DETERMINATION OF HYDRAULIC PROPERTIES IN THE VICINITY OF A LANDFILL NEAR ANTIOCH, ILLINOIS

By Robert T. Kay and John D. Earle

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may want to use metric (International System) units, the inch-pound values in this report may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per day per foot [(ft/d)/ft]	0.3048	meter per day per meter [(m/d)/m]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

A hydrogeologic investigation was conducted in and around a landfill near Antioch, Illinois, in December 1987. The investigation consisted, in part, of an aquifer test that was designed to determine the hydraulic connection between the hydrogeologic units in the area. The hydrogeologic units consist of a shallow, unconfined, sand and gravel aquifer of variable thickness that overlies an intermediate confining unit of variable thickness composed predominantly of till. Underlying the till is a deep, confined, sand and gravel aquifer that serves as the water supply for the village of Antioch. The aquifer test was conducted in the confined aquifer.

Aquifer-test data were analyzed using the Hantush and Jacob method for a leaky confined aquifer with no storage in the confining unit. Calculated transmissivity of the confined aquifer ranged from 1.96×10^{4} to 2.52×10^{4} foot squared per day and storativity ranged from 2.10×10^{-4} to 8.71×10^{-4}. Leakage through the confining unit ranged from 1.29×10^{-4} to 7.84×10^{-4} foot per day per foot, and hydraulic conductivity of the confining unit ranged from 3.22×10^{-3} to 1.96×10^{-2} foot per day.

The Hantush method for analysis of a leaky confined aquifer with storage in the confining unit also was used to estimate aquifer and confining-unit properties. Transmissivity and storativity values calculated using the Hantush method are in good agreement with the values calculated from the Hantush and Jacob method.

Properties of the confining unit were estimated using the ratio method of Neuman and Witherspoon. The estimated diffusivity of the confining unit ranged from 50.36 to 68.13 feet squared per day. A value for the vertical hydraulic conductivity of the confining unit calculated from data obtained using both the Hantush and the Neuman and Witherspoon methods was within the range of values calculated by the Hantush and Jacob method.

The aquifer-test data clearly showed that the confining unit is hydraulically connected to the confined aquifer. The aquifer-test data also indicated that the unconfined aquifer becomes hydraulically connected to the deep sand and gravel aquifer within 24 hours after the start of pumping in the confined aquifer.

INTRODUCTION

A hydrogeologic investigation was conducted during December 1987 to estimate the hydraulic connection between the hydrogeologic units in the vicinity of a landfill located near the southeastern corner of the village of Antioch, Lake County, Illinois (fig. 1). The investigation was conducted by the U.S. Environmental Protection Agency (USEPA); their consultants, Ecology and Environment, Inc.[1]; and the U.S. Geological Survey (USGS). The USGS participated in the investigation as part of an Interagency Agreement with USEPA.

The landfill was in operation from 1963 through 1984. During that time, an unknown quantity of wastes were deposited at the landfill. These wastes are alledged to have included solvents, heavy metals, cutting oils, and hydraulic oils. Polychlorinated biphenols have been determined to be present at the landfill (Ecology and Environment, Inc., 1987, sec. 2, p. 1).

Wells used by the village of Antioch for its public water supply are located about 500, 1,000, and 1,400 ft (feet) from the southwestern corner of the landfill (fig. 2) and draw water from a confined sand and gravel aquifer (henceforth referred to as the confined aquifer) that underlies the landfill. Because of the close proximity of the water-supply wells to the landfill, the USEPA felt that the hazardous substances deposited in the landfill could present a threat to human health if they were to enter the confined aquifer.

The investigation was designed to determine the potential for ground-water migration from the landfill into the confined aquifer. Thirteen observation wells were used in the investigation; their locations are shown in figure 2. The investigation had two phases. The first phase consisted of monitoring water levels in observation wells while monitoring pumping of the municipal wells in the area. The first phase was designed to determine what phenomena, other than pumping in Antioch municipal well AMW4, were capable of influencing the magnitude of drawdown in each of the hydrogeologic units in the area. The second phase consisted of a constant-discharge aquifer test in which well AMW4 was pumped for 24 hours and water-level response in selected observation wells was measured. The second phase was designed to quantify the hydraulic properties of the hydrogeologic units in the area and to determine the potential for ground-water migration from the landfill into the confined aquifer.

Purpose and Scope

This report describes the hydraulic properties of the confined aquifer and an overlying confining unit (henceforth referred to as the confining unit) in the vicinity of a landfill near Antioch, Illinois, and establishes the existence of hydraulic connection between the primary hydrogeologic units near the landfill. A description of the hydrogeology of the study area is given, and the results and interpretation of water-level monitoring and aquifer testing are presented.

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[1]Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

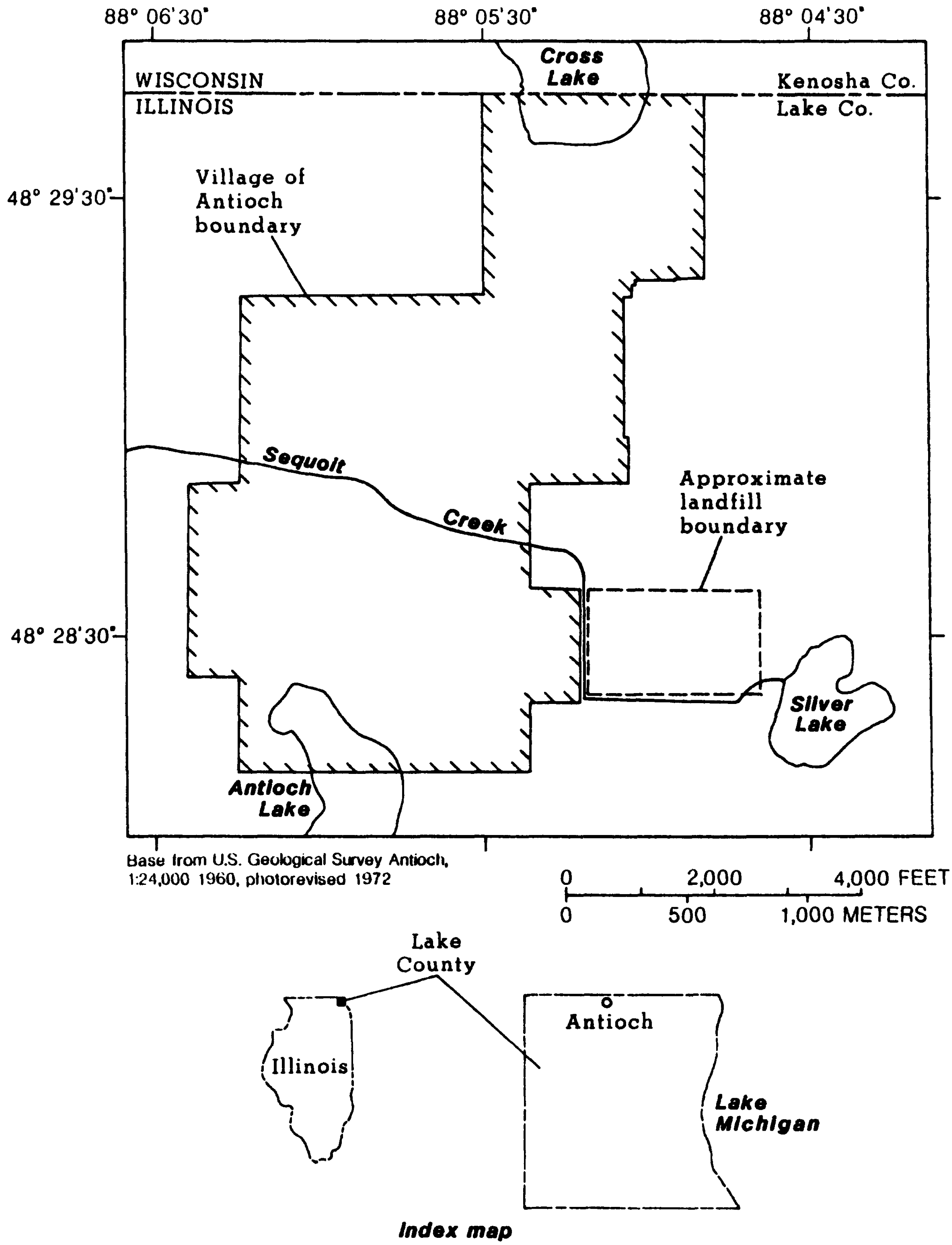

Figure 1.--Location of landfill site near Antioch, Illinois.

