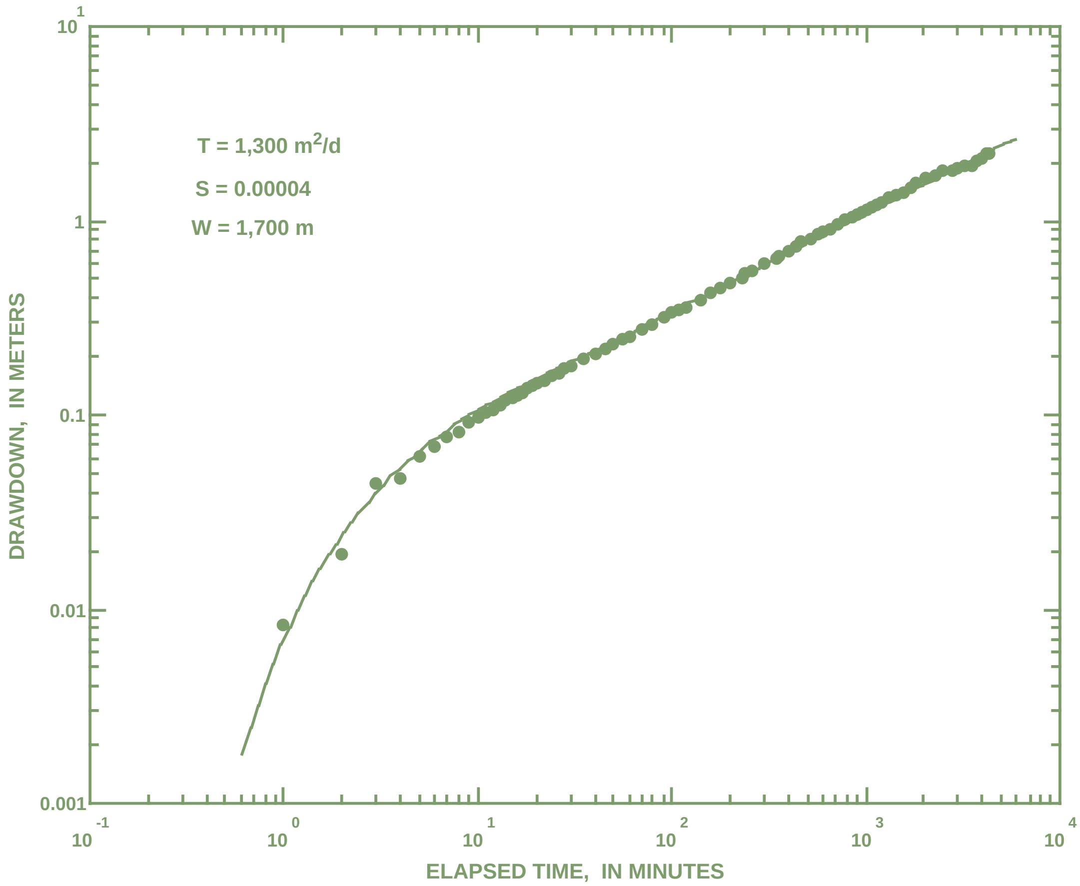
U.S. Department of the Interior
U.S. Geological Survey

Review of Aquifer Test Results for the Lansdale Area, Montgomery County, Pennsylvania, 1980-95

Open-File Report 98-294



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U.S. Department of the Interior
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Review of Aquifer Test Results for the Lansdale Area, Montgomery County, Pennsylvania, 1980-95

by Daniel J. Goode and Lisa A. Senior

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Lemoyne, Pennsylvania
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
	Flow rate	
meter per second (m / s)	3.281	foot per second (ft / s)
meter per day (m / d)	3.281	foot per day (ft / d)
meter per year (m / yr)	3.281	foot per year (ft / yr)
cubic meter per second (m^3 / s)	35.31	cubic foot per second (ft^3 / s)
cubic meter per day (m^3 / d)	35.31	cubic foot per day (ft^3 / d)
liter per second (L / s)	15.85	gallon per minute (gal / min)
liter per minute (L / min)	0.2642	gallon per minute (gal / min)
cubic meter per day (m^3 / d)	264.2	gallon per day (gal / d)
	Specific capacity	
liter per second per meter [(L / s) / m]	4.831	gallon per minute per foot [(gal / min) / ft]
meter squared per day (m^2 / d)	0.0559	gallon per minute per foot [(gal / min) / ft]
	Hydraulic conductivity	
meter per day (m / d)	3.281	foot per day (ft / d)
	Transmissivity	
meter squared per day (m^2 / d)	10.76	foot squared per day (ft^2 / d)

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

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ABSTRACT

Aquifer and aquifer-isolation test results in and around North Penn Area 6 Superfund Site, Lansdale, Montgomery County, Pa., are reviewed to provide estimated aquifer properties for use in a numerical model of ground-water flow. This review was made to support remedial action investigations by U.S. Environmental Protection Agency (USEPA), Region III, Philadelphia. The data reviewed are from files of the U.S. Geological Survey, USEPA, and water companies, and from unpublished consultant reports prepared for USEPA and corporations in the Lansdale area. Tested wells are in fractured sedimentary rocks of the Brunswick Formation, which are Triassic-aged, dipping shales and sandstones. Review procedures include, in some cases, new analyses of drawdown during pumping and recovery by use of analytical models of flow to wells. Estimated aquifer transmissivities (T) range from zero to about 1,300 m^2/d (meters squared per day); most tests indicate T between 10 and 100 m^2/d. Aquifer-isolation testing results indicate that most flow enters wells at a few discrete zones, probably fractures or bedding-plane openings. The vertical connection between the zones in a single borehole with multiple producing zones commonly is negligible. This suggests that the formation is vertically anisotropic; the hydraulic conductivity is much larger in the horizontal direction than in the vertical direction. Some evidence of well-field-scale horizontal anisotropy exists, with maximum transmissivity aligned with the regional northeast strike of bedding, but this evidence is weak because of the small number of observation wells, particularly wells screened in isolated depth intervals. Analysis of recovery data after constant-pumping-rate aquifer tests and of drawdown during step tests suggests that a significant fraction, perhaps as much as 85 percent, of the drawdown in some production wells is due to well loss or skin effects in or very near the pumped well and is not caused by resistance to flow in the surrounding formations.

INTRODUCTION

Water-supply and industrial wells in the area around Lansdale, Pa., have been contaminated with low concentrations of organic solvents (CH2M Hill, Inc., 1991). In the past, water pumped from these wells was treated at significant cost before use. Recently, wells have been abandoned as more economical water sources become available. The removal of these wells from service will result in changes in ground-water flow directions in the area of contamination and may result in further spreading of contaminants. In cooperation with the U.S. Environmental Protection Agency (USEPA), the U.S. Geological Survey (USGS) is developing a ground-water flow model of subsurface formations beneath the North Penn Area 6 (NP6) Superfund Site (fig. 1) to examine current and past hydrologic conditions and to estimate response of the ground-water system to pumping changes.

Purpose and Scope

Records of aquifer and aquifer-isolation tests in the Lansdale area are reviewed and analyzed to provide estimates of hydraulic properties, primarily transmissivity (T) and storage coefficient (S), of the fractured-rock aquifer. Reviewed and analyzed information includes data collected by USGS and from USEPA and private corporation files and unpublished reports. Data sets are analyzed quantitatively to estimate aquifer T and, in most cases, S.

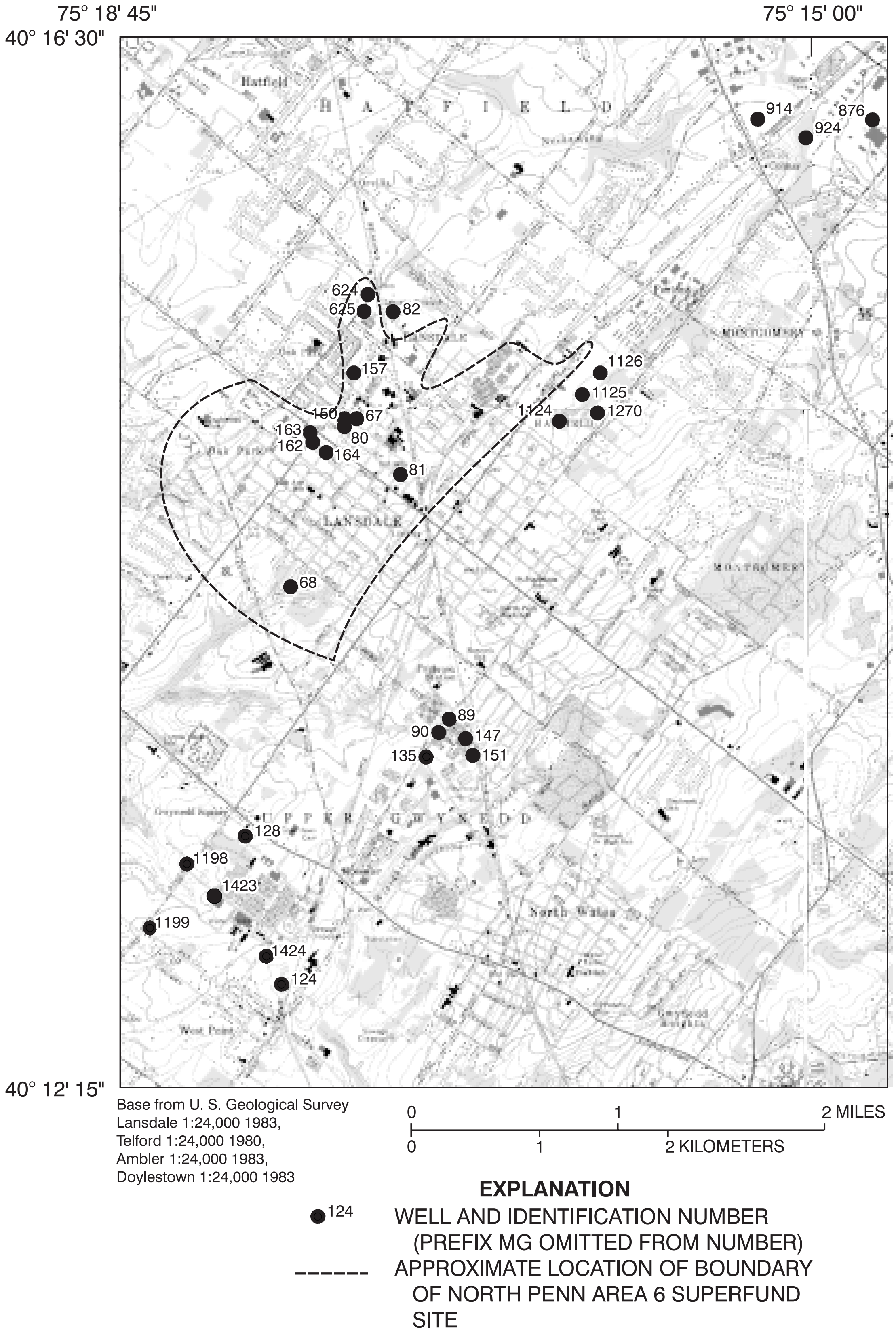

Figure 1. Location of study area and wells. (Boundary of North Penn Area 6 Superfund Site from CH2M Hill, Inc. (1991)).

Acknowledgments

Reports and data files on aquifer testing in the Lansdale area were provided by USEPA, Region III, Philadelphia, Pa., as part of the NP6 project managed by Greg Ham. Kathryn Davies, also of USEPA, provided guidance during this review. Additional information was provided by North Penn Water Authority, Lansdale, Pa.

Numerous USGS staff contributed to this report. Kevin E. Grazul and James E. Bubb prepared some graphics for this report. Charles R. Wood assisted with well database information. Ronald A. Sloto, Todd S. Miller, and Keith J. Halford are acknowledged for their helpful reviews of this report. Analyses in this report reflect contributions by and discussions with Dennis W. Risser.

HYDROGEOLOGIC SETTING

Lansdale, Pa., is in the Triassic Lowlands Section of the Piedmont Physiographic Province. Lansdale and the surrounding area are underlain by sedimentary rocks of the Brunswick Group (lower beds) and Lockatong Formation of the Newark Supergroup (Lyttle and Epstein, 1987). Contacts between the Brunswick Group and the underlying Lockatong Formation are conformable and gradational, and the two formations may interfinger. The lower beds of the Brunswick Group consist predominantly of homogeneous, soft, red to reddish-brown and gray to greenish-gray mudstones and clay- and mud-shales. Bedding is irregular and wavy. Some beds are micaceous. Interbedded silt-shales and siltstones are fairly well sorted. Mudcracks, ripple marks, crossbeds, and burrows are common in all beds. The Brunswick Group rocks contain detrital cycles of medium- to dark-gray and olive- to greenish-gray, thin-bedded and evenly bedded shale and siltstone, similar to the underlying Lockatong Formation. Rocks of the Lockatong Formation contain detrital cycles of gray to black calcareous shale and siltstone, with some pyrite, and chemical cycles of gray to black dolomitic siltstone and marlstone with lenses of pyritic limestone, overlain by massive gray to red siltstone with analcime (Lyttle and Epstein, 1987). The beds of the Brunswick Group and Lockatong Formation strike northeast and dip about 15˚ to the northwest in the vicinity of the site. The bedrock is covered by a thin weathered zone, generally less than a few meters thick, and by an equally thin soil layer.

The Lockatong Formation commonly is relatively resistant to erosion and tends to form ridges that rise above flat or rolling topography underlain by rocks of the Brunswick Group. Lansdale and the surrounding area are underlain mostly by rocks of the Brunswick Group and are on relatively flat upland terrain that is a surface-water divide between the Wissahickon Creek to the southwest, Towamencin Creek to the west, and tributaries to the West Branch Neshaminy Creek to the north and northeast.

Ground water beneath Lansdale originates from infiltration of local precipitation and discharges to streams and to pumping wells. After infiltrating through soil and saprolite, ground water moves through vertical and horizontal fractures in the shale and siltstones (Newport, 1971). The aquifer transmissivity is controlled by the size of the openings, or aperture, and by the degree of interconnectedness of openings (Sloto, 1994). Primary porosity is very low or nonexistent. Permeability and storage are very low. Ground water in rocks of the Brunswick Group and Lockatong Formation may be under confined, unconfined, and(or) perched conditions. Ground water in the aquifer generally is under confined or partially confined conditions, resulting in local artesian conditions.

The ground-water flow system can be characterized as a multi-aquifer system composed of high-permeability layers separated from each other by semi-confining layers. Shallow and deep ground-water flow systems may exist at the site. Ground-water levels fluctuate with pumping and seasonal variations in recharge. Water from the upper system may drain locally to streams and also leak downward to a deeper ground-water flow system. Wells constructed as open-hole boreholes penetrate both systems, and water levels measured in these wells represent composite heads. Where differences in potentiometric head are present, water in the borehole flows from zones of higher head to zones of lower head. Ground water generally flows in a direction similar to the topographic gradient. The natural direction of flow can be altered by pumping. Pumping from deep zones may induce downward flow from shallow zones. Longwill and Wood (1965) report that maximum well yields in the Brunswick Formation are generally obtained at depths from about 60 m (200 ft) to about 170 m (550 ft) below land surface. The variable nature of the subsurface permeability is reflected in variable well yields; nearby wells drilled to similar depths commonly have very different yields (Rima, 1955).

STUDY METHODS

Results of aquifer tests conducted from 1980 to 1995 are reviewed and summarized. In addition, water-level and drawdown (initial water level minus water level during testing) data from several previously conducted well tests are reanalyzed by use of standard methods (Theis, 1935; Cooper and Jacob, 1946). For some tests, this analysis is done with graphs from original reports. For other tests, printed water-level or drawdown records were input manually or scanned and converted to digital data for re-analysis. Although a number of datapoints were lost during this process, sufficient data were retained to adequately characterize the drawdown during the tests. Digital data files created for this study are archived at the USGS Pennsylvania District office and are available on request.

Several graphical-analysis techniques are used to portray the hydraulic response of tested wells or tested intervals within wells and, in some cases, to estimate aquifer properties (primarily T and S) from drawdown data. Plots of linear-drawdown as a function of linear time are useful for portraying ‘real-time’ features of the test and for identifying borehole storage effects, which occur when all or most of the water pumped from the well is derived from water stored in the borehole and not from inflow to the well from the tested formation.

A standard method for analyzing well tests involves plotting log-drawdown as a function of log-time and using the Theis (1935) type-curve-matching procedure to estimate aquifer properties. This plot emphasizes the early-time part of the test and can be used with several different conceptual mathematical models of ground-water flow, such as those described by Reed (1980). Theoretical drawdown as a function of time for several different conceptual models is shown in figure 2. For example, a straight line with half slope on the log-log plot is characteristic of linear flow, commonly observed in fractured-rock systems (fig. 2F). Although the hydrogeologic assumptions of the Theis model are never completely satisfied in the field, this model provides a common framework to compare boreholes. Use of more realistic and more complicated models commonly yields large-scale and late-time T and S similar to the Theis method (for example, Dagan, 1967; Neuman, 1975). For an analysis of one test, a more complicated model for an aquifer limited in extent in one direction is used. This model is based on image well theory and the Theis model, and its application is described in the section “Aquifer Test of Mg-1125, February and October 1989.” Linear superposition of two Theis solutions is used to analyze drawdown in a well affected by two pumped wells in the section “Aquifer Test of Mg-67 and Mg-80, March 1980.”

A derivative of the Theis method, suitable for large-dimensionless-time response, is based on a plot of linear-drawdown as a function of log-time (Cooper and Jacob, 1946). A straight line on this plot is indicative of Theis or infinite, confined-aquifer response at large-dimensionless time.

A new procedure (Goode, 1997) was employed for analysis of water-level recovery data for a few tests. This type-curve method employs a plot of log-drawdown as a function of normalized time (time since pumping stopped divided by duration of pumping) and allows estimates of T at the pumped well that are not affected by well loss. This method is similar to the Theis (1935) method for recovery but incorporates early-dimensionless-time response, particularly useful for observation wells. Recovery of observation wells commonly does not satisfy the large-dimensionless-time approximation because dimensionless time is inversely proportional to radial distance squared.

Step-test data are analyzed by use of procedures of Hantush and Bierschenk (see Kruseman and de Ridder, 1990, p. 200). The incremental head change due to each pumping-rate increment is determined graphically by extrapolation on a semi-log plot of drawdown (linear) as a function of time (logarithmic). The linear and nonlinear (well-loss) terms for the drawdown equation are determined from the plot of the sum of incremental drawdowns divided by pumping rate as a function of pumping rate. Theoretically, the linear part of the drawdown is due to resistance to flow in the formation and the nonlinear term is due to turbulent flow in or very close to the borehole.

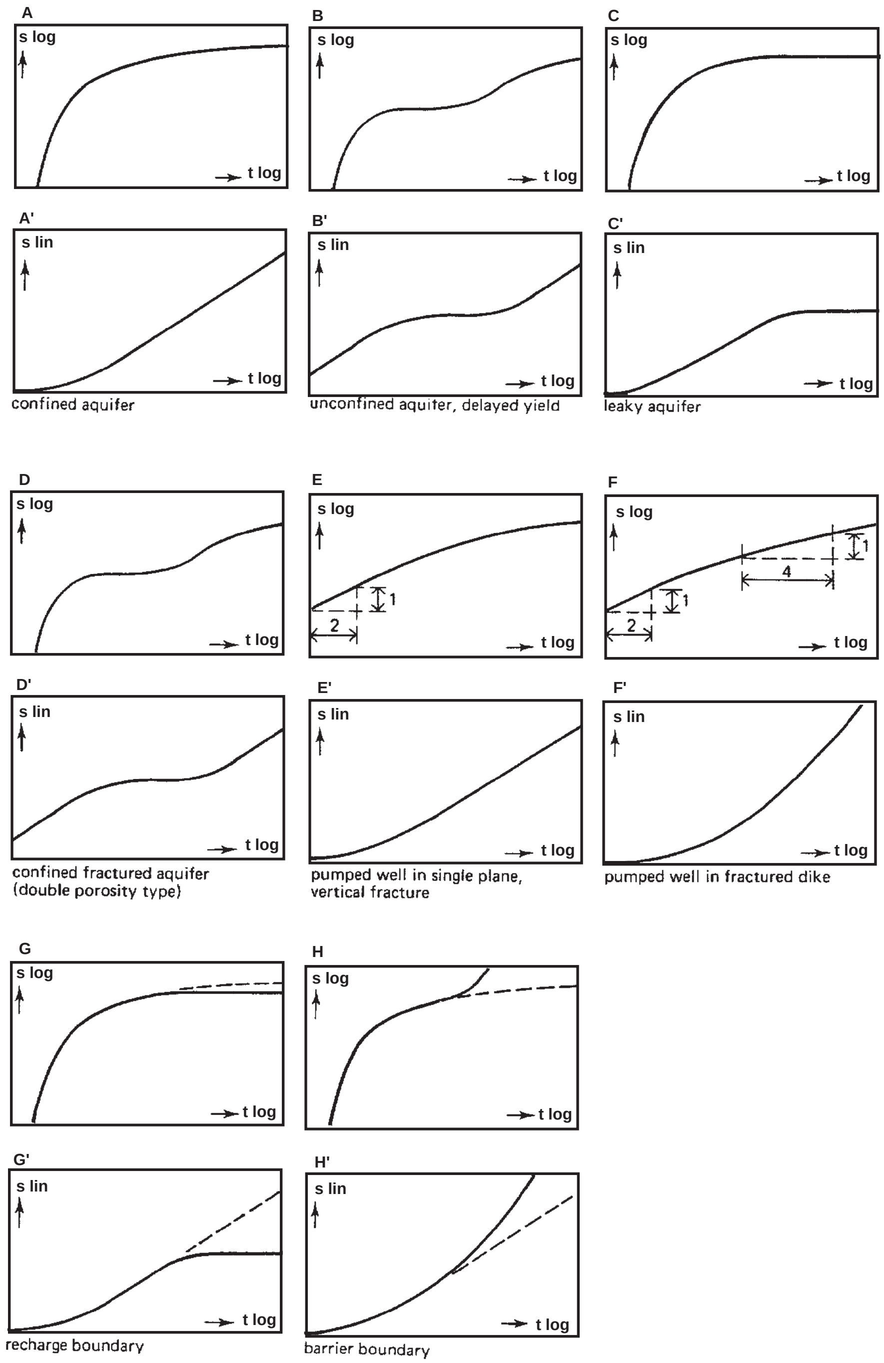

Figure 2. Log-log and semi-log plots of theoretical drawdown (s) as a function of time (t) for several conceptual models: (A) confined; (B) unconfined; (C) leaky; (D) double porosity; (E) single vertical fracture; (F) permeable dike in less-permeable aquifer; (G) confined with recharge boundary; (H) confined with impermeable boundary (modified from Kruseman and de Ridder, 1990, and published with permission by International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands).

Information on antecedent and background water-level trends is not available for most of the tests reviewed. The analyses here are based on the assumption that measured water-level changes are caused by pumping at the test well. Measured water-level changes may also be caused by recharge, drainage, pumping at other wells, air pressure fluctuations, and other processes. Generally these water-level changes are small compared to those caused by test-well pumping; hence, errors in estimated hydraulic properties are correspondingly small. However, some amount of uncertainty in these estimated properties is caused by our inability to remove antecedent and background water-level changes using available information.

Well identifiers used here generally correspond to the USGS Pennsylvania well-numbering system. The letters "Mg" refer to Montgomery County, and the numbers are sequential as wells are scheduled in the USGS database. Local well identifiers also are given parenthetically in most cases. A limited number of wells used in this report are not in the USGS Pennsylvania well database and are referred to here by their local identifier.

AQUIFER TESTING IN THE LANDSDALE AREA

Aquifer Test of Mg-67 and Mg-80, March 1980

Water-level measurements were made in eight observation wells and in the pumped wells during pumping of Mg-67 (local well L 8) and Mg-80 (Allied Paint #1) beginning on March 25, 1980 (U.S. Environmental Protection Agency, unpublished data files). Pumping at an average rate of 370 L / min (98 gal / min) began in Mg-67 at 0900 on March 25, 1980. At 1100 on the same day, pumping began in Mg-80 at an average rate of 280 L / min (74 gal / min). Pumping in Mg-80 stopped at 1700 on the same day; hence Mg-80 was pumped for a total of 6 hours. Pumping in Mg-67 continued until 0900 on March 27, 1980, hence, Mg-67 was pumped for a total of 48 hours.

Estimated T and S from the aquifer test of Mg-67 and Mg-80 are summarized in table 1. Some characteristics of drawdown in different wells are discussed below in separate sections.The pumping of two separate wells during the same tests can be incorporated in models of drawdown during pumping to estimate T and S from drawdown. However, these procedures are much more complicated and time consuming than traditional Theis or Cooper-Jacob analyses. With one exception, the analyses in this section are based on single pumped well models, which are considered to be only rough approximations of the field situation. Drawdown in one well (Mg-150) is analyzed with a preliminary model accounting for two pumped wells.

Table 1. *Transmissivity and storage coefficient estimates from water levels during pumping of Mg-67 and Mg-80 in March 1980*

[L/min, liters per minute; m^2/d, square meters per day; m, meters; m bls, meters below land surface; Q, pumping rate]

Well	Transmissivity (m^2/d)	Storage coefficient	Radial distance (m)	Open interval (m bls)	Method	Pumping rate used in analysis
Mg-67	31	0.0014	0.1	6-87	Cooper-Jacob	Q= 370 L / min, Mg-67 only
Mg-67	25	.012			Theis	Q= 370 L / min, Mg-67 only
Mg-67	99				Recovery (Goode)	Q=370 L / min, Mg-67 only
Mg-157	99	.0004	310	14-87	Theis	Q=370 L / min, Mg-67 only
Mg-162	99	.00009	366	9-232	Theis	Q=370 L / min, Mg-67 only
Mg-163	85	.00015	339	9-92	Theis	Q=370 L / min, Mg-67 only
Mg-164	85	.00013	366	9-123	Theis	Q=370 L / min, Mg-67 only
Mg-80	202			40-98	Cooper-Jacob	Q=280 L / min, Mg-80 only
Mg-80	79				Recovery (Goode)	Q=280 L / min, Mg-80 only
Mg-150	150	.0002	r_1=161 r_2=56	13-123	Theis; 2 wells	Q_1=370 L / min; Mg-67 Q_2=280 L / min; Mg-80

Drawdown in Pumped Well Mg-67

Drawdown in pumped well Mg-67 is analyzed by the Cooper-Jacob method (fig. 3). A straight line is visually fit to the data in a linear-drawdown as a function of log-time format. The slope of this line yields an estimated T = 31 m^2/d (330 ft^2/d). Analysis by use of the Theis model in log-log format yields T = 25 m^2/d (270 ft^2/d) (fig. 4). All of the plotted data fall on the large-time part of the Theis curve, supporting application of the Cooper-Jacob method. However, the value of S = 0.012 by use of the Theis method is too high for confined or semi-confined fractured-rock aquifers in general. If well loss or a low-permeability skin is present, the Theis estimate would be low. Well loss is generally a pressure drop caused by turbulent flow between the formation just outside the borehole and the measurement location within the borehole. A skin is a thin zone at the borehole that has a permeability distinct from that of the surrounding formation. A low-permeability skin causes an exaggerated drawdown in the pumped well compared to the formation drawdown.

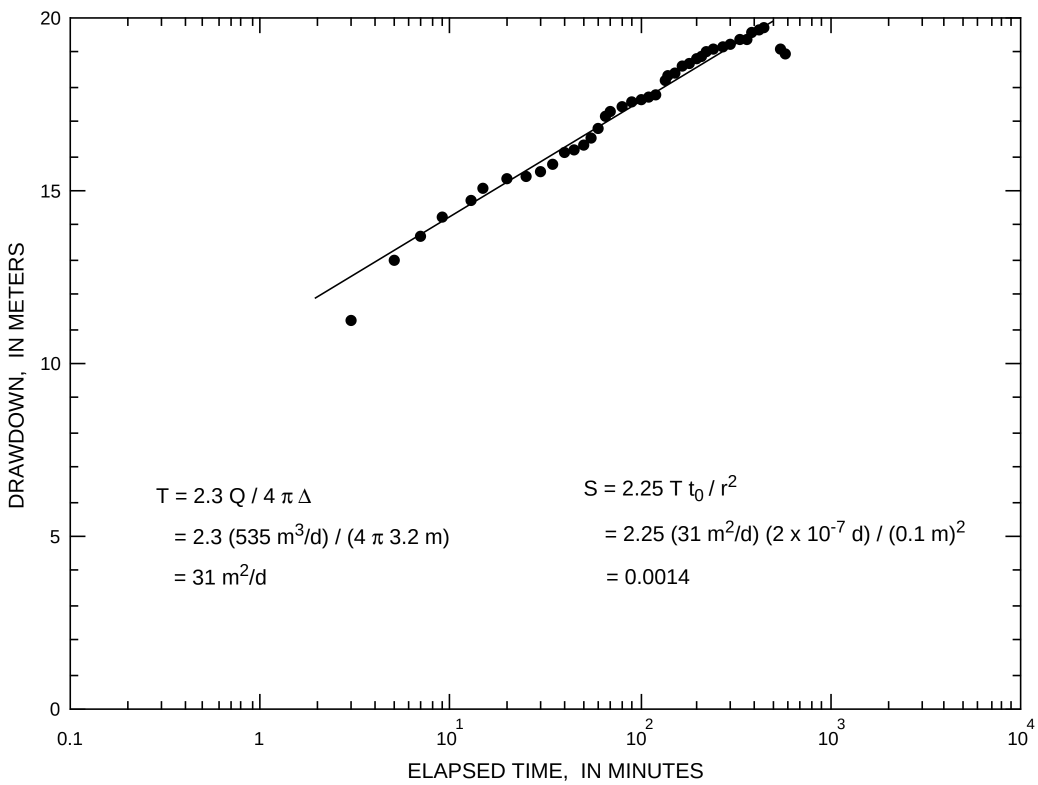

Figure 3. Drawdown in pumped well Mg-67, Lansdale area, March 1980, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

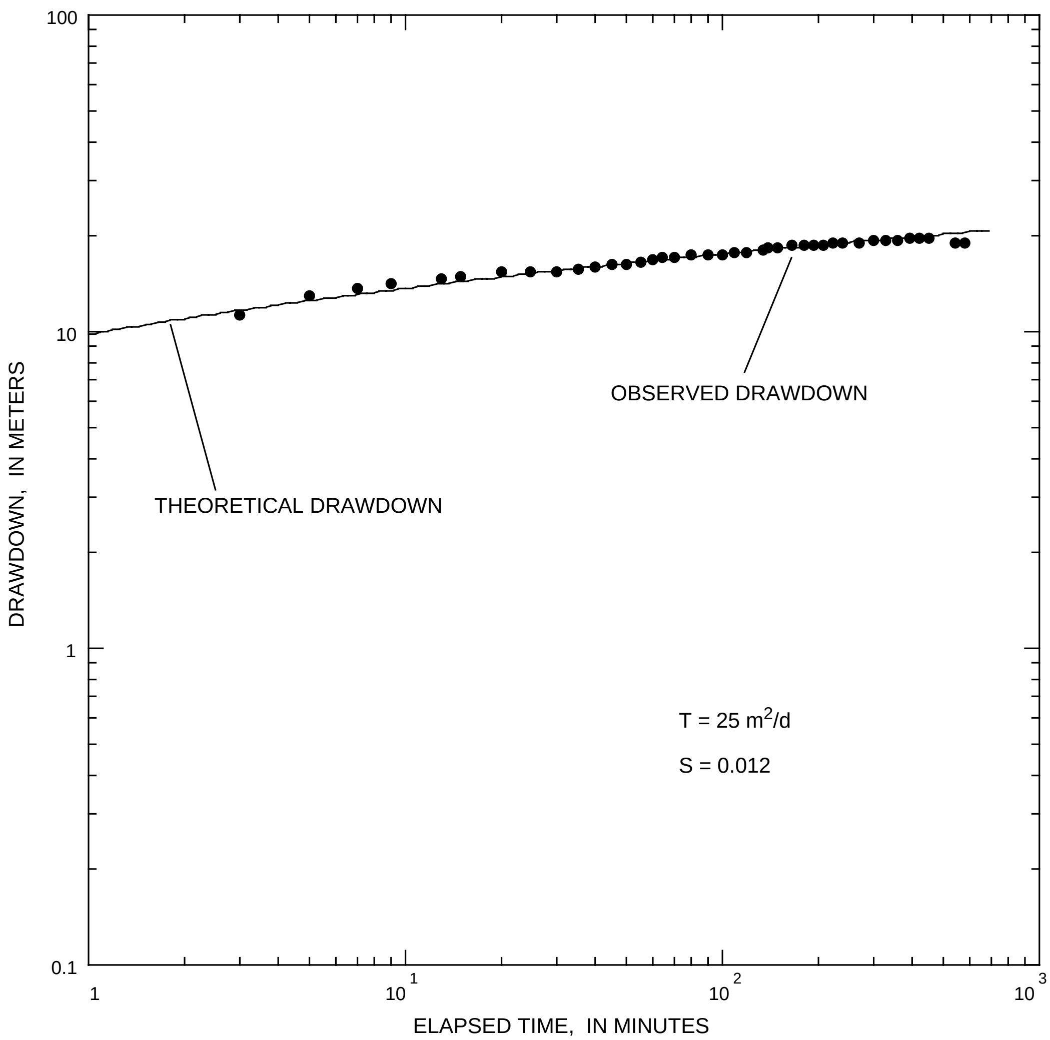

Figure 4. Drawdown in pumped well Mg-67, Lansdale area, March 1980, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

The recovery method of Goode (1997) yields an estimated T = 99 m^2 / d (1,070 ft^2 / d) from recovery data in Mg-67 (fig. 5). The early recovery is very rapid and probably is caused by well loss or a low-permeability skin, which causes the drawdown in the well to be much greater than that in the nearby formation during pumping. However, after pumping stops, flow rates dissipate quickly, and the water level in the well is much closer to that in the formation. The higher T estimated with this method is three to four times that from the pumping-period data and indicates that well loss during pumping accounts for about 75 percent of the drawdown in the pumped well.

