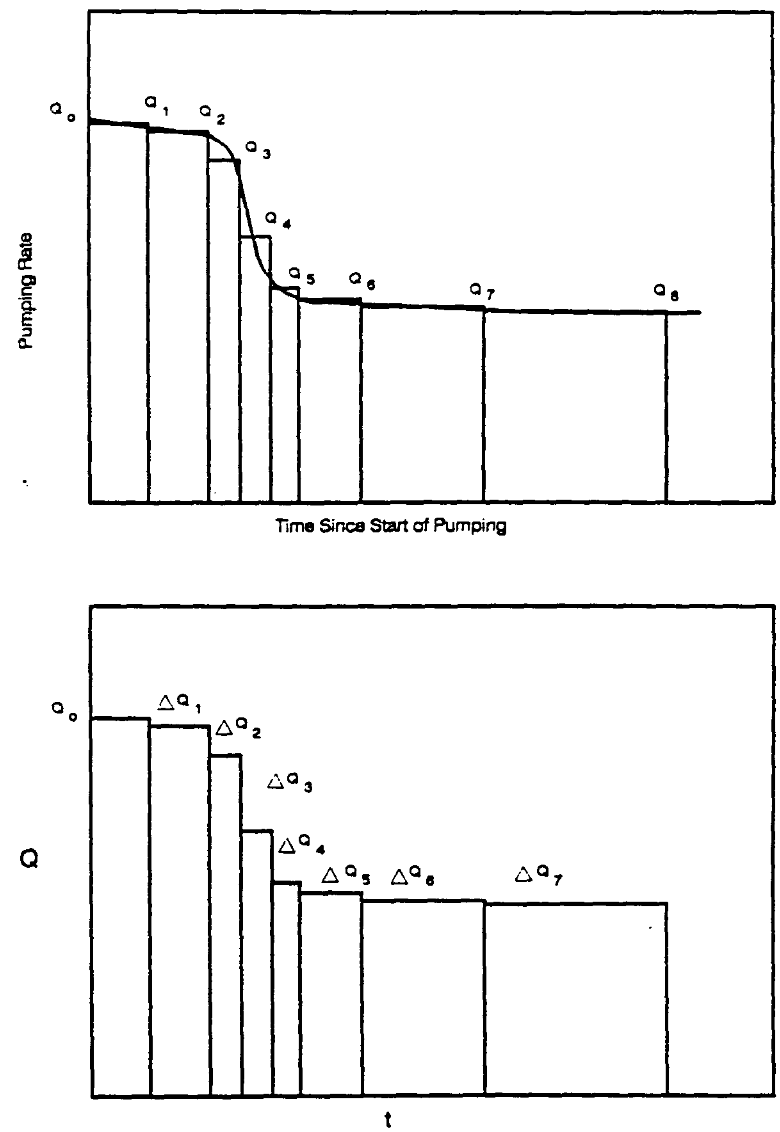

Figure 1. Nomenclature for continuously varying pumping rate

$$s(r,t)=\frac{Q_0}{4\pi T}W(u_0)+\frac{\Delta Q_1}{4\pi T}W(u_1)+\cdots\cdots+\frac{\Delta Q_m}{4\pi T}W(u_m) \tag{9}$$

where

$$u_j=\frac{r^2S}{4T(t-t_j)}, \tag{10}$$

$$\Delta Q_i=Q_i-Q_{i-1} \tag{11}$$

and t_j is the time since the start of the pumping rate Q_j, and t is the time since pumping began. This approach is valid because the equation (8) is a linear function of the pumping rate.

Jacob correction method

In an unconfined aquifer, the thickness of the saturated zone diminishes during the process of pumping, therefore Theis solution can not be directly applied. It was suggested by Jacob (1963) that "If the Theis graphical method is used for determining the hydraulic constants of an aquifer under water-table conditions, the observed drawdown should be corrected for the decrease in saturated thickness. This is especially true if the drawdown is a large fraction of the original saturated thickness,...". The correction method was developed by Jacob by comparing the Thiem equations (Bear, 1979) for a confined aquifer and an unconfined aquifer.

According to Darcy's law, the equation for the steady radial flow to a well in a confined aquifer is

$$Q_w = -2\pi r T \frac{\partial s}{\partial r} \tag{12}$$

By integrating equation (12) between any two distances r_1 and $r_2(>r_1)$, we obtain

$$s(r_1) - s(r_2) = \left(\frac{Q_w}{2\pi T}\right) \ln\left(\frac{r_2}{r_1}\right) \tag{13}$$

Equation (13) is called the Thiem equation.

Based on Dupuit's approximation, the Thiem equation for modeling the steady radial flow to a well in an unconfined aquifer is

$$K = \frac{Q_w \ln\left(\frac{r_2}{r_1}\right)}{\pi (h_2^2 - h_1^2)} \tag{14}$$

where h = the height of the water table above an impervious bottom, (L), and K = hydraulic conductivity, (L/T).

Jacob rewrote equation (14) as

$$Km = \frac{2mQ_w \ln\left(\frac{r_2}{r_1}\right)}{2\pi (h_2^2 - h_1^2)} = \frac{Q_w \ln\left(\frac{r_2}{r_1}\right)}{2\pi \left[\left(\frac{h_2^2}{2m} + \frac{m}{2}\right) - \left(\frac{h_1^2}{2m} + \frac{m}{2}\right)\right]} \tag{15}$$

where m = the initial thickness of the saturated zone, (L). Substituting s = m - h into equation (15) gives

$$Km=\frac{Q_w \ln(\frac{r_2}{r_1})}{2\pi[(s_1-\frac{s_1^2}{2m})-(s_2-\frac{s_2^2}{2m})]} \tag{16}$$

$$Km=\frac{Q_w \ln(\frac{r_2}{r_1})}{2\pi(s'_1-s'_2)} \tag{17}$$

$$s'=s-s^2/2m \tag{18}$$

where s′ is called the corrected drawdown, and Km is defined as the initial transmissivity, also denoted as T′. As a result, equation (17) has the same form as equation (13).

By using the concept of the corrected drawdown, Jacob rearranged the governing equation of unsteady flow in an unconfined aquifer into a similar form of the governing equation for the confined aquifer condition. Based on Dupuit's assumptions, the second-order differential equation governing the radial flow of water in an unconfined aquifer is (Bear, 1979)

$$Kh[(\frac{\partial^2 h}{\partial r^2})+(\frac{1}{r})(\frac{\partial h}{\partial r})]=S_y(\frac{\partial h}{\partial t}) \tag{19}$$

Substituting (m-s) for h in equation (19), yields

$$Km[(\frac{\partial^2 s'}{\partial r^2})+(\frac{1}{r})(\frac{\partial s'}{\partial r})]=[\frac{m}{(m-s)}]S_y(\frac{\partial s'}{\partial r}) \tag{20}$$

which can be rewritten as

where T′ = Km = initial transmissivity and S'_y = S_ym/(m-s) =

$$T'[(\frac{\partial^2 s'}{\partial r^2})+(\frac{1}{r})(\frac{\partial s'}{\partial r})]=S'_y(\frac{\partial s'}{\partial t}) \qquad (21)$$

apparent storativity.

Equation (21) is equivalent to equation (1), the governing equation for radial flow to a well in a confined aquifer. If s is much smaller than m, S'_y can be considered essentially constant, and treated as one approximate solution of S_y. Then by the application of the graphical method of the Theis solution to the corrected drawdown (s'), the value of T' and the approximate value of S_y can be estimated for an unconfined aquifer; the hydraulic conductivity is given by K = T'/m.

When applying the Jacob correction method, one should be aware of the following limitations;

(i)This method in effect heavily relies on the Dupuit's assumptions and will fail when vertical gradients become significant.

(ii)Drawdown data collected during the early time of pumping may not conform to this method, since the vertical flow may be significant during the early pumping.

FIELD SITE AND EXPERIMENT PROCEDURE

Field Site

The study field is located about 7.5 miles west of Ames and 0.5 mile south of highway I-30 at the Agricultural Engineering-Agronomy Farm near Boone city, Iowa. A U.S.G.S. topographic map (Boone East, Iowa) of the study field is given in Figure 2. Figure 3 shows the approximate location of the test site. The ground surface of the test site is covered by short grass and has an average gradient of about 3%. The soil profile of the area consists of oxidized glacial till deposit underlain by an unoxidized layer. Wang (1990) performed triaxial permeameter tests to estimate hydraulic conductivity in the vertical direction using soil samples from the same study area. The results suggest that the vertical hydraulic conductivity of the oxidized till is at least 1 order of magnitude higher than that of unoxidized till. Therefore, it is believed that the unoxidized till layer can be treated as an aquitard and the oxidized till layer acts as an unconfined aquifer. According to the result of ground water monitoring, the water table usually is within the depth of 1.5′ to 3.5′ from the ground surface and the flow gradient and direction is about the same as those of the ground surface.

Sixteen wells were installed in three radial lines

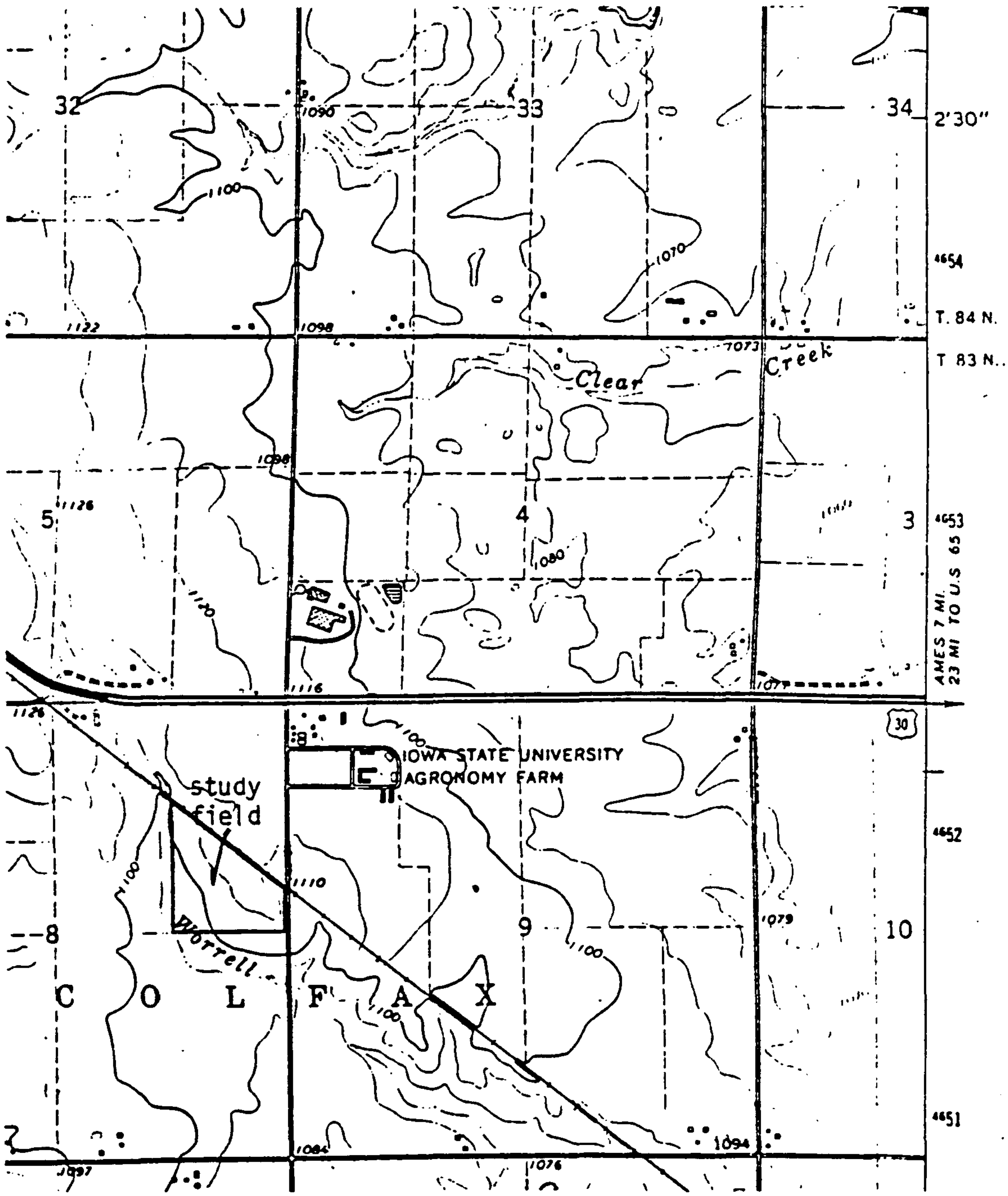

Figure 2. Location of the study field

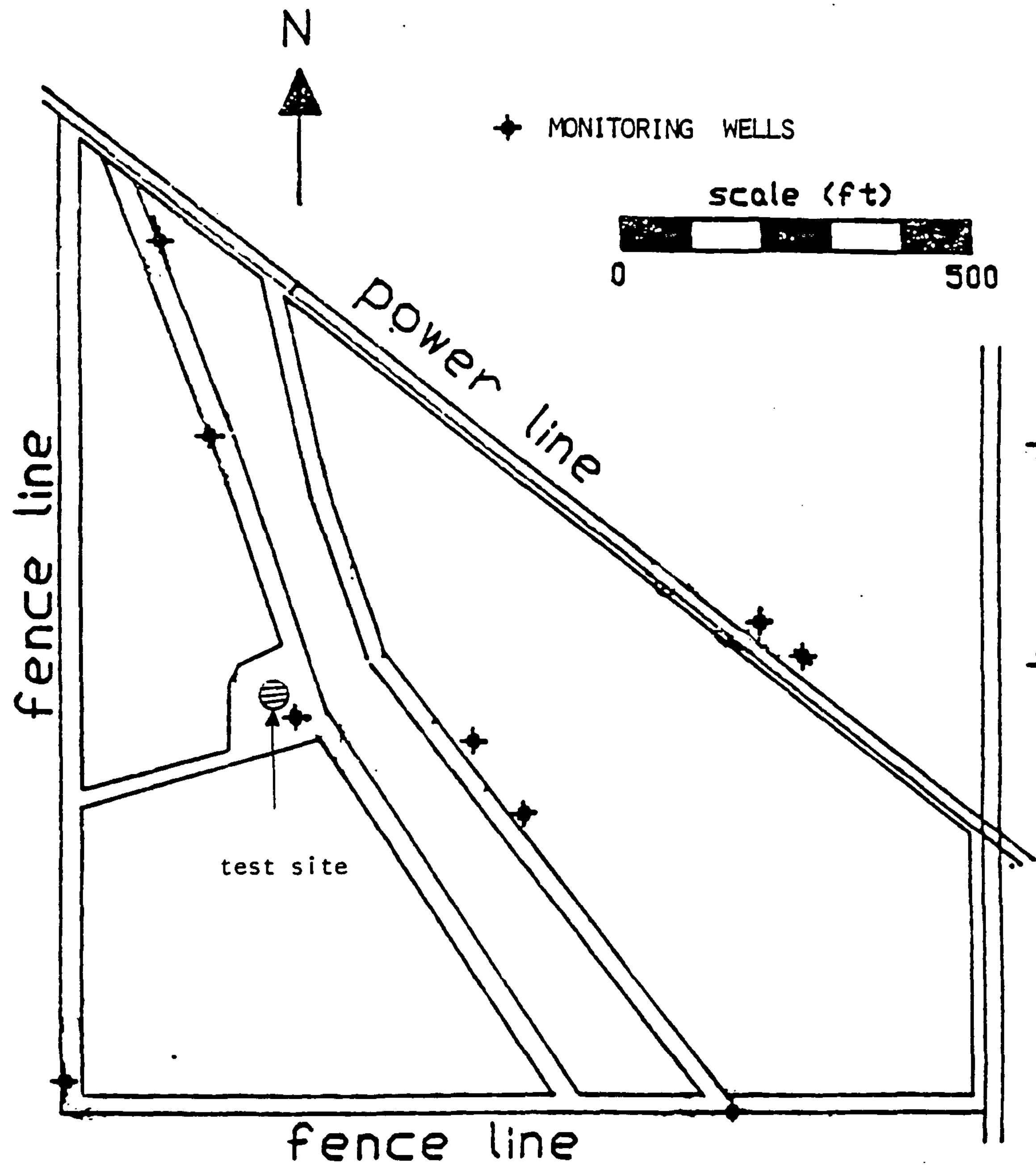

Figure 3. Location of the test site

centered at the pumping well with approximately a 120 degree angle between the radial lines. At approximately 3, 6, 9, 12 and 20 feet from the pumping well, an observation well was installed in each line. A plan view of the wall layout is shown in Figure 4, along with the designation used for each well and the gradients and directions of the ground surface and the ground water flow. The well boreholes were installed by a machine drill with a four-inch diameter solid stem auger. All of the wells are about 15′ deep. The well material is two-inch diameter schedule 40 PVC pipe connected to a ten-foot long screen with 0.01-inch-wide slots. The ten-foot screens were packed with gravel from the bottom to approximately one foot above the screen. The wells were finished with a bentonite clay pack from top of the gravel pack to about 2 inches below the top of the well. A vertical cross-section view of a representative well is shown in Figure 5.

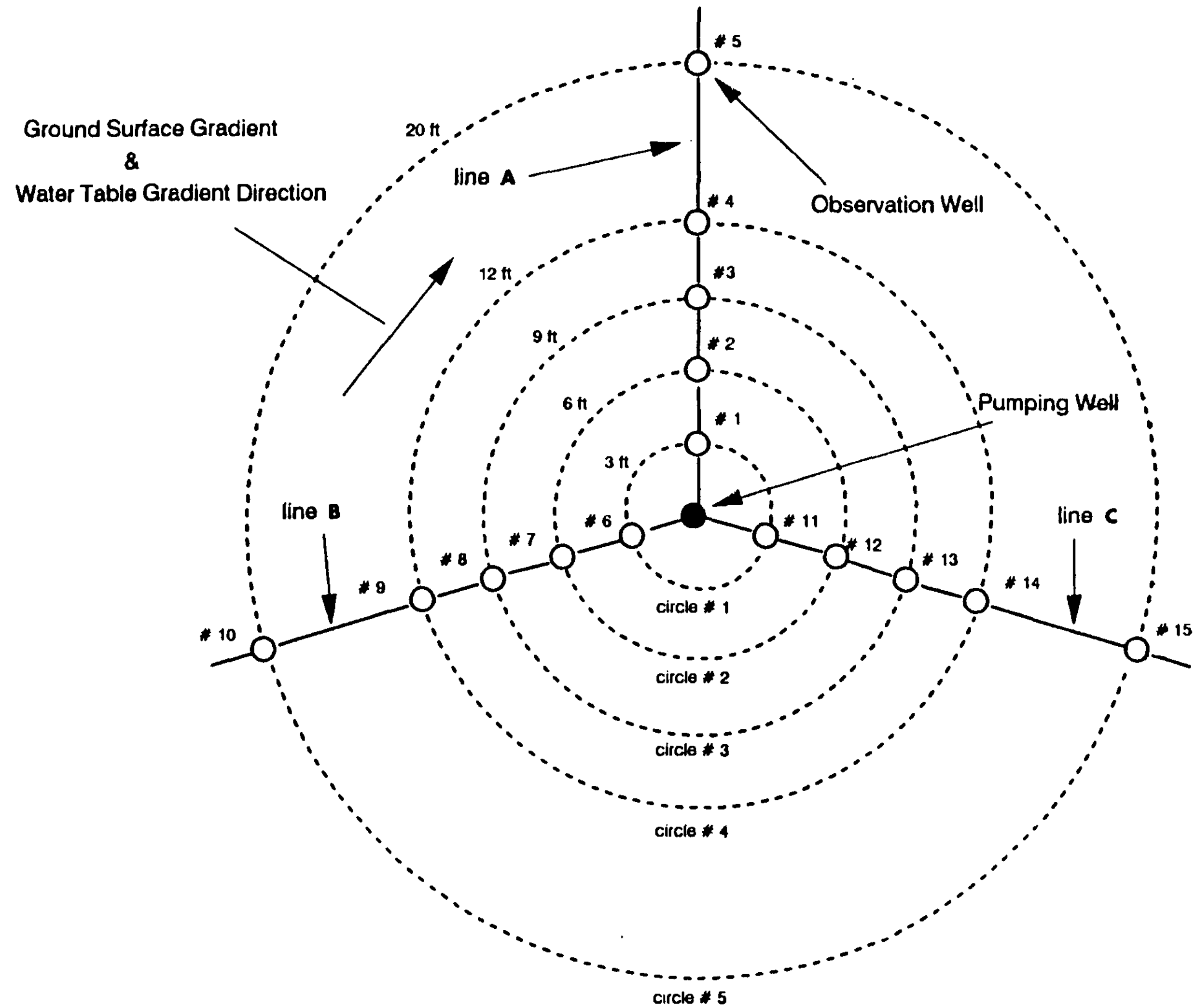

Figure 4. Plan view of the well layout

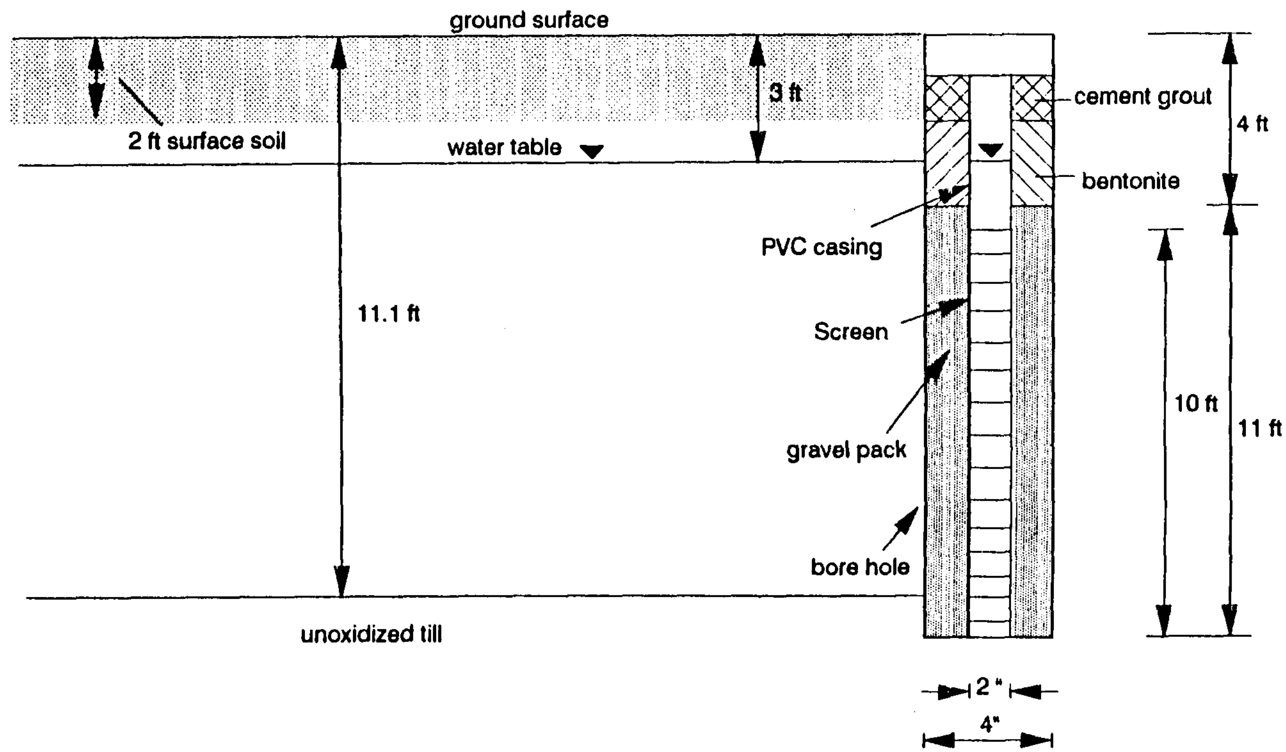

Figure 5. Vertical cross-section view of a representative well

Experiment Procedure

This experiment includes two phases; field test and data analysis.

Field test

During the well construction, soil samples were taken by shelby tubes with a length of 2.5′ from each well at two different depths: 5′ to 7.5′ and 10′ to 12.5′ from the ground surface. The shelby tubes were sealed by wax and duct tape right after the sampling. Before the soil character tests, the shelby tubes were cut into three equal sections and were sealed again. The tests of determining particle size distribution, particle density, and bulk density of the soil samples were conducted according to Das (1988). From the soil samples taken from 10′ to 12.5′, the transition zone of the oxidized and unoxidized till was distinguished by color.

After the construction of wells, well development work was done by repeatly pumping out water, pouring water in, and applying air pressure until the water in the well was fairly clean. Site survey and ground water table monitoring were also performed to determine the gradients and directions of the ground surface and ground water flow. Then, the site is ready for the pumping test.

Two constant-head pumping tests were conducted in the test site. The first one, with three feet of constant drawdown in the pumping well, was performed on July, 31, 1990 and the duration of pumping was about 9.5 hours. The second one, with five feet of constant drawdown in the pumping well, was performed on August, 6, 1990 and the duration of pumping was about 24 hours. Test #1 had a thicker saturated zone and a larger natural drawdown rate than test #2. The different conditions between the two pumping tests are summarized in Table 2.

Immediately prior to the tests, the initial depths from the ground surface to the water table in all of the wells were recorded. Then the average initial thickness of the saturated zone was determined by subtracting the initial average depth to the water table from the average depth of the transition zone(11.1'). The transition zone will be discussed in the soil character test section. The test site natural drawdown rate was determined by the water table level data recorded one day before the beginning of the test and the data recorded just before the test was conducted. It was assumed that the average rate of the natural drawdown during the pumping test is the same as that of the 24 hours proceding the test.

Preparation prior to the beginning of the pumping test includes: connecting two 12-foot rubber tubings to a peristaltic pump with two pumping heads, using a steel rod to support the tubings and lower the tubings from the top of the pumping well to the desired depth, and starting a generator

Table 2. The different conditions between the two pumping tests

	Test #1	Test #2
Pumping time	9.5 hr	24 hr
Initial average depth to water table	2.24 ft	2.90 ft
Initial average thickness of the saturated zone	8.86 ft	8.20 ft
Constant drawdown in the pumping well	3.04 ft	4.92 ft
Natural drawdown rate	0.23 ft/day	0.095 ft/day

to provide electrical power (see Figure 6). The pumping tests were started by running the pump at its full speed (43 ml/sec.). Then the pumping rates were measured with two graduated cylinders as frequently as necessary, while, water levels were manually measured with the aid of an electric probe. Early in the test the water levels in the wells near the pumping well were measured more often due to rapid drawdown response. As the test progressed, measurement periods were adjusted based on the response observed from previous measurements.

Data analysis

To account for the requirement of discrete changes based on the concept of super-position principle, the observed continuously decreasing pumping rates were divided into many intervals. The interval durations are inversely proportional

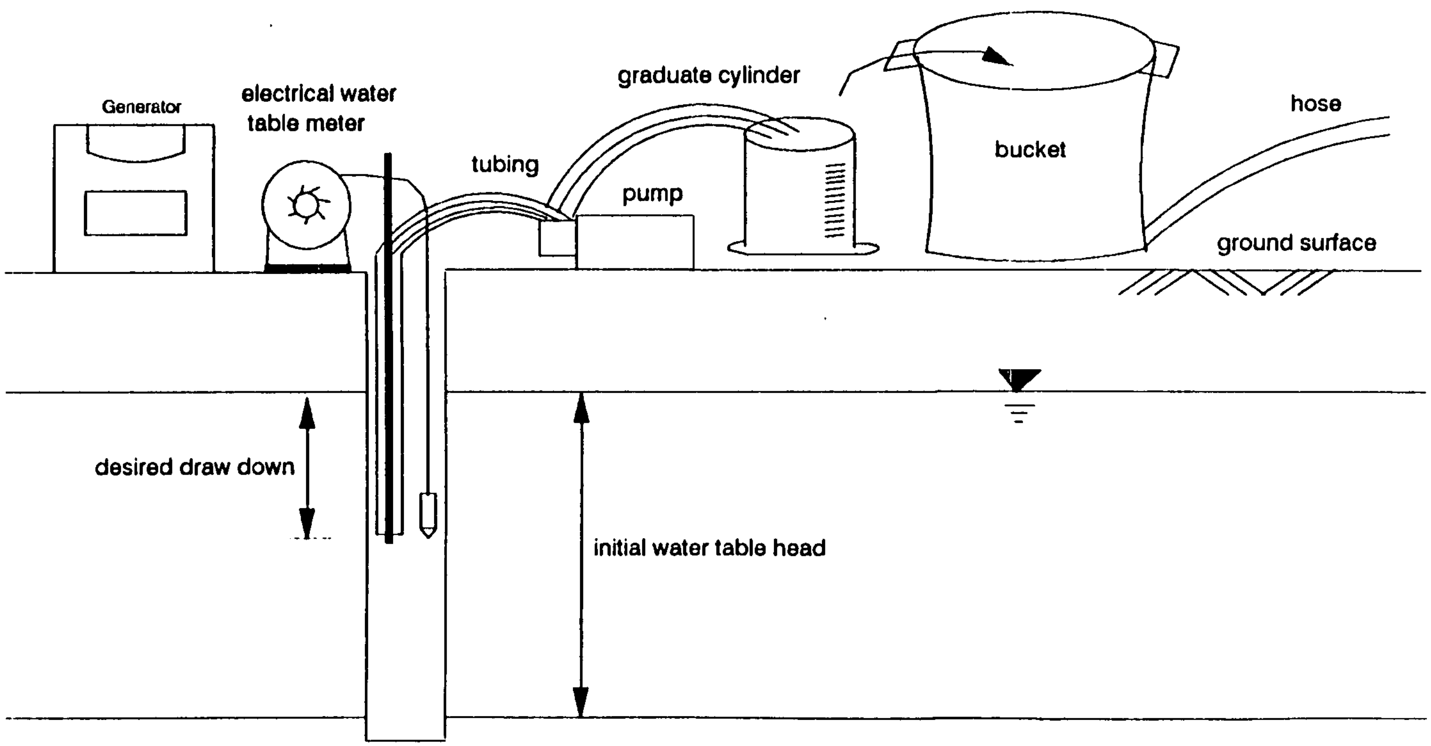

Figure 6. Schematic diagram of the equipment layout

to the rate of change of pumping.

The observed drawdown response data were corrected first by subtracting the natural drawdown, then applying the Jacob correction method, equation (18). Finally, the super-position Theis solution, equation (9) was applied to the adjusted data.

The method used in determining T′ and S'_y along with super-position Theis solution is called a least squares fitting method. A theoretical drawdown curve can be obtained by assigning a set of T′ and S'_y to the super-position Theis solution. The method of least squares is used as the criteria for determining the best fit. Therefore, the target T′ and S'_y are those values which can minimize the sum of squared differences between the observed and predicted corrected drawdown generated by super-position Theis solution, which can be written as,

$$\text{minimize} \quad F(T', S'_y) = \sum_{i=1}^{n} \left(S'_o(r_i, t_i) - S_t(r_i, t_i, T', S'_y) \right)^2 \qquad (22)$$

where S'_o is the observed drawdown data corrected by both natural drawdown and Jacob correction, S_t is the theoretical drawdown predicted by super-position Theis solution, and n is the number of data points.

RESULTS AND DISCUSSION

Soil Character Test

Results

Because of sampling difficulties, soil samples were not obtained from well #3 at both depths; 5'-7.5' and 10'-12.5', and well #5 at the depth; 10'-12.5'. Shelby tubes were found empty after pulling out from the above locations. As a consequence, the information about the depth of the transition zone for well #3 and well #5 and the soil character of well #3 are not available.

The transition zone which is located between the oxidized till and the unoxidized till was very clear visually and was situated at a depth between 10.02' and 12.35'. The results are listed in Table 2. The transition zone in line B in Figure 4 was relatively flat, between 10.02' to 10.34', but fluctuated in line A and line C. The average depth of the transition is 11.1 feet. The results were also plotted in Figure 7.

The soil samples taken from the oxidized zone are mainly yellow-brown soil. Root holes were found in the soil samples taken from depth 5.8' to 6.7', but not in the soil samples taken from a depth greater than 10'. Some roots were found in the root holes, but most of the root holes were empty. The directions of the root holes were random. Fractures

Table 3. The depth of transition zone

Well No.	1	2	4	6	7	8	9
Depth (ft)	11.42	12.35	11.37	10.02	10.3	10.29	10.34
Well No.	10	11	12	13	14	15	P[a]
Depth (ft)	10.24	11.20	11.42	11.67	11.66	12.08	10.89

[a]P: the pumping well

characterized by reddish oxidized materials were found in samples taken from oxidized till and most were oriented vertically. The unoxidized till was uniform and consisted of dark gray soil.