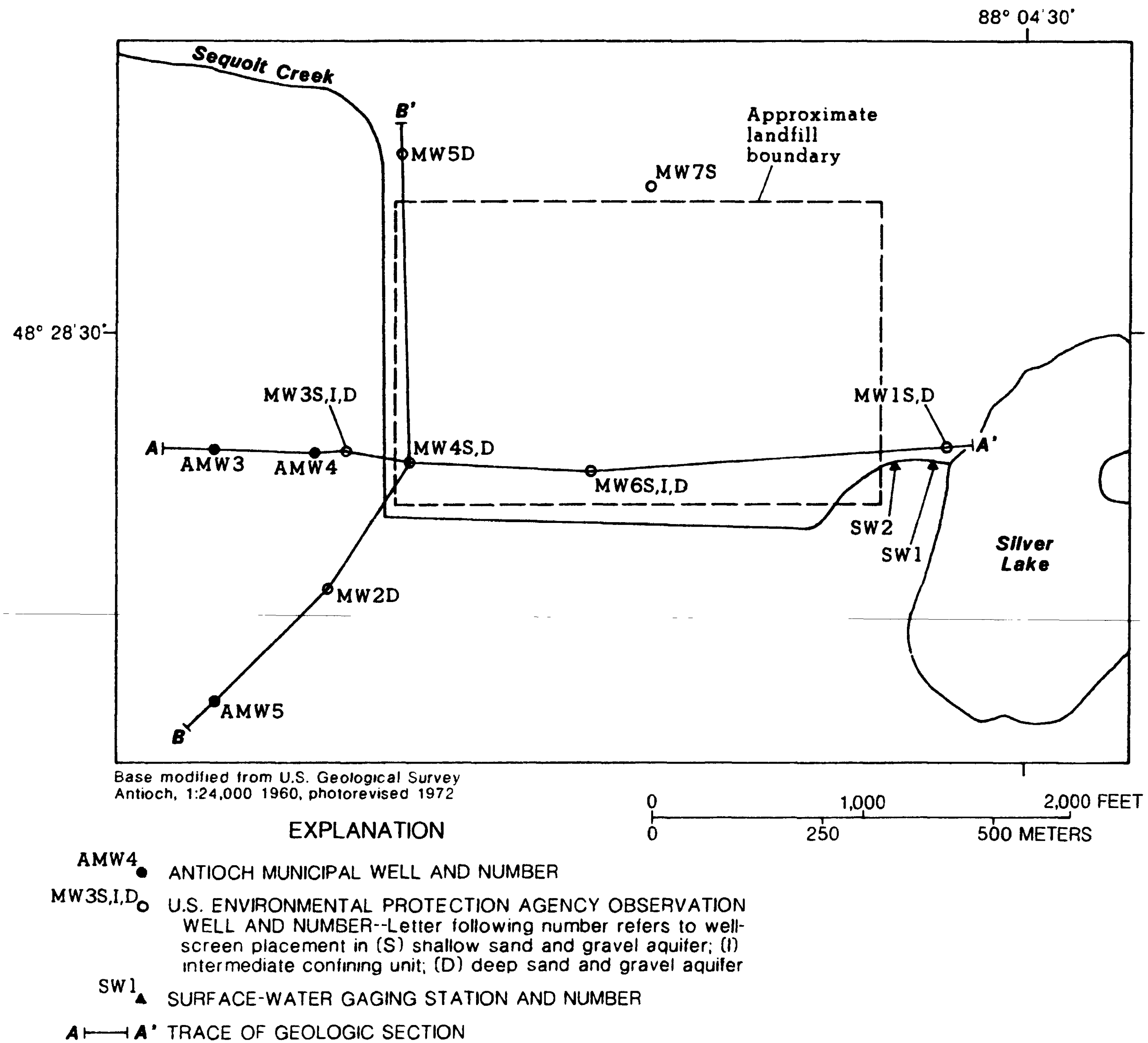

Figure 2.--Location of wells, gaging stations, and lines of geologic section.

Hydrogeology

The geologic deposits in the area consist of about 200 ft of unconsolidated materials overlying bedrock of Silurian dolomite (Piskin and Bergstrom, 1967, plate 1; Willman and others, 1967, map). The four hydrogeologic units in the area are a shallow, unconfined sand and gravel aquifer (henceforth referred to as the unconfined aquifer), an intermediate confining unit of till (confining unit), a deep confined sand and gravel aquifer (confined aquifer) that is used by the village of Antioch for its water supply, and a deep confining unit of till (figs. 3 and 4). Well logs obtained from Ecology and Environment, Inc., describe 1.5-ft sections of material collected from a split-spoon sampler at 3.5-ft intervals. The logs indicate that the unconfined aquifer ranges in thickness from zero in the area of USEPA observation wells MW5D, MW7, and MW2D to about 30 ft at well MW6D. The confining unit ranges in thickness from about 25 ft in the area of well MW6D to about 85 ft at well MW5D. The cited values for confining-unit thickness at wells MW3D and MW6D are the maximum values possible from the well-log data; the actual values may be as much as 3.5 ft less. The thickness of the confined aquifer in the area of the landfill is unknown, but logs of well AMW3 and a test hole for well AMW5, obtained from the Illinois State Water Survey, indicate a thickness of about 55 to 60 ft. The thickness of the deep confining unit is unknown, but the log of the test hole indicates that it is at least 60 ft thick at well AMW5.

Water-level data from the hydrogeologic units in the area indicate that ground-water flow has both vertical and horizontal components (table 1). Head values from wells MW1S, MW3S, MW4S, MW6S, and MW7 indicate that the ground water flows in a southerly direction beneath the landfill and discharges into Sequoit Creek (D. J. Yeskis, U.S. Environmental Protection Agency, oral commun., 1988). Head values in the unconfined aquifer indicate that ground water in that aquifer has the potential to flow downward into the confining unit. Head values in the confining unit indicate that ground water there has the potential for flow into the confined aquifer. No wells are open to the deep confining unit, so the potential for flow within that unit is unknown.

Locally, the direction of ground-water flow in the confined aquifer is controlled by pumping of the municipal wells. Because water levels in the confined aquifer were continually responding to pumping, or the termination of pumping, in these wells, unstressed flow directions in the confined aquifer could not be determined during the investigation. The water-level data indicate that flow in the confined aquifer is toward the well that had been pumped most recently (D. J. Yeskis, U.S. Environmental Protection Agency, oral commun., 1988).

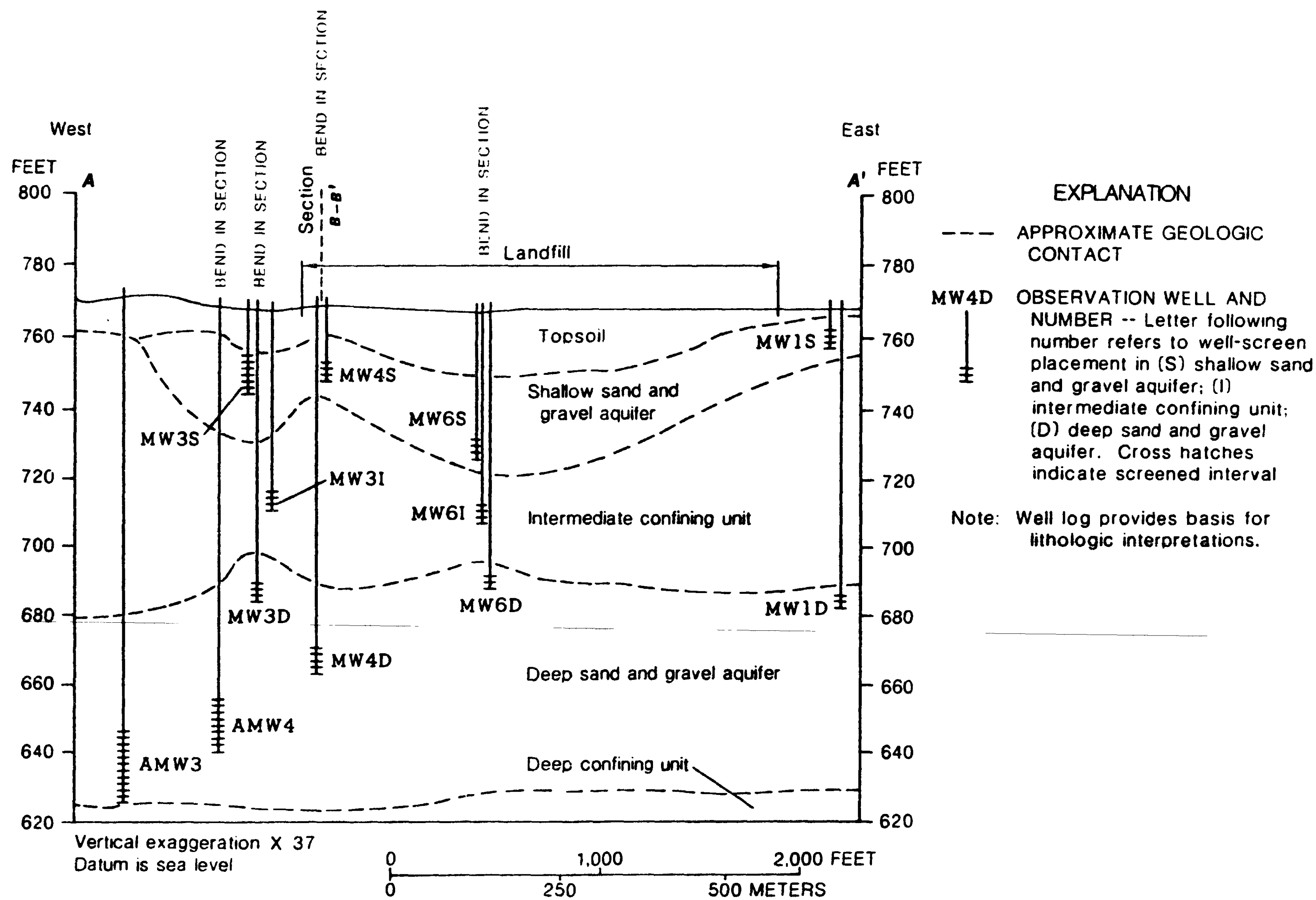

Figure 3.--Geologic section A-A'.

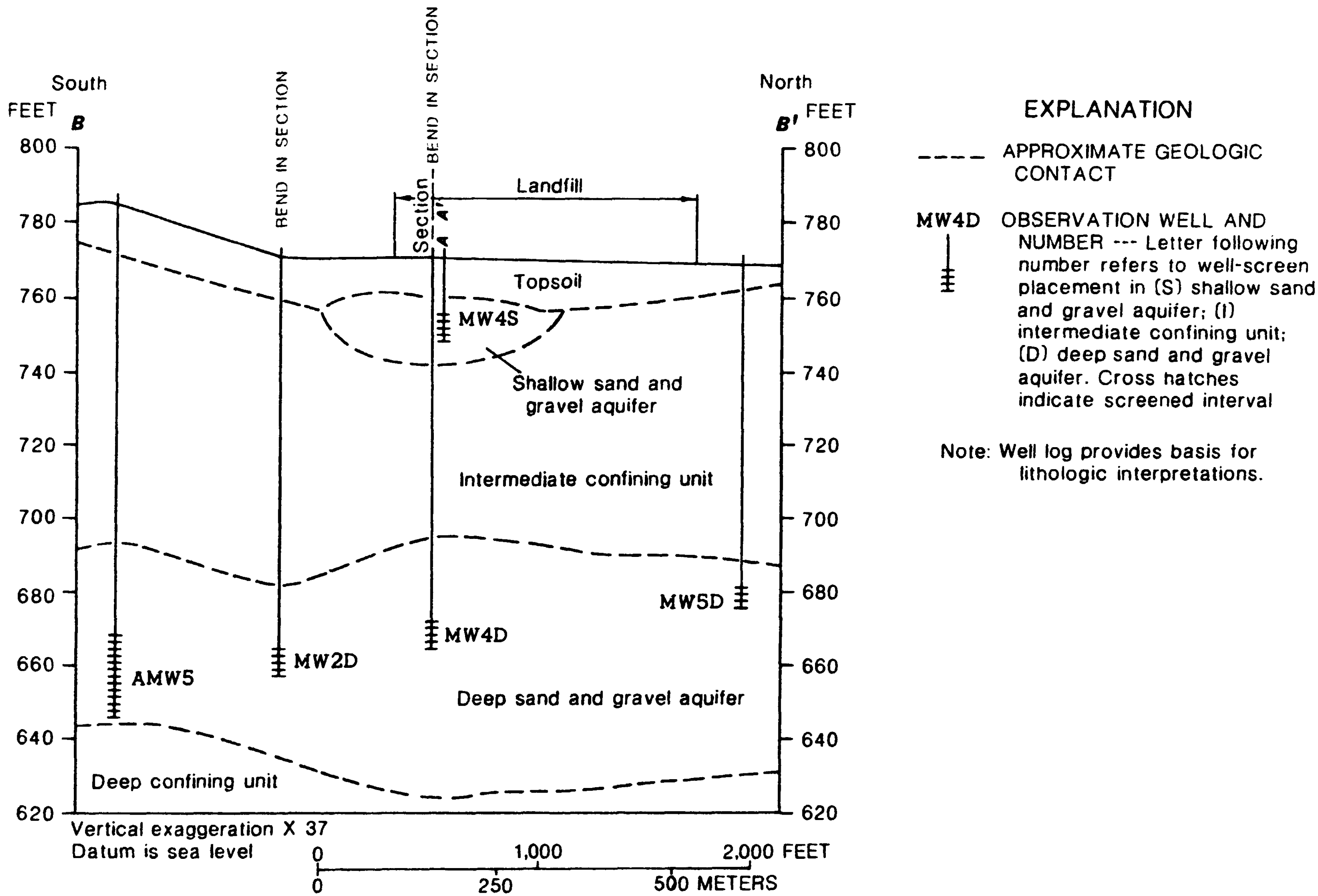

Figure 4.--Geologic section B-B'.