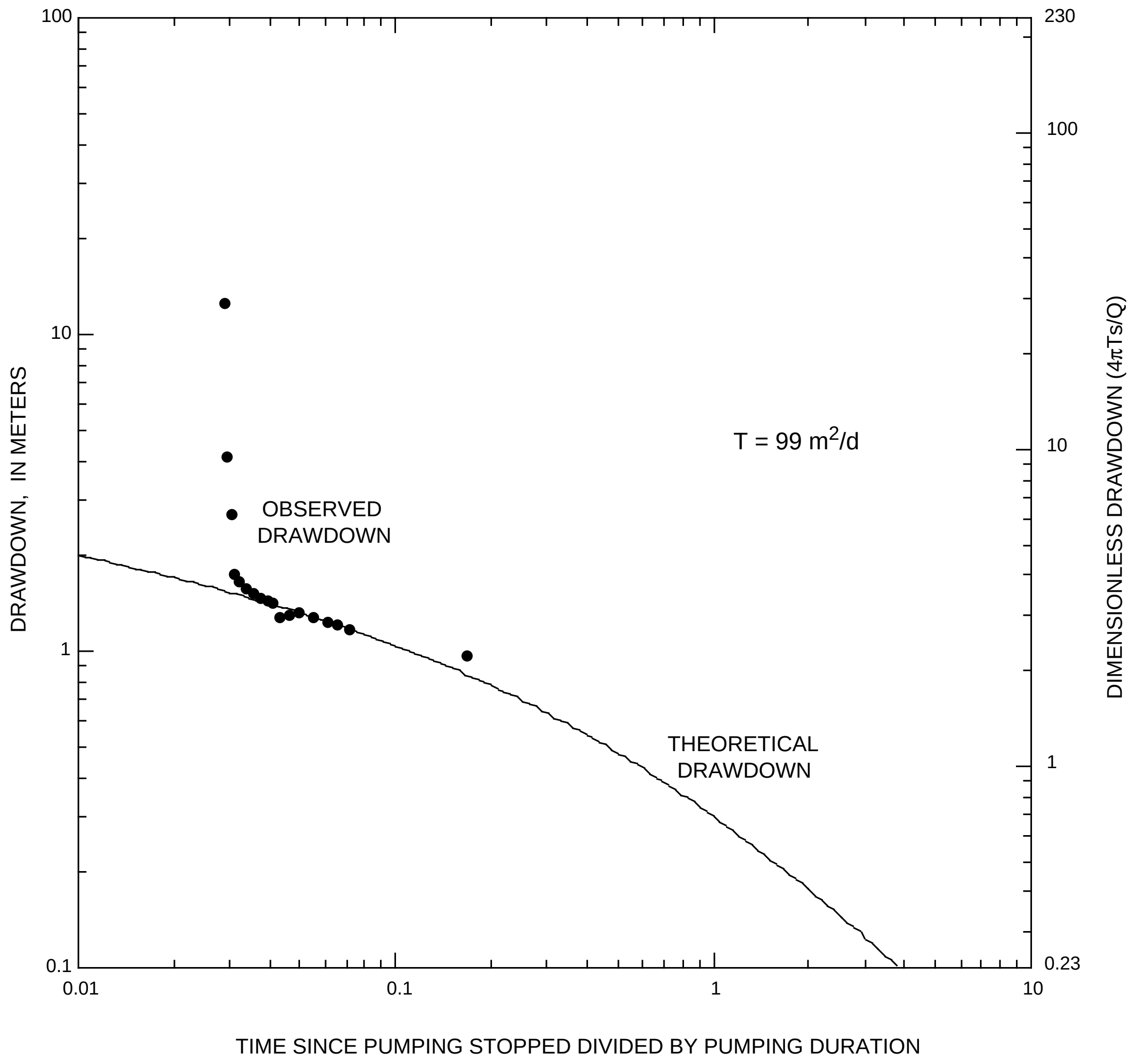

Figure 5. Drawdown during recovery in pumped well Mg-67, Lansdale area, March 1980, and estimate of transmissivity (T) by method of Goode (1997).

Drawdown in Second Pumped Well Mg-80

Drawdown in Mg-80, which was pumped at 280 L / min for 6 hours during the aquifer test of Mg-67, also is analyzed to estimate T. Drawdown of between 0 and 0.26 m (0.85 ft) was observed in Mg-80 prior to pumping, while Mg-67 was pumped (fig. 6). When the pump in Mg-80 was started, the drawdown increased rapidly to about 12 m (40 ft) and increased very slowly after about 15 minutes of pumping.

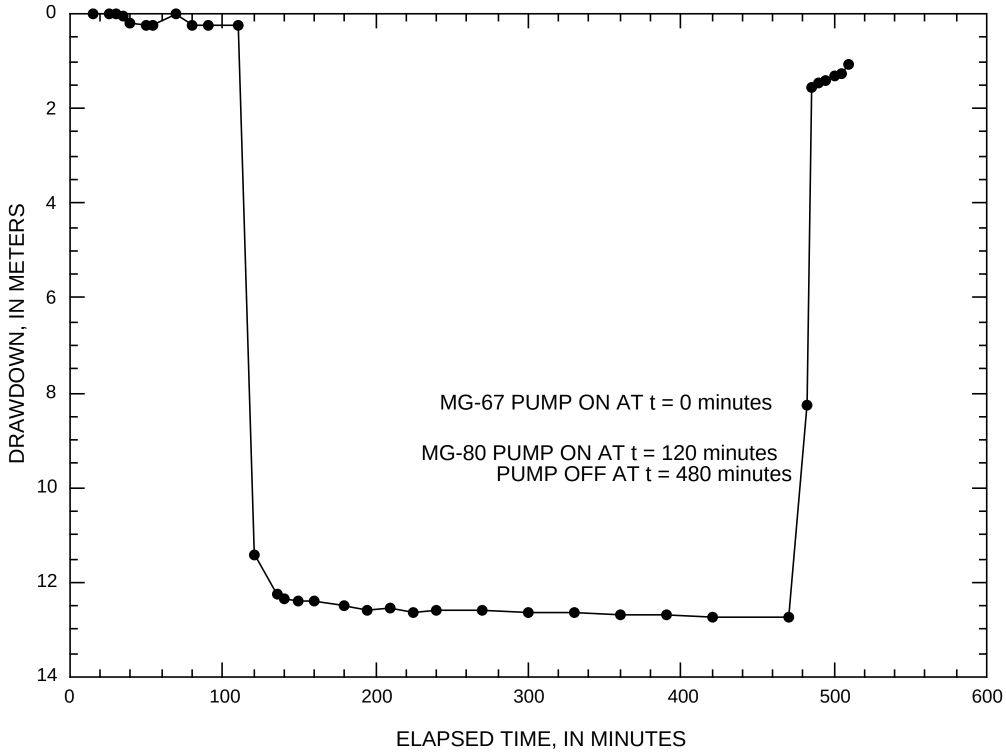

Figure 6. Drawdown in pumped well Mg-80 in Lansdale area, March 1980.

The Theis log-log plot of drawdown as a function of time of pumping in Mg-80 is too flat to match with the theoretical Theis response. Application of the Cooper-Jacob method yields T = 202 m^2 / d (2,170 ft^2 / d) (fig. 7). The match of the short-recovery (after Mg-80 pump was turned off) data to the Theis curve of Goode (1997) is marginal but yields T = 71 m^2 / d (770 ft^2 / d). Projecting the theoretical drawdown during recovery back in time (fig. 8), the formation drawdown of Mg-80 when pumping stopped is estimated to be closer to 3 m (10 ft) than to 12 m (40 ft), suggesting significant well loss or skin effects, about 75 percent of the total drawdown, during pumping. All these results are considered to only approximately characterize the formation; better estimates of T could be derived from a more complicated model that matches the field data better than the analyses presented here.

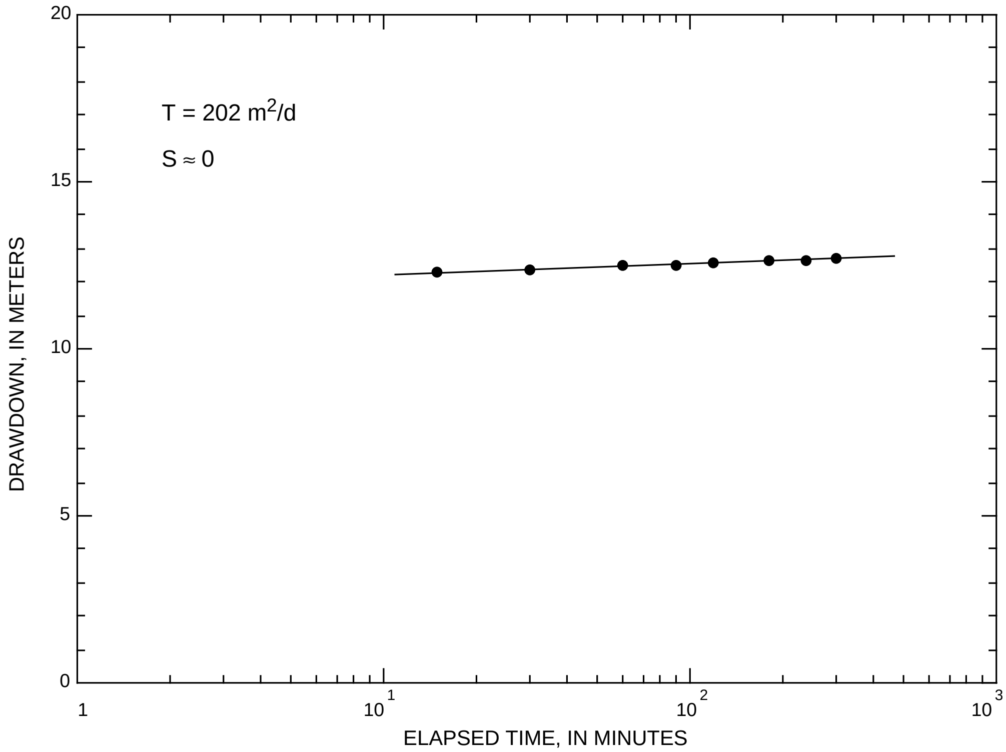

Figure 7. Drawdown in pumped well Mg-80 in Lansdale area, March 1980, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

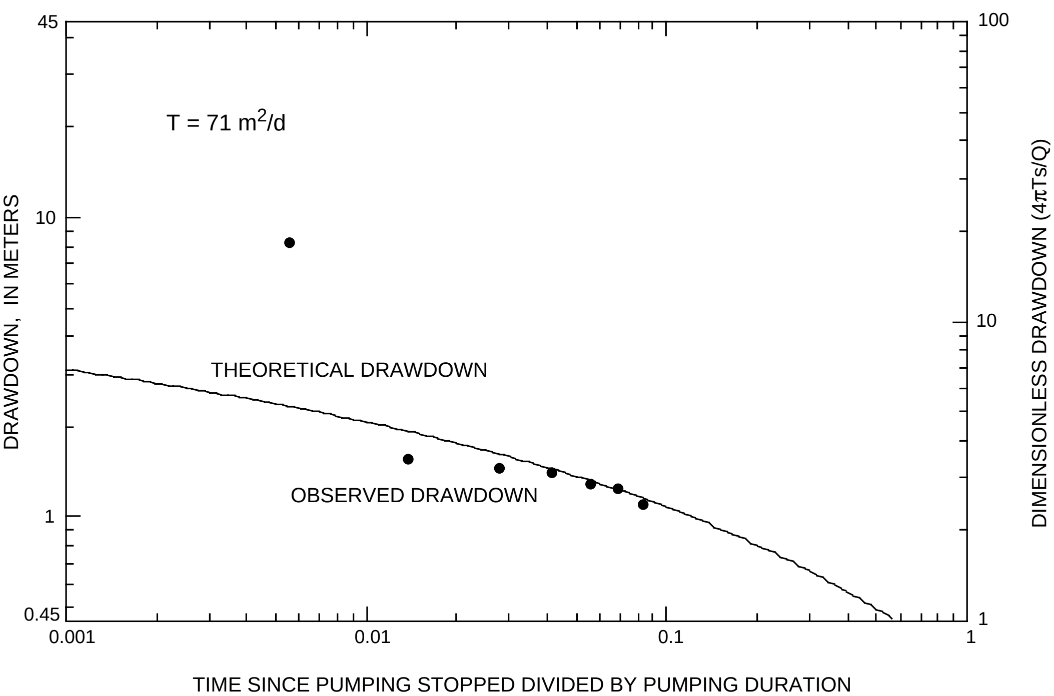

Figure 8. Drawdown during recovery in pumped well Mg-80 in Lansdale area, March 1980, and estimate of transmissivity (T) by method of Goode (1997).

Drawdown in Observation Wells

Water levels also were measured in eight observations wells. Wells Mg-624 (Rex #2), Mg-625 (Rex #1), and Mg-81 (L-27) were not substantially affected by the pumping in Mg-67 and Mg-80. However, water levels in Mg-162, Mg-163, Mg-164 (Rybond 2, 3, 4), Mg-157 (former F.M. Weaver), and Mg-150 (Allied Paint #2) responded to the pumping.

The drawdown in wells Mg-157, Mg-162, Mg-163, and Mg-164 and a match between the Theis model and drawdown at wells Mg-163 and Mg-164 are shown in figure 9. This match and a similar match to Mg-157 yield T ranging between 88 and 114 m^2 / d (950 and 1,230 ft^2 / d) by use of the pumping rate from well Mg-67 alone. Only this well's pumping rate is used in this analysis because the drawdown trends do not respond significantly to pumping in Mg-80. The momentary increases in drawdown in the observation wells correspond to short-duration pumping of the observation wells to collect water-quality samples. Soon after this sampling, the water level in the observation wells returns to levels consistent with pre-sampling levels. Nonetheless, these fluctuations in the water levels caused by sampling may have a minor effect on estimated T and S.

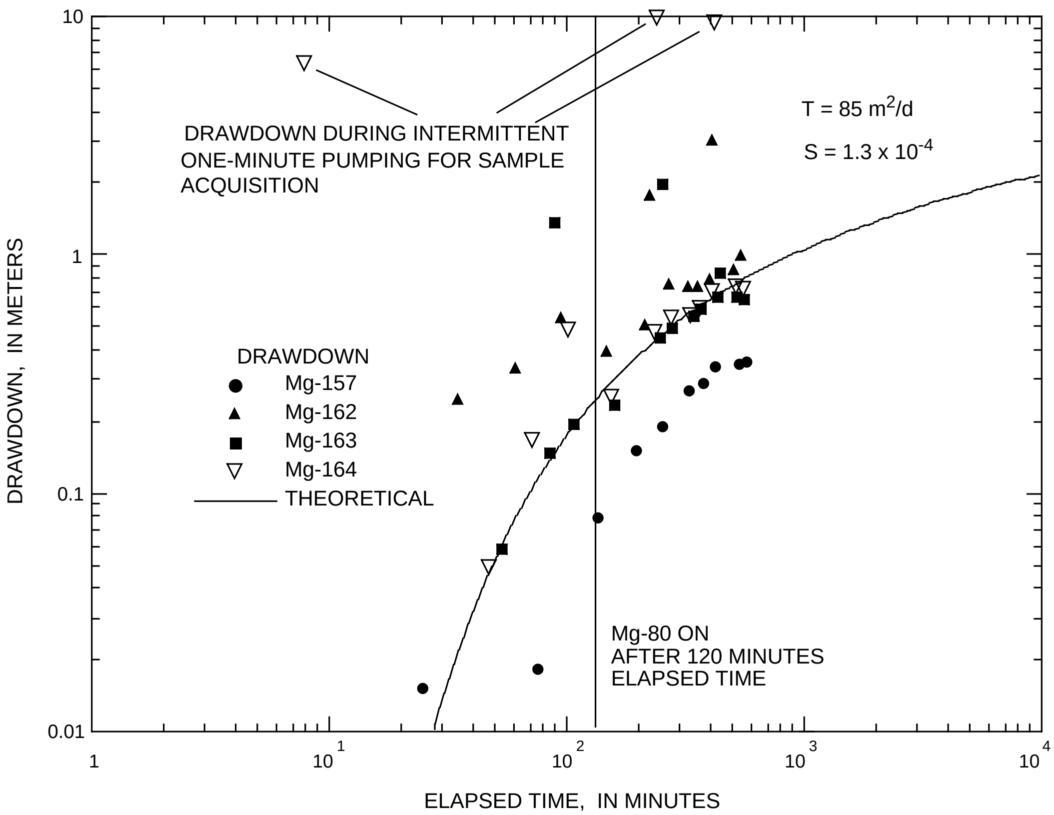

Figure 9. Drawdown in observation wells Mg-157, Mg-162, Mg-163, and Mg-164 during pumping of Mg-67 and Mg-80 in Lansdale area, March 1980, and estimates of transmissivity (T) and storage coefficient (S) from drawdown at Mg-163 and Mg-164 by Theis (1935) method.

In contrast to other observation wells, drawdown in observation well Mg-150 (Allied Paint #2) had distinct periods of response to Mg-67 pumping and to both Mg-80 and Mg-67 pumping after Mg-80 pumping began (fig. 10). Applying Theis' theory, the total drawdown in an observation well affected by two pumped wells is the superposition or sum of the drawdown due to each pumped well separately. Drawdown in Mg-150 appears to agree well with the Theis model (fig. 10) and the match yields an estimated T = 150 m^2/d (1,610 ft^2/d), similar to T from the other observation wells. The estimated $S = 4 \times 10^{-4}$ is at the upper end of the range expected for fractured rock.

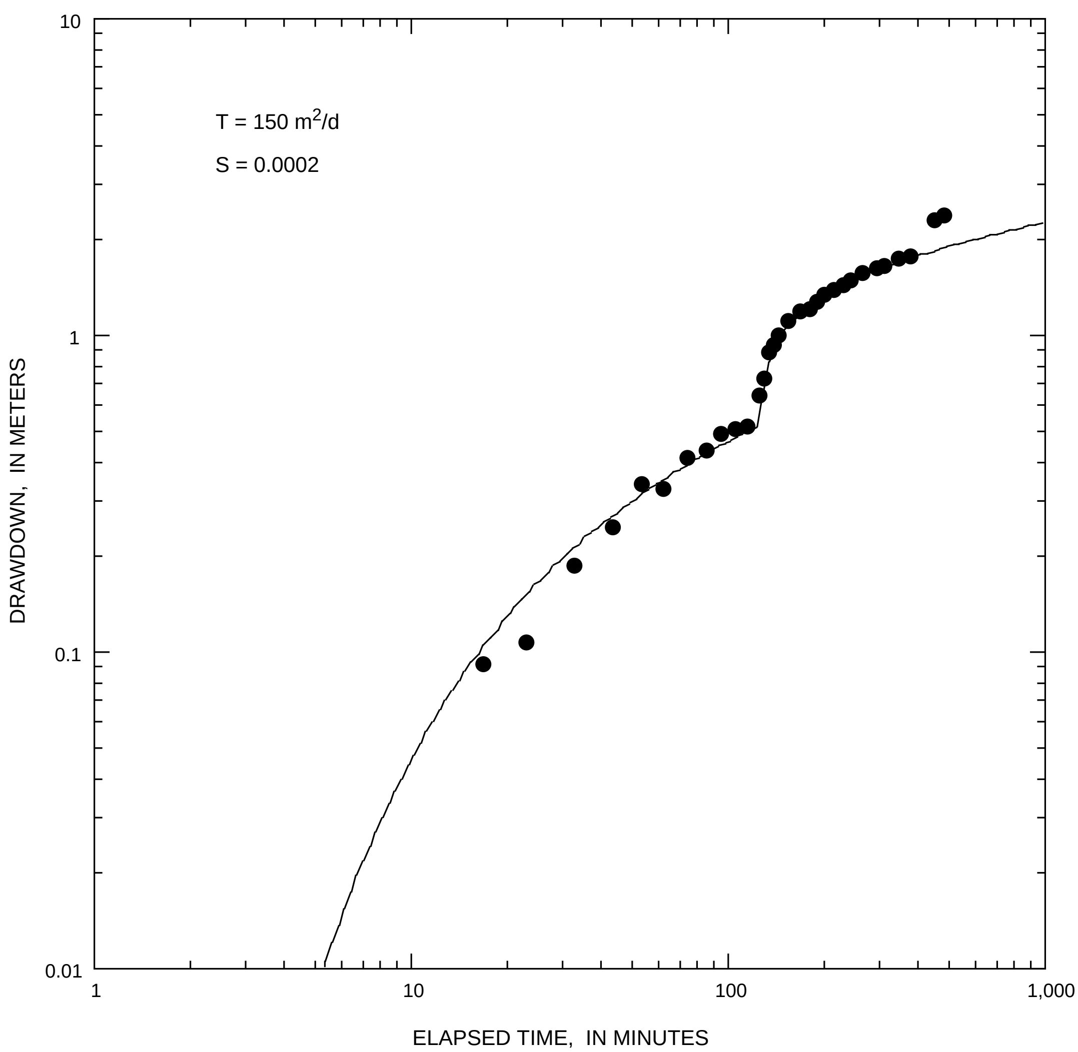

Figure 10. Drawdown in Mg-150 during pumping of Mg-67 and Mg-80 in Lansdale area, March 1980, and estimates of transmissivity (T) and storage coefficient (S) by superposition of Theis (1935) solutions.

Aquifer-Isolation Testing of Mg-67 and Mg-68, January 1983

Sutton (1983) describes aquifer-isolation tests and associated sampling carried out by Earth Data, Inc., on wells Mg-67 (L 8) and Mg-68 (L 9) for North Penn Water Authority (NPWA). Hydraulic testing was accomplished by pumping an isolated zone in each borehole between a pair of inflatable packers. Drawdown was measured in the pumped zone and in the borehole zones above and below the inflated packers. If there is no leakage around the inflated packers in the borehole, and there is no high-permeability connections between the isolated zone and the rest of the borehole in the rock near the borehole, then drawdown would be expected in only the isolated, pumped zone. Tests also were run without packers inflated and with only one packer inflated to estimate production from zones that were not isolated for testing. This review focuses on tests of isolated zones with both packers inflated.

The results of aquifer-isolation testing in Mg-67 are summarized in table 2. Drawdown in non-pumped zones above and below the pumped zone was essentially zero, suggesting very low vertical hydraulic conductivity in the vicinity of the borehole.The estimates of T by Sutton (1983) using the Theis method should be considered as only rough approximations because of the short duration of pumping (less than 30 minutes). The Theis method is not applicable to drawdown in the 14.3 - 20.1 m depth zone because the drawdown was essentially constant in time.

Specific capacities (table 2) are based on pumping between 30 and 60 minutes. The open-hole specific capacity is estimated as about 85 m^2/d (4.75 (gal / min) / ft), about 20 percent higher than the sum of the isolated zone specific capacities. This suggests that about 20 percent of the well yield is from parts of the borehole that were not tested. Examination of the composite specific-capacity data (Sutton, 1983, p. 62) indicates that this additional yield is approximately split between depth intervals 42.7 - 46.3 m and 52.1 - 55.5 m. These data also suggest that essentially zero yield occurs below the bottom tested zone.

Sutton (1983) provides estimates of specific capacity after 30-60 minutes of pumping for similar aquifer-isolation testing in well Mg-68 (table 3). For this test, hydraulic head was recorded graphically from pressure transducers, but analyses of these data by Theis or Cooper-Jacob methods was not attempted (Sutton, 1983). Two tests were done in each zone such that the isolated zone drawdown was approximately 2 and 3 m; only the 3-m-drawdown results are presented here. With packers inflated, static water levels in lower zones were higher than the open-hole static water level, implying an upward gradient in hydraulic head in the formation. Sutton (1983) observes evidence of either leakage between isolated zones in the borehole or actual hydraulic connection between isolated zones outside the borehole. In contrast to results for Mg-67, a significant part of the well yield is from depths more than 70 m below land surface. The estimated open-hole specific capacity is 77 m^2/d. The tested zones include almost all parts of Mg-68.

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Table 2. *Summary of results of aquifer-isolation testing in Mg-67 (Sutton, 1983)*
[m^2/d, square meters per day; m bls, meters below land surface; --, no data available]

Depth interval of isolated zone (m bls)	Specific capacity[1] (m^2/d)	Percent of open-hole specific capacity	Transmissivity (m^2/d)	U.S. Geological Survey notes
8.5 - 14.3	0	0	--	
14.3 - 20.1	14.1	17	--	Almost constant drawdown
21.3 - 27.1	28.3	33	8.6	Theis method
36.9 - 42.7	18.4	22	2.5	Theis method
46.3 - 52.1	2.7	3	--	
55.5 - 61.3	4.8	6	--	
76.8 - 82.6	0	0	--	
Open hole	85	100	--	Specific capacity of open hole larger than sum of individual zones (68.3 m^2/d)

[1] Specific capacity after pumping between 30 and 60 minutes.

Table 3. *Summary of results of aquifer-isolation testing in Mg-68 (Sutton, 1983)*
[m^2/d, square meters per day; m bls, meters below land surface]

Depth interval of isolated zone (m bls)	Specific capacity[1] (m^2/d)	Percent of open-hole specific capacity
23 - 29	0	0
31 - 37	34.5	45
39 - 45	14.4	19
47 - 54	15.7	21
68 - 74	0	0
74 - 142	11.8	15
Open hole	[2]76.4	100

[1] Specific capacity is based on pumping between 30 and 60 minutes.
[2] Estimated as sum of zone values.

Aquifer Test of Mg-624

Drawdown was measured in Mg-624 (Rex #2) during 25 minutes of pumping at a rate of about 45 L / min (12 gal / min) (U.S. Environmental Protection Agency, unpublished data files). The pump was set at 27 m (90 ft) below land surface, and the well was pumped until the water level dropped to the pump intake in about 25 minutes. Recovery measurements are not available.

The late-time part of the drawdown record agrees fairly well with the Theis theory and yields an estimated T = 0.53 m^2 / d (5.8 ft^2 / d) (fig. 11). However, the best fit also yields an estimate of S = 0.26, implying unconfined or water-table conditions. Similar values of T = 0.59 m^2 / d (6.4 ft^2 / d) and S = 0.21 are obtained from the Cooper-Jacob straight-line semi-log fit (fig. 12).

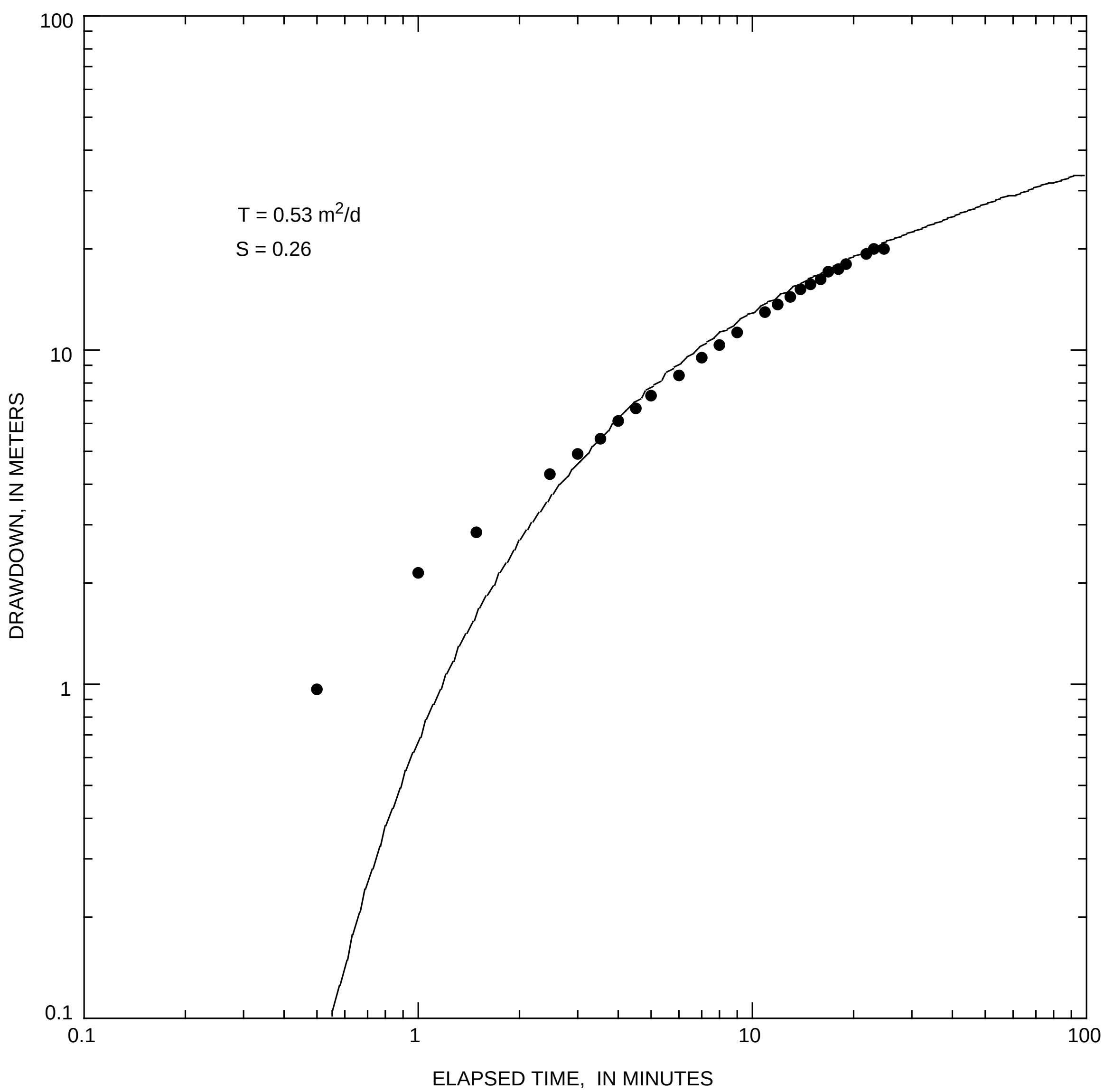


Figure 11. Drawdown in pumped well Mg-624 in Lansdale area and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

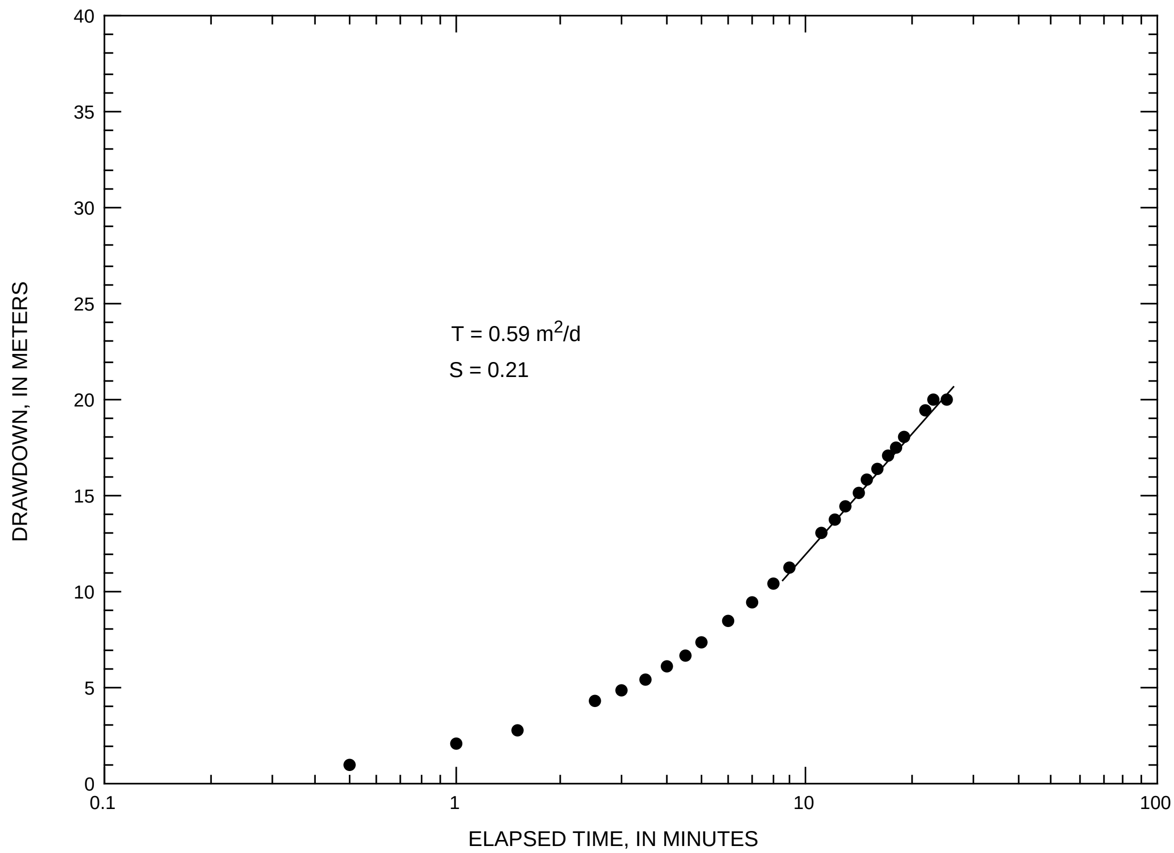


Figure 12. Drawdown in pumped well Mg-624 in Lansdale area and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Aquifer Test of Mg-625, March 1980

A 4-hour constant-rate open-hole pump test was conducted in Mg-625 (Rex #1) by USEPA on March 18, 1980 (U.S. Environmental Protection Agency, unpublished data files). The pumping rate declined during the test; average pumping rate was 320 L / min (85 gal / min). Water levels in the pumped well were difficult to measure because of “cascading” inflow to the borehole above the free surface, and original data sheets indicate that the water-level probe was malfunctioning. Maximum reported drawdown after 4 hours of pumping was 35 m (114 ft). Recovery of the pumped well was monitored for 90 minutes, and drawdown decreased suddenly between 35 minutes [26 m (86 ft)] and 40 minutes [9.5 m (31 ft)] of recovery.

