DETERMINATION OF AQUIFER PROPERTIES OF THE DAKOTA AQUIFER IN WASHINGTON COUNTY, KANSAS FROM A PUMPING TEST

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EXECUTIVE SUMMARY

The objective of this pumping test was to estimate the hydraulic conductivity and storativity of a sandstone and the leakance of its overlying mudstone confining layer in the Dakota aquifer at a site in Washington County, Kansas. Prior to this test little was known about the hydraulic properties of the Dakota aquifer in this area although it is an important source of water. The test was performed near Clifton in August 1990 using a high-yield irrigation well and an observation well drilled by the Kansas Geological Survey.

Drawdown in the observation well was recorded during pumping of the irrigation well. It was then adjusted to compensate for (1) atmospheric pressure fluctuations, (2) recovery of the water level from a previous period of pumping and (3) interference from another pumping well. From water level fluctuations due to atmospheric pressure changes it was found that the barometric efficiency of the aquifer at this location is 95%, which implies its structure is very rigid. The first 27 hours of the compensated drawdown-time curve was fitted to the Hantush-Jacob leaky artesian well function by a computer program using non-linear regression. The average hydraulic conductivity and storativity of the sandstone and the leakance from the upper confining layer were calculated from this period of drawdown to be 570 gpd/sq.ft., 1.28×10^{-4}, and 3.8×10^{-8} min^{-1}, respectively. Later drawdown was greater than expected probably due to decreasing aquifer transmissivity, caused by thinning of the sandstone away from the test site rather than an abrupt no-flow boundary.

1.0 INTRODUCTION

Pumping tests using observation wells provide invaluable information concerning the transmissivity and storage of an aquifer. They can also be used to estimate the leakage from less permeable sediments which confine the aquifer.

The Dakota aquifer is the second most geographically extensive aquifer system in Kansas. Although aquifer properties have been determined in a few areas of southwestern Kansas by means of pumping tests, there is no published record of any pumping test using observation wells in north-central Kansas. Therefore, little is known about the hydraulic properties of the aquifer in this part of the state.

The purpose of this report is to describe a pumping test in a sandstone of the Dakota aquifer in north-central Kansas (Figure 1) in August 1990. The test was performed by pumping a high-yield irrigation well at a constant rate and observing drawdown in a nearby observation well. The drawdown was corrected by compensating for the effects of well interference, atmospheric pressure changes, and continuing recovery of the water level from a previous period of pumping. The compensated drawdown was then used to determine the transmissivity and storativity of the aquifer and the degree of leakage of water from the confining layers. The drawdown data are tabulated and plotted in appendix 4 and Figure 9 respectively.

2.0 BACKGROUND INFORMATION

2.1 Geology

The Dakota aquifer consists of interbedded sandstones and mudstones deposited in fluvial, deltaic, and nearshore marine systems during the early Cretaceous Period (Macfarlane, Whittemore et al., 1991, p. 9). The Dakota Formation is the main geologic unit of the aquifer in Kansas, although the Kiowa Formation and Cheyenne Sandstone are also important components of the aquifer throughout much of the state.

Most of the sediments of the aquifer are fluvial system deposits; sandstones accumulated in active river channels and mudstones were deposited on floodplains and, to a minor extent, in abandoned channels. The resulting sedimentary architecture is complicated; sandstone bodies interbedded within mudstone are not in horizontal sheets. On the contrary the sandstone typically occurs in a beltlike pattern, concentrated in irregular lenses which differ in thickness, aerial extent and the degree with which they interconnect.

In 1989 and 1990, nine test holes were drilled in Washington, Republic, and Cloud counties northeast of the Republican River valley (Figure 2) to aid in understanding the sedimentary architecture of the aquifer in this area. The legal locations of the test holes and lease names are listed in Table 1.

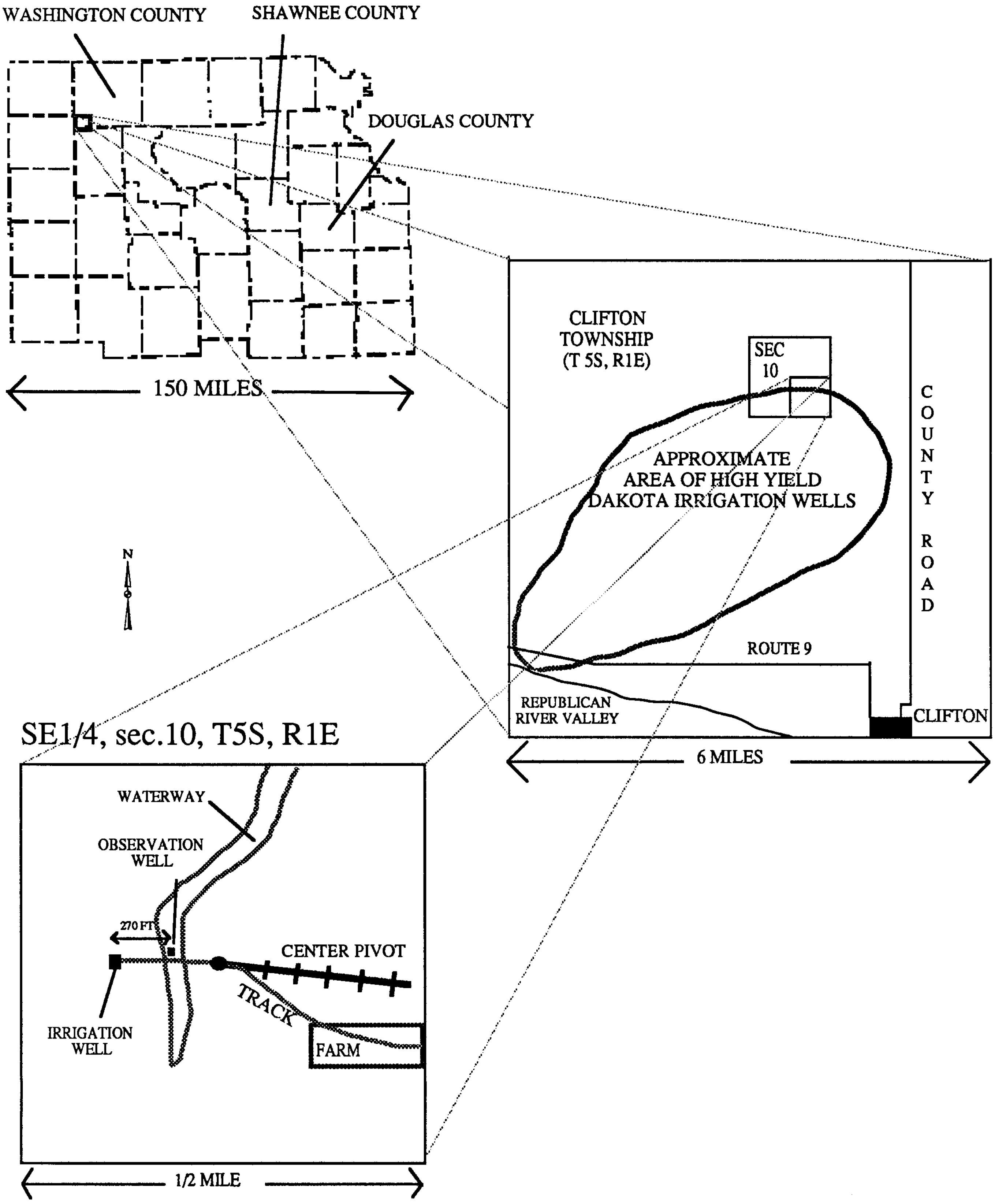


FIGURE 1. LOCATION OF PUMPING TEST SITE IN SE1/4, SEC.10, T5S, R1E, WASHINGTON COUNTY

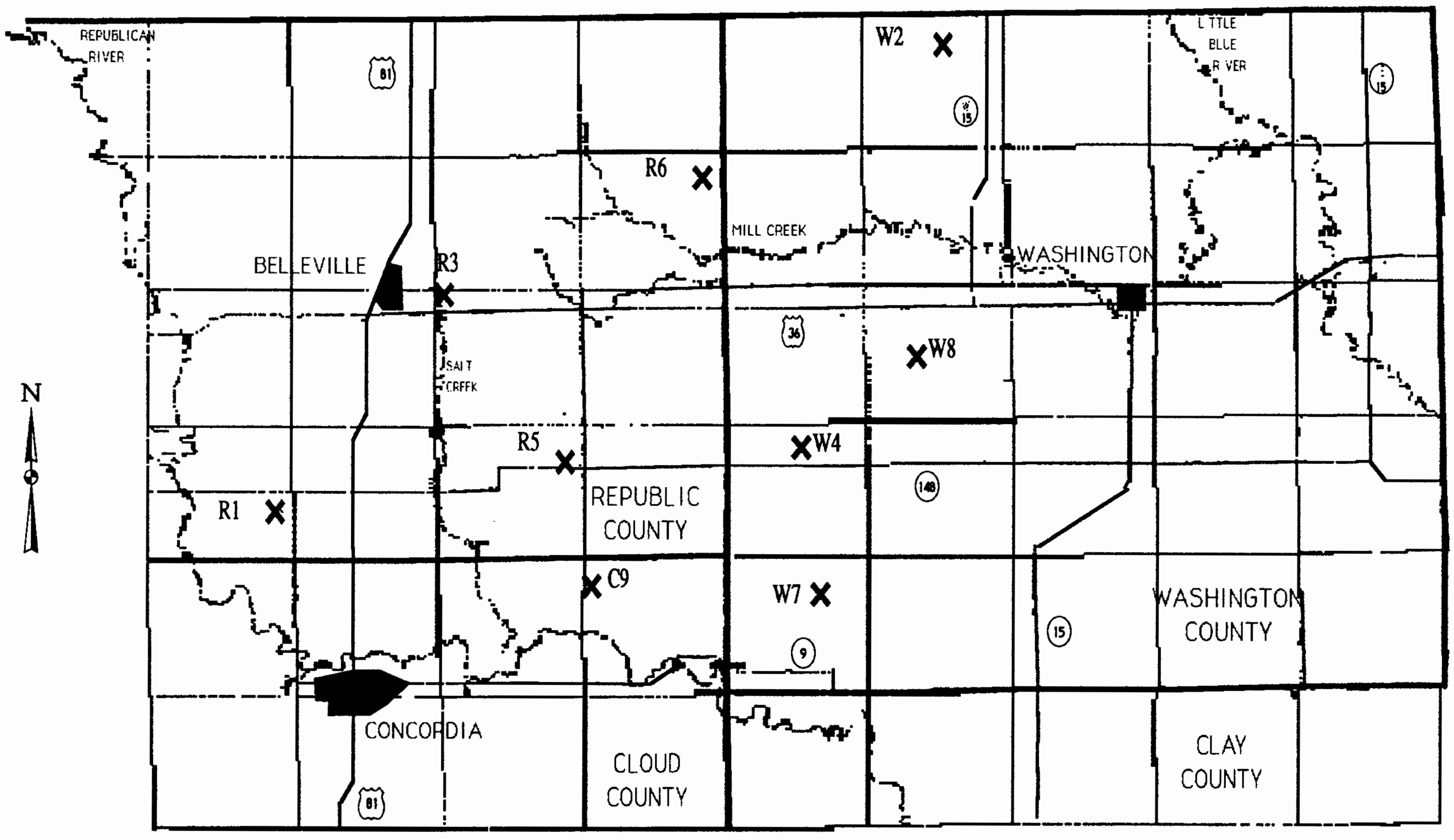


FIGURE 2

Locations of nine test holes in north-central Kansas drilled by the KGS in 1989 and 1990.

TABLE 1. Test holes drilled by the KGS in Republic, Washington, and Cloud counties between fall 1989 and fall 1990.

Hole Number[a]	Date Drilled	Lease Name	Location
R1	9/89	Kenyon	Sec. 24, T4S, R4W
W2	11/89	Gaydusek	Sec. 10, T1S, R2E
R3	4/90	Popelka	Sec. 6, T3S, R2W
W4	4/90	Peterson	Sec. 10, T4S, R1E
R5	4/90	Benyshek	Sec. 12, T4S, R2W
R6	4/90	Cromwell	Sec. 12, T2S, R1W
W7	5/90	Leiszler	Sec. 10, T5S, R1E
W8	5/90	Nanninga	Sec. 16, T3S, R2E
C9	9/90	Feight	Sec. 7, T5S, R1W

a. R indicates Republic County, W indicates Washington County and
C indicates Cloud County

Cores were taken from R1 and W2 (Figure 2) and borehole geophysical logs were obtained from these test holes. This information was used to determine the detailed characteristics of the geologic framework of the aquifer, to correlate sequences of rocks between R1 and W2, and to infer the environments in which the sediments were deposited. (Macfarlane, Wade et al., 1991). Seven other test holes were drilled and logged geophysically to determine the exact depth of changes in lithology; core samples were not obtained from these test holes. A monitoring well was installed in hole W7 and this was used as the observation well (O.1) in the pumping test.

The results of the drilling were correlated among all of the test holes. Figure 3b is a 'fence diagram' showing the correlations made between the holes in the vicinity of the pumping-test site. The true dip of the formations is not depicted in Figure 3b. In reality, the base of the Dakota Formation dips to the west-northwest at approximately 10 ft/mi. The Kiowa Formation pinches out toward the east and is not present at the site of the pumping test (Figure 3b). The Cheyenne Sandstone, which constitutes part of the aquifer in much of the southern part of the state, is not present in north-central Kansas.

A sandstone is present at the base of the Dakota Formation in all the test holes except C9, which did not penetrate the entire thickness of the formation. Although this basal sandstone is laterally continuous throughout the area, its thickness is highly variable, and ranges from 20 to 145

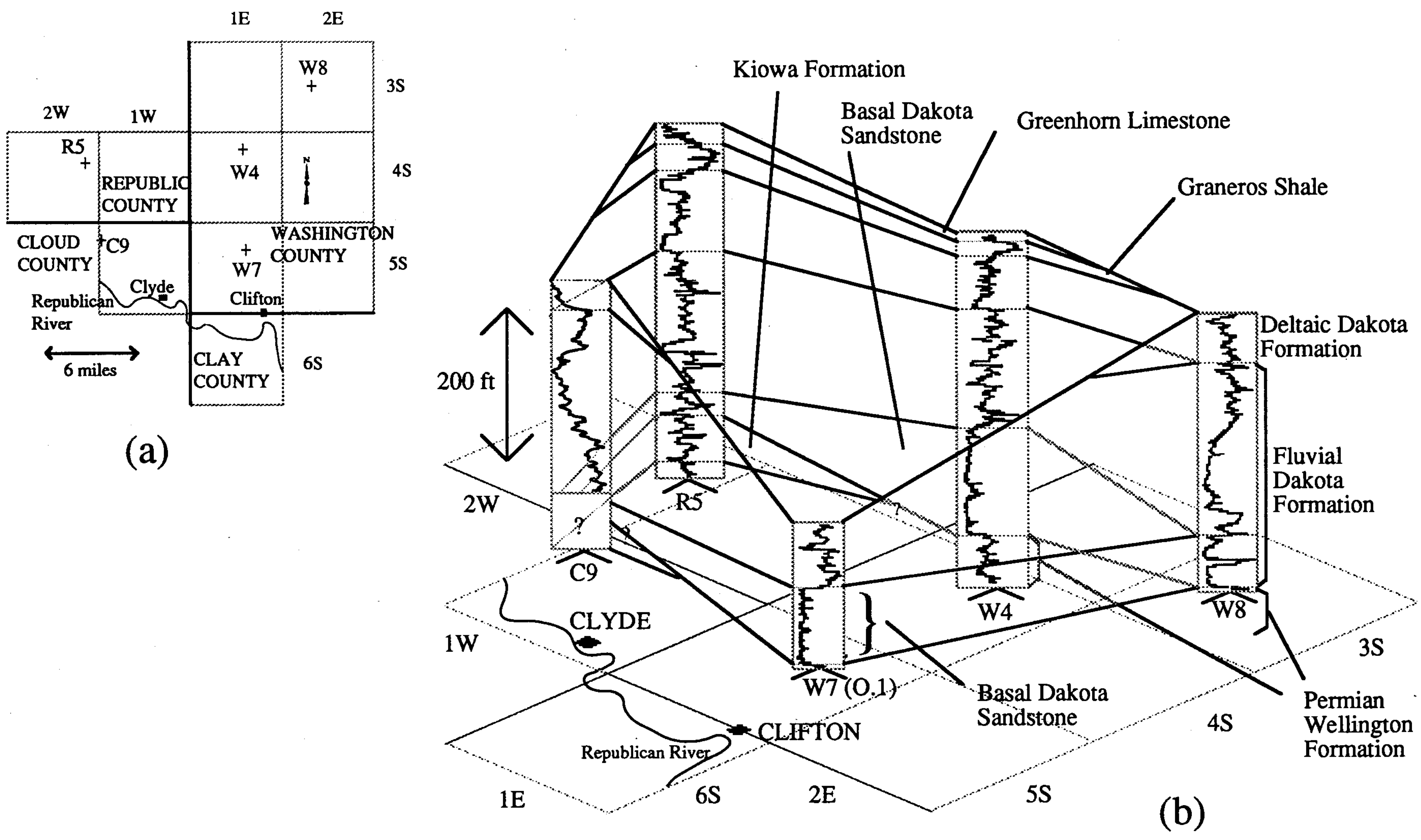


FIGURE 3. Test holes drilled by the KGS in the vicinity of the pumping test site. The observation well used in the pumping test (O.1) was constructed in test hole W7.