Table 1.--Observation-well data and water levels at 1130 hours on December 16, 1987

Well number	Altitude of measuring point, in feet above sea level	Screened interval, in feet below land surface	Depth to water, in feet below measuring point	Water-level altitude, in feet above sea level
MW1S	768.60	6.71- 12.41	4.30	764.30
MW1D	768.60	86.71- 92.41	37.89	730.71
MW2D	770.72	107.41-112.77	40.70	730.02
MW3S	770.10	16.81- 22.51	6.98	763.12
MW3I	769.89	55.00- 58.00	35.66	734.23
MW3D	769.63	77.28- 82.58	39.31	730.32
MW4S	773.63	17.17- 22.87	10.76	762.81
MW4D	772.66	98.14-103.84	41.92	730.74
MW5D	767.74	87.44- 93.14	36.40	731.34
MW6S	769.89	36.00- 41.70	6.68	763.21
MW6I	770.20	59.06- 62.76	22.57	747.63
MW6D	770.09	77.47- 83.17	39.22	730.87
MW7	767.48	3.61- 9.46	3.36	764.12

DETERMINATION OF HYDRAULIC PROPERTIES

Data Collection

Ground- and surface-water levels, as well as barometric pressure, were monitored throughout the investigation. Water levels in observation wells MW1S and 1D; MW2D; MW3S, 3I, and 3D; MW4S and 4D; and MW6S, 6I, and 6D were monitored with pressure transducers. The accuracy of the water levels obtained from the pressure transducers was checked periodically with steel-tape measurements. Water-level measurements were taken periodically at two surface-water-altitude measuring stations in Sequoit Creek near Silver Lake (fig. 2). Barometric-pressure readings were continuously recorded at the site and checked daily with readings from a weather station about 20 miles to the east.

The municipal wells were checked periodically to determine if they were pumping, and the rate of discharge and total discharge was recorded from readings of in-line totalizing flow meters. The accuracy of the flow-meter readings could not be verified. This enabled the pumping history of the municipal wells to be determined to within a few minutes of when the pumping at each well began and ended. These readings showed that well AMW3 was not pumped at any time during the investigation, that well AMW4 was pumped only during the aquifer test, and that well AMW5 was not pumped while the aquifer test was being conducted.

The hydraulic properties of the confined aquifer and the confining unit were estimated from data obtained during a pumping test at well AMW4. The aquifer test began at 1035 hours on December 17, when well AMW4 began to be pumped at a constant rate of 575 gallons per minute (110,952 cubic feet per day), and ended at 1100 hours on December 18.

Results of Water-Level Monitoring

All the water-level data obtained during the investigation were collected and plotted on hydrographs. When water-level measurements were compared to the pumping sequence of the municipal wells and barometric pressure, a qualitative idea of the phenomena that influence the water-level response in the hydrogeologic units in the area was obtained. Recognition of the presence of these influences was essential for obtaining accurate estimates of the confined aquifer and confining-unit properties.

Water levels in the confined aquifer were influenced by pumping the aquifer and by barometric pressure changes (figs. 5-7). When the confined aquifer was pumped, water levels declined; when the confined aquifer was not pumped, water levels rose. The only exception to this trend was the rise in water level that occurred from approximately 1800 hours on December 14 to 2400 hours on December 15 while well AMW5 was pumped continuously. The rise and subsequent decline in water level that took place during that time mirrors the decline and eventual rise in barometric pressure (fig. 5). The strong correlation between water-level elevation and barometric pressure during the first 30 hours of the investigation suggests that variations in the barometric pressure produced the changes in water level during this time.

Water levels in the wells open to the confining unit showed no significant response to barometric pressure changes but did respond to pumping during the aquifer test (fig. 8). When well AMW4 was pumped, water levels in wells MW3D, MW3I, and MW6I showed an initial rise, then fell continuously until pumping ceased. The initial rise in water level in these wells was probably the result of an increase in pore-water pressure brought on by shear stress induced by pumping the confined aquifer (Wolff, 1970, p. 1726). When pumping in well AMW4 ceased, water levels in the confining unit stopped falling and began to rise. Water-level response during the aquifer test indicates that the confining unit is hydraulically connected to the confined aquifer.

Water levels in the unconfined aquifer showed some correlation with barometric pressure fluctuations but showed no clearly defined response to pumping in the confined aquifer (figs. 9 and 10). Water levels in wells MW1S and MW6S showed an overall rise during the aquifer test while water levels in well MW4S declined. These trends were continuations of background trends and show no

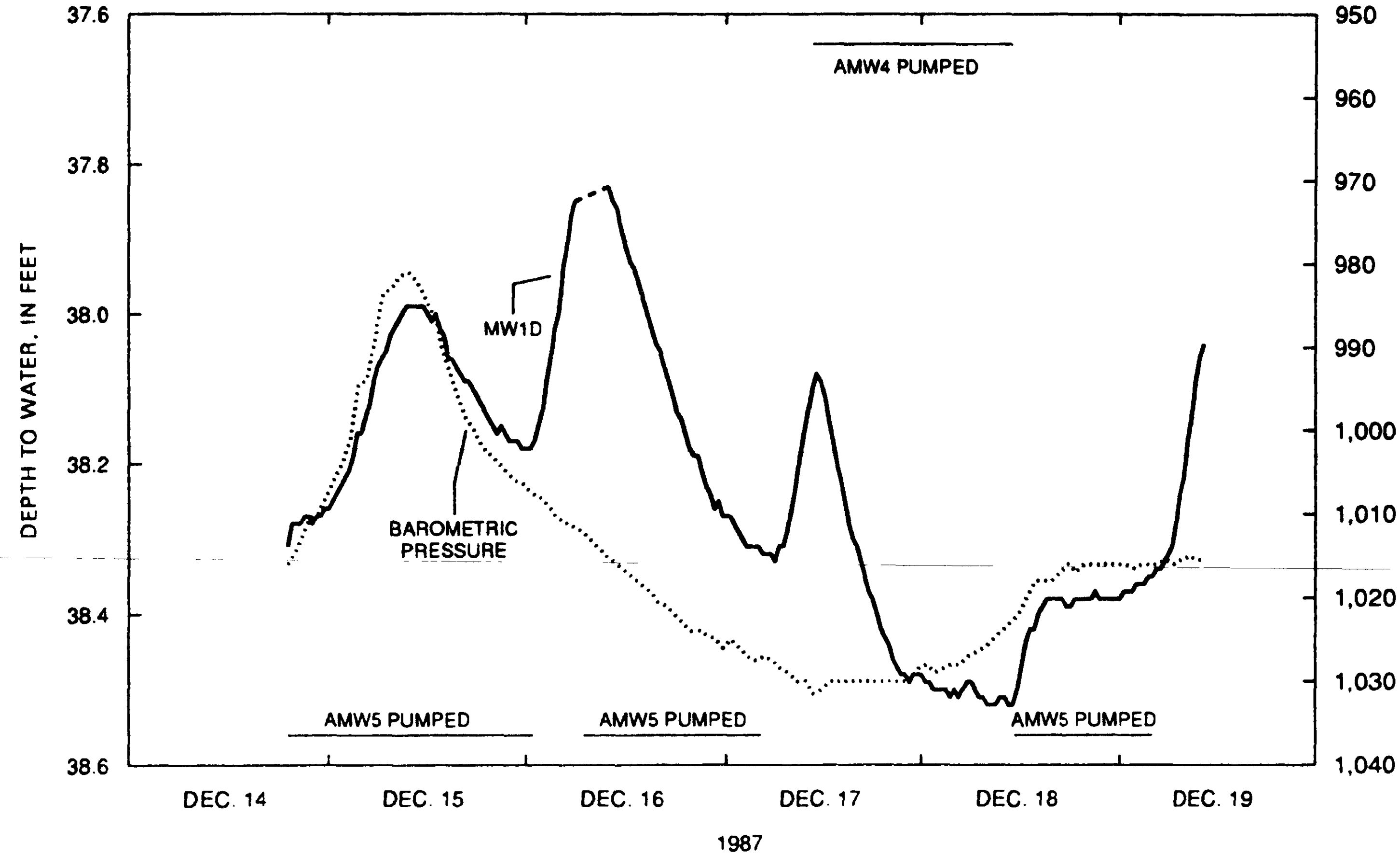

Figure 5.--Depth to water in observation well MW1D and barometric pressure at the landfill, December 14-19, 1987. Water-level data dashed where inferred.