For the analysis here, it is assumed that the drawdowns measured before 40 minutes are 16.6 m (54.5 ft) too large because of measurement errors. After performing this correction, the late-time recovery data matches the Theis theory (Goode, 1997) reasonably well (fig. 13), yielding T = 30 m^2 / d (320 ft^2 / d). Analysis of these corrected data by use of Theis’ recovery method (not shown) yields T = 31 m^2 / d (340 ft^2 / d). The drawdown during pumping is not considered reliable for estimation of aquifer properties because of the probe malfunction, the erratic measured drawdown possibly caused by cascading water, and probable well-loss effects indicated by the rapid early recovery of the pumped well water levels (fig. 13).

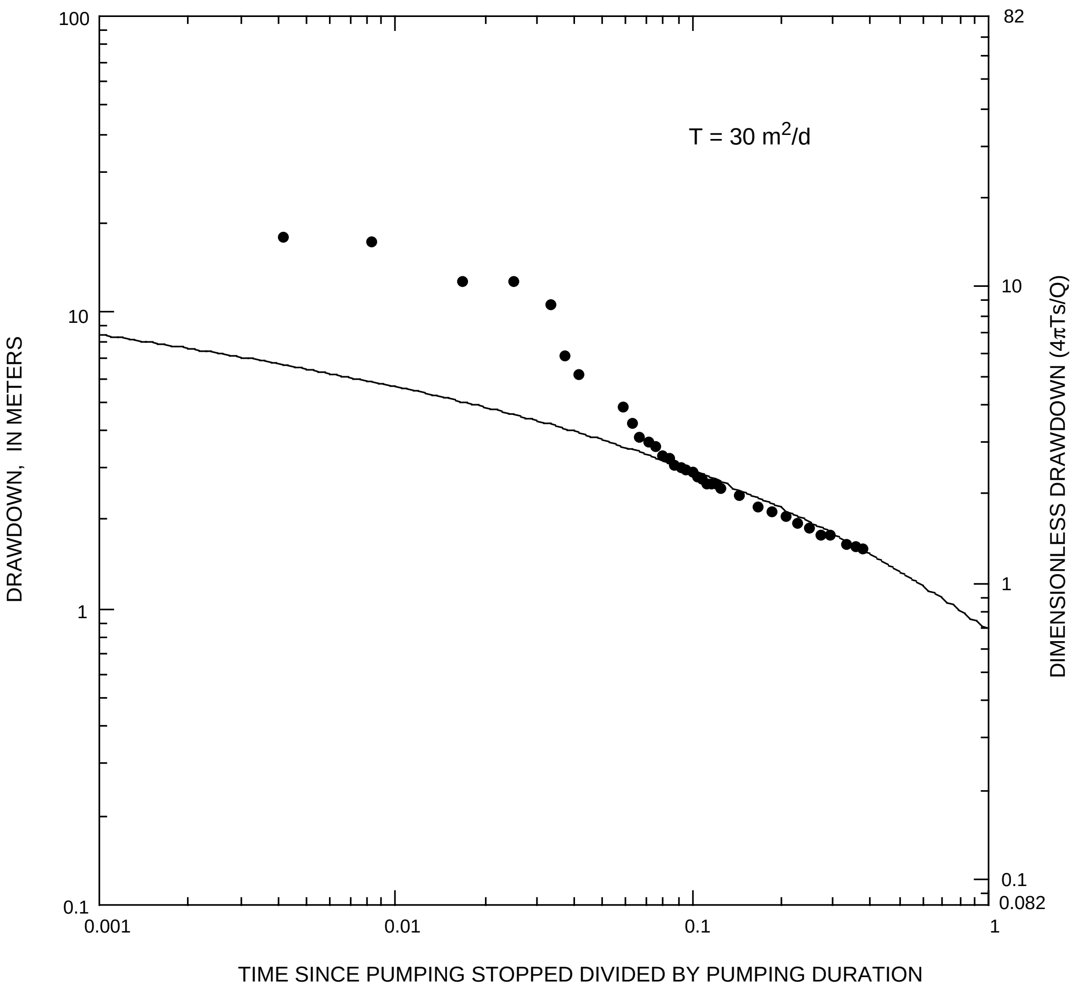


Figure 13. Drawdown during recovery in pumped well Mg-625 in Lansdale area, March 1980, and estimate of transmissivity (T) by method of Goode (1997).

Very recently, new monitor wells were installed near Mg-624 and Mg-625 in Lansdale (QST Environmental, Inc., 1998). Aquifer-testing results reported by QST include T's ranging from 14 to 62 m^2/d (150 to 670 ft^2/d). Although these data were not included in the review procedures for this report, these values are similar to results from aquifer tests reviewed here.

Water levels were also monitored in Mg-624 (Rex #2) and Mg-82 (Lansdale Sewer Plant Well) on 8-day strip charts (not shown). Both charts indicate that the water levels were not static prior to pumping of Mg-625. A maximum drawdown of about 0.6 m (2 ft) was observed in Mg-624. Pumping in Mg-625 had less effect on the water level in Mg-82; drawdown was more gradual, and the maximum drawdown was about 0.09 m (0.3 ft). The water level in Mg-624 began to rise immediately after pumping in Mg-625 stopped, but water levels in Mg-82 continued to fall for 2 days, although at a noticeably slower rate than during pumping. Measurable rainfall (5 mm (0.2 in) on the day of pumping) also may have influenced water-level changes, especially in the observation wells. These nonideal conditions obviously have some affect on estimated T and S, but sufficient data are not available to correct measured drawdowns.

Aquifer Test of Mg-1125, October 1982

A 48-hour aquifer test was conducted in Mg-1125 (NP 61) starting on October 19, 1982 (North Penn Water Authority, unpublished data files). The well was pumped at a rate of 770 L / min (203 gal / min) for 48 hours and then at an increased rate of 1,100 L / min (289 gal / min) for 50 minutes. Drawdown during pumping and recovery was monitored in the pumped well, and water levels in observation well Mg-1124 (NP 58) were recorded on a strip chart. Limited data also are available for a step test of Mg-1125 at rates of 380, 770, and 1,150 L / min (100, 203, and 305 gal / min).

A Cooper-Jacob (1946) analysis of drawdown in pumped well Mg-1125 yields T = 81 m^2/d (872 ft^2/d) (fig. 14). The late-time part of the test data does not fall on the matched straight line, suggesting intersection of a flow barrier (see fig. 3H') or other conditions that would result in increased resistance to flow towards the well. Except for this last part of the data, the Theis plot (not shown) is essentially a straight line with slope less than 1 / 4 on the log-log plot. A large and relatively constant well loss could cause drawdown in the pumped well to increase only slightly in time.

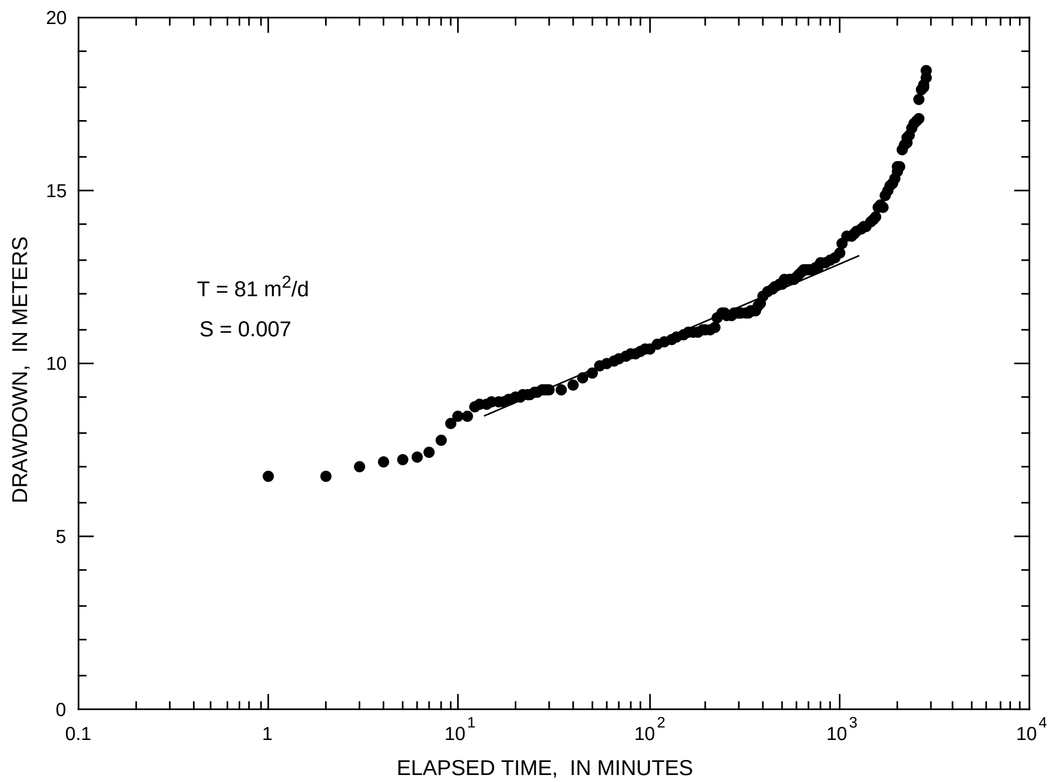


Figure 14. Drawdown in pumped well Mg-1125 in Lansdale area, October 1982, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Recovery data yields T = 125 m^2 / d (1,345 ft^2 / d) by use of the standard Theis (1935) large-time procedure (fig. 15) and T = 80 m^2 / d (860 ft^2 / d) by use of the Goode (1997) method (fig. 16). The rapid initial decrease in drawdown during recovery suggests significant well loss or skin effect in the pumped well. The late-time drawdown is higher than predicted by the theory. The intercept of the Theis recovery method plot [at $t/(t-t_p)=1$, where t is the time since pumping began and t_p is the pumping duration; that is, at very late time during recovery] is not at zero drawdown, and the log-log plot does not match the type curves of Goode (1997) precisely. This sustained drawdown at late time during recovery could be caused by a background trend of decreasing water levels. Examination of the strip chart in observation well Mg-1124 indicates that water levels were dropping at a rate of about 0.15 m / d prior to the test. Assuming that this rate of regional decline continued, water levels would not be expected to recover fully to pre-pumping levels.

Detailed analysis of the observation-well data was not conducted, but the general nature of the data can be summarized. After the initial few minutes, drawdown increased almost linearly in time. The maximum drawdown, not adjusted for the background trend, is approximately 2.5 m, and after a day of recovery, the drawdown had decreased to about 1.9 m. Drawdown in the pumped well was about 2 m after 1 day of recovery. Small drawdown differences between the pumped well and the observation well during recovery is consistent with Theis late-time recovery theory.

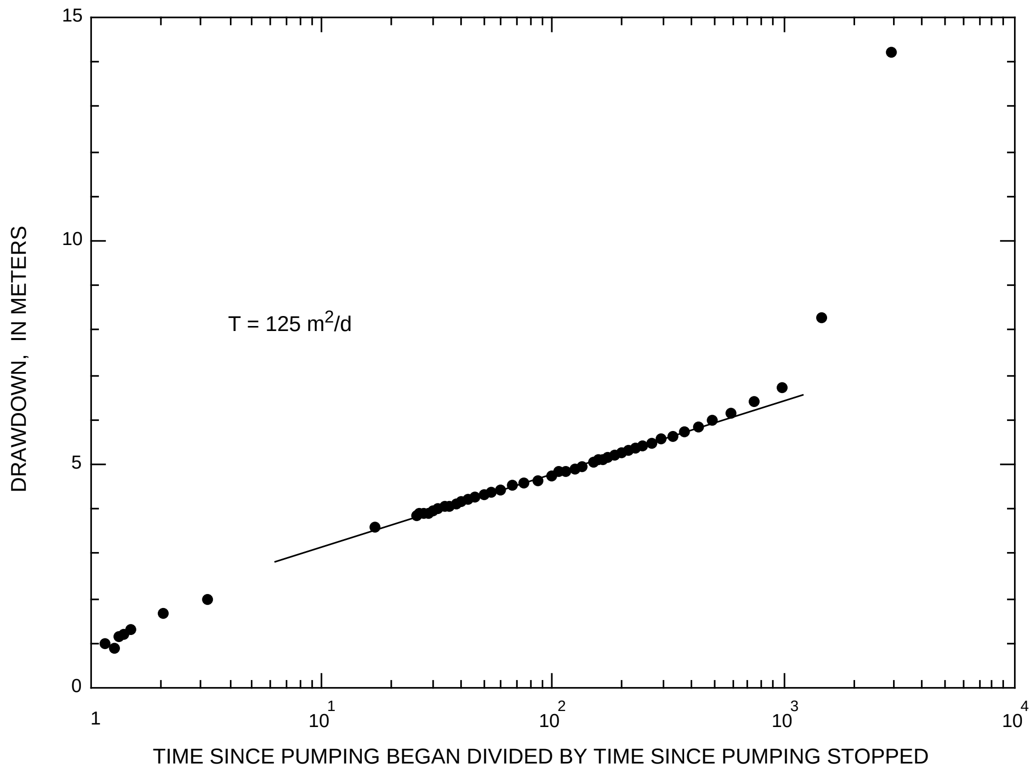


Figure 15. Drawdown during recovery in pumped well Mg-1125 in Lansdale area, October 1982, and estimate of transmissivity (T) by Theis (1935) method.

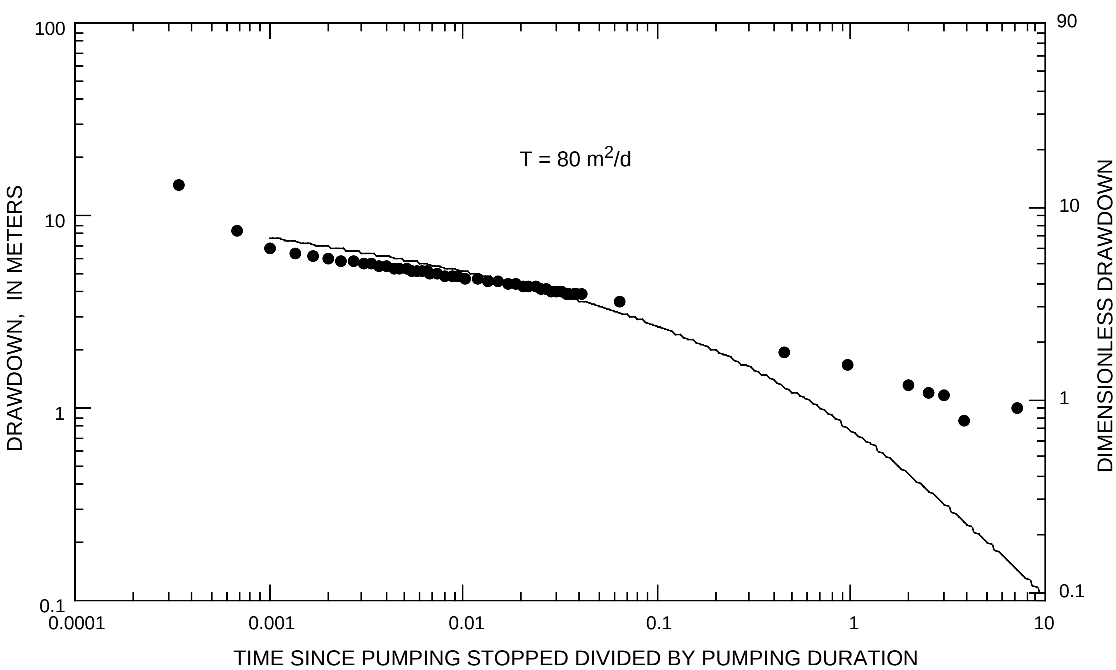


Figure 16. Drawdown during recovery in pumped well Mg-1125 in Lansdale area, October 1982, and estimate of transmissivity (T) by method of Goode (1997).

Preliminary analysis of step-test data also suggests that the well loss or skin effect is significant in Mg-1125 at prevailing pumping rates. The plot of linear drawdown as a function of log-time during three sequential steps of increased pumping rate (fig. 17) shows that the drawdown does not increase proportionally to the pumping rate but increases substantially more. Analysis of drawdown during pumping rate steps of 380 and 770 L / min (100 and 203 gal / min) suggests that nonlinear well loss accounts for about 65 percent of drawdown at the higher pumping rate. Thus, the drawdown in the pumped well is likely to be about three times higher than levels in the formation close to the pumped well, when the pumping rate is 770 L / min.

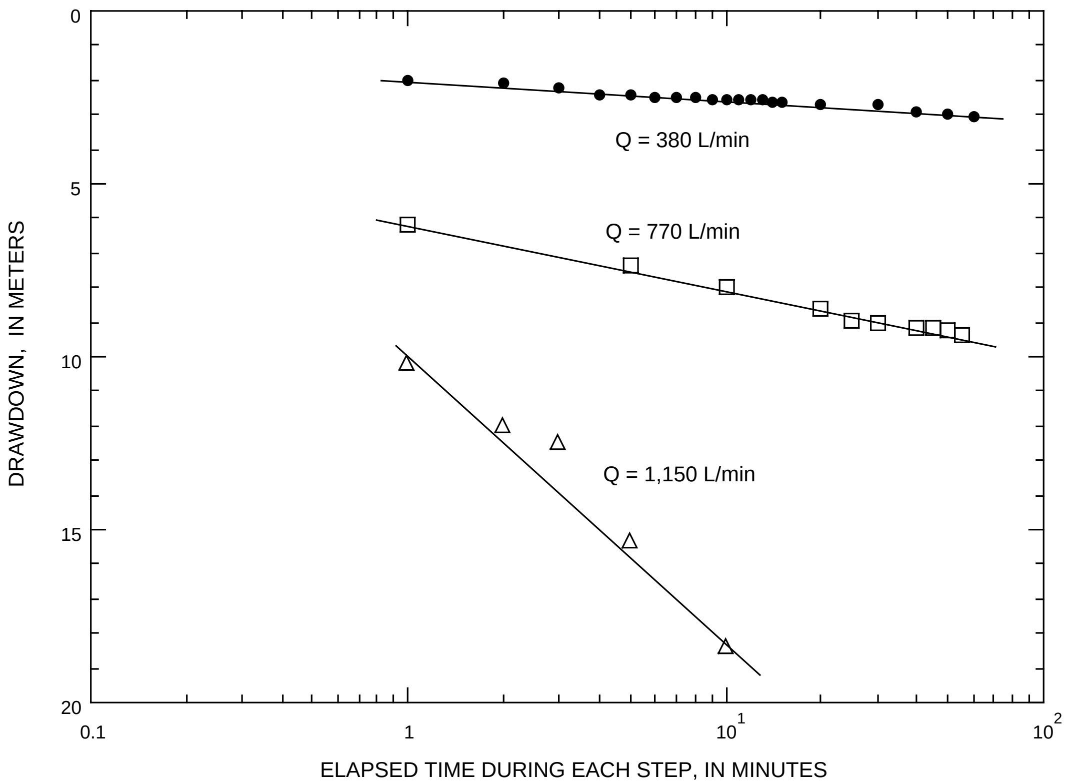


Figure 17. Drawdown in pumped well Mg-1125 in Lansdale area, October 1982, during step test with pumping rates (Q) of 380, 770, and 1,150 liters per minute.

Aquifer Test of Mg-1125, February and October 1989

Two 48-hour aquifer tests were conducted in Mg-1125 in February and October 1991 (U.S. Geological Survey, unpublished data). Mg-1125 was pumped at 770 L / min (203 gal / min), and water levels were monitored in it and in observation wells Mg-1124 (NP 58) and Mg-1126 (NP 62). These observation wells are on either side of the pumped well along regional strike of the dipping bedrock. The regional strike of bedding is assumed to be about N45E in the area (Newport, 1971). An additional observation well, Mg-1270, was installed for the October 1991 test south-east (up-dip) of the pumped well.

A Cooper-Jacob analysis of drawdown in the pumped well yields T = 120 m^2 / d (1,300 ft^2 / d) (fig. 18). This result is similar to that from the 1982 test described in the previous section. Drawdown in the pumped well during the two different aquifer tests was similar; drawdown was slightly more than 1 m larger during the February test than during the October test. An abrupt shift in drawdown levels between 200 and 1,000 minutes was measured during the October test.

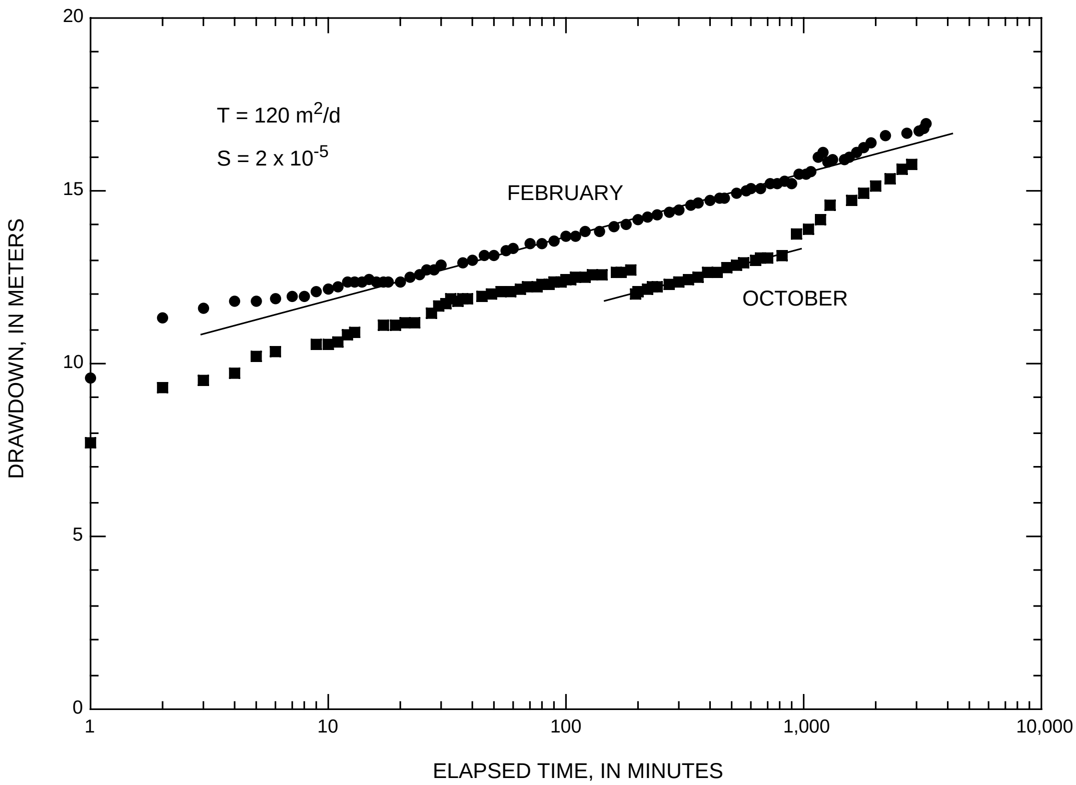


Figure 18. Drawdown in pumped well Mg-1125 in Lansdale area, February and October 1991, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Drawdown in the observation wells does not match the Theis theory in either the log-log plot (fig. 19) or in the semi-log format (not shown). A Theis match to just the early-time part of the drawdown at all three observation wells yields T values of 1,150, 930, and 580 m^2 / d (12,400, 10,000, and 6,200 ft^2 / d) for wells Mg-1124, 1126, and 1270, respectively. Well Mg-1270, oriented in the assumed up-dip direction from the pumped well, yields the smallest of these T values. The nearly linear trend in the log-log plot at large time, at a slope of about 0.5, suggests ‘linear’ flow conditions. Linear flow conditions can be found where there is horizontal flow in an infinite aquifer towards a finite-length vertical fracture, or in a narrow fault zone of infinite length (fig. 2). Type curves are developed for the case of a homogeneous confined aquifer bounded by two parallel no-flow boundaries by image well theory (Ferris and others, 1962; Kruseman and de Ridder, 1990). The theoretical model assumes that the well is at the center of an aquifer that is infinite in one coordinate direction and has uniform width (W) in the other direction. For the type curve used here, it is assumed that the observation well is also on the centerline of this infinite-length, finite-width aquifer. Drawdown in Mg-1124 (NP58) matches theoretical drawdown in a finite-width aquifer (fig. 20). From the match shown (fig. 20), T = 1,300 m^2 / d (14,000 ft^2 / d), significantly higher than estimates from the pumped well during both pumping and recovery. This estimate of T is similar to the value from the standard Theis method (1,150 m^2 / d; 12,400 ft^2 / d).

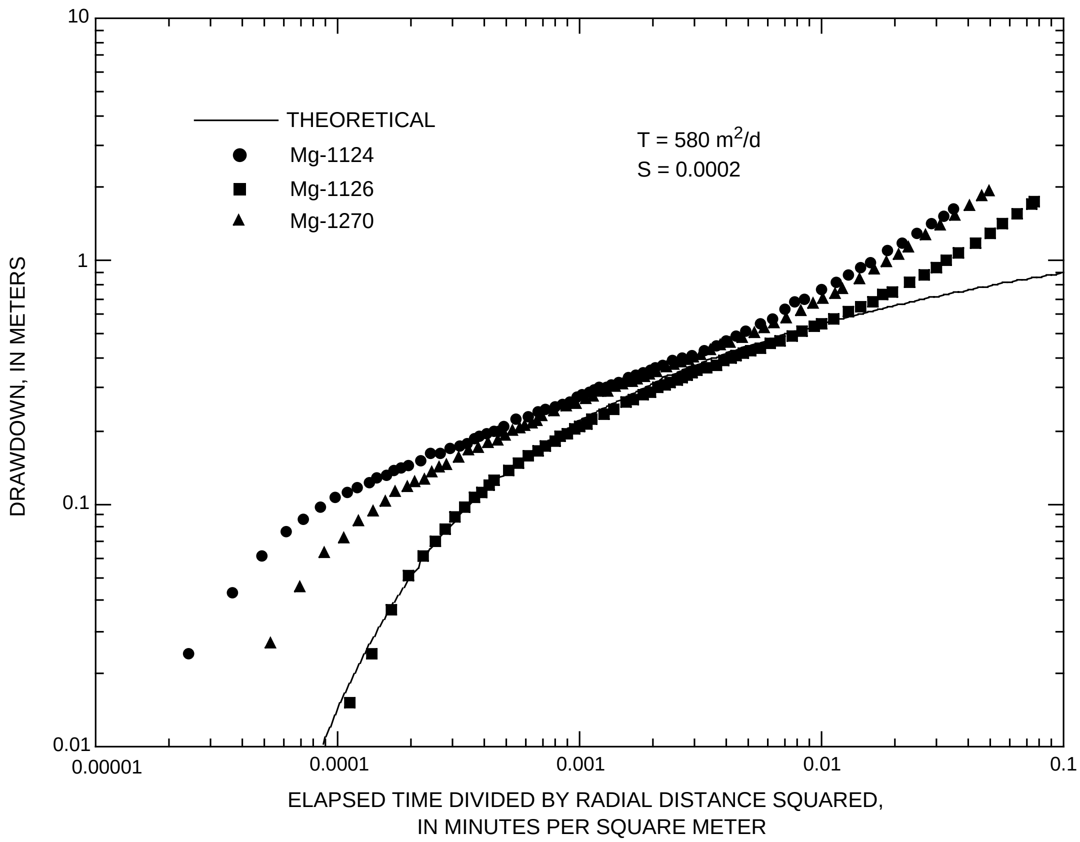


Figure 19. Drawdown in observation wells Mg-1124, Mg-1126, and Mg-1270 during pumping of Mg-1125 in Lansdale area, October 1991, and estimate of transmissivity (T) and storage coefficient (S) from drawdown in Mg-1126 by Theis (1935) method.

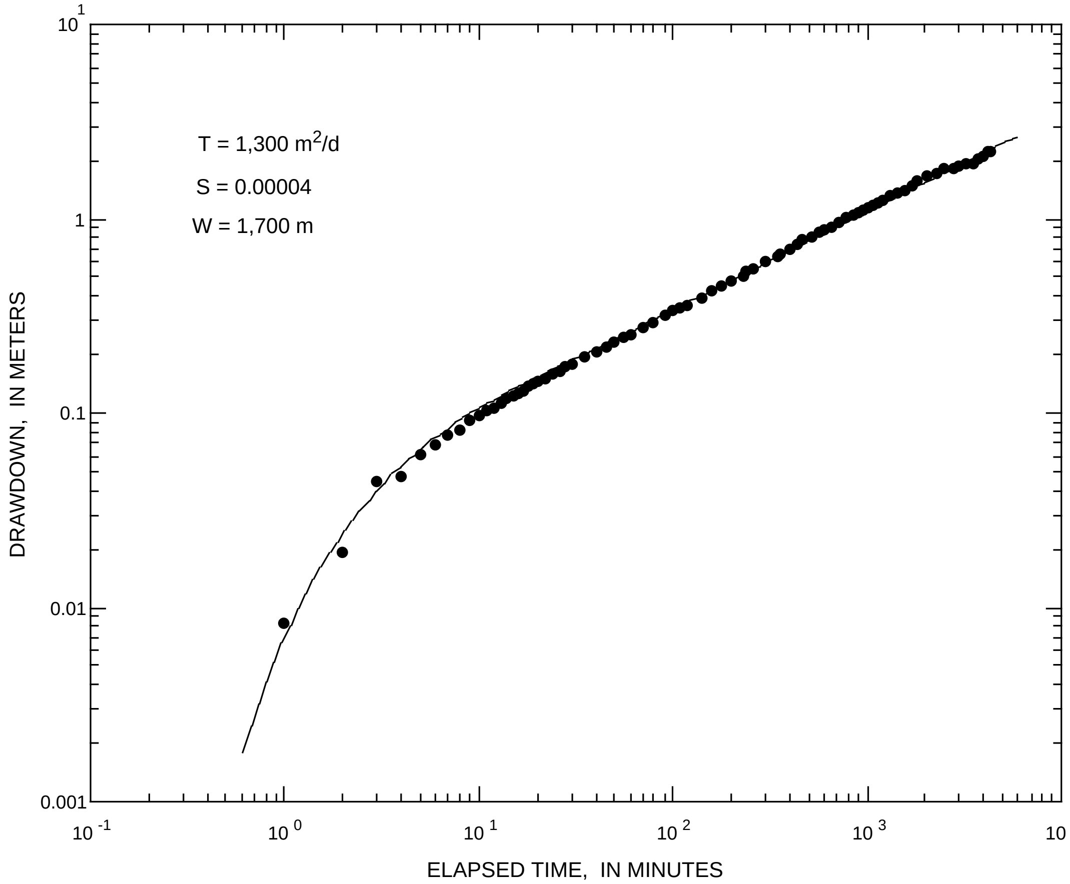


Figure 20. Drawdown in observation well Mg-1124 during pumping of Mg-1125 in Lansdale area, February 1991, and estimates of transmissivity (T) and storage coefficient (S) by image well method for a strip aquifer of infinite length but uniform finite width (W), based on Theis (1935) solution.

Analysis of observation-well drawdown as a function of distance at large time yields T values consistent with those from analysis of pumped well drawdown but much lower than the Theis and 'linear' flow estimates above. Hydraulic-head gradients between the observation wells and pumped well are near equilibrium during the latter part of the test. For example, during the February test, the head difference between observation well Mg-1124 and pumped well Mg-1125 at 10, 100, and 1,000 minutes is 12, 13, and 14 m (40, 44, and 46 ft), respectively. Hence, the flow system is near steady-state equilibrium at the well-field scale. Applying Thiem's steady-state method (Bear, 1979) to the observed drawdown as a function of distance for each observation well separately yields T values ranging from about 50 to about 100 m^2/d, depending on the observation well used and the assumed effective pumped-well radius. The different results for the early-time Theis match and the late-time Thiem analysis suggest that the underlying model, which assumes confined horizontal flow in an infinite aquifer, is not an accurate characterization of the flow system at the well-field scale.

Aquifer Testing at Merck

Locations of pumped and observation wells at the Merck facility used in this report are shown in figure 21.

Aquifer Test of Mg-125, May 1986

Roy F. Weston, Inc. (1986) conducted a constant-rate aquifer test in Mg-125 (PW-2) in May 1986. Analysis of drawdown in observation wells Mg-123 (B), Mg-1658 (1-85), and Mg-1572 (11-85) by Theis and Cooper-Jacob methods yielded T values ranging from 80 to 130 m^2/d (900 to 1,400 ft^2/d) (table 4). Estimated S ranged from 2×10^{-4} to 7×10^{-4}, consistent with confined conditions. Several wells located at similar radial distances from the pumped well did not exhibit drawdown during the test, suggesting heterogeneous or anisotropic hydraulic conductivity (Roy F. Weston, Inc., 1986).