(a) Test hole locations.

(b) Fence diagram showing the gamma ray logs of the test holes. The logs are a measure of the natural gamma radiation of the rocks penetrated by the borehole. This is an approximation of the clay content; more clayey rocks (mudstone and shale) plot to the right and less clayey rocks (sandstone and limestone) plot to the left.

ft in a horizontal distance of 11 miles between holes W4 and R5 (Figure 3). (The upper part of this channel sandstone appears to be very muddy in the gamma log of hole R5 (Figure 3b) probably due to the presence of mud rip-up clasts.)

A laterally continuous broad body of sandstone seems an unlikely product of the fluvial system described above in which the dominant lithology is overbank mudstone. However, the first sediments of the Dakota Formation in this area were deposited by relatively high-energy, high-competence streams immediately following a period of erosion when the space available for sediment accumulation was low due to a drop in sea level. This resulted in much reworking of the first Dakota Formation sediments and there was therefore little preservation of low-energy overbank mudstone and a high degree of interconnection between different channel sandstones. The basal sandstone is likely to be thickest in paleovalleys cut into the Permian and Kiowa surface by the Dakota streams and at locations where stream channels later stacked on top of one another as the depositional slope lessened and overbank mudstone began to be preserved between the channels.

2.2 Geohydrology

The sandstones of the Dakota aquifer generally yield significant water to wells, in contrast to the mudstones which have very low permeabilities and therefore act as aquitards. The amount of water a sandstone can yield depends on its continuous areal extent and thickness as well as its grain size and degree of cementation. The good lateral continuity of the basal sandstone is therefore very important to the flow of ground water in the lower part of the Dakota aquifer.

The site of the pumping test is in the outcrop belt of the Dakota Formation where erosion has reduced the thickness of the aquifer to less than 200 ft (Figure 3b, Figure 4). The sandstone in which the wells are screened is medium grained, well sorted, and poorly cemented, which is typical of the sandstone at the base of the Dakota Formation in north-central Kansas. However, its thickness of 100 ft is quite unusual. This great thickness of saturated sandstone at such a shallow depth is the main reason why irrigation wells are concentrated in this township, particularly to the southwest of the pumping test site (Figure 1). The sandstone is confined by Dakota mudstone above and Permian shale below. The difference in hydraulic conductivity between the sandstone and its confining beds was anticipated to be many orders of magnitude, and leakage effects on drawdown during the pumping test were expected to be low.

3.0 PRE-TEST PREPARATIONS

3.1 Drilling, Construction, and Development of the Observation Well, O.1

The observation well, O.1, was drilled by the Kansas Geological Survey in May 1990. It was located 270 ft from a high-yield center-pivot irrigation well, henceforth referred to as I.1, on the edge of a waterway near the center of SE$^1/_4$ Sec. 10, T.5S, R.1E near Clifton, southwestern Washington County (Figure 1). Optimum distance between O.1 and I.1 was determined from expected drawdown based on estimates of aquifer transmissivity as well as on practicalities such as site access, position of underground pipe and cable, and location of the waterway.

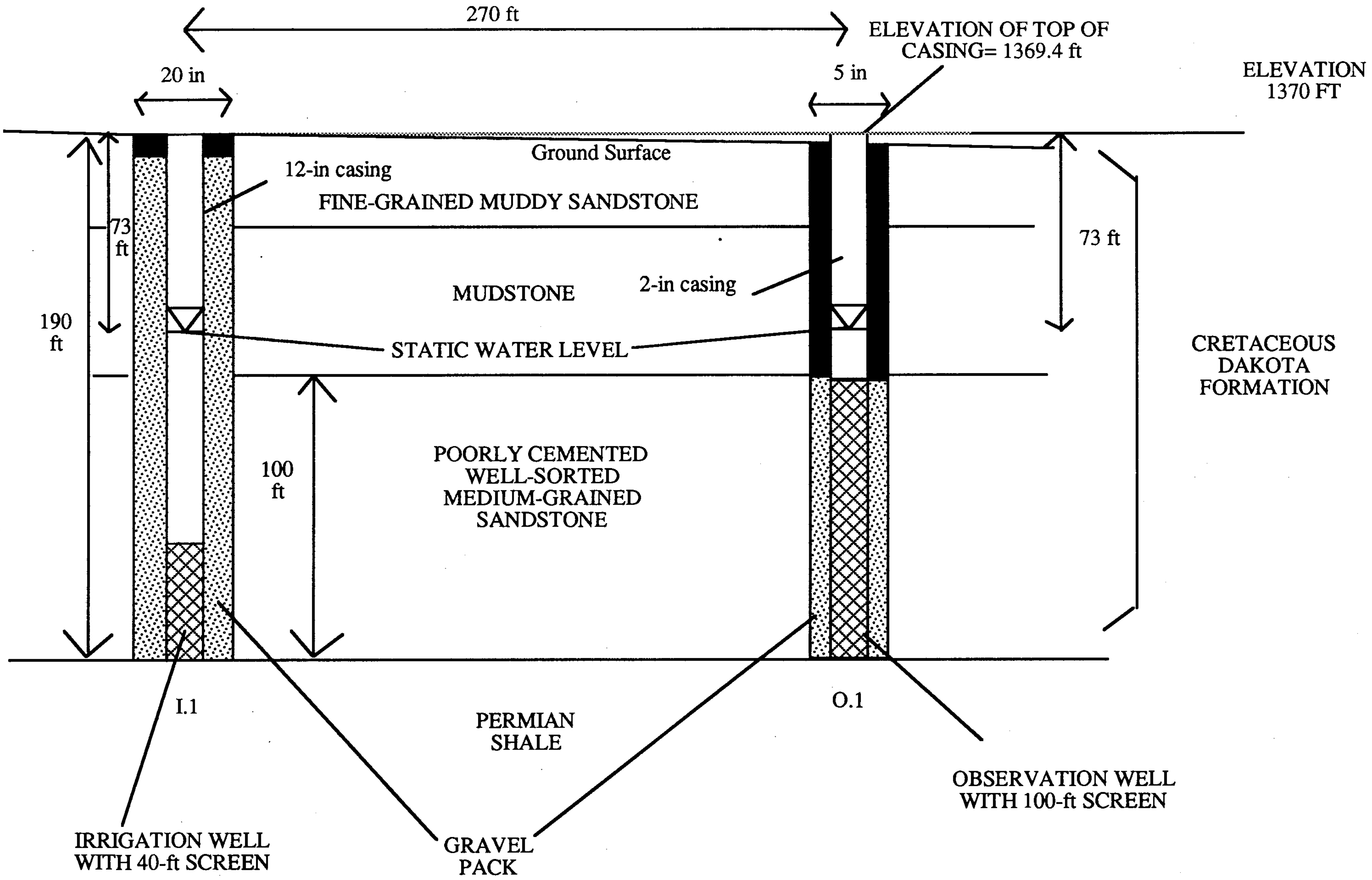
A 5-in hole was drilled using mud rotary with a drag bit to a depth of 191 ft. The hole was then logged using gamma ray, spontaneous potential, resistivity, and caliper measuring tools. The gamma ray log of the hole is shown in Figure 3b. This information was used to determine the exact depth to the top and base of the sandstone aquifer. O.1 was then constructed as shown in Figure 4; it was screened and gravel packed throughout the sandstone to insure no vertical flow effects during a pumping test. The total length of screen used was 100 ft. Immediately above the screen and gravel pack, the borehole was sealed with 7 ft of bentonite chips. The uppermost 75 ft of hole was filled with a mixture of bentonite chips and shale which had sluffed off into the hole overnight. The hole was plugged at the top with bentonite chips and finally a steel cover was cemented into the ground over the PVC casing.

The well was developed using compressed air later in the month to remove accumulated fluids, mud, and cuttings . The air line was lowered to the bottom of the well and air was forced through it using a compressor. This lifted water from the well at a rate of approximately 20 GPM. The well was developed for three hours in this way until there was no trace of drilling mud in the water.

3.2 Monitoring Equipment

(a) On July 2, 1990, two transducers were set in O.1 at a depth of 95 ft below the top of the casing, i.e. 22.4 ft below the May static water-level. The transducers were designed for a pressure range of 10 psi which is equivalent to 23 ft of water. These transducers were connected to a Hermit Data Logger which was programmed to record the depth to water to the nearest .01 ft from the top of the casing every hour. Two transducers were used rather than one in order to insure consistency of measurements and to insure that data were not lost due to a transducer malfunctioning. This precaution proved to be worthwhile later in July when one of the transducers ceased to function. The water-level monitoring station was protected with a weatherproof, insulated cover.

(b) On the same day a barograph was located 1/4 mile from the well in a farm building and calibrated by the atmospheric pressure at the local weather station in Concordia. This instrument



(NOT TO SCALE)

FIGURE 4. Cross section of the aquifer and the irrigation and observation wells.

recorded the atmospheric pressure for the rest of the summer on paper charts. According to manufacturers specifications, the barograph had an accuracy of ±0.15 mb and a resolution of 0.2 mb. The accuracy and resolution of this instrument were insured by periodically comparing its reading to the local weather station reading at various pressures.

(c) On July 12, a McCrometer bolt-on saddle, propellor-driven flow meter was fitted onto the irrigation well. This device indicates the flow rate using an odometer which displays total gallons pumped as well as current pumping rate. To insure straight, laminar flow and accuracy of the meter, the manufacturer recommends a minimum of 8 inches of straight pipe downstream from the meter and 40 inches upstream. The length of straight, constant-diameter pipe leading from the well was limited so the meter was installed with 8.5 inches of straight pipe downstream and 35.5 inches upstream. Straightening vanes were therefore also installed immediately upstream from the meter.

The meter was calibrated for a pipe with an internal diameter of 7.872 ins (internal radius 0.328 ft). The actual internal diameter of the pipe, measured during installation of the meter, is 8.24 ins; its radius is 0.343 ft. Flow rate through a pipe is proportional to the square of its internal radius (IR^2). The IR^2 of the pipe is 9.6% greater than the IR^2 the meter was calibrated for. Flow meter readings were therefore corrected by multiplying by a factor of 1.096.

3.3 Pre-Test Data Acquisition and Analysis

Before the pumping test began on August 7, data were collected from the monitoring equipment described above for 4 weeks. I.1 was in use for most of the first 11 days of this period, through to July 21. Between 04:00 hrs, July 21 and 14:36 hrs, August 7, I.1 was not pumped due to wet weather. From July 22 to August 6 none of the other irrigation wells in the field to the southwest were pumped either. This allowed the aquifer to recover to within 3 ft of its pre-irrigation season level from a maximum drawdown of close to 16 ft.

The water-level data were downloaded from the datalogger directly onto a microcomputer at the Kansas Geological Survey. Atmospheric pressure data in millibars were entered into the microcomputer at the keyboard and converted into feet of water. These data were used

(1) to check that the transducers were set at a suitable depth and were performing accurately;
(2) to insure that all the monitoring equipment was functioning properly;
(3) to decide on an initial pumping rate for the irrigation well which could be sustained at maximum drawdown in that well.

Depths to water and atmospheric pressure fluctuations from the first week of August were also used to quantify the effects of (a) aquifer barometric efficiency and recovery; and (b) well interference from another irrigation well which began pumping on August 6. These effects were then used to adjust the raw water-level data from the observation well in order to observe fluctuations from pumping only.

3.3 (a) Barometric Efficiency and Recovery of the Aquifer

Atmospheric pressure data recorded on the barograph in early August are tabulated in Appendix 1. The uncommon pressure unit 'feet of water' was used to facilitate easy comparison of the amplitudes of the atmospheric-pressure and water-level fluctuations. Water-level data from early August are tabulated in Appendix 2. Both water-level and atmospheric-pressure data were processed and analyzed using the Lotus123 and Grapher software.

At the start of August the water level in the aquifer was still recovering from the period of pumping which had ended 10 days previously. This can be seen in Figure 5, a graph of depth to water and atmospheric pressure measured between 00:00 hrs, August 1 and 09:00 hrs, August 6. The water level rose overall despite an increase in atmospheric pressure which had the effect of pushing the water level down.

The water level of a recovering aquifer rises at a rate which decreases with time as the water level approaches its pre-pumping static level. At large time since pumping ceased, the recovery rate of an aquifer is typically inversely proportional to time and the total amount of recovery per log cycle of time is a constant. (In the same way, at large time during pumping of a well, drawdown vs. time will plot as a straight line on semilog. paper; this property is used by the Jacob Straight-Line Method for solution of pumping test data.)

Two values of time were selected (0 hrs and 92 hrs in Figure 5) at which the atmospheric pressure was the same. These times correspond to 260 hrs and 352 hrs after I.1 was switched off respectively. The difference in depth to water at these times was due solely to the recovery of the aquifer because there was no difference in atmospheric pressure. The rate of recovery per log cycle of time during this period was assumed to be constant and it was determined from the slope of a straight line connecting these two points on a graph of depth to water against log time. This rate was found to be 4.0 ft per log cycle of time, which means that the water level would rise 4.0 ft during the period between 100 and 1000 hours after pumping ceased.

Recovery, R, since 00:00 hrs, August 1, could then be described in the following way:

$$R = 4.0 \times (\log (t + 260) - \log 260)$$

where t = time (hrs) from 00:00 hrs August 1st onwards.
Using this formula, when $t = 0$ (at 00:00 hrs, August 1), $R = 0$
and when $t = 100$ hrs (at 04:00 hrs, August 5) $R = 0.57$ ft.