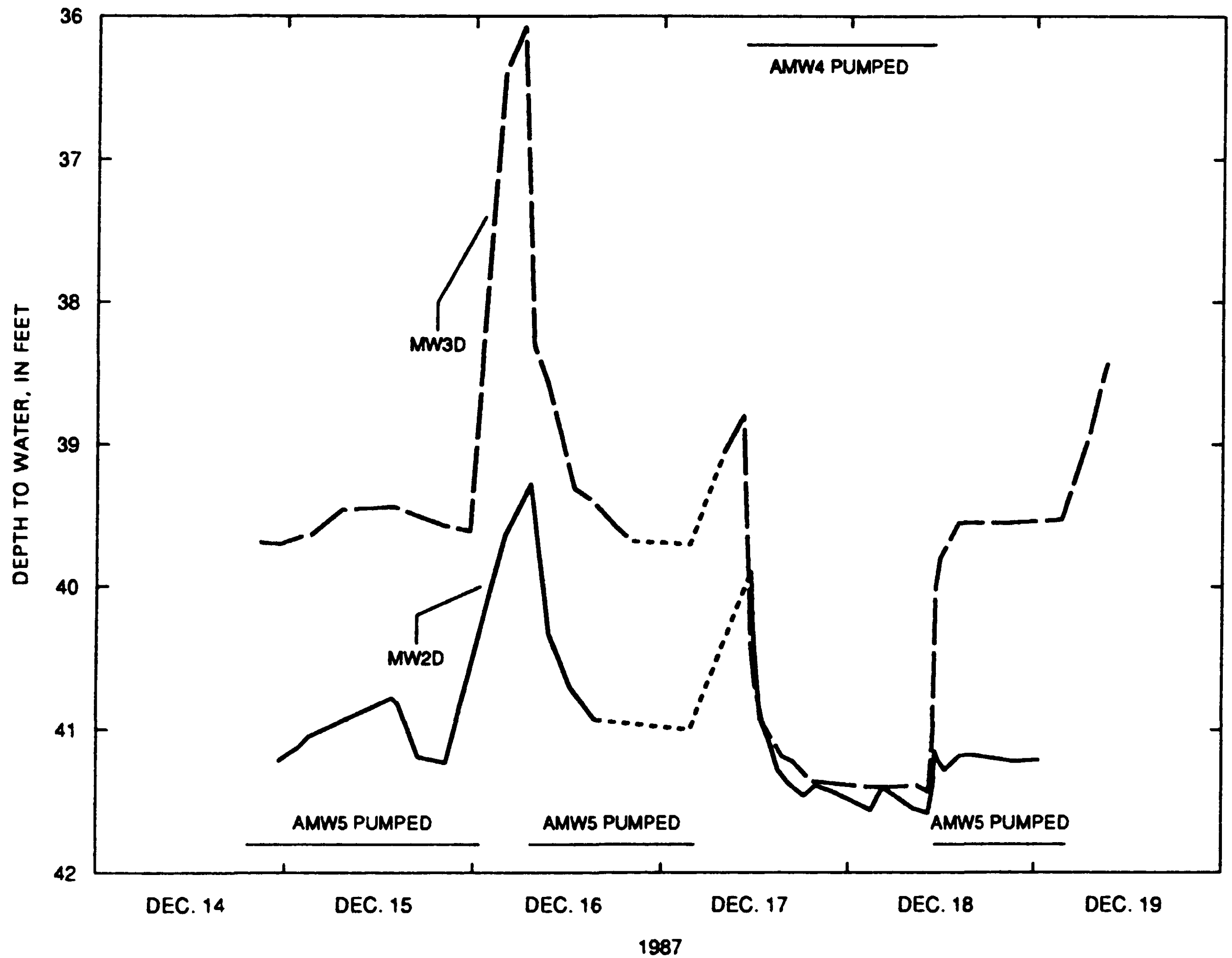

Figure 6.--Depth to water in observation wells MW2D and MW3D, December 14-19, 1987. Dashed where inferred.

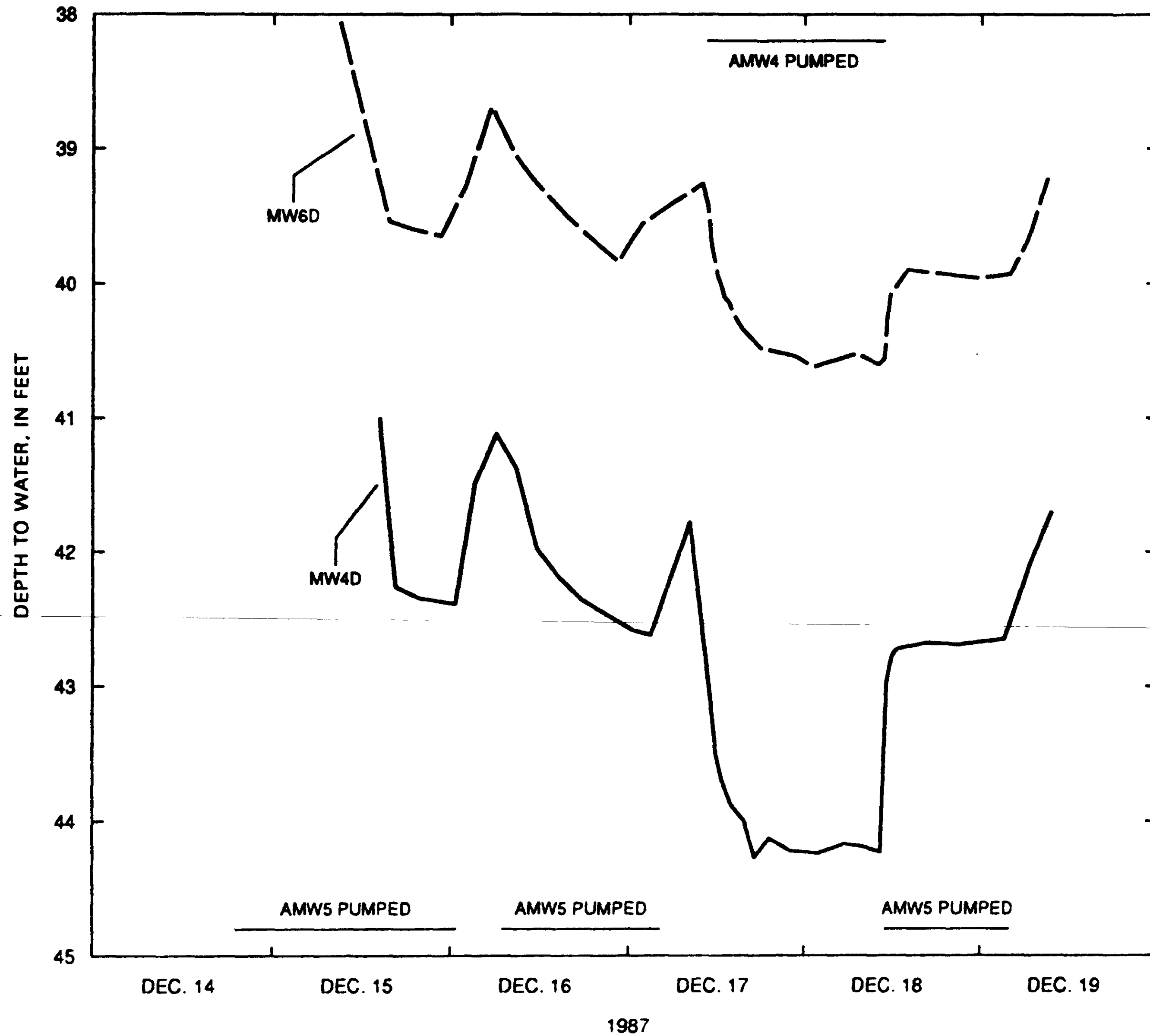

Figure 7.--Depth to water in observation wells MW4D and MW6D, December 15-19, 1987. Dashed where inferred.

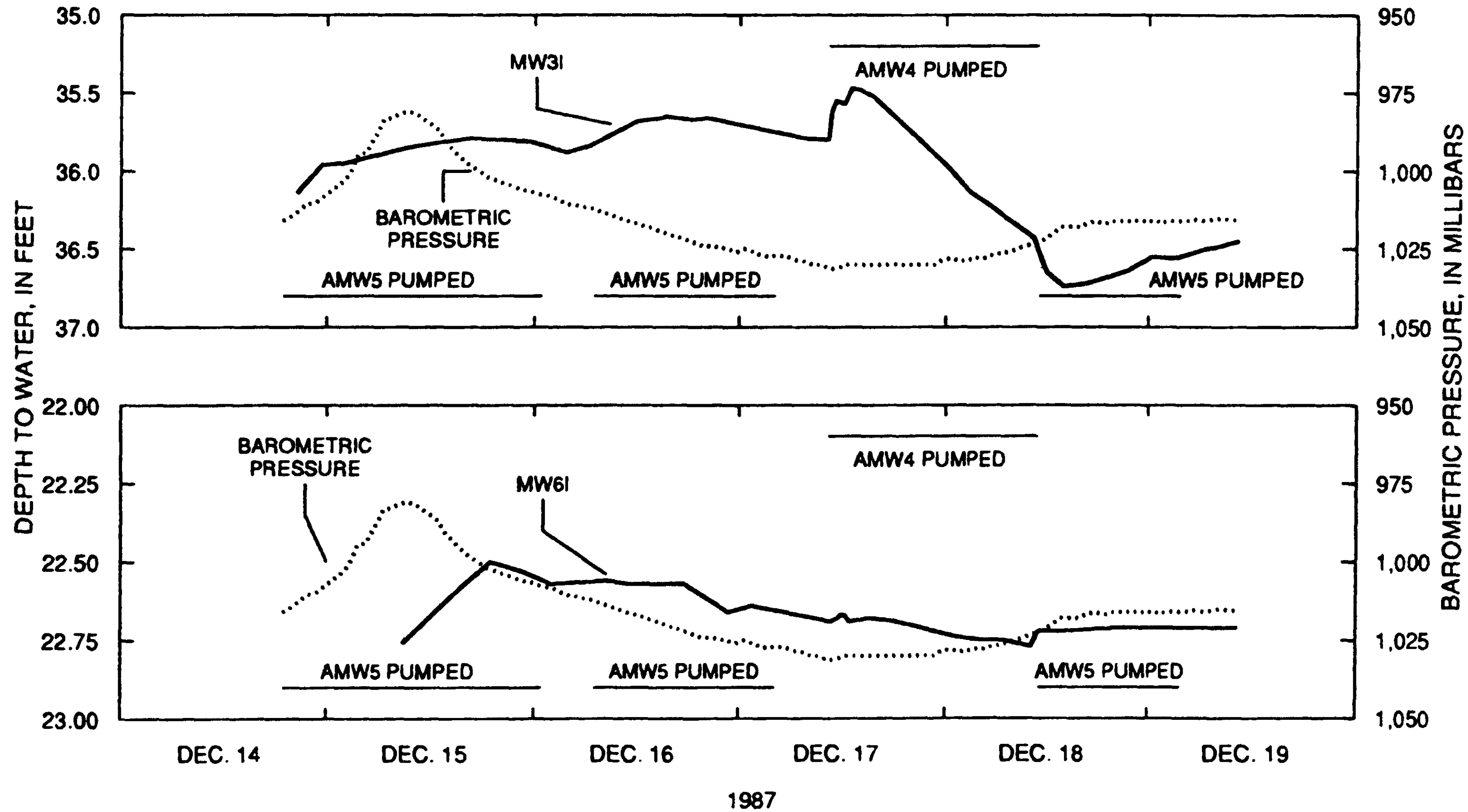

Figure 8.--Water levels in observation wells MW3I and MW6I and barometric pressure at the landfill, December 14-19, 1987.