Soil character tests were mainly performed on oxidized soil samples from the depth between 5.8′ and 6.7′. Two oxidized soil samples from the depth between 11.7′ and 12.5′, and two unoxidized soil samples from depth between 10.8′ and 11.7′ were also analyzed.

The particle densities of the oxidized till and unoxidized till were the same, 2.69 $\pm$0.01 g/cm^3. The results of the bulk density tests are shown in Table 4 and indicate that the oxidized till has a slightly lower density than the unoxidized till. The average bulk densities of the oxidized till and the unoxidized till were 1.84 g/cm^3, and 1.91 g/cm^3 respectively.

The results of the particle size distribution tests are shown in Table 5 and by points in Figure 8. There is no clear

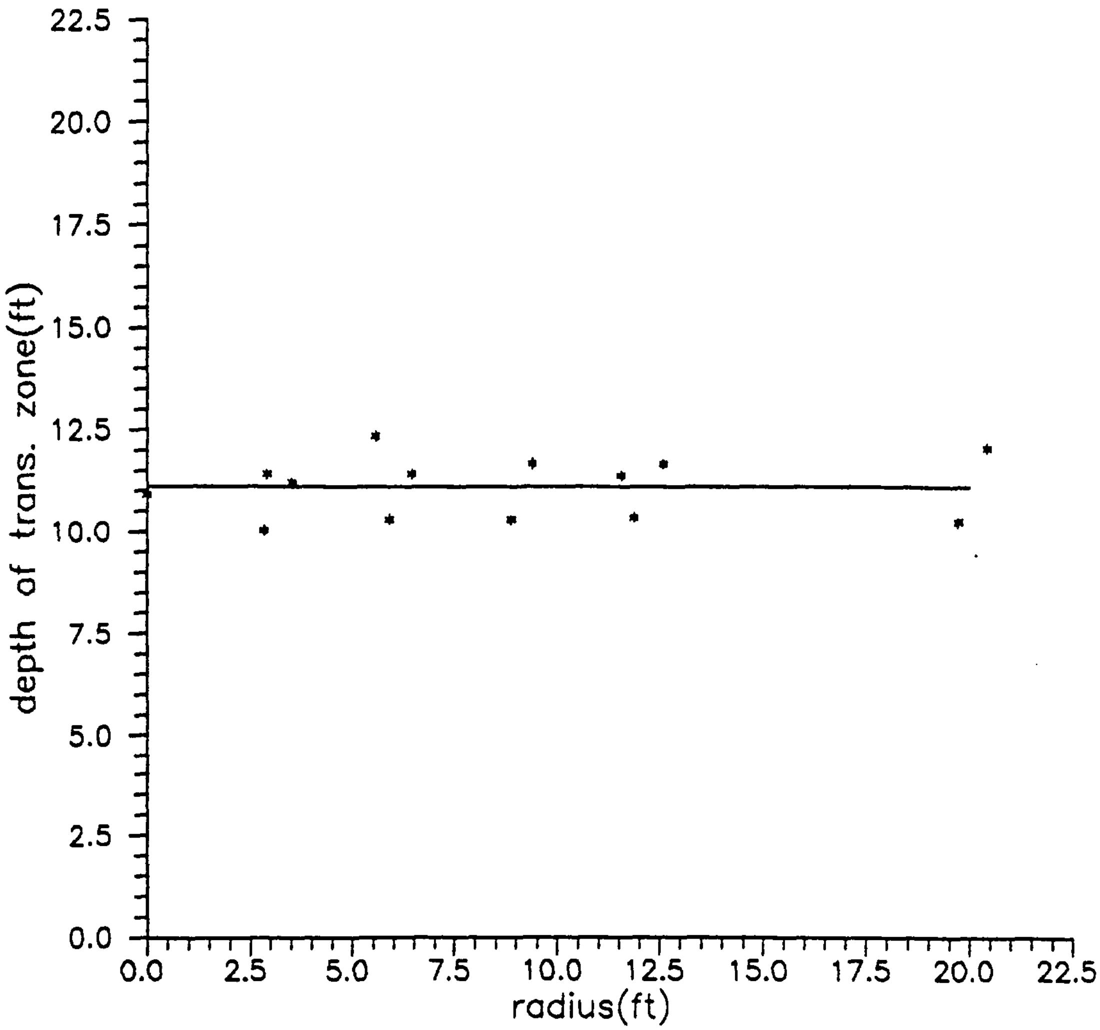

Figure 7. Depth of transition zone versus radial distance

Table 4. Result of soil character tests (A)

Well #	depth[a] ft	weathered	bulk density g/cm³	porosity %
1	5.8-6.7	yes	1.83	32.0
2	5.8-6.7	yes	1.82	32.3
4	5.8-6.7	yes	1.85	31.2
5	5.8-6.7	yes	1.89	29.7
6	5.8-6.7	yes	1.79	33.5
7	5.8-6.7	yes	1.85	31.2
8	5.8-6.7	yes	1.83	32.0
9	5.8-6.7	yes	1.83	32.0
10	5.8-6.7	yes	1.83	32.0
11	5.8-6.7	yes	1.85	31.2
12	5.8-6.7	yes	1.82	32.3
15	5.8-6.7	yes	1.84	31.6
P	5.8-6.7	yes	1.84	31.6
12	11.7-12.5	yes	1.86	30.9
15	11.7-12.5	yes	1.86	30.9
7	10.8-11.7	No	1.90	29.4
9	10.8-11.7	No	1.91	29.0
		average	1.85	31.3
	standard deviation		0.03	1.10

[a]Depth: measured from the ground surface

Table 5. Result of soil character tests (B)

Well #	depth[b] ft	weathered	particle size distribution[a] gravel %	sand %	silt %	clay %
1	5.8-6.7	yes	2.6	58.2	27.9	11.4
2	5.8-6.7	yes	2.4	57.2	28.6	11.8
4	5.8-6.7	yes	4.6	51.4	31.6	12.4
5	5.8-6.7	yes	3.3	54.5	32.1	10.1
6	5.8-6.7	yes	3.4	52.4	34.1	10.1
7	5.8-6.7	yes	2.9	54.4	31.9	10.8
8	5.8-6.7	yes	3.3	52.8	31.5	12.4
9	5.8-6.7	yes	3.0	57.1	30.1	9.8
10	5.8-6.7	yes	3.5	56.1	28.0	12.4
11	5.8-6.7	yes	3.1	54.9	29.7	12.4
12	5.8-6.7	yes	3.2	55.7	31.3	9.8
15	5.8-6.7	yes	1.5	55.4	33.2	9.8
P	5.8-6.7	yes	2.8	55.2	31.0	11.1
12	11.7-12.5	yes	5.0	52.7	35.5	6.8
15	11.7-12.5	yes	4.3	48.8	38.2	8.8
7	10.8-11.7	No	4.7	51.9	31.3	12.1
9	10.8-11.7	No	5.6	50.2	34.1	10.1
		average	3.5	54.1	31.8	10.7
	standard deviation		1.0	2.5	2.6	1.5

[a]Particle classification: (USDA classification)
gravel: >2 mm, sand: 2-0.05 mm
silt: 0.05-0.002 mm, clay: <0.002 mm

[b]Depth: measured from the ground surface

	gravel	sand	silt	clay
x	3.5	54.1	31.8	10.7
s.d.	±1.0	±2.5	±2.6	±1.5

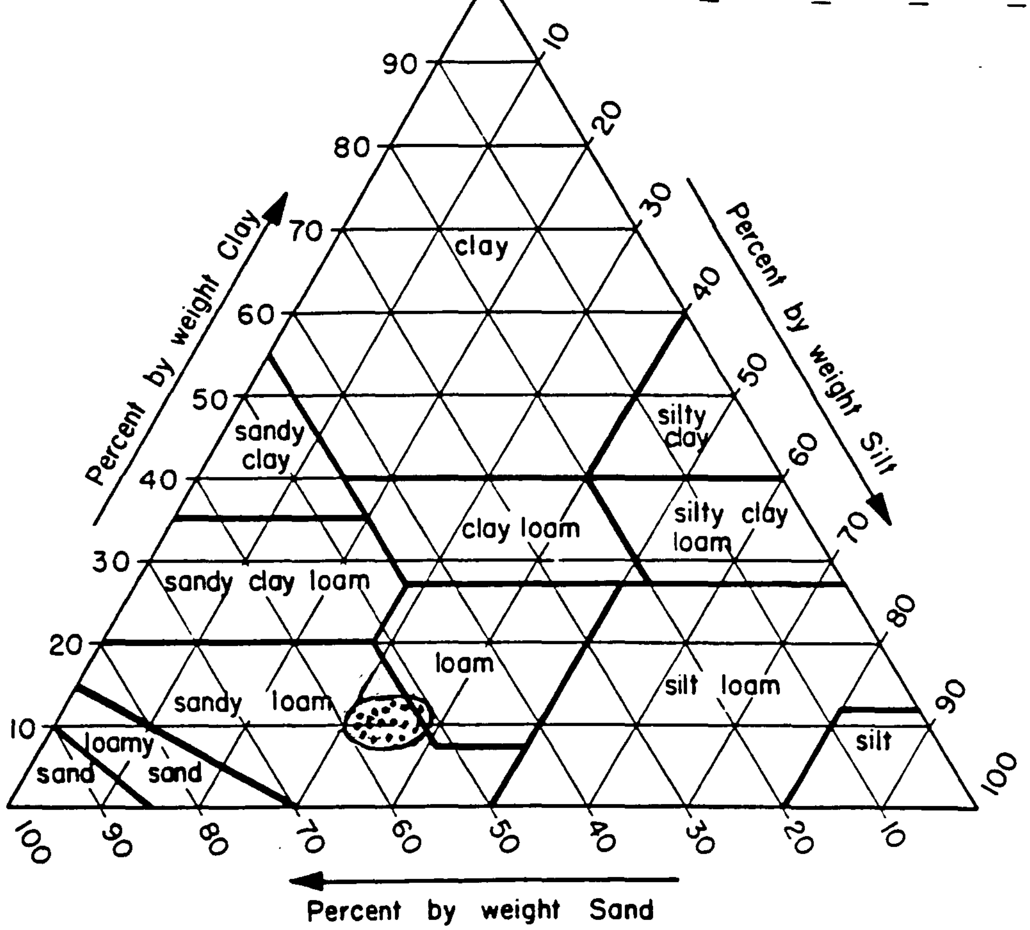

Figure 8. Textural data for the test site

difference between the oxidized till and the unoxidized till. The soil is uniform and classified as sandy loam, close to loam. The average percentage of particle size are: clay (<0.002 mm diameter) 10.7% (S.D.= $\pm$ 1.5), silt (0.002-0.05 mm) 31.8% (S.D.= $\pm$ 2.6), sand (0.05-2.00 mm) 54.1% (S.D.= $\pm$ 2.5), and gravel (>2.00 mm) 3.5% (S.D.= $\pm$1.0).

Discussion

It is clear that the bottom of the oxidized till layer is not flat and horizontal. However, for practical purposes, it is assumed that the bottom of the oxidized till is flat and horizontal, and has an average depth, 11.1′. The error associated with this assumption is ignored.

Root holes and fractures may affect not only the bulk density, but also the hydraulic conductivity. It is recognized that fractures may dramatically increase the hydraulic conductivity. But, the knowledge about how the root holes affect the hydraulic conductivity is very limited.

Two pieces of evidences suggest that the till deposit at the test site consists of subglacial till. (i) The bulk density of this study area, 1.85 g/cm^3, is close to the mean value of subglacial till density, 1.89 g/cm^3, given by Lutenegger (1983). (ii) The soil in the test site was uniform in texture, a characteristic of subglacial till. In addition, Wang (1990), who did soil classification tests on the same field, also reached the same conclusion.

Constant-Head Pumping Test

Results of pumping test #1

Pumping rate and drawdown response With an initial pumping rate of 43 ml/sec., the water table in the pumping well fell 3.04 feet from its initial level to the desired constant depth in about five minutes. Before the water table reached the desired depth, the pumping rate was in the range of 43 ml/sec to 46.7 ml/sec. The pumping rate clearly started to decline when the water table reached the desired depth. At the end of pumping (9.5 hours of pumping), the pumping rate decreased to 12.5 ml/sec. Figure 9 graphs the curves of the pumping rate over time.

The curve of the pumping rate vs time was also plotted on a log-log scale diagram (Figure 10). From the log-log diagram, there is a linear relationship between log Q and log t after reaching the constant drawdown level, which is the same as the relationship predicted by Marino and Yeh(1972) for constant head recharge in unconfined aquifers. The linear best fit line is also plotted in Figure 10.

The drawdown, as measured in the observation wells, responded rapidly to the pumping. Within one minute, there was some drawdown observed in the observation wells three feet away from the pumping well. After one hour of pumping, the wells 20 feet from the pumping well had shown measurable drawdown. The drawdown response in the first 2.5 hours of

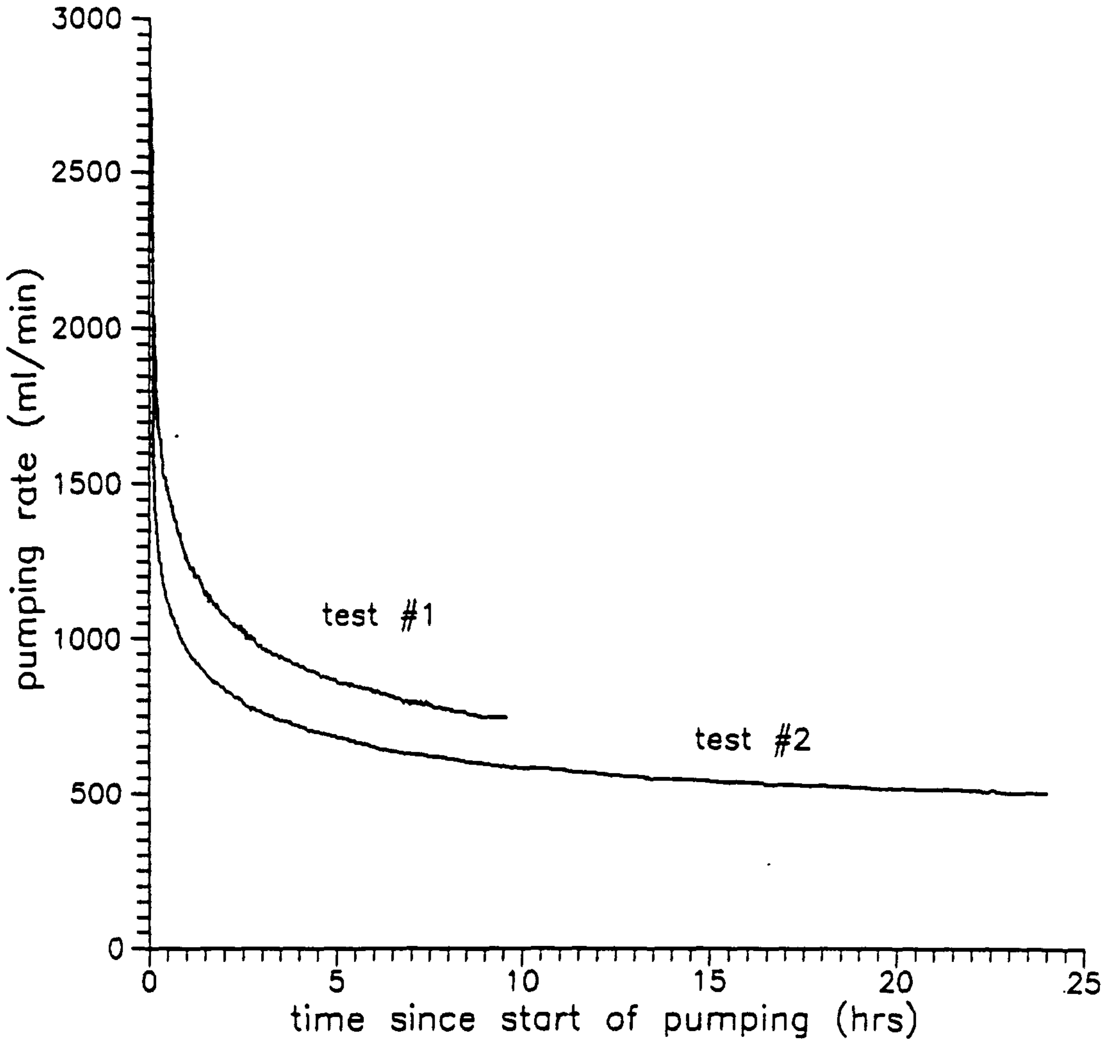

Figure 9. Test #1 & test #2, pumping rate versus time, in normal scale

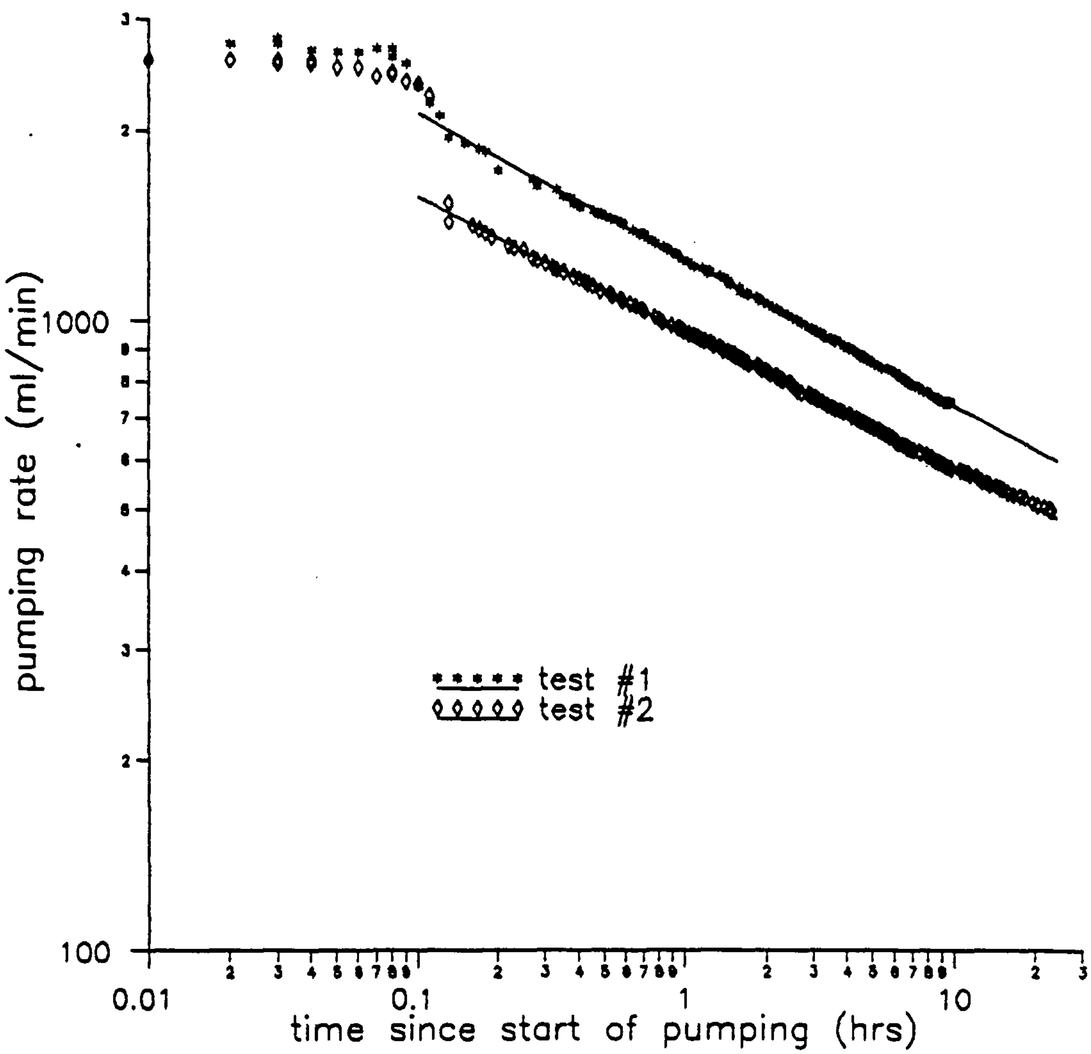

Figure 10. Test #1 & test #2, pumping rate versus time, in log-log scale

pumping are shown in Figures 11, 12, and 13. Each graph represents four observation wells placed on a line radiating from the pumping well (see previous test site description for exact placement). The curves of the drawdown response during the 9.5 hour pumping period for the observation wells located on each radial line are plotted in Figures 14, 15, and 16. From the drawdown response curves shown in Figures 14, 15, and 16, it is evident that the curves are fairly smooth considering the measurement error (±0.01 ft) of the water table meter. The hydrologic parameters of the wells 20 feet from the pumping well could not be determined because it was uncertain if the low reading was due to measurement error or actual drawdown. Therefore, the drawdown data of the wells located 20 feet from the pumping well were not included in the analysis.

After nine and a half hours of pumping, the pumping rates and drawdown responses appeared fairly stable. In the last hour of pumping, the pumping rate fell only 10 ml/min. (760 ml/min. to 750 ml/min.) and in the last one and one half hours, the drawdown responses of all observation wells increased by 0.02 to 0.03 feet.

Hydraulic conductivity and specific yield   The estimations of initial transmissivity and specific yield are based on the data of observed drawdown corrected by subtracting the natural drawdown and applying the Jacob

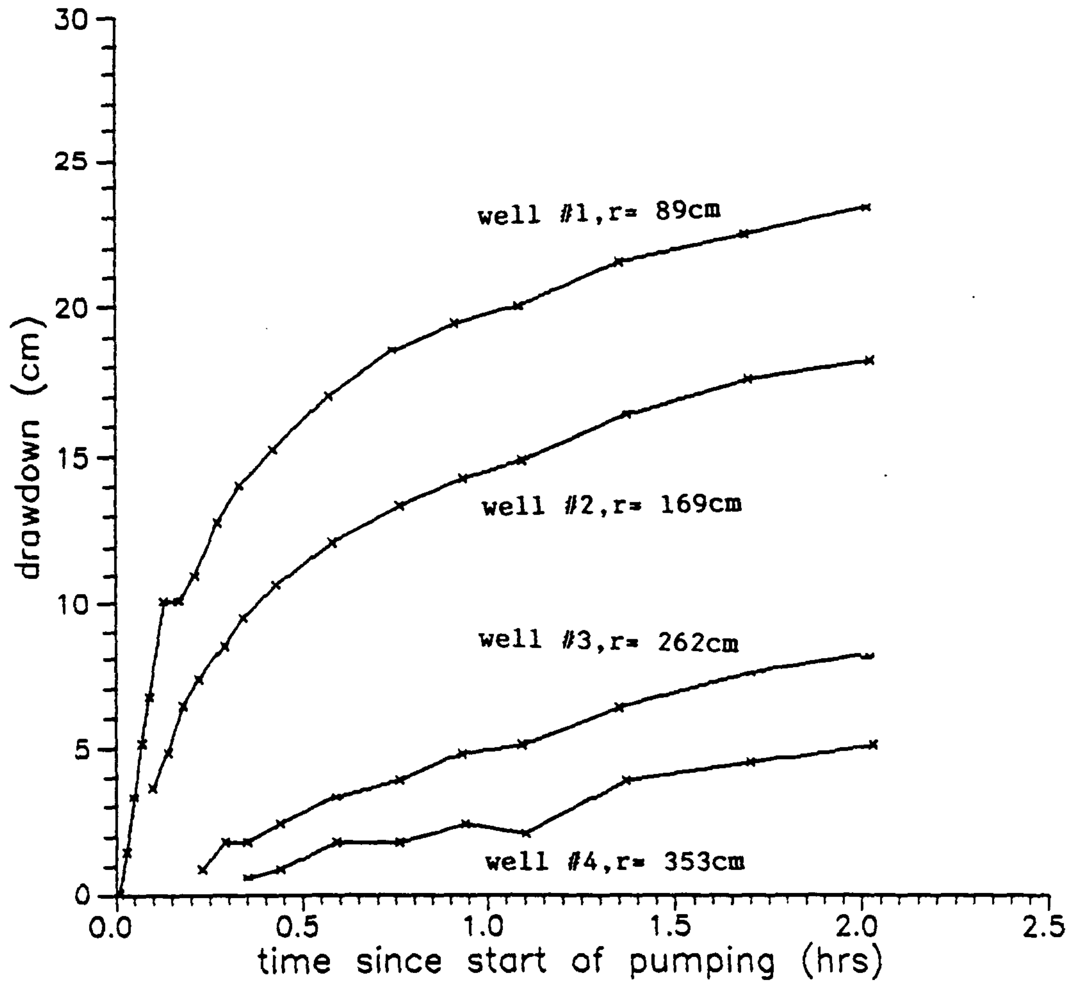

Figure 11. Test #1, drawdown response curves of wells on line A in the first 2.5 hours of pumping

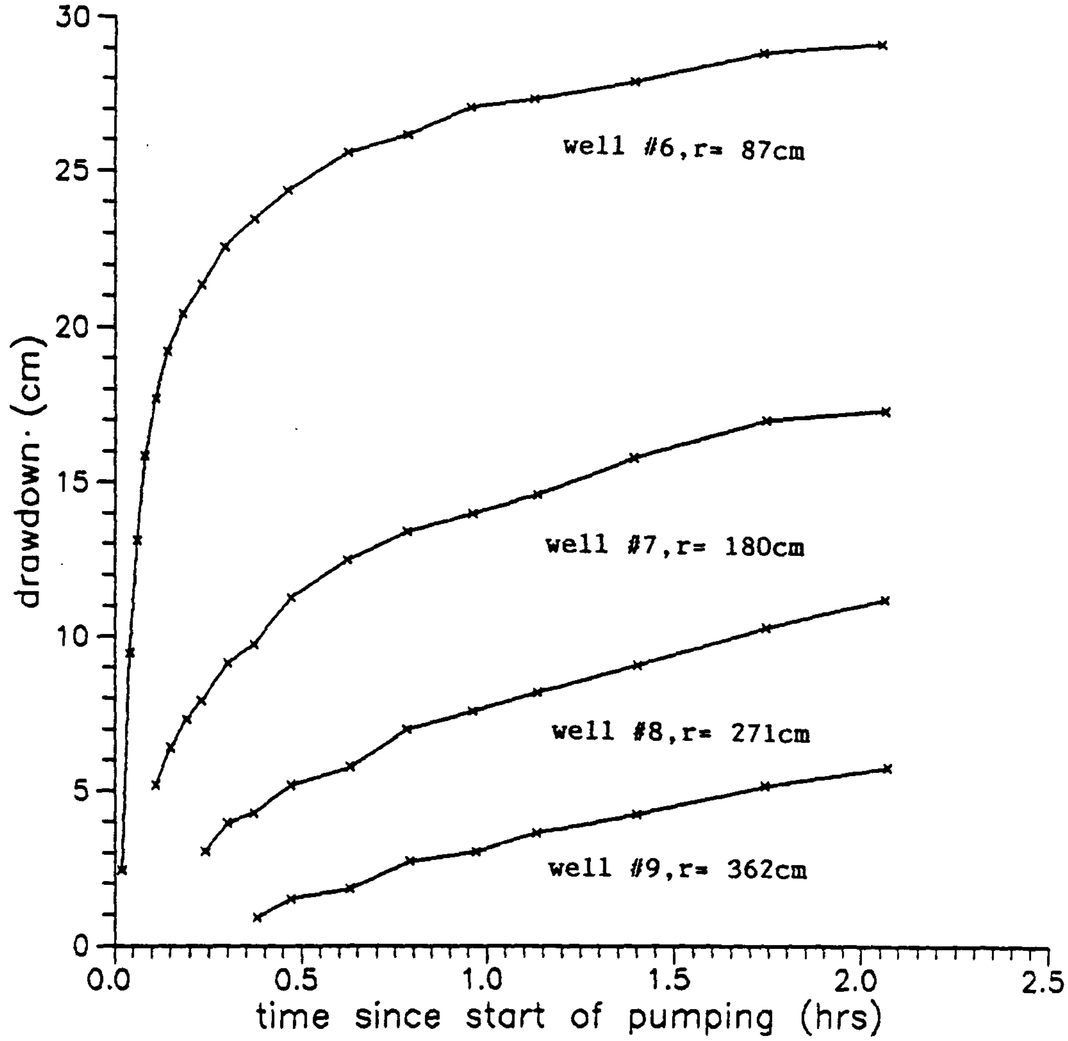

Figure 12. Test #1, drawdown response curves of wells on line B in the first 2.5 hours of pumping

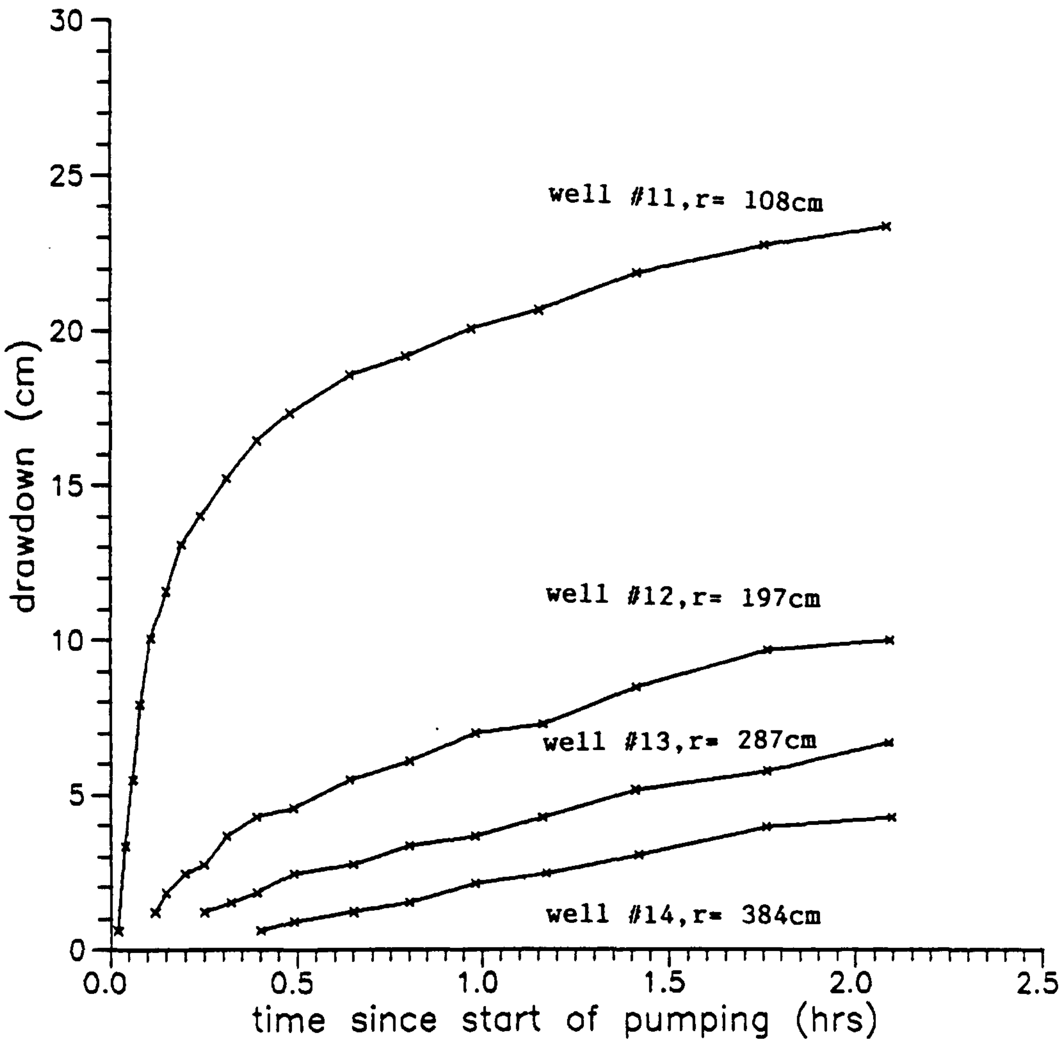

Figure 13. Test #1, drawdown response curves of wells on line C in the first 2.5 hours of pumping