Depths to water during the first 130 hours of August were then adjusted to mask the recovery of the aquifer in the following way:

$$d' = d - (-R)$$

(because depth to water is positive downwards and recovery is positive upwards)

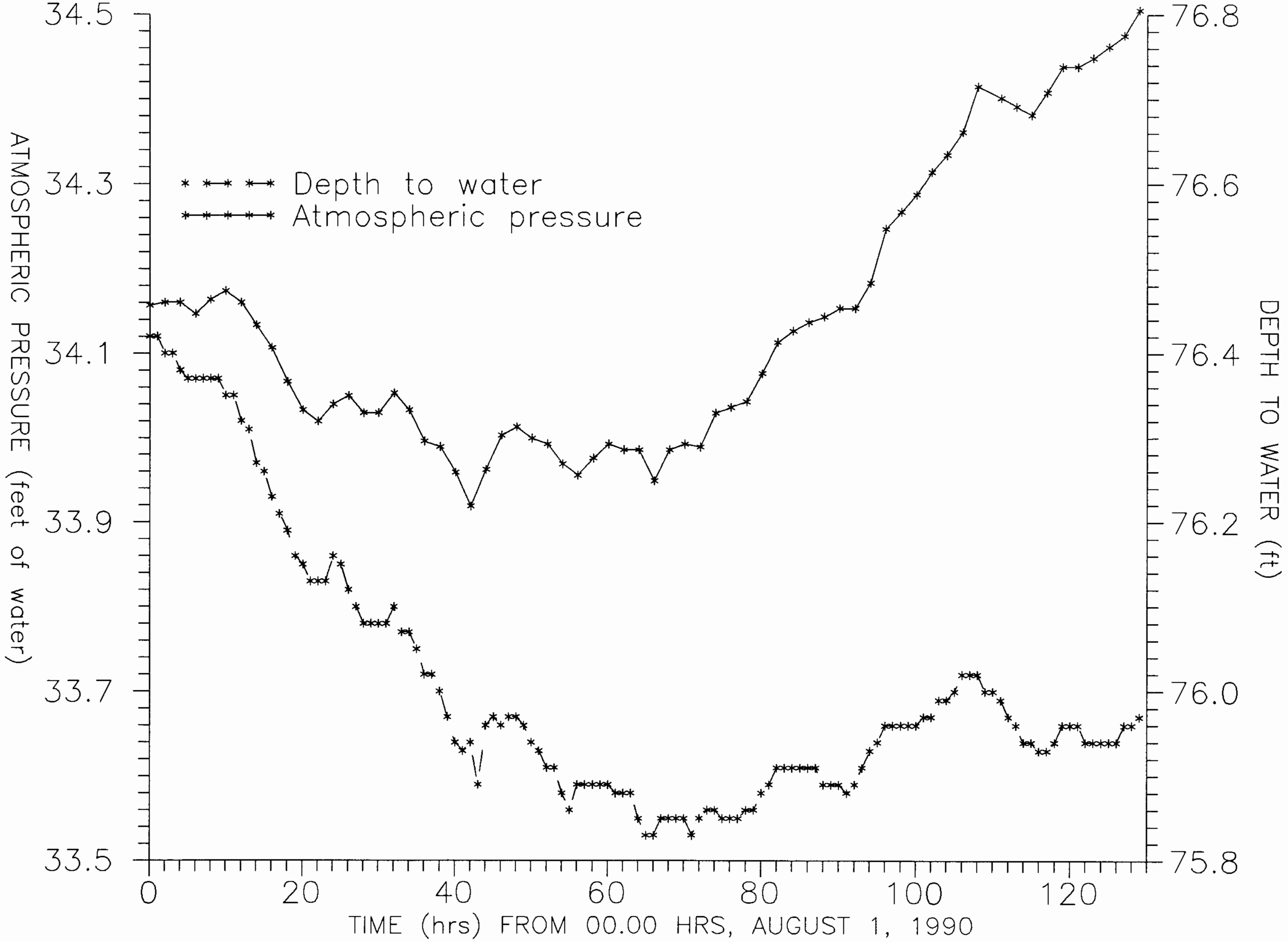


FIGURE 5. Atmospheric pressure and depth to water (d) in 0.1, early August 1990.

i.e. $d' = d + R$

where

d' = depth to water (ft) compensated for aquifer recovery, and

d = depth to water (ft) recorded on the Hermit.

t, d, and d' are tabulated in Appendix 2.

Figure 6 is a plot of d' and atmospheric pressure vs. time. The variations in water level are in phase with and of similar amplitude to the variations in atmospheric pressure. The effect of an increase in atmospheric pressure is to push the water level in the well down in the same way as the water level in a manometer would be pushed down. Similarly, a decrease in atmospheric pressure causes a rise in the water level in the well. From Figure 6 it can be seen that the overall drop in atmospheric pressure during the first 40 hours of August of a little over 0.2 ft of water induced a change in water level of the same amplitude. Also, the increase in atmospheric pressure of 0.50 ft of water during the following 88 hours induced an increase in depth to water of 0.47 ft.

The barometric efficiency of an aquifer, BE, equals $\Delta h/\Delta p_a$, where Δh is the change in water level in feet induced by a change in atmospheric pressure, Δp_a, measured in feet of water.

Overall, Figure 6 shows that changes induced in the water level are 0.95 (± 0.05) times the magnitude of changes in the pressure. This means that the barometric efficiency of the aquifer is close to 0.95 (± 0.05). A barometric efficiency of this magnitude is quite exceptional and implies that its structure is very rigid and that it is well sealed off by confining sediments. The barometric efficiency of most confined aquifers is between 0.20 and 0.75 (Todd, 1967, p. 159).

Todd (1967, p. 161) gives a formula linking the barometric efficiency of an aquifer to its modulus of elasticity (E_s), the porosity (α) of its structure and the bulk modulus of compression of water (E_w) which is approximately 300,000 psi.

$$BE = \frac{\alpha E_s}{\alpha E_s + E_w}$$

From this formula it can be seen that BE is close to 1 if $E_s >> E_w$.

If BE = 0.95 and the porosity, α, is estimated at approximately 30%,

$$0.95 = 0.3E_s / (0.3E_s + E_w).$$

It follows that $E_s = 63E_w$

i.e. the modulus of elasticity of the structure of the aquifer is 63 times the bulk modulus of compression of water and the structure of the aquifer is therefore very rigid. This seems unlikely due to the poor lithification of the Dakota sandstone, but it may reflect high competence of the

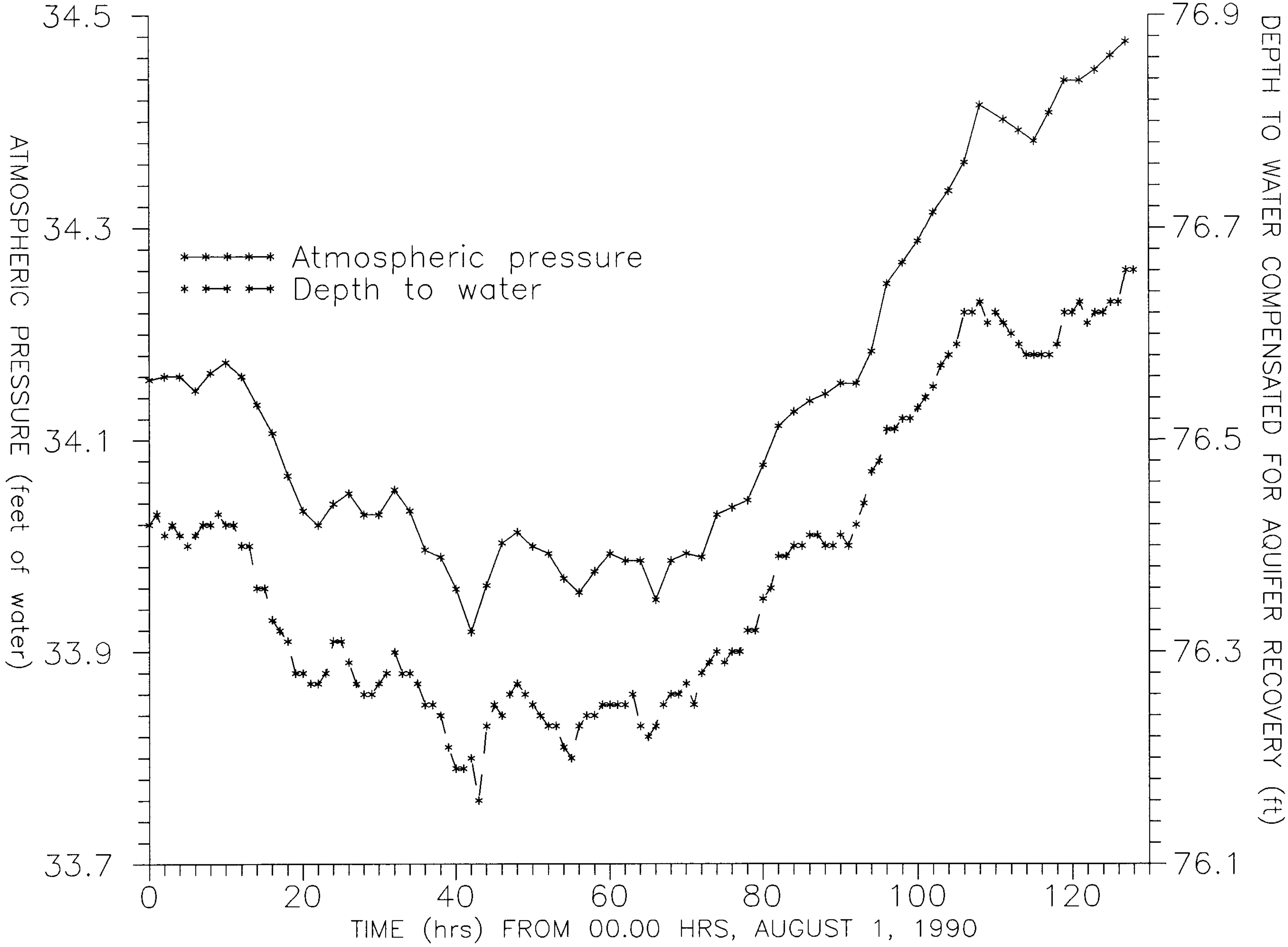


FIGURE 6. Atmospheric pressure and depth to water in 0.1 compensated for aquifer recovery (d'), early August 1990.

overlying confining beds and good compaction of the sandstone when it was buried by several hundred feet of sediment later in the Cretaceous Period.

Todd (1967, p. 162) also describes a way of estimating the storativity of a confined aquifer from its barometric efficiency:

$$\text{Storativity, } S = \alpha\gamma b/E_w BE$$

where γ = specific weight of water = 62.37 lbs/ft^3 at 60 °F,
and b = thickness of aquifer.

$$\text{Using this formula, } S = \frac{0.3 \times 62.37 \times 100}{300{,}000 \times 12^2\ (\text{ft}^2) \times 0.95} = 4.6\text{E-}5.$$

This result is approximately $^1/_3$ the magnitude of S determined later from the pumping test and raises questions concerning the validity of the above formulae linking barometric efficiency and storativity in a confined aquifer. However, it is beyond the scope of this report to explore this subject further. For the purpose of this pumping test it is sufficient to note that changes in atmospheric pressure induce changes in water level in the observation well of approximately the same amplitude.

3.3 (b) Interference Due to Second Pumping Well, I.2

At 09:36 hrs, August 6, 29 hours before the beginning of the pumping test, a second nearby irrigation well, I.2, 2200 feet to the west of I.1 was started up at an unknown pumping rate and began to affect the water level in O.1.

Measured drawdown due to this well was adjusted for the aquifer recovery rate of 4.0 ft per log cycle determined above. It was also adjusted for effects of atmospheric pressure changes at the rate of 0.032 ft of water level increase per millibar decrease in pressure (representing a barometric efficiency of 95% determined as described above). The effects of these adjustments on the I.2 drawdown curve are illustrated in Figure 7. The compensated drawdown due to I.2 was determined to be 0.70(±0.5) ft per log cycle of time from this semilog plot. The measured and adjusted depths to water used in Figure 7 are tabulated in Appendix 3.

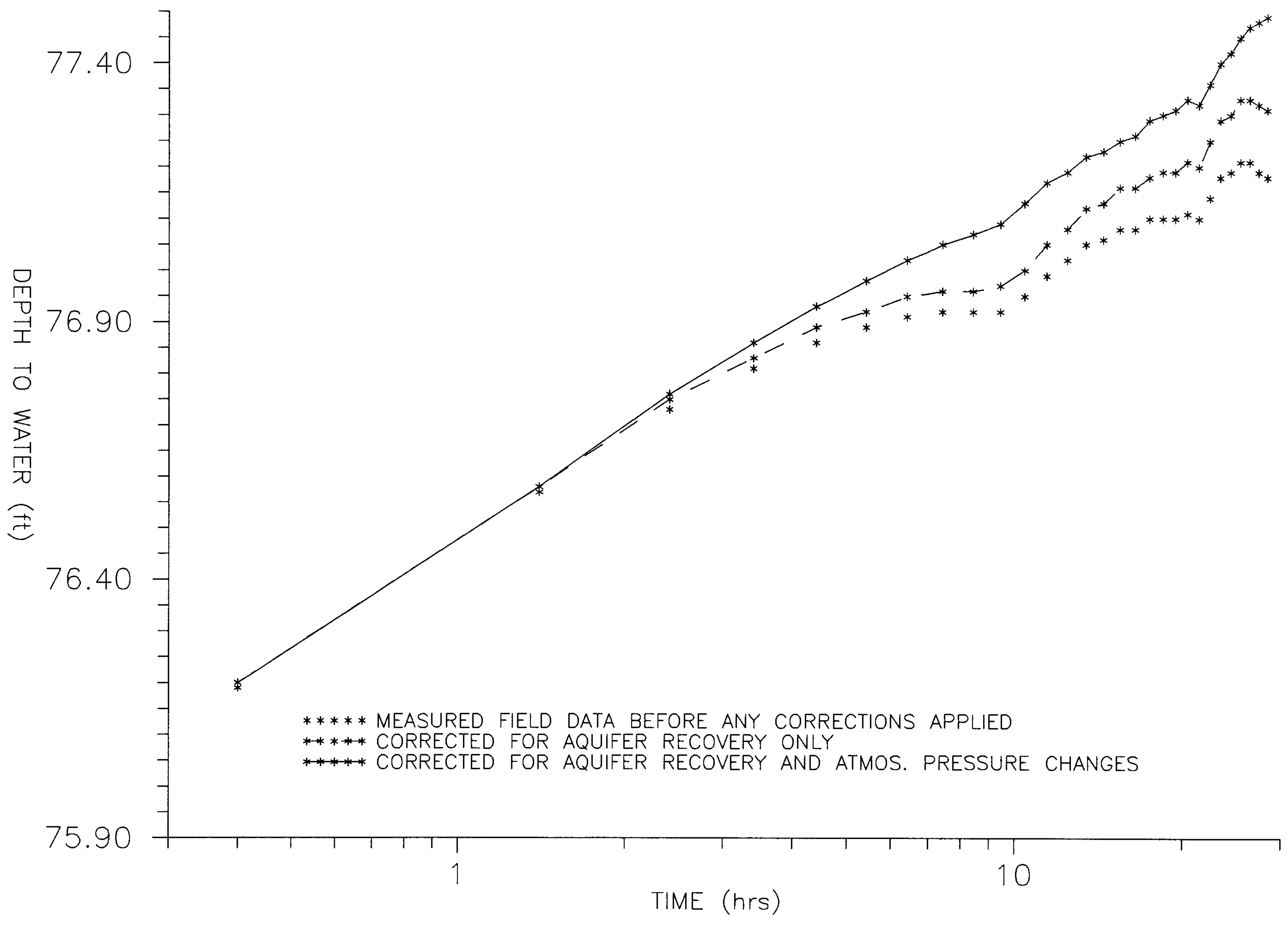


FIGURE 7. Drawdown due to an irrigation well, 1.2, 0.42 miles from 0.1.

4.0 THE PUMPING TEST

4.1 Methodology

Theis (1935) related the drawdown in an observation well to the discharge rate of water from a pumping well using aquifer properties of transmissivity and storativity:

$$s^* = (Q/4\pi T)\ W(u)$$

where W(u) is the "well function," an infinite series given by

$W(u) = \left[\ -.5772 - \ln u + u - u^2/2x2! + u^3/3x3! - u^4/4x4! + \ldots.\right].$

The argument u is given as

$u = r^2S/4Tt.$

In these equations, s* is the drawdown induced in the observation well at a distance, r, from the pumping well after a time, t , of pumping if the well is pumped at a constant rate, Q. T and S are the aquifer properties of transmissivity and storativity respectively.

In applying this solution, it is assumed that flow is in the range of Darcy's Law and that water is discharged instantaneously from storage in the aquifer when pumping begins. It is also assumed that the wells fully penetrate the aquifer, which has constant thickness and negligible slope and is homogeneous and isotropic.

The Theis solution does not consider the possibility of leakage of water from the confining layers above or below the aquifer. Hantush and Jacob (1954) modified the Theis solution to include consideration of leakage from a confining layer:

$$s^* = (Q/4pT)\ W(u, r/B)$$

B is the "leakage factor," given by

$B = (Tb'/K')^{1/2},$

assuming there is only one leaky confining layer, where

b' is the thickness of the confining layer, and

K' is its vertical hydraulic conductivity.

In addition to the assumptions listed above, this Hantush-Jacob solution assumes leakage through the confining layer is vertical and proportional to drawdown, the head in the deposits supplying the leakage is constant, and storage in the confining bed is negligible.

The equation is valid for all values of r_s (radius of well screen), provided that

$$r_s/B < 0.1 \text{ and } t > (30r_s^2S/T)\ [1 - (10r_s/b)^2]$$

In order to determine T, S, and B using the Hantush-Jacob or Theis well functions, drawdown in an observation well should be recorded over a range of time from seconds to hours while the pumping well is discharging at a constant rate. A common method of solution facilitated by modern computing capabilities is to use non-linear regression to estimate the values of T, S, and B that produce synthetic drawdown/time data which most closely match the observed data in terms of the sum of the squared residuals. (The residual is the difference between observed and synthetic drawdown at a particular time.) This method was used to estimate aquifer properties from the pumping-test drawdowns.