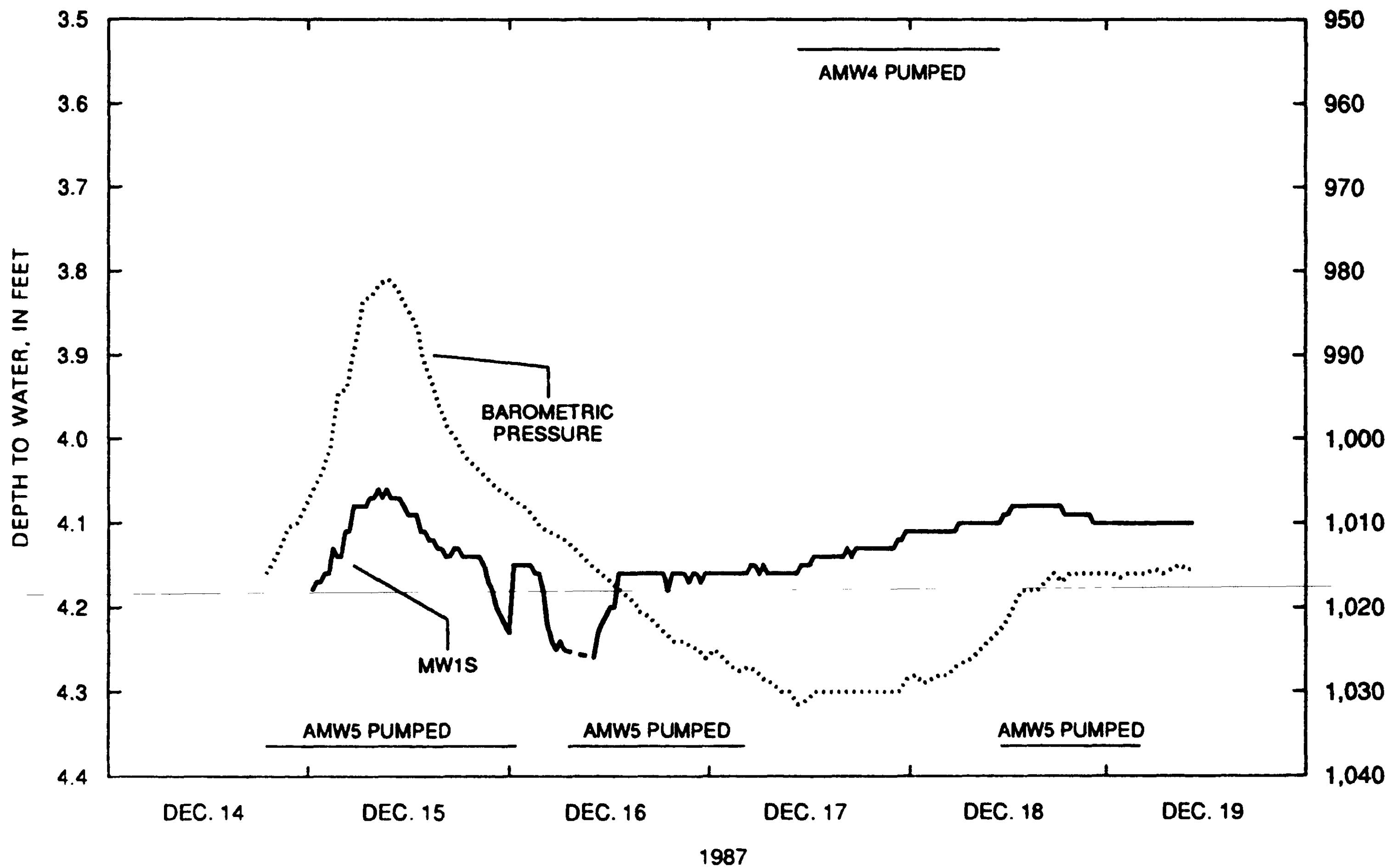

Figure 9.--Depth to water in observation well MW1S and barometric pressure at the landfill, December 14-19, 1987. Water level dashed where inferred.

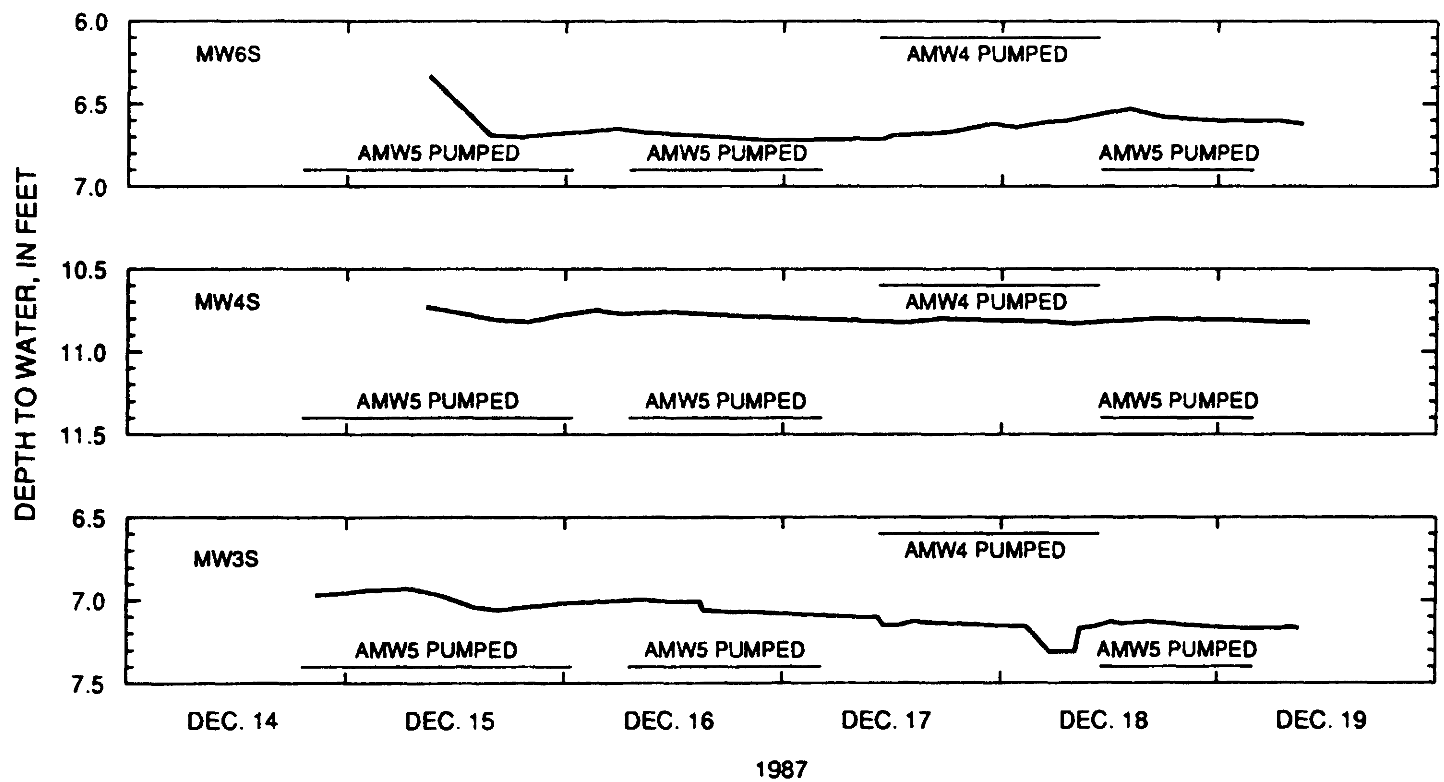

Figure 10.--Water-level readings in observation wells MW6S, MW4S, and MW3S, December 14-19, 1987.

clearly defined relation to pumping in the confined aquifer. The water level in well MW3S showed an overall decline during the aquifer test and a significant drop approximately 19 hours after the test began. The water level in well MW3S rose after this drop while well AMW4 was still being pumped, indicating that pumping in the confined aquifer was probably not the cause of the water-level decline.

Results of Aquifer Testing

Time-drawdown data from the pumping phase of the aquifer test departed from the Theis-type curve, which also indicated that the confined aquifer is hydraulically connected with the confining unit (fig. 11). To quantify the hydraulic properties of the confined aquifer and the confining unit, the aquifer-test data were analyzed using the Hantush and Jacob (1955) method for a leaky confined aquifer with no storage in the confining unit, the Hantush (1960) method for a leaky confined aquifer with storage in the confining unit, and the ratio method of Neuman and Witherspoon (1972). Because pumping at well AMW5 began 13 minutes after the termination of pumping at well AMW4, data from the recovery phase of the aquifer test was not analyzed to determine aquifer properties.

The methods of aquifer-test-data analysis used in this report assume the following conditions:

1. Constant discharge (Q) from the pumped well.

2. The pumped well is of infinitesimal diameter and fully penetrates the aquifer.

3. The confined aquifer is overlain everywhere by a confining unit having uniform hydraulic conductivity (k'), specific storage (Ss'), and thickness (b') and underlain by an impermeable boundary.

4. The confining unit is overlain by an infinite constant-head plane source.

5. Flow in the aquifer is two dimensional and radial in the horizontal plane, and flow in the confining unit is vertical.

Most of the assumptions were met or closely approximated at the site. The assumptions of a confining unit of uniform thickness and a fully penetrating pumped well were not met. The assumption of radial horizontal flow in the aquifer was not met in the area of well MW3D. The assumption of no leakage from underlying deposits into the pumped aquifer cannot be tested with available data.