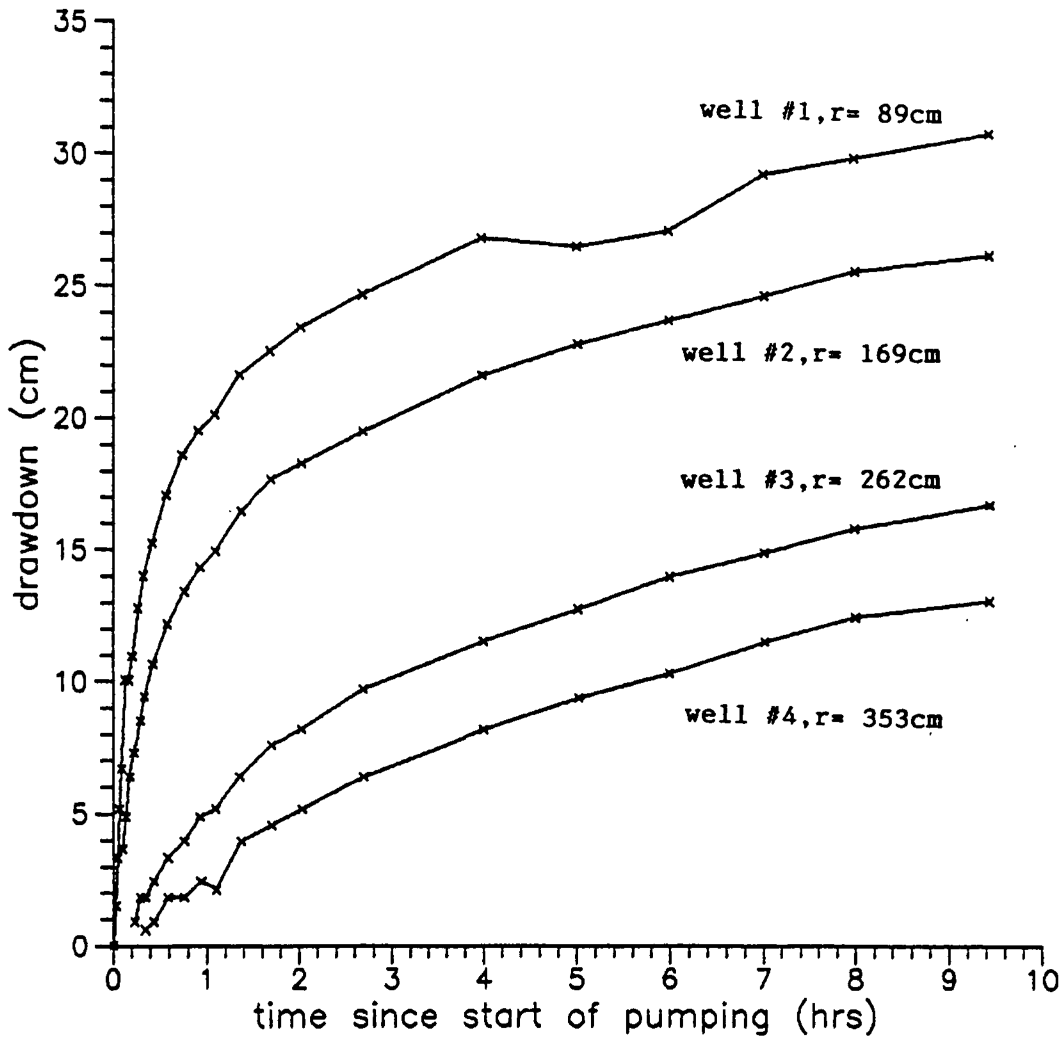

Figure 14. Test #1, drawdown response curves of wells on line A over the 9.5 hour pumping period

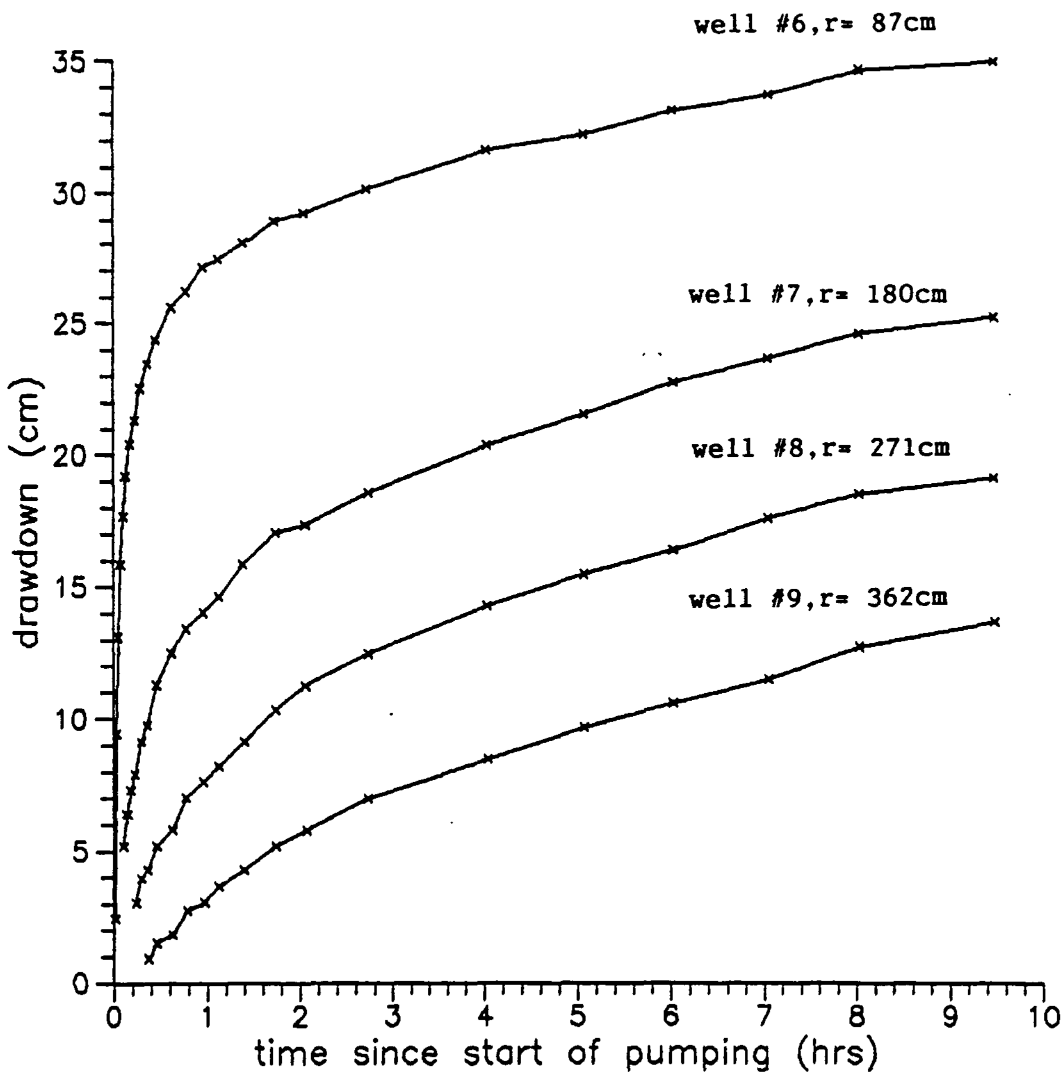

Figure 15. Test #1, drawdown response curves of wells in line B over the 9.5 hour pumping period

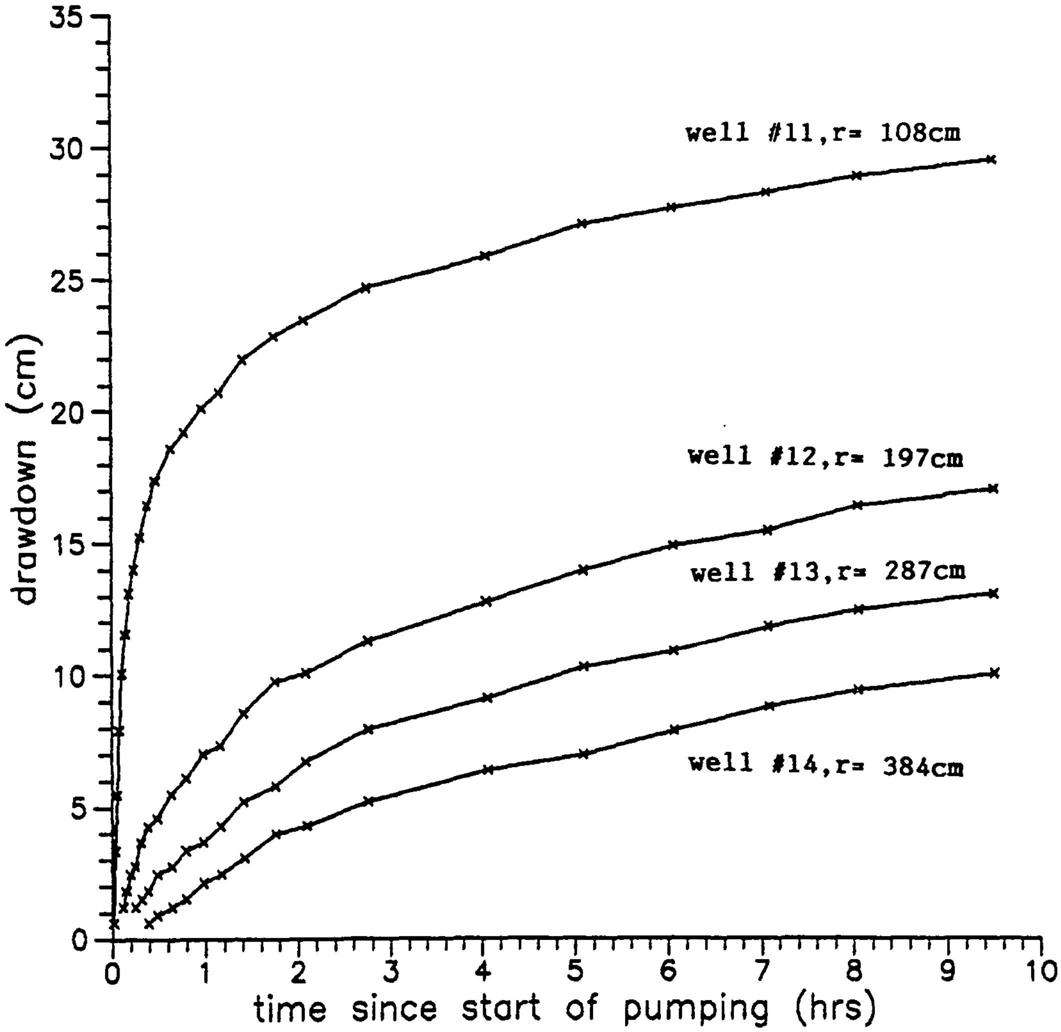

Figure 16. Test #1, drawdown response curves of wells in line C over the 9.5 hour pumping period

correction (18). As mentioned in the literature review, the initial drawdown period following the beginning of pumping may be affected by the vertical flow component and should therefore not be included in the data analysis. Vertical flow is not accounted for in the mathematical model. After several trials, it was determined that the drawdown data of the first two hours of pumping should be excluded in the least squares fitting. The initial transmissivity and specific yield for each individual well was estimated by applying the least squares estimation (22) to the adjusted drawdown data of each individual well. Here, equation (22) was fitted for each of the 12 observation wells. The results are shown in Table 6. The estimated hydraulic conductivities of each well were obtained by dividing the initial transmissivity by the initial thickness of the saturated zone (8.86 feet). The arithmetic mean hydraulic conductivity is 6.9×10^{-4} cm/s and the geometric mean is 6.8×10^{-4} cm/s. The arithmetic mean specific yield is 0.0286, while the geometric mean is 0.0276.

Another average hydraulic conductivity and specific yield were calculated to contrast with the average hydraulic conductivities and the specific yields obtained from the individual wells. They were obtained by using the adjusted drawdown data of all wells to fit the least square equation. The average hydraulic conductivity and specific yield determined by the above method were found to be 6.2×10^{-4}

Table 6. Estimations of the flow parameters by test #1

Well #	distance cm	ME	SEE	S_y	T' cm^2/s	K cm/s
1	89.0	0.0051	0.64	0.048	0.1480	5.5E-04
2	169.0	0.0053	0.39	0.021	0.1525	5.6E-04
3	262.1	0.0077	0.28	0.029	0.1778	6.6E-04
4	352.8	0.0033	0.32	0.027	0.1890	7.0E-04
6	86.9	0.0054	0.53	0.029	0.1447	5.4E-04
7	179.8	0.0069	0.53	0.020	0.1592	5.9E-04
8	271.2	0.0069	0.33	0.018	0.1753	6.5E-04
9	362.1	0.0016	0.35	0.023	0.2053	7.6E-04
11	107.6	0.0029	0.28	0.030	0.1565	5.8E-04
12	196.6	0.0034	0.26	0.037	0.2056	7.6E-04
13	286.6	0.0030	0.15	0.031	0.2376	8.8E-04
14	384.0	0.0044	0.21	0.030	0.3002	1.1E-03
	arithmetic mean			0.0286	0.1876	6.9E-04
	standard deviation			0.0141	0.0880	3.3E-04
	coeff. of variation			0.4916	0.4689	0.4783
	geometric mean			0.0276	0.1833	6.8E-04
all wells		0.11	2.26	0.019	0.1662	6.2E-04

cm/s and 0.019 respectively; these are listed in the last row of Table 6. The values estimated by using all the data are smaller than the values of estimations using the data from individual wells.

The least squares fitting curves of each individual well on each of the three lines are shown in Figures 17, 18, and 19. In the initial pumping period, the fitting curves underestimate the drawdown response and it is not until later that the fitting curves capture the drawdown response well. To better measure the accuracy of the fit, the mean error (ME) and the standard error of the estimate (SEE) are calculated and listed in Table 6. ME is the average of the errors while SEE is the standard deviation of the absolute values of the errors (Herzberg, 1983).

Results of pumping test #2

Pumping rate and drawdown response The conditions of test #2 are contrasted with the conditions of test #1 in Table 2. As expected, the curve of the pumping rate vs time plotted on a log-log scale (Figure 10) appears linear after reaching the constant drawdown level. Figure 10 also shows that the pumping rates of test #2 were lower than those of test #1.

The pattern of the drawdown response of test #2 is quite similar to that of test #1. Figures 20, 21, and 22 show the drawdown response in the first 2.5 hours of pumping and the

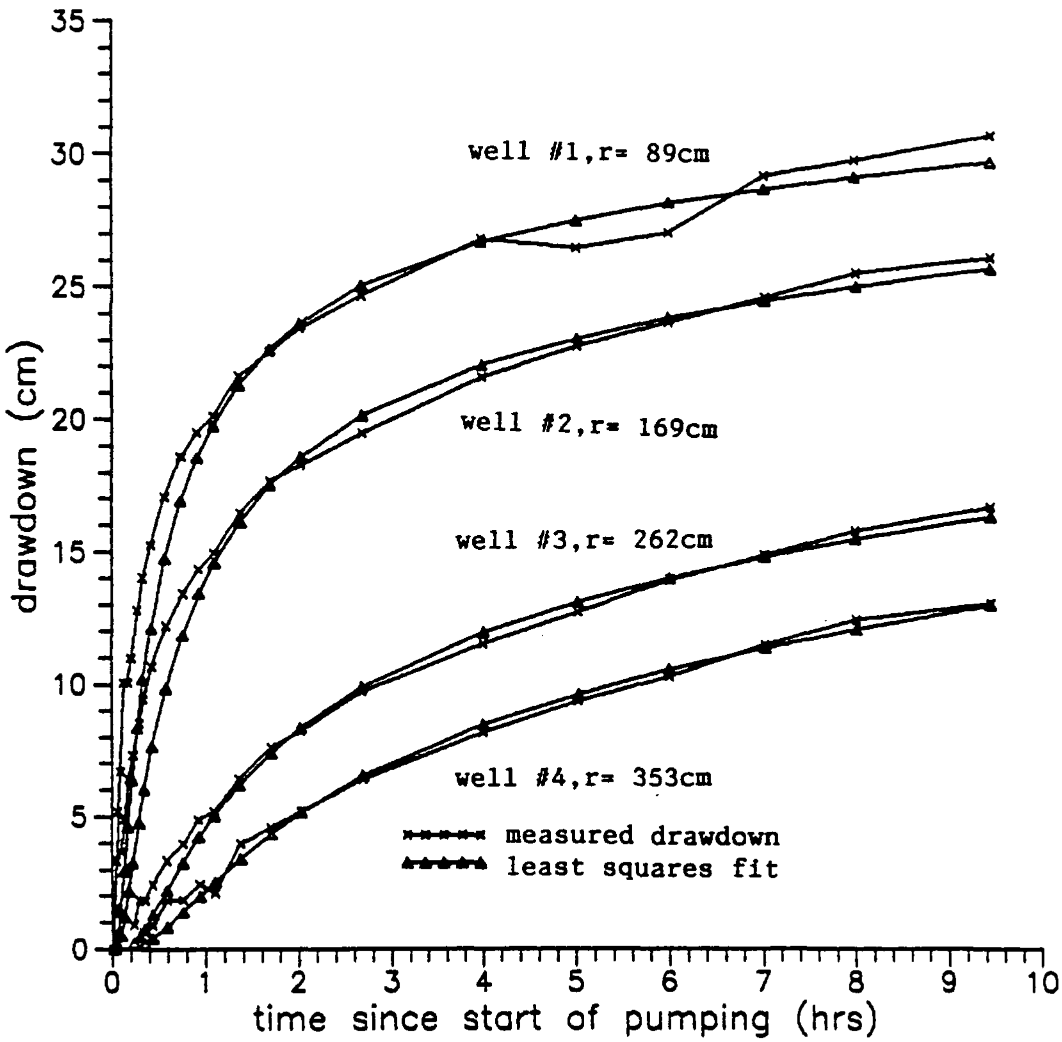

Figure 17. Test #1, the curves of the drawdown response and the least squares fitting for wells on line A

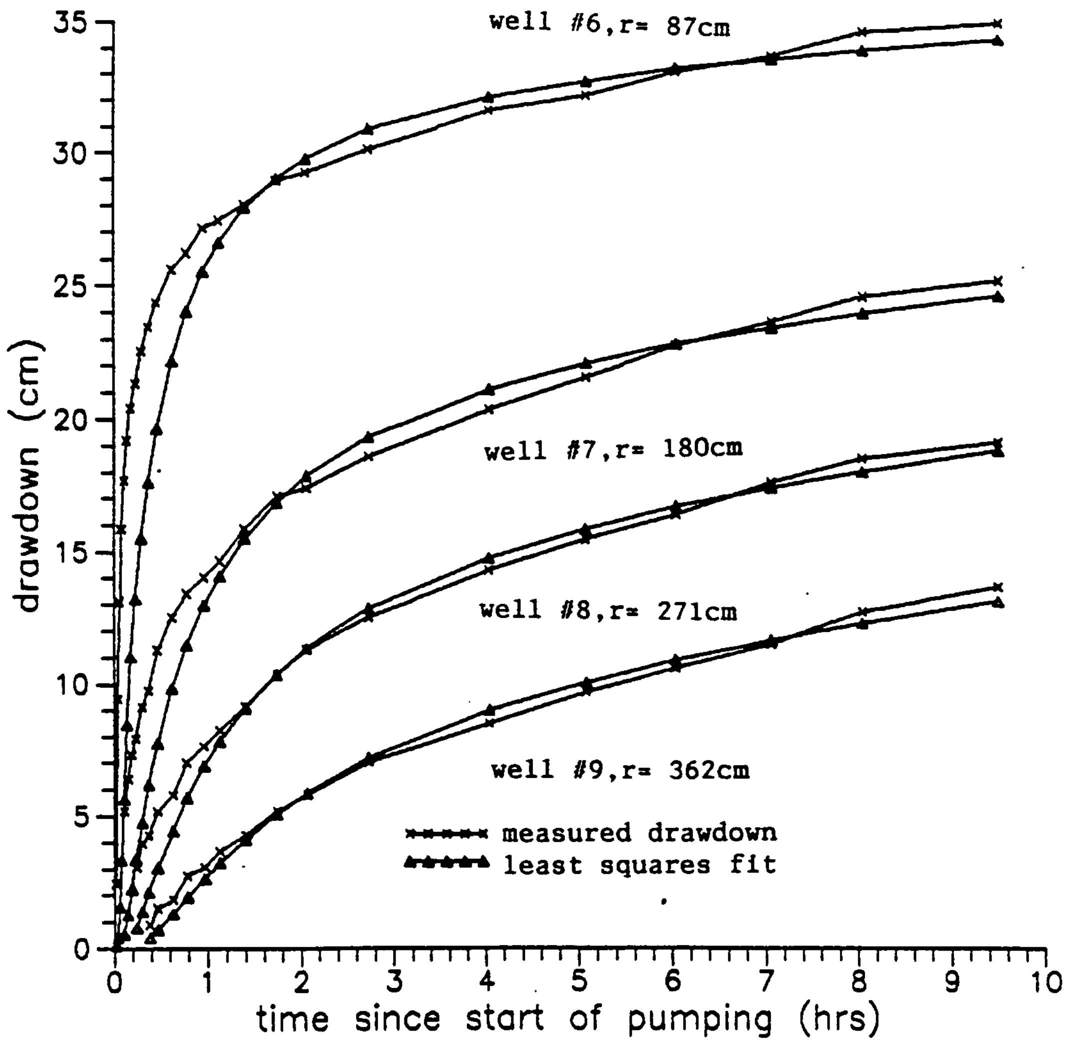

Figure 18. Test #1, the curves of the drawdown response and the least squares fitting for wells on line B

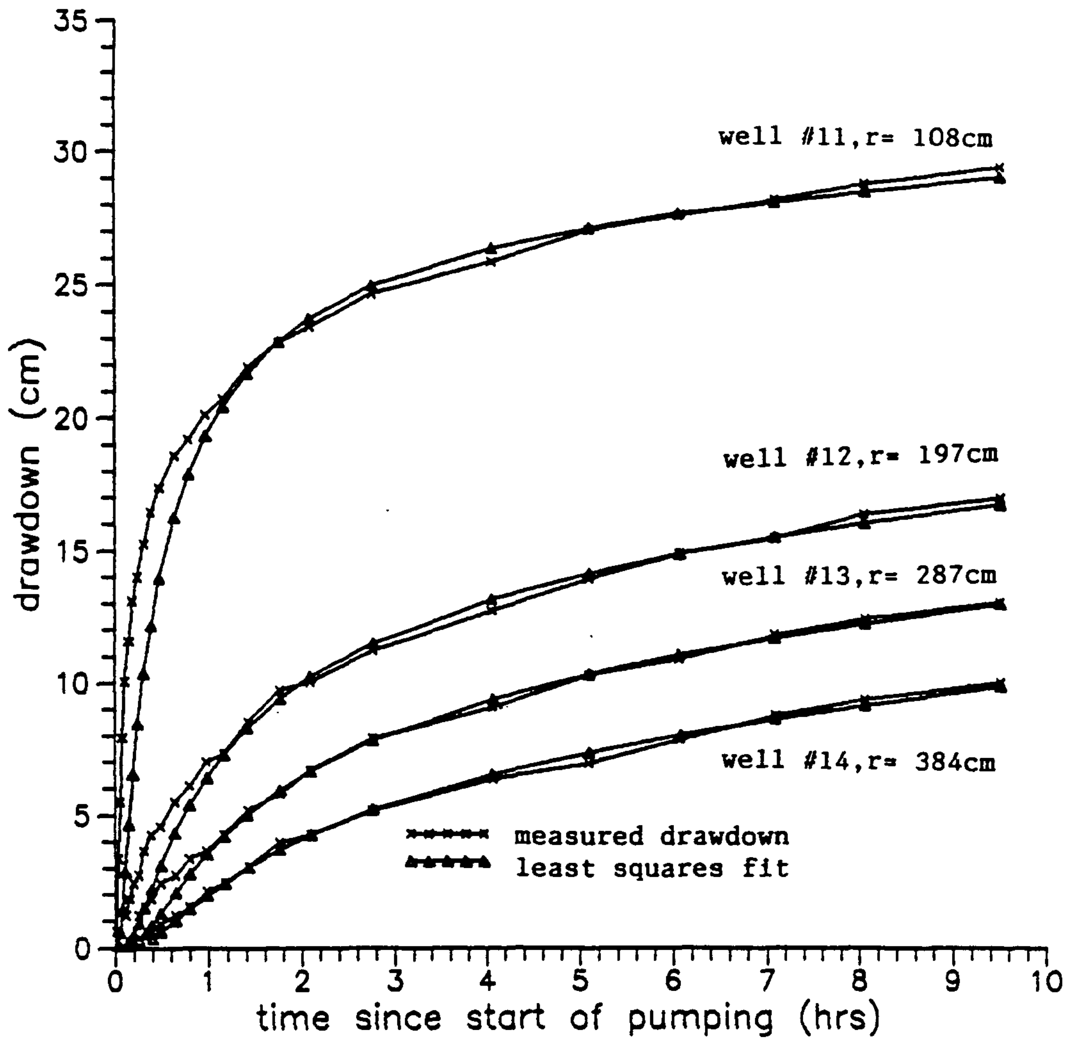

Figure 19. Test #1, the curves of the drawdown response and the least squares fitting for wells on line C

curves of drawdown response over the 24 hour pumping period for the observation wells located on the same radial line are plotted in Figures 23, 24, and 25. As with test #1, the drawdown, as measured in the observation wells, responded rapidly to the pumping. In contrast to test #1, the drawdown response of test #2 are flatter. As with test #1, the drawdown response data from wells located 20 feet from the pumping well were not included in the analysis.

After 24 hours of pumping, the pumping rates and drawdown responses appeared fairly stable. In the last three hours of pumping, the pumping rate fell only 10 ml/min. (513 ml/min. to 503 ml/min) and the drawdown responses of all observation wells increased by 0.02 to 0.03 feet.

Hydraulic conductivity and specific yield   As with test #1, drawdown data during the first two hours of pumping were excluded from the least square fitting. Table 7 shows the results of initial transmissivities, specific yields, and estimated hydraulic conductivities of each individual well, along with their arithmetic and geometric means. The estimated hydraulic conductivities were obtained by dividing the initial transmissivities by the initial thickness of the saturated zone (8.20 feet). The arithmetic mean hydraulic conductivity is 5.2×10^{-4} cm/s and the geometric mean is 4.9×10^{-4} cm/s. The arithmetic mean apparent specific yield is 0.045, while the geometric mean is 0.041.

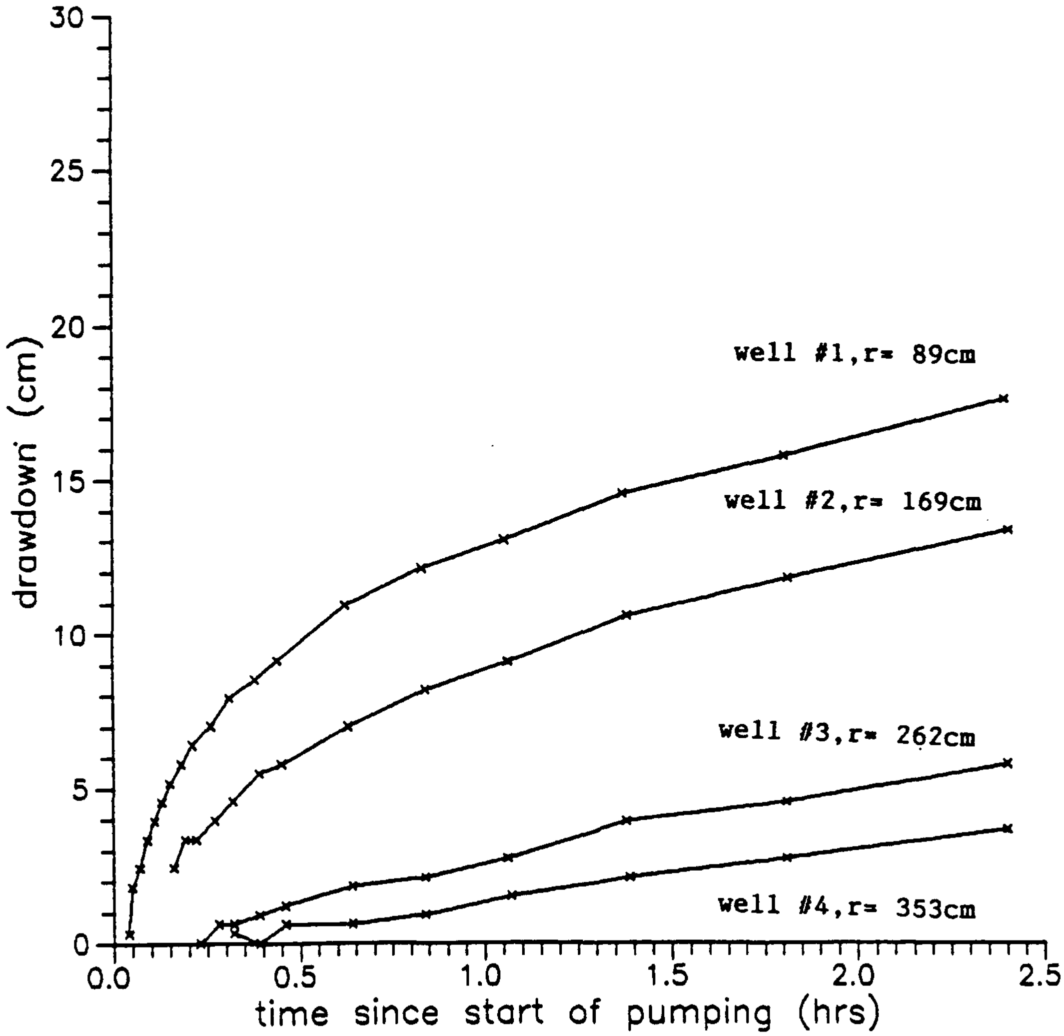

Figure 20. Test #2, drawdown response curves of wells on line A in the first 2.5 hours of pumping

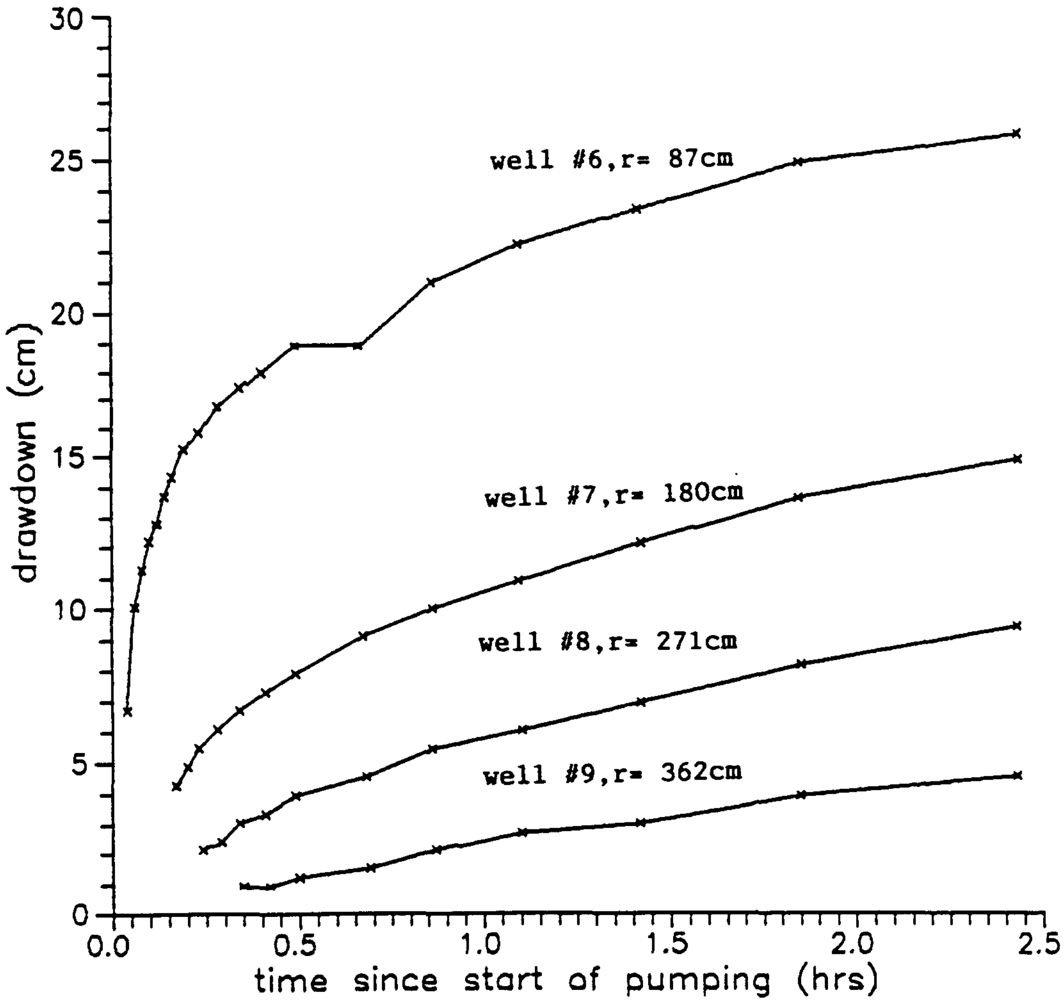

Figure 21. Test #2, drawdown response curves of wells on line B in the first 2.5 hours of pumping