Due to the water stored in a well when pumping begins, water will not be released instantaneously from storage in the aquifer and so, at early time, the Hantush-Jacob and Theis well functions are not valid. Walton (1987, p. 3) provides a formula with which to determine the critical time after which pumping well storage becomes insignificant:

$$t_s = (5.4E5\ (r_w^2 - r_c^2))\ /\ T$$

where t_s = critical time (min),

r_w = internal radius of well casing, (ft),

r_c = external radius of drop pipe inside well, (ft) and

T = transmissivity of the aquifer, (gpd/ft).

For well I.1, $r_w = 0.5$ ft, $r_c = 0.25$ ft and T = 57000 gpd/ft (from section 5),

Therefore, using the formula above, $t_s = 1.8$ min.

To insure no well storage effects, final values of T, S, and L were determined using only data from later than 3 minutes into the pumping test (section 5).

4.2 Pumping-Test Data

The pumping test itself began at 14:36 hrs, August 7th, 29.00 hours after I.2 began pumping. The irrigation well, I.1, was pumped at a rate of 592 GPM. During irrigating in July, this rate had been determined to be the normal sustainable pumping rate of the well after several hours of pumping. Initially, the pump was throttled back so as not to exceed this rate while the water level in the well was still high. Total volume pumped was read from the odometer every 5 minutes for the first 30 minutes of the test to determine the pumping rate as accurately as possible and to insure it was constant. No variation in the pumping rate was detected.

The datalogger was programmed to record depths to water to the nearest 0.01 ft at logarithmically increasing time intervals beginning at 0.2 seconds. (Drawdown was calculated to the nearest 0.01 ft for a time t after the onset of pumping by subtracting the initial depth from the depth at time t.) Pumping of I.1 was stopped after 33 hours when drawdown was nearly 9 ft and the time interval between depth measurements was 100 minutes. Eight hours later, pumping was resumed at the same rate for a further 70 hours, during which a maximum drawdown of 11.64 ft was reached. Recovery of the aquifer was then recorded for over 100 hours at a rate of one measurement every 100 minutes for the first 50 hours, dropping to one every 127 minutes for the last 50 hours.

Measured depth to water, drawdown, and compensated drawdown from this nine-day period are tabulated in Appendix 4. Figure 9 shows the fully compensated and original observed drawdown plotted against logarithmic time for the complete nine days of data.

Drawdown was adjusted to compensate for the effects of overall aquifer recovery, drawdown due to I.2, and atmospheric pressure changes. These corrections are described below in section 4.3.

4.3 Corrections Made to Drawdown

4.3 (a) Compensating for I.2

Measured drawdown due to pumping of I.1 was adjusted to remove the effect of I.2.

I.1 began pumping 29.0 hours after I.2 and the drawdown due to I.2 before I.1 began pumping had been determined to be 0.70 ft per log cycle of time (see section 3.3 (b), above). Assuming this rate continues to be remain constant (which is a reasonable assumption after large time), drawdown due to I.2 after I.1 began pumping can be expressed in the following way:

$$s\ (I.2) = 0.70 \times (\log ((t/60)+29.0)-\log 29.0)$$

where t is time (min) since pumping of I.1 began,
log 29 is the log time at the start of pumping of I.1
and log ((t/60)+29.0) is the log time after I.1 has been pumping t minutes.

Drawdown, s' (ft), in O.1 compensated for interference from I.2 can then be expressed in the following way:

$$s' = s - s\ (I.2)$$

where s = drawdown (ft) in O.1 due to I.1 and I.2, calculated directly from measured depths to water. By substituting for s (I.2),

$$s' = s - 0.70 \times (\log ((t/60)+29.0)-\log 29.0).$$

For example, at time, $t = 0$, $s' = s = 0$.

After 1000 minutes of pumping of I.1 ($t = 1000$ min), drawdown in O.1 due to I.2 (s (I.2)) is 0.14 ft, so drawdown due to I.1 (s') is 0.14 ft less than the drawdown directly calculated from measured depth to water(s),

i.e. at t=1000 min, s' = (s - 0.14) ft.
Similarly at t = 2000 min ($33^1/_3$ hrs), s' = (s - 0.23) ft.

This well-interference adjustment decreases all drawdowns 30 minutes or more after pumping began.

4.3 (b) Compensating for Aquifer Recovery

Drawdown was adjusted to remove the effect of aquifer recovery, which was still occuring at a rate of approximately 0.1 ft/day, 17 days after I.1 was last pumped.

The pumping test began 418.6 hours after I.1 was last pumped. The recovery rate per log cycle of time had been determined to be 4.0 ft per log cycle of time between 260 and 352 hours (see section 3.3 (a), above). Assuming this rate per log cycle continues to remain constant, continuing recovery, R, during the pumping test period can be expressed in the following way:

R = 4.0 x (log ((t/60)+418.6) - log 418.6)
where t is time (min) since pumping of I.1 began,
log 418.6 is the log time since recovery began, at the start of pumping of I.1, and
log ((t/60)+418.6) is the log time since recovery began, after I.1 has been pumping t minutes.

Drawdown, s" (ft), compensated for aquifer recovery as well as interference from I.2, can then be expressed as follows:

s" = s' + R.

Substituting for R:

s" = s' + 4.0 x (log ((t/60)+418.6) - log 418.6)
where t is time (min) since pumping of I.1 began.
For example, using this formula, at time, t = 0, s" = s' = s = 0.
After 1000 minutes of pumping of I.1 (t = 1000 min), recovery in O.1 since the pumping test began is 0.07 ft, so drawdown due to I.1 and compensated for recovery (s") is 0.07 ft more than the drawdown compensated for interference from I.2 but not for recovery (s'),
i.e. at t = 1000 min, s" = (s' + 0.07) = (s - 0.07) ft.
Similarly at t = 2000 min ($33^1/_3$hrs), s" = (s' + 0.13) ft = (s - 0.10) ft.

This recovery adjustment had the effect of increasing all drawdowns 90 minutes or more after pumping began.

4.3 (c) Compensating for Atmospheric Pressure Changes

Drawdown was adjusted to remove the effect of atmospheric pressure changes.

Drawdown in O.1 due to an increase in atmospheric pressure is given by the product of the barometric efficiency and the increase in pressure measured in feet of water. The barometric efficiency of the aquifer had previously been determined to be 0.95 (see section 3.3 (a), above). Drawdown was therefore compensated for changes in atmospheric pressure using the following formula:

$$s^* = s'' - 0.95 \times \Delta p_a$$

where Δp_a = difference (in feet of water) between the atmospheric pressure at time t and the atmospheric pressure at the start of the pumping test (Δp_a is positive for increased pressure and negative for decreased pressure), and

s^* = drawdown (ft) compensated for aquifer recovery, interference from I.2, and atmospheric pressure changes, referred to henceforth as the "compensated drawdown."

Atmospheric pressure measurements recorded on charts during the pumping test and values of Δp_a are tabulated in Appendix 5. Values of Δp_a were determined for all times at which depth to water was recorded from a plot of the atmospheric pressure measurements in Appendix 5 (Figure 8).

Examples of the effect of eliminating atmospheric pressure changes during the pumping test are:

at $t = 0$, $s^* = s'' = s' = s = 0$

at $t = 1000$ min, $s^* = (s'' + 0.14)$ ft $= (s' + 0.21) = (s + 0.07)$ ft

and at $t = 2000$ min, $s^* = (s'' + 0.20)$ ft $= (s' + 0.33)$ ft $= (s + 0.10)$ ft.

This pressure adjustment affects all drawdown measurements 24 minutes or more after pumping began. This is due to a sharp decrease in atmospheric pressure coinciding with the first 24 hours of the test (Figure 8). Atmospheric pressure never rose above its initial level throughout the nine days of pumping test data collection. Δp_a was always negative and so all drawdowns after 24 minutes were greater once they were adjusted for the change in atmospheric pressure.

4.5 Results and Interpretation

Determinations of transmissivity, storage, the leakage factor of the confining layer, and approximate boundary conditions were made from the initial period of uninterrupted pumping only, for the following reasons:

1. There is a high density of data from this period; 75% of the drawdown data were collected during the first 2000 minutes (Appendix 4).
2. I.2 was being pumped continuously through this period but the later pumping history of this well is unknown and therefore the correction made to account for pumping of I.2 is unreliable at

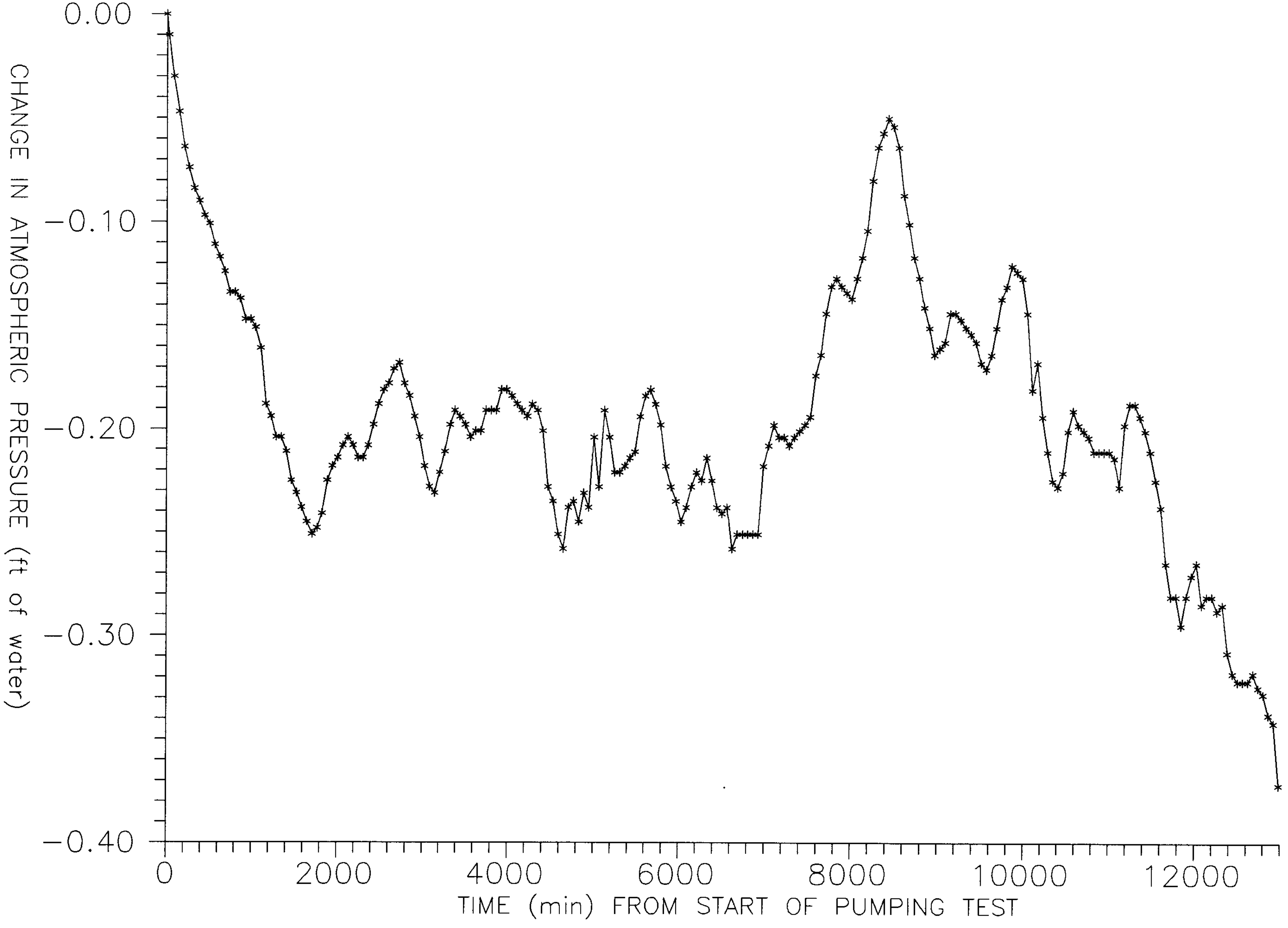


FIGURE 8. Change in atmospheric pressure during the pumping test.

later time. Figure 9 shows significant fluctuations in drawdown during the second period of pumping of I.1 which are probably due to I.2 being switched on and off.

3. It can be seen from Figure 9 and Appendix 4 that the difference between the observed and compensated drawdowns is very small during this period, particularly at early time.

Suprpump (Bohling et al., 1990), a microcomputer software package incorporating the Hantush-Jacob and Theis well functions, was used to analyze the compensated drawdown/time data (see Methodology, above). Suprpump uses non-linear regression to estimate the well function parameters that produce synthetic drawdown/time data which most closely match the observed data in terms of the sum of the squared residuals. The solutions of the well function parameters for various intervals of time are listed in Table 2.

Values of transmissivity, storativity, and leakage coefficient were determined using the leaky artesian Hantush-Jacob function, the theory of which is described above under Methodology. Figure 10 shows the compensated drawdown data points and the computer-generated fitted curve for the period 3 to 1600 minutes using this function. It can be seen from the graph that the match is very good. A simple Theis analysis (Figure 11) of the same data produced a significantly poorer fit in terms of the root mean squared residuals (.08880 compared to .06566).

It was found that when the data from earlier time were also considered using the Hantush-Jacob function, the difference they made to the aquifer properties was less than 3% in the case of transmissivity and storativity and less than 7% in the case of the leakage coefficient.

Figure 12 shows that the synthetic curve of Figure 10, when extended to early time, matches the early compensated drawdown surprisingly well. This is despite the expected effect of pumping well storage. If well storage was important the observed drawdowns would be expected to lie significantly below the computer generated curve at early time.

The best fit to the first 1600 minutes of data was obtained without simulating boundary conditions. Thus, no significant boundary effects were observed in the first 1600 minutes of data. Therefore, final estimates of aquifer parameters were made from the interval 3–1600 minutes. The best fit to the data from the interval 3–2000 minutes was obtained by including parallel no-flow boundaries at a distance of approximately 2 miles. Later drawdowns are increased significantly by boundary or aquifer thinning effects or possibly by well interference from another pumping well. This is particularly obvious (Figure 9) in the upward deviation of the drawdowns recorded later than 3000 minutes. In addition, recovery data recorded after pumping stopped are best matched with synthetic drawdowns using a lower transmissivity than during initial pumping and also simulating two barrier boundaries approximately 2 miles away.