In an effort to correct for, or eliminate, the presence of extraneous effects on the time-drawdown data, several assumptions were made:

1. The wells in the deep aquifer had a barometric efficiency of 50 percent;

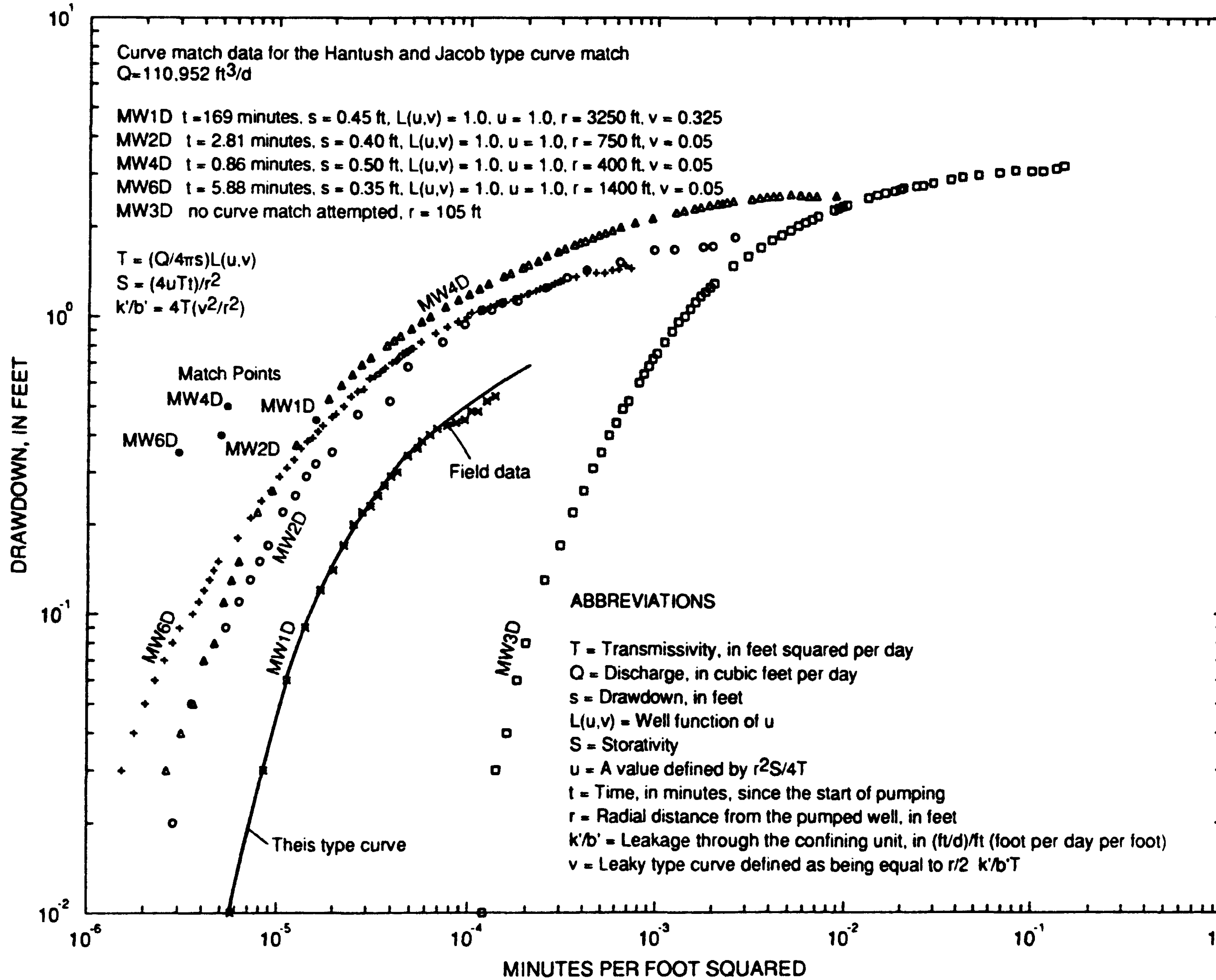

Figure 11.--Curve-match data for observation wells MW1D, MW2D, MW4D, and MW6D using the Hantush and Jacob method.

2. there was no hydraulic connection between surface-water bodies and the confined aquifer;

3. recovery from pumping at well AMW5 had no influence on the drawdown data during the early and late phases of the aquifer test; and

4. the effects of partial penetration of the pumped well are insignificant in wells MW1D, MW2D, and MW6D.

A barometric efficiency of 50 percent represents the probable maximum for the aquifer (E. P. Weeks, U.S. Geological Survey, oral commun., 1988) and results in estimates of confining-unit properties that are probably slightly lower than the actual values. The assumption that there was no hydraulic connection between the confined aquifer and surface-water bodies was based on data that showed no changes in surface-water altitudes in Sequoit Creek during the test. The assumption that recovery after pumping well AMW5 did not affect drawdown in the observation wells during the early and late phases of the test was based on calculations indicating that water-level changes in the observation wells caused by recovery of well AMW5 would be less than 0.01 ft until approximately 330 minutes into the aquifer test (Rushton, 1985, p. 364). Pumping-history data indicate that recovery effects ceased approximately 1,000 minutes into the aquifer test. Calculations presented by Walton (1978, p. 314) showed that, if the confined aquifer is 100 ft thick and the horizontal-to-vertical hydraulic-conductivity ratio is less than 21:1, then partial penetration effects are insignificant at distances greater than 700 ft from the pumped well. Wells MW1D, MW2D, and MW6D are greater than 700 ft from the pumped well. Horizontal-to-vertical hydraulic-conductivity ratios calculated by Weeks (1969, p. 213) for confined sand and gravel aquifers indicate that ratios less than 21:1 are realistic.

The hydraulic properties of the confined aquifer and confining unit were estimated using the Hantush and Jacob (1955) method for a leaky confined aquifer with no storage in the confining unit. Plots of drawdown in the confined aquifer (s) as a function of time (t) since the start of pumping, divided by the square of the radial distance (r) from the pumped well, were constructed on log-log graph paper and matched against the type curve (fig. 11). The match-point data represent the values of the four coordinate points--L(u,v), u, s, and t/r^2--obtained from the type curve and field-data curve at a point common to both curves when they are matched. The values for the confined aquifer transmissivity (T) and storativity (S), leakage through the confining unit (k'/b'), and confining-unit hydraulic conductivity (k') calculated using the Hantush and Jacob method, are presented in table 2. Because partial-penetration effects have significantly influenced the magnitude of the drawdown at well MW3D, the hydraulic properties of the confined aquifer and confining unit were not estimated with this data. Because partial-penetration effects may or may not have significantly influenced the drawdown data at well MW4D, the hydraulic properties of the confined aquifer and confining unit were estimated from the well MW4D data; those values are not included in the discussion. Because flow in the confining unit is assumed to be vertical, all estimates of confining-unit hydraulic conductivity made from the aquifer-test data are estimates of the vertical hydraulic conductivity of the confining unit.

Table 2.--Confined-aquifer transmissivity and storativity, leakage through the confining unit, and confining-unit hydraulic conductivity calculated using the Hantush and Jacob (1955) method

Well number	Transmissivity (foot squared per day)	Storativity	Leakage (foot per day per foot)	Confining unit hydraulic conductivity (foot per day)
MW1D	$1.96x10^{4}$	$8.71x10^{-4}$	$7.84x10^{-4}$	$1.96x10^{-2}$
MW2D	$2.21x10^{4}$	$3.07x10^{-4}$	$3.93x10^{-4}$	$9.82x10^{-3}$
MW4D[1]	$1.77x10^{4}$	$2.64x10^{-4}$	$1.11x10^{-3}$	$2.78x10^{-2}$
MW6D	$2.52x10^{4}$	$2.10x10^{-4}$	$1.29X10^{-4}$	$3.22x10^{-3}$

[1]Well in which partial penetration effects are assumed to be significant.

Calculated transmissivity of the confined aquifer ranged from $1.96x10^{4}$ to $2.52x10^{4}$ ft^2/d (feet squared per day). Estimated storativity of the confined aquifer ranged from $2.10x10^{-4}$ to $8.71x10^{-4}$. Estimates for leakage through the confining unit ranged from $1.29x10^{-4}$ to $7.84x10^{-4}$ (ft/d)/ft (foot per day per foot).

In the Hantush and Jacob (1955) method, the hydraulic conductivity of a confining unit is equal to the rate of leakage through the confining unit multiplied by the thickness of the confining unit. If the confining unit is assumed to be 25 ft thick, the minimum thickness observed in the area, the calculated hydraulic conductivity of the confining unit ranged from $3.22x10^{-3}$ to $1.96x10^{-2}$ ft/d (feet per day).

A better estimate of the confined-aquifer and confining-unit properties was obtained when the aquifer-test data were analyzed using the Hantush (1960) method for a leaky confined aquifer with storage in the confining unit (fig. 12). Using equations modified from Javendel (1984, p. 73 and 75), transmissivity and storativity of the confined aquifer, and the product of the hydraulic conductivity of the confining unit and specific storage of the confining unit, were determined.

The product of the specific storage of the confining unit and the hydraulic conductivity of the confining unit is obtained from

$$k'Ss' = \{(\Delta)^2 TS\}, \quad (1)$$

where

$$\Delta = (4B)/r, \quad (2)$$

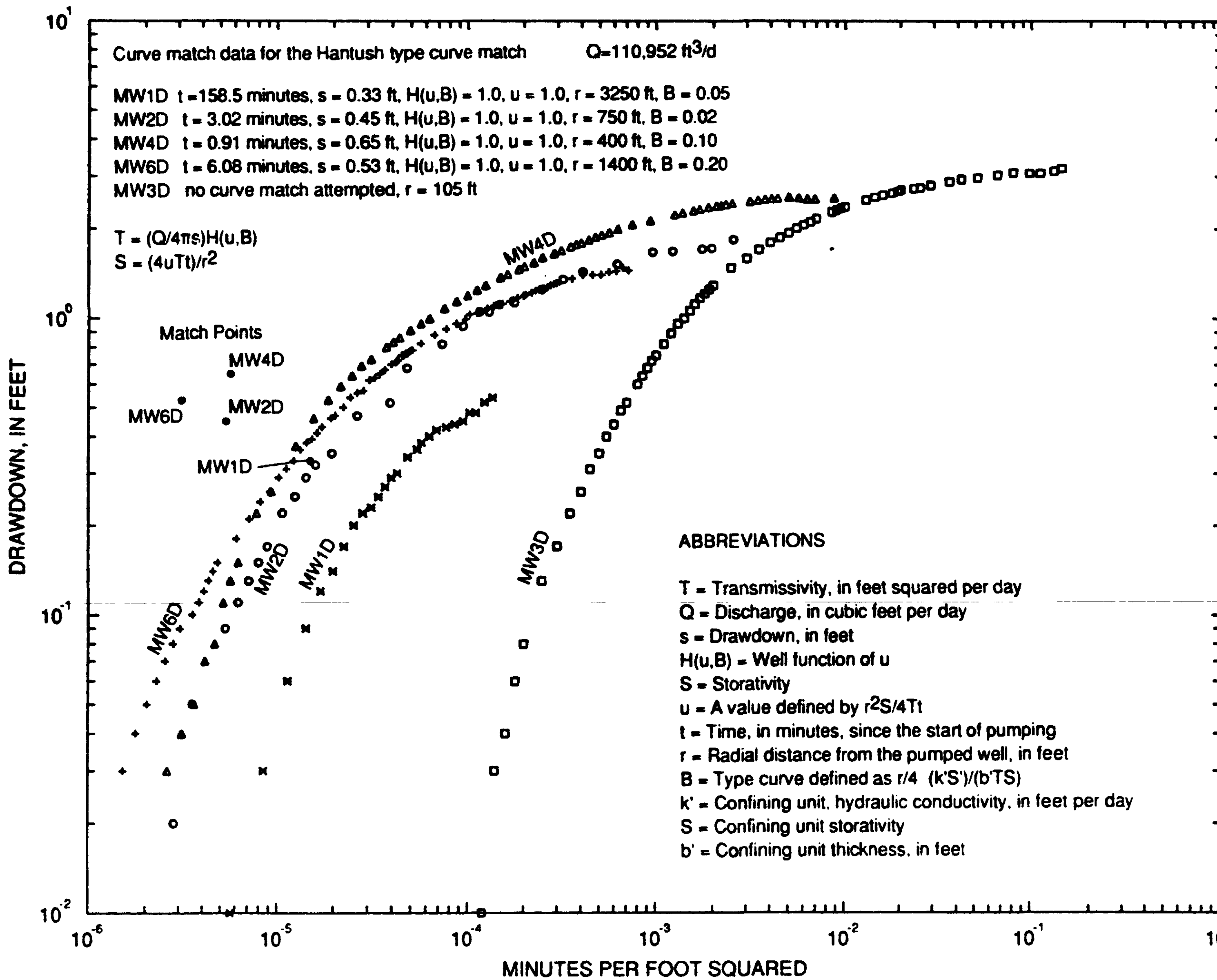

Figure 12.--Curve-match data for observation wells MW1D, MW2D, MW4D, and MW6D using the Hantush method.

and

k' is the hydraulic conductivity of the confining unit, in feet per day;

T is the transmissivity of the confined aquifer, in feet squared per day;

S is the storativity of the confined aquifer (dimensionless);

Ss' is the specific storage of the confining unit, in ft^{-1};

B is the value of the type-curve match (dimensionless); and

r is the radial distance of the observation well from the pumped well, in feet.