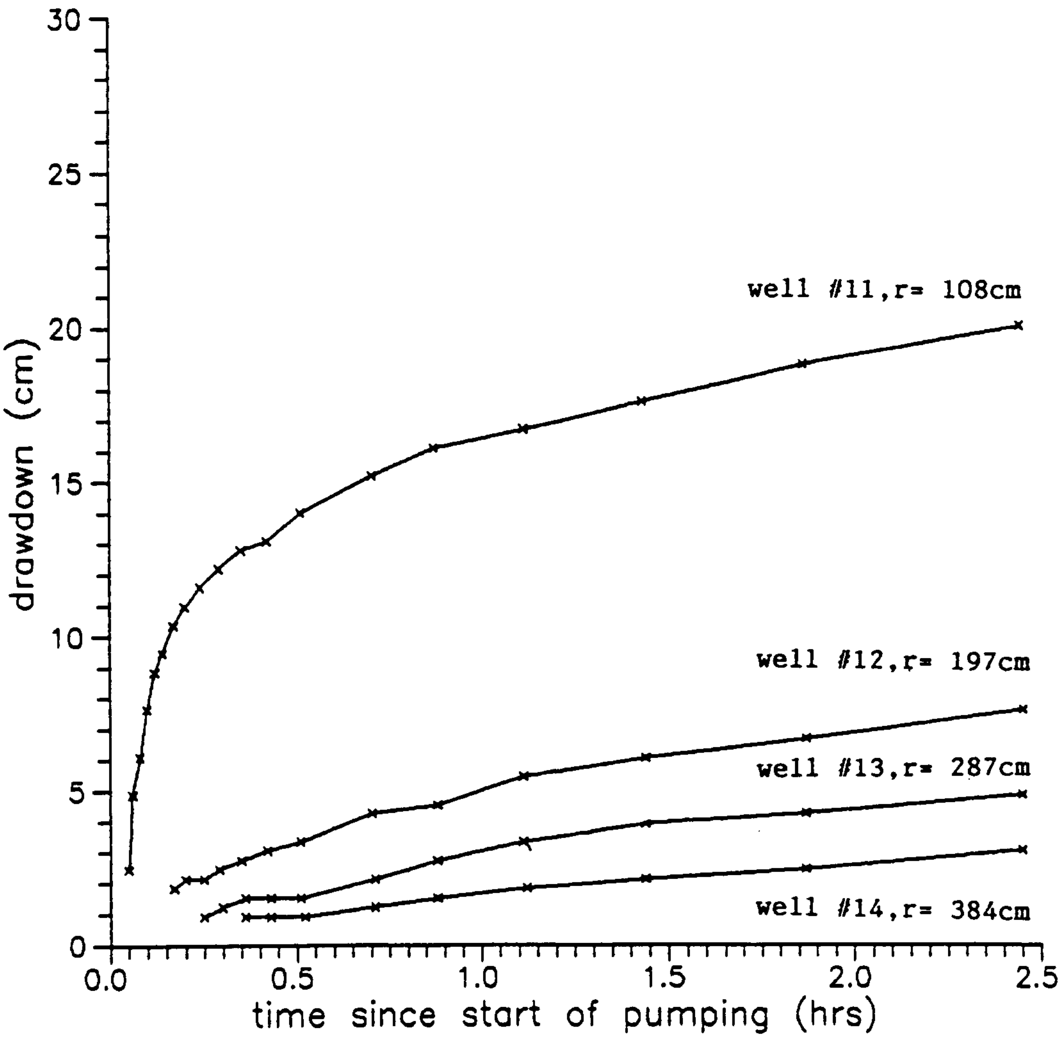

Figure 22. Test #2, drawdown response curves of wells on line C in the first 2.5 hours of pumping

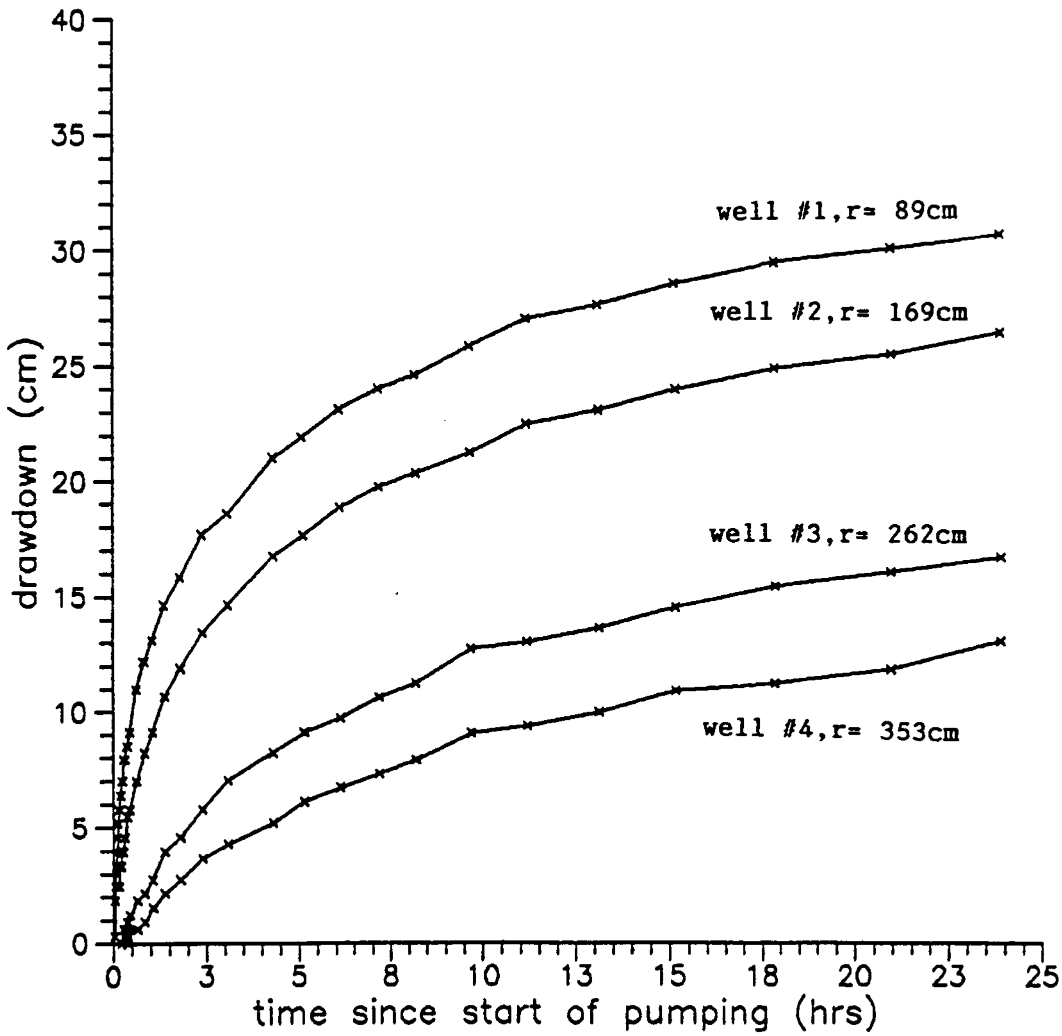

Figure 23. Test #2, drawdown response curves of wells on line A over the 24 hour pumping period

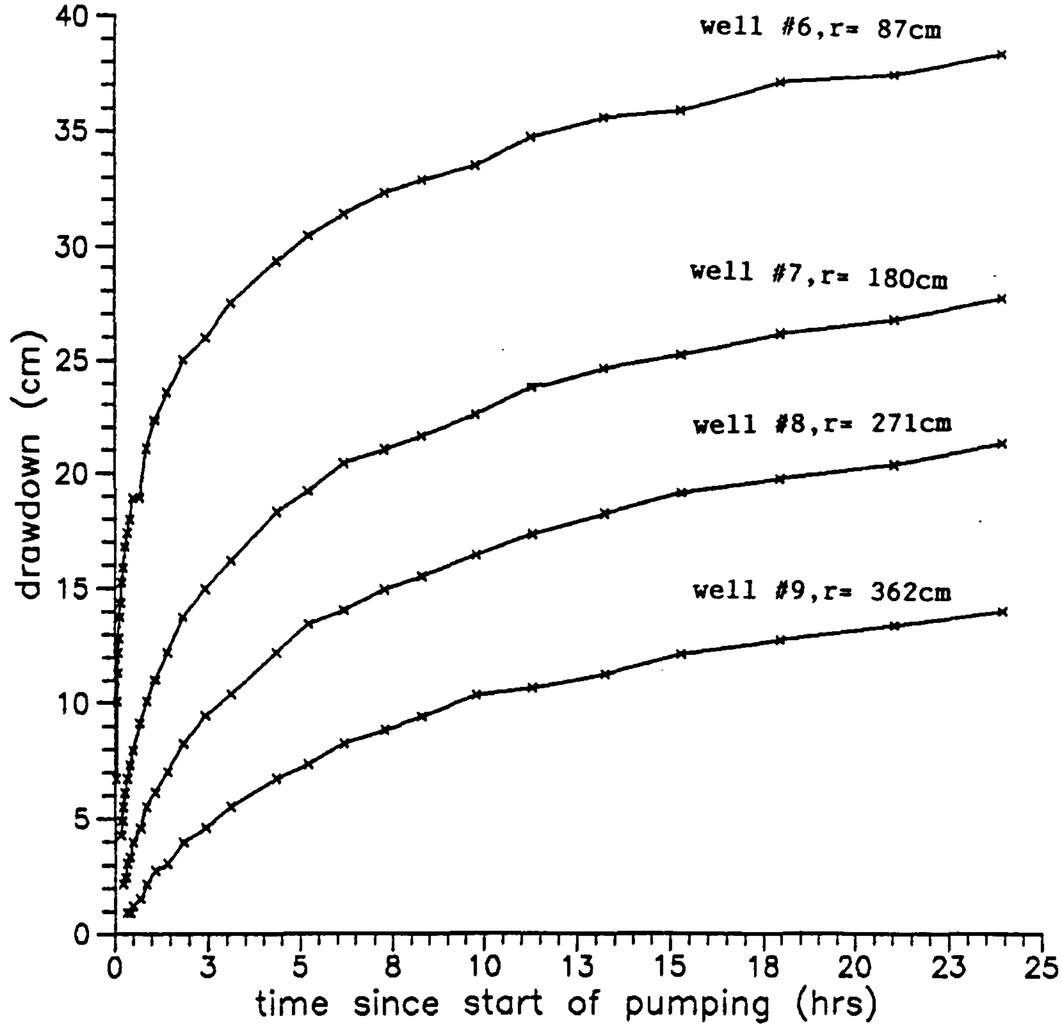

Figure 24. Test #2, drawdown response curves of wells on line B over the 24 hour pumping period

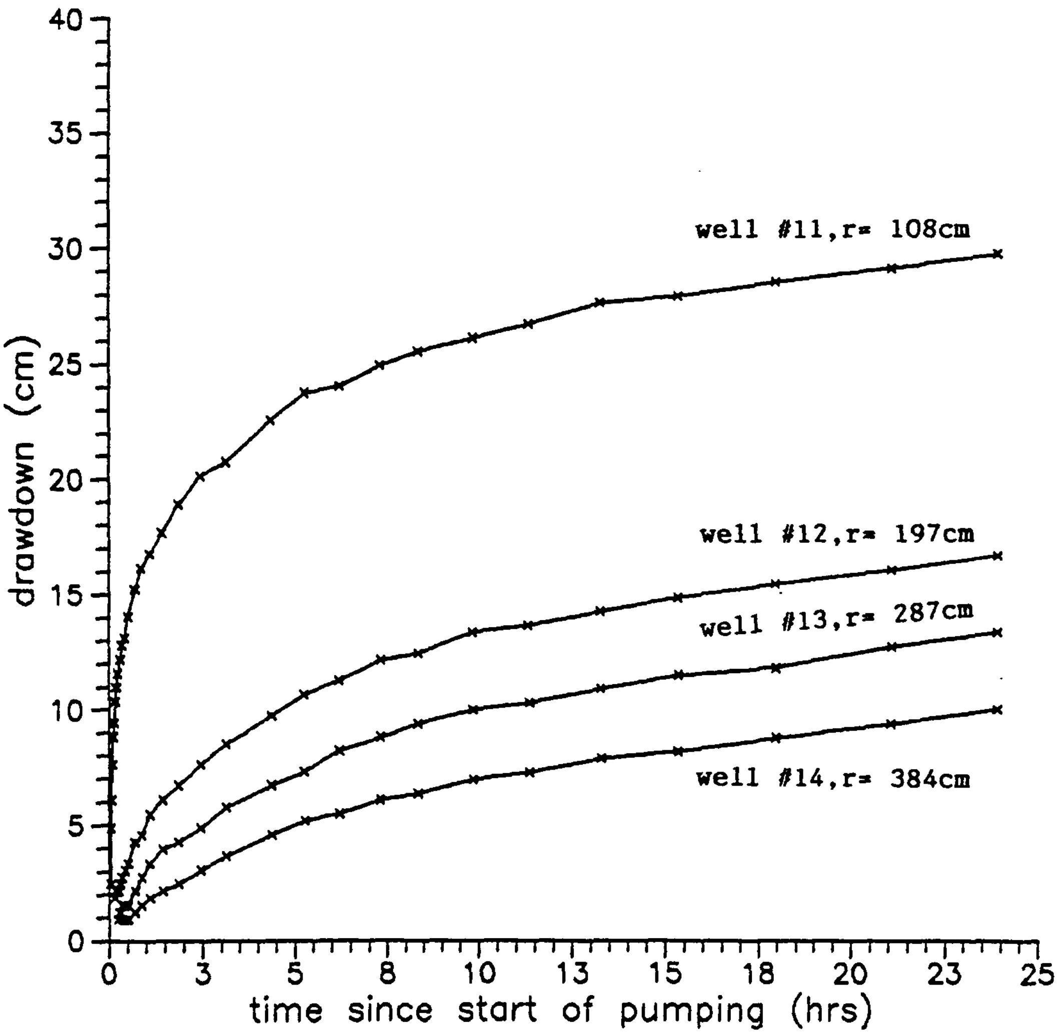

Figure 25. Test #2, drawdown response curves of wells on line C over the 24 hour pumping period

Table 7. Estimations of the flow parameters by test #2

Well #	distance cm	ME	SEE	S_y	T' cm^2/s	K cm/s
1	89.0	0.0023	0.33	0.101	0.0854	3.4E-04
2	169.0	0.0022	0.22	0.040	0.0937	3.7E-04
3	262.1	0.0044	0.26	0.040	0.1252	5.0E-04
4	352.8	0.0060	0.26	0.037	0.1557	6.2E-04
6	86.9	0.0011	0.24	0.059	0.0789	3.2E-04
7	179.8	0.0020	0.26	0.030	0.0932	3.7E-04
8	271.2	0.0031	0.24	0.023	0.1090	4.4E-04
9	362.1	0.0017	0.13	0.027	0.1529	6.1E-04
11	107.6	0.0006	0.22	0.050	0.1014	4.1E-04
12	196.6	0.0005	0.13	0.052	0.1490	6.0E-04
13	286.6	0.0006	0.16	0.040	0.1757	7.0E-04
14	384.0	0.0003	0.20	0.036	0.2419	9.7E-04
	arithmetic mean			0.0446	0.1302	5.2E-04
	standard deviation			0.0198	0.0454	1.8E-04
	coeff. of variation			0.4431	0.3486	0.3462
	geometric mean			0.0413	0.1232	4.9E-04
all wells		0.08	2.71	0.039	0.1104	4.4E-04

The average hydraulic conductivity and specific yield obtained by applying the adjusted drawdown data of all wells to the least squares fitting are listed in the last row in Table 7. The average hydraulic conductivity is 4.4 x 10^{-4} cm/s and specific yield is 0.039. As with test #1, the values estimated by using all the data are smaller than the values of estimations using the data from individual wells.

All the values of hydraulic conductivities of test #2 are relatively smaller than those of test #1, while the values of specific yields are relatively larger. The non-consistency of K's and S_y's between the tests will be discussed later.

The least squares fitting curves of the each individual well on each of the three lines are shown in Figures 26, 27, and 28. They show that in the early pumping, as expected, the fitting curves underestimate the drawdown response, but estimate the drawdown response well later. To provide a better evaluation of the accuracy of the fit, ME and SEE are calculated and listed in Table 7.

Discussion

Figure 9 and Table 8 illustrate two major differences between pumping test #1 and test #2. Even though the constant drawdown of test #1 is smaller than that of test #2 (3.04 feet to 4.92 feet), the pumping rate of test #1 is higher, and the estimated hydraulic conductivities from test #1 are

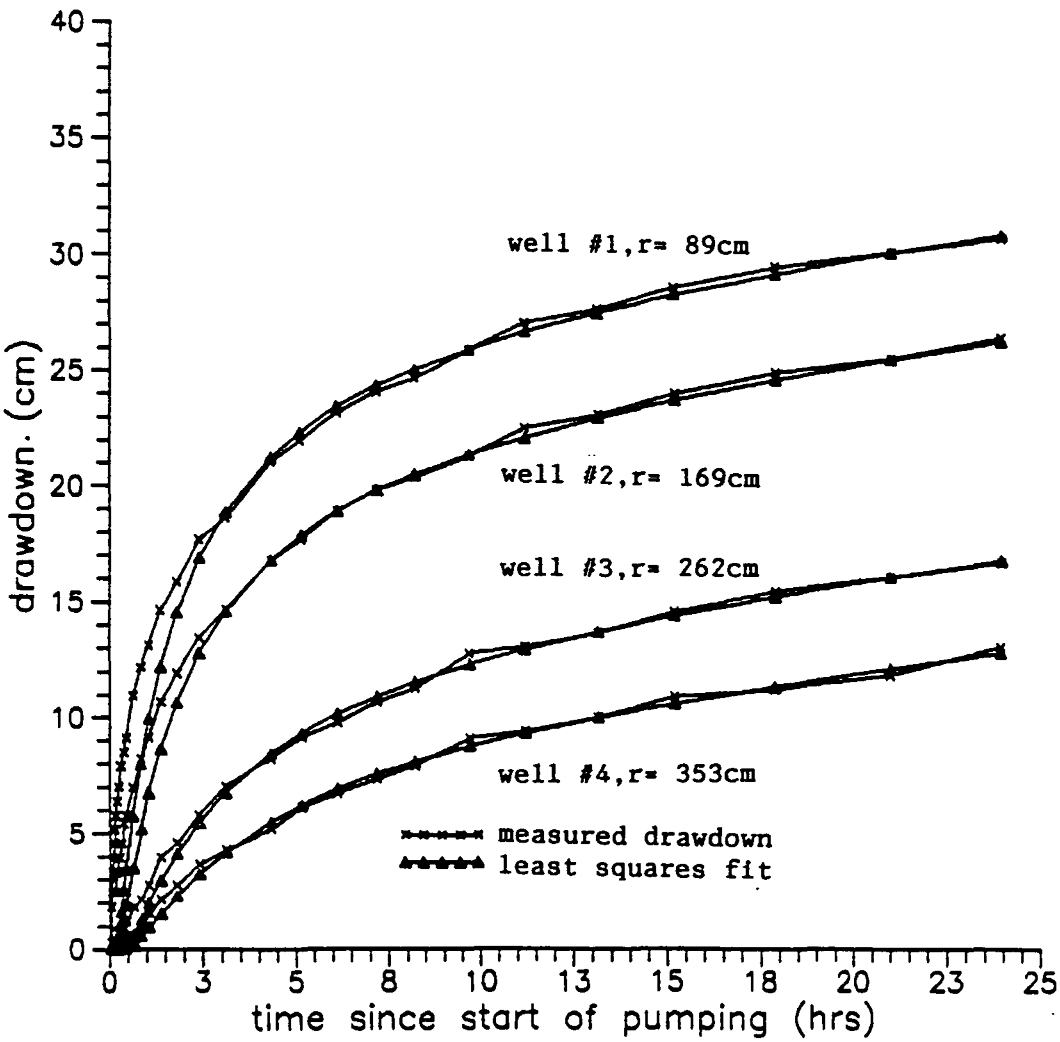

Figure 26. Test #2, the curves of the drawdown response and the least squares fitting for wells on line A

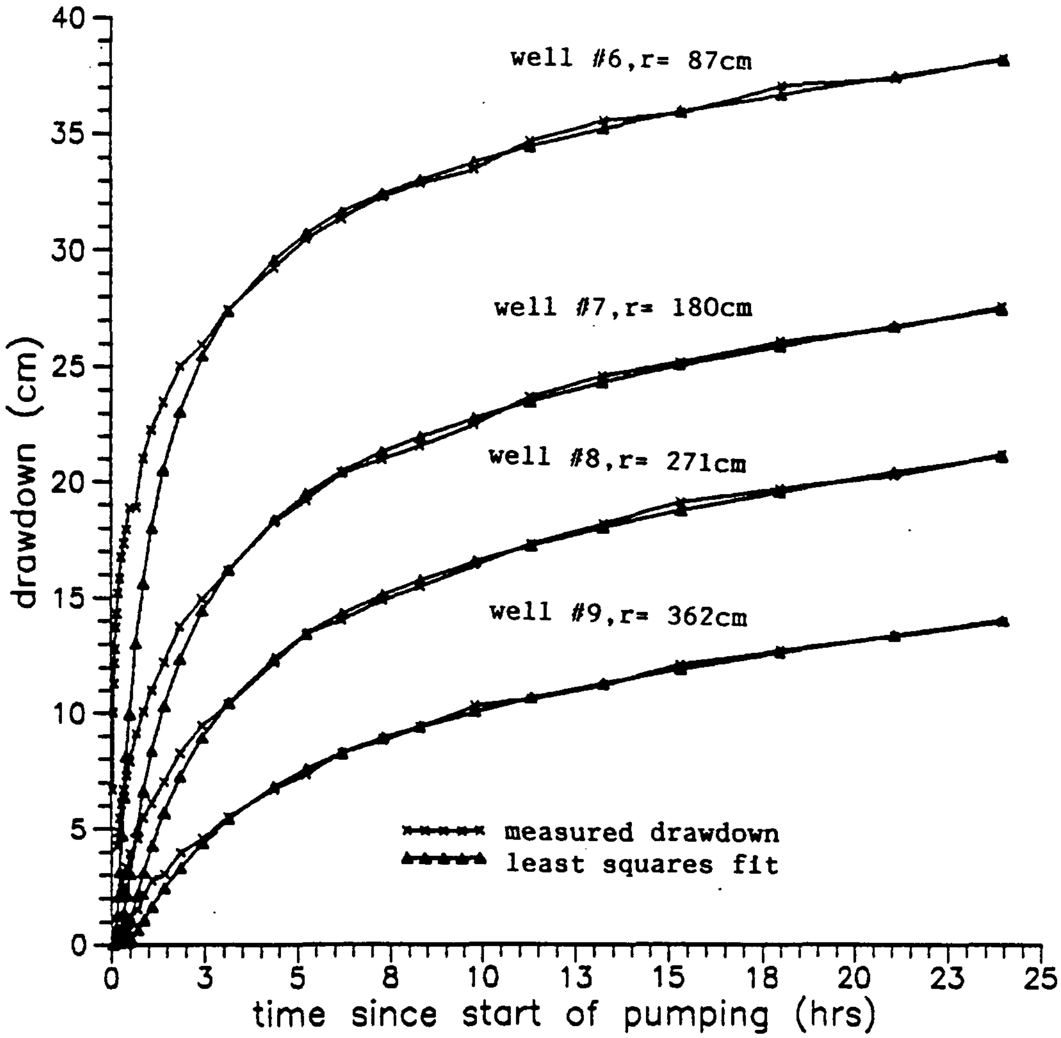

Figure 27. Test #2, the curves of the drawdown response and the least squares fitting for wells on line B

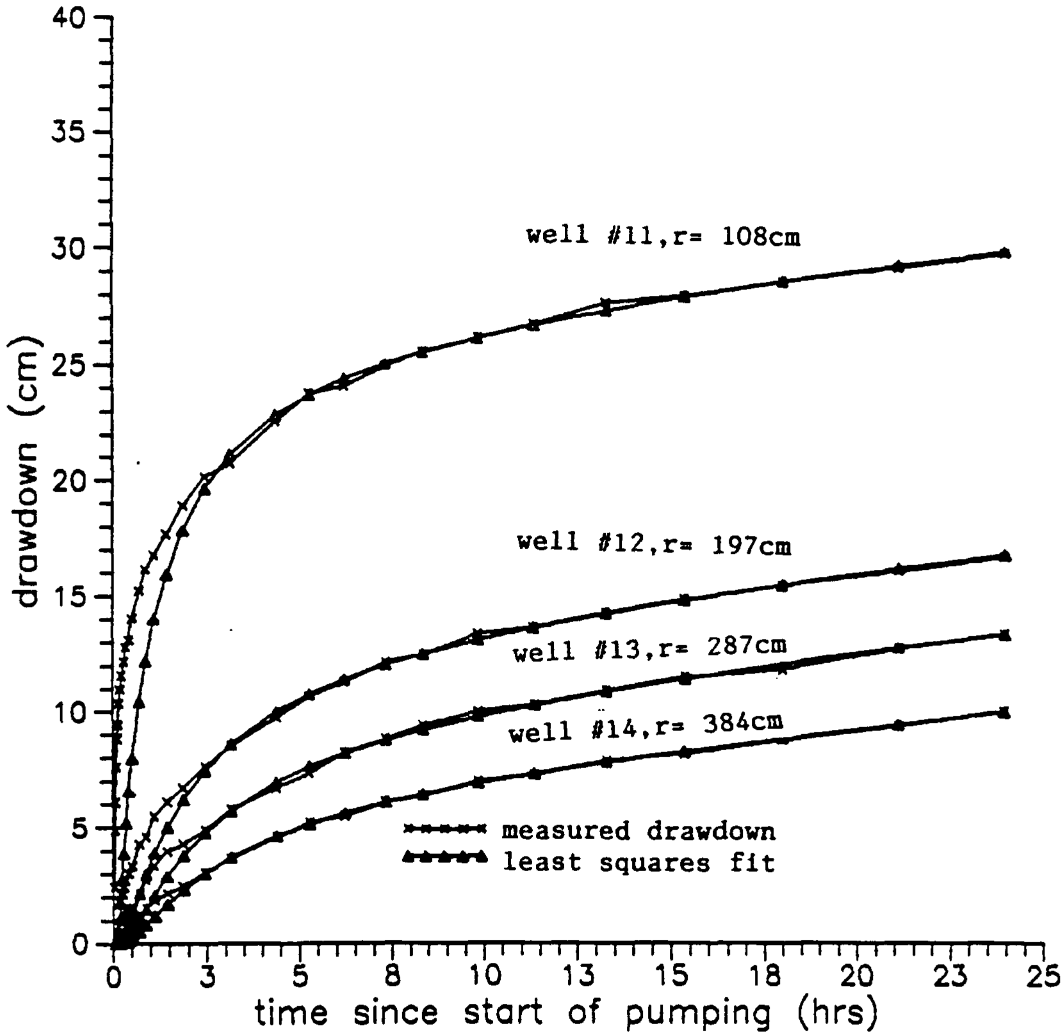

Figure 28. Test #2, the curves of the drawdown response and the least squares fitting for wells on line C

Table 8. Comparison of flow parameters estimated by both pumping tests and slug tests

	Pumping Test				Slug Test
	Test #1		Test #2		
Well #	S_y	K cm/s	S_y	K cm/s	K cm/s
1	0.048	5.5E-04	0.101	3.4E-04	2.0E-04
2	0.021	5.6E-04	0.040	3.7E-04	1.8E-04
3	0.029	6.6E-04	0.040	5.0E-04	1.0E-04
4	0.027	7.0E-04	0.037	6.2E-04	1.4E-04
6	0.029	5.4E-04	0.059	3.2E-04	2.9E-04
7	0.020	5.9E-04	0.030	3.7E-04	3.3E-04
8	0.018	6.5E-04	0.023	4.4E-04	2.1E-04
9	0.023	7.6E-04	0.027	6.1E-04	2.8E-04
11	0.030	5.8E-04	0.050	4.1E-04	1.9E-04
12	0.037	7.6E-04	0.052	6.0E-04	2.6E-04
13	0.031	8.8E-04	0.040	7.0E-04	2.9E-04
14	0.030	1.1E-03	0.036	9.7E-04	2.6E-04
arithmetic mean	0.029	6.9E-04	0.045	5.2E-04	2.3E-04
geometric mean	0.028	6.8E-04	0.041	4.9E-04	2.2E-04
all wells	0.019	6.2E-04	0.039	4.4E-04	

higher than those of test #2 for each well, while the specific yield estimates are lower. Given the natural variability of field experiments and the difficulty in isolating particular parameters or boundary conditions, firm conclusions about the reasons for the differences between test #1 and #2 cannot be made. The following offers some possible reasons for the differences.

The Theis solution yields a vertically averaged hydraulic conductivity. It has been suggested that the hydraulic conductivity of weathered till decreases with depth and that root holes may significantly increase the bulk hydraulic conductivity (D'Astous et al., 1989). If this is indeed the case, then it would be expected that the larger initial saturated thickness of test #1, when compared to test #2 (0.64 feet), would result in a higher pumping rate and higher estimates of the vertically averaged hydraulic conductivity.

Specific yield is treated as a constant in the mathematical model, but it is well known that gravity drainage takes time and the specific yield increases with time until it approaches an ultimate value (Prill et al., 1965). If the time required for drainage is significant at this site, then it would be expected that test #2, with a duration of 24 hours, would yield a higher estimate of specific yield than test #1, with a duration of 9.5 hours.

Also, it may be noted in table 8 that the estimated hydraulic conductivities generated by both tests increase with increasing radial distance from the pumping well. This phenomenon may due to the existence of a smeared clay zone along the borehole walls of the pumping well. The smeared clay zone, thought to occur from auger drilling in tills, can significantly reduce the hydraulic conductivity in the immediate vicinity of the pumping well (D'Astous et al., 1989). The Theis solution fit to data from a monitoring well yields an average of the hydraulic conductivity between the pumping well and the monitoring well. If a smeared zone exists, its influence on the Theis least squares fit will decrease with an increase in the monitoring well distance, yielding an apparent increase in the average hydraulic conductivity with an increase in radial distance.

Even though the purpose of the Jacob correction method is to account for the effect associated with the decreasing saturated zone thickness during pumping, the Jacob correction only accounts for a part of the effect associated with the decreasing thickness of the saturated zone when the drawdown is a relatively large portion of the saturated zone thickness. In this case the hydraulic conductivity from the wells near the pumping well, where the drawdown is considered a large portion of the saturated zone thickness, may be underestimated (Jacob, 1963). The degree of underestimation decreases with increasing radial distance since the drawdown decreases. This could also account in part for the hydraulic conductivity increases with increasing distance from the pumping well. The increase in hydraulic conductivity with distance could be a combination of inadequacy in the Jacob approximation and borehole smearing.

The results of slug tests which were performed by Lemar in the same test site are also shown in Table 8 for the purpose of comparing the results to the pumping tests. It is clear that the average hydraulic conductivity of the slug tests is lower than those generated by the pumping tests. In studies in fluvial materials, Bradbury et al. (1990) also observed the phenomenon that the estimated hydraulic conductivity of a pumping test, which has a larger operational scale (influence area) than a slug test, tends to be higher than that of a slug test. Since slug tests only estimate the hydraulic conductivity in the immediate vicinity of the studied wells, a smeared zone (as mentioned previously) along the borehole walls of the studied wells would significantly reduce the estimated hydraulic conductivities. However, for the pumping tests the reduction of the average hydraulic conductivity due to the smeared zone along the borehole walls of the pumping well may be averaged out and become insignificant, since the pumping tests have a much larger operational scale than the slug tests. The comparison between the results of the pumping tests and the slug tests suggests that hydraulic conductivity measurements based on slug tests should be used with some caution and are likely to underestimate the bulk hydraulic conductivity.

CONCLUSION

This work has demonstrated that the constant head pumping test is a good tool for investigating the flow parameters in the oxidized glacial till in central Iowa. The constant head pumping test is especially preferred when the aquifer is located in a relatively low permeable media with small saturated thickness. By the two tests, it is estimated that the average hydraulic conductivity in the oxidized till at the test site is about 5.3 x 10^{-4} cm/s, with a range from 3 x 10^{-4} cm/s to 1 x 10^{-3} cm/s. The average specific yield is around 3% with a range from 2% to 10%. The average hydraulic conductivity estimated by the two pumping tests is higher than that estimated by the slug tests. The other important results in this work are summarized below.

1. The results of the soil character tests support that the soil deposit at the test site is subglacial till. The transition zone of the oxidized till and the unoxidized till has an average depth of 11.1 feet and is not smooth.

2. For pumping in a shallow unconfined aquifer of relatively low permeability, increasing the drawdown in the pumping well does not necessarily result in an increasing pumping rate.

3. After the drawdown in the pumping well reaches a constant level, there is a linear relationship between the

pumping rate and the pumping time in a log-log scale. This is true at least within the first day of pumping.

4. The drawdown response was observed to react very rapidly. For the wells which were near the pumping well, the water table started to fall as soon as pumping started.

5. The estimated hydraulic conductivities of the observation wells tends to increase with increasing radial distance from the pumping well.