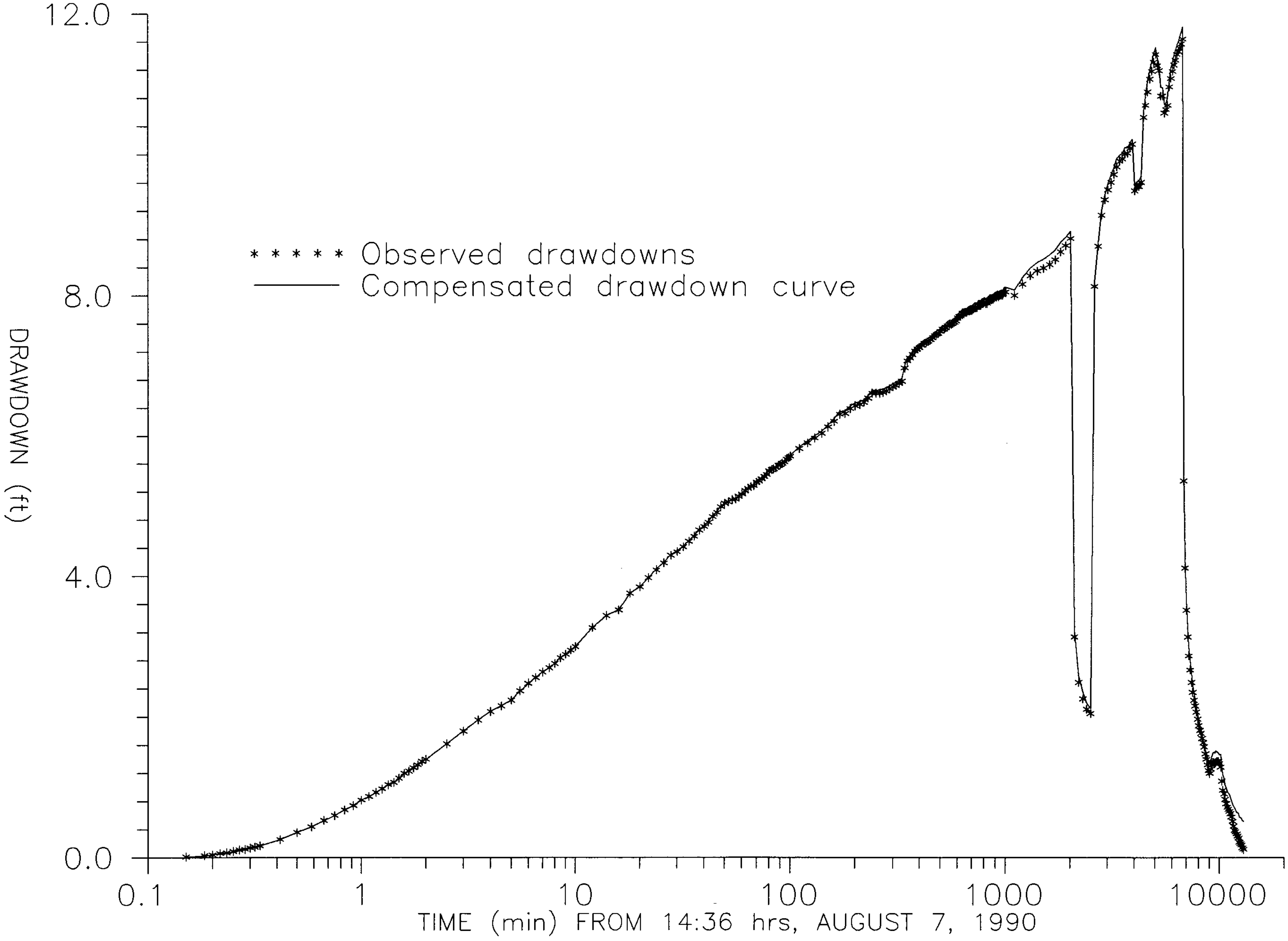


FIGURE 9. Observed and compensated drawdowns over the full nine days of the pumping test.

TABLE 2

Values of aquifer properties determined from the pumping test. Underlined values are set as known quantities.

Period of data considered (min)	Transmissivity, T (ft^2/min)	Storativity, S	Leakage coefficient, L (ft^{-1})	RMS res. (ft)	No-flow boundaries simulated
3-1600	5.643	1.088E-4	Theis; L not considered	.08880	NONE
0-1000	5.368	1.237E-4	.7702E-4	.05997	NONE
0-1600	5.359	1.241E-4	.7955E-4	.06055	NONE
0-2000	5.387	1.229E-4	.7245E-4	.06224	NONE
3-1000	5.315	1.277E-4	.8460E-4	.06531	NONE
3-1600	5.314	1.277E-4	.8506E-4	.06566	NONE
3-2000	5.363	1.249E-4	.7510E-4	.06789	NONE
3-2000	5.304	1.281E-4	.8939E-4	.06655	2, each 2 miles away
6717-9000	4.510	1.277E-4	.4362E-4	.06263	NONE
6717-9000	4.380	1.277E-4	.8073E-4	.04261	2, each 2 miles away

where L is the inverse of the leakage factor, i.e. $L = 1/B = (K'/Tb')^{1/2}$, and RMS res. is the "root mean squared residual" or the quadratic mean difference between observed and synthetic drawdown. It is a measure of how well the synthetic drawdown fits the observed drawdown.

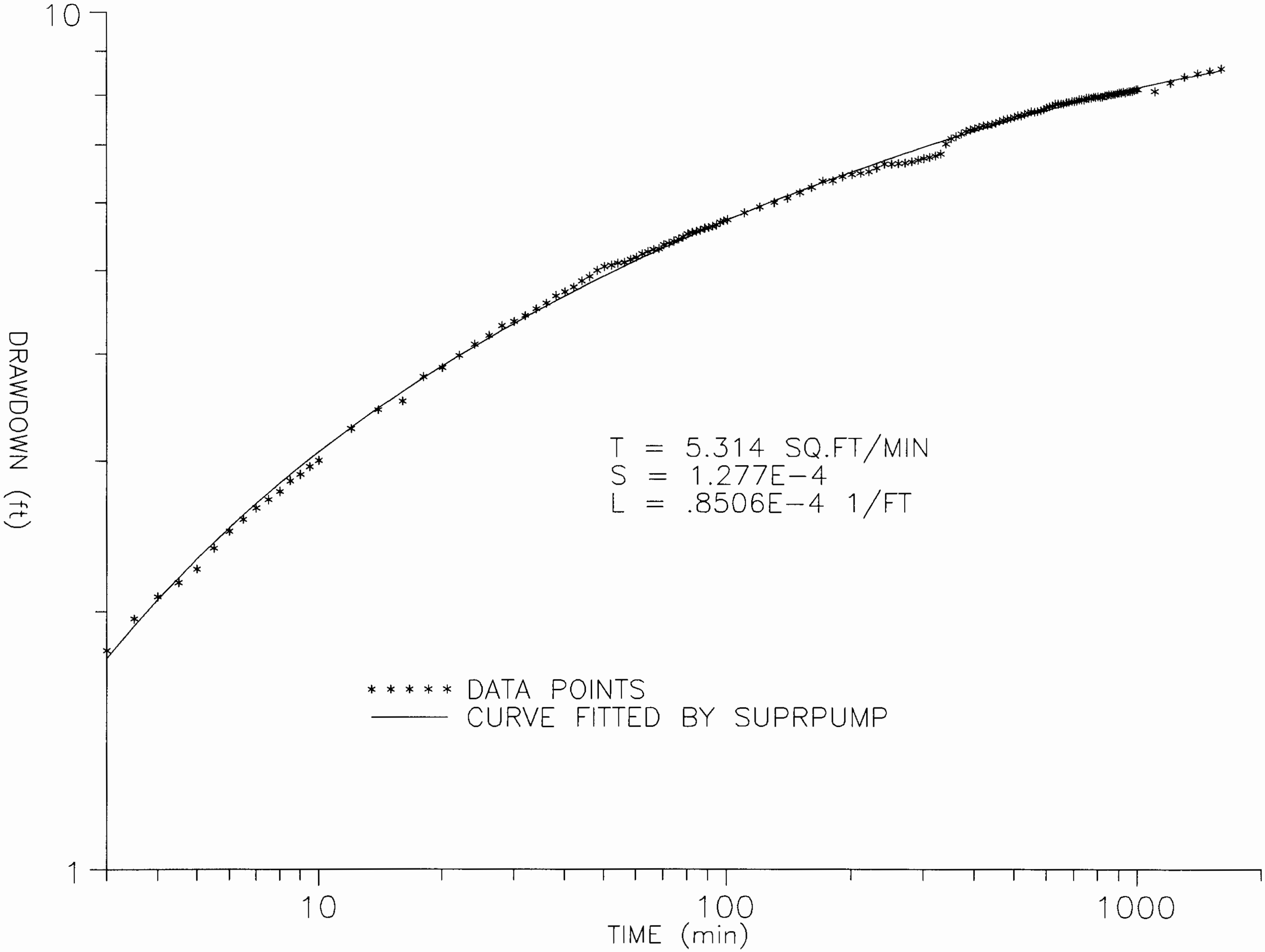


FIGURE 10. Leaky artesian analysis of compensated drawdown between 3 and 1600 minutes of pumping.

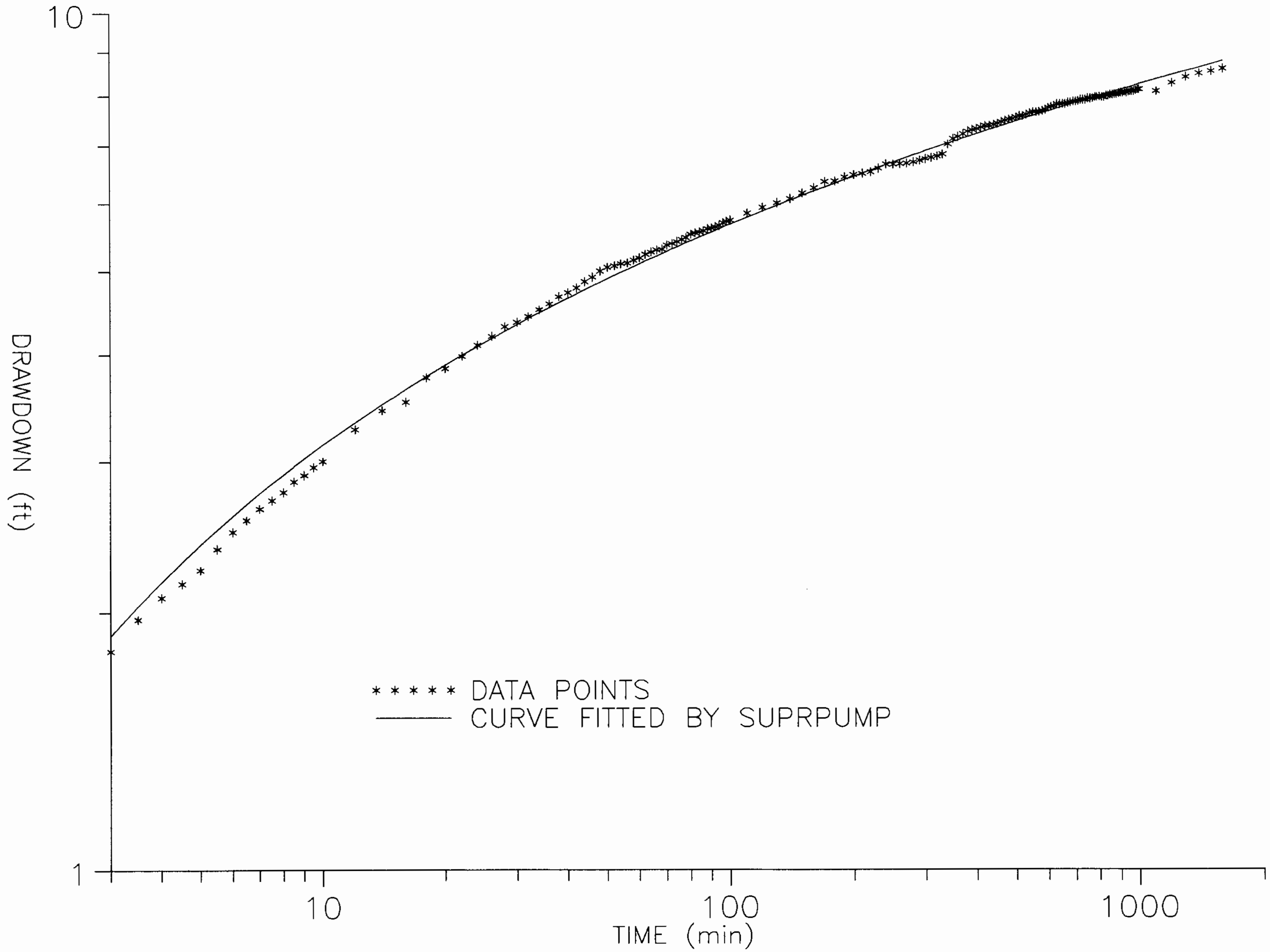


FIGURE 11. Theis analysis of compensated drawdown between 3 and 1600 minutes of pumping (leakage not considered).

These features of the later drawdown and recovery are probably due to the sandstone thinning within approximately 2 miles of the site rather than terminating abruptly. A sudden limit to the extent of the sandstone is unlikely geologically because this sandstone lies at the erosional base of the Dakota Formation which is laterally continuous in test holes in the area (Figure 3b). However, at this site the basal sandstone is exceptionally thick and a thinning of this sandstone within a few thousand feet is therefore likely. This interpretation is supported by the fact that irrigation wells in the area are not scattered universally but are concentrated to the south and west of the site, where the yield is highest, implying that the sandstone thins toward the north and east.

From the data collected between 3 and 1600 minutes,

$T = 5.3(\pm 0.3)\ ft^2/min = 7600\ (\pm 400)\ ft^2/day$

$S = 1.28(\pm 0.06)x10^{-4}$

$L = 0.85(\pm 0.08)x10^{-4}\ ft^{-1}$

The Hantush-Jacob conditions that $r_s/B < 0.1$ and $t > (30r_s{}^2S/T)\ [1 - (10r_s/b)^2]$ were both satisfied for all values of t at which drawdowns were measured.

From $L = 1/B = (k'/Tb')^{1/2}$,

'leakance', k'/b', $= L^2T = 3.8(\pm 0.6)x10^{-8}\ min^{-1}$.

Estimated saturated thickness of mudstone above sandstone aquifer,

b' = 40(±5)ft . (Although hydraulic head in the aquifer before irrigation season was only 15 ft above the top of the aquifer, it is likely that the mudstone above that level is very nearly if not completely saturated.)

Therefore, vertical hydraulic conductivity of confining layer,

$k' = 1.5(\pm 0.4)x10^{-6}ft/min = 2.2(\pm 0.6)x10^{-3}ft/day\ (= 0.81(\pm 0.22)ft/yr)$

$= \underline{0.016(\pm 0.004)gal/day/ft^2}\ (= 6.0(\pm 1.6)\ gal/yr/ft^2)$.

If the saturated thickness of the confining layer is only 18(±3) ft, vertical hydraulic conductivity of the confining layer,

$k' = 6.9(\pm 2.1)x10^{-7}\ ft/min = 9.9(\pm 3.0)x10^{-4}\ ft/day\ (= 0.36(\pm 0.12)ft/yr)$,

$= \underline{7.4(\pm 2.2)x10^{-3}\ gal/day/ft^2}\ (= 2.7(\pm 0.8)\ gal/yr/ft^2)$.

Both of these are reasonable results within the range expected of a clay-rich mudstone.

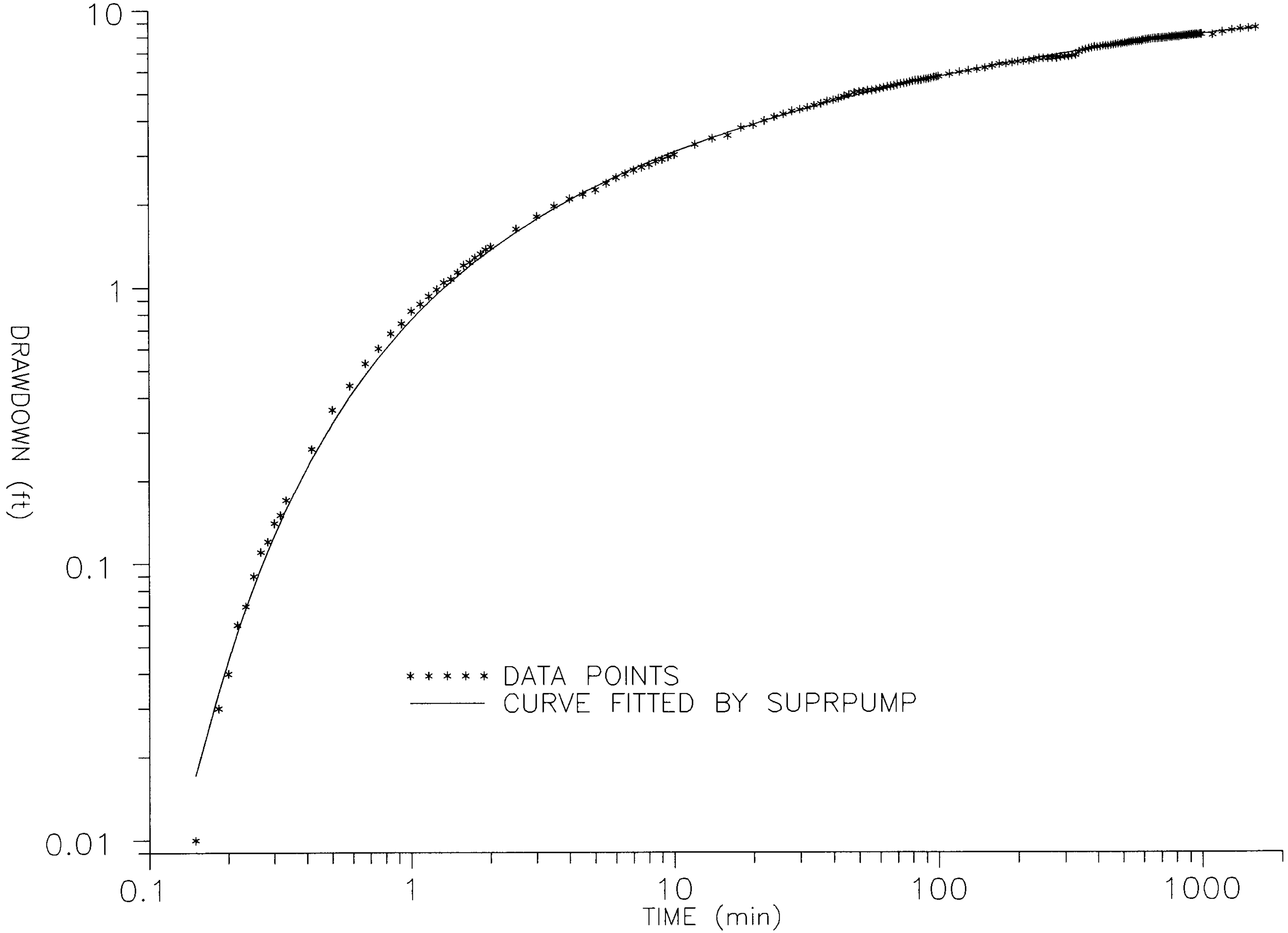


FIGURE 12. Compensated drawdown between 0.15 and 1600 minutes of pumping and the fitted curve from FIGURE 10.