Table 4. *Transmissivity and storage coefficient estimates from drawdown during pumping of Mg-125, Merck & Co., West Point, Pa., May 1986 (Roy F. Weston, Inc., 1986)*

[m^2/d, square meters per day; m, meters; bls, below land surface; ? depths unknown]

Observation well	Transmissivity (m^2/d)	Storage coefficient	Radial distance (m)	Open interval (m bls)	Analysis method
Mg-123	130	0.0004	91	10 - 168	Theis
	156	.0003			Cooper-Jacob
Mg-1658	98	.0002	305	? - ?	Theis
	143	.00014			Cooper-Jacob
Mg-1572	109	.00007	283	? - 68	Theis
	149	.00007			Cooper-Jacob

Aquifer Test of Mg-128, November 1993

Nittany Geoscience Inc. (NGI) (1994a) conducted a 48-hour aquifer test of Mg-128 (PW-5) in November 1993, pumping at an average rate of 380 L / min (100 gal / min), and monitored water levels in the pumped well and in several observation wells. Analysis of drawdown in the pumped well by use of the Cooper-Jacob large-time method yielded T = 7.2 m^2/d on the basis of drawdown between about 150 and 1,500 minutes after the pump started (Nittany Geoscience Inc., 1994a). After 1,500 minutes, the drawdown rate increased substantially (compared to the large-time model prediction) and this led to a decreased estimated T = 2.9 m^2/d for the latter part of the test. This increase in rate of drawdown also was observed in most shallow observation wells (Nittany Geoscience Inc., 1994a). NGI (1994a) suggested that this increased drawdown in the shallow observation wells could be caused by an increase in vertical leakage downward to the deeper zone. An anisotropic horizontal-flow confined-aquifer (Theis) model was used to estimate the transmissivity of the shallow zone [21 - 30 m (70 - 100 ft) below land surface (bls)] because wells at similar radial distances had widely varying drawdowns (fig. 22). The maximum and minimum components of the shallow zone T were estimated as 75 and 5 m^2/d, respectively. The non-directional effective T for the shallow zone (the geometric mean of the maximum and minimum components) was 19 m^2/d. Isotropic analysis of the drawdown observed in one deep zone [82 - 88 m (270 - 290 ft) bls] well yielded T = 3.5 m^2/d.

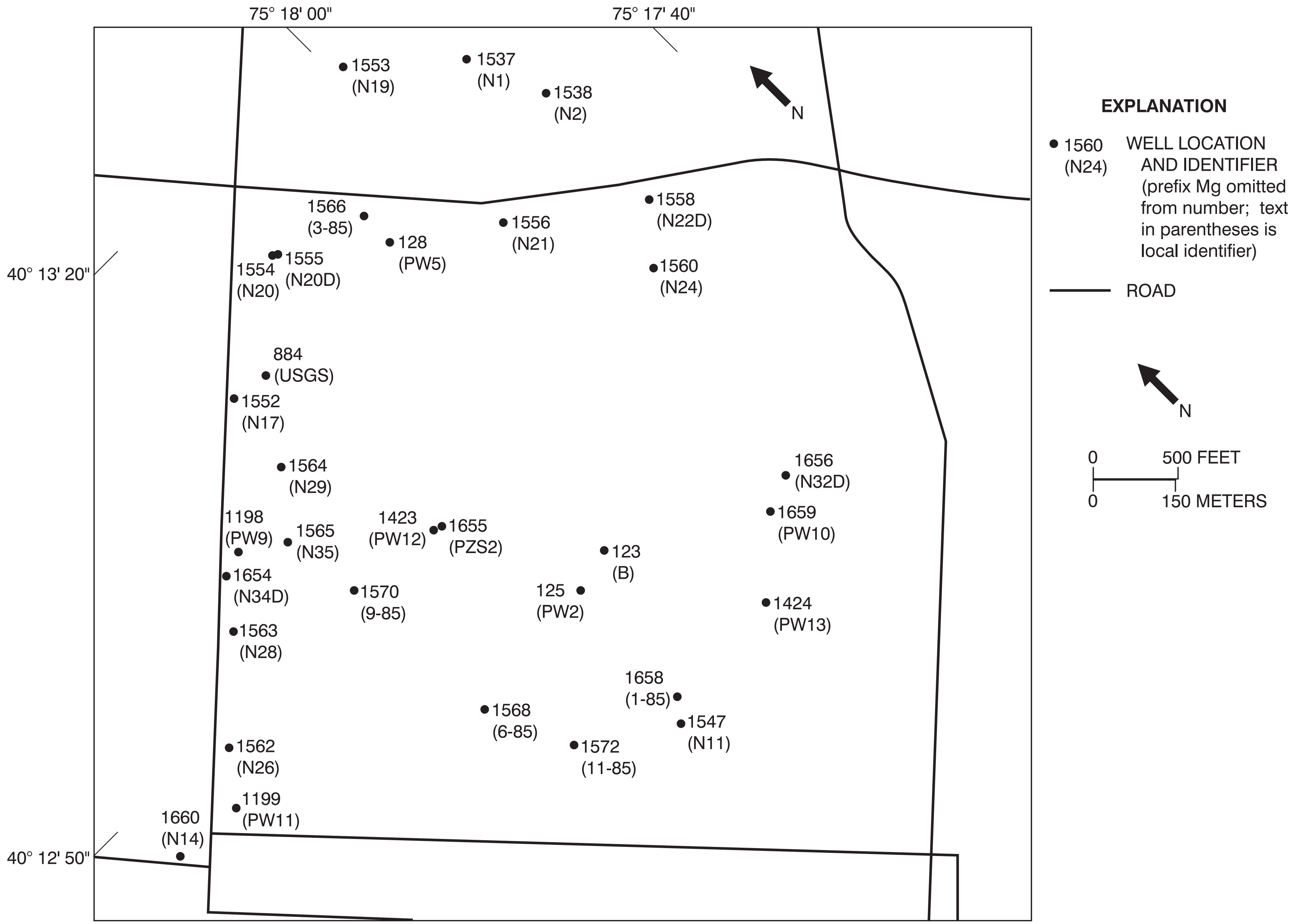


Figure 21. Locations of pumping and observation wells at Merck, Sharpe & Dome facility, near Lansdale, Pa.

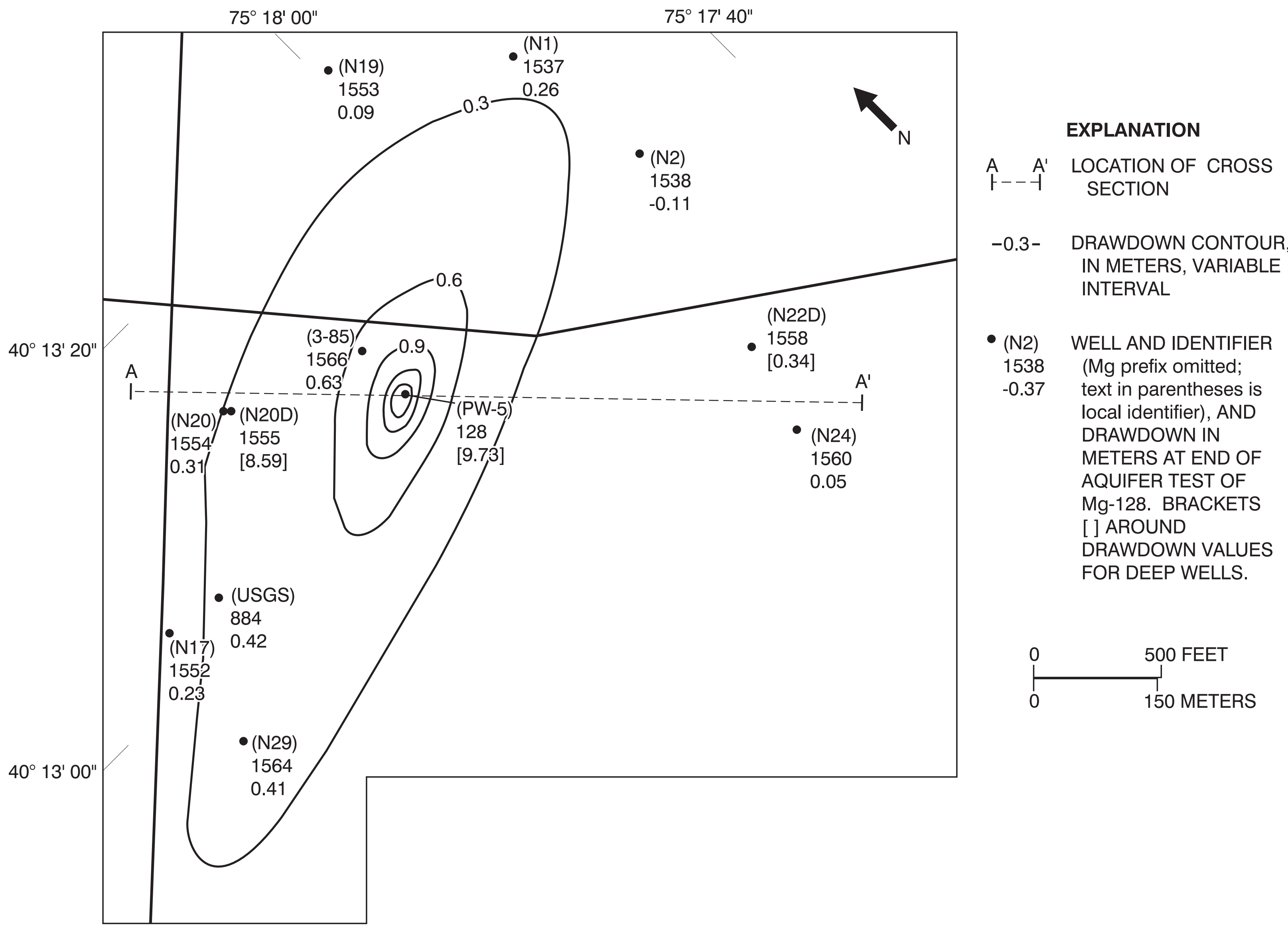


Figure 22. Drawdown in wells in the area of pumped well Mg-128 in Lansdale area, November 1993, at end of 48-hour aquifer test (Nittany Geoscience, Inc., 1994a).

Several conceptual inconsistencies in the analysis methods used by NGI (1994a) are suggested. Drawdown was estimated in each of the two separate depth zones by use of the total pumping rate. Proper analysis would use only that part of the total pumping rate that entered the well from each zone. Thus, if each zone contributed half of the total pumping rate, then the estimated T values of NGI (1994a) would be twice the correct values. Moreover, in heterogeneous systems, the highest drawdown is generally observed in the zones of highest T. Drawdown in the deep zone may be very close to the drawdown in the pumped well because of the high permeability connection between the observation well and the pumped well (fig. 23). If this conceptual model is appropriate, then most flow into the well would be coming from the deep zone, and the T of the shallow zone could be overestimated. This conceptual model could be verified with analytical (Papadopulos, 1966) or numerical models (Rutledge, 1991; McDonald and Harbaugh, 1988), but these complex analysis methods are beyond the scope of the current review. The uniformly increased drawdown throughout the shallow zone may also be due to vertical flow downward to a system of high permeability fractures in a finite area at depth. Drawdowns within such a fracture cluster might be essentially uniform in space and cause relatively uniform vertical leakage from the overlying zones.

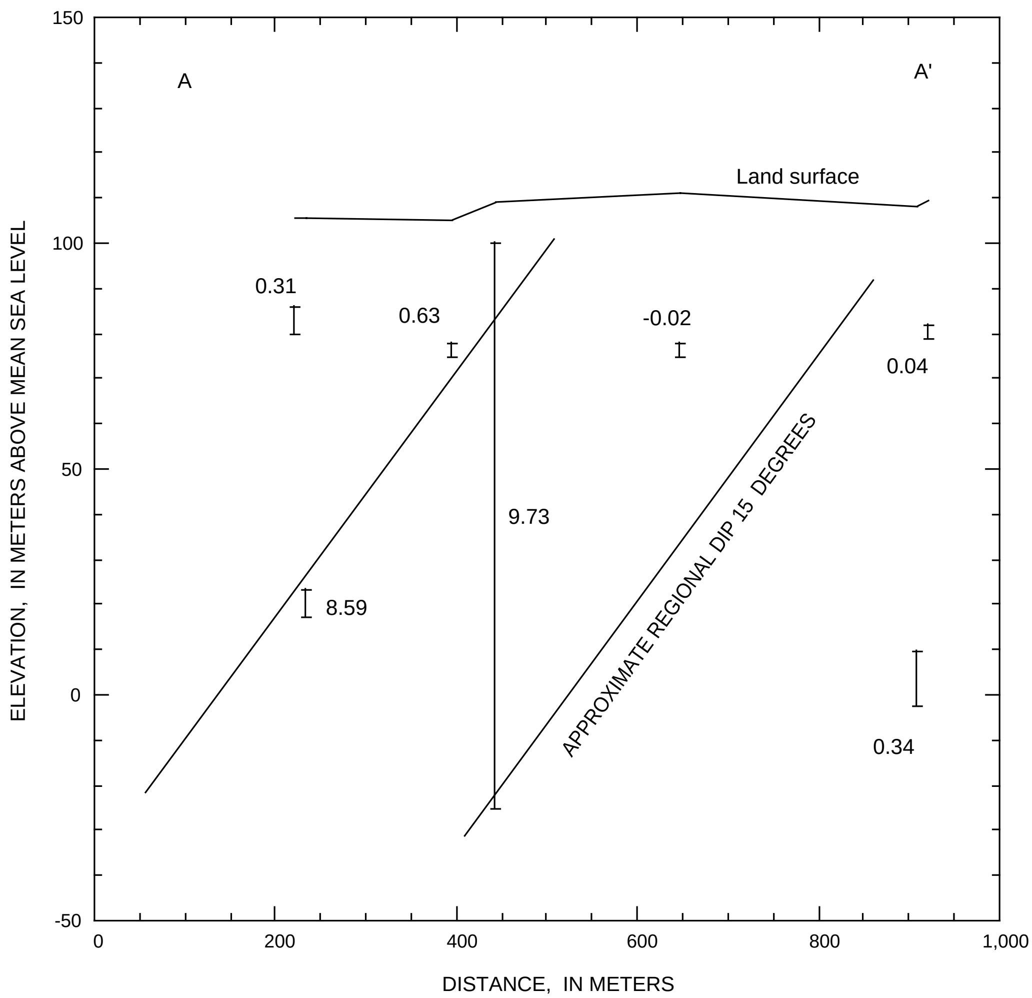


Figure 23. Cross-section showing regional dip of bedrock and drawdown in wells in the area of pumped well Mg-128 in Lansdale area, November 1993, at end of 48-hour aquifer test (Nittany Geoscience, Inc., 1994a). Drawdowns at wells not located on cross section are translated to the cross section by moving along the strike direction.

The Theis log-log plot of drawdown in the pumped well and in deep zone well Mg-1555 (N20D) [located near Mg-1554 (N20)] (fig. 24) shows that the Theis curve does not match the observed drawdown, hence the basic assumptions of the large-time Cooper-Jacob analysis are not met. The log-log plot shows essentially straight line response with a slope of about 1/3 for the pumped well. The difference between the drawdown in the pumped well and in well Mg-1555 is consistently between 1.2 and 1.5 m (4 and 5 ft) for the entire record (fig. 25). This suggests that the flow system between Mg-1555 and the pumped well is in quasi-equilibrium. That is, the flow rate, which is proportional to head gradient, between Mg-1555 and Mg-128 is essentially constant, and the increasing drawdown of both is due to depletion of storage in parts of the flow system beyond (or above) Mg-1555.

The increased drawdown (a maximum of approximately 0.5 m (1.5 ft) of additional drawdown) in the shallow zone at about 1,700 minutes after the test began may not be directly related to the pumping of Mg-128. Possible causes for the sudden increased drawdown include initiation of pumping in a nearby production well or a significant increase in atmospheric pressure. As postulated by NGI (1994a), this increased rate of drawdown in the shallow zone may be caused by increased leakage downward to the deeper zone where drawdowns are higher. However, the increase in drawdown rate in such a conceptual model would probably not be so abrupt. Such a response would also indicate that most flow entering the pumped well is coming from the deeper zone; only in this case will the effect of the leakage on water levels be greater than the drawdown due to horizontal flow to the pumped well.

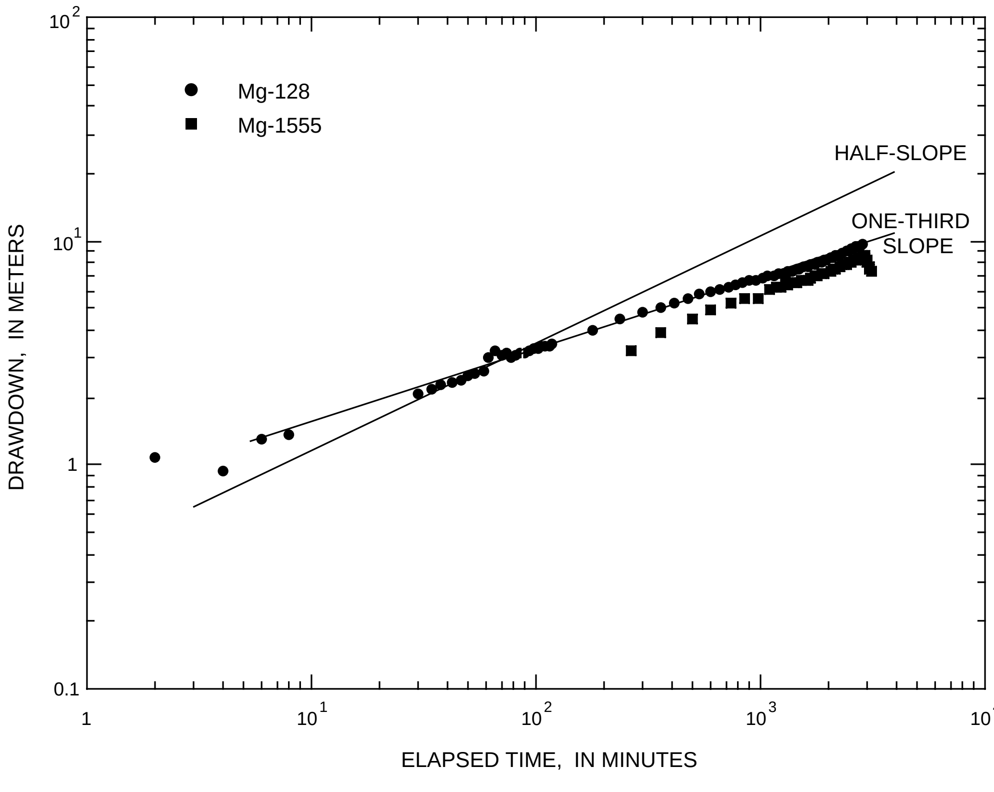


Figure 24. Drawdown in observation well Mg-1555 and pumped well Mg-128 in Lansdale area, November 1993, in log-log format.

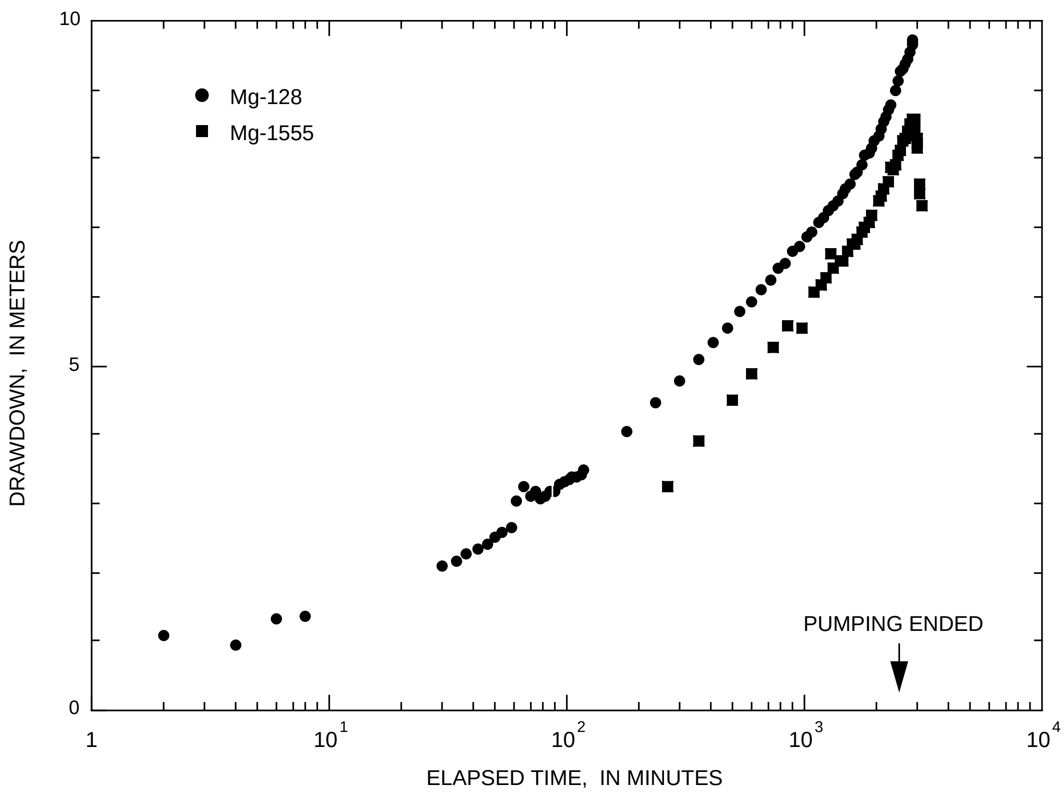


Figure 25. Drawdown in observation well Mg-1555 and pumped well Mg-128 in Lansdale area, November 1993, in semi-log format.

Aquifer Test of Mg-1198, September 1988

NGI (1988a) conducted a step test on Mg-1198 (PW-9) starting on September 19, 1988. Because of problems with regulation of the discharge, the initial pumping rate was erratic, and the test was halted temporarily. After re-starting the test, the pumping rate was about 265 L / min (70 gal / min). A subsequent step change resulted in an increase to about 322 L / min (85 gal / min) with a declining rate in time. Attempts to increase the rate for another step change were not successful. Drawdown was measured in the pumped well and in observation well Mg-1565 (N30). Water-level measurements also were made in observation wells Mg-1563 (N28) and Mg-1564 (N29), but the initial water level was not measured; hence, drawdown cannot be computed. However, the drawdown at both these wells, which are about 150 m (500 ft) from the pumped well, was greater than 0.3 m (1 ft) during the period that was measured. Several non-standard features of this test limit the usefulness of the data for estimation of aquifer properties.

Analysis of the drawdown data from observation well Mg-1565 provides a rough estimate of aquifer properties in the vicinity of Mg-1198. Cooper-Jacob analysis of the drawdown at observation well Mg-1565 yields an estimated T = 120 m^2 / d (1,300 ft^2 / d) (fig. 26). The Theis match yields T = 98 m^2 / d (1,050 ft^2 / d) (fig. 27). From the Theis match, the storage coefficient is estimated as 2×10^{-4}. Because of scatter in the observed drawdown, the match for the Theis and Cooper-Jacob methods is not very good. Better estimates of aquifer properties could be obtained from a more controlled test with a constant pumping rate and measurement of drawdown at all affected observation wells.

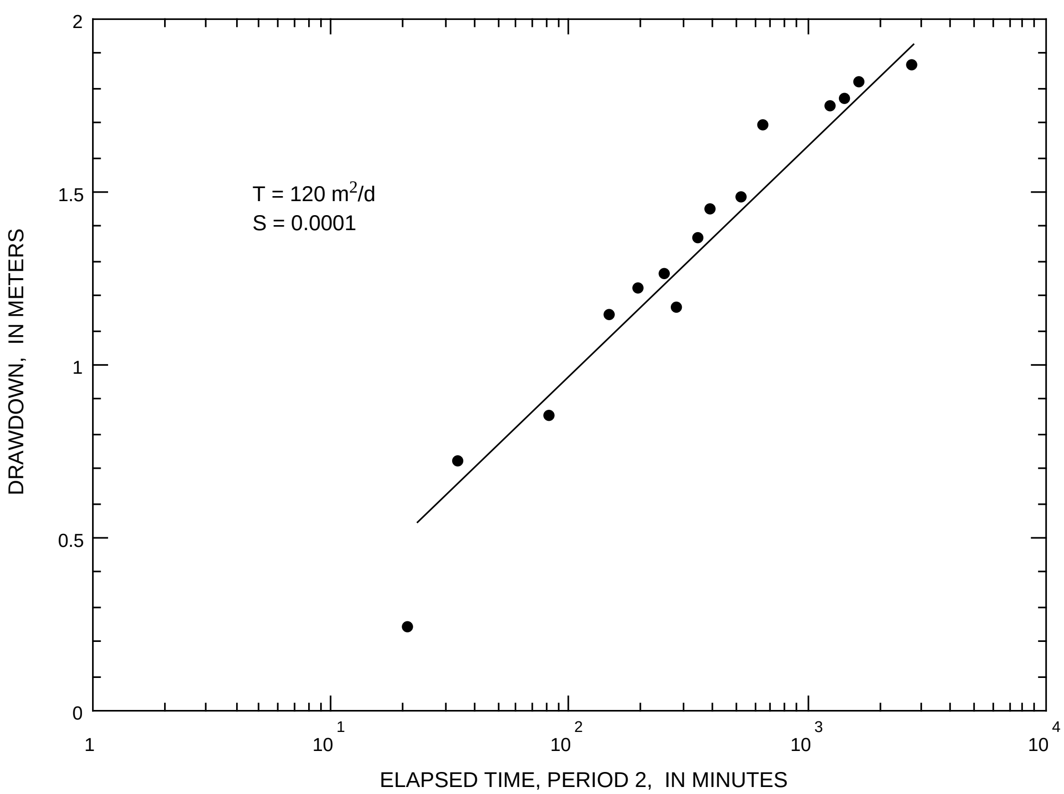


Figure 26. Drawdown in observation well Mg-1565 during pumping of Mg-1198 in Lansdale area, September 1988, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

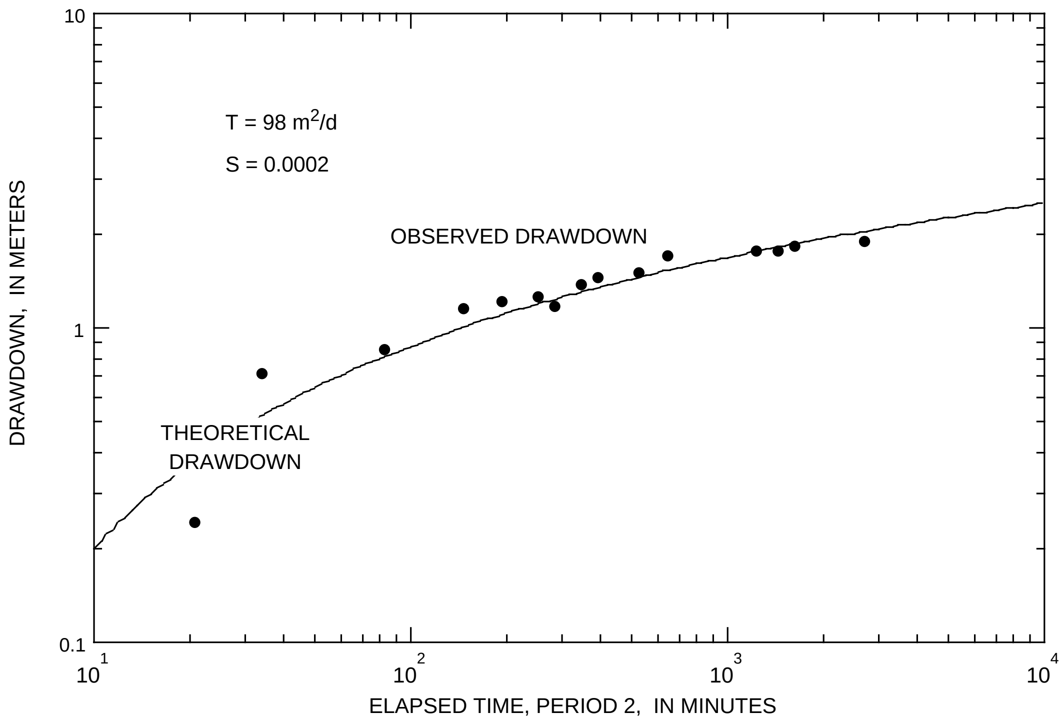


Figure 27. Drawdown in observation well Mg-1565 during pumping of Mg-1198 in Lansdale area, September 1988, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

Aquifer Test of Mg-1659, September 1988

Preliminary review of the drawdown data for a production step test of Mg-1659 (PW-10) in September 1988 indicates that it is not suitable for aquifer-property estimation because of the erratic drawdown observed in the pumped well during the test. The specific-capacity data estimated by NGI (1988b) is probably not reliable because the quick recovery of the pumped well to water levels greater than 1.5 m (5 ft) above the initial level indicates that water-level fluctuations during the pumping period were not due to pumping of the tested well. This well is believed to have been abandoned in October 1993.

Aquifer Test of Mg-1199, April 1989

NGI (1989) conducted step and constant-rate aquifer tests in April 1989 on Mg-1199 (PW-11). From these results, NGI (1989) estimated a specific capacity of 20 to 23 m^2/d (1.1 to 1.3 (gal/min)/ft) and predicted an elongated (anisotropic) cone of depression caused by long-term pumping at a rate of 230 L/min (60 gal/min), the estimated “safe yield.”

Drawdown at observation wells Mg-1660 (N14), Mg-1562 (N26), and Mg-1563 (N28) (fig. 28) during pumping of Mg-1199 does not match the Theis model type curve. The drawdown is close to a straight line with a slope of about 0.4 on the log-log plot. A slope of 0.5 on this plot would be indicative of linear flow, commonly observed in fractured rock. Deviation from the half slope at late time may be indicative of recharge to the fractures from overlying or underlying formations.

Observed recovery also does not agree with the Theis model curves (fig. 29). The rapid initial recovery of the pumped well suggests that a significant part of the drawdown in the pumped well is caused by well loss or skin effects.

A step test was conducted in Mg-1199 on April 17, 1989. Measured water levels during four steps of 100 minutes each and subsequent recovery in Mg-1199 and in observation well Mg-1562 indicate that drawdown during each step was essentially constant, partly because the pumping rate was decreasing somewhat during each step (fig. 30). Analysis of step-drawdown data (fig. 31) indicates that at 300 L / min (80 gal / min) about 50 percent of the drawdown measured in the pumped well is caused by head loss in the formation and about 50 percent is caused by well loss or skin effects. This suggests that use of pumped-well drawdown during pumping will underestimate T by a factor of about two, if well loss is ignored during the analysis.

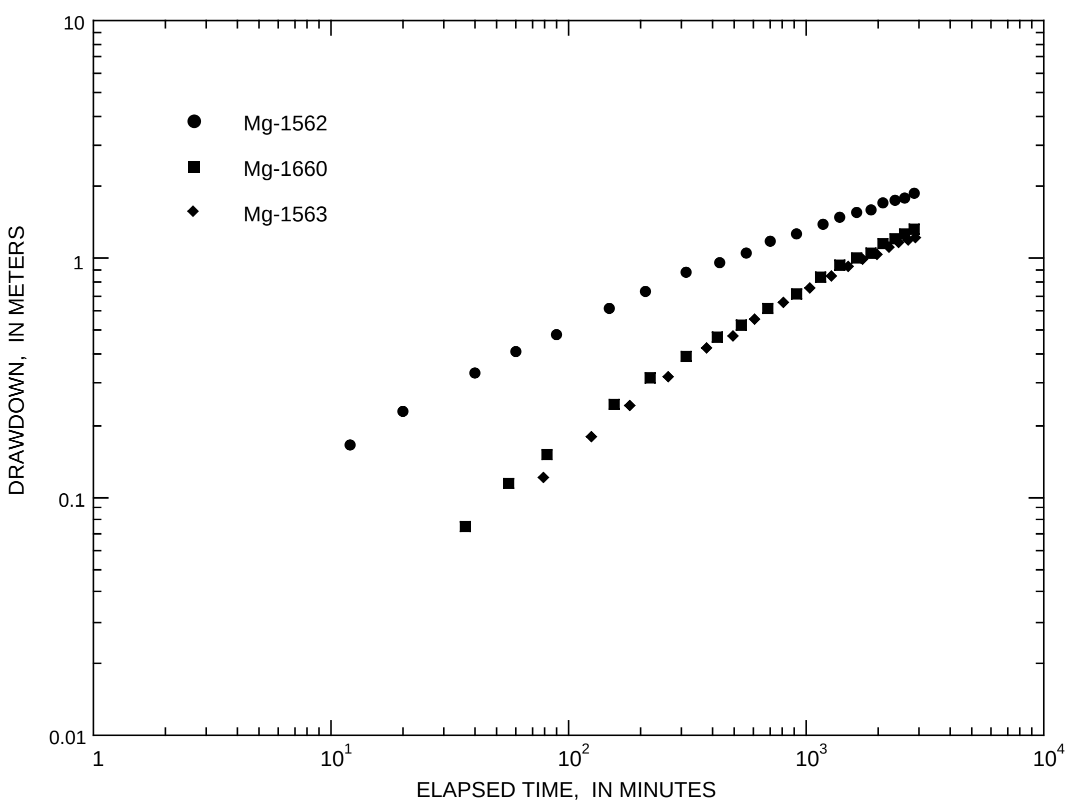


Figure 28. Drawdown in observation wells Mg-1660, Mg-1562, and Mg-1563 during pumping of Mg-1199 in Lansdale area, April 1989, in log-log format.