6. After ignoring the early time drawdown response, the Theis solution matches the observed drawdown reasonably well.

RECOMMENDATION FOR FURTHER RESEARCH

1. A constant head pumping test with pumping time longer than 24 hours should be performed to verify the pattern of the drawdown response beyond 24 hours of pumping.

2. In order to determine whether the initial thickness of the saturated zone significantly affects the determination of K and S_y, a constant head pumping test with the same initial thickness of the saturated zone as that of test #1 or test #2, and a different constant drawdown in the pumping well should be performed.

3. A constant head pumping test with a smaller constant drawdown in the pumping well than that of test #1 is needed for understanding the effect of the magnitude of the constant drawdown on the estimation of K and S_y.

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APPENDIX A. ORIGINAL DATA of PUMPING RATE vs TIME

Pumping Test #1, 07/17/90

Recorded Pumping Rate vs Time

Time (sec)	Time (hr)	Flow Rate (ml/min)
30	0.01	2580
60	0.02	2740
90	0.03	2740
120	0.03	2800
150	0.04	2680
180	0.05	2660
210	0.06	2660
240	0.07	2700
270	0.08	2700
300	0.08	2620
330	0.09	2560
360	0.10	2360
390	0.11	2220
420	0.12	2120
450	0.13	1960
480	0.13	1960
540	0.15	1920
600	0.17	1880
660	0.18	1860
720	0.20	1740
780	0.22	1680
840	0.23	1750
900	0.25	1680
960	0.27	1680
1020	0.28	1640
1080	0.30	1640
1140	0.32	1600
1200	0.33	1620
1260	0.35	1580
1320	0.37	1570
1380	0.38	1540
1440	0.40	1520
1500	0.42	1520

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
1560	0.43	1520
1620	0.45	1500
1680	0.47	1480
1740	0.48	1490
1800	0.50	1470
1860	0.52	1460
1920	0.53	1460
1980	0.55	1450
2040	0.57	1440
2100	0.58	1430
2160	0.60	1430
2220	0.62	1430
2280	0.63	1400
2340	0.65	1400
2400	0.67	1380
2460	0.68	1390
2520	0.70	1380
2580	0.72	1360
2640	0.73	1360
2700	0.75	1350
2760	0.77	1340
2820	0.78	1340
2880	0.80	1330
2940	0.82	1340
3000	0.83	1320
3060	0.85	1310
3120	0.87	1310
3180	0.88	1300
3240	0.90	1300
3300	0.92	1290
3360	0.93	1280
3420	0.95	1280
3480	0.97	1260

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
3540	0.98	1260
3600	1.00	1270
3660	1.02	1250
3720	1.03	1260
3780	1.05	1250
3840	1.07	1230
3900	1.08	1240
3960	1.10	1230
4020	1.12	1230
4080	1.13	1230
4140	1.15	1220
4200	1.17	1230
4260	1.18	1230
4320	1.20	1200
4380	1.22	1210
4440	1.23	1210
4500	1.25	1200
4560	1.27	1200
4620	1.28	1200
4680	1.30	1200
4740	1.32	1200
4800	1.33	1190
4860	1.35	1190
4920	1.37	1190
4980	1.38	1180
5040	1.40	1180
5100	1.42	1170
5160	1.43	1160
5220	1.45	1150
5280	1.47	1150
5340	1.48	1140
5400	1.50	1150
5460	1.52	1150
5520	1.53	1140
5580	1.55	1140
5640	1.57	1140
5700	1.58	1120

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
5760	1.60	1120
5820	1.62	1140
5880	1.63	1130
6000	1.67	1115
6060	1.68	1110
6120	1.70	1120
6180	1.72	1110
6240	1.73	1110
6300	1.75	1110
6360	1.77	1100
6420	1.78	1110
6480	1.80	1110
6540	1.82	1100
6600	1.83	1100
6660	1.85	1090
6720	1.87	1090
6780	1.88	1090
6840	1.90	1090
6900	1.92	1080
6960	1.93	1080
7020	1.95	1080
7080	1.97	1080
7140	1.98	1080
7200	2.00	1070
7260	2.02	1070
7320	2.03	1070
7380	2.05	1070
7440	2.07	1070
7500	2.08	1060
7560	2.10	1060
7740	2.15	1053
7800	2.17	1050
7860	2.18	1050
7920	2.20	1050
7980	2.22	1050
8040	2.23	1050
8100	2.25	1040

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
8160	2.27	1050
8220	2.28	1040
8280	2.30	1040
8340	2.32	1040
8400	2.33	1040
8460	2.35	1040
8520	2.37	1030
8580	2.38	1030
8640	2.40	1040
8700	2.42	1030
8760	2.43	1040
8820	2.45	1020
8880	2.47	1030
8940	2.48	1030
9000	2.50	1020
9060	2.52	1030
9120	2.53	1030
9180	2.55	1010
9240	2.57	1000
9300	2.58	1020
9360	2.60	1010
9420	2.62	1010
9480	2.63	1000
9540	2.65	1010
9600	2.67	1000
9660	2.68	1000
9720	2.70	1000
9780	2.72	1010
9840	2.73	1000
9900	2.75	1000
9960	2.77	1000
10020	2.78	1000
10140	2.82	985
10260	2.85	985
10380	2.88	975
10500	2.92	980
10620	2.95	980

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
10740	2.98	970
10860	3.02	970
10980	3.05	970
11100	3.08	960
11220	3.12	965
11340	3.15	960
11460	3.18	960
11580	3.22	960
11700	3.25	950
11820	3.28	950
11940	3.32	950
12060	3.35	950
12180	3.38	950
12300	3.42	945
12420	3.45	940
12540	3.48	945
12660	3.52	940
12780	3.55	940
12900	3.58	935
13020	3.62	935
13140	3.65	935
13260	3.68	930
13380	3.72	930
13500	3.75	930
13620	3.78	925
13740	3.82	920
13860	3.85	920
13980	3.88	920
14100	3.92	920
14220	3.95	920
14340	3.98	915
14460	4.02	910
14580	4.05	910
14700	4.08	910
14820	4.12	910
14940	4.15	905
15060	4.18	905

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
15180	4.22	900
15300	4.25	900
15420	4.28	900
15540	4.32	895
15660	4.35	895
15780	4.38	895
15900	4.42	895
16020	4.45	890
16140	4.48	890
16260	4.52	890
16380	4.55	885
16500	4.58	880
16620	4.62	880
16740	4.65	880
16860	4.68	880
16980	4.72	875
17100	4.75	875
17220	4.78	875
17340	4.82	870
17460	4.85	870
17580	4.88	870
17700	4.92	870
17820	4.95	870
17940	4.98	870
18060	5.02	860
18180	5.05	860
18300	5.08	860
18420	5.12	860
18540	5.15	855
18660	5.18	860
18780	5.22	860
18900	5.25	855
19020	5.28	860
19140	5.32	850
19260	5.35	850
19380	5.38	860
19500	5.42	855

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
19620	5.45	850
19740	5.48	850
19860	5.52	850
19980	5.55	850
20100	5.58	845
20220	5.62	850
20340	5.65	845
20460	5.68	845
20580	5.72	840
20700	5.75	840
20820	5.78	840
20940	5.82	840
21060	5.85	840
21180	5.88	835
21300	5.92	840
21420	5.95	830
21540	5.98	835
21660	6.02	830
21780	6.05	830
21900	6.08	835
22020	6.12	830
22140	6.15	825
22260	6.18	825
22380	6.22	825
22500	6.25	825
22620	6.28	825
22740	6.32	820
22860	6.35	820
22980	6.38	820
23100	6.42	815
23220	6.45	815
23340	6.48	815
23460	6.52	815
23580	6.55	810
23700	6.58	810
23820	6.62	810
23940	6.65	810

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
24060	6.68	810
24180	6.72	805
24300	6.75	805
24420	6.78	795
24540	6.82	800
24660	6.85	800
24780	6.88	800
24900	6.92	795
25020	6.95	790
25140	6.98	800
25260	7.02	795
25380	7.05	800
25500	7.08	795
25620	7.12	800
25740	7.15	795
25860	7.18	795
25980	7.22	795
26100	7.25	800
26220	7.28	790
26340	7.32	790
26460	7.35	790
26580	7.38	800
26700	7.42	790
26820	7.45	795
26940	7.48	790
27060	7.52	785
27180	7.55	790
27300	7.58	780
27420	7.62	780
27540	7.65	780
27660	7.68	780
27780	7.72	780
27900	7.75	785
28020	7.78	780
28140	7.82	780
28260	7.85	775
28380	7.88	780

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
28500	7.92	775
28620	7.95	775
28740	7.98	775
28860	8.02	775
28980	8.05	770
29100	8.08	775
29220	8.12	770
29340	8.15	770
29460	8.18	770
29580	8.22	770
29700	8.25	770
29820	8.28	765
29940	8.32	770
30060	8.35	770
30180	8.38	770
30300	8.42	765
30420	8.45	770
30540	8.48	765
30660	8.52	760
30780	8.55	760
30900	8.58	760
31020	8.62	760
31140	8.65	760
31260	8.68	760
31380	8.72	755
31500	8.75	760
31620	8.78	755
31740	8.82	755
31860	8.85	750
31980	8.88	755
32100	8.92	750
32220	8.95	750
32340	8.98	750
32460	9.02	750
32580	9.05	750
32700	9.08	750
32820	9.12	750

Continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
32940	9.15	750
33060	9.18	750
33180	9.22	750
33300	9.25	750
33420	9.28	750
33540	9.32	750
33660	9.35	750
33780	9.38	750
33900	9.42	750
34020	9.45	750
34140	9.48	750
34260	9.52	750
34380	9.55	750

Pumping Test #2, 08/06/90

Pumping Rate vs Time:

Time (sec)	Time (hr)	Flow Rate (ml/min)
20	0.01	2580
40	0.01	2580
60	0.02	2580
80	0.02	2580
100	0.03	2580
120	0.03	2550
140	0.04	2580
160	0.04	2550
180	0.05	2520
210	0.06	2520
240	0.07	2440
270	0.08	2460
300	0.08	2480
330	0.09	2400
360	0.10	2380
390	0.11	2280
420	0.12	2120
450	0.13	1540
480	0.13	1440
510	0.14	1440
540	0.15	1440
570	0.16	1420
600	0.17	1400
630	0.18	1400
660	0.18	1380
690	0.19	1360
720	0.20	1360
780	0.22	1320
840	0.23	1310
900	0.25	1300
960	0.27	1260
1020	0.28	1250
1080	0.30	1240
1140	0.32	1220
1200	0.33	1210

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
1260	0.35	1200
1320	0.37	1200
1380	0.38	1180
1440	0.40	1170
1500	0.42	1160
1560	0.43	1150
1620	0.45	1140
1680	0.47	1140
1740	0.48	1120
1800	0.50	1120
1860	0.52	1110
1920	0.53	1100
1980	0.55	1100
2040	0.57	1090
2100	0.58	1080
2160	0.60	1080
2220	0.62	1070
2280	0.63	1070
2340	0.65	1060
2400	0.67	1060
2460	0.68	1050
2520	0.70	1040
2580	0.72	1040
2640	0.73	1040
2700	0.75	1040
2760	0.77	1020
2820	0.78	1020
2880	0.80	1010
2940	0.82	1000
3000	0.83	1000
3060	0.85	1000
3120	0.87	1000
3180	0.88	990
3240	0.90	990
3300	0.92	990

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
3360	0.93	980
3420	0.95	980
3480	0.97	980
3540	0.98	970
3600	1.00	970
3720	1.03	960
3840	1.07	955
3960	1.10	950
4080	1.13	940
4200	1.17	935
4320	1.20	935
4440	1.23	930
4560	1.27	920
4680	1.30	920
4800	1.33	915
4920	1.37	905
5040	1.40	905
5160	1.43	900
5280	1.47	895
5400	1.50	890
5520	1.53	885
5640	1.57	880
5760	1.60	875
5880	1.63	870
6000	1.67	865
6120	1.70	860
6240	1.73	865
6360	1.77	855
6480	1.80	860
6600	1.83	855
6720	1.87	850
6840	1.90	845
6960	1.93	845
7080	1.97	840
7200	2.00	835
7320	2.03	830
7440	2.07	830
7560	2.10	830
7680	2.13	825

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
7800	2.17	820
7920	2.20	820
8040	2.23	815
8160	2.27	810
8280	2.30	810
8400	2.33	810
8520	2.37	810
8640	2.40	805
8760	2.43	800
8880	2.47	795
9000	2.50	790
9120	2.53	790
9240	2.57	780
9360	2.60	780
9480	2.63	780
9600	2.67	775
9720	2.70	765
9840	2.73	775
9960	2.77	775
10080	2.80	775
10200	2.83	770
10320	2.87	770
10440	2.90	765
10560	2.93	765
10680	2.97	765
10800	3.00	760
10920	3.03	760
11040	3.07	755
11160	3.10	755
11280	3.13	755
11400	3.17	755
11520	3.20	750
11640	3.23	750
11760	3.27	750
11880	3.30	750
12000	3.33	740
12120	3.37	740
12240	3.40	740
12360	3.43	740

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
12480	3.47	735
12600	3.50	735
12720	3.53	735
12840	3.57	730
12960	3.60	730
13080	3.63	730
13200	3.67	730
13320	3.70	730
13440	3.73	725
13560	3.77	730
13680	3.80	725
13800	3.83	720
13920	3.87	720
14040	3.90	720
14160	3.93	720
14280	3.97	715
14400	4.00	720
14520	4.03	715
14640	4.07	715
14760	4.10	710
14880	4.13	710
15000	4.17	710
15120	4.20	705
15240	4.23	700
15360	4.27	700
15480	4.30	705
15600	4.33	705
15720	4.37	700
15840	4.40	700
15960	4.43	700
16080	4.47	700
16200	4.50	700
16320	4.53	700
16440	4.57	695
16560	4.60	695
16680	4.63	695
16800	4.67	690
16920	4.70	690
17040	4.73	690

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
17160	4.77	690
17280	4.80	690
17400	4.83	685
17520	4.87	685
17640	4.90	685
17760	4.93	685
17880	4.97	685
18000	5.00	680
18120	5.03	680
18240	5.07	680
18360	5.10	680
18480	5.13	680
18600	5.17	680
18720	5.20	675
18840	5.23	675
18960	5.27	675
19080	5.30	675
19200	5.33	670
19320	5.37	670
19440	5.40	670
19560	5.43	670
19680	5.47	670
19800	5.50	665
19920	5.53	665
20040	5.57	665
20160	5.60	665
20280	5.63	665
20400	5.67	665
20520	5.70	660
20700	5.75	660
20880	5.80	660
21060	5.85	657
21240	5.90	653
21420	5.95	650
21600	6.00	650
21780	6.05	647
21960	6.10	647
22140	6.15	643
22320	6.20	643

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
22500	6.25	643
22680	6.30	643
22860	6.35	643
23040	6.40	640
23220	6.45	640
23400	6.50	640
23580	6.55	640
23760	6.60	637
23940	6.65	633
24120	6.70	633
24300	6.75	633
24480	6.80	630
24660	6.85	630
24840	6.90	630
25020	6.95	630
25200	7.00	627
25380	7.05	627
25560	7.10	627
25740	7.15	627
25920	7.20	627
26100	7.25	627
26280	7.30	627
26460	7.35	623
26640	7.40	623
26820	7.45	620
27000	7.50	620
27180	7.55	620
27360	7.60	620
27540	7.65	620
27720	7.70	620
27900	7.75	620
28080	7.80	617
28260	7.85	617
28440	7.90	617
28620	7.95	613
28800	8.00	613
28980	8.05	613
29160	8.10	613
29340	8.15	613

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
29520	8.20	610
29700	8.25	610
29880	8.30	607
30060	8.35	607
30240	8.40	607
30420	8.45	603
30600	8.50	603
30780	8.55	603
30960	8.60	603
31140	8.65	603
31320	8.70	600
31500	8.75	600
31680	8.80	600
31860	8.85	600
32040	8.90	600
32220	8.95	597
32400	9.00	597
32580	9.05	597
32760	9.10	597
32940	9.15	593
33120	9.20	593
33300	9.25	593
33480	9.30	593
33660	9.35	593
33840	9.40	590
34020	9.45	590
34200	9.50	593
34380	9.55	590
34560	9.60	590
34740	9.65	587
34920	9.70	587
35100	9.75	587
35280	9.80	590
35460	9.85	587
35640	9.90	587
35820	9.95	587
36000	10.00	587
36180	10.05	587
36360	10.10	587

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
36540	10.15	587
36720	10.20	587
36900	10.25	587
37080	10.30	587
37260	10.35	587
37440	10.40	583
37620	10.45	583
37800	10.50	587
37980	10.55	587
38160	10.60	583
38340	10.65	583
38520	10.70	583
38700	10.75	580
38880	10.80	580
39060	10.85	580
39240	10.90	580
39420	10.95	580
39600	11.00	580
39780	11.05	580
39960	11.10	580
40140	11.15	577
40320	11.20	577
40500	11.25	577
40680	11.30	573
40860	11.35	573
41040	11.40	573
41220	11.45	573
41400	11.50	573
41580	11.55	573
41760	11.60	573
41940	11.65	573
42120	11.70	573
42300	11.75	573
42480	11.80	573
42660	11.85	573
42840	11.90	573
43020	11.95	570
43200	12.00	570
43380	12.05	570

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
43560	12.10	570
43740	12.15	567
43920	12.20	567
44100	12.25	567
44280	12.30	563
44460	12.35	563
44640	12.40	563
44820	12.45	563
45000	12.50	563
45180	12.55	563
45360	12.60	560
45540	12.65	560
45720	12.70	560
45900	12.75	560
46080	12.80	560
46260	12.85	560
46440	12.90	560
46620	12.95	560
46800	13.00	560
46980	13.05	560
47160	13.10	557
47340	13.15	557
47520	13.20	557
47700	13.25	557
47880	13.30	553
48060	13.35	557
48240	13.40	553
48420	13.45	553
48600	13.50	553
48780	13.55	553
48960	13.60	553
49140	13.65	553
49320	13.70	553
49500	13.75	553
49680	13.80	553
49860	13.85	553
50040	13.90	553
50220	13.95	553
50400	14.00	553

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)	Time (sec)	Time (hr)	Flow Rate (ml/min)
50580	14.05	553	57600	16.00	537
50760	14.10	553	57780	16.05	537
50940	14.15	550	57960	16.10	537
51120	14.20	553	58140	16.15	537
51300	14.25	553	58320	16.20	537
51480	14.30	550	58500	16.25	537
51660	14.35	550	58680	16.30	537
51840	14.40	550	58860	16.35	537
52020	14.45	550	59040	16.40	537
52200	14.50	550	59220	16.45	533
52380	14.55	550	59400	16.50	533
52560	14.60	546	59580	16.55	533
52740	14.65	546	59760	16.60	533
52920	14.70	546	59940	16.65	533
53100	14.75	546	60120	16.70	533
53280	14.80	546	60300	16.75	533
53460	14.85	546	60480	16.80	533
53640	14.90	543	60660	16.85	533
53820	14.95	546	60840	16.90	533
54000	15.00	543	61020	16.95	533
54180	15.05	543	61200	17.00	533
54360	15.10	543	61380	17.05	533
54540	15.15	543	61560	17.10	533
54720	15.20	540	61740	17.15	533
54900	15.25	540	61920	17.20	533
55080	15.30	540	62100	17.25	533
55260	15.35	540	62280	17.30	533
55440	15.40	540	62460	17.35	533
55620	15.45	540	62640	17.40	533
55800	15.50	537	62820	17.45	530
55980	15.55	540	63000	17.50	530
56160	15.60	540	63180	17.55	530
56340	15.65	540	63360	17.60	530
56520	15.70	540	63540	17.65	530
56700	15.75	537	63720	17.70	530
56880	15.80	537	63900	17.75	530
57060	15.85	540	64080	17.80	530
57240	15.90	537	64260	17.85	530
57420	15.95	537	64440	17.90	530

continued

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
64620	17.95	530
64800	18.00	530
64980	18.05	530
65160	18.10	530
65340	18.15	527
65520	18.20	527
65700	18.25	527
65880	18.30	527
66060	18.35	527
66240	18.40	527
66420	18.45	527
66600	18.50	527
66780	18.55	527
66960	18.60	527
70020	19.45	517
70200	19.50	517
70380	19.55	517
70560	19.60	517
70740	19.65	517
70920	19.70	517
71100	19.75	513
71280	19.80	520
71460	19.85	517
71640	19.90	517
71820	19.95	517
72000	20.00	517
72180	20.05	517
72360	20.10	517
72540	20.15	517
72720	20.20	517
72900	20.25	513
73080	20.30	513
73260	20.35	513
73440	20.40	513
73620	20.45	513
73800	20.50	513
73980	20.55	513
74160	20.60	513
74340	20.65	513
74520	20.70	513
74700	20.75	513
74880	20.80	513
75060	20.85	513
75240	20.90	513
75420	20.95	513
75600	21.00	517
75780	21.05	513
75960	21.10	517
76140	21.15	513
76320	21.20	513
76500	21.25	513
76680	21.30	513
76860	21.35	513
77040	21.40	513
77220	21.45	510
77400	21.50	513
77580	21.55	510
77760	21.60	513
77940	21.65	513
78120	21.70	513
78300	21.75	510
78480	21.80	510
78660	21.85	510
78840	21.90	510
79020	21.95	510
79200	22.00	510
79380	22.05	510
79560	22.10	510
79740	22.15	510
79920	22.20	510
80100	22.25	510
80280	22.30	506
80460	22.35	506
80640	22.40	506
80820	22.45	506
81000	22.50	510
81180	22.55	510
81360	22.60	510

continued

Time (sec)	Time (hr)	Flow Rate (ml/min)
81540	22.65	506
81720	22.70	506
81900	22.75	506
82080	22.80	503
82260	22.85	503
82440	22.90	503
82620	22.95	503
82800	23.00	503
82980	23.05	503
83160	23.10	503
83340	23.15	503
83520	23.20	503
83700	23.25	503
83880	23.30	503
84060	23.35	503
84240	23.40	503
84420	23.45	503
84600	23.50	503
84780	23.55	503
84960	23.60	503
85140	23.65	503
85320	23.70	503
85500	23.75	503
85680	23.80	503
85860	23.85	503
86040	23.90	503
86220	23.95	503
86400	24.00	503

APPENDIX B. SIMPLIFIED DATA of PUMPING RATE vs TIME, USED for ANALYSIS

Test #1, Simplified pumping rate data
(for data analysis)

Time sec.	Time hr	Flow rate ml/sec.	Time sec.	Time hr	Flow rate ml/sec.
0	0.00	45.13	10620	2.95	16.12
150	0.04	44.67	11220	3.12	15.93
270	0.08	41.89	11820	3.28	15.78
360	0.10	35.00	12420	3.45	15.65
450	0.13	31.62	13020	3.62	15.50
660	0.18	28.54	13620	3.78	15.33
900	0.25	27.33	14220	3.95	15.18
1140	0.32	26.29	14820	4.12	15.03
1380	0.38	25.25	15420	4.28	14.90
1620	0.45	24.58	16020	4.45	14.75
1860	0.52	24.08	16620	4.62	14.62
2100	0.58	23.58	17220	4.78	14.50
2340	0.65	22.90	17820	4.95	14.37
2640	0.73	22.33	18420	5.12	14.30
2940	0.82	21.80	19020	5.28	14.22
3240	0.90	21.23	19620	5.45	14.15
3540	0.98	20.87	20220	5.62	14.03
3840	1.07	20.50	20820	5.78	13.95
4140	1.15	20.27	21420	5.95	13.87
4440	1.23	20.00	22020	6.12	13.75
4740	1.32	19.77	22620	6.28	13.63
5040	1.40	19.23	23220	6.45	13.53
5340	1.48	19.07	23820	6.62	13.42
5640	1.57	18.72	24420	6.78	13.28
6000	1.67	18.53	25020	6.95	13.30
6300	1.75	18.40	25620	7.12	13.25
6600	1.83	18.13	26220	7.28	13.22
6900	1.92	17.97	26820	7.45	13.08
7200	2.00	17.80	27420	7.62	13.02
7500	2.08	17.55	28020	7.78	12.95
7920	2.20	17.43	28620	7.95	12.88
8220	2.28	17.30	29220	8.12	12.82
8520	2.37	17.20	29820	8.28	12.82
8820	2.45	17.13	30420	8.45	12.68
9120	2.53	16.83	31020	8.62	12.63
9420	2.62	16.70	31620	8.78	12.53
9720	2.70	16.70	32220	8.95	12.50
10020	2.78	16.35	32820	9.12	12.50
continued			34380	9.55	12.50

Test #2, Simplified pumping rate data
(for data analysis)

Time sec.	Time hr	flow rate ml/sec.	Time sec.	Time hr	flow rate ml/sec.
180	0.05	42.78	15840	4.40	11.69
300	0.08	41.25	16440	4.57	11.64
420	0.12	38.25	17040	4.73	11.52
540	0.15	24.42	17640	4.90	11.44
660	0.18	23.34	18240	5.07	11.36
840	0.23	22.17	18840	5.23	11.29
1080	0.30	21.04	19440	5.40	11.19
1320	0.37	20.12	20040	5.57	11.11
1560	0.43	19.41	20700	5.75	11.04
1800	0.50	18.83	21600	6.00	10.89
2040	0.57	18.33	22500	6.25	10.73
2280	0.63	17.91	23400	6.50	10.67
2520	0.70	17.53	24300	6.75	10.57
2820	0.78	17.19	25200	7.00	10.47
3120	0.87	16.69	26100	7.25	10.43
3420	0.95	16.42	27000	7.50	10.36
3840	1.07	16.06	27900	7.75	10.32
4440	1.23	15.62	28800	8.00	10.24
5040	1.40	15.20	29700	8.25	10.18
5640	1.57	14.82	30600	8.50	10.07
6240	1.73	14.44	31500	8.75	10.01
6840	1.90	14.21	32400	9.00	9.96
7440	2.07	13.93	33300	9.25	9.89
8040	2.23	13.70	34200	9.50	9.84
8640	2.40	13.48	35100	9.75	9.78
9240	2.57	13.18	36000	10.00	9.77
9840	2.73	12.91	36900	10.25	9.76
10440	2.90	12.84	37800	10.50	9.73
11040	3.07	12.67	38700	10.75	9.69
11640	3.23	12.54	39600	11.00	9.64
12240	3.40	12.39	40500	11.25	9.61
12840	3.57	12.24	41400	11.50	9.52
13440	3.73	12.14	42300	11.75	9.52
14040	3.90	12.04	43200	12.00	9.50
14640	4.07	11.94	44100	12.25	9.44
15240	4.23	11.77	45000	12.50	9.35

continued

continued

Time sec.	Time hr	flow rate ml/sec.
45900	12.75	9.31
46800	13.00	9.30
47700	13.25	9.26
48600	13.50	9.20
49500	13.75	9.19
51300	14.25	9.18
53100	14.75	9.11
54900	15.25	9.03
56700	15.75	8.96
58500	16.25	8.92
60300	16.75	8.87
62100	17.25	8.85
63900	17.75	8.81
65700	18.25	8.78
70380	19.55	8.62
72180	20.05	8.57
73980	20.55	8.53
75780	21.05	8.52
77580	21.55	8.51
79380	22.05	8.48
81180	22.55	8.44
86400	24.00	8.38

APPENDIX C. DATA of OBSERVED DRAWDOWN and PREDICTED DRAWDOWN vs TIME

Well #1

Test #1

Time hr	O.D.[a] cm	P.D.[b] cm
0.01	0.03	0.00
0.03	1.52	0.02
0.05	3.35	0.17
0.07	5.18	0.63
0.09	6.71	1.40
0.13	10.06	2.94
0.17	10.06	4.62
0.21	10.97	6.38
0.27	12.80	8.35
0.33	14.02	10.19
0.42	15.24	12.09
0.57	17.07	14.73
0.74	18.59	16.93
0.91	19.51	18.54
1.08	20.12	19.75
1.35	21.64	21.29
1.68	22.56	22.63
2.01	23.47	23.61
2.67	24.69	25.06
3.97	26.82	26.73
4.98	26.52	27.59
5.97	27.13	28.27
6.98	29.26	28.78
7.96	29.87	29.23
9.41	30.78	29.80

Test #2

Time hr	O.D. cm	P.D. cm
0.04	0.30	0.00
0.05	1.83	0.01
0.07	2.44	0.01
0.09	3.35	0.02
0.11	3.96	0.03
0.13	4.57	0.06
0.15	5.18	0.12
0.18	5.79	0.27
0.21	6.40	0.51
0.26	7.01	1.02
0.31	7.92	1.60
0.38	8.53	2.55
0.44	9.14	3.50
0.62	10.97	5.76
0.83	12.19	8.02
1.05	13.11	9.94
1.37	14.63	12.18
1.80	15.85	14.52
2.39	17.68	16.88
3.08	18.59	18.85
4.30	21.03	21.22
5.08	21.95	22.31
6.07	23.16	23.42
7.13	24.08	24.33
8.14	24.69	25.05
9.61	25.91	25.94
11.12	27.13	26.71
13.06	27.74	27.59
15.11	28.65	28.36
17.81	29.57	29.25
20.92	30.18	30.17
23.87	30.78	30.93

[a]O.D.: observed drawdown
[b]P.D.: predicted drawdown

Well #2

Test #1

Time hr	O.D. cm	P.D. cm
0.10	3.66	0.49
0.14	4.88	1.18
0.18	6.40	2.18
0.22	7.32	3.27
0.29	8.53	4.79
0.34	9.45	6.03
0.43	10.67	7.65
0.58	12.19	9.84
0.76	13.41	11.86
0.93	14.33	13.42
1.09	14.94	14.57
1.37	16.46	16.14
1.69	17.68	17.55
2.02	18.29	18.61
2.68	19.51	20.20
3.98	21.64	22.12
5.00	22.86	23.14
5.98	23.77	23.92
7.00	24.69	24.57
7.98	25.60	25.11
9.42	26.21	25.79

Test #2

Time hr	O.D. cm	P.D. cm
0.16	2.44	0.05
0.19	3.35	0.11
0.22	3.35	0.21
0.27	3.96	0.45
0.32	4.57	0.76
0.39	5.49	1.32
0.45	5.79	1.92
0.63	7.01	3.52
0.84	8.23	5.20
1.06	9.14	6.75
1.38	10.67	8.63
1.81	11.89	10.63
2.40	13.41	12.75
3.09	14.63	14.56
4.31	16.76	16.78
5.12	17.68	17.86
6.09	18.90	18.90
7.16	19.81	19.81
8.18	20.42	20.52
9.64	21.34	21.39
11.14	22.56	22.15
13.09	23.16	23.02
15.14	24.08	23.79
17.83	24.99	24.67
20.94	25.60	25.59
23.88	26.52	26.34

Well #3

Test #1

Time hr	O.D. cm	P.D. cm
0.23	0.91	0.22
0.29	1.83	0.47
0.35	1.83	0.78
0.44	2.44	1.29
0.59	3.35	2.22
0.76	3.96	3.27
0.93	4.88	4.23
1.09	5.18	5.03
1.35	6.40	6.15
1.70	7.62	7.40
2.02	8.23	8.37
2.68	9.75	9.91
3.99	11.58	12.00
5.00	12.80	13.17
5.99	14.02	14.08
7.00	14.94	14.89
7.98	15.85	15.55
9.43	16.76	16.41

Test #2

Time hr	O.D. cm	P.D. cm
0.23	0.00	0.03
0.28	0.61	0.05
0.32	0.61	0.08
0.39	0.91	0.15
0.46	1.22	0.26
0.64	1.83	0.70
0.84	2.13	1.30
1.06	2.74	2.00
1.38	3.96	2.95
1.81	4.57	4.10
2.40	5.79	5.47
3.09	7.01	6.74
4.31	8.23	8.42
5.15	9.14	9.30
6.11	9.75	10.15
7.17	10.67	10.92
8.18	11.28	11.54
9.66	12.80	12.33
11.16	13.11	13.00
13.11	13.72	13.78
15.16	14.63	14.48
17.84	15.54	15.30
20.94	16.15	16.15
23.89	16.76	16.86

Well #4

Test #1

Time hr	O.D. cm	P.D. cm
0.35	0.61	0.23
0.44	0.91	0.41
0.59	1.83	0.82
0.76	1.83	1.39
0.94	2.44	1.99
1.10	2.13	2.52
1.37	3.96	3.41
1.70	4.57	4.34
2.03	5.18	5.16
2.69	6.40	6.53
3.99	8.23	8.52
5.01	9.45	9.69
5.99	10.36	10.62
7.01	11.58	11.45
7.99	12.50	12.14
9.43	13.11	13.05