6.0 ERRORS

6.1 Flow Meter

As is often the case in pumping tests, the main source of error in this test is likely to be in the value of the pumping rate. During the first 30 minutes of pumping, in which the pumping rate was determined every five minutes, there was no detectable variation in the rate. However, for the rest of the test the pumping rate was not observed. In theory, in a homogeneous aquifer, the Jacob semilog plot in Figure 9 should follow a straight line after the initial curve at early time but slight deviations from a straight line can be seen in this graph. These changes in gradient are likely to be due to slight fluctuations in the pumping rate but may also reflect inhomogeneities in the aquifer.

Two other factors contributed to error in the flow rate measurement: one was the lack of sufficient straight pipe upstream from the meter to satisfy manufacturers recommendations. Also, a correction factor had to be introduced because the meter was calibrated for a pipe of 5% smaller I.D. The correction factor was based on field measurements made of the I.D. of the pipe when it was cut open during installation of the meter.

The combined effect of these factors is that the pumping rate is not accurate to better than ± 5%,

i.e. Pumping rate = 592 ± 30 GPM.

6.2 Other Pumping Wells

Drawdown due to another pumping well 2200 ft away was noted and corrected for (see error 4 below). Other irrigation wells between 1 and 3 miles away to the south and southwest were not pumping at the time the test was begun. If any of them had been activated during the pumping test, the effects would have probably been seen in the observation well within a few hours. Graph 4 shows there were no significant sudden increases in drawdown during the first 1600 minutes which were attributable to the onset of pumping at one of these wells.

6.3 Transducers

The accuracy of each transducer was checked at various water levels during preliminary testing in July. This was done by comparing the transducer values displayed on the Hermit datalogger with measurements from an electric water level tape. It was found that one transducer was malfunctioning part of the time but the other one was consistently within 0.05 ft of the electric tape measurements. At no time during the collection of water level data did the head above the transducers exceed the range they were designed for and at no time did the water level drop below the level of the transducers. Values of depth to water used for analysis before and during the pumping test were those measured by the transducer which had proved itself to be consistently accurate. Transducer error is not therefore a significant factor in the determination of the aquifer properties.

6.4 Other Influences on Water Level

The combined effect of atmospheric pressure fluctuations, overall aquifer recovery since it was last pumped, and well interference during the pumping test was not cumulative, i.e. they did not all alter the drawdown in the same direction. On the contrary, they cancelled each other out to some extent. In addition, their influence on drawdown was least significant at low time (and not detectable at all before 24 minutes of pumping) and most significant at high time. The early data are the most important in determining values of transmissivity (T) and storativity (S) of the aquifer. Thus, compensating for well I.2, aquifer recovery and atmospheric pressure changes did not significantly affect the values of T and S determined by analysis of the drawdown/time data. However, the leakage factor determined for the confining layer was altered by over 10% when the data were adjusted as described above. This is because leakage effects are only seen at relatively high time in a pumping test.

After adjustments were made to the drawdown data for the three external factors noted above, there was no significant influence on the water level in O.1 other than the pumping of I.1. This means that errors due to external influences on the water level can be discounted.

6.5 Aquifer Parameters Determined by Suprpump

Suprpump calculated the 95% confidence limits of the aquifer properties it determined. These were ± 1% for transmissivity, T, ± 3% for Storativity, S and ± 9% for leakage coefficient, L.

The program, Aquitest (Heidari and Hemmet, 1991), which also estimates aquifer parameters using non-linear regression, was used to check the results. The results obtained for T, S, and L were all within 0.5% of the results obtained using Suprpump.

The assumption that leakage only occured through the upper confining layer may not be true. If there was significant leakage from the Permian shale underlying the aquifer during the pumping test, the value of k' for the upper confining layer determined from L would be a low estimate of the true value.

6.6 Water Level Falling Below Top of Screen

The top of the sandstone aquifer being tested is at a depth of 85.0 ft below ground level, i.e. 87.5 ft below the top of the casing, which is the datum from which depth to water measurements were taken. At no time during the first 33 hours of the pumping test did the water level in the observation well fall below this level.

Thus, the effect of the water level falling below the top of the aquifer was not a factor in this pumping test.

6.7 Vertical Flow

I.1 is screened through the lower 40 ft of the sandstone only (Figure 2). Close to the pumping well shortly after pumping began vertical flow may be significant and this can affect the drawdown in an observation well. O.1 was therefore positioned a large distance from I.1 and was screened throughout the sandstone making the effect of the partially penetrating pumping well negligible.

7.0 CONCLUSIONS

7.1 Aquifer Hydraulic Properties

Horizontal transmissivity, $T = 7600\ (\pm 400)\ \text{ft}^2/\text{day}$
$= 57000\ (\pm 3000)$ gpd/ft

Horizontal hydraulic conductivity, $k = 76\ (\pm 4)$ ft/day
$= 570(\pm 30)\text{gal/day/ft}^2$

This hydraulic conductivity is high for a sandstone- it is more typical of an unconsolidated sand such as Ogallala sand. This is mainly due to the general lack of cement in this sandstone. The poor lithification of the sandstone at the pumping test site is typical of the river channel sandstones of the Dakota Formation. Its grain size is also typical of a sandstone at the base of the formation but is at the high end of the range found in Dakota river channel sandstones in general. Therefore, this hydraulic conductivity can be considered a representative value for the basal sandstone of the formation although it is likely to be greater than the hydraulic conductivity of most sandstones higher in the formation.

The transmissivity, which is directly related to potential well yields, is not normally as great as determined in this test because most fluvial sandstones of the Dakota Formation, including the basal sandstone, are not as thick as the one studied in this pumping test.

Storativity, $S = 1.28(\pm 0.06)\times 10^{-4}$.

Thus, $1.3\times 10^{-6}\ \text{ft}^3$ (0.0012 ounces) of water is released from one cubic foot of the aquifer if the hydraulic head drops by one foot. This is the "specific storage" of the aquifer. This result, although apparently very small, is within the normal range typical of a confined aquifer. Watts (1989) estimated the specific storage of the Dakota aquifer in southwestern Kansas to be 2×10^{-6} ft^{-1}.

Assuming there is no leakage from the Permian shale underlying the sandstone, the leakage coefficient, L of the upper confining layer $=1/B = 0.85(\pm0.08)\times10^{-4}$ ft^{-1}.

For the confining layer, leakance, $k'/b' = 3.8(\pm0.6)\times10^{-8}$ min^{-1}.

Maximum vertical hydraulic conductivity of the confining layer, assuming 40 feet of saturated mudstone immediately overlies the sandstone,

k'= 8 gallons per year per square foot = 1 ft/yr.

This means that recharge of the sandstone aquifer cannot exceed 8 gal/yr/ft^2 (1 ft/yr) through the confining layer. Recharge is likely to be much less than this upper limit because most of the confining layer is probably not completely saturated with water and therefore has a lower hydraulic conductivity than this.

However, if there was any significant leakage from the underlying Permian shale during the pumping test, the maximum k' of the upper confining layer would be greater than the 1 ft/yr estimated above.

7.2 Thickness and Extent of Aquifer

The sandstone aquifer at the site of this pumping test is 100 ft thick. Drawdown during pumping and recovery later than 1600 minutes was affected as if no-flow boundaries were present several thousand feet from the site. Recovery data recorded after pumping stopped are consistent with a lower transmissivity than during initial pumping. This is probably due to the sandstone thinning within 2 miles of the site rather than terminating abruptly. A sudden limit to the extent of the sandstone is unlikely geologically because this sandstone is the basal sandstone of the Dakota Formation, which in test holes in the area is laterally continuous although variable in thickness.

7.3 Compensated Drawdown.

The combined effect of well interference, aquifer recovery, and atmospheric pressure changes on the drawdown during the pumping test was not cumulative. On the contrary, by chance these factors cancelled each other out to some extent; the decrease in atmospheric pressure and the continuing recovery from a previous period of pumping raised the water level whereas well interference from another pumping well lowered the water level. In addition, their influence on drawdown was least significant at low time (and not detectable at all before 24 minutes of pumping) and most significant at high time.

Thus, compensating drawdowns for the factors listed above did not significantly affect the values of T and S determined by analysis of early drawdown/time data.

However, the leakage factor determined for the confining layer was altered by over 10% when the data were adjusted as described above. This is because leakage effects are only significant at relatively high time in a pumping test.

7.4 Barometric Efficiency and Aquifer Storativity

The storativity (S) of the aquifer determined from the pumping test was three times the value of the storativity estimated from an equation linking S to the barometric efficiency of the aquifer. The barometric efficiency method is therefore not an accurate way of determining S, although it is useful in estimating its order of magnitude.

7.5 Current Water Use and its Impact on the Aquifer

Water is currently being pumped from the Dakota aquifer in T. 5S, R. 1E of southwestern Washington County at a rate of several hundred acre-feet per year. However, there has only been a slight drop in water levels in the aquifer in this township since most of the irrigation wells were constructed in the 1970s and early 1980s. Therefore the aquifer must be receiving recharge of several hundred acre feet per year. Leakage through the confining layer in this township alone could not account for all this recharge. It is likely that much of the recharge to the sandstone in southwestern Washington County originally enters the aquifer in topographically higher areas in the west-central part of the county (where ground-water usage is relatively low) and flows toward the south through interconnected sandstones, ultimately discharging into the Republican River valley aquifer.

ACKNOWLEDGMENTS

Allen Macfarlane provided the inspiration for this project and contributed with much helpful advice from the planning stage to the writing stage.

In the field, the KGS drill crew, lead by Joe Anderson and Mel Kleinschmidt, drilled the observation well in addition to all the other test holes listed in table 1. John Healey logged the holes, fitted the flow meter to the irrigation well and developed the observation well. The pumping test could not have been performed without the preliminary work of these professionals as well as the full cooperation of landowners Jim and John Leiszler.

During the analysis of the drawdown, Geoff Bohling kindly supplied customized variations of his program, Suprpump, which helped in the consideration of boundary conditions in particular.

Allen Macfarlane, Manoutch Heidari, Carl McElwee, and Janet Coleman reviewed the manuscript. I thank them for their time and their suggestions which helped improve the paper.

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REFERENCES

Bohling, G.C., C. D. McElwee, J.J. Butler, and W. Liu, 1990, Users guide to well test design and analysis with Suprpump Version 1.0: Kansas Geological Survey Computer Program Series #93.

Hantush, M.S., and C.E. Jacob, 1954, Plane potential flow of ground-water with linear linkage: Transactions, American Geophysical Union, 35, p. 917-936

Heidari, M., and M. Hemmet, 1991, Aquitest, software to conduct automated aquifer test analysis: unpublished report.

Macfarlane, P.A., A. Wade, J.H. Doveton, and V.J. Hamilton, 1991, Revised stratigraphic interpretation and implications for pre-Graneros paleogeography from test-hole drilling in central Kansas: Kansas Geological Survey Open-file Report 91-1A, 73 p.

Macfarlane, P.A., D.O. Whittemore, M.A. Townsend, J.J. Butler Jr., J.H Doveton, V.J. Hamilton, J. Coleman, T.M. Chu, A. Wade, and G.L. Macpherson, 1991, The Dakota Aquifer Program: Annual Report, FY90: Kansas Geological Survey Open-file Report 91-1, 42p.

Todd, D.K., 1967, Ground Water Hydrology: John Wiley & Sons, 336 p.

Theis, C.V., 1935, The lowering of the piezometric surface and the rate and discharge of a well using ground-water storage: Transactions, American Geophysical Union, 16, p. 519-524.

Watts, K.R., 1989, Potential hydrologic effects of ground-water withdrawals from the Dakota aquifer, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2304, 47 p.

Walton, W.C., 1987, Groundwater pumping tests, design and analysis: Lewis, 201 p.

APPENDIX 1

Atmospheric pressure recorded using a barograph located 1/4 of a mile from the observation well during the first week of August 1990.

TIME (hrs) from 00:00 hrs, August 1	ATMOSPHERIC PRESSURE (mb)	ATMOSPHERIC PRESSURE (ft of water)
0	1019.3	34.157
2	1019.4	34.160
4	1019.4	34.160
6	1019.0	34.147
8	1019.5	34.163
10	1019.8	34.173
12	1019.4	34.160
14	1018.6	34.133
16	1017.8	34.106
18	1016.6	34.066
20	1015.6	34.033
22	1015.2	34.019
24	1015.8	34.039
26	1016.1	34.050
28	1015.5	34.029
30	1015.5	34.029
32	1016.2	34.053
34	1015.6	34.033
36	1014.5	33.996
38	1014.3	33.989
40	1013.4	33.959
42	1012.2	33.919
44	1013.5	33.962
46	1014.7	34.003
48	1015.0	34.013
50	1014.6	33.999
52	1014.4	33.993
54	1013.7	33.969

56	1013.3	33.956
58	1013.9	33.976
60	1014.4	33.993
62	1014.2	33.986
64	1014.2	33.986
66	1013.1	33.949
68	1014.2	33.986
70	1014.4	33.993
72	1014.3	33.989
74	1015.5	34.029
76	1015.7	34.036
78	1015.9	34.043
80	1016.9	34.076
82	1018.0	34.113
84	1018.4	34.127
86	1018.7	34.137
88	1018.9	34.143
90	1019.2	34.153
92	1019.2	34.153
94	1020.1	34.184
96	1022.0	34.247
98	1022.6	34.267
100	1023.2	34.287
102	1024.0	34.314
104	1024.6	34.334
106	1025.4	34.361
108	1027.0	34.415
111	1026.6	34.401
113	1026.3	34.391
115	1026.0	34.381
117	1026.8	34.408
119	1027.7	34.438
121	1027.7	34.438
123	1028.0	34.448
125	1028.4	34.462
127	1028.8	34.475

129	1029.7	34.505
130	1029.8	34.509
131	1029.7	34.505
132	1029.4	34.495
133	1028.9	34.478
134	1028.4	34.462
135	1027.8	34.442
136	1027.5	34.432
137	1026.8	34.408
138	1026.3	34.391
139	1025.9	34.378
140	1025.8	34.375
141	1026.0	34.381
142	1026.2	34.388
143	1026.5	34.398
144	1026.5	34.398
145	1026.6	34.401
146	1026.5	34.398
147	1026.4	34.395
148	1026.3	34.391
149	1026.1	34.385
150	1025.9	34.378
151	1026.0	34.381
152	1026.2	34.388
153	1026.2	34.388
154	1026.0	34.381
155	1025.8	34.375
156	1025.5	34.365
157	1024.6	34.334
158 (14:00 hrs, August 7)	1024.0	34.314

APPENDIX 2

Depths to water in O.1 during a period of no pumping of the aquifer.

t = time from 00:00 hrs August 1, 1990,

d = depth to water in observation well O.1, measured by transducer from top of casing and recorded on the datalogger,

d' = depth to water from top of casing, adjusted to remove the effect of aquifer recovery.