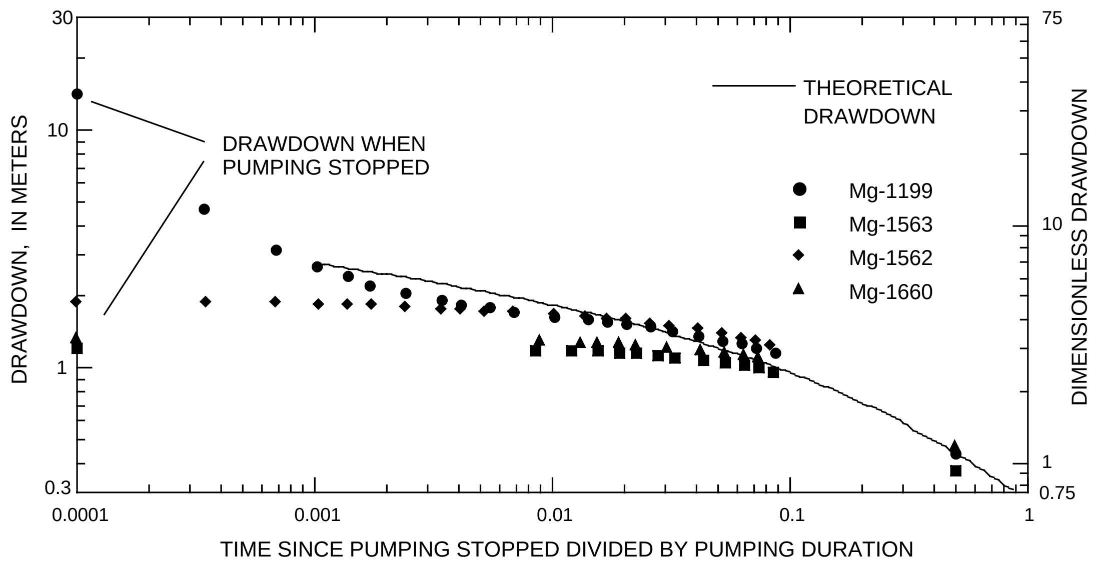


Figure 29. Drawdown during recovery in observation wells Mg-1660, Mg-1562, and Mg-1563 and in the pumped well Mg-1199 in Lansdale area, April 1989, in log-log format.

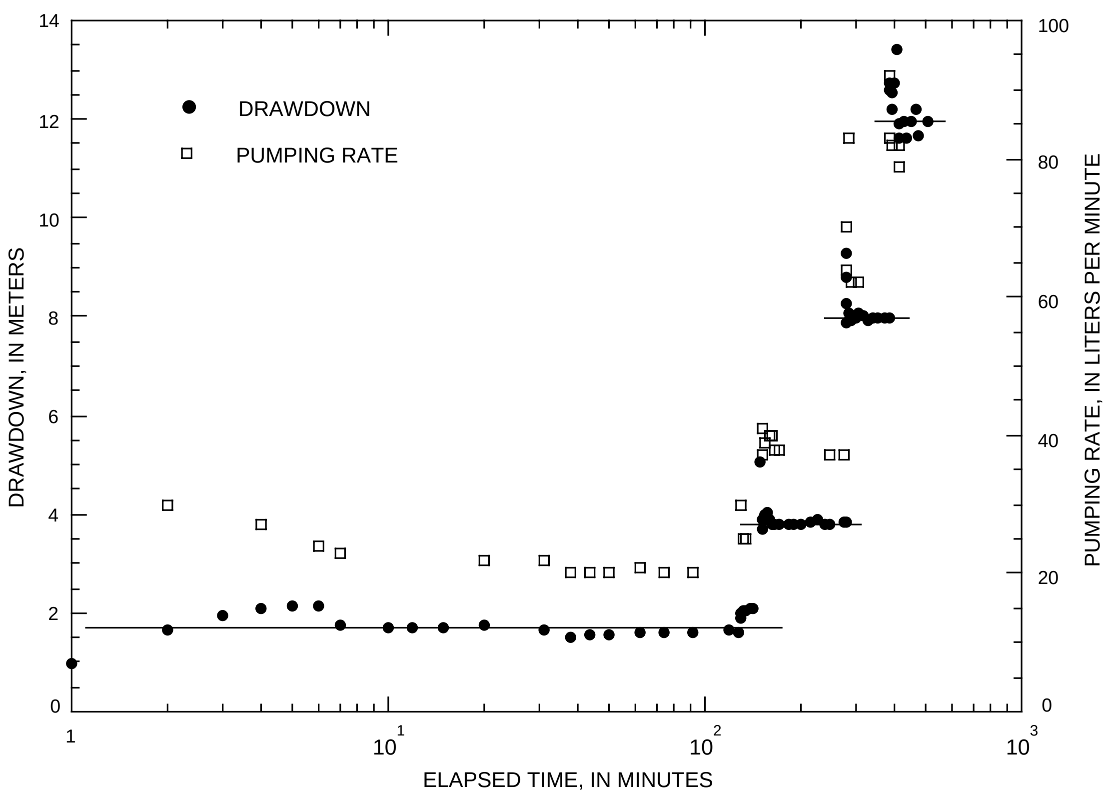


Figure 30. Drawdown and pumping rate in pumped well Mg-1199 in Lansdale area, April 17, 1989, during step test, in semi-log format.

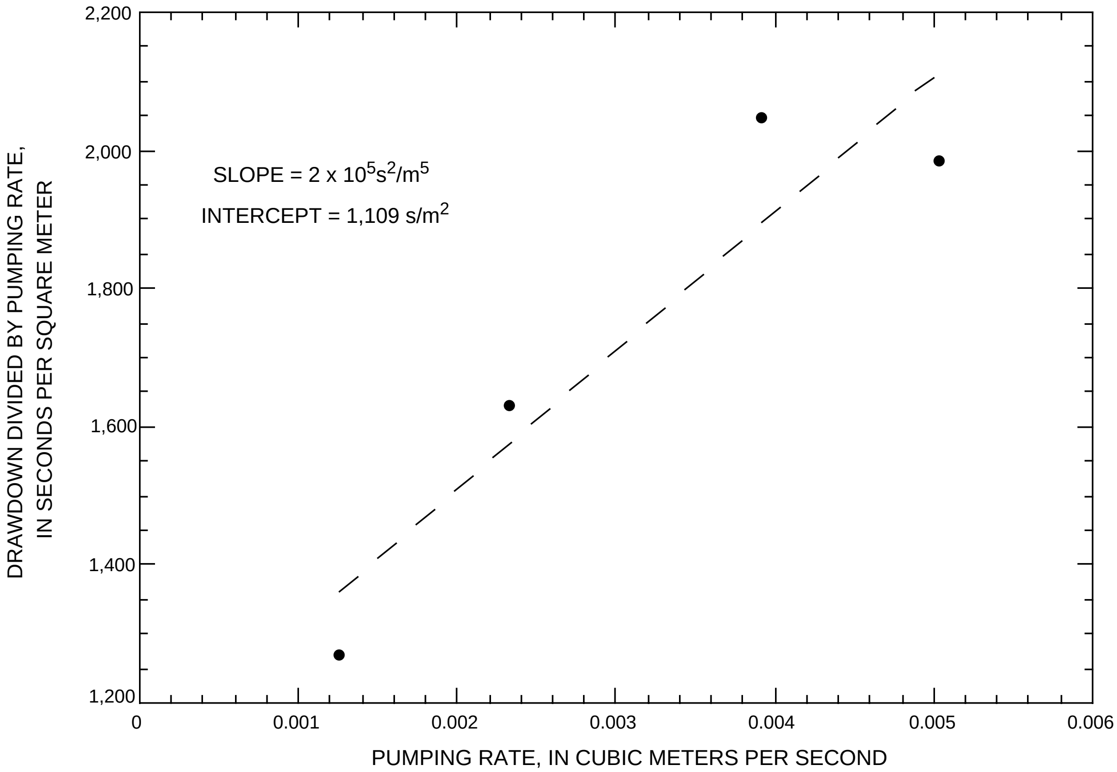


Figure 31. Sum of incremental drawdown divided by pumping rate as a function of pumping rate for step test in Mg-1199, Lansdale area, April 1989, for estimation of linear (formation loss) and nonlinear (well loss) components of drawdown by Hantush and Bierschenk method (Kruseman and de Ridder, 1990).

Aquifer Test of Mg-1423, February 1994

NGI (1994b) conducted a combined step and constant-rate aquifer test in Mg-1423 (PW-12) beginning on February 15, 1994. NGI (1994b) estimated the ‘sustained yield’ of the well as about 270 L / min (70 gal / min) on the basis of an extrapolation of the 48-hour drawdown to 90 days. After the step tests and the immediately subsequent 48-hour test, maximum drawdown in the pumped well was about 31 m (103 ft); drawdowns in nearby observation wells ranged from 0 to about 1 m (3 ft). The maximum observed drawdown in the observation wells was in well Mg-1568 (6-85), oriented southwest from the pumped well, approximately aligned with the assumed NE strike of formation bedding in the area. NGI (1994b) did not analyze observed drawdown to estimate aquifer properties.

Drawdown in the pumped well during each step after 60 minutes (fig. 32) is used to estimate a nonlinear well-loss term by use of procedures of Hantush and Bierschenk (see Kruseman and de Ridder, 1990, p. 200). Analysis of step-test results (fig. 33) suggest that, at the long-term pumping rate of 270 L / min, about 80 percent of the drawdown is from nonlinear well loss and 20 percent of drawdown is head loss in the formation.

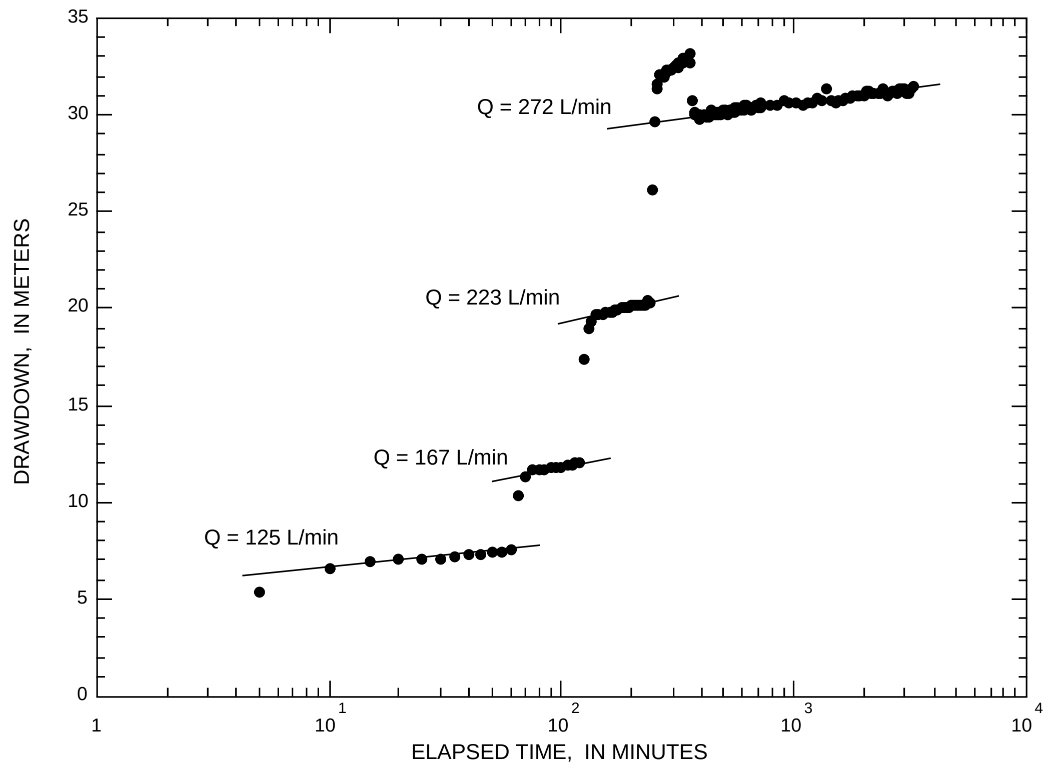


Figure 32. Drawdown in pumped well Mg-1423 in Lansdale area, during step test on February 15, 1994, in semi-log format.

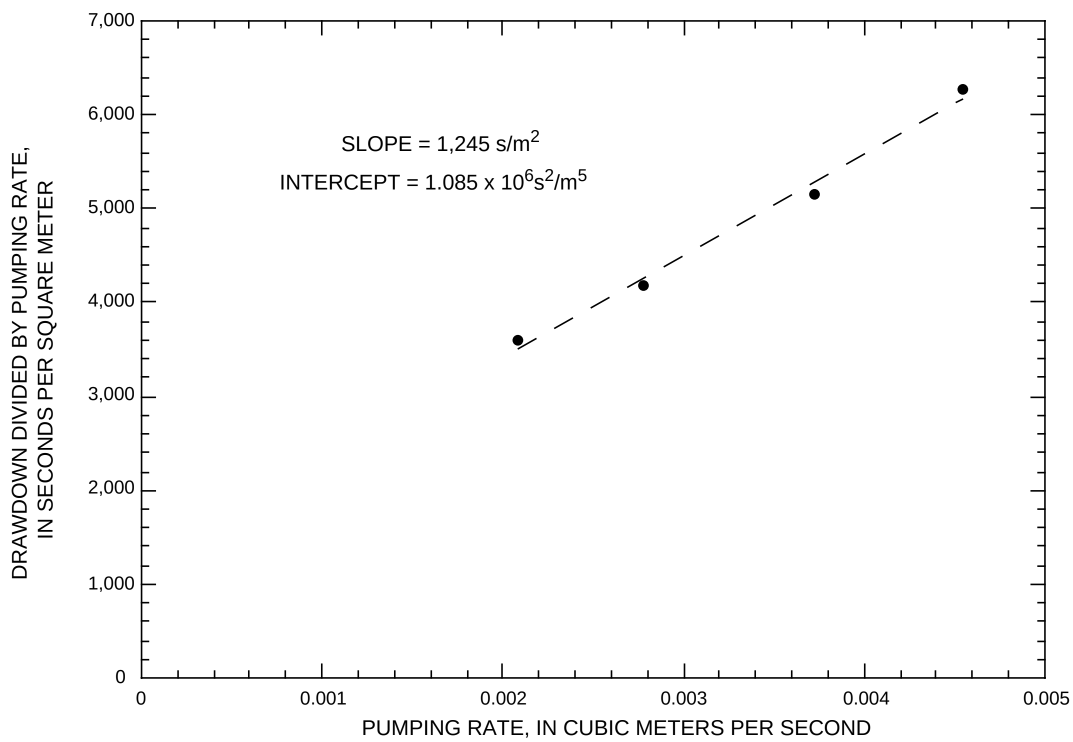


Figure 33. Sum of incremental drawdown divided by pumping rate as a function of pumping rate for step test in Mg-1423, Lansdale area, February 15, 1994, for estimation of linear (formation loss) and nonlinear (well loss) components of drawdown by Hantush and Bierschenk method (Kruseman and de Ridder, 1990).

Drawdown in observation wells Mg-1556 (N21), Mg-1654 (N34D), Mg-1655 (PZS2), Mg-1568 (6-85), and Mg-1570 (9-85) during the 48-hour aquifer test does not match the Theis theoretical curve (fig. 34). The log-log plot of drawdown in the observation well with the highest drawdown is approximated by straight segments with slope between 0.5 and 1.0. Drawdown follows a straight line of 0.5 slope on the log-log plot for linear flow conditions, common in fractured-rock aquifers (see fig. 2E and 2F). A straight line of slope 1.0 corresponds to bounded aquifers at large time when all pumping comes from storage. The drawdown in the pumped well is almost constant during the 48-hour test and cannot be used to estimate T.

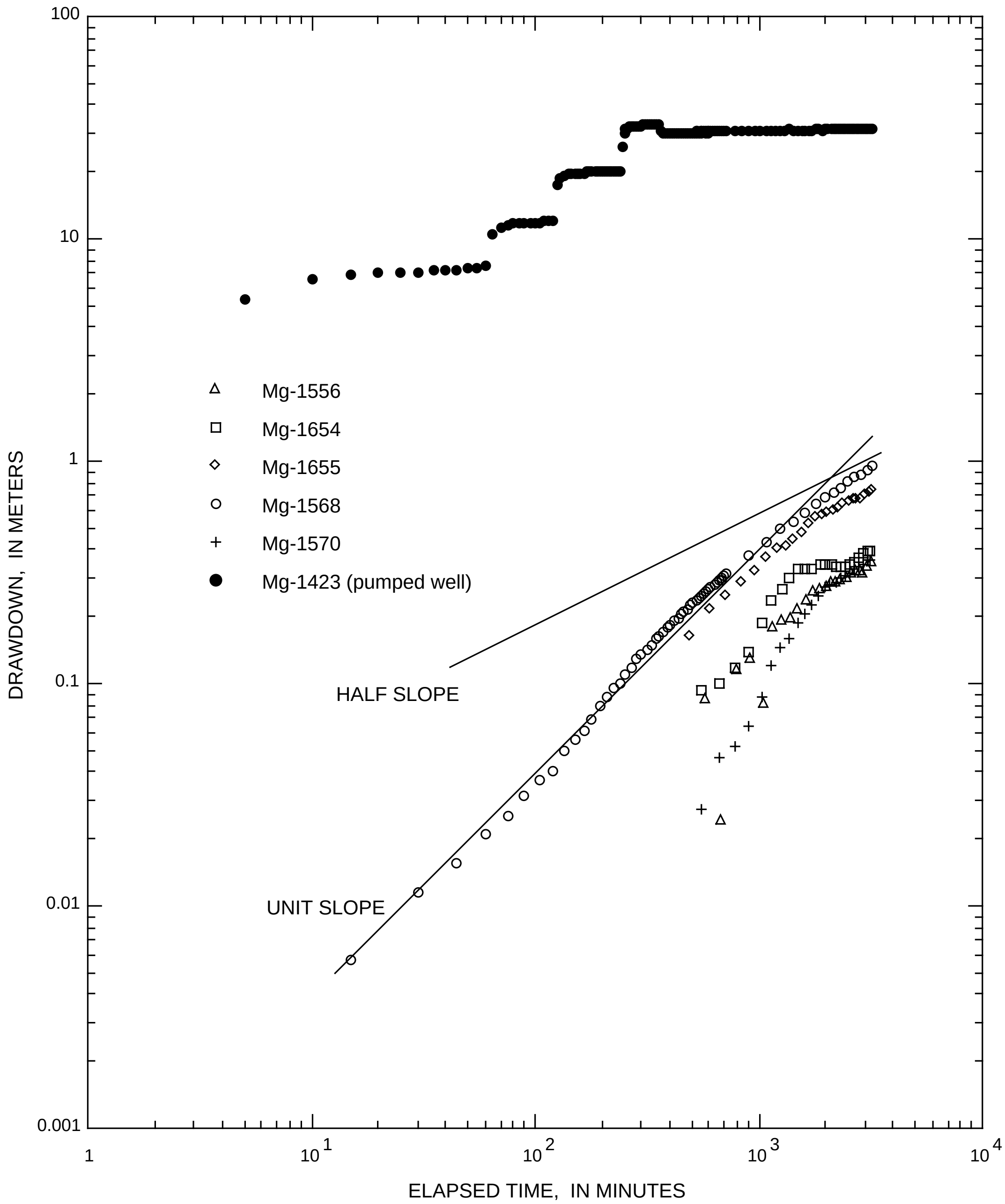


Figure 34. Drawdown in observation wells Mg-1556, Mg-1654, Mg-1655, Mg-1568, and Mg-1570, and in pumped well Mg-1423 in Lansdale area during step test and subsequent 48-hour aquifer test, February 1994, in log-log format.

Analysis of pumped well recovery by use of the method of Goode (1997) yields T = 39 m^2 / d (fig. 35). The model curve also suggests that drawdown in the formation near the pumped well when pumping stopped was closer to 10 m than to the 31 m drawdown measured in the pumped well. This exaggerated drawdown in the pumped well is consistent with the step-test analysis above. The general pattern of almost no recovery in the observation wells at early-recovery time is consistent with the theory of Goode (1997). On the basis of that theory, recovery in the observation wells would tend to be small until the pumped well recovers to comparable levels.

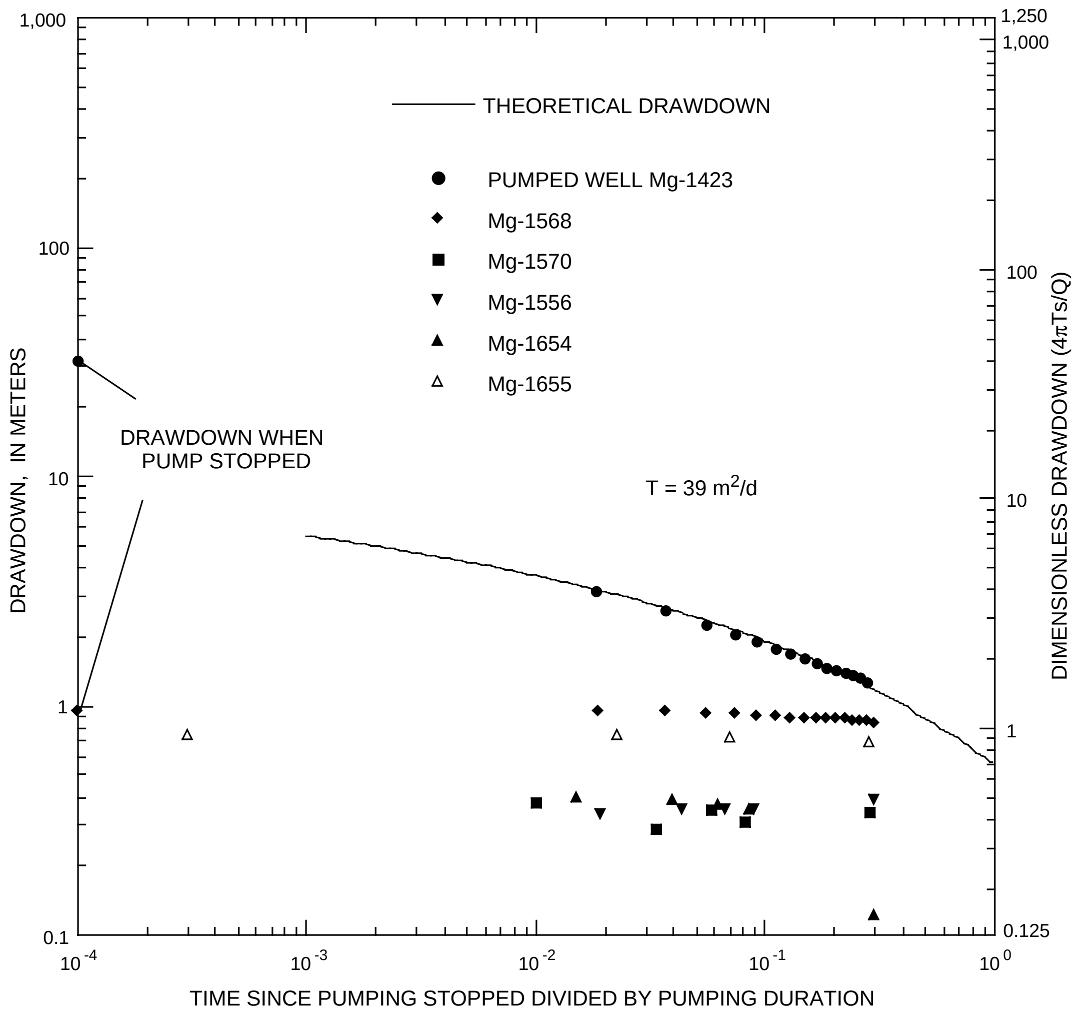


Figure 35. Drawdown during recovery in observation wells Mg-1556, Mg-1654, Mg-1655, Mg-1568, and Mg-1570 and in pumped well Mg-1423 in Lansdale area after step test and subsequent 48-hour aquifer test, February 1994, and estimation of transmissivity (T) by method of Goode (1997).

Aquifer Test of Mg-1424, February 1994

NGI (1994b) conducted a combined step and constant-rate aquifer test in Mg-1424 (PW-13) beginning on February 8, 1994. NGI (1994b) estimated the 'sustained yield' of the well as about 470 L / min on the basis of the extrapolation of the 48-hour drawdown to 90 days. After the step tests and the immediately subsequent 48-hour test, maximum drawdown in the pumped well was about 20 m (67 ft); drawdowns in nearby observation wells ranged from 0 to over 6 m (20 ft). The maximum observed drawdown in the observation wells was in well Mg-1656 (N32D), oriented E-NE from the pumped well, approximately aligned with the assumed NE strike of formation bedding in the area. NGI (1994b) did not analyze observed drawdown to estimate aquifer properties.

Application of the Cooper-Jacob method to drawdown observed in Mg-1656 (N32D) yields T = 44 m^2 / d (fig. 36). Unfortunately, the early-time drawdown, which is necessary to match the Theis model curve, was not measured. Many observation wells at similar and even smaller distances from the pumped well exhibited much smaller drawdown. Drawdown at all of the wells during recovery does not match the Theis theory. The pumped-well drawdown during pumping does not appear to be on a large-time straight line in the Cooper-Jacob semi-log plot.

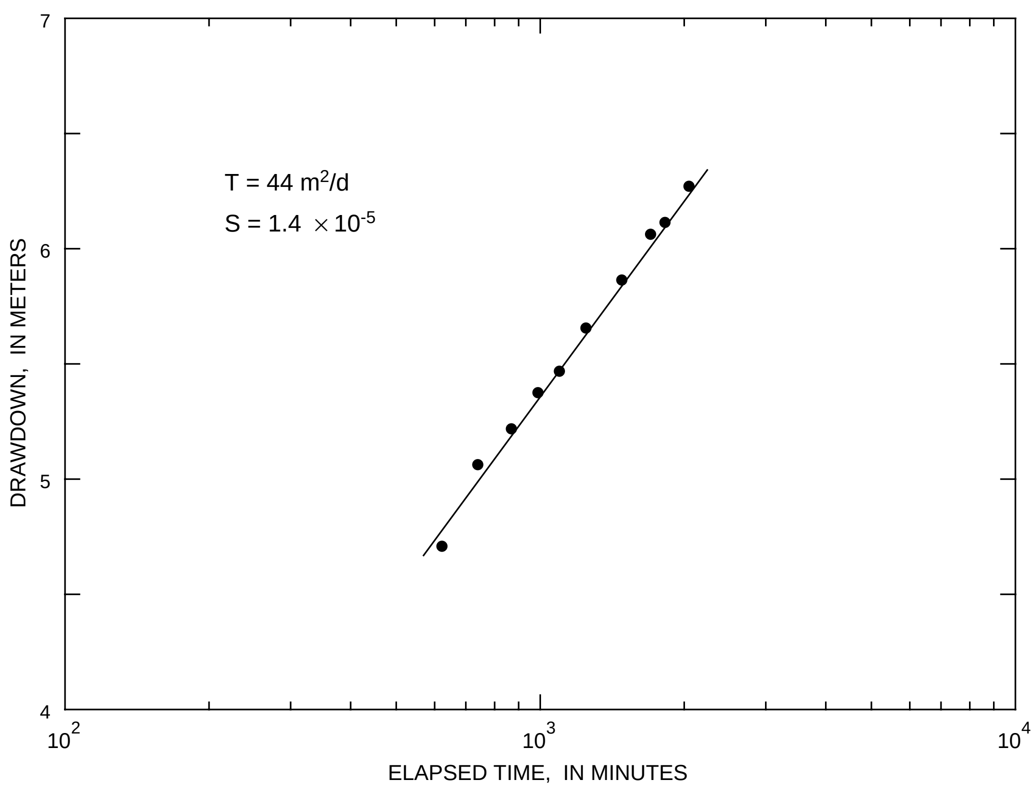


Figure 36. Drawdown in observation well Mg-1656 during pumping of Mg-1424 in Lansdale area, February 1994, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Aquifer-Isolation Testing at Ford, March 1992

Aquifer-isolation tests were conducted in five wells at the Ford Electronics and Refrigeration Corporation (FERCO) facility, Lansdale, Pa., in March 1992 by Earth Data Incorporated (Converse Consultants East, 1994). The tested wells were Mg-89 (well 1), Mg-90 (well 2), Mg-135 (well 3), Mg-147 (well 4), and Mg-151 (well 5). Well locations are shown in figure 1. Information about the tests and hydraulic data reported by Converse Consultants East (1994) is summarized in table 5. A straddle-packer system, consisting of two inflatable borehole packers with a pump between the packers, was used to separately test three or four isolated zones within each borehole. Reported specific capacity of the 30 to 40 m (100 to 130 ft) zones isolated in the boreholes ranges from 0.41 to 82 m^2 / d (0.023 to 4.6 (gal / min) / ft). Specific capacity decreases with depth in four of the wells (Mg-89, Mg-90, Mg-147 and Mg-151), but in Mg-135, the specific capacity is greatest in the deepest zone. To estimate the open-hole specific capacity (productivity coefficient), Converse Consultants East (1994) summed the specific capacities for the tested zones in each borehole, with minor but unexplained adjustments. These estimates indicate that the open-hole specific capacities of Mg-147 and Mg-151 are about one order of magnitude (a factor of 10 times) greater than the specific capacities of the other wells. All depths in this section are from Converse Consultants East (1994) and are assumed to be depths below top of casing (BTOC).

Table 5. *Summary information on packer tests at Ford Plant, Lansdale, Pennsylvania (from Converse Consultants East, 1994)*

[m, meters; min, minutes; L/min, liters per minute; L, liters; m^2/d, square meters per day; --, no data available]

U.S. Geological Survey well identification number	Zone	Depth to top of interval (m)	Depth to bottom of interval (m)	Length of interval (m)	Duration of test (min)	Pumping rate (L/min)	Total volume pumped (L)	Drawdown (m)	Specific capacity (m^2/d)
Mg-89	1	18.8	54.0	35.3	64	97	6,070	10.5	13.3
Mg-89	2	55.2	85.7	30.5	113	33	3,450	45.8	1.0
Mg-89	3	86.9	117.4	30.5	122	34	3,610	64.5	.8
Mg-89	4	106.7	146.6	39.9	83	42	3,280	60.1	1.0
Mg-90	1	17.6	51.8	34.2	65	79	5,180	14.6	7.8
Mg-90	2	51.8	82.3	30.4	71	55	4,090	31.2	2.5
Mg-90	3	82.3	112.8	30.4	84	48	4,110	35.7	1.9
Mg-90	4	112.8	150.8	38.0	--	--	0	--	not tested
Mg-135	1	16.9	54.9	37.9	58	47	3,970	34.9	.3
Mg-135	2	54.9	85.3	30.4	71	55	3,350	47.8	1.6
Mg-135	3	85.7	116.1	30.4	58	66	3,620	19.9	4.8
Mg-135	4	109.5	146.0	36.5	57	71	3,620	15.0	6.8
Mg-147	1	18.6	43.9	25.3	51	87	4,391	2.6	48.1
Mg-147	2	43.9	74.4	30.4	48	83	4,020	5.5	21.5
Mg-147	3	74.4	104.9	30.4	143	20	2,949	69.5	.4
Mg-147	4	108.2	138.7	30.4	58	85	4,822	11.8	10.4
Mg-151	1	11.7	45.7	34.0	64	70	4,637	1.2	82.8
Mg-151	2	45.8	76.2	30.4	78	64	4,841	11.8	7.9
Mg-151	3	76.2	106.7	30.4	49	61	3,800	14.6	5.9
Mg-151	4	106.7	137.2	30.4	79	44	3,395	32.4	1.9

During the testing of zone 1 in each borehole, the upper packer was not inflated. This allowed the storage of water in the borehole, which changes as the water surface in the well drops, to contribute to the pumping. This borehole storage caused the drawdown in zone 1 of all wells to increase more gradually (at early time) than the drawdown in the enclosed zones 2-4. Drawdown increased very rapidly immediately after the pump was started in zones 2-4. When the upper packer was inflated, the water surface was hydraulically isolated from the pumped middle zone. It is likely that the early-time response in zone 1 of each well would have been more similar to the other zones if the upper packer had been inflated in the open borehole or in the casing but below the water surface in the well.

Several of the datasets presented by Converse Consultants East (1994) are noted to have cyclic fluctuations in reported drawdown. For example, the drawdown in the upper pumped zone 1 of Mg-151 is dominated by a 0.3 m (1 ft) cycle in drawdown, which is large compared to the maximum drawdown of 1.2 m (4.0 ft). The cause of these oscillations in reported water levels is not apparent, and use of these data to estimate aquifer properties may yield erroneous values. The drawdown datasets presented by Converse Consultants East (1994) that have unexplained fluctuations are not used in this review.

Transmissivities estimated by use of several methods of analysis from these aquifer-isolation tests are summarized in table 6. Some characteristics of drawdown during each test are discussed below in separate sections. Methods of analysis include Theis match or Cooper-Jacob straight line fit of drawdown data and Theis match of recovery data for the pumped zone only. Drawdown or recovery data for zones other than the pumped zone are not used to estimate T.