Test #2

Time hr	O.D. cm	P.D. cm
0.32	0.30	0.04
0.39	0.00	0.07
0.46	0.61	0.10
0.64	0.61	0.27
0.84	0.91	0.56
1.07	1.52	0.94
1.39	2.13	1.53
1.81	2.74	2.28
2.40	3.66	3.23
3.10	4.27	4.17
4.32	5.18	5.49
5.16	6.10	6.20
6.12	6.71	6.90
7.18	7.32	7.55
8.19	7.92	8.09
9.67	9.14	8.77
11.17	9.45	9.36
13.12	10.06	10.05
15.17	10.97	10.68
17.84	11.28	11.42
20.96	11.89	12.19
23.89	13.11	12.85

Well #6

Test #1

Time hr	O.D. cm	P.D. cm
0.02	2.44	0.13
0.04	9.45	0.42
0.06	13.11	1.58
0.08	15.85	3.33
0.11	17.68	5.64
0.14	19.20	8.46
0.18	20.42	11.02
0.23	21.34	13.24
0.29	22.56	15.54
0.37	23.47	17.61
0.46	24.38	19.65
0.62	25.60	22.18
0.78	26.21	24.03
0.95	27.13	25.53
1.12	27.43	26.59
1.39	28.04	27.90
1.73	28.96	29.02
2.05	29.26	29.81
2.72	30.18	30.96
4.02	31.70	32.21
5.06	32.31	32.84
6.02	33.22	33.35
7.04	33.83	33.67
8.02	34.75	34.02
9.47	35.05	34.45

Test #2

Time hr	O.D. cm	P.D. cm
0.04	6.71	0.01
0.06	10.06	0.01
0.08	11.28	0.06
0.10	12.19	0.19
0.12	12.80	0.43
0.14	13.72	0.73
0.16	14.33	1.26
0.19	15.24	2.10
0.23	15.85	3.16
0.28	16.76	4.74
0.34	17.37	6.40
0.40	17.98	8.11
0.49	18.90	9.97
0.66	18.90	13.03
0.86	21.03	15.61
1.09	22.25	18.00
1.41	23.47	20.53
1.84	24.99	23.05
2.43	25.91	25.44
3.12	27.43	27.37
4.35	29.26	29.60
5.21	30.48	30.70
6.16	31.39	31.65
7.24	32.31	32.43
8.26	32.92	33.08
9.73	33.53	33.83
11.23	34.75	34.54
13.18	35.66	35.31
15.26	35.97	36.03
17.92	37.19	36.81
21.01	37.49	37.63
23.91	38.40	38.31

Well #7

Test #1

Time hr	O.D. cm	P.D. cm
0.11	5.18	0.57
0.15	6.40	1.26
0.19	7.32	2.24
0.23	7.92	3.36
0.30	9.14	4.76
0.37	9.75	6.19
0.47	11.28	7.74
0.62	12.50	9.83
0.78	13.41	11.48
0.96	14.02	12.96
1.13	14.63	14.08
1.39	15.85	15.49
1.74	17.07	16.86
2.06	17.37	17.84
2.73	18.59	19.34
4.03	20.42	21.17
5.06	21.64	22.16
6.03	22.86	22.91
7.04	23.77	23.53
8.02	24.69	24.06
9.47	25.30	24.73

Test #2

Time hr	O.D. cm	P.D. cm
0.17	4.27	0.11
0.20	4.88	0.23
0.23	5.49	0.43
0.28	6.10	0.81
0.34	6.71	1.38
0.41	7.32	2.15
0.49	7.92	3.09
0.67	9.14	4.93
0.86	10.06	6.61
1.09	10.97	8.34
1.42	12.19	10.29
1.84	13.72	12.33
2.43	14.94	14.41
3.13	16.15	16.21
4.35	18.29	18.37
5.21	19.20	19.48
6.17	20.42	20.46
7.24	21.03	21.32
8.27	21.64	22.01
9.74	22.56	22.84
11.24	23.77	23.58
13.18	24.69	24.41
15.27	25.30	25.16
17.93	26.21	26.01
21.02	26.82	26.89
23.91	27.74	27.60

Well #8

Test #1

Time hr	O.D. cm	P.D. cm
0.24	3.05	0.79
0.30	3.96	1.40
0.37	4.27	2.12
0.47	5.18	3.05
0.63	5.79	4.45
0.78	7.01	5.68
0.96	7.62	6.87
1.13	8.23	7.82
1.40	9.14	9.06
1.74	10.36	10.35
2.06	11.28	11.32
2.73	12.50	12.85
4.03	14.33	14.82
5.06	15.54	15.92
6.03	16.46	16.76
7.04	17.68	17.49
8.02	18.59	18.10
9.47	19.20	18.89

Test #2

Time hr	O.D. cm	P.D. cm
0.24	2.13	0.09
0.29	2.44	0.18
0.34	3.05	0.36
0.41	3.35	0.65
0.49	3.96	1.06
0.68	4.57	2.10
0.86	5.49	3.09
1.10	6.10	4.26
1.42	7.01	5.68
1.85	8.23	7.23
2.43	9.45	8.92
3.13	10.36	10.46
4.35	12.19	12.38
5.22	13.41	13.40
6.17	14.02	14.30
7.26	14.94	15.14
8.28	15.54	15.80
9.76	16.46	16.61
11.26	17.37	17.32
13.19	18.29	18.12
15.28	19.20	18.85
17.93	19.81	19.68
21.02	20.42	20.55
23.91	21.34	21.26

Well #9

Test #1

Time hr	O.D. cm	P.D. cm
0.38	0.91	0.42
0.47	1.52	0.72
0.63	1.83	1.32
0.79	2.74	1.94
0.97	3.05	2.63
1.13	3.66	3.23
1.40	4.27	4.11
1.74	5.18	5.08
2.07	5.79	5.87
2.73	7.01	7.18
4.04	8.53	9.03
5.07	9.75	10.12
6.03	10.67	10.95
7.05	11.58	11.71
8.03	12.80	12.35
9.48	13.72	13.19

Test #2

Time hr	O.D. cm	P.D. cm
0.35	0.91	0.08
0.42	0.91	0.15
0.50	1.22	0.26
0.69	1.52	0.63
0.87	2.13	1.06
1.10	2.74	1.63
1.42	3.05	2.40
1.85	3.96	3.32
2.43	4.57	4.39
3.13	5.49	5.43
4.35	6.71	6.81
5.22	7.32	7.57
6.18	8.23	8.26
7.27	8.84	8.93
8.28	9.45	9.45
9.77	10.36	10.12
11.27	10.67	10.70
13.21	11.28	11.37
15.28	12.19	11.99
17.94	12.80	12.71
21.03	13.41	13.46
23.92	14.02	14.10

Well #11

Test #1

Time hr	O.D. cm	P.D. cm
0.02	0.61	0.10
0.04	3.35	0.13
0.06	5.49	0.55
0.08	7.92	1.41
0.11	10.06	2.85
0.15	11.58	4.64
0.19	13.11	6.55
0.24	14.02	8.46
0.31	15.24	10.35
0.39	16.46	12.16
0.48	17.37	13.97
0.64	18.59	16.25
0.79	19.20	17.89
0.97	20.12	19.34
1.15	20.73	20.41
1.41	21.95	21.69
1.75	22.86	22.88
2.08	23.47	23.75
2.75	24.69	24.99
4.05	25.91	26.44
5.08	27.13	27.20
6.05	27.74	27.81
7.06	28.35	28.25
8.04	28.96	28.66
9.49	29.57	29.20

Test #2

Time hr	O.D. cm	P.D. cm
0.05	2.44	0.00
0.06	4.88	0.00
0.08	6.10	0.01
0.10	7.62	0.18
0.12	8.84	0.37
0.14	9.45	0.62
0.17	10.36	1.11
0.20	10.97	1.75
0.24	11.58	2.76
0.29	12.19	3.90
0.35	12.80	5.25
0.42	13.11	6.57
0.51	14.02	7.97
0.70	15.24	10.46
0.87	16.15	12.17
1.11	16.76	14.00
1.43	17.68	15.93
1.86	18.90	17.84
2.44	20.12	19.63
3.14	20.73	21.10
4.36	22.56	22.82
5.25	23.77	23.70
6.19	24.08	24.42
7.29	24.99	25.05
8.32	25.60	25.57
9.80	26.21	26.18
11.29	26.82	26.75
13.23	27.74	27.39
15.33	28.04	27.99
17.96	28.65	28.65
21.06	29.26	29.36
23.92	29.87	29.95

Well #12

Test #1

Time hr	O.D. cm	P.D. cm
0.12	1.22	0.09
0.15	1.83	0.23
0.20	2.44	0.49
0.25	2.74	0.92
0.31	3.66	1.51
0.39	4.27	2.23
0.49	4.57	3.09
0.64	5.49	4.35
0.80	6.10	5.38
0.98	7.01	6.42
1.16	7.32	7.29
1.41	8.53	8.30
1.76	9.75	9.41
2.09	10.06	10.25
2.76	11.28	11.55
4.05	12.80	13.23
5.09	14.02	14.19
6.06	14.94	14.93
7.07	15.54	15.58
8.04	16.46	16.12
9.50	17.07	16.84

Test #2

Time hr	O.D. cm	P.D. cm
0.17	1.83	0.04
0.20	2.13	0.06
0.25	2.13	0.13
0.29	2.44	0.26
0.35	2.74	0.48
0.42	3.05	0.79
0.51	3.35	1.20
0.70	4.27	2.15
0.88	4.57	2.94
1.11	5.49	3.89
1.44	6.10	5.00
1.87	6.71	6.20
2.45	7.62	7.45
3.15	8.53	8.58
4.37	9.75	10.00
5.26	10.67	10.76
6.19	11.28	11.41
7.31	12.19	12.05
8.33	12.50	12.53
9.81	13.41	13.14
11.29	13.72	13.68
13.24	14.33	14.30
15.33	14.94	14.89
17.96	15.54	15.55
21.07	16.15	16.26
23.93	16.76	16.84

Well #13

Test #1

Time hr	O.D. cm	P.D. cm
0.25	1.22	0.27
0.32	1.52	0.51
0.39	1.83	0.85
0.49	2.44	1.31
0.65	2.74	2.09
0.80	3.35	2.78
0.98	3.66	3.53
1.16	4.27	4.21
1.41	5.18	5.01
1.76	5.79	5.94
2.09	6.71	6.68
2.76	7.92	7.85
4.06	9.14	9.44
5.09	10.36	10.38
6.06	10.97	11.12
7.07	11.89	11.77
8.05	12.50	12.33
9.50	13.11	13.07

Test #2

Time hr	O.D. cm	P.D. cm
0.25	0.91	0.05
0.30	1.22	0.08
0.36	1.52	0.15
0.43	1.52	0.27
0.51	1.52	0.46
0.71	2.13	0.96
0.88	2.74	1.44
1.11	3.35	2.07
1.44	3.96	2.86
1.87	4.27	3.77
2.45	4.88	4.76
3.15	5.79	5.71
4.37	6.71	6.93
5.26	7.32	7.61
6.21	8.23	8.22
7.32	8.84	8.80
8.33	9.45	9.26
9.82	10.06	9.84
11.32	10.36	10.34
13.26	10.97	10.94
15.34	11.58	11.50
17.97	11.89	12.13
21.07	12.80	12.82
23.93	13.41	13.39

Well #14

Test #1

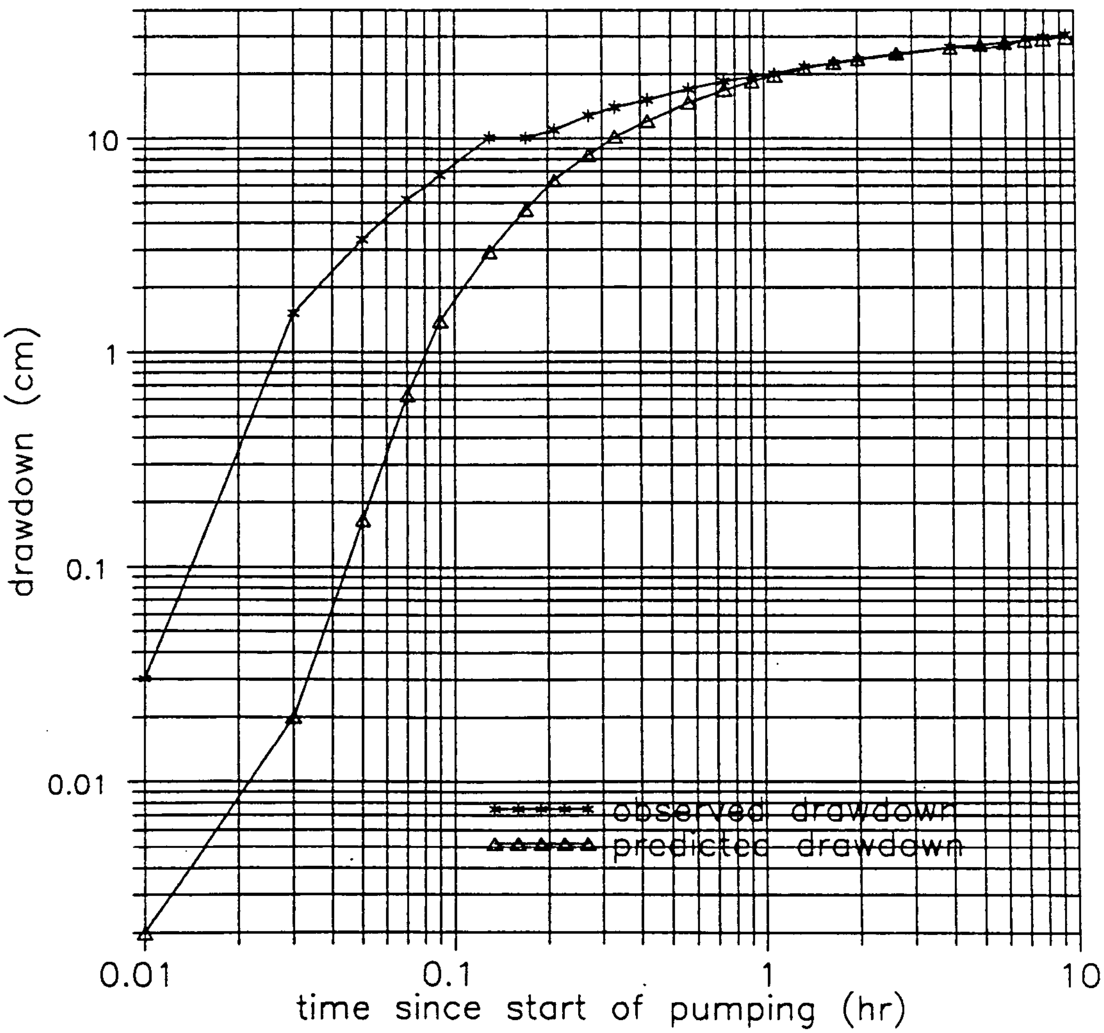
Time hr	O.D. cm	P.D. cm
0.40	0.61	0.37
0.49	0.91	0.61
0.65	1.22	1.04
0.80	1.52	1.47
0.98	2.13	1.96
1.17	2.44	2.43
1.42	3.05	3.01
1.76	3.96	3.71
2.10	4.27	4.28
2.76	5.18	5.23
4.06	6.40	6.59
5.09	7.01	7.42
6.07	7.92	8.08
7.08	8.84	8.68
8.05	9.45	9.21
9.51	10.06	9.92

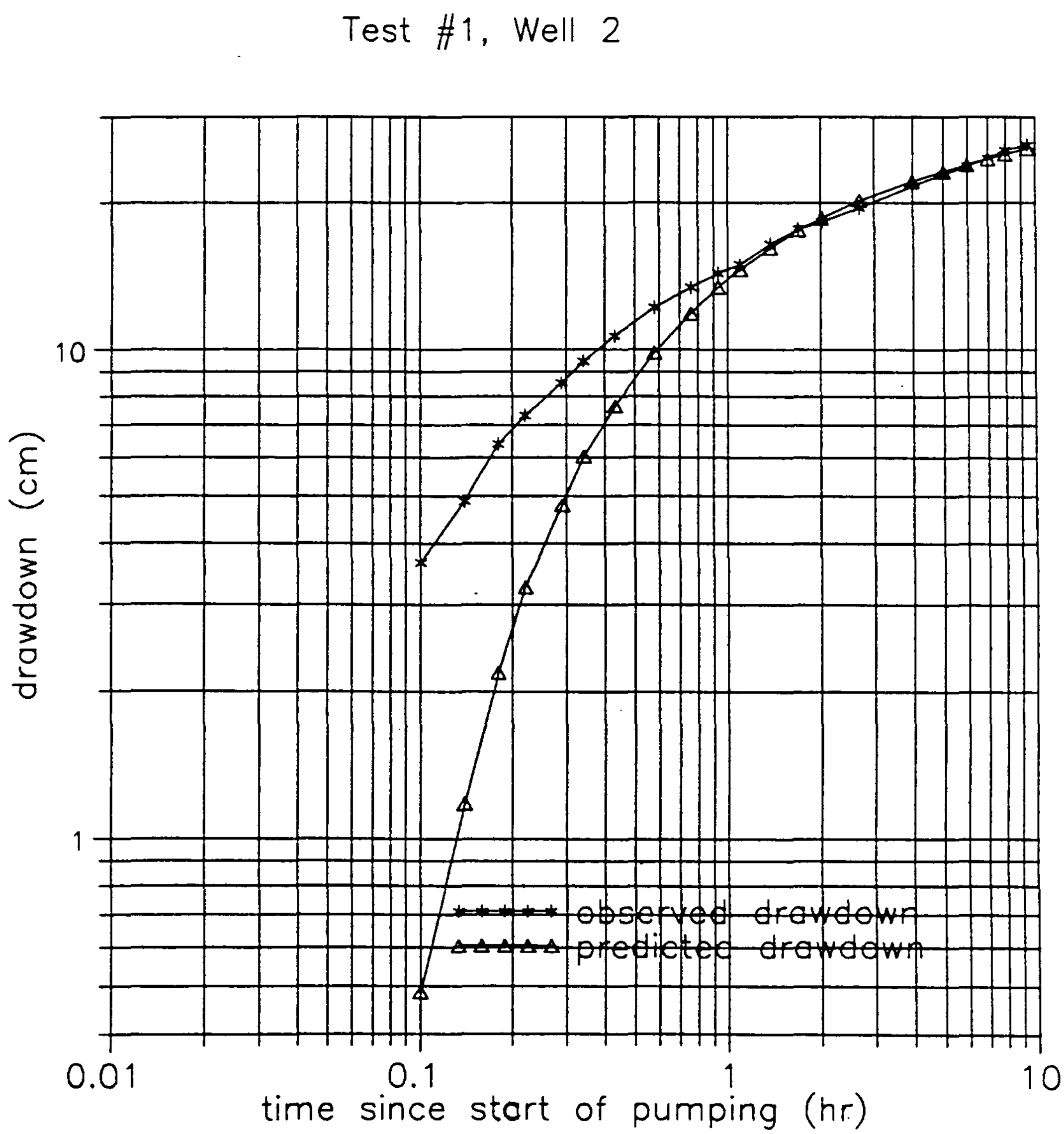
Test #2

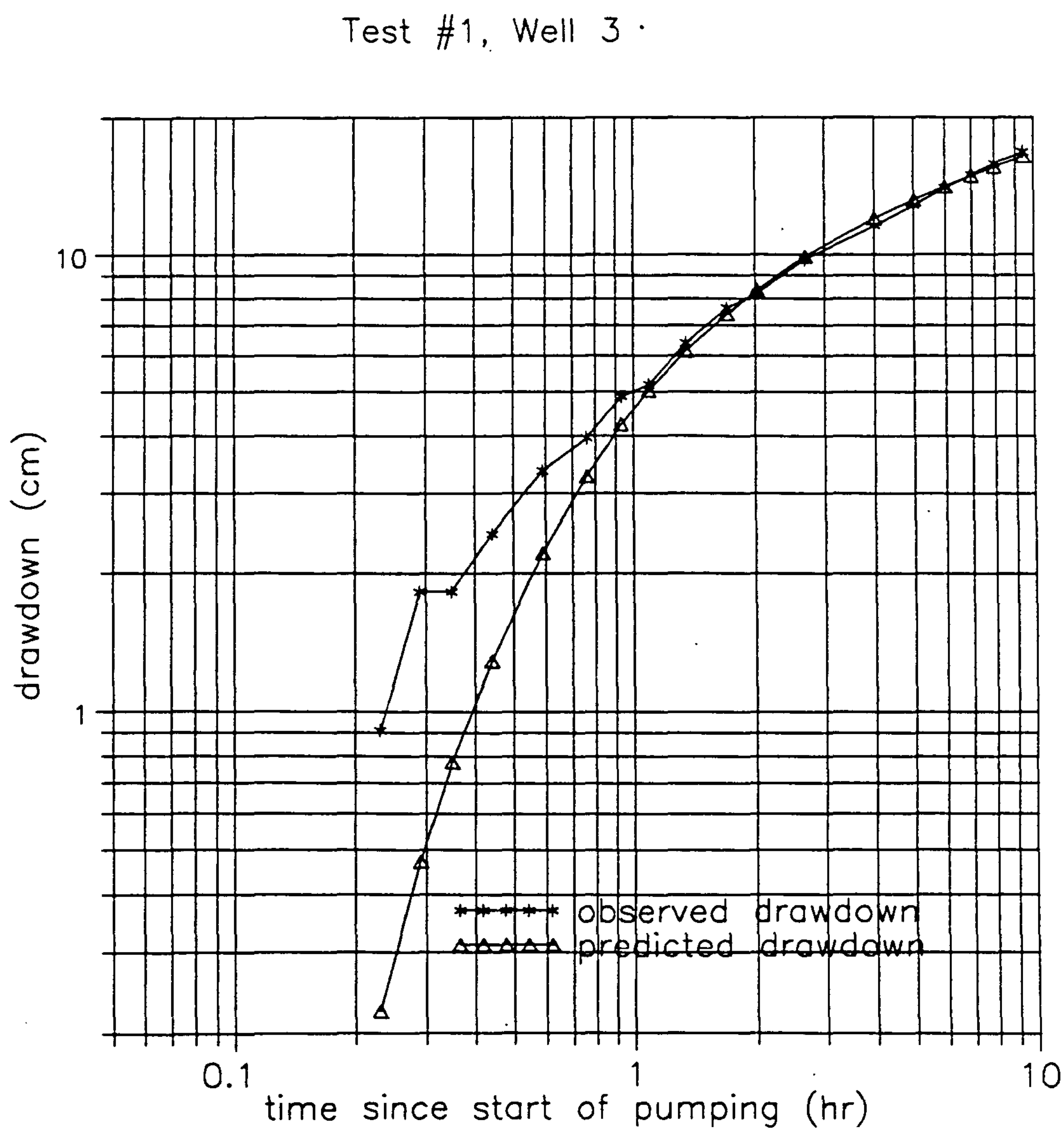
Time hr	O.D. cm	P.D. cm
0.36	0.91	0.08
0.43	0.91	0.14
0.52	0.91	0.23
0.71	1.22	0.50
0.88	1.52	0.78
1.12	1.83	1.18
1.44	2.13	1.69
1.87	2.44	2.30
2.45	3.05	3.00
3.15	3.66	3.69
4.38	4.57	4.61
5.28	5.18	5.13
6.21	5.49	5.60
7.32	6.10	6.07
8.34	6.40	6.44
9.83	7.01	6.91
11.32	7.32	7.34
13.27	7.92	7.84
15.34	8.23	8.32
17.98	8.84	8.88
21.08	9.45	9.49
23.93	10.06	10.00

APPENDIX D. CURVE FITTING DIAGRAMS in LOG-LOG SCALE

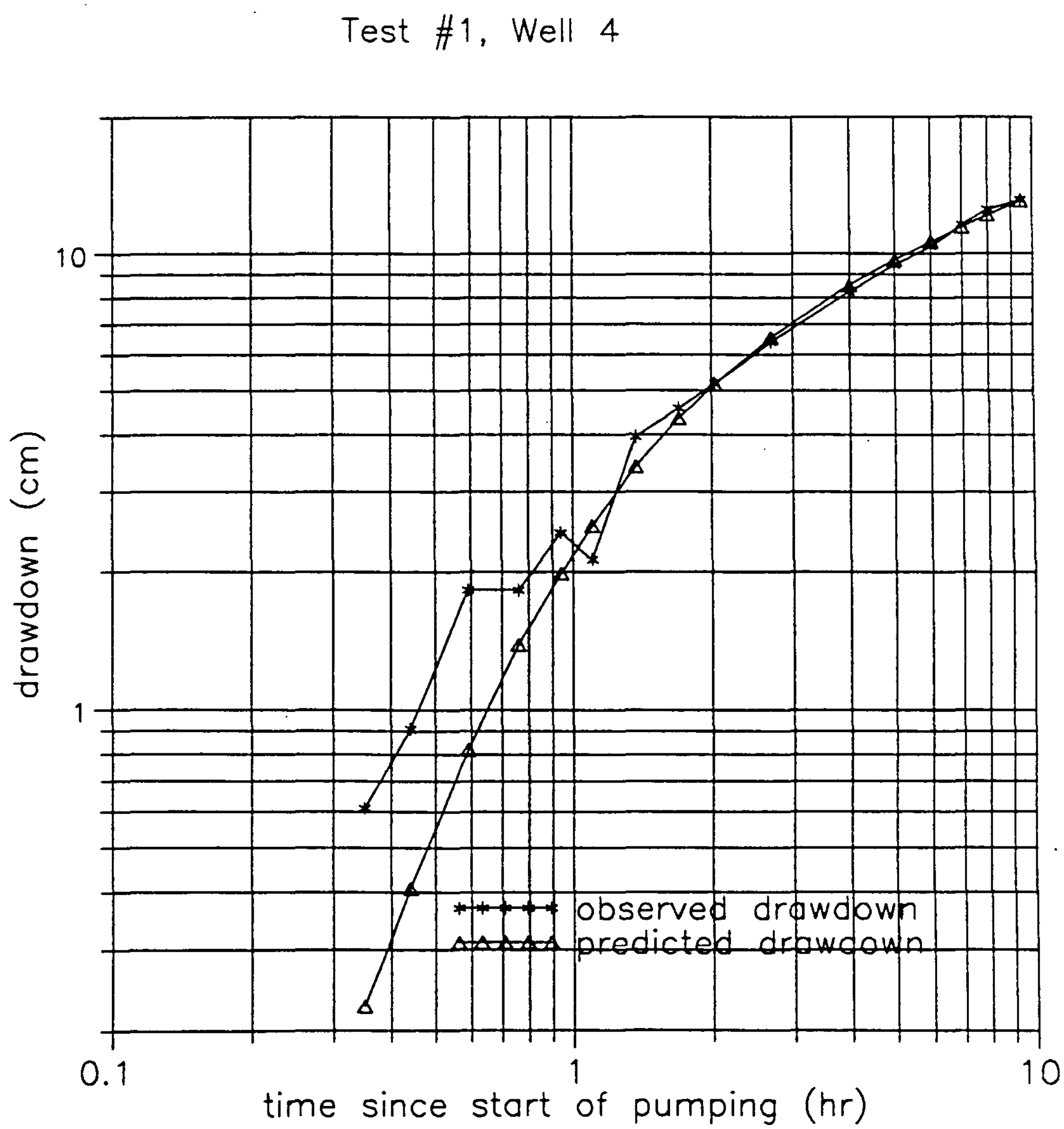
Test #1, Well 1


10
1
0.1
0.01
drawdown (cm)
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

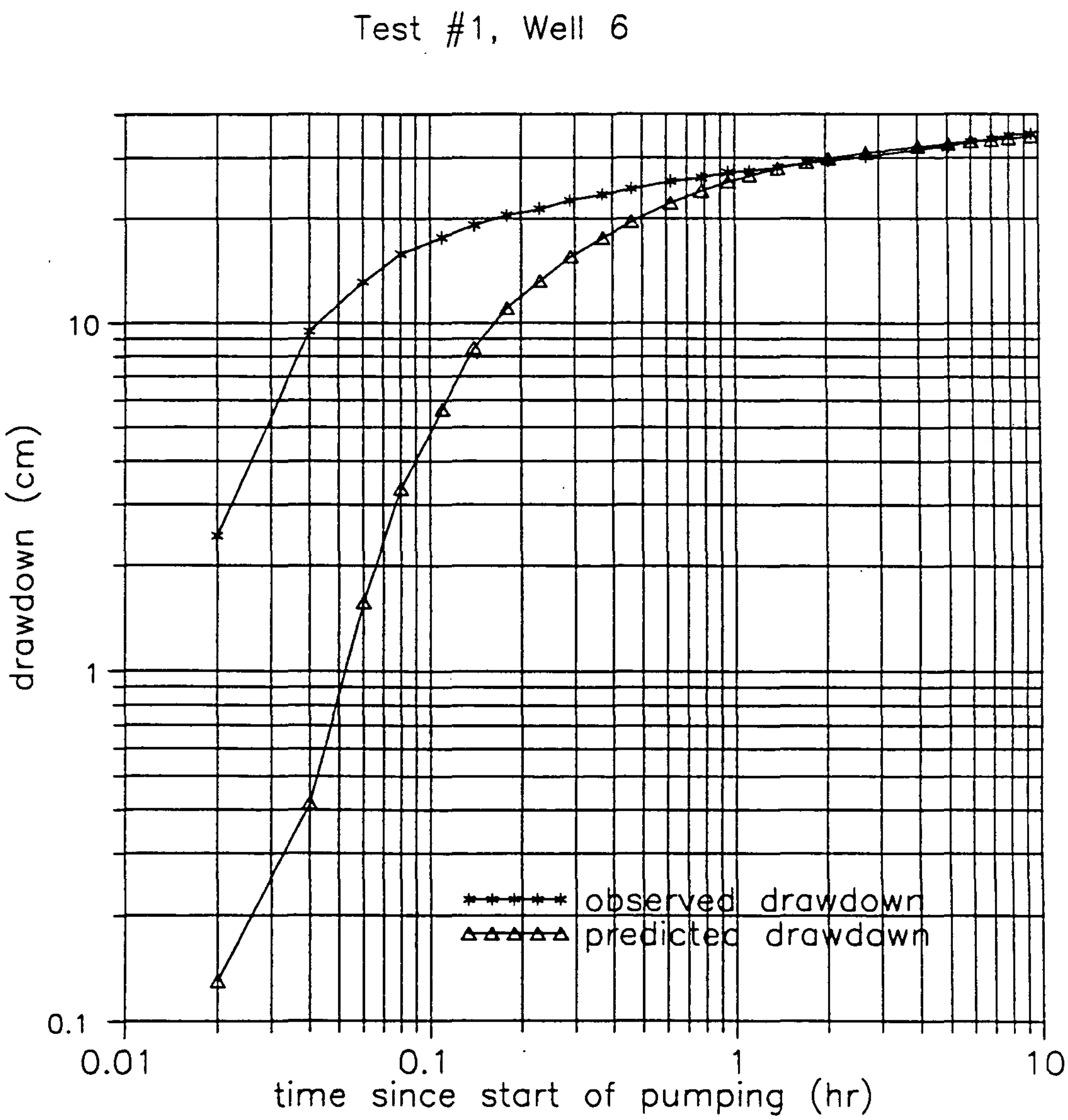

Test #1, Well 2
drawdown (cm)
10
1
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