The results of the aquifer-test analysis using the Hantush (1960) method are presented in table 3.

Table 3.--Confined-aquifer transmissivity and storativity, and the product of the confining-unit hydraulic conductivity and specific storage determined from the Hantush (1960) method

Well number	Transmissivity (foot squared per day)	Storativity	Product of confining layer hydraulic conductivity and specific storage (per day)
MW1D	$2.68x10^{4}$	$1.12x10^{-3}$	$1.14x10^{-7}$
MW2D	$1.96x10^{4}$	$2.93x10^{-4}$	$6.55x10^{-8}$
MW4D[1]	$1.36x10^{4}$	$2.14x10^{-4}$	$2.91x10^{-6}$
MW6D	$1.67x10^{4}$	$1.44x10^{-4}$	$7.84x10^{-7}$

[1]Well in which partial-penetration effects are assumed to be significant.

Calculated transmissivity of the confined aquifer ranged from $1.67x10^{4}$ to $2.68x10^{4}$ ft^2/d, storativity of the confined aquifer ranged from $1.44x10^{-4}$ to $1.12x10^{-3}$, and the product of k' and Ss' ranged from $6.55x10^{-8}$ to $7.84x10^{-7}$ day^{-1}. Transmissivity and storativity of the confined aquifer calculated by the Hantush (1960) method are in good agreement with the values calculated from the Hantush and Jacob (1955) method (table 2).

The aquifer-test data also were analyzed using the ratio method of Neuman and Witherspoon (1972). The ratio method relies primarily on drawdown data from a confining unit to determine the hydraulic properties of the confining unit. Because drawdown in the confining unit is not influenced by leakage from underlying deposits, the intermediate properties calculated using the ratio method is considered to be more accurate than those calculated from the Hantush and Jacob (1955) and Hantush (1960) methods.

The ratio method relies on a family of type curves constructed from a plot of the ratio of drawdown in a confining unit to the drawdown in a confined aquifer (s'/s) as a function of dimensionless time in the confining unit (t'D) at a given distance (r) from the pumped well and at a given time (t) (fig. 13). Each curve of s'/s as a function of t'D corresponds to a different value of dimensionless time in the confined aquifer (tD) where

$$tD = Tt/Sr^2, \qquad (3)$$

and

$$t'D = (k't)/(Ss'z^2), \qquad (4)$$

where

z is the vertical distance of any point in the confining unit above the confined aquifer, in feet.

The first step in using the ratio method was to obtain estimates of transmissivity (T) and storativity (S) that were representative of the confined aquifer. Values of $T = 2.00 \times 10^4$ ft^2/d and $S = 5.10 \times 10^{-4}$ were chosen. These values are slightly lower than the average values obtained from the Hantush (1960) method and provide conservative estimates of tD.

Once representative values of T and S were obtained, the value of tD was calculated using equation 3 for wells MW3D and MW6D at selected values of time (t) since the start of pumping. The value of tD at well MW3D ranged from 817 to 3,813 during the period when drawdown was measured in the wells open to the confining unit (table 4); tD at well MW6D ranged from 4.72 to 19.45 (table 5). When the data from wells MW3I and MW3D were analyzed, a tD of 1,000 was assumed to improve the curve match. When the data from wells MW6I and MW6D were analyzed, a tD of 10 was assumed to improve the curve match.

Once tD was determined, the value of s'/s at selected values of t was calculated from the data for wells MW3I, MW3D, MW6I, and MW6D (fig. 14 and tables 4 and 5). When s'/s was calculated from the MW3I and MW3D well data, it was assumed that partial penetration of the pumped well influenced the amount of drawdown in both wells to the same degree. Therefore, partial penetration of the pumped well did not affect the value of s'/s calculated from the MW3I and MW3D well data (E. P. Weeks, U.S. Geological Survey, oral commun., 1989). With the values of tD and s'/s known, t'D was found from the curve match (fig. 13 and tables 4 and 5).

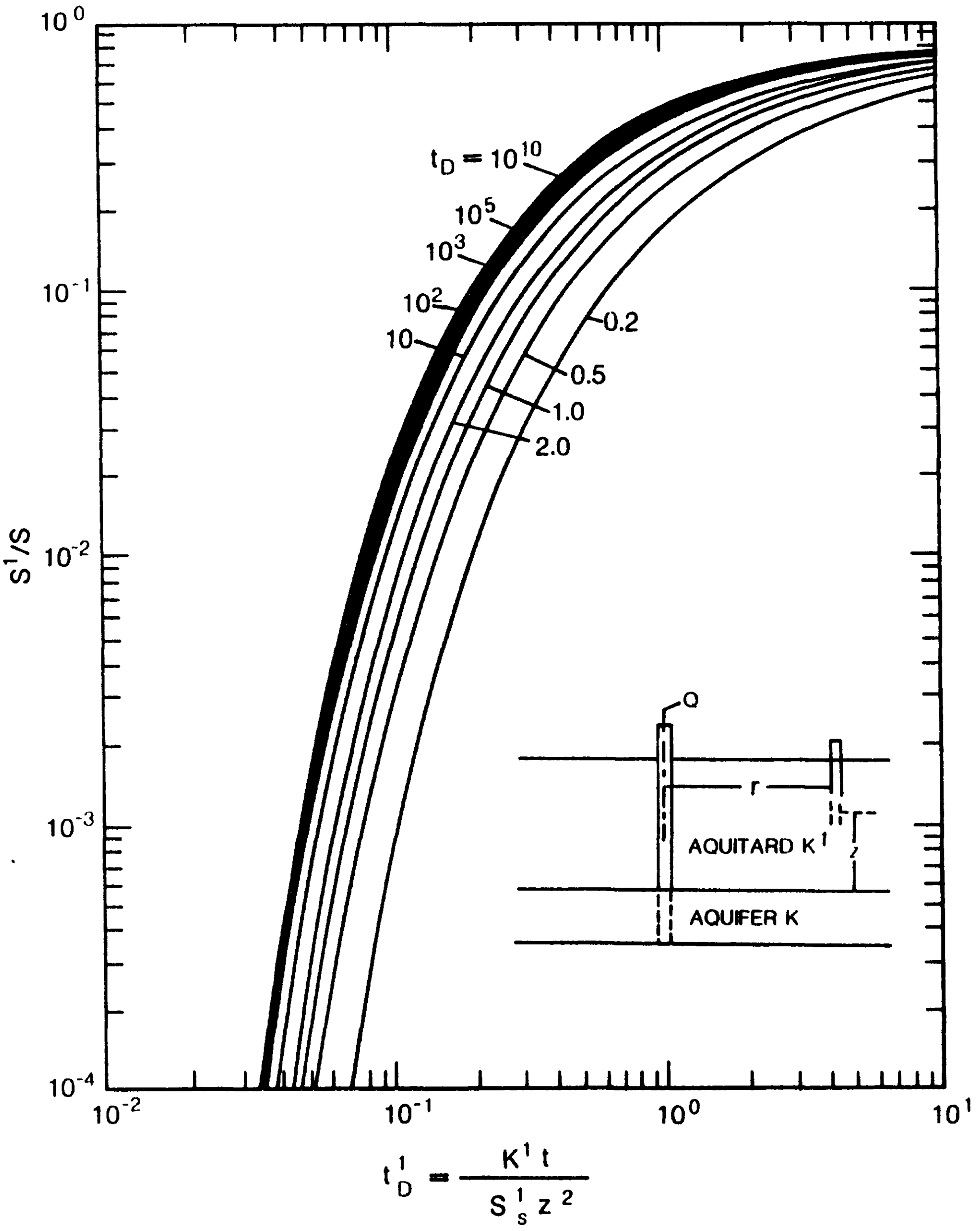

Figure 13.--The variation of s'/s with t'D for a semi-infinite confining unit (from Javendel, 1984, p. 81). Reprinted with permission of the National Water Well Association.