Table 6. *Estimates of horizontal transmissivity of individual depth intervals from packer tests at Ford Plant, Lansdale, Pennsylvania. Test conducted by and drawdown data from Earth Data Inc. (see Converse Consultants East, 1994)*

[L/min, liters per minute; m^2/d, square meters per day; m, meters; --, not determined; >, greater than; dd, drawdown]

U.S. Geological Survey well identification number	Depth interval (m)	Pumping rate (L/min)	Transmissivity (m^2/d)			Specific capacity (m^2/d)	Comments
			Theis	Cooper/ Jacob	Rg [1]		
Mg-89	19-54	97	8.1	4.3	--	13	perfectly flat dd 10-22 min; bottom zone max dd >1 m, straight line with 0.6 slope in log-log plot
Mg-135	86-116	66	--	10.0	9.1	4.8	dd too straight for Theis match; bottom zone dd max almost 1 m; recovery too fast, short time for recovery meas.
Mg-135	109-146	71	--	6.2	13.5	6.8	dd too flat and straight for Theis match; top zone dd maximum 0.2 m
Mg-147	19-44	87	22	28	35	48	dramatic change in dd after 38 minutes pumping from erratic to smooth; early time Cooper-Jacob gives 16 m^2/d;
Mg-151	107-137	44	--	6	--	1.9	dd not static when pumping started; very flat dd; no fit possible for Theis or Recovery log-log plots

[1] Recovery type curve method of Goode (1997).

Mg-89, Zone 1, 19 - 54 m

Drawdown data collected during this test is suspect because of a period of perfectly constant drawdown during the test. Drawdown in pumped zone 1 initially decreased at a rate of about 2 m in 5 minutes but then remained constant from about 10 minutes to about 22 minutes after pumping began (fig. 37). There is no physically plausible explanation for this temporal pattern of drawdown during constant-rate pumping. After this period, drawdown looks realistic. However, the early drawdown trend and the trend after the constant drawdown period do not appear to be visually consistent. In contrast, the observed drawdown in the underlying unpumped zone (55-147 m (181-481 ft)) gradually increases during the entire pumping period. The fact that both zones recover to about the same level by about 95 minutes after pumping started suggests that the drawdown during recovery in the pumped zone is representative of field conditions. The maximum drawdown in the unpumped section of the borehole was more than 1 m, suggesting either leakage between the zones within the borehole or a hydraulic connection between the upper pumped zone and the underlying zone through rock outside the borehole.

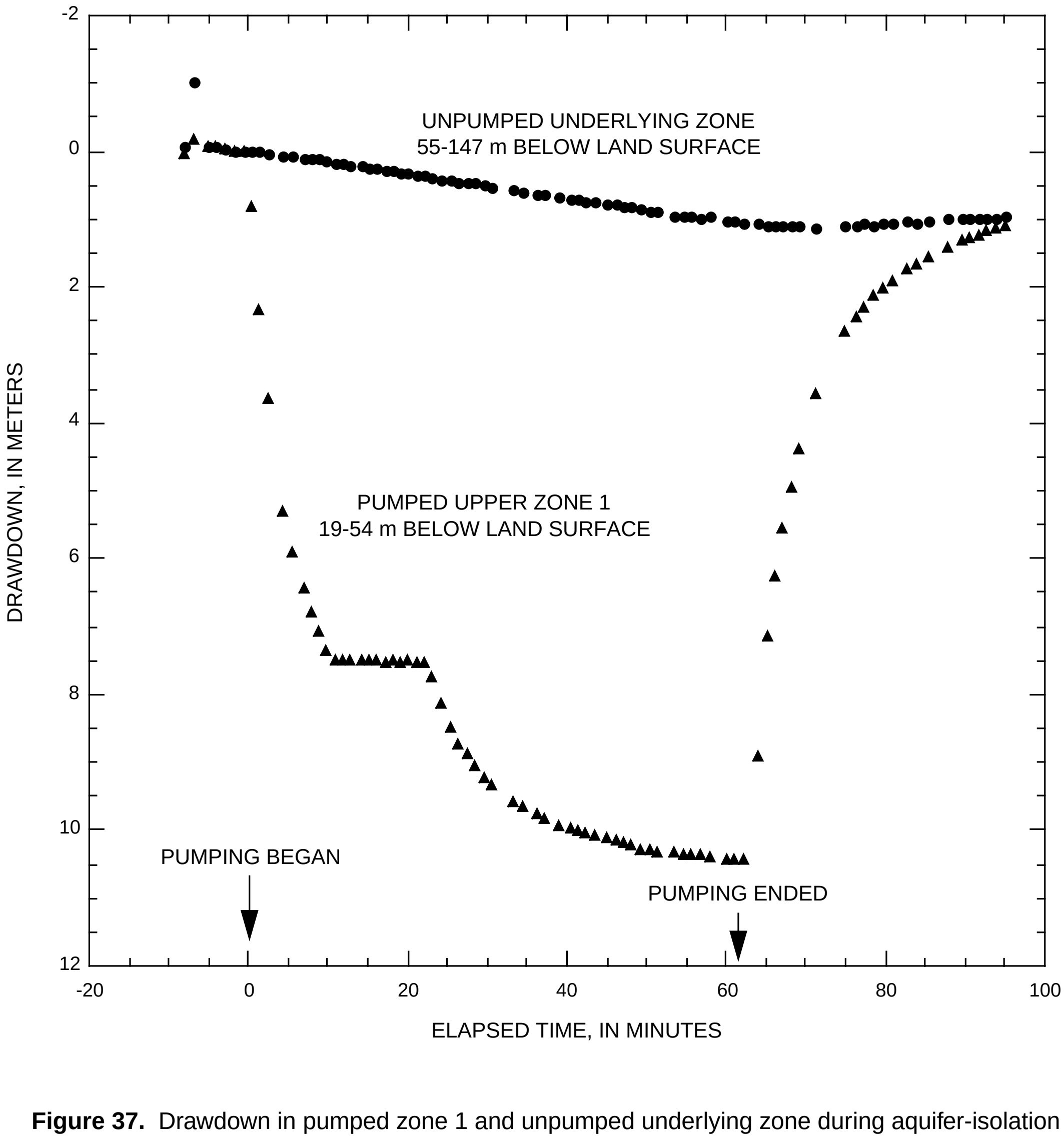


Figure 37. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-89 in Lansdale area, March 1992.

The Theis log-log type curve match to the drawdown data indicates T = 8.1 m^2/ d (fig. 38). However, the Theis fit is somewhat questionable because of the flat part of the drawdown curve. On the log-log plot (fig. 38), an apparent slope of 0.6 is identified in the drawdown of the unpumped underlying zone of the borehole. A slope of 0.5 in this format is indicative of 'linear' or one-dimensional flow. This linear response can be generated by, for example, purely vertical flow from over and underlying rock to a large horizontal fracture with essentially uniform drawdown. Alternatively, a finite vertical fracture with one-dimensional flow in the surrounding rock can also generate this characteristic response.

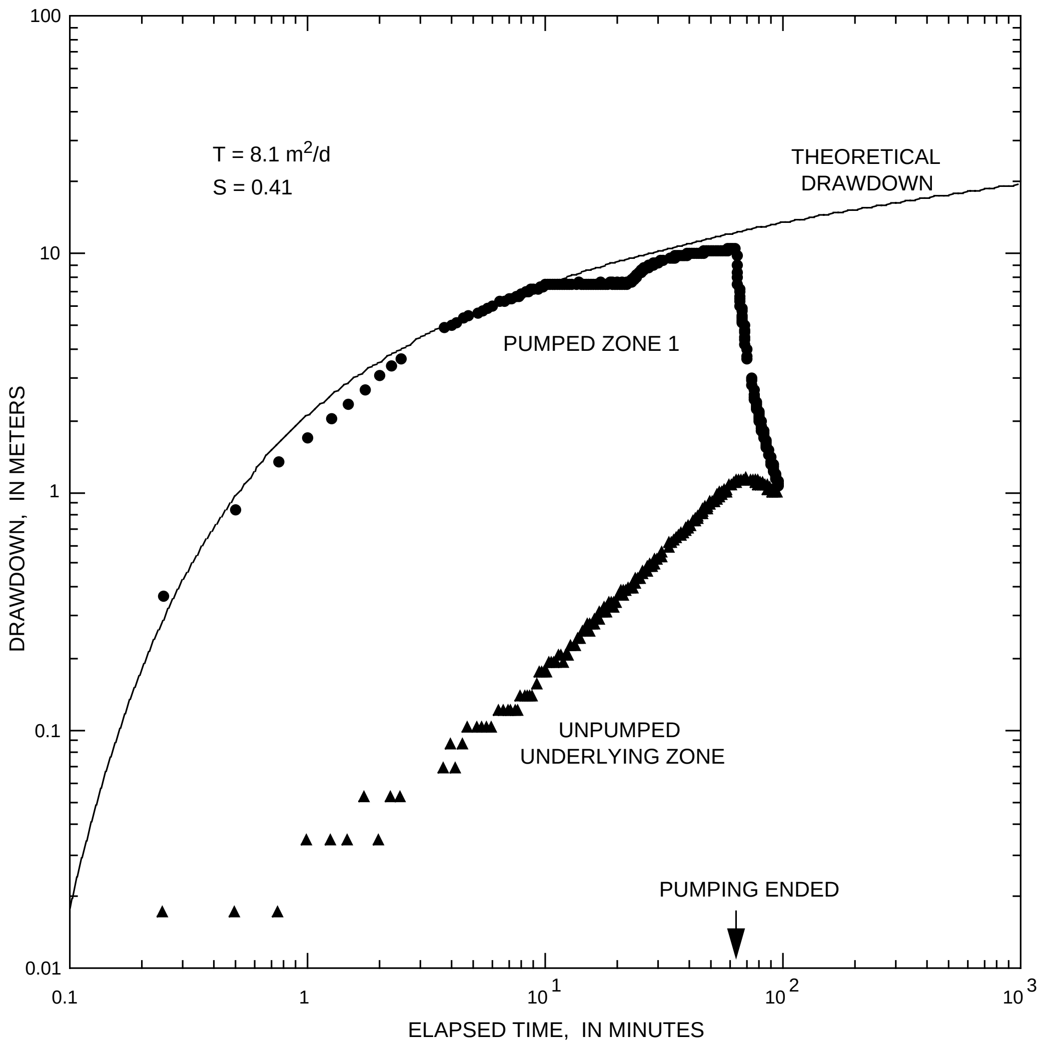


Figure 38. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-89 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

A straight line can be fit to the drawdown before the flat part of the curve in semi-log or Cooper-Jacob format (fig. 39), yielding T = 4.3 m^2/d. After the flat part of the drawdown curve, a straight line is not apparent, and if one is assumed at very large time, the slope is different from that exhibited by the early time part of the data.

The match between the recovery data and the theoretical Theis recovery curve is poor; observed recovery occurs faster than predicted by theory for the latter part of the monitored period (fig. 40). This might be caused by recharge to the pumped zone by an over- or underlying lower-permeability leakage source. The drawdowns in the pumped and unpumped zones are almost equal at the end of the recovery monitoring period, indicating some hydraulic connection between the monitored zones.

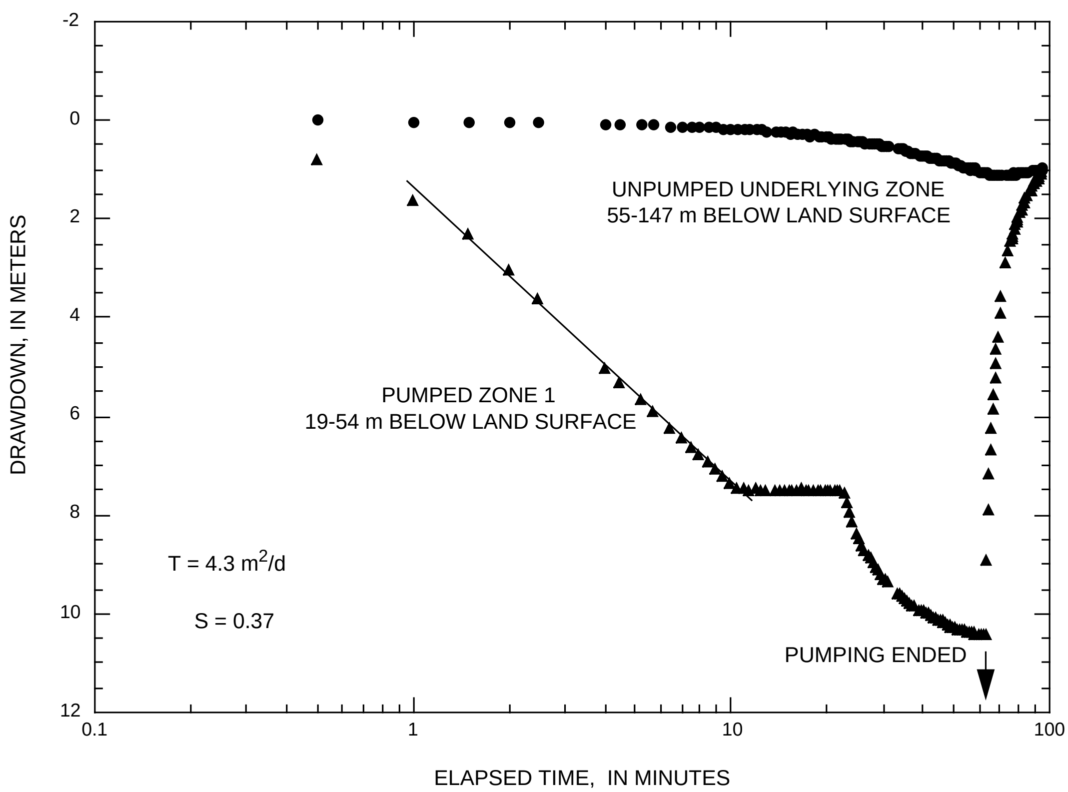


Figure 39. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-89 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

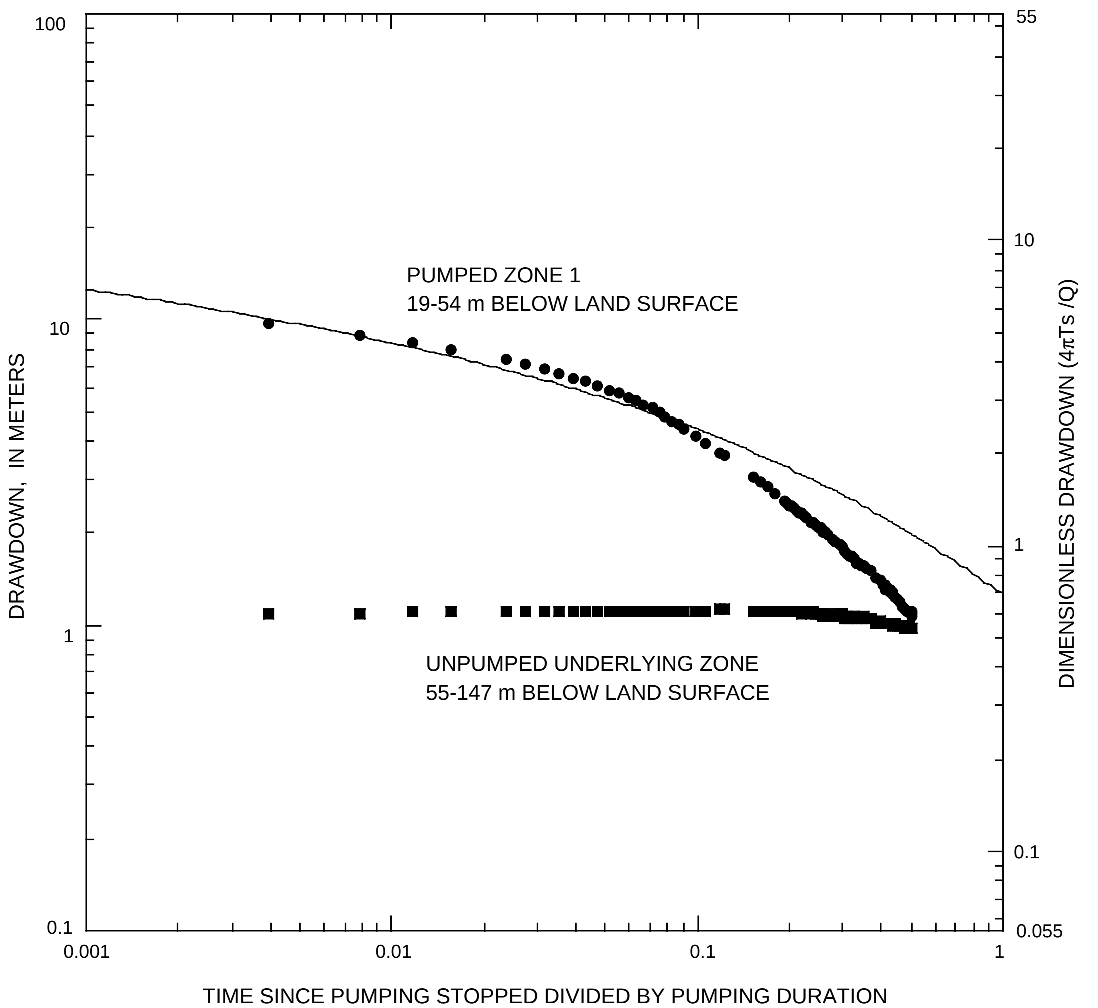


Figure 40. Drawdown during recovery in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-89 in Lansdale area, March 1992, and theoretical drawdown by method of Goode (1997).

Mg-135, Zone 3, 86 - 116 m

A Theis match was not possible to the drawdown in the pumped zone (fig. 41) because the drawdown curve is essentially a straight line after the first few minutes of pumping. This type of response also occurs in other wells in the area, for example, Mg-67 (L8), in which the well loss was estimated to be up to 80 percent of the total drawdown in the pumped well. Drawdown in the underlying zone follows a straight line with a slope of 0.5 on the Theis plot, possibly indicating linear-flow conditions. The drawdown in the overlying zone does not indicate significant hydraulic connection either within or outside the borehole between the overlying and pumped zones. The stepped and fluctuating pattern in drawdown for this zone is indicative of the resolution of the recorded water levels. A straight-line fit is possible in the Cooper-Jacob plot (fig. 42), yielding $T = 10\ m^2/d$.

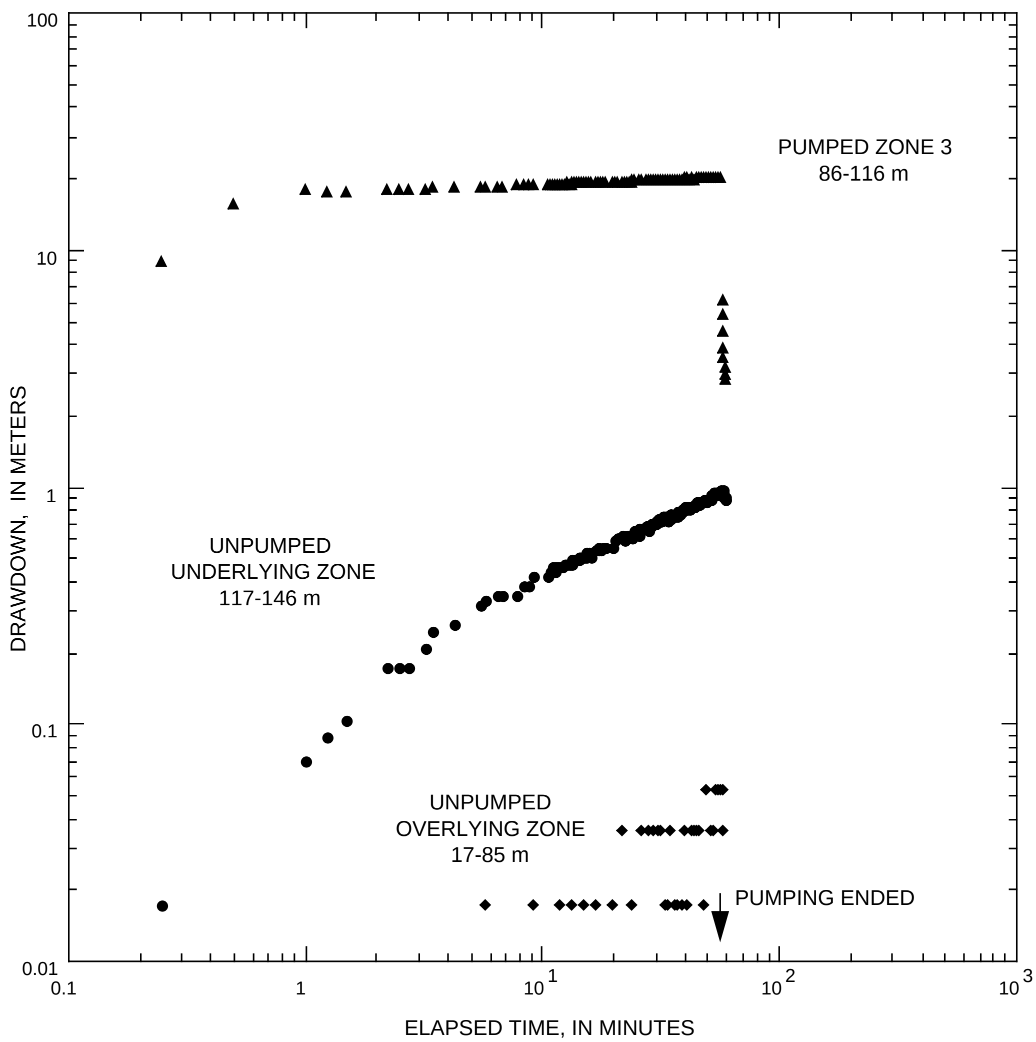


Figure 41. Drawdown in pumped zone 3 and unpumped overlying and underlying zones during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, in log-log format.

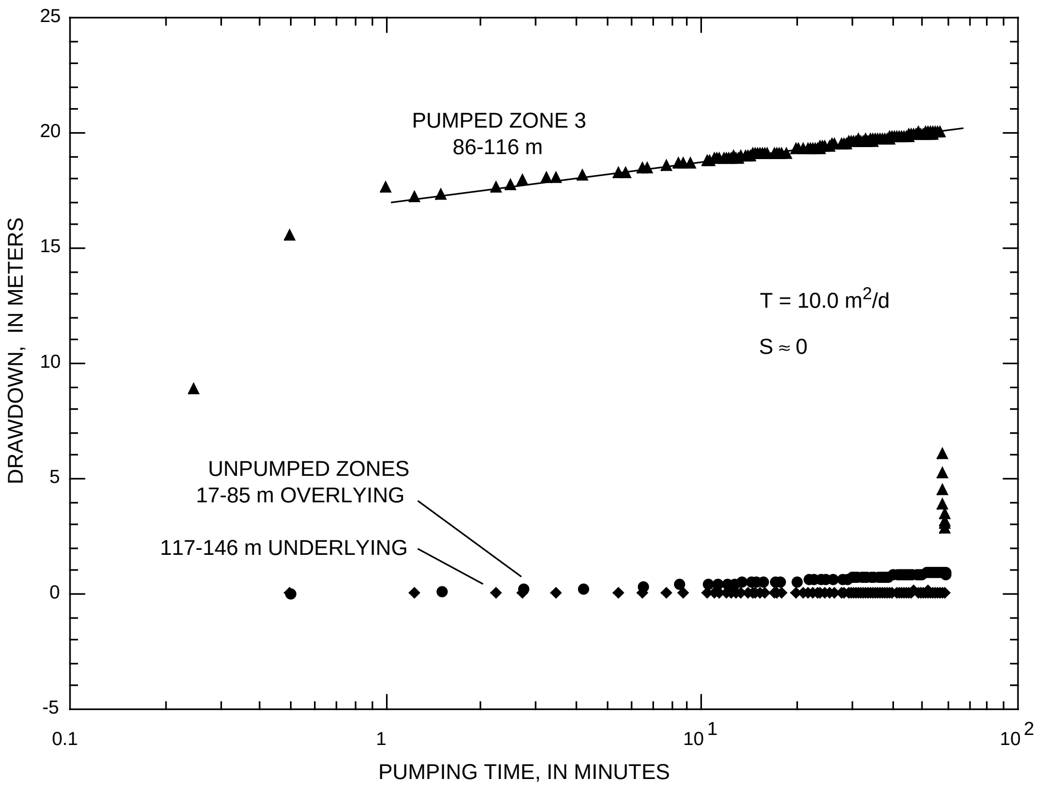


Figure 42. Drawdown in pumped zone 3 and unpumped overlying and underlying zones during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

The rapid recovery of the pumped zone at a rate faster than that predicted by the theory (fig. 43) suggests that the drawdown in the pumped zone may be exaggerated with respect to the drawdown in the formation. This could be caused by other nearby pumping or by a low-permeability skin or region immediately around the borehole. Nonetheless, the estimated T = 9.1 m^2/ d from the recovery type curve match is close to that identified from the Cooper-Jacob plot for the pumping-period drawdown. If the well loss or skin causes a constant head loss during pumping (that is, the head loss is independent of the drawdown), the Cooper-Jacob slope can be used to estimate formation T because the slope of the semi-log drawdown line does not depend on a constant well loss or skin factor, but only on the formation T. The recovery analysis is also independent of a constant well-loss term (Kruseman and de Ridder, 1990). The negligible recovery of the non-pumped zones is similar to the Theis theory for observation wells at early time (Goode, 1997). The pumped well recovers most quickly because flow is towards the well on all sides and initial gradients are large. In observation wells, gradients are lower when pumping stops, and flow occurs both towards the observation well and away from it towards the pumped well. The extent of recovery depends on the net flow into the well. Unfortunately, recovery was not monitored for sufficient time to address many of the possible alternative explanations for the observed early time response.

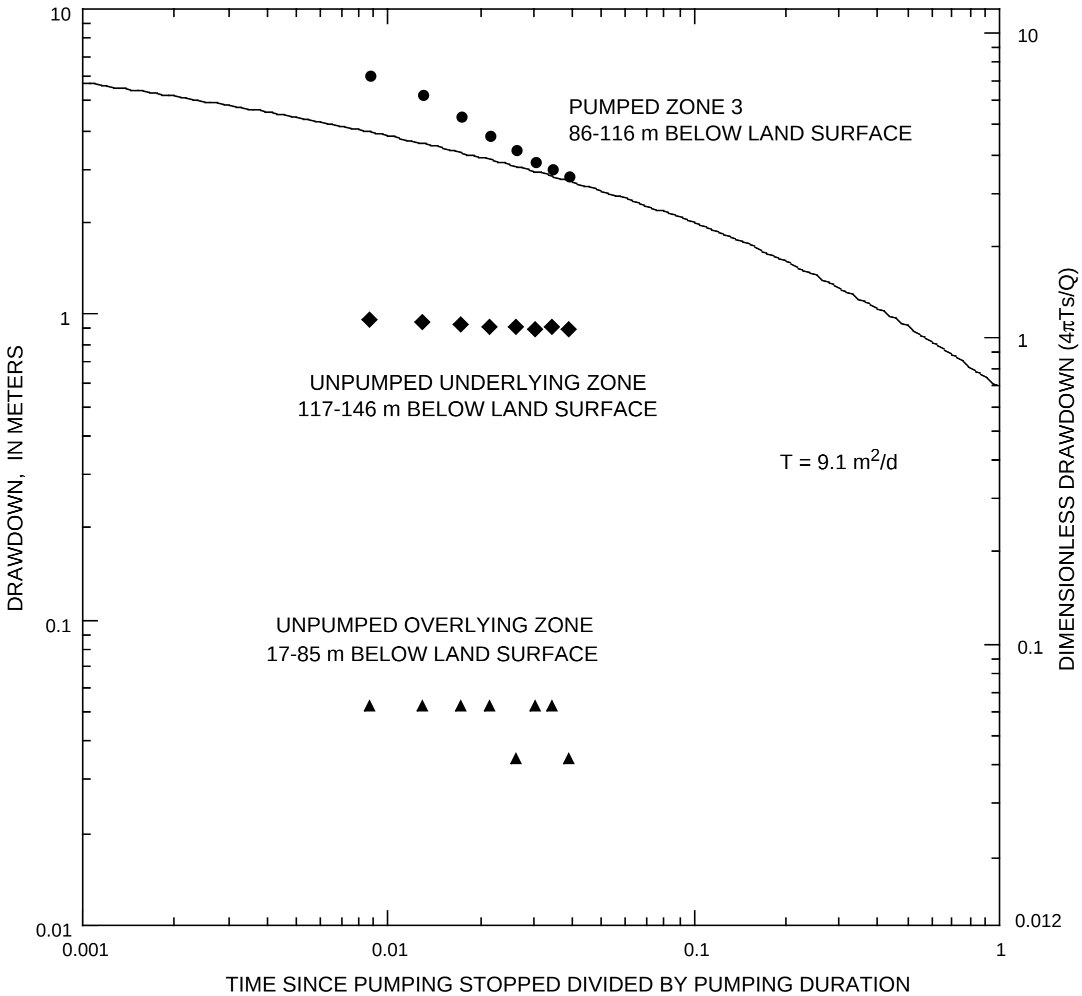


Figure 43. Drawdown during recovery in pumped zone 3 and unpumped overlying and underlying zones during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, and transmissivity (T) by method of Goode (1997).

The part of the borehole isolated in pumped zone 3 overlapped with that in zone 4, which is discussed in the next section. In particular, the section of the borehole contained in both zones (109-116 m (359-381 ft)) coincides with the contact between the upper Lockatong and lower Brunswick Formations inferred by Converse Consultants East (1994, pl. 1). Numerous authors have suggested that openings along bedding contacts account for most of the large-scale T in the Brunswick Formation (for example, Michalski, 1990; Michalski and Britton, 1997), although high-angle cross-bed fractures may provide most of the formation's permeability at large depths (Morin and others, 1997). Furthermore, the contaminant concentrations reported for samples collected from the isolated zones 3 and 4 are very similar. These data suggest that the overlapping section of the borehole may be contributing a significant fraction of the yield of both zones during pumping. That is, the estimated transmissivities may be largely dependent on the relatively high T in the overlapping section of the borehole. Adding the T or specific capacities of zones 3 and 4 would overestimate the corresponding values for the entire borehole by counting this section twice.

Mg-135, Zone 4, 109 - 146 m

As discussed above, zone 4 overlaps somewhat with zone 3 in Mg-135. If this part of the borehole has a significant part of the T of each zone, the hydraulic response of the two zones might be similar during pumping.

Drawdown in zone 4 (fig. 44), pumped at 71 L / min, is less than that in zone 3 pumped at 66 L / min (fig. 41). This suggests that the T of zone 4 is higher than that of zone 3, as quantified by the specific capacities of 4.8 m^2 / d (0.268 (gal / min) / ft) for zone 3 and 6.8 m^2 / d (0.379 (gal / min) / ft) for zone 4. However, the actual pumping rates may have been more similar than the rates identified by Converse Consultants East (1994). An average pumping rate for the entire test can be calculated by dividing the total volume of water pumped by the duration of pumping; this procedure suggests that the average pumping rates for zones 3 and 4 were 62.5 and 63.6 L / min (16.5 and 16.8 gal / min), respectively. In these drawdown data, as well as data for other zones, fluctuations and, more likely, gradual decreases in pumping rate will influence the shapes of the drawdown curves. Drawdown in zone 3 is relatively constant after an initial rapid increase (fig. 41), whereas the drawdown in zone 4 increases more rapidly at later time (fig. 45). This rate of increase of drawdown in time is used to estimate transmissivity in the Theis and Cooper-Jacob methods, and, hence, the relative T of the two zones may be opposite that of their specific capacities reported by Converse Consultants East (1994).

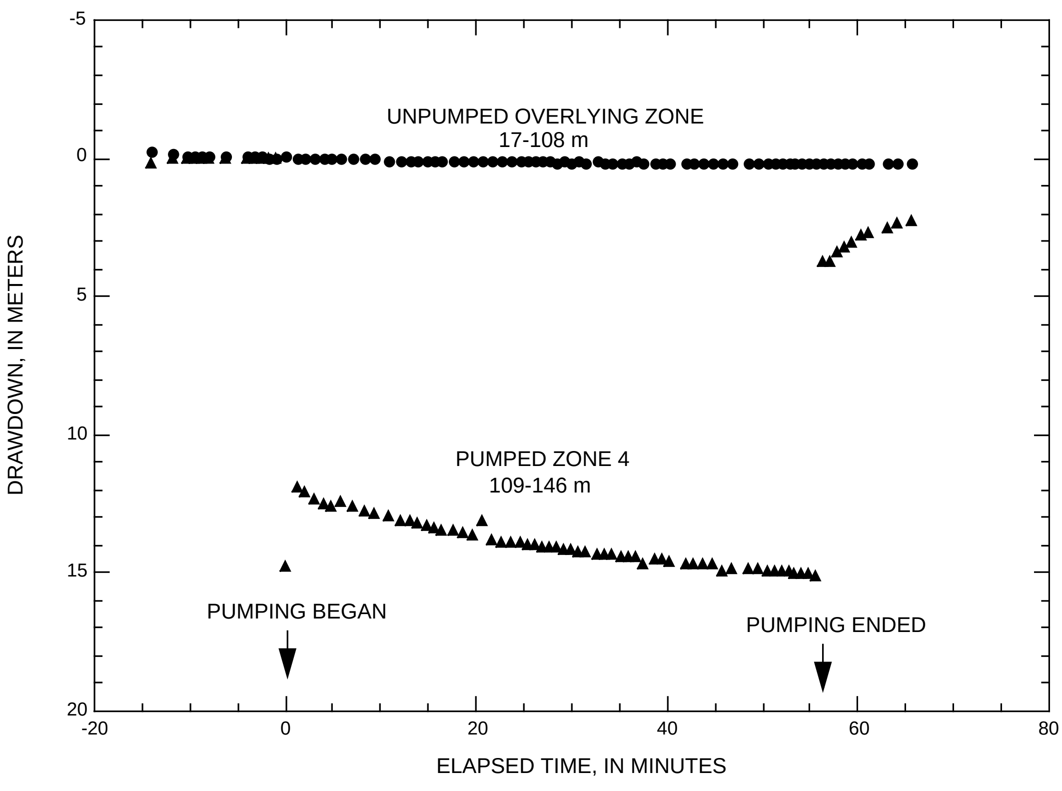


Figure 44. Drawdown in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992.