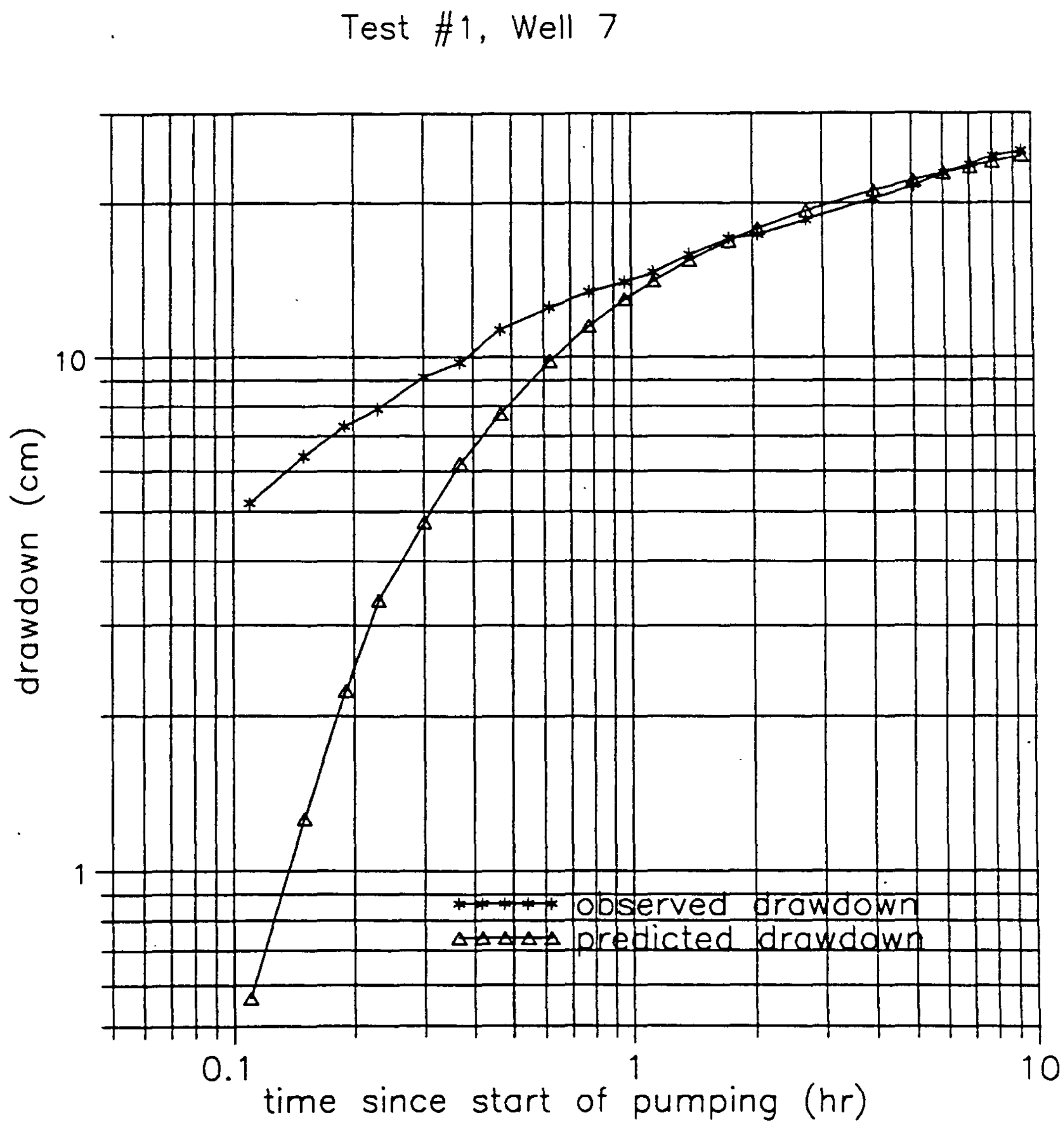


Test #1, Well 3
drawdown (cm)
10
1
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

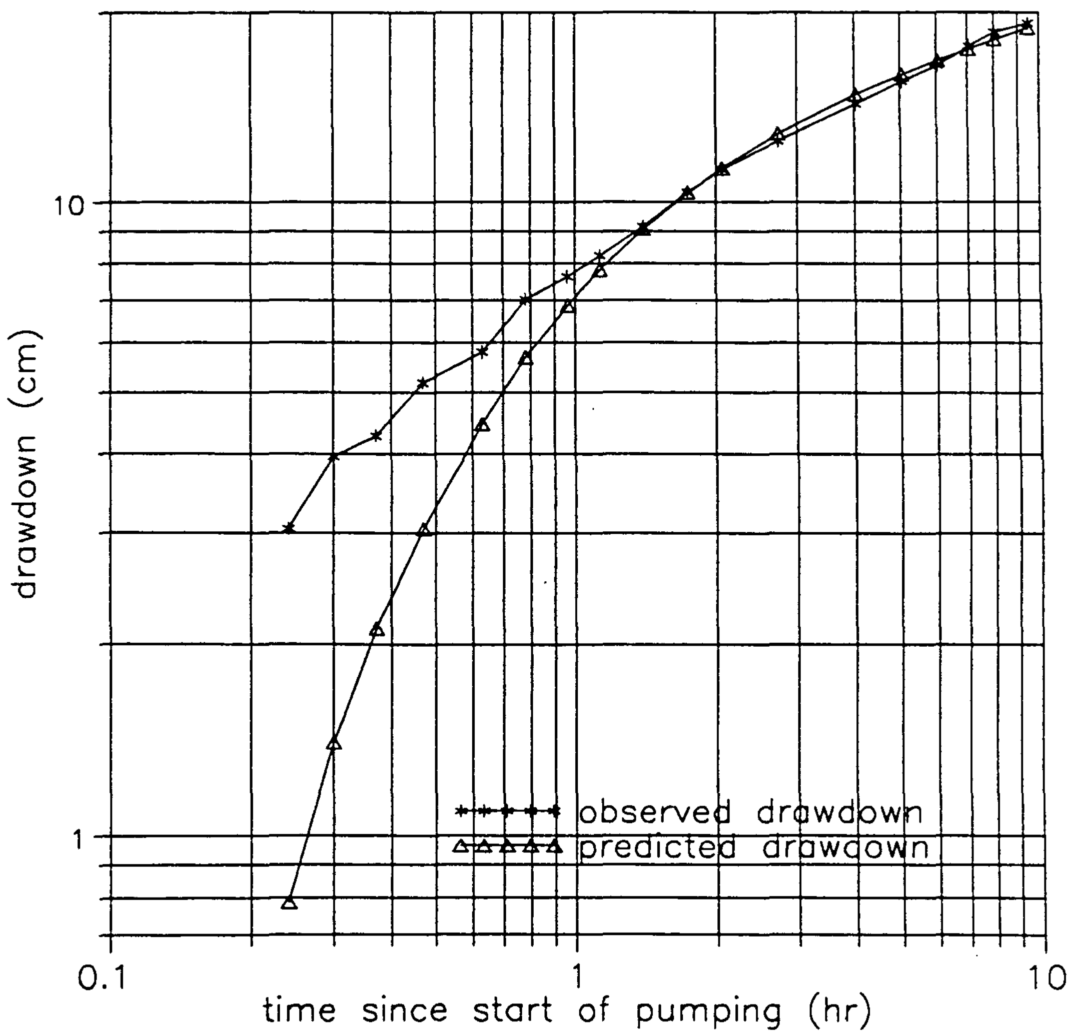


Test #1, Well 4
10
1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

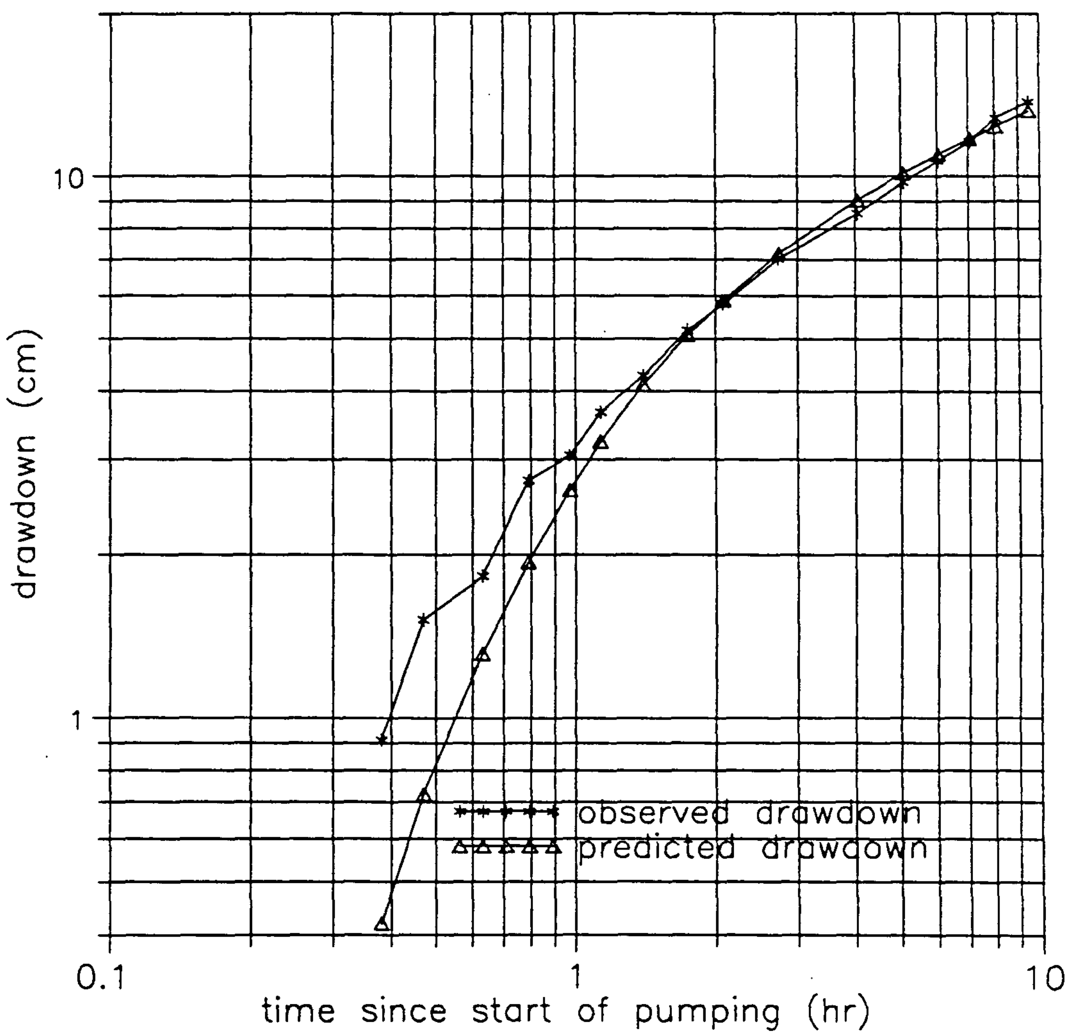

Test #1, Well 6
drawdown (cm)
10
1
0.1
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

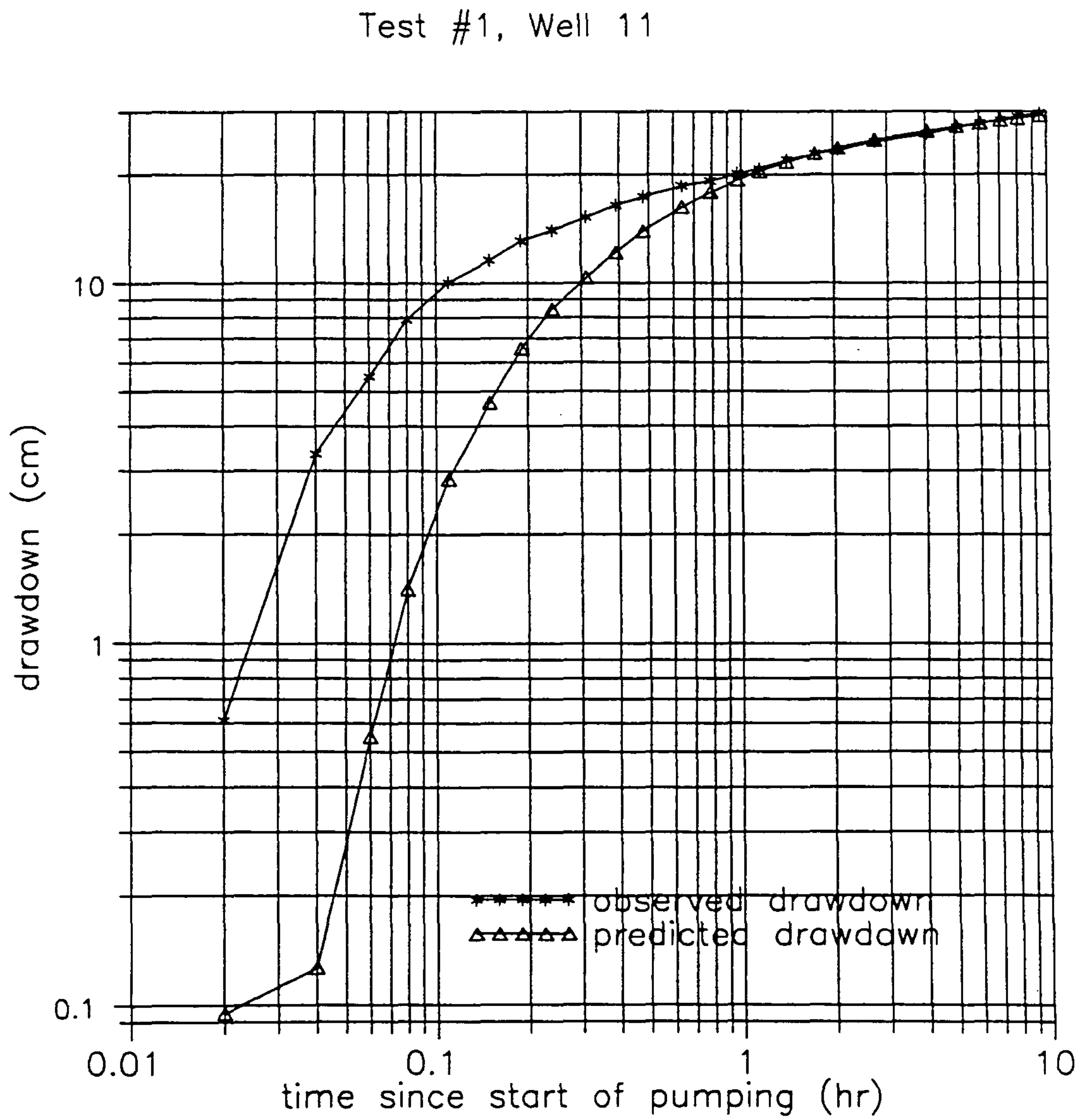

Test #1, Well 7
10
1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

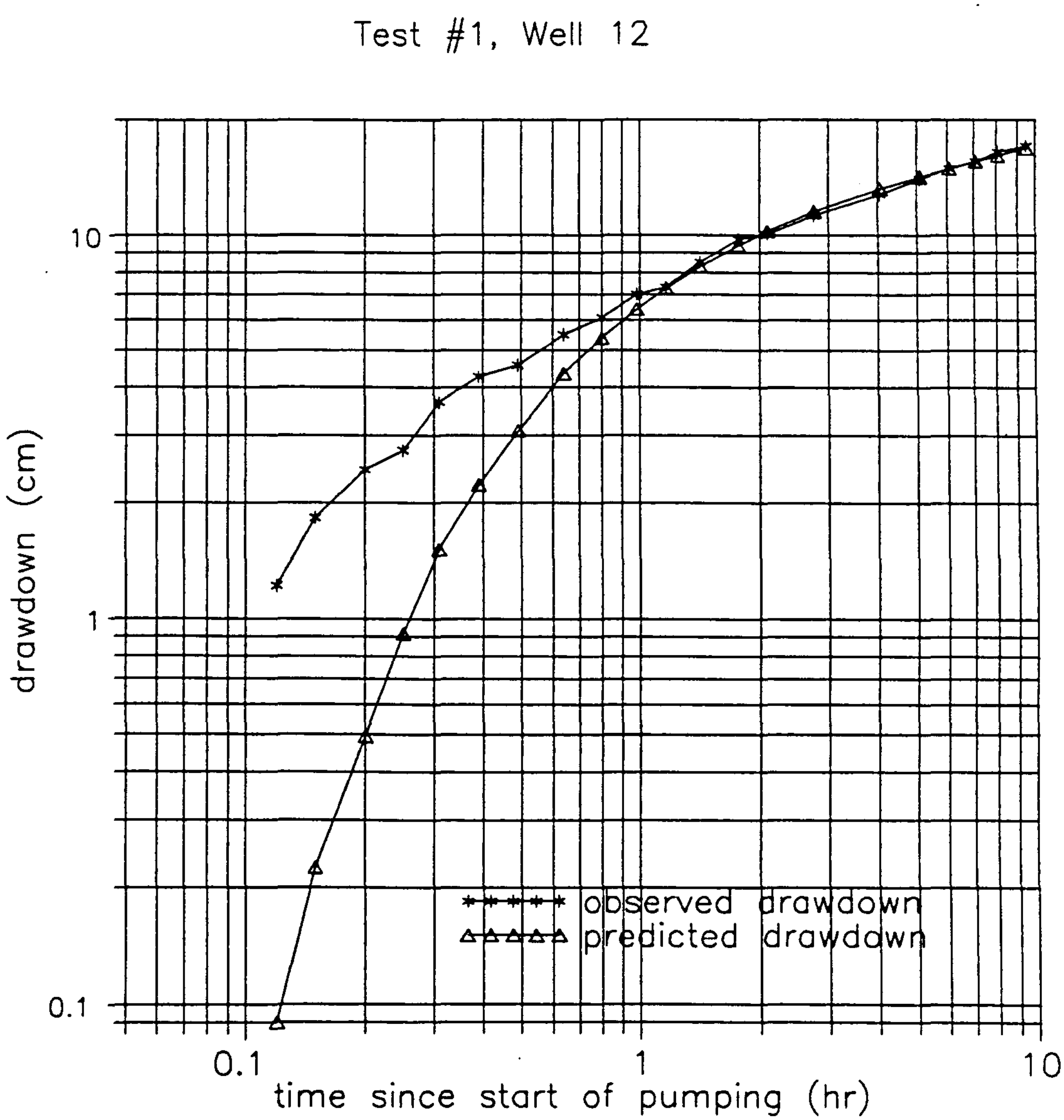
Test #1, Well 8

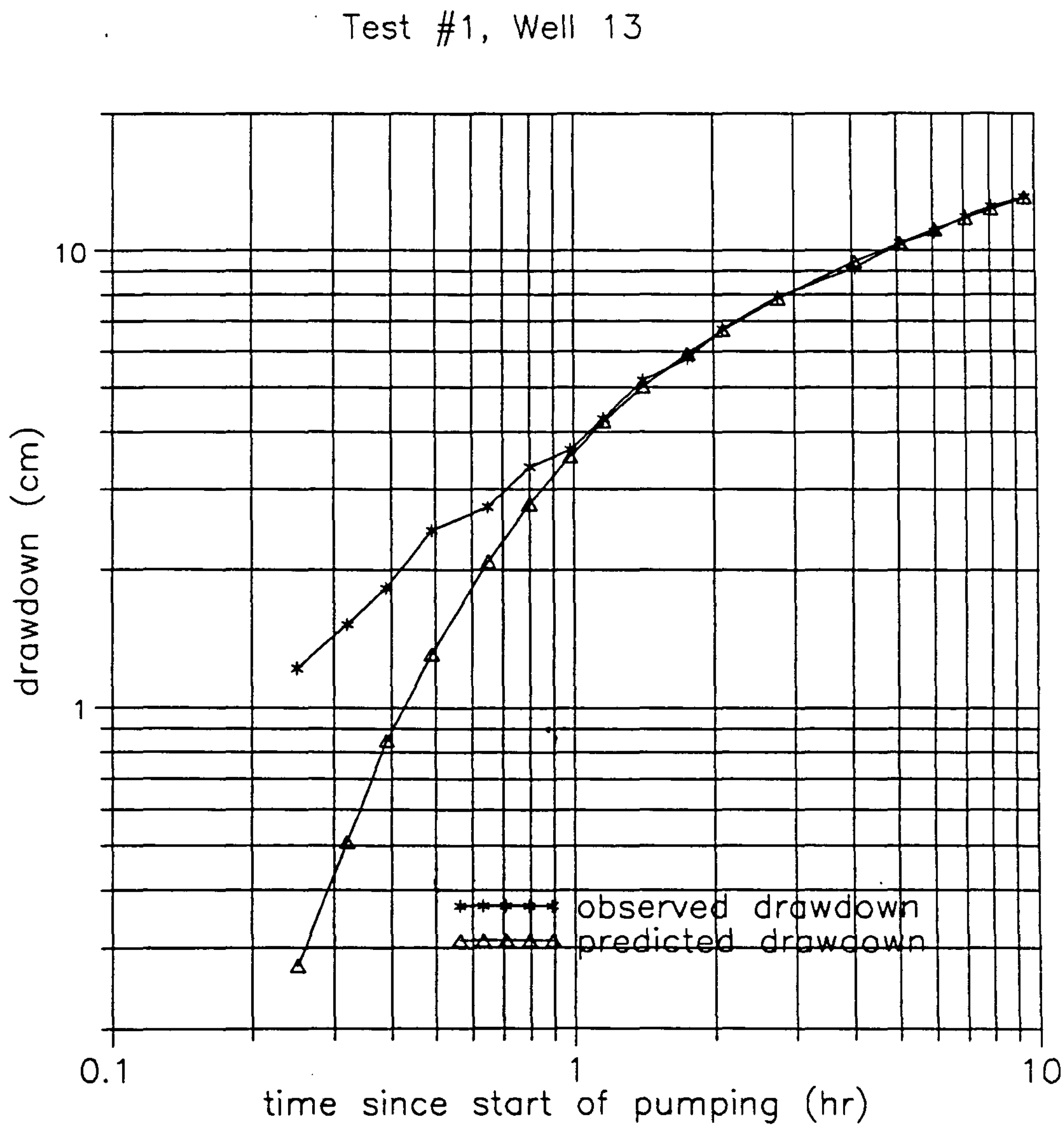

10
1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

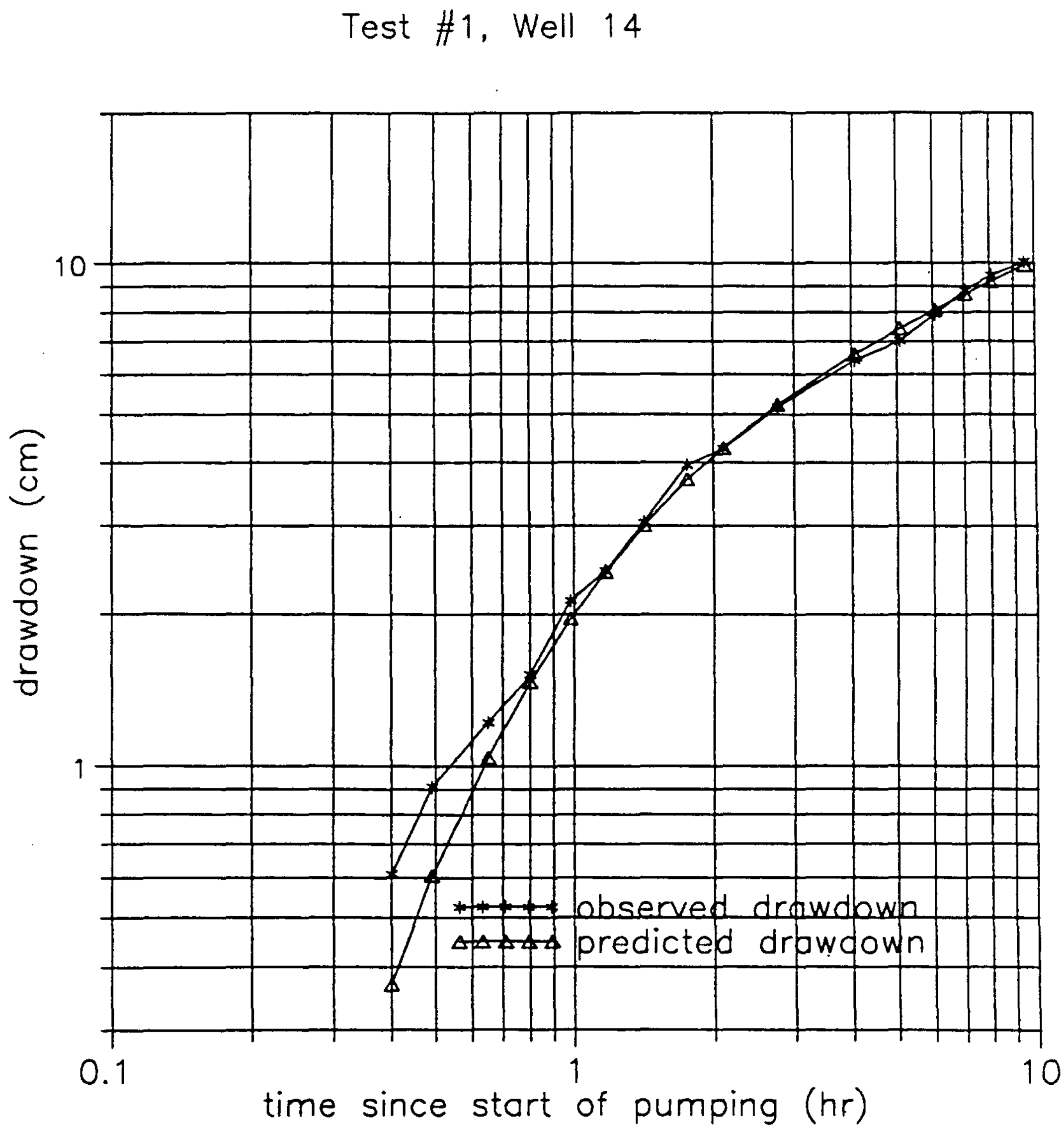
Test #1, Well 9

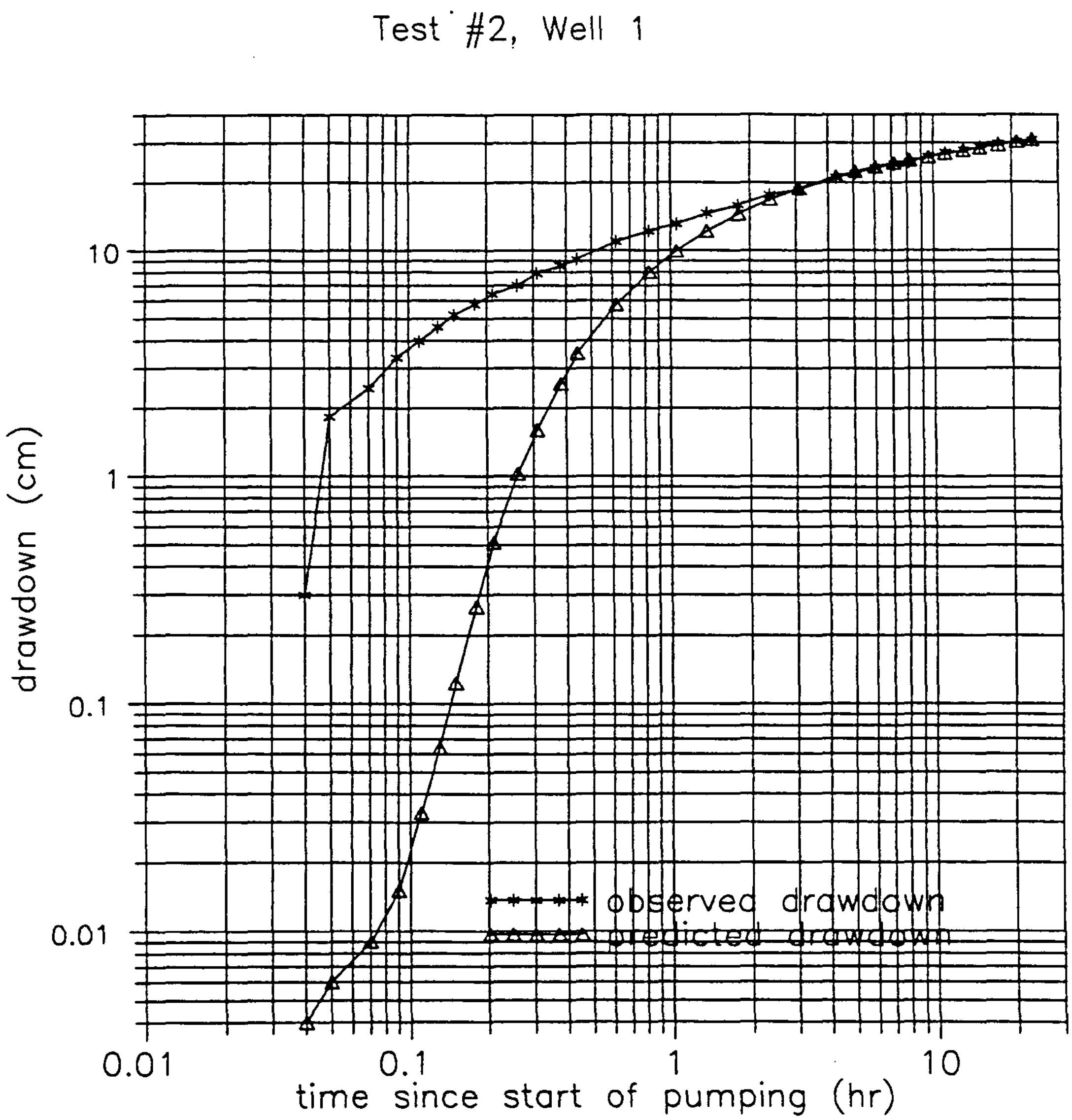

10
1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown


Test #1, Well 11
drawdown (cm)
10
1
0.1
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

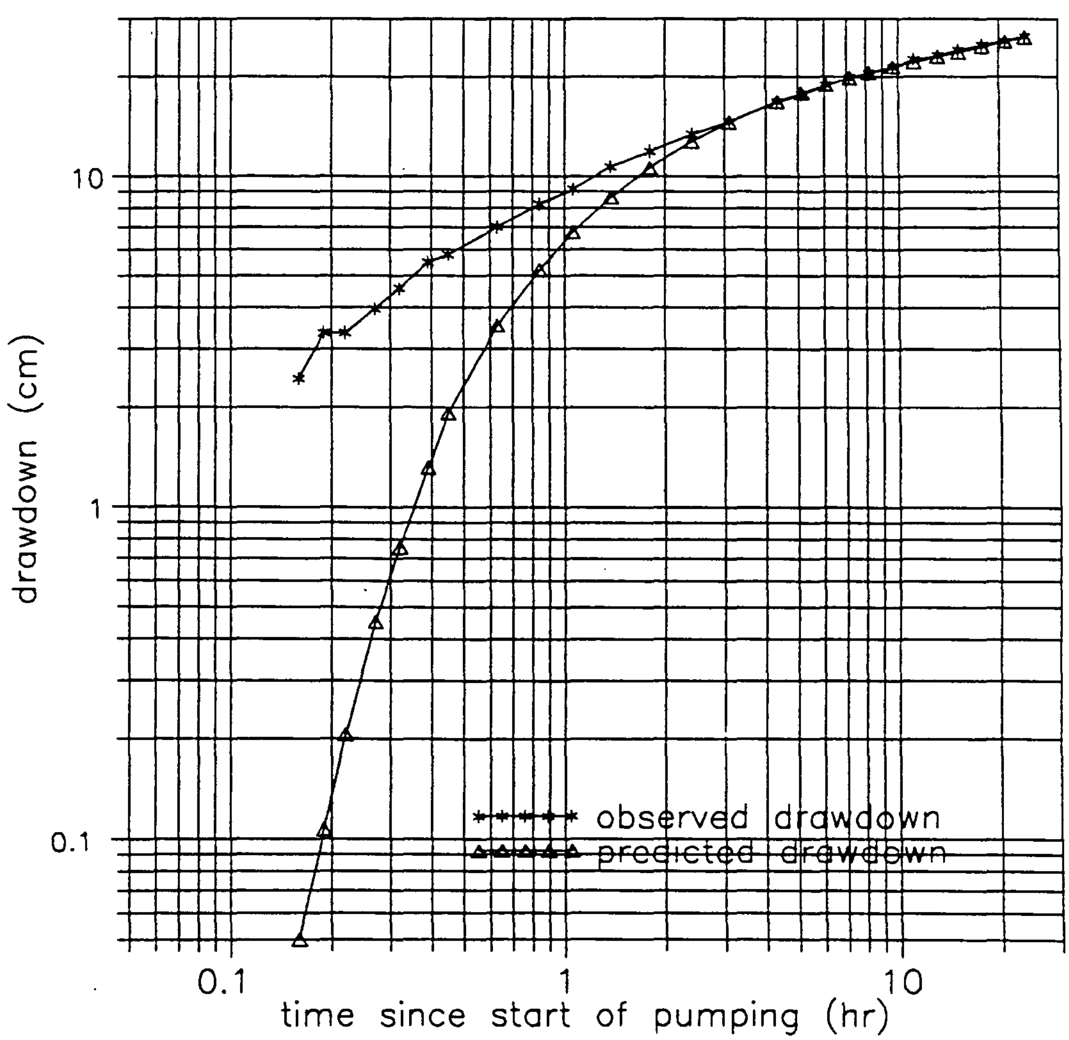

Test #1, Well 12
10
1
0.1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

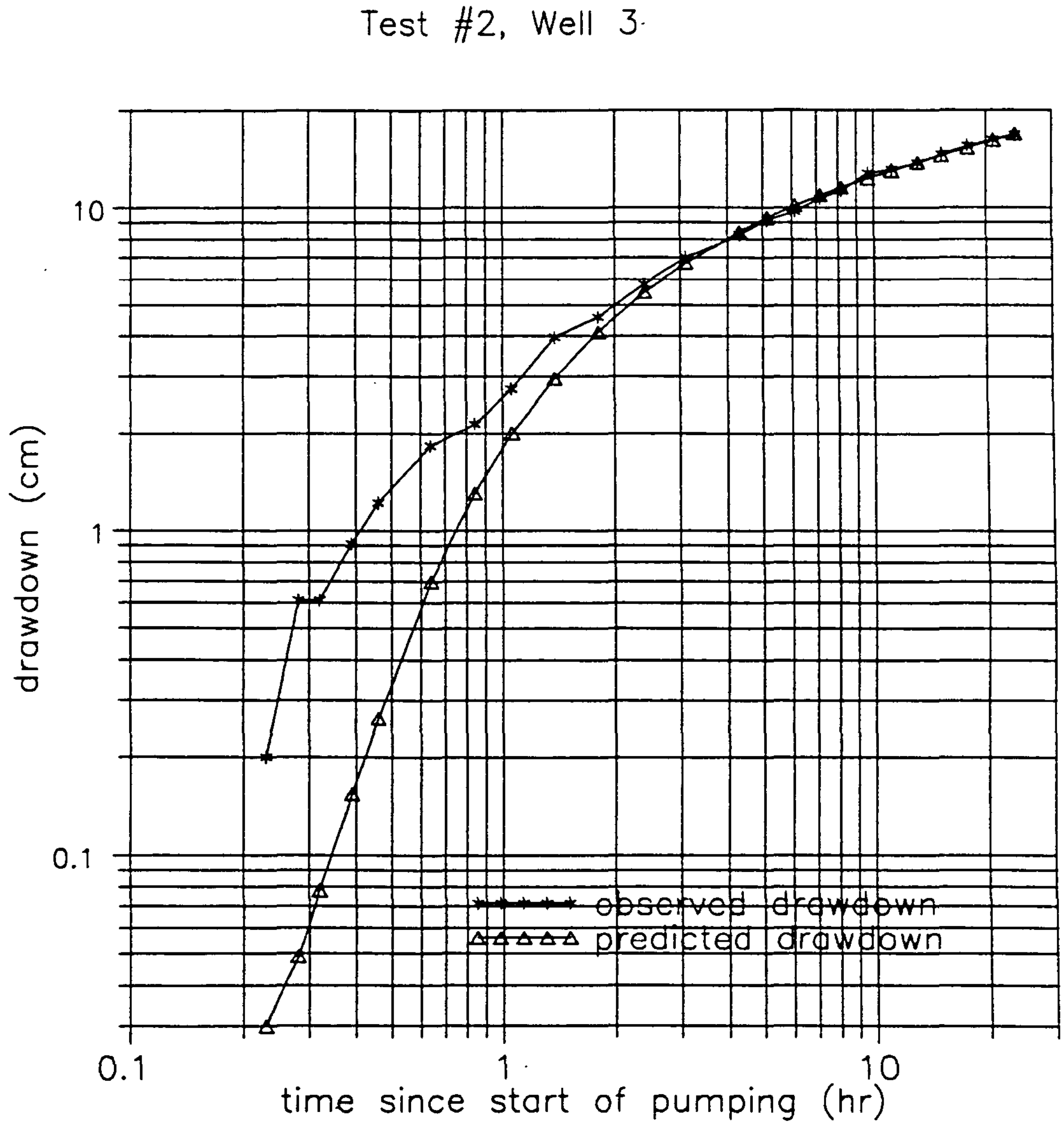

Test #1, Well 13
10
1
0.1
1
10
drawdown (cm)
time since start of pumping (hr)
observed drawdown
predicted drawdown