t (ft)	d (ft)	d' (ft)
0	76.42	76.42
1	76.42	76.43
2	76.40	76.41
3	76.40	76.42
4	76.38	76.41
5	76.37	76.40
6	76.37	76.41
7	76.37	76.42
8	76.37	76.42
9	76.37	76.43
10	76.35	76.42
11	76.35	76.42
12	76.32	76.40
13	76.31	76.40
14	76.27	76.36
15	76.26	76.36
16	76.23	76.33
17	76.21	76.32
18	76.19	76.31
19	76.16	76.28
20	76.15	76.28
21	76.13	76.27
22	76.13	76.27
23	76.13	76.28
24	76.16	76.31
25	76.15	76.31

26	76.12	76.29
27	76.10	76.27
28	76.08	76.26
29	76.08	76.26
30	76.08	76.27
31	76.08	76.28
32	76.10	76.30
33	76.07	76.28
34	76.07	76.28
35	76.05	76.27
36	76.02	76.25
37	76.02	76.25
38	76.00	76.24
39	75.97	76.21
40	75.94	76.19
41	75.93	76.19
42	75.94	76.20
43	75.89	76.16
44	75.96	76.23
45	75.97	76.25
46	75.96	76.24
47	75.97	76.26
48	75.97	76.27
49	75.96	76.26
50	75.94	76.25
51	75.93	76.24
52	75.91	76.23
53	75.91	76.23
54	75.88	76.21
55	75.86	76.20
56	75.89	76.23
57	75.89	76.24
58	75.89	76.24
59	75.89	76.25
60	75.89	76.25
61	75.88	76.25

62	75.88	76.25
63	75.88	76.26
64	75.85	76.23
65	75.83	76.22
66	75.83	76.23
67	75.85	76.25
68	75.85	76.26
69	75.85	76.26
70	75.85	76.27
71	75.83	76.25
72	75.85	76.28
73	75.86	76.29
74	75.86	76.30
75	75.85	76.29
76	75.85	76.30
77	75.85	76.30
78	75.86	76.32
79	75.86	76.32
80	75.88	76.35
81	75.89	76.36
82	75.91	76.39
83	75.91	76.39
84	75.91	76.40
85	75.91	76.40
86	75.91	76.41
87	75.91	76.41
88	75.89	76.40
89	75.89	76.40
90	75.89	76.41
91	75.88	76.40
92	75.89	76.42
93	75.91	76.44
94	75.93	76.47
95	75.94	76.48
96	75.96	76.51
97	75.96	76.51

98	75.96	76.52
99	75.96	76.52
100	75.96	76.53
101	75.97	76.54
102	75.97	76.55
103	75.99	76.57
104	75.99	76.58
105	76.00	76.59
106	76.02	76.62
107	76.02	76.62
108	76.02	76.63
109	76.00	76.61
110	76.00	76.62
111	75.99	76.61
112	75.97	76.60
113	75.96	76.59
114	75.94	76.58
115	75.94	76.58
116	75.93	76.58
117	75.93	76.58
118	75.94	76.59
119	75.96	76.62
120	75.96	76.62
121	75.96	76.63
122	75.94	76.61
123	75.94	76.62
124	75.94	76.62
125	75.94	76.63
126	75.94	76.63
127	75.96	76.66
128	75.96	76.66
129 (09:00 hrs, August 6)	75.97	76.67

APPENDIX 3

Depths to water in the observation well during pumping of irrigation well I.2, 2200 ft away.

t = time from 09:36 hrs August 6, 1990,

d = depth to water measured by transducer from top of casing and recorded on the datalogger,

d' = depth to water from top of casing, adjusted to remove the effect of aquifer recovery

d" = depth to water from top of casing, adjusted to remove the effect of aquifer recovery and atmospheric pressure changes

t (hrs)	d (ft)	d' (ft)	d" (ft)
0.0	75.97	75.97	75.97
0.4	76.19	76.20	76.20
1.4	76.57	76.58	76.58
2.4	76.73	76.75	76.76
3.4	76.81	76.83	76.86
4.4	76.86	76.89	76.93
5.4	76.89	76.92	76.98
6.4	76.91	76.95	77.02
7.4	76.92	76.96	77.05
8.4	76.92	76.96	77.07
9.4	76.92	76.97	77.09
10.4	76.95	77.00	77.13
11.4	76.99	77.05	77.17
12.4	77.02	77.08	77.19
13.4	77.05	77.12	77.22
14.4	77.06	77.13	77.23
15.4	77.08	77.16	77.25
16.4	77.08	77.16	77.26
17.4	77.10	77.18	77.29
18.4	77.10	77.19	77.30
19.4	77.10	77.19	77.31
20.4	77.11	77.21	77.33
21.4	77.10	77.20	77.32
22.4	77.14	77.25	77.36
23.4	77.18	77.29	77.40

24.4	77.19	77.30	77.42
25.4	77.21	77.33	77.45
26.4	77.21	77.33	77.47
27.4	77.19	77.32	77.48
28.4	77.18	77.31	77.49

APPENDIX 4

Depth to water and drawdown in observation well during pumping test, i.e. during pumping of I.1.

t = time from 14:36 hrs August 7, 1990,
d = depth to water measured by transducer from top of casing and recorded on the datalogger,
s = drawdown calculated directly from recorded depth to water,
s' = drawdown compensated for interference from I.2,
s" = drawdown compensated for aquifer recovery as well as interference from I.2
s*= drawdown compensated for aquifer recovery, interference from I.2 and atmospheric pressure changes, i.e. the "compensated drawdown."

t (mins)	d (ft)	s (ft)	s' (ft)	s" (ft)	s*(ft)
0.000	77.18	0.00	0.00	0.00	0.00
0.003	77.18	0.00	0.00	0.00	0.00
0.007	77.18	0.00	0.00	0.00	0.00
0.010	77.18	0.00	0.00	0.00	0.00
0.013	77.18	0.00	0.00	0.00	0.00
0.017	77.18	0.00	0.00	0.00	0.00
0.020	77.18	0.00	0.00	0.00	0.00
0.023	77.18	0.00	0.00	0.00	0.00
0.027	77.18	0.00	0.00	0.00	0.00
0.030	77.18	0.00	0.00	0.00	0.00
0.033	77.18	0.00	0.00	0.00	0.00
0.050	77.18	0.00	0.00	0.00	0.00
0.067	77.18	0.00	0.00	0.00	0.00
0.083	77.18	0.00	0.00	0.00	0.00
0.10	77.18	0.00	0.00	0.00	0.00
0.12	77.19	0.01	0.01	0.01	0.01
0.13	77.19	0.01	0.01	0.01	0.01
0.15	77.19	0.01	0.01	0.01	0.01
0.17	77.21	0.03	0.03	0.03	0.03
0.18	77.21	0.03	0.03	0.03	0.03
0.20	77.22	0.04	0.04	0.04	0.04
0.22	77.24	0.06	0.06	0.06	0.06

0.23	77.25	0.07	0.07	0.07	0.07
0.25	77.27	0.09	0.09	0.09	0.09
0.27	77.29	0.11	0.11	0.11	0.11
0.28	77.30	0.12	0.12	0.12	0.12
0.30	77.32	0.14	0.14	0.14	0.14
0.32	77.33	0.15	0.15	0.15	0.15
0.33	77.35	0.17	0.17	0.17	0.17
0.42	77.44	0.26	0.26	0.26	0.26
0.50	77.54	0.36	0.36	0.36	0.36
0.58	77.62	0.44	0.44	0.44	0.44
0.67	77.71	0.53	0.53	0.53	0.53
0.75	77.78	0.60	0.60	0.60	0.60
0.83	77.86	0.68	0.68	0.68	0.68
0.92	77.92	0.74	0.74	0.74	0.74
1.00	78.00	0.82	0.82	0.82	0.82
1.08	78.05	0.87	0.87	0.87	0.87
1.17	78.11	0.93	0.93	0.93	0.93
1.25	78.16	0.98	0.98	0.98	0.98
1.33	78.22	1.04	1.04	1.04	1.04
1.42	78.25	1.07	1.07	1.07	1.07
1.50	78.31	1.13	1.13	1.13	1.13
1.58	78.38	1.20	1.20	1.20	1.20
1.67	78.41	1.23	1.23	1.23	1.23
1.75	78.46	1.28	1.28	1.28	1.28
1.83	78.50	1.32	1.32	1.32	1.32
1.92	78.55	1.37	1.37	1.37	1.37
2.00	78.58	1.40	1.40	1.40	1.40
2.50	78.80	1.62	1.62	1.62	1.62
3.00	78.98	1.80	1.80	1.80	1.80
3.50	79.14	1.96	1.96	1.96	1.96
4.00	79.26	2.08	2.08	2.08	2.08
4.50	79.34	2.16	2.16	2.16	2.16
5.00	79.42	2.24	2.24	2.24	2.24
5.50	79.55	2.37	2.37	2.37	2.37
6.00	79.66	2.48	2.48	2.48	2.48
6.50	79.74	2.56	2.56	2.56	2.56

7.00	79.82	2.64	2.64	2.64	2.64
7.50	79.88	2.70	2.70	2.70	2.70
8.00	79.94	2.76	2.76	2.76	2.76
8.50	80.02	2.84	2.84	2.84	2.84
9.00	80.07	2.89	2.89	2.89	2.89
9.50	80.13	2.95	2.95	2.95	2.95
10.0	80.18	3.00	3.00	3.00	3.00
12.0	80.45	3.27	3.27	3.27	3.27
14.0	80.62	3.44	3.44	3.44	3.44
16.0	80.70	3.52	3.52	3.52	3.52
18.0	80.94	3.76	3.76	3.76	3.76
20.0	81.03	3.85	3.85	3.85	3.85
22.0	81.16	3.98	3.98	3.98	3.98
24.0	81.27	4.09	4.09	4.09	4.10
26.0	81.37	4.19	4.19	4.19	4.20
28.0	81.48	4.30	4.30	4.30	4.31
30.0	81.53	4.35	4.34	4.35	4.36
32.0	81.60	4.42	4.41	4.42	4.43
34.0	81.68	4.50	4.49	4.50	4.51
36.0	81.75	4.57	4.56	4.57	4.58
38.0	81.84	4.66	4.65	4.66	4.67
40.0	81.89	4.71	4.70	4.71	4.72
42.0	81.95	4.77	4.76	4.77	4.78
44.0	82.03	4.85	4.84	4.85	4.86
46.0	82.09	4.91	4.90	4.91	4.92
48.0	82.17	4.99	4.98	4.99	5.00
50.0	82.22	5.04	5.03	5.03	5.05
52.0	82.24	5.06	5.05	5.05	5.07
54.0	82.27	5.09	5.08	5.08	5.10
56.0	82.28	5.10	5.09	5.09	5.11
58.0	82.32	5.14	5.13	5.13	5.15
60.0	82.35	5.17	5.16	5.16	5.18
62.0	82.40	5.22	5.21	5.21	5.23
64.0	82.43	5.25	5.24	5.24	5.26
66.0	82.46	5.28	5.27	5.27	5.29
68.0	82.47	5.29	5.28	5.28	5.30

70.0	82.52	5.34	5.33	5.33	5.36
72.0	82.54	5.36	5.35	5.35	5.38
74.0	82.57	5.39	5.38	5.38	5.41
76.0	82.60	5.42	5.41	5.41	5.44
78.0	82.63	5.45	5.44	5.44	5.47
80.0	82.68	5.50	5.49	5.49	5.52
82.0	82.70	5.52	5.51	5.51	5.54
84.0	82.71	5.53	5.52	5.52	5.55
86.0	82.73	5.55	5.54	5.54	5.57
88.0	82.76	5.58	5.57	5.57	5.60
90.0	82.77	5.59	5.57	5.58	5.61
92.0	82.79	5.61	5.59	5.60	5.63
94.0	82.81	5.63	5.61	5.62	5.65
96.0	82.85	5.67	5.65	5.66	5.69
98.0	82.87	5.69	5.67	5.68	5.71
100	82.89	5.71	5.69	5.70	5.73
110	83.00	5.82	5.80	5.81	5.84
120	83.08	5.90	5.88	5.89	5.93
130	83.15	5.97	5.95	5.96	6.00
140	83.22	6.04	6.02	6.03	6.07
150	83.31	6.13	6.10	6.12	6.16
160	83.39	6.21	6.18	6.19	6.25
170	83.49	6.31	6.28	6.29	6.35
180	83.50	6.32	6.29	6.30	6.36
190	83.57	6.39	6.36	6.37	6.43
200	83.61	6.43	6.40	6.41	6.47
210	83.63	6.45	6.42	6.43	6.49
220	83.66	6.48	6.44	6.46	6.52
230	83.72	6.54	6.50	6.52	6.58
240	83.79	6.61	6.57	6.59	6.65
250	83.79	6.61	6.57	6.59	6.65
260	83.79	6.61	6.57	6.59	6.66
270	83.80	6.62	6.58	6.59	6.67
280	83.82	6.64	6.59	6.61	6.69
290	83.85	6.67	6.62	6.64	6.72
300	83.88	6.70	6.65	6.67	6.75

310	83.90	6.72	6.67	6.69	6.77
320	83.93	6.75	6.70	6.72	6.80
330	83.96	6.78	6.73	6.75	6.83
340	84.15	6.97	6.92	6.94	7.02
350	84.25	7.07	7.01	7.04	7.12
360	84.29	7.11	7.05	7.08	7.16
370	84.34	7.16	7.10	7.13	7.21
380	84.39	7.21	7.15	7.18	7.26
390	84.42	7.24	7.18	7.21	7.29
400	84.44	7.26	7.20	7.22	7.31
410	84.47	7.29	7.23	7.25	7.34
420	84.50	7.32	7.25	7.28	7.37
430	84.51	7.33	7.26	7.29	7.38
440	84.53	7.35	7.28	7.31	7.40
450	84.55	7.37	7.30	7.33	7.42
460	84.58	7.40	7.33	7.36	7.45
470	84.61	7.43	7.36	7.39	7.48
480	84.63	7.45	7.38	7.41	7.50
490	84.64	7.46	7.38	7.42	7.51
500	84.67	7.49	7.41	7.45	7.54
510	84.70	7.52	7.44	7.48	7.57
520	84.70	7.52	7.44	7.48	7.57
530	84.72	7.54	7.46	7.50	7.60
540	84.75	7.57	7.49	7.53	7.63
550	84.77	7.59	7.51	7.54	7.65
560	84.77	7.59	7.51	7.54	7.65
570	84.78	7.60	7.51	7.55	7.66
580	84.80	7.62	7.53	7.57	7.68
590	84.82	7.64	7.55	7.59	7.70
600	84.86	7.68	7.59	7.63	7.74
610	84.88	7.70	7.61	7.65	7.76
620	84.89	7.71	7.62	7.66	7.77
630	84.93	7.75	7.66	7.70	7.81
640	84.93	7.75	7.65	7.70	7.81
650	84.94	7.76	7.66	7.71	7.82
660	84.94	7.76	7.66	7.71	7.82

670	84.96	7.78	7.68	7.73	7.84
680	84.96	7.78	7.68	7.73	7.85
690	84.97	7.79	7.69	7.74	7.86
700	84.97	7.79	7.69	7.74	7.86
710	84.99	7.81	7.71	7.75	7.88
720	85.01	7.83	7.72	7.77	7.90
730	85.01	7.83	7.72	7.77	7.90
740	85.01	7.83	7.72	7.77	7.90
750	85.04	7.86	7.75	7.80	7.93
760	85.04	7.86	7.75	7.80	7.93
770	85.05	7.87	7.76	7.81	7.94
780	85.07	7.89	7.78	7.83	7.96
790	85.07	7.89	7.78	7.83	7.96
800	85.08	7.90	7.79	7.84	7.97
810	85.07	7.89	7.77	7.83	7.96
820	85.07	7.89	7.77	7.83	7.96
830	85.10	7.92	7.80	7.86	7.99
840	85.10	7.92	7.80	7.86	7.99
850	85.12	7.94	7.82	7.88	8.01
860	85.12	7.94	7.82	7.88	8.01
870	85.13	7.95	7.83	7.89	8.02
880	85.13	7.95	7.83	7.89	8.02
890	85.15	7.97	7.84	7.91	8.04
900	85.16	7.98	7.85	7.91	8.05
910	85.16	7.98	7.85	7.91	8.05
920	85.18	8.00	7.87	7.93	8.07
930	85.16	7.98	7.85	7.91	8.05
940	85.18	8.00	7.87	7.93	8.07
950	85.19	8.01	7.88	7.94	8.08
960	85.19	8.01	7.88	7.94	8.08
970	85.19	8.01	7.88	7.94	8.08
980	85.21	8.03	7.89	7.96	8.10
990	85.23	8.05	7.91	7.98	8.12
1000	85.23	8.05	7.91	7.98	8.12
1100	85.18	8.00	7.85	7.93	8.08
1200	85.34	8.16	8.00	8.08	8.26