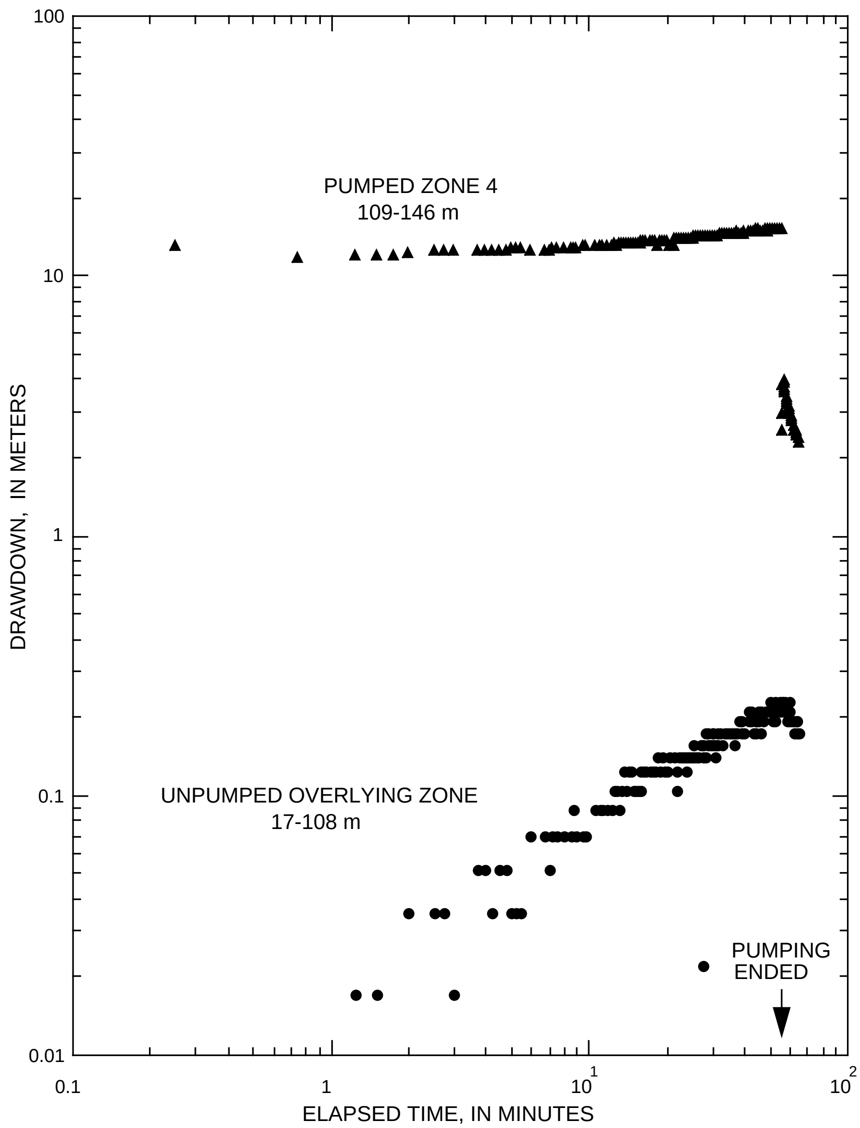


Figure 45. Drawdown in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, in log-log format.

As with zone 3, the drawdown in zone 4 is too flat to fit to the Theis log-log plot (fig. 45). Maximum drawdown in the upper zone is about 0.2 m in response to pumping. This suggests either leakage between the zones in the borehole or a low-permeability hydraulic connection between the pumped zone and overlying rock outside the borehole.

The slope of the straight line (large time) part of the pumped zone drawdown on the Cooper-Jacob plot indicates T = 6.2 m^2/ d for zone 4 (fig. 46), lower than the Cooper-Jacob estimate of T = 10 m^2/ d for zone 3. This ranking of T's, zone 3 greater than zone 4, is opposite the ranking of specific capacities.

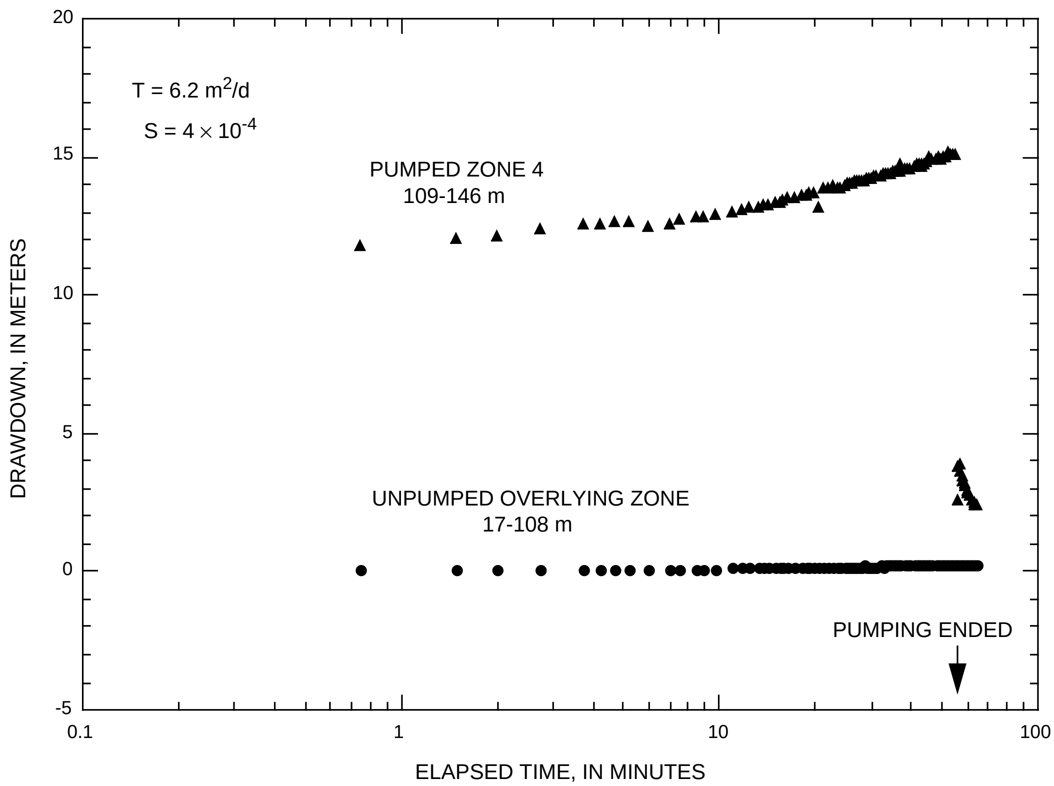


Figure 46. Drawdown in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Drawdown during recovery of pumped zone 4 does not match the theoretical curve exactly, but the marginal match (fig. 47) yields T = 13.5 m^2/ d, about twice as high as the Cooper-Jacob estimate from pumping-period data.

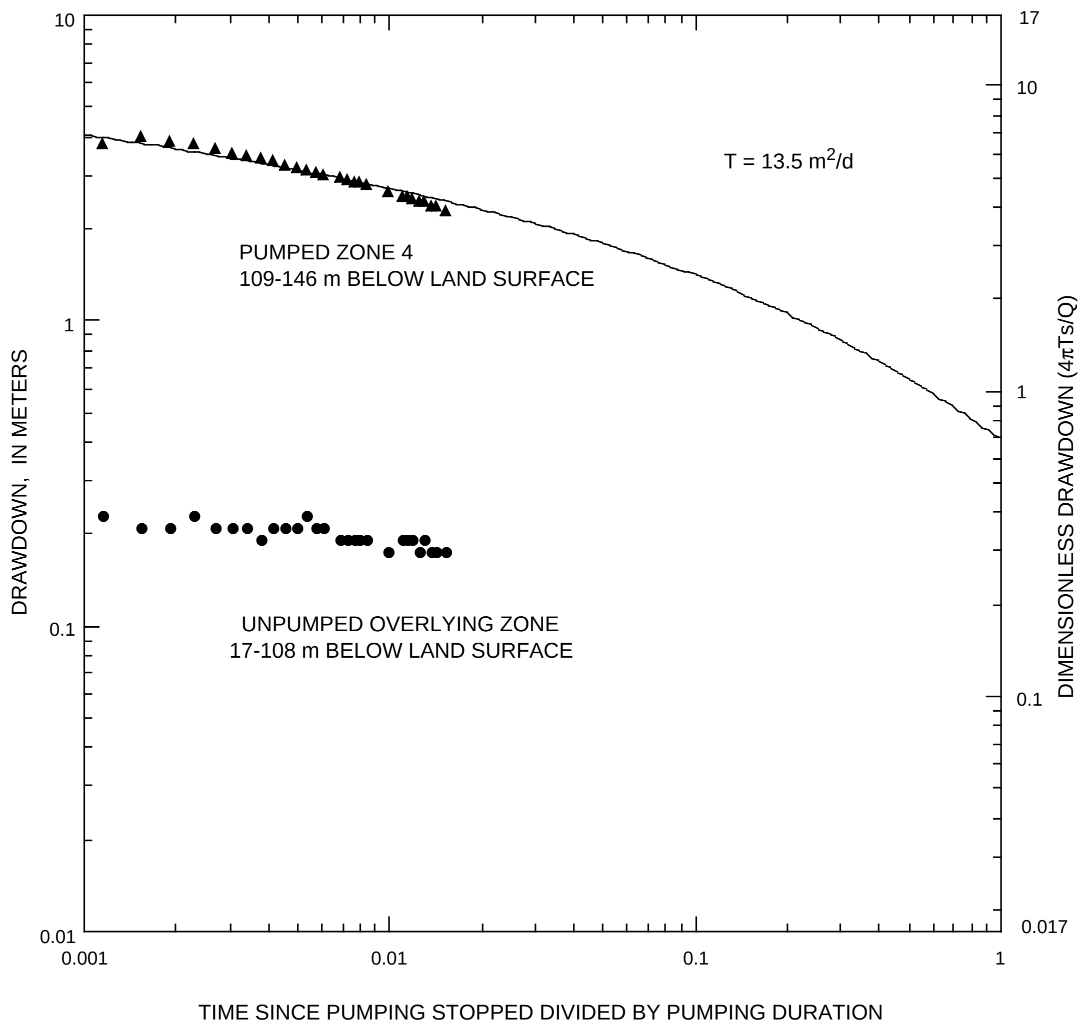


Figure 47. Drawdown during recovery in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-135 in Lansdale area, March 1992, and transmissivity (T) by method of Goode (1997).

Mg-147, Zone 1, 19 - 44 m

The reported drawdown for the test in Mg-147 pumped zone 1 was erratic until about 38 minutes after pumping started, and subsequent drawdown changes smoothly in time (fig. 48). This suggests that the data may be poor. For the unpumped section of the borehole, the drawdown is essentially zero, except for the erratic data at early time. As noted above, the drawdown in pumped zone 1 increases more gradually at early time because the water surface is open to the atmosphere in the pumped zone, and hence a much larger volume of water must be removed from the borehole to lower the water pressure.

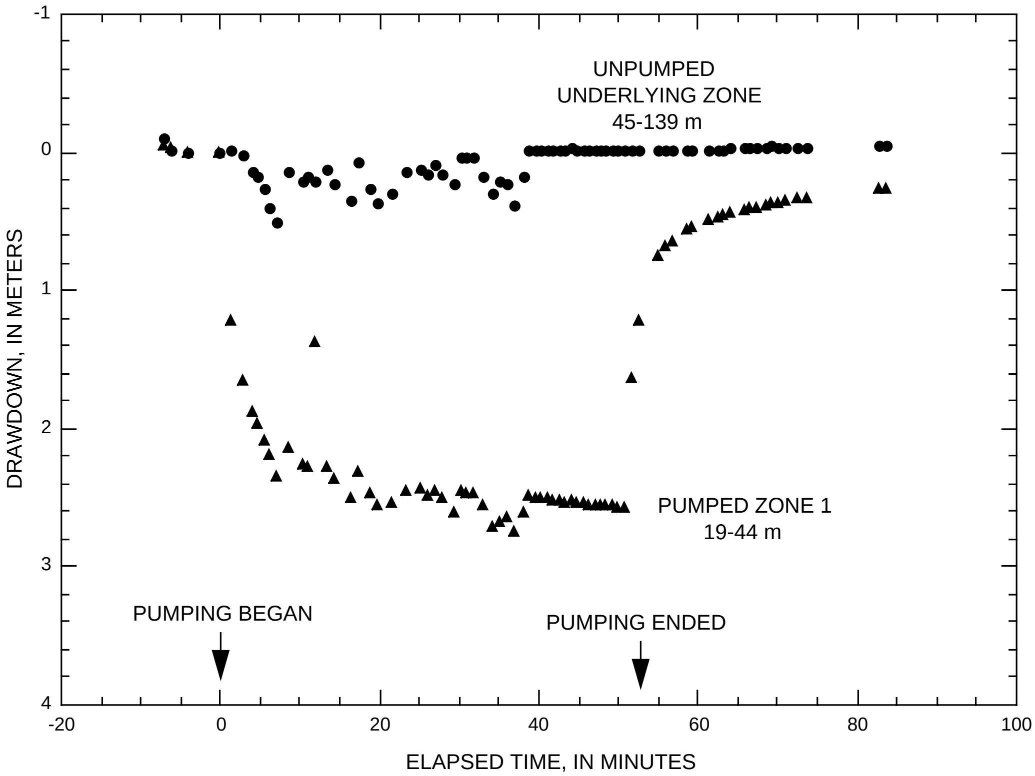


Figure 48. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-147 in Lansdale area, March 1992.

A Theis plot match is chosen that goes through the smooth part of the drawdown data at large time and that has a similar shape, but is offset from, the erratic part of the data (fig. 49). This fit yields a T = 15 m^2/ d.

The Cooper-Jacob plot yields a T = 28 m^2/ d for the smooth late-time part of the pumped zone drawdown (fig. 50). A reasonable fit may also be made to the early-time (<10 minutes) part of the data that yields a somewhat lower T = 16 m^2/ d.

The recovery data matches well with the Theis theory after about 3 minutes and yields an estimated T = 35 m^2/ d (fig. 51). As noted in previous sections, the late-time recovery data are not affected by well loss or skin effect, and the T estimated from recovery data will be higher than that estimated from pumping period drawdown where such effects are present.

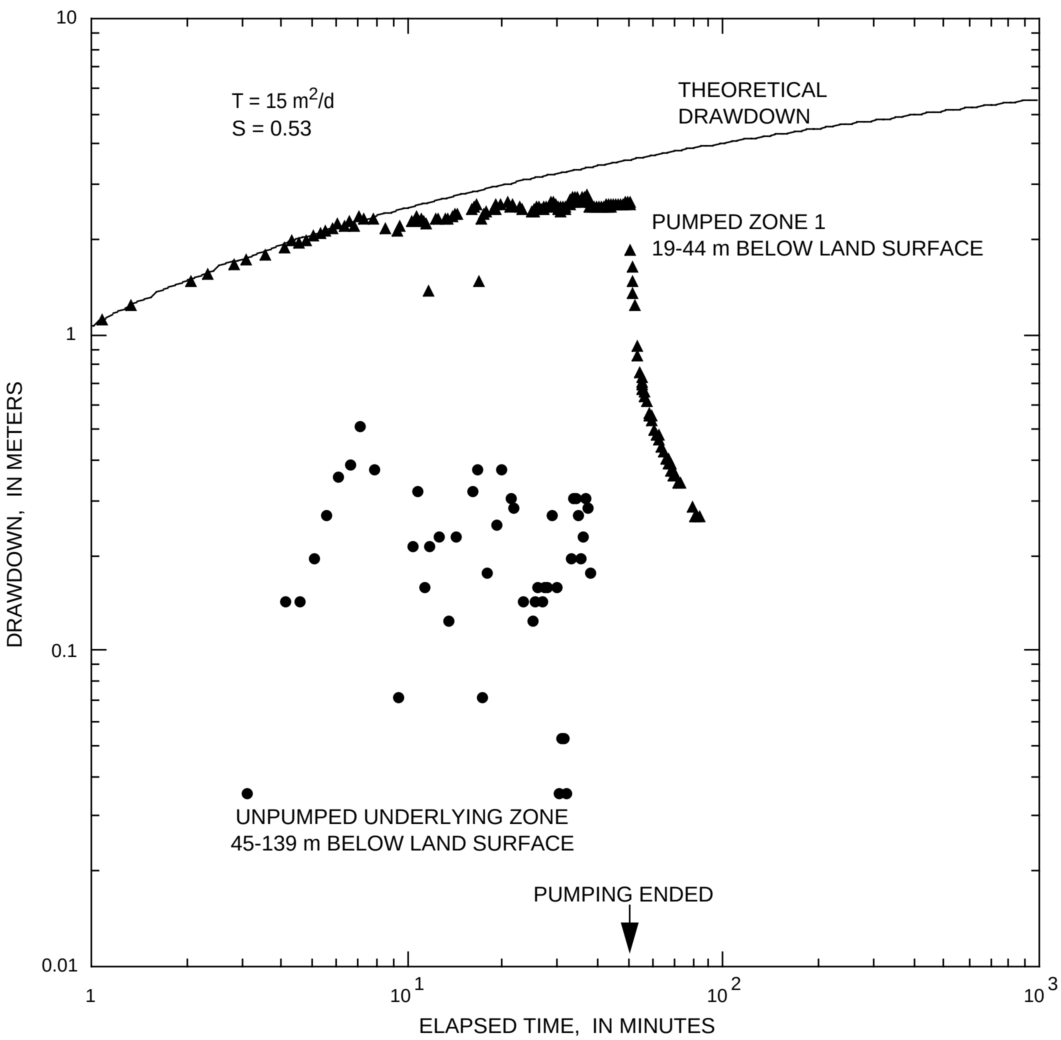


Figure 49. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-147 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

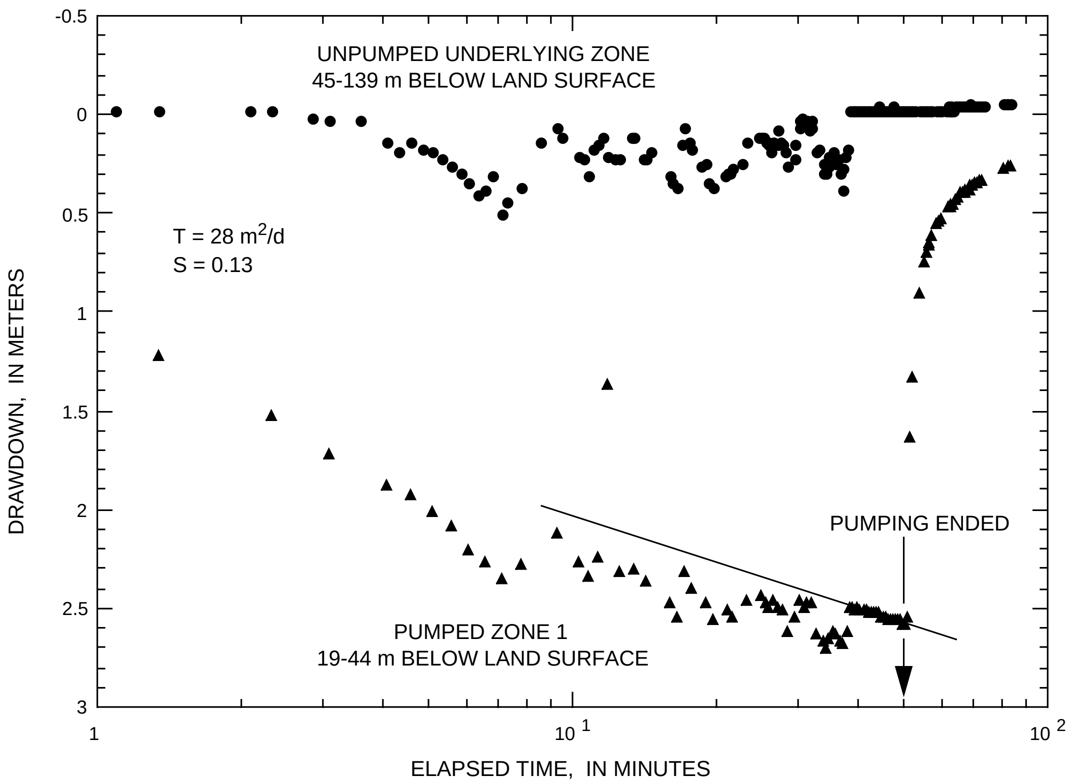


Figure 50. Drawdown in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-147 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

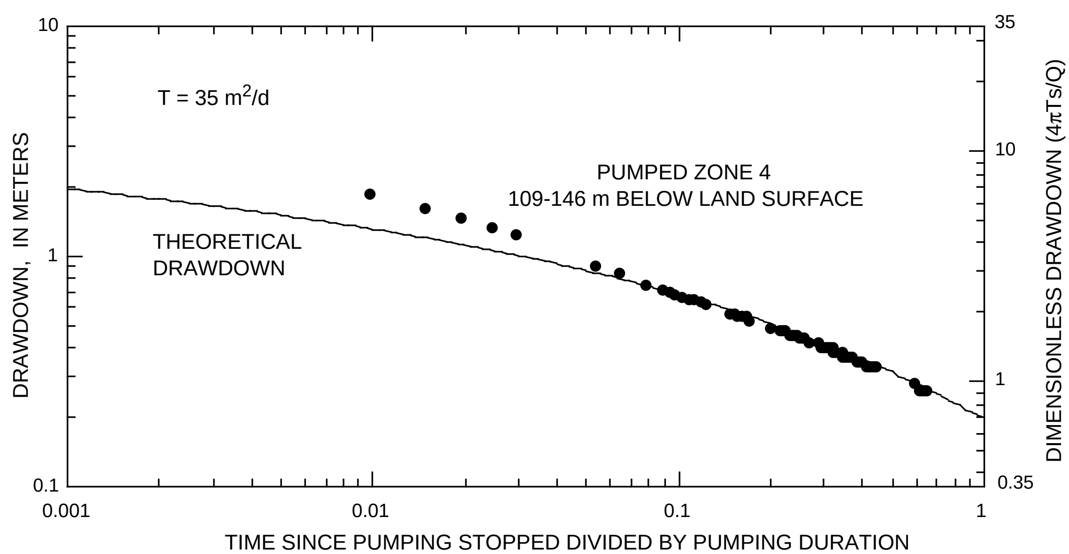


Figure 51. Drawdown during recovery in pumped zone 1 and unpumped underlying zone during aquifer-isolation testing of Mg-147 in Lansdale area, March 1992, and estimate of transmissivity (T) by method of Goode (1997).

Mg-151, Zone 4, 107 - 137 m

Zone 4 was the interval from 106.7 m (350.1 ft) to the bottom of the borehole, 137.2 m (450 ft). The reported specific capacity is low (1.95 m^2 / d; 0.109 (gal / min) / ft). The zone was pumped at the rate of 49 L / min (13 gal / min) initially, but the rate decreased somewhat during the test such that the average rate during the 79 minutes of pumping was about 43 L / min (11.3 gal / min). The overlying zone of the hole did not respond to pumping in any discernible way, indicating a good seal between the packer and the borehole wall and low permeability outside the borehole in the vicinity of the packer. Drawdown in the pumped zone jumped to over 30 m almost instantly and increased slightly from about 31 to about 32.5 m during pumping (fig. 52). After the pump was turned off, the drawdown instantly decreased to about 19 m, and then decreased slightly to about 17.5 m after over 100 minutes of recovery (fig. 52). The rapid recovery immediately after pumping was stopped, and the then almost static water level indicates that the drawdown in the formation very close to the pumped zone was closer to 20 m than to 30 m. This may be the result of a skin effect caused by a low-permeability zone immediately around the borehole.

Because the drawdown changed only slightly during both pumping and recovery periods, the Theis log-log curve match and the log-log recovery curve match were not possible. For the pumping period, the log-log plot of drawdown as a function of time was essentially flat and would only match the Theis plot at very large dimensionless time. The drawdown during recovery does not match the shape of the Theis recovery solution; the drawdown decreases too slowly compared to the theoretical curve.

Semi-log plots of drawdown as a function of time indicate linear parts that can be analyzed by use of the Cooper-Jacob method. However, these methods are based on the Theis solution, and the data clearly do not match the Theis model; hence, this procedure should be considered only a crude approximation. Analysis of drawdown during pumping indicates a T of about 6 m^2 / d; the recovery period drawdown slope indicates a T of about 3 m^2 / d (fig. 53). These estimates indicate only the general range of the actual T, which is low relative to the other zones tested at this site.

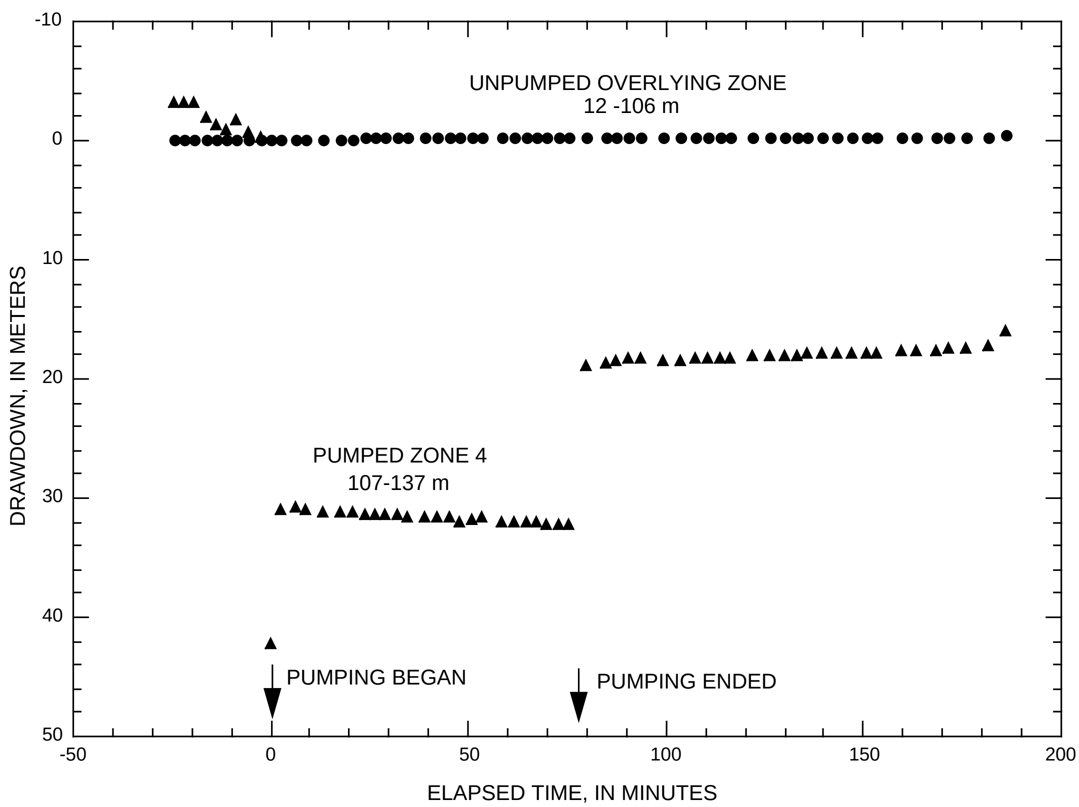


Figure 52. Drawdown in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-151 in Lansdale area, March 1992.

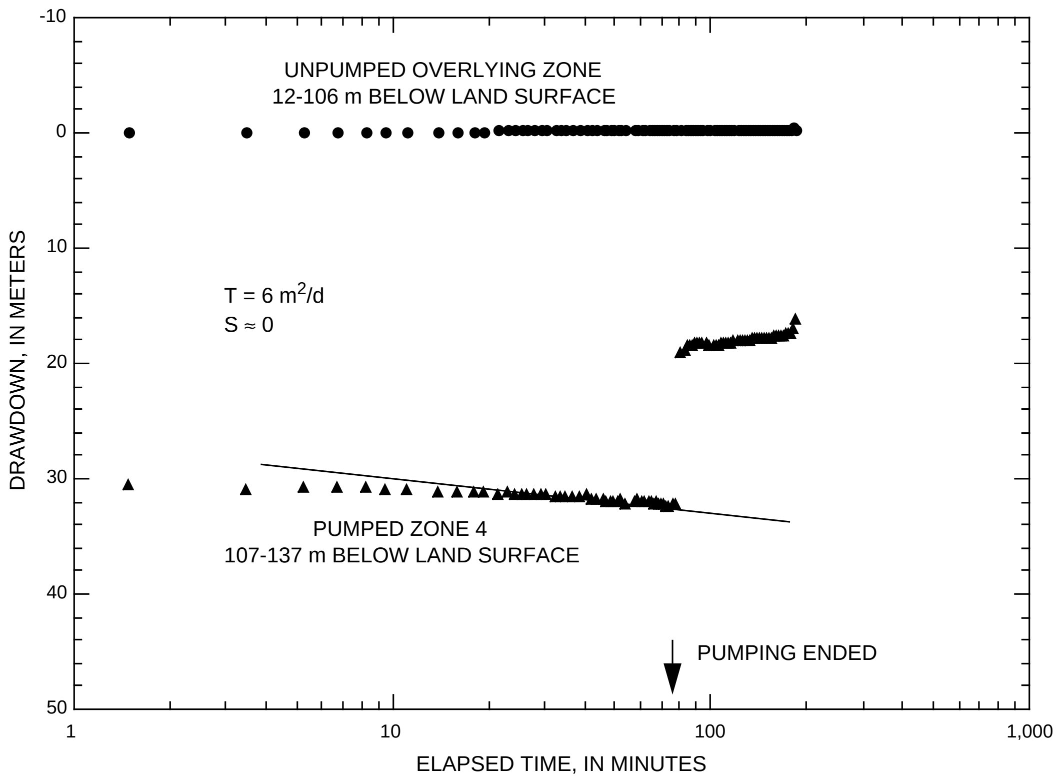


Figure 53. Drawdown in pumped zone 4 and unpumped overlying zone during aquifer-isolation testing of Mg-151 in Lansdale area, March 1992, and estimates of transmissivity (T) and storage coefficient (S) by Cooper-Jacob (1946) method.

Aquifer Test of Mg-924, April 1980

An aquifer test was conducted in well Mg-924 (NP 21) in April 1980 (U.S. Environmental Protection Agency, unpublished data files). Pumping began at 1000 on April 8 and continued for 48 hours to 1000 on April 10. The average pumping rate was 1,510 L / min (400 gal / min). Water levels were measured in several observation wells; most were relatively shallow test holes on the American Electronics Laboratory (AEL) property (fig. 54). Raingage readings indicate 7 mm (0.3 in.) of precipitation between 0700 on 5 April and 0700 on 9 April, and 20 mm (0.8 in.) between 0700 on 9 April and 0700 on 10 April. The pumped well is 153 m (500 ft) deep and casing extends to 15 m (50 ft) below land surface. Observation well Mg-876 (AEL Drink) is 91 m (300 ft) deep and the “AEL Test Hole” observation wells 1-18 range between 8.5 and 15.8 m (28 and 52 ft) deep. The depth of Cloverdale Park Well is not known. Drawdown in the pumped well was measured by air line and recorded on a circular chart; these graphical data are not analyzed in this review.