Test #1, Well 14
10
1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown


Test #2, Well 1
drawdown (cm)
10
1
0.1
0.01
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

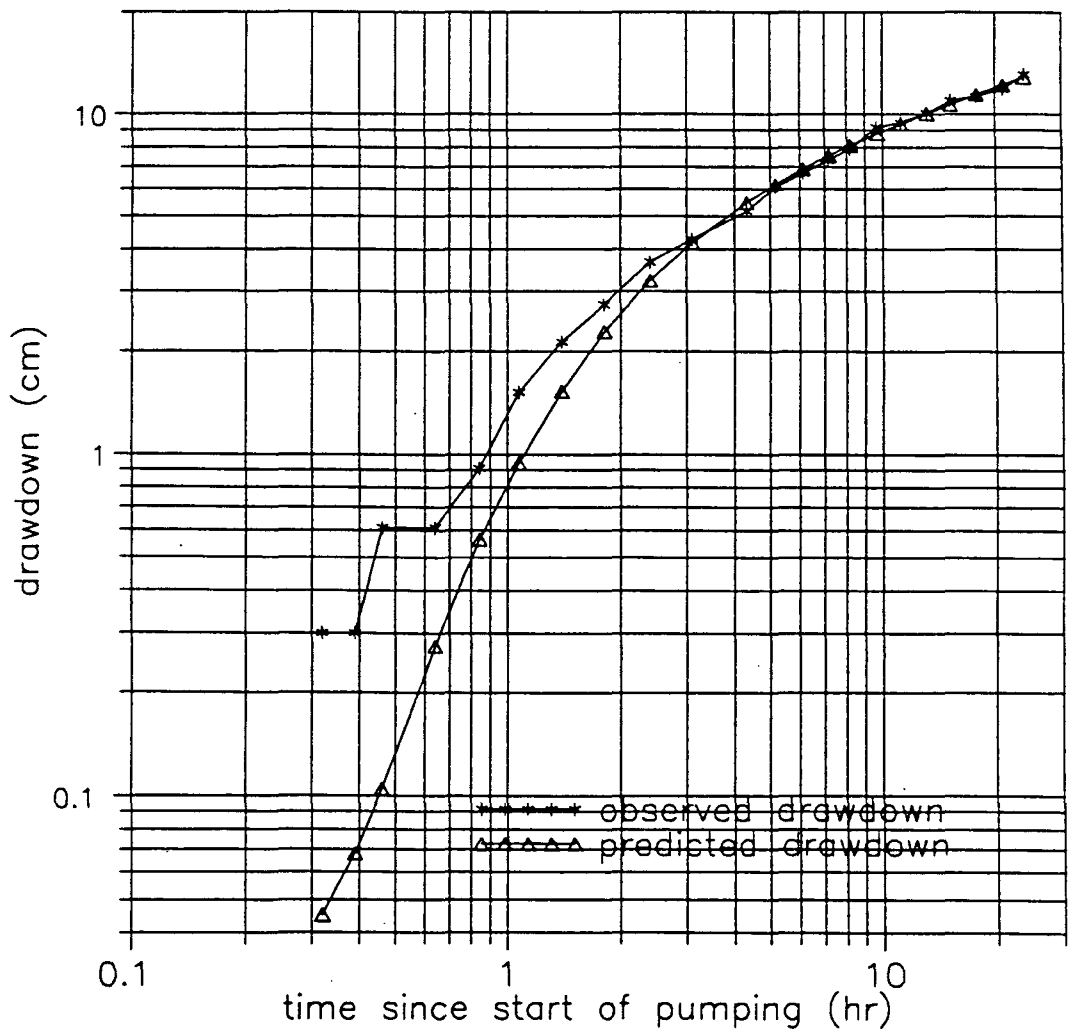
Test #2, Well 2

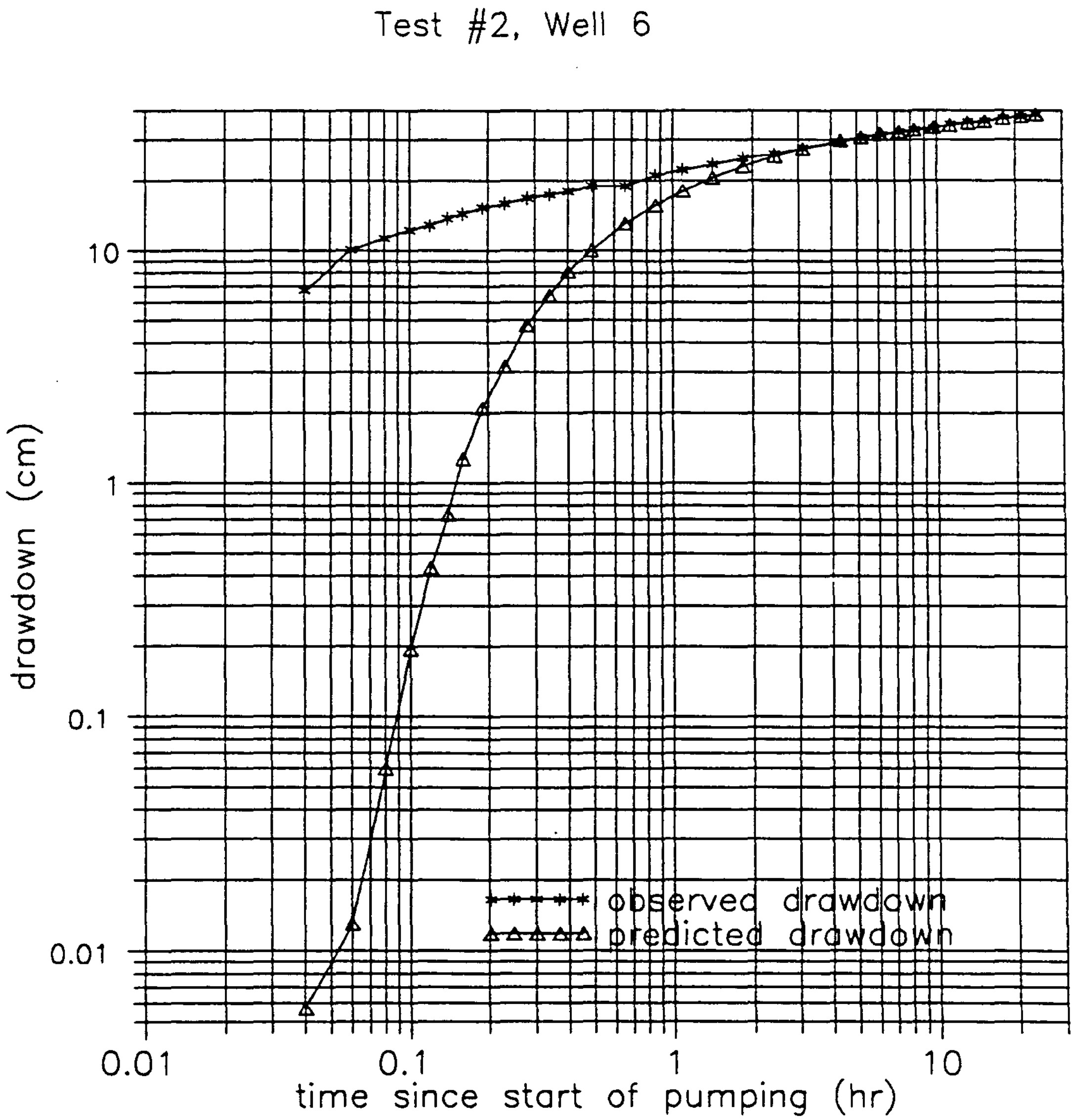

10
1
0.1
drawdown (cm)
observed drawdown
predicted drawdown
0.1
1
10
time since start of pumping (hr)



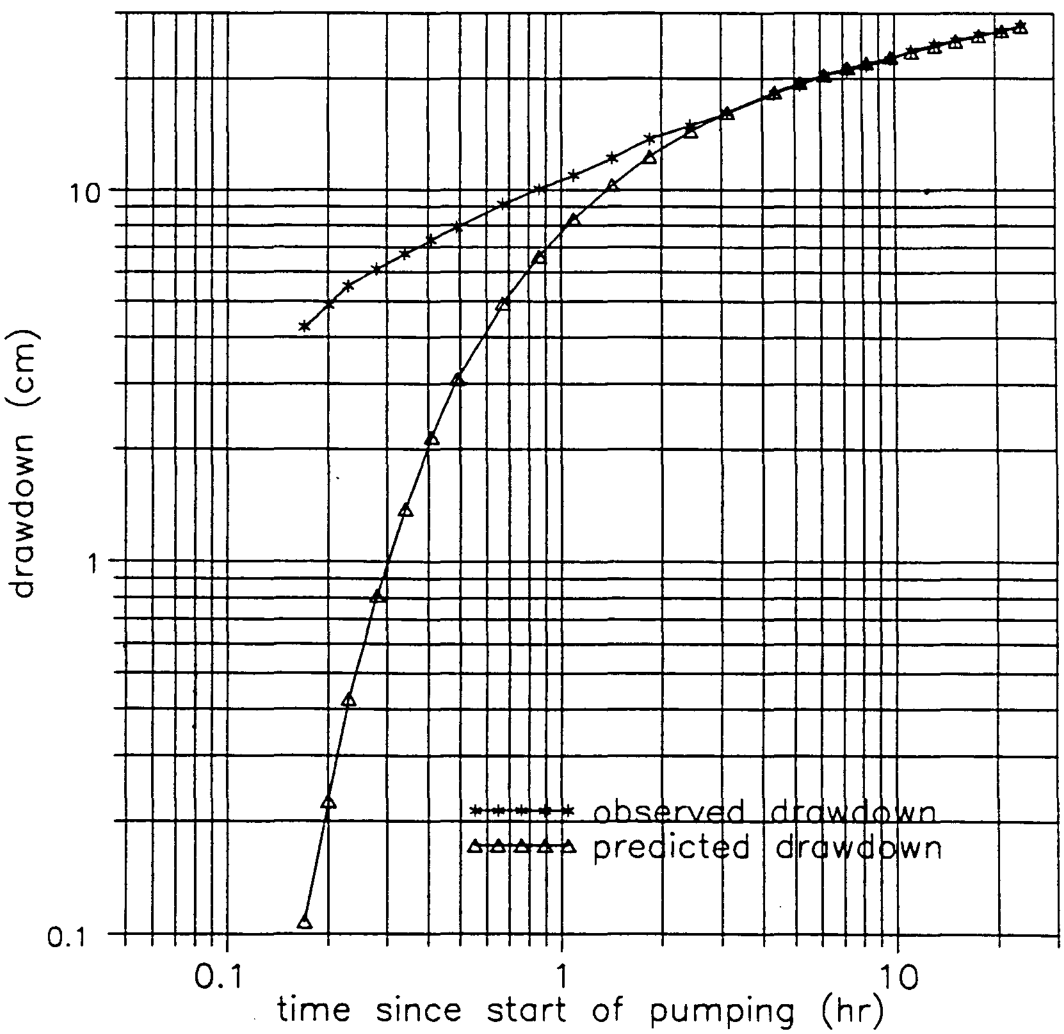
Test #2, Well 3
10
1
0.1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

Test #2, Well 4


10
1
0.1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

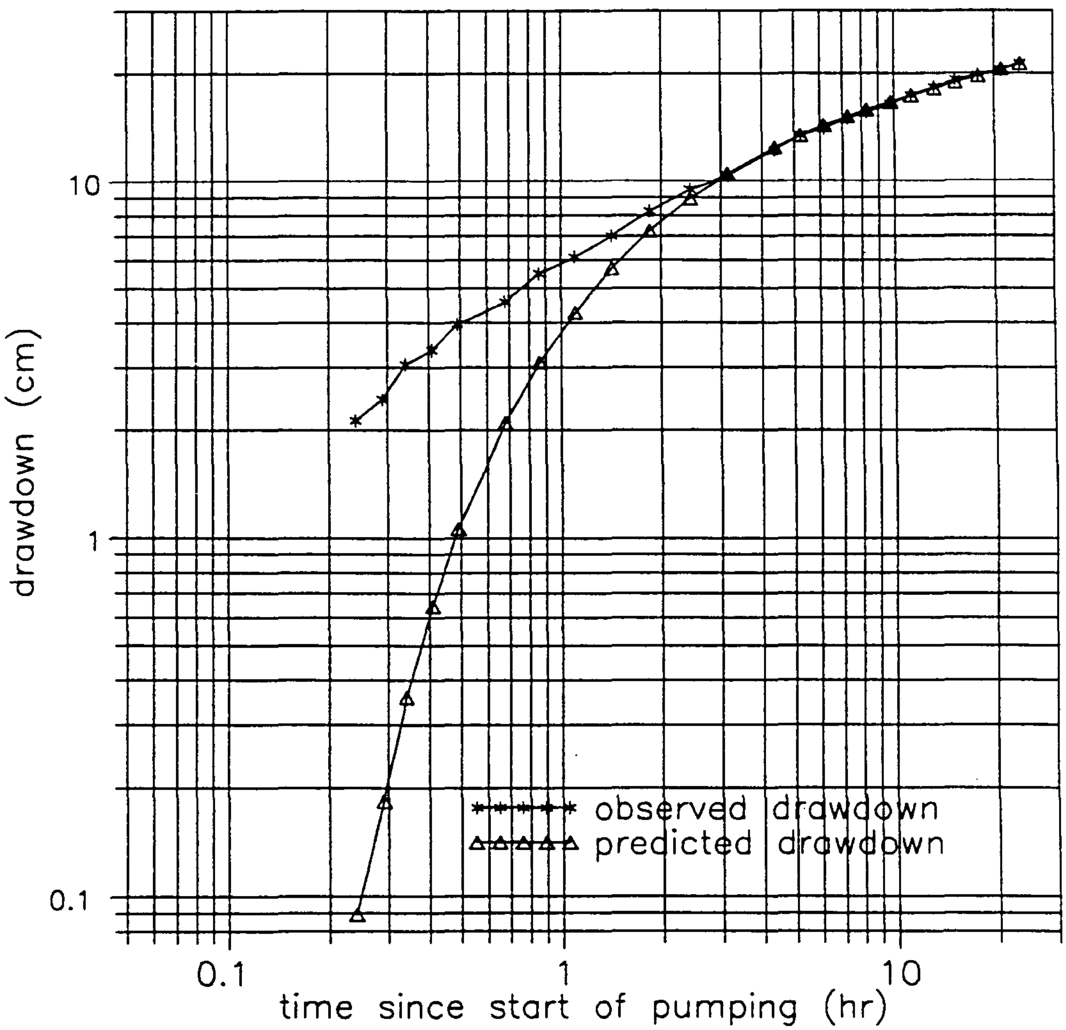

Test #2, Well 6
drawdown (cm)
10
1
0.1
0.01
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

Test #2, Well 7

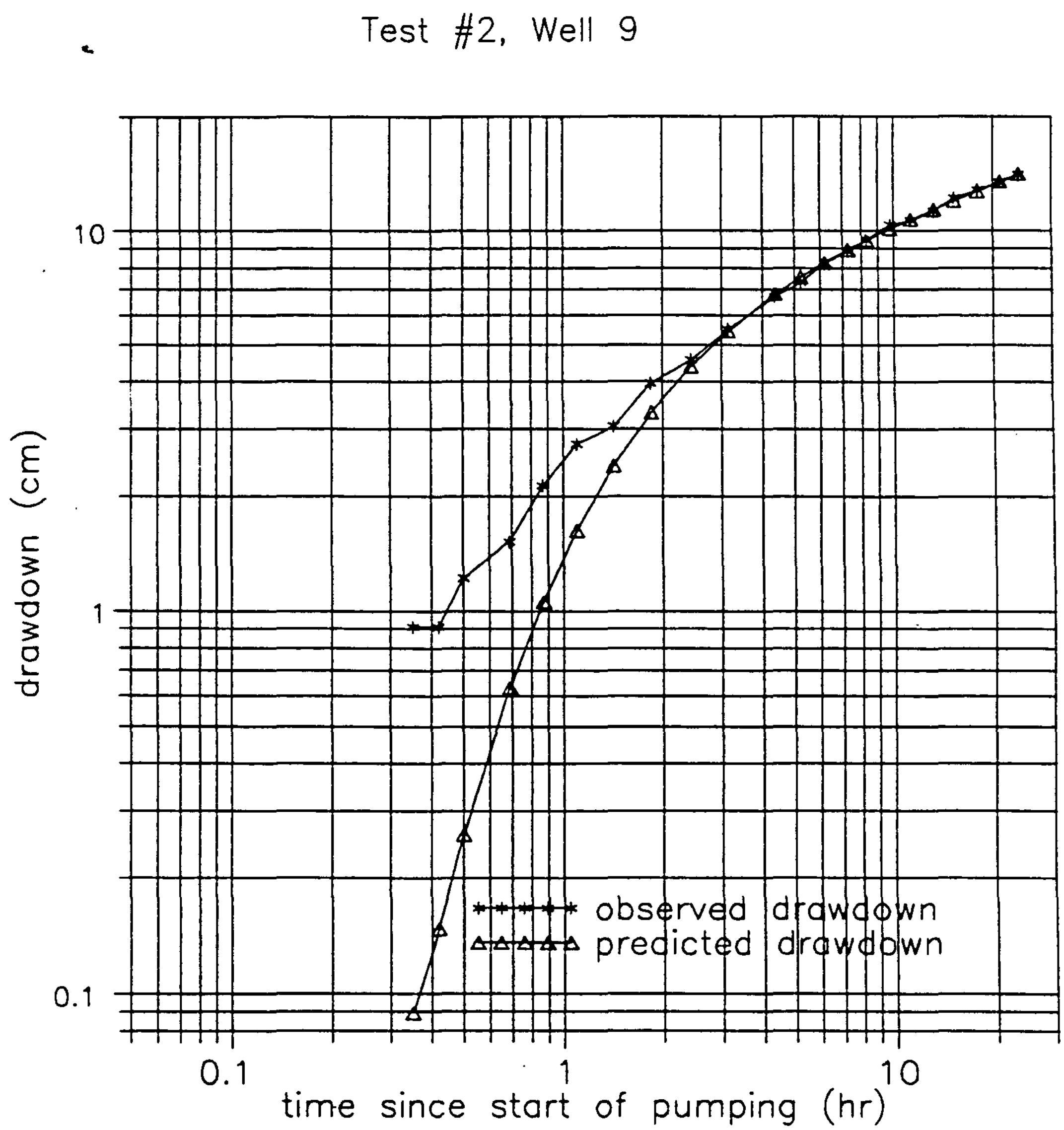


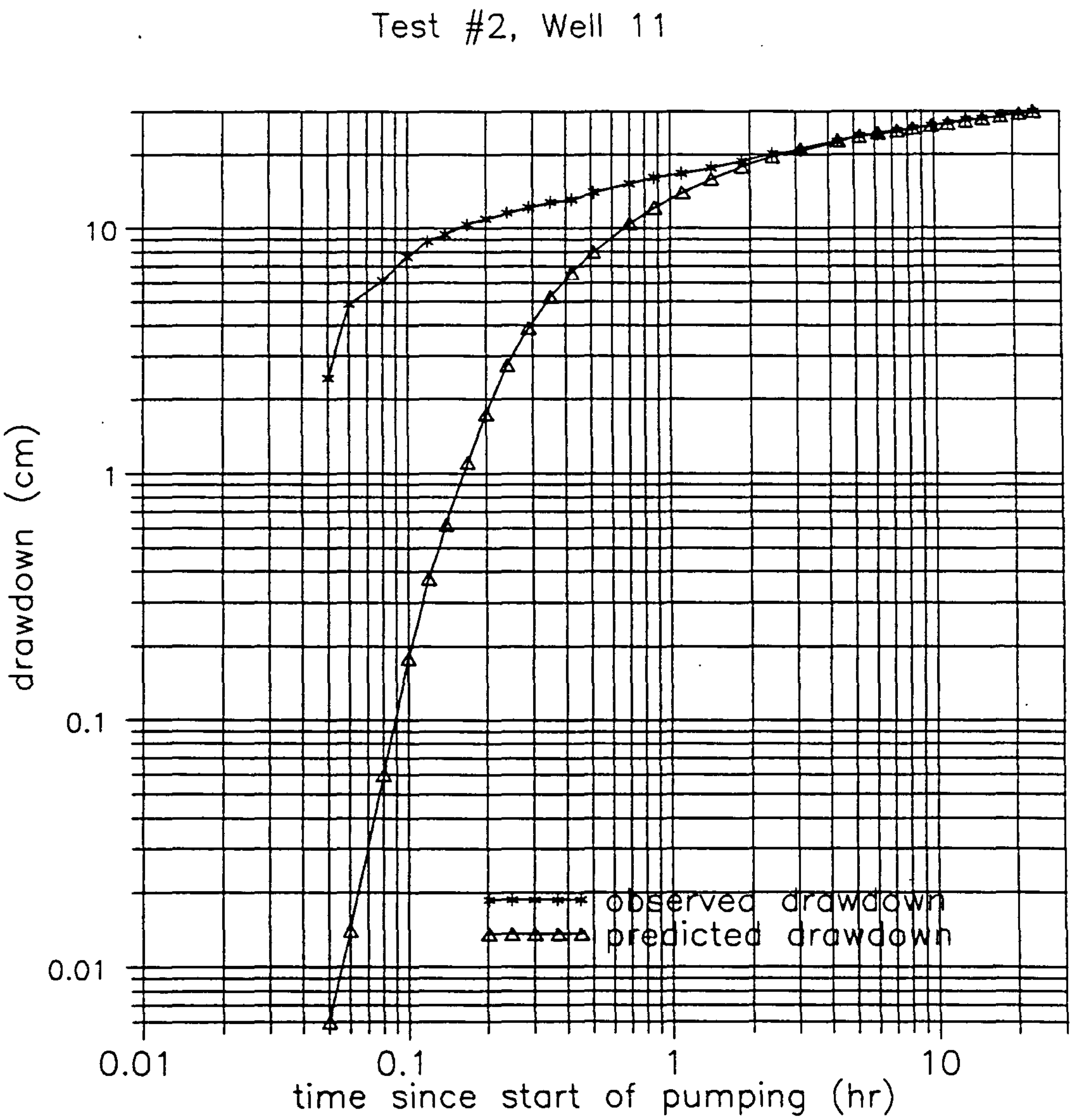
10
1
0.1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

Test #2, Well 8

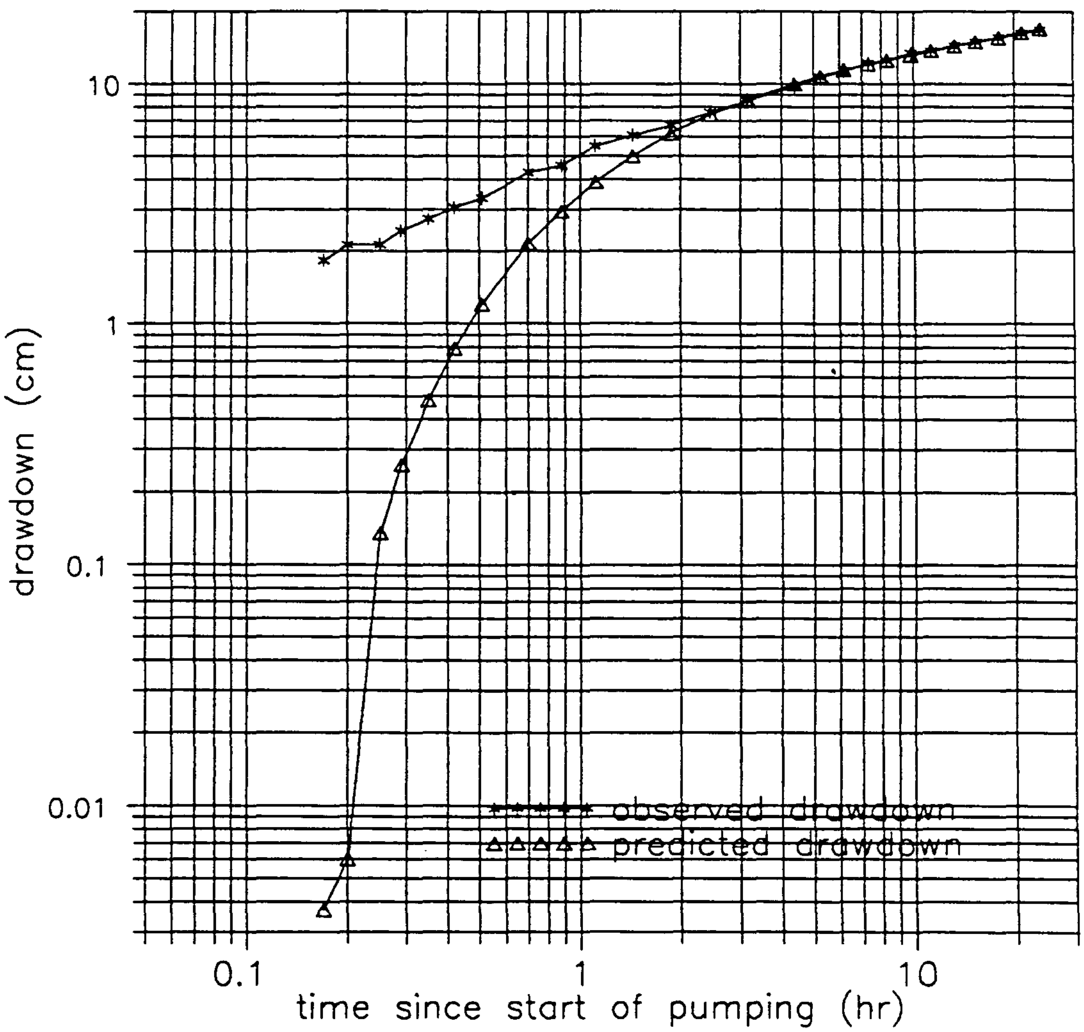


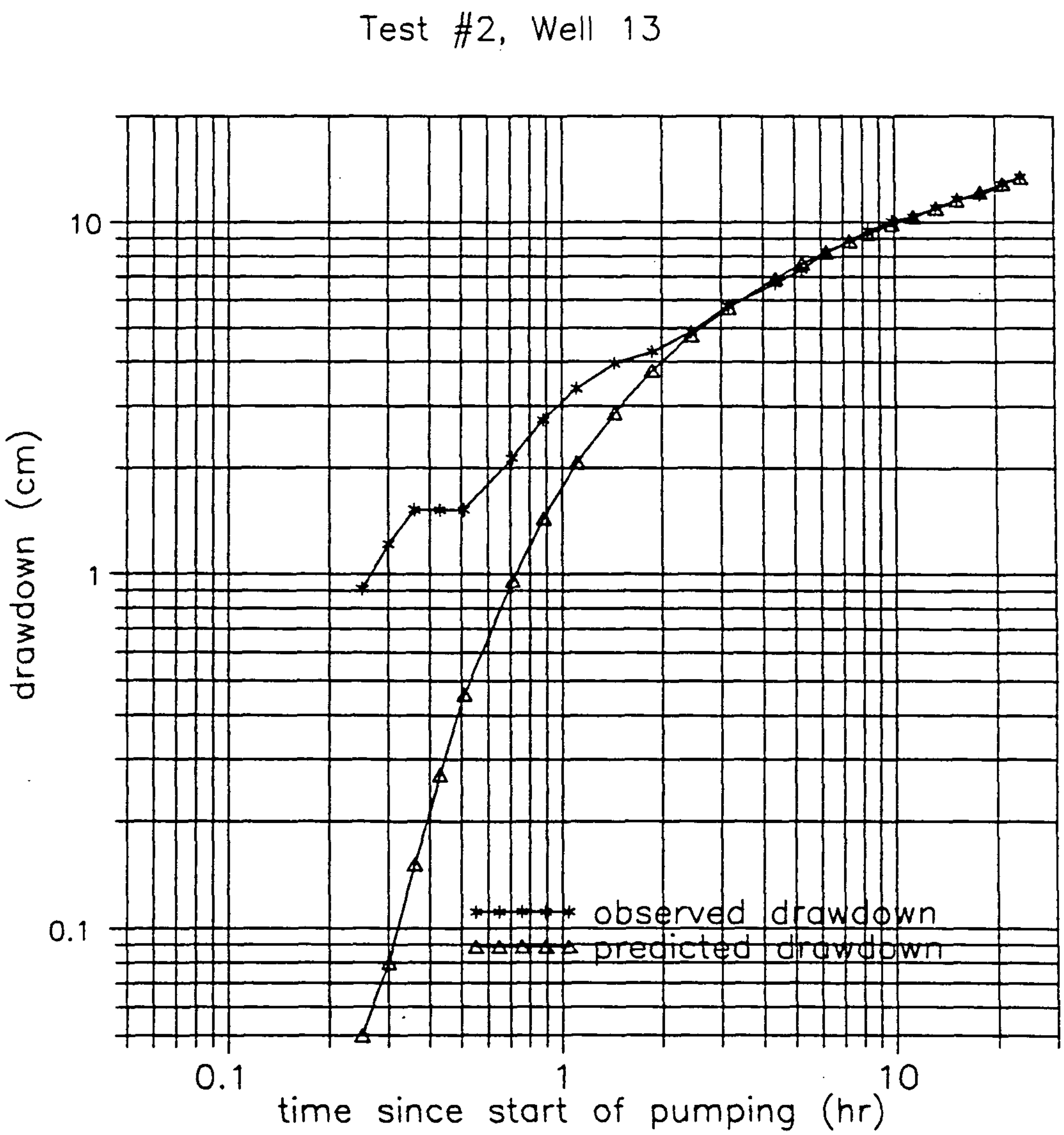
10
1
0.1
drawdown (cm)
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown


Test #2, Well 9
drawdown (cm)
10
1
0.1
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown


Test #2, Well 11
10
1
0.1
0.01
drawdown (cm)
0.01
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

Test #2, Well 12




Test #2, Well 13
drawdown (cm)
10
1
0.1
0.1
1
10
time since start of pumping (hr)
observed drawdown
predicted drawdown

Test #2, Well 14