1300	85.46	8.28	8.11	8.20	8.39
1400	85.53	8.35	8.17	8.27	8.47
1500	85.57	8.39	8.20	8.30	8.52
1600	85.62	8.44	8.24	8.35	8.58
1700	85.69	8.51	8.30	8.42	8.65
1800	85.80	8.62	8.40	8.53	8.76
1900	85.89	8.71	8.49	8.61	8.83
2000	85.99	8.81	8.58	8.71	8.91
2100	80.32	3.14	2.90	3.04	3.24
2200	79.67	2.49	2.24	2.39	2.59
2300	79.44	2.26	2.00	2.16	2.36
2400	79.29	2.11	1.85	2.01	2.20
2500	79.23	2.05	1.78	1.95	2.12
2600	85.31	8.13	7.85	8.02	8.19
2700	85.88	8.70	8.42	8.59	8.75
2800	86.32	9.14	8.85	9.03	9.21
2900	86.54	9.36	9.06	9.25	9.44
3000	86.68	9.50	9.20	9.39	9.59
3100	86.79	9.61	9.30	9.50	9.72
3200	86.90	9.72	9.40	9.61	9.82
3300	87.01	9.83	9.51	9.72	9.95
3400	87.09	9.91	9.58	9.80	9.99
3500	87.12	9.94	9.60	9.83	10.02
3600	87.19	10.01	9.67	9.90	10.10
3700	87.20	10.02	9.67	9.91	10.10
3800	87.27	10.09	9.74	9.98	10.17
3900	87.33	10.15	9.79	10.05	10.22
4000	86.67	9.49	9.13	9.39	9.56
4100	86.73	9.55	9.18	9.45	9.62
4200	86.73	9.55	9.18	9.45	9.63
4300	86.79	9.61	9.23	9.51	9.69
4400	87.71	10.53	10.15	10.43	10.62
4500	87.88	10.70	10.31	10.60	10.82
4600	88.07	10.89	10.50	10.79	11.03
4700	88.25	11.07	10.67	10.97	11.20
4800	88.36	11.18	10.78	11.08	11.31

4900	88.49	11.31	10.90	11.21	11.44
5000	88.60	11.42	11.01	11.33	11.52
5100	88.44	11.26	10.84	11.17	11.36
5200	88.37	11.19	10.77	11.10	11.30
5300	88.01	10.83	10.41	10.74	10.95
5400	88.01	10.83	10.40	10.74	10.95
5500	87.77	10.59	10.16	10.50	10.70
5600	87.82	10.64	10.20	10.55	10.73
5700	87.88	10.70	10.26	10.62	10.79
5800	88.14	10.96	10.51	10.88	11.07
5900	88.26	11.08	10.63	11.00	11.22
6000	88.36	11.18	10.73	11.10	11.33
6100	88.45	11.27	10.81	11.19	11.42
6200	88.52	11.34	10.88	11.26	11.48
6300	88.60	11.42	10.95	11.35	11.55
6400	88.64	11.46	10.99	11.39	11.60
6500	88.69	11.51	11.04	11.44	11.67
6600	88.75	11.57	11.09	11.50	11.74
6700	88.82	11.64	11.16	11.57	11.81
6800	82.54	5.36	4.88	5.30	5.53
6900	81.30	4.12	3.63	4.06	4.30
7000	80.70	3.52	3.03	3.46	3.66
7100	80.32	3.14	2.65	3.08	3.27
7200	80.05	2.87	2.37	2.81	3.01
7300	79.85	2.67	2.17	2.62	2.81
7400	79.67	2.49	1.99	2.44	2.63
7500	79.53	2.35	1.84	2.30	2.49
7600	79.42	2.24	1.73	2.19	2.35
7700	79.34	2.16	1.65	2.11	2.25
7800	79.25	2.07	1.55	2.03	2.15
7900	79.15	1.97	1.45	1.93	2.05
8000	79.06	1.88	1.36	1.84	1.97
8100	78.99	1.81	1.28	1.77	1.89
8200	78.95	1.77	1.24	1.73	1.83
8300	78.88	1.70	1.17	1.67	1.73
8400	78.82	1.64	1.10	1.61	1.66

8500	78.76	1.58	1.04	1.55	1.61
8600	78.66	1.48	0.94	1.45	1.54
8700	78.58	1.40	0.86	1.38	1.48
8800	78.50	1.32	0.77	1.30	1.42
8900	78.42	1.24	0.69	1.22	1.36
9000	78.38	1.20	0.65	1.18	1.34
9100	78.44	1.26	0.70	1.25	1.39
9200	78.50	1.32	0.76	1.31	1.44
9300	78.54	1.36	0.80	1.35	1.49
9400	78.54	1.36	0.80	1.35	1.50
9500	78.52	1.34	0.77	1.33	1.49
9600	78.54	1.36	0.79	1.36	1.52
9700	78.55	1.37	0.80	1.37	1.51
9800	78.55	1.37	0.79	1.37	1.50
9900	78.55	1.37	0.79	1.37	1.49
10000	78.52	1.34	0.76	1.35	1.47
10127	78.47	1.29	0.71	1.30	1.47
10254	78.27	1.09	0.50	1.10	1.30
10381	78.14	0.96	0.37	0.98	1.19
10508	78.09	0.91	0.32	0.93	1.13
10635	78.01	0.83	0.23	0.85	1.04
10762	77.95	0.77	0.17	0.79	0.99
10889	77.90	0.72	0.12	0.75	0.95
11016	77.87	0.69	0.08	0.72	0.92
11143	77.84	0.66	0.05	0.69	0.91
11270	77.81	0.63	0.02	0.67	0.85
11397	77.76	0.58	-0.03	0.62	0.81
11524	77.70	0.52	-0.10	0.56	0.77
11651	77.63	0.45	-0.17	0.50	0.74
11778	77.57	0.39	-0.23	0.44	0.71
11905	77.55	0.37	-0.26	0.42	0.69
12032	77.52	0.34	-0.29	0.40	0.65
12159	77.49	0.31	-0.32	0.37	0.64
12286	77.46	0.28	-0.35	0.34	0.62
12413	77.40	0.22	-0.42	0.29	0.58
12540	77.38	0.20	-0.44	0.27	0.57

12667	77.36	0.18	-0.46	0.25	0.56
12794	77.32	0.14	-0.51	0.22	0.53
12921	77.30	0.12	-0.53	0.20	0.52

APPENDIX 5

Atmospheric pressure measurements recorded on a barograph 1/4 of a mile from the observation well during the pumping test.

t = time since 14:36 hrs, August 7, 1990, when pumping began,

p_a = atmospheric pressure,

Δp_a = change in atmospheric pressure since pumping began.

t (mins)	p_a (mb)	p_a (ft of water)	Δp_a (ft of water)
0	1023.5	34.298	0.00
24	1023.2	34.287	-0.01
84	1022.6	34.267	-0.03
144	1022.1	34.251	-0.05
204	1021.6	34.234	-0.06
264	1021.3	34.224	-0.07
324	1021.0	34.214	-0.08
384	1020.8	34.207	-0.09
444	1020.6	34.200	-0.10
504	1020.5	34.197	-0.10
564	1020.2	34.187	-0.11
624	1020.0	34.180	-0.12
684	1019.8	34.174	-0.12
744	1019.5	34.163	-0.13
804	1019.5	34.163	-0.13
864	1019.4	34.160	-0.14
924	1019.1	34.150	-0.15
984	1019.1	34.150	-0.15
1044	1019.0	34.147	-0.15
1104	1018.7	34.137	-0.16
1164	1017.9	34.110	-0.19
1224	1017.7	34.103	-0.19
1284	1017.4	34.093	-0.20
1344	1017.4	34.093	-0.20
1404	1017.2	34.086	-0.21
1464	1016.8	34.073	-0.23

1524	1016.6	34.066	-0.23
1584	1016.4	34.060	-0.24
1644	1016.2	34.053	-0.25
1704	1016.0	34.046	-0.25
1764	1016.1	34.050	-0.25
1824	1016.3	34.056	-0.24
1884	1016.8	34.073	-0.23
1944	1017.0	34.080	-0.22
2004	1017.1	34.083	-0.21
2064	1017.3	34.090	-0.21
2124	1017.4	34.093	-0.20
2184	1017.3	34.090	-0.21
2244	1017.1	34.083	-0.21
2304	1017.1	34.083	-0.21
2364	1017.3	34.090	-0.21
2424	1017.6	34.100	-0.20
2484	1017.9	34.110	-0.19
2544	1018.1	34.117	-0.18
2604	1018.2	34.120	-0.18
2664	1018.4	34.127	-0.17
2724	1018.5	34.130	-0.17
2784	1018.2	34.120	-0.18
2844	1018.0	34.113	-0.18
2904	1017.7	34.103	-0.19
2964	1017.4	34.093	-0.20
3024	1017.0	34.080	-0.22
3084	1016.7	34.070	-0.23
3144	1016.6	34.066	-0.23
3204	1016.9	34.076	-0.22
3264	1017.2	34.086	-0.21
3324	1017.6	34.100	-0.20
3384	1017.8	34.107	-0.19
3444	1017.7	34.103	-0.19
3504	1017.6	34.100	-0.20
3564	1017.4	34.093	-0.20
3624	1017.5	34.096	-0.20

3684	1017.5	34.096	-0.20
3744	1017.8	34.107	-0.19
3804	1017.8	34.107	-0.19
3864	1017.8	34.107	-0.19
3924	1018.1	34.117	-0.18
3984	1018.1	34.117	-0.18
4044	1018.0	34.113	-0.18
4104	1017.9	34.110	-0.19
4164	1017.8	34.107	-0.19
4224	1017.7	34.103	-0.19
4284	1017.9	34.110	-0.19
4344	1017.8	34.107	-0.19
4404	1017.5	34.096	-0.20
4464	1016.7	34.070	-0.23
4524	1016.5	34.063	-0.24
4584	1016.0	34.046	-0.25
4644	1015.8	34.040	-0.26
4704	1016.4	34.060	-0.24
4764	1016.5	34.063	-0.24
4824	1016.2	34.053	-0.25
4884	1016.6	34.066	-0.23
4944	1016.4	34.060	-0.24
5004	1017.4	34.093	-0.20
5064	1016.7	34.070	-0.23
5124	1017.8	34.107	-0.19
5184	1017.4	34.093	-0.20
5244	1016.9	34.076	-0.22
5304	1016.9	34.076	-0.22
5364	1017.0	34.080	-0.22
5424	1017.1	34.083	-0.21
5484	1017.2	34.086	-0.21
5544	1017.7	34.103	-0.19
5604	1018.0	34.113	-0.18
5664	1018.1	34.117	-0.18
5724	1017.9	34.110	-0.19
5784	1017.6	34.100	-0.20

5844	1017.0	34.080	-0.22
5904	1016.7	34.070	-0.23
5964	1016.5	34.063	-0.24
6024	1016.2	34.053	-0.25
6084	1016.4	34.060	-0.24
6144	1016.7	34.070	-0.23
6204	1016.9	34.076	-0.22
6264	1016.8	34.073	-0.23
6324	1017.1	34.083	-0.21
6384	1016.8	34.073	-0.23
6444	1016.4	34.060	-0.24
6504	1016.3	34.056	-0.24
6564	1016.4	34.060	-0.24
6624	1015.8	34.040	-0.26
6684	1016.0	34.046	-0.25
6744	1016.0	34.046	-0.25
6804	1016.0	34.046	-0.25
6864	1016.0	34.046	-0.25
6924	1016.0	34.046	-0.25
6984	1017.0	34.080	-0.22
7044	1017.3	34.090	-0.21
7104	1017.6	34.100	-0.20
7164	1017.4	34.093	-0.20
7224	1017.4	34.093	-0.20
7284	1017.3	34.090	-0.21
7344	1017.4	34.093	-0.20
7404	1017.5	34.096	-0.20
7464	1017.6	34.100	-0.20
7524	1017.7	34.103	-0.19
7584	1018.3	34.123	-0.17
7644	1018.6	34.133	-0.16
7704	1019.2	34.153	-0.14
7764	1019.6	34.167	-0.13
7824	1019.7	34.170	-0.13
7884	1019.6	34.167	-0.13
7944	1019.5	34.163	-0.13

8004	1019.4	34.160	-0.14
8064	1019.7	34.170	-0.13
8124	1020.0	34.180	-0.12
8184	1020.4	34.194	-0.10
8244	1021.1	34.217	-0.08
8304	1021.6	34.234	-0.06
8364	1021.8	34.241	-0.06
8424	1022.0	34.247	-0.05
8484	1021.9	34.244	-0.05
8544	1021.6	34.234	-0.06
8604	1020.9	34.210	-0.09
8664	1020.5	34.197	-0.10
8724	1020.0	34.180	-0.12
8784	1019.7	34.170	-0.13
8844	1019.3	34.157	-0.14
8904	1019.0	34.147	-0.15
8964	1018.6	34.133	-0.16
9024	1018.7	34.137	-0.16
9084	1018.8	34.140	-0.16
9144	1019.2	34.153	-0.14
9204	1019.2	34.153	-0.14
9264	1019.1	34.150	-0.15
9324	1019.0	34.147	-0.15
9384	1018.9	34.143	-0.15
9444	1018.8	34.140	-0.16
9504	1018.5	34.130	-0.17
9564	1018.4	34.127	-0.17
9624	1018.6	34.133	-0.16
9684	1019.0	34.147	-0.15
9744	1019.4	34.160	-0.14
9804	1019.6	34.167	-0.13
9864	1019.9	34.177	-0.12
9924	1019.8	34.174	-0.12
9984	1019.7	34.170	-0.13
10044	1019.2	34.153	-0.14
10104	1018.1	34.117	-0.18

10164	1018.5	34.130	-0.17
10224	1017.7	34.103	-0.19
10284	1017.2	34.086	-0.21
10344	1016.8	34.073	-0.23
10404	1016.7	34.070	-0.23
10464	1016.9	34.076	-0.22
10524	1017.5	34.096	-0.20
10584	1017.8	34.107	-0.19
10644	1017.6	34.100	-0.20
10704	1017.5	34.096	-0.20
10764	1017.4	34.093	-0.20
10824	1017.2	34.086	-0.21
10884	1017.2	34.086	-0.21
10944	1017.2	34.086	-0.21
11004	1017.2	34.086	-0.21
11064	1017.1	34.083	-0.21
11124	1016.7	34.070	-0.23
11184	1017.6	34.100	-0.20
11244	1017.9	34.110	-0.19
11304	1017.9	34.110	-0.19
11364	1017.7	34.103	-0.19
11424	1017.5	34.096	-0.20
11484	1017.2	34.086	-0.21
11544	1016.8	34.073	-0.23
11604	1016.4	34.060	-0.24
11664	1015.6	34.033	-0.27
11724	1015.1	34.016	-0.28
11784	1015.1	34.016	-0.28
11844	1014.7	34.003	-0.30
11904	1015.1	34.016	-0.28
11964	1015.4	34.026	-0.27
12024	1015.6	34.033	-0.27
12084	1015.0	34.013	-0.29
12144	1015.1	34.016	-0.28
12204	1015.1	34.016	-0.28
12264	1014.9	34.009	-0.29

12324	1015.0	34.013	-0.29
12384	1014.3	33.989	-0.31
12444	1014.0	33.979	-0.32
12504	1013.9	33.976	-0.32
12564	1013.9	33.976	-0.32
12624	1013.9	33.976	-0.32
12684	1014.0	33.979	-0.32
12744	1013.8	33.972	-0.33
12804	1013.7	33.969	-0.33
12864	1013.4	33.959	-0.34
12924	1013.3	33.956	-0.34
12984	1012.4	33.926	-0.37