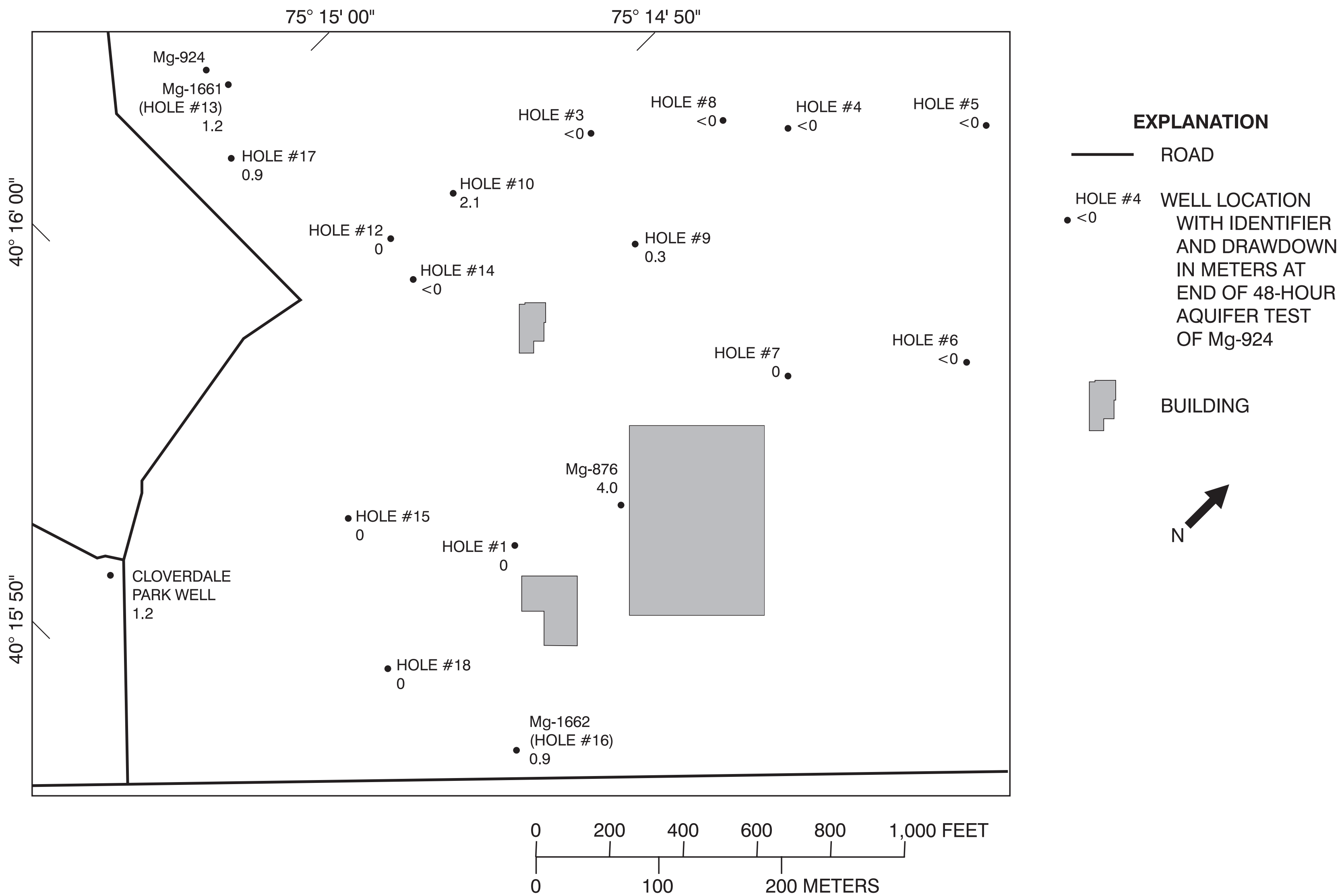


Figure 54. Locations of wells and drawdown in meters at end of 48-hour aquifer test in the area of pumped well Mg-924 in Lansdale area, November 1993 (U.S. Environmental Protection Agency, unpublished data files).

Drawdown measured in observation well Mg-876, which is about 490 m (1,600 ft) from the pumped well, matches the Theis theory and yields an estimated T = 400 m^2/d (4,300 ft^2/d) and S = 10^{-4} (fig. 55). Unfortunately, early-time drawdown was not measured; the first reported drawdown is at 62 minutes after pumping began. Furthermore, the assumed static water level was measured 19 hours before pumping began. Nonetheless, the good agreement between drawdown and the Theis model, especially the result of a low storage coefficient, suggests that the drawdown record is reasonably reliable. Analysis of drawdown during recovery also matches the theory, except for the last recorded value, and yields estimated T = 350 m^2/d (3,800 ft^2/d) (fig. 56). The more rapid recovery than predicted by theory for the last recorded value may be due to recharge from precipitation.

Rising water levels were observed in AEL Test Holes 1, 3-9, 12, 14, and 18. Some of these wells exhibited an initial response to pumping in Mg-924, but recharge from rainfall apparently contributed to overall rising water levels by the latter part of the test. No apparent response to pumping was observed in Mg-914 (NP 12).

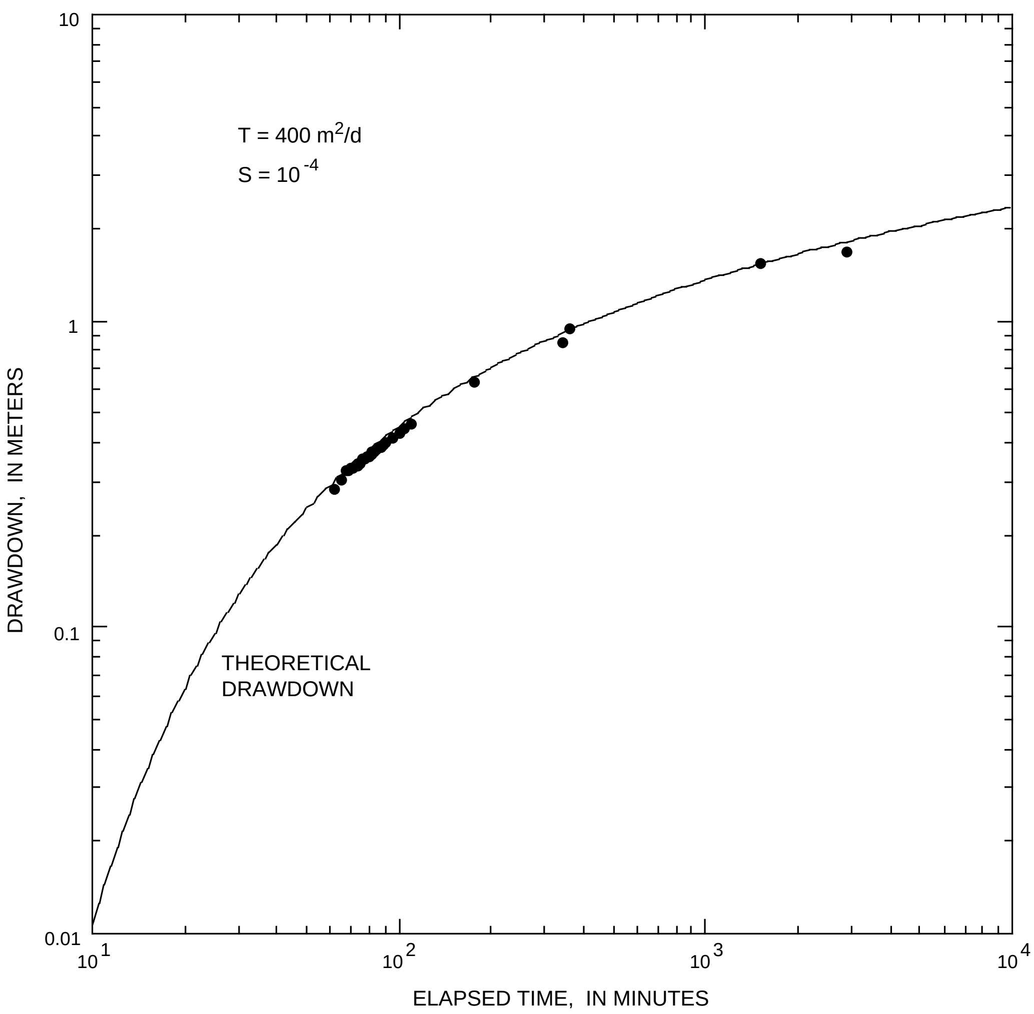


Figure 55. Drawdown in observation well Mg-876 during pumping of Mg-924 in Lansdale area, April 1980, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

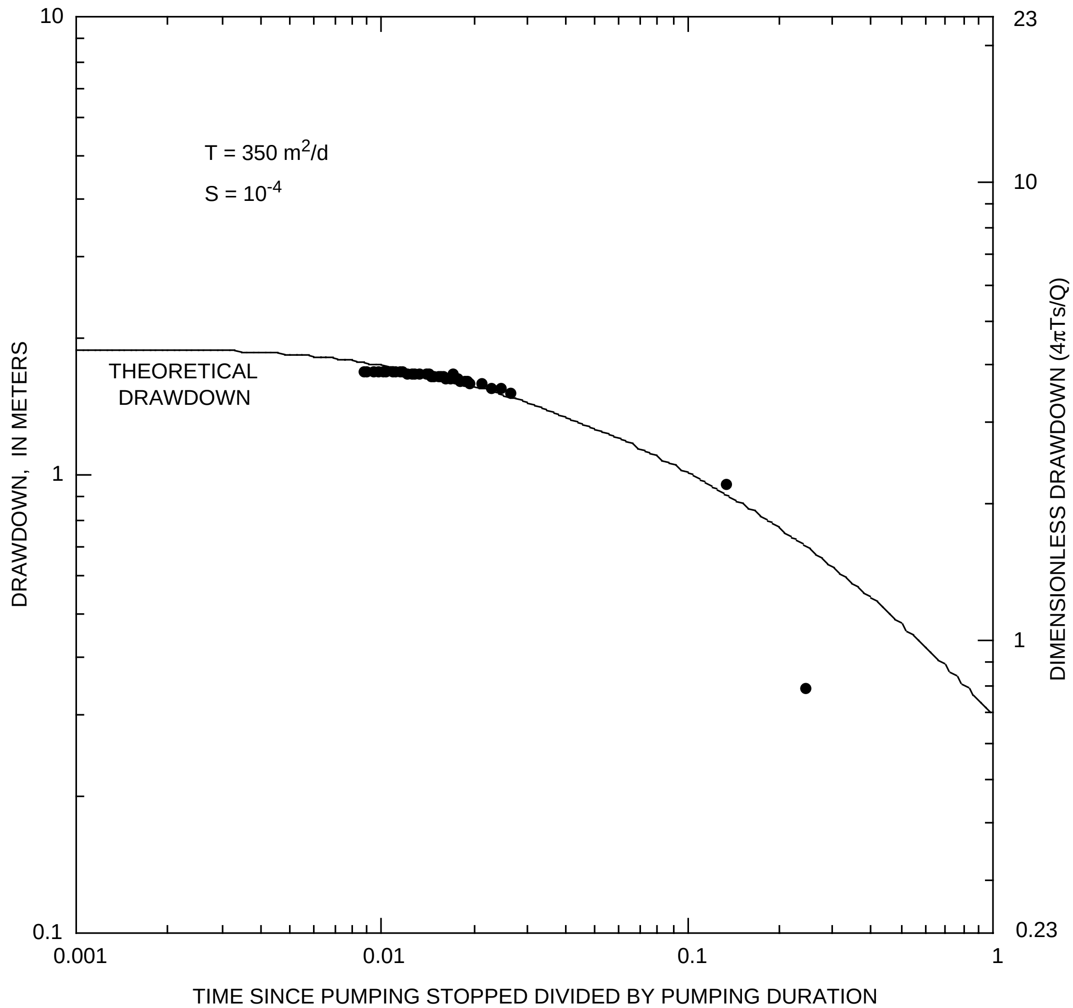


Figure 56. Drawdown during recovery in observation well Mg-876 after pumping of Mg-924 in Lansdale area, April 1980, and estimate of transmissivity (T) and storage coefficient (S) by method of Goode (1997).

Increasing drawdown consistent with response to pumping was observed in AEL Test Holes 10, Mg-1661 (AEL Test Hole 13), Mg-1662 (AEL Test Hole 16), and AEL Test Hole 17 and in Cloverdale Park Well. However, only data from Mg-1661 and Mg-1662 are analyzed in this review. The Cloverdale Park Well data are recorded on a strip chart. Drawdown during the latter part of the test was not recorded because of malfunctions in the float, pulley, or recorder system. Drawdown in AEL Test Hole 17, also recorded on a strip chart, shows steps in the data that are not consistent with gradually increasing drawdowns caused by constant-rate pumping. The initial static water level was not recorded in AEL Test Hole 10, although the water level dropped several feet in a gradual manner consistent with response to pumping.

The observed drawdown in Mg-1661 matches the Theis theory well, yielding an estimated T = 855 m^2 / d (9,200 ft^2 / d) and S = 0.06 (fig. 57). This well is approximately 6 m (20 ft) from the pumped well but is much shallower (total depth is 14 m (46 ft)). Because of its shallow depth, it is likely that the drawdown in Mg-1661 is smaller than that in the fractures or fracture-zones providing most flow to Mg-924. Hence, this T estimate is likely larger than the actual T for the deeper primary production zone(s) for Mg-924. The large S is also indicative of unconfined or water-table conditions. As with Mg-876, drawdown during recovery also matches the model reasonably well, except for the last recorded drawdown, which may reflect recharge (fig. 58). From the recovery match, the estimated T = 570 m^2 / d (6,100 ft^2 / d).

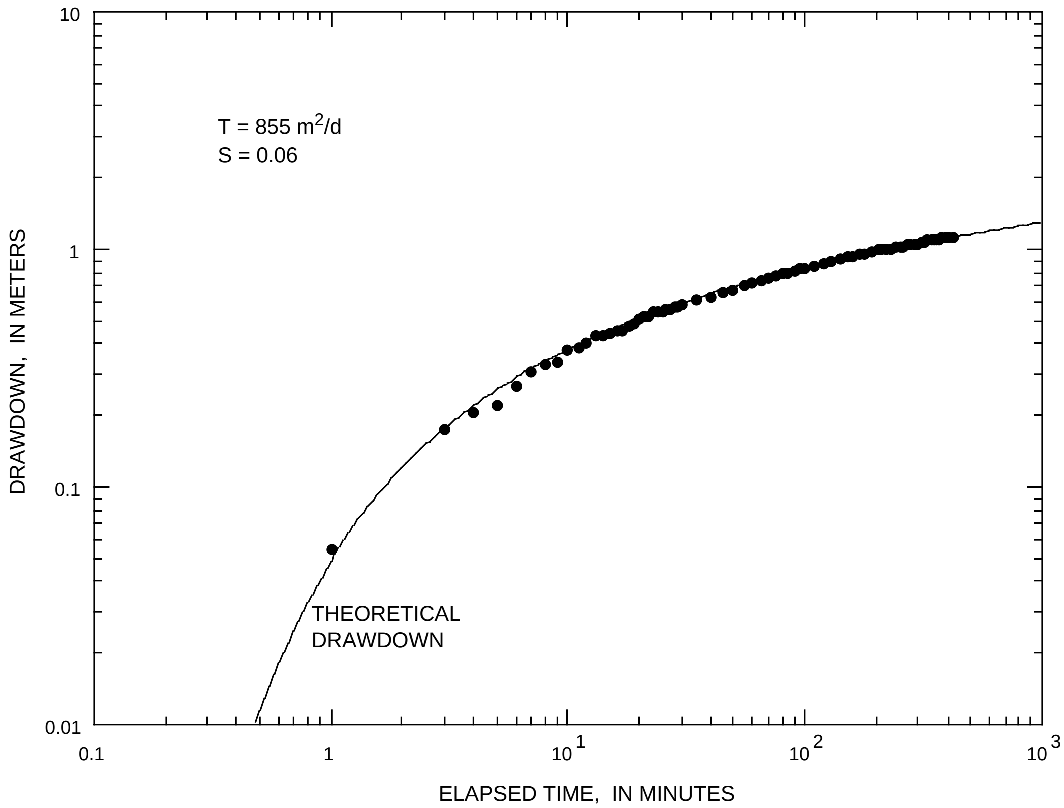


Figure 57. Drawdown in observation well Mg-1661 during pumping of Mg-924 in Lansdale area, April 1980, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

Drawdown in Mg-1662 (AEL Test Hole 16) responds later to pumping because of its large radial distance of almost 610 m (2,000 ft) from the pumped well (fig. 59), compared to Mg-1661. The Theis match to the relatively few data collected yield estimated T = 195 m^2 / d (2,100 ft^2 / d) and S = 0.001. This storage coefficient is between the values estimated from Mg-876 and Mg-1661.

The spatial pattern of drawdown (estimated for some wells) after 48 hours of pumping does not suggest planar radial flow towards the pumped well (fig. 54). The fact that the deepest observation well exhibits the largest drawdown strongly suggests a three-dimensional nature to the flow system with the primary production zone or zones at depths in the bedrock below the screened interval of most observation wells. The observed drawdowns do not exhibit an obvious anisotropic pattern.

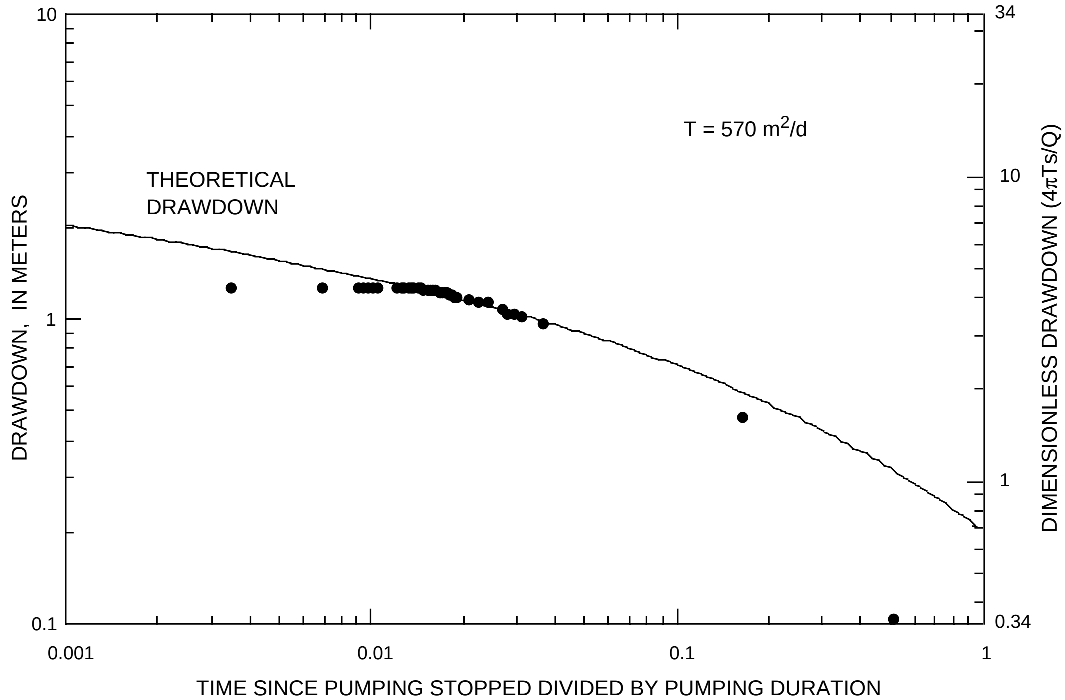


Figure 58. Drawdown during recovery in observation well Mg-1661 after pumping of Mg-924 in Lansdale area, April 1980, and estimate of transmissivity (T) by method of Goode (1997).

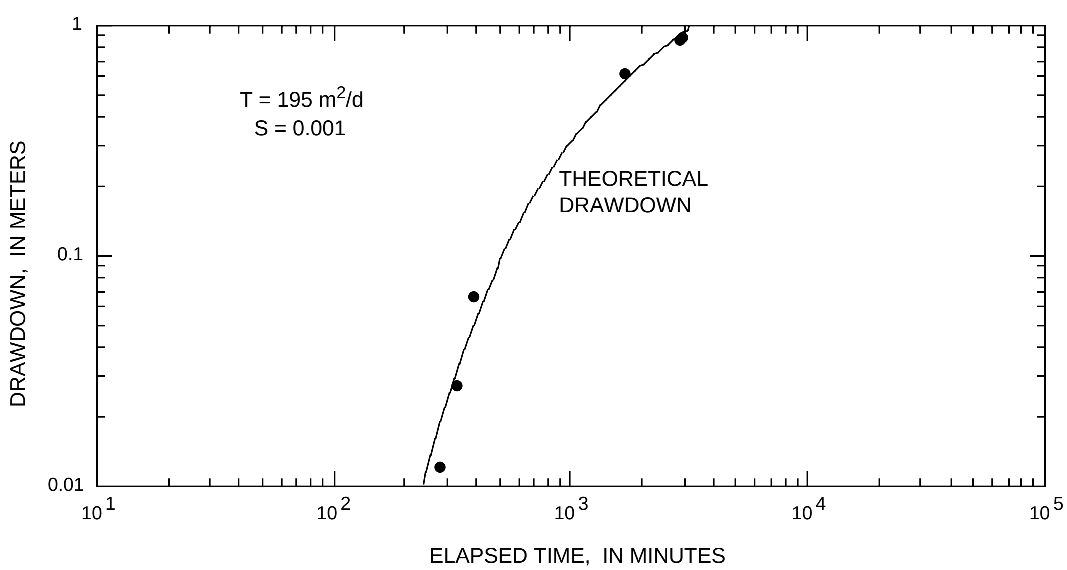


Figure 59. Drawdown in observation well Mg-1662 during pumping of Mg-924 in Lansdale area, April 1980, and estimates of transmissivity (T) and storage coefficient (S) by Theis (1935) method.

SUMMARY AND CONCLUSIONS

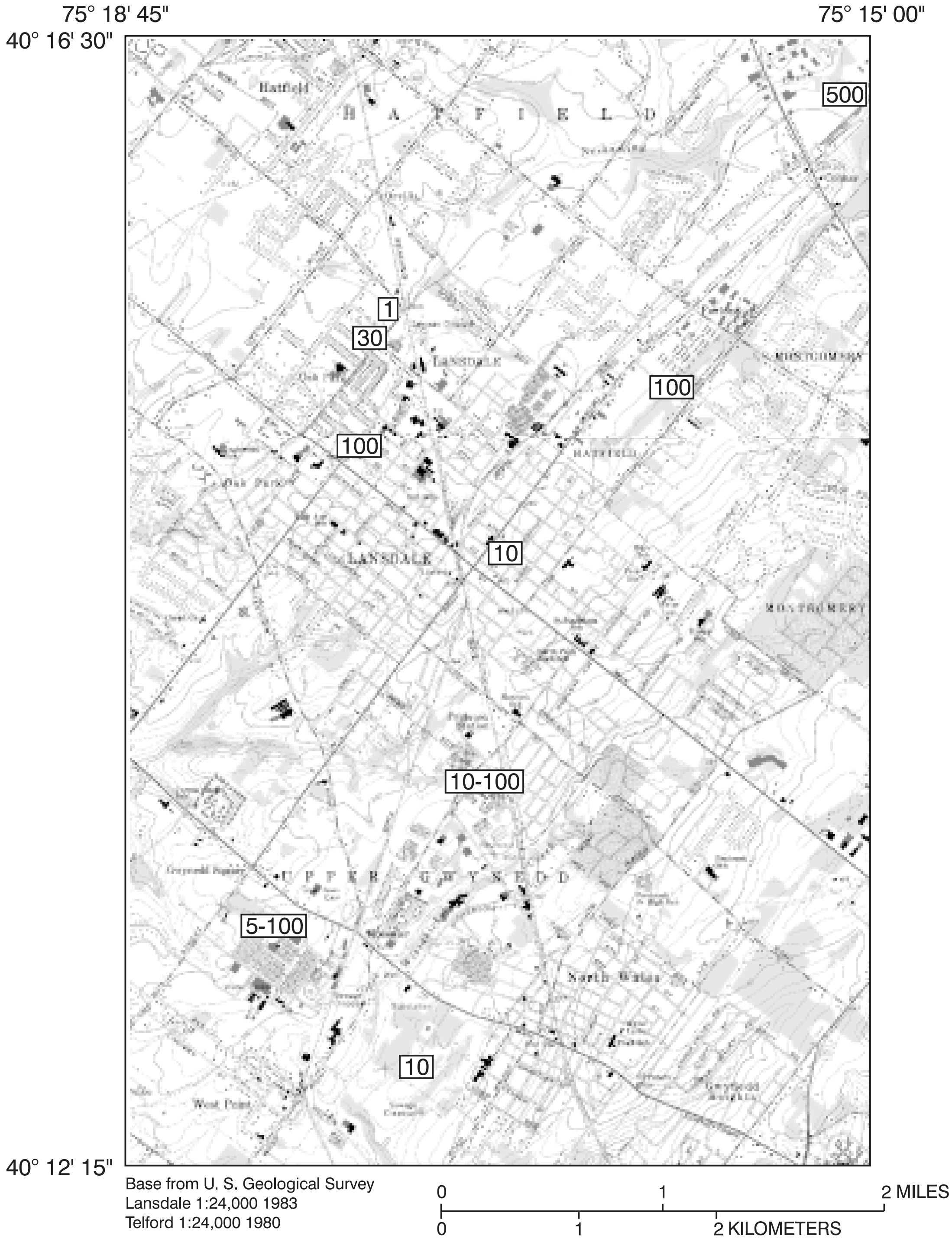
Estimated aquifer transmissivity (T) ranges from zero to about 1,300 m^2/d; most tests indicate T between 10 and 100 m^2/d (fig. 60, table 7). Drawdown data from several aquifer tests do not closely match the theoretical Theis curves, indicating that, in those cases, the assumption of radial, confined flow is not valid. Several of the test results exhibit straight-line features of half-slope on log-log plots of drawdown as a function of time; these features are commonly associated with flow in fractures.

Aquifer-isolation testing results indicate that most flow enters wells at a few discrete horizons (table 8), probably associated with fractures or bedding-plane openings. The depth of most productive zones ranged from 18 to 146 m bls, and generally productivity decreased with depth, although few data are available to evaluate depths below 150 m. The use of specific capacity to rank individual productive zones may yield a different order than ranking by transmissivity (see table 6).

Within a single borehole with multiple producing zones, the vertical hydraulic conductivity between the zones appears to be very low in many aquifer-isolation tests. This suggests a strong vertical anisotropy in hydraulic conductivity with highest values in the horizontal direction. Some evidence of well-field-scale horizontal anisotropy aligned with the assumed NE strike of bedding exists, but this evidence is considered weak because of the small number of observation wells, particularly wells screened in isolated intervals.

Analysis of water-level recovery after constant-rate aquifer tests and of drawdown during step tests (table 9), suggests that a significant fraction, perhaps as much as 85 percent, of the drawdown in pumped wells is due to well loss or skin effects in or very near the pumped well and is not caused by resistance to flow in the surrounding formations.

The hydraulic conductivity, transmissivity, and storage coefficient values estimated here approximate the properties of fractured rock in the Lansdale area. Simple aquifer-test analysis methods are used here in order to efficiently estimate properties at many locations in and around Lansdale. More accurate models of three-dimensional flow in these dipping beds could be developed to provide more detailed characterization of flow conditions at particular locations, which might be required for predictions of flow at local scales. The wide range of estimated transmissivities underscores the heterogeneity of the fractured-rock formation; hydraulic properties at new well locations cannot be accurately estimated because these properties vary by orders of magnitude over relatively small distances. The accuracy of these estimates is further reduced by limitations in this review, including the lack of antecedent and background water-level trend information, lack of accurate pumping-rate information, and generally unknown data quality. Removing these limitations would reduce uncertainties associated with these results, but it is considered unlikely that the overall regional-scale results would be significantly different.



EXPLANATION

[10] TRANSMISSIVITY, IN SQUARE METERS PER DAY

Figure 60. Distribution of transmissivity values in square meters per day estimated from review of existing well testing information in the Lansdale area.

Table 7. *Estimates of transmissivity and storage coefficient determined from open-hole aquifer tests in wells near Lansdale, Pennsylvania*

[L/min, liters per minute; m^2/d, square meters per day; r, well radius for pumped well, radial distance from pumped well for observation wells; m bls, meters below land surface; Method: C-J, Cooper-Jacob; T, Theis; R, Recovery-Theis; Rg, Recovery-Goode; Source: USGS, U.S. Geological Survey; NGI, Nittany Geosciences Incorporated, 1988a&b, 1989, 1994a&b; Weston, Roy F. Weston, Inc., 1986]

Pumped (left) and observation (right) well U.S. Geological Survey local number		Pumping rate (L/min)	Pumping duration (hours)	Method of analysis	Transmissivity (m^2/d)	Storage coefficient	r[1] (meters)	Open depth interval (m bls)	Source of analysis
Mg-67		370	48	C-J	31	0.0014	0.1	6-87	USGS
		370		T	25	.012			USGS
		370		Rg	99				USGS
	Mg-157	370		T	99	.0004	310	14-87	USGS
	Mg-162	370		T	99	.00009	366	9-232	USGS
	Mg-163	370		T	85	.00015	339	9-92	USGS
	Mg-164	370		T	85	.00013	366	9-123	USGS
	Mg-80	280	6	C-J	202			40-98	USGS
				Rg	79				USGS
	Mg-150[2]	370 280		T-2 well	150	.0004	161 56	13-123	USGS
Mg-624		45	.42	T	.53	.26	.1	26-187	
				C-J	.59	.21			USGS
Mg-625		320	4	Rg	31		.1	13-122	USGS
Mg-1125[3]		770	48	C-J	81	.007	.08-.13	18-122	USGS
		1,110	.83						
				R	127				USGS
				Rg	80				USGS
Mg-1125		770	48	C-J	120	.00002	.08-.13	18-122	USGS
	Mg-1124			strip[4]	1,300	.00004	285		USGS
	Mg-1124			T	1,150	.00005			USGS
	Mg-1126			T	580	.0002	238		USGS
	Mg-1270			T	927	.0001	189		USGS
	Mg-1124			Thiem	83		285		USGS
	Mg-1126			Thiem	78		238		USGS
	Mg-1270			Thiem	83		189		USGS
Mg-123		380	24+?						
	Mg-123			T	130	.0004	91		Weston
	Mg-123			C-J	156	.0003	91		Weston
	Mg-1658			T	98	.0002	305		Weston
	Mg-1658			C-J	143	.00014	305		Weston
	Mg-1572			T	109	.00007	283		Weston
	Mg-1572			C-J	149	.00007	283		Weston
Mg-128[5]		380	48	C-J	28; 11		.08-.15	10-134	NGI
Mg-128				R	17				NGI
	shallow[6]	380		T	75	.002		21-30	NGI
	shallow[7]	380		T-aniso	19; 292	.002		21-30	NGI
	Mg-1555	380		T	14	.0005	208	82-88	NGI
Mg-1198		265,322	step						
	N30			C-J	120	.0001	82		USGS
	N30			T	98	.0002	82		USGS
Mg-1423		270	step, 48	Rg	39		.1	24-137	USGS

Table 7. *Estimates of transmissivity and storage coefficient determined from open-hole aquifer tests in wells near Lansdale, Pennsylvania—Continued*

[L/min, liters per minute; m^2/d, square meters per day; r, well radius for pumped well, radial distance from pumped well for observation wells; m bls, meters below land surface; Method: C-J, Cooper-Jacob; T, Theis; R, Recovery-Theis; Rg, Recovery-Goode; Source: USGS, U.S. Geological Survey; NGI, Nittany Geosciences Incorporated, 1988a&b, 1989, 1994a&b; Weston, Roy F. Weston, Inc., 1986]

Pumped (left) and observation (right) well U.S. Geological Survey local number	Pumping rate (L/min)	Pumping duration (hours)	Method of analysis	Transmissivity (m^2/d)	Storage coefficient	r[1] (meters)	Open depth interval (m bls)	Source of analysis
Mg-1424	470	step, 48				0.1	25-137	
Mg-1656			C-J	44	.00001	232	97-103	USGS
Mg-924	1,510	48						
Mg-876			T	400	.0001	490		USGS
Mg-876			Rg	350	.0001			USGS
Mg-1661			T	855	.06	6		USGS
Mg-1661			Rg	570				USGS
Mg-1662			T	195	.001	600		USGS

[1] Well radii and radial distances are estimates from reports, files and maps; not measured in field.

[2] Top distance and pumping rates are for Mg-67, bottom values are for Mg-80.

[3] Top pumping rate and duration are for first part of test, bottom values for second part of test.

[4] Strip aquifer method, image wells based on Theis.

[5] First transmissivity value is for 100 - 1,500 minutes, second value is for 1,500 - 2,880 minutes.

[6] Transmissivity is effective nondirectional geometric mean; shallow zone observation wells Mg-884, Mg-1537, Mg-1538, Mg-1552, Mg-1553, Mg-1554, Mg-1556, Mg-1560, Mg-1564, and Mg-1566.

[7] First transmissivity is in minimum direction, second is in maximum direction; Shallow zone observation wells Mg-884, Mg-1537, Mg-1538, Mg-1552, Mg-1553, Mg-1554, Mg-1556, Mg-1560, Mg-1564, and Mg-1566.

Table 8. *Summary of aquifer-isolation tests in wells near Lansdale, Pennsylvania*
[--, transmissivity not estimated]

Pumped well U.S. Geological Survey local number (other identifier)	Depth of open hole (meters)	Specific capacity of open hole or total of zones (square meters per day)	Depth of most productive zone (meters)	Specific capacity of most productive zone (percent of total) (square meters per day)	Transmissivity of most productive zone (square meters per day)	Transmissivity method
Mg-67	89	85	21-27	28.3 (33)	8.6	Theis
Mg-68	152	77	31-37	34.5 (45)	--	
Mg-89	147	16	19-54	13.2 (83)	8.1	Theis
Mg-90	151	12.3	18-52	7.8 (63)	--	
Mg-135	146	13	109-146	6.8 (50)	6.2	Cooper-Jacob
Mg-147	139	81	19-44	48.0 (60)	22	Theis
Mg-151	137	99	12-46	83.0 (84)	--	

Table 9. *Estimates of well loss determined from step tests and recovery analyses in wells near Lansdale, Pennsylvania*
[Data sources: NPWA, North Penn Water Authority files, Lansdale Pa.; NGI, Nittany Geosciences Incorporated, 1988a&b, 1989, 1994a&b]

Pumped well U.S. Geological Survey local number (other identifier)	Pumping rates (Liters/minute)				Duration of each step (minutes)	Maximum drawdown (meters)	Well loss, percent of drawdown	Source of data
Step tests								
Mg-1125	380	770	1,100		60	27	65	NPWA
Mg-1198	265	322			120	32	75	NGI
Mg-1199	113	155	265	300	100	12	50	NGI
Mg-1423	125	165	220	270	60	9.3	80	NGI
Recovery analyses								
Mg-67		370			17,280	20	85	EPA
Mg-80		270			360	12	75	EPA
Mg-625		320			360	35	70	EPA

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