Table 4.--Calculated dimmensionless time in the aquifer (tD), ratio of drawdown in the confining unit to drawdown in the aquifer (s'/s), dimensionless time in the confining unit (t'D), and confining-unit diffusivity (a') from the data for wells MW3I and MW3D

[ft^2/d, feet squared per day]

Time (minutes)	tD	s'/s	t'D	a' (ft^2/d)
300	817	1.23×10^{-2}	0.09	62.21
400	1,089	3.73×10^{-2}	.12	62.21
500	1,362	5.43×10^{-2}	.14	58.06
600	1,632	8.00×10^{-2}	.18	62.21
700	1,906	1.09×10^{-1}	.23	68.13
800	2,179	1.34×10^{-1}	.26	67.39
900	2,451	1.54×10^{-1}	.29	66.82
1,000	2,723	1.77×10^{-1}	.33	68.43
1,100	2,996	2.00×10^{-1}	.35	65.99
1,200	3,268	2.23×10^{-1}	.42	72.58
1,400	3,813	2.79×10^{-1}	.52	77.02

Table 5.--Calculated dimensionless time in the aquifer (tD), ratio of drawdown in the confining unit to drawdown in the aquifer (s'/s), dimensionless time in the confining unit (t'D), and confining-unit diffusivity (a') from the data for wells MW6I and MW6D

[ft^2/d, feet squared per day]

Time (minutes)	tD	s'/s	t'D	a' (ft^2/d)
340	4.72	8.69×10^{-3}	0.09	54.89
400	5.56	1.46×10^{-2}	.10	51.84
500	6.95	2.80×10^{-2}	.14	58.06
600	8.34	3.79×10^{-2}	.15	51.84
700	9.73	4.74×10^{-2}	.17	50.36
800	11.12	5.18×10^{-2}	.18	46.66
900	12.50	5.92×10^{-2}	.19	43.78
1,100	15.72	7.41×10^{-2}	.21	39.59
1,400	19.45	8.15×10^{-2}	.22	32.58

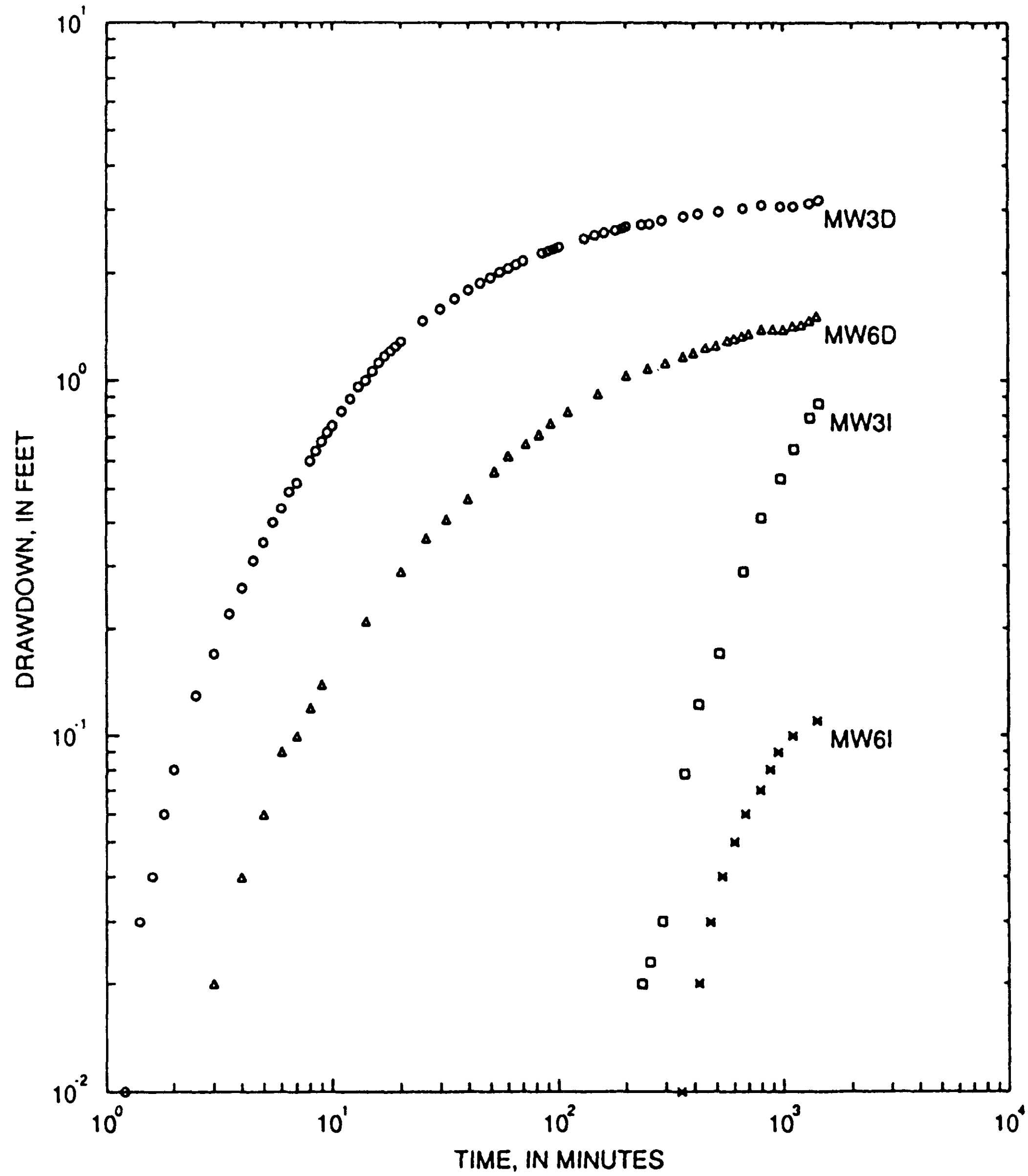

Figure 14.--Time-drawdown plots for observation wells MW3I, MW3D, MW6I, and MW6D during the aquifer test, December 17-18, 1987.

Knowing t'D, t, and z^2 (z = 12 ft, the maximum possible distance, based on the well and lithologic logs, from the base of the intermediate confining unit to the bottom of wells MW3I and MW6I), the confining-unit diffusivity (a') was calculated from the MW3I, MW3D, MW6I, and MW6D well data by solving the following equation:

$$a' = k'/Ss' = (t'Dz^2)/t. \qquad (5)$$

As table 4 indicates, the a' determined from the MW3I and MW3D well data is fairly consistent throughout the duration of the aquifer test. Diffusivity values calculated from the MW6I and MW6D well data are consistent for approximately the first 700 minutes of the test then decline steadily for the remainder of the test (table 5). Because the calculated values of a' decreased with increasing time at wells MW6S, 6I, and 6D, the value of a' calculated at t = 700 minutes was chosen as the representative value for the confining unit at each location. The values calculated at t = 700 minutes were chosen because the early time values are generally the most representative (Neuman and Witherspoon, 1972, p. 1294). At t = 700 minutes, the value of a' in the area of wells MW3S, 3I, and 3D was calculated to be 68.13 ft^2/d. The value of a' in the area of wells MW6S, 6I, and 6D at t = 700 minutes was estimated to be 50.36 ft^2/d.

Having obtained values for the product of the confining-unit hydraulic conductivity from the Hantush (1960) method and the quotient of the confining-unit hydraulic conductivity and specific storage from the Neuman and Witherspoon (1972) method, the value of the confining-unit hydraulic conductivity (k') can be calculated from

$$k'^2 = (k'/Ss')(k'Ss'). \qquad (6)$$

Using the data in table 3 for well MW6D, k'Ss' = 7.84×10^{-7} 1/d. Using the data in table 5 at t = 700 minutes, a' = k'/Ss' = 50.36 ft^2/d. Substituting these values and solving equation 6 gives a value of k' = 6.28×10^{-3} ft/d. This value is within the range of values for k' determined from the Hantush and Jacob (1955) method. This value also is within the range of laboratory-determined k' values of 2.27×10^{-3} ft/d and 1.13×10^{-1} ft/d for two samples from the intermediate confining unit (Douglas Yeskis, U.S. Environmental Protection Agency, written commun., 1988).

Hydraulic connection between the confining unit and the confined aquifer has been established by the aquifer test. Hydraulic connection between the unconfined aquifer and the confined aquifer has yet to be proven because water levels in wells MW3S, MW4S, and MW6S, open to the unconfined aquifer, showed no clearly defined response to pumping in the confined aquifer (fig. 10).

The most likely reasons for the lack of water-level response in the unconfined aquifer during the aquifer test are

1. The confined aquifer was not pumped long enough for the effects of pumping to be transmitted through the confining unit, or

2. the transmissivity and specific yield of the unconfined aquifer are high enough that the leakage induced by pumping in the confined aquifer was too slight to induce drawdown.

The time needed to induce drawdown in the unconfined aquifer because of pumping from the confined aquifer was calculated to determine which phenomena best explains the lack of water-level response in the unconfined aquifer.

The time required to induce drawdown at a given point in the confining unit can be estimated by solving equation 5 for t. At well MW3D, the confining unit is about 30 ft thick (fig. 3). If drawdown at the top of the confining unit at well MW3D is assumed to be 0.01 ft and drawdown in the confined aquifer is observed to be 3.0 ft (fig. 14), $s'/s = 3.33 \times 10^{-3}$ and $t'_D = 6.00 \times 10^{-2}$ is obtained from the curve match (fig. 13). If $a' = 68.13$ ft^2/d, $t'_D = 6.00 \times 10^{-2}$, and $z = 30$ ft, by solving equation 5 for t, it is estimated that it would take about 19 hours of pumping in the confined aquifer to produce 0.01 ft of drawdown at the top of the confining unit at well MW3D. At well MW6D, the confining unit is about 25 ft thick (fig. 3). If drawdown at the top of the confining unit at well MW6D is assumed to be 0.01 ft and drawdown in the confined aquifer is observed to be 1.35 ft (fig. 14), $s'/s = 7.14 \times 10^{-3}$ and $t'_D = 0.08$ is obtained form the curve match (fig. 13). If $a' = 50.36$ ft^2/d, $t'_D = 0.08$, and $z = 25$ ft, by solving equation 5 for t, it is estimated that it would take about 24 hours of pumping in the confined aquifer to produce 0.01 ft of drawdown at the top of the confining unit at well MW6D.

The calculations indicate that leakage from the unconfined aquifer was induced by pumping the confined aquifer during the aquifer test. This indicates that no drawdown was detected because the transmissivity and specific yield of the unconfined shallow aquifer are large compared to leakage. If leakage from the unconfined aquifer through the confining unit has, in fact, been induced by pumping in the confined aquifer, then any contaminants present in both the unconfined aquifer and the confining unit can flow into the confined aquifer.

SUMMARY AND CONCLUSIONS

Aquifer-test data in the vicinity of a landfill near Antioch, Illinois, were analyzed using three different techniques. The Hantush and Jacob (1955) method indicates that the calculated transmissivity of the confined aquifer ranged from 1.96×10^{4} to 2.52×10^{4} ft^2/d, the storativity of the confined aquifer ranged from 2.10×10^{-4} to 8.71×10^{-4}, the calculated leakage through the confining unit ranged between 1.29×10^{-4} and 7.84×10^{-3} (ft/d)/ft, and the hydraulic conductivity of the confining unit ranged from 3.22×10^{-4} to 1.96×10^{-2} ft/d. The Hantush (1960) method calculates similar values for aquifer transmissivity and storativity. The Neuman and Witherspoon (1972) ratio method indicates that the diffusivity of the confining unit ranges from 50.36 to 68.13 ft^2/d. The vertical hydraulic conductivity of the confining unit was calculated to be 6.28×10^{-3} ft/d using data obtained from both the Hantush and the Neuman and Witherspoon methods.

Aquifer-test data indicate that the confining unit is hydraulically connected to the confined aquifer. Although no clear evidence exists to prove that the unconfined aquifer is hydraulically connected to the confined aquifer, it is calculated that the unconfined aquifer became hydraulically connected to the confined aquifer within 24 hours after pumping began in the confined aquifer.

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