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Ground-Water System, Estimation of Aquifer Hydraulic Properties, and Effects of Pumping on Ground-Water Flow in Triassic Sedimentary Rocks in and near Lansdale, Pennsylvania

by Lisa A. Senior and Daniel J. Goode

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CONVERSION FACTORS AND ABBREVIATIONS

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
<u>Length</u>		
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
<u>Area</u>		
acre	0.4047	hectare
square mile (mi ²)	2.590	square kilometer
<u>Mass</u>		
pound, avoirdupois (lb)	0.4536	kilogram
<u>Temperature</u>		
degree Fahrenheit (°F)	$^{\circ}\text{C} = 5/9 \times (^{\circ}\text{F} - 32)$	degree Celsius
<u>Other Abbreviations</u>		
μg/L	micrograms per liter	
mg/L	milligrams per liter	

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.

GROUND-WATER SYSTEM, ESTIMATION OF AQUIFER HYDRAULIC PROPERTIES, AND EFFECTS OF PUMPING ON GROUND-WATER FLOW IN TRIASSIC SEDIMENTARY ROCKS IN AND NEAR LANSDALE, PENNSYLVANIA

by Lisa A. Senior and Daniel J. Goode

ABSTRACT

Ground water in Triassic-age sedimentary fractured-rock aquifers in the area of Lansdale, Pa., is used as drinking water and for industrial supply. In 1979, ground water in the Lansdale area was found to be contaminated with trichloroethylene, tetrachloroethylene, and other man-made organic compounds, and in 1989, the area was placed on the U.S. Environmental Protection Agency's (USEPA) National Priority List as the North Penn Area 6 site. To assist the USEPA in the hydrogeological assessment of the site, the U.S. Geological Survey began a study in 1995 to describe the ground-water system and to determine the effects of changes in the well pumping patterns on the direction of ground-water flow in the Lansdale area. This determination is based on hydrologic and geophysical data collected from 1995-98 and on results of the simulation of the regional ground-water-flow system by use of a numerical model.

Correlation of natural-gamma logs indicate that the sedimentary rock beds strike generally northeast and dip at angles less than 30 degrees to the northwest. The ground-water system is confined or semi-confined, even at shallow depths; depth to bedrock commonly is less than 20 feet (6 meters); and depth to water commonly is about 15 to 60 feet (5 to 18 meters) below land surface. Single-well, aquifer-interval-isolation (packer) tests indicate that vertical permeability of the sedimentary rocks is low. Multiple-well aquifer tests indicate that the system is heterogeneous and that flow appears primarily in discrete zones parallel to bedding. Preferred horizontal flow along strike was not observed in the aquifer tests for wells open to the pumped interval. Water levels in wells that are open to the pumped interval, as projected along the dipping stratigraphy, are drawn down more than water levels in wells that do not intersect the pumped interval. A regional potentiometric map based on measured water levels indicates that ground water flows from Lansdale towards discharge areas in three drainages, the Wissahickon, Towamencin, and Neshaminy Creeks.

Ground-water flow was simulated for different pumping patterns representing past and current conditions. The three-dimensional numerical flow model (MODFLOW) was automatically calibrated by use of a parameter estimation program (MODFLOWP). Steady-state conditions were assumed for the calibration period of 1996. Model calibration indicates that estimated recharge is 8.2 inches (208 millimeters) and the regional anisotropy ratio for the sedimentary-rock aquifer is about 11 to 1, with permeability greatest along strike. The regional anisotropy is caused by up- and down-dip termination of high-permeability bed-oriented features, which were not explicitly simulated in the regional-scale model. The calibrated flow model was used to compare flow directions and capture zones in Lansdale for conditions corresponding to relatively high pumping rates in 1994 and to lower pumping rates in 1997. Comparison of the 1994 and 1997 simulations indicates that wells pumped at the lower 1997 rates captured less ground water from known sites of contamination than wells pumped at the 1994 rates. Ground-water flow rates away from Lansdale increased as pumpage decreased in 1997.

A preliminary evaluation of the relation between ground-water chemistry and conditions favorable for the degradation of chlorinated solvents was based on measurements of dissolved-oxygen concentration and other chemical constituents in water samples from 92 wells. About 18 percent of the samples contained less than or equal to 5 milligrams per liter dissolved oxygen, a concentration that indicates reducing conditions favorable for degradation of chlorinated solvents.

INTRODUCTION

Ground water in the area of the Borough of Lansdale has been withdrawn since the early 20th century for use as drinking water and for industrial supply. In 1979, water from public-supply wells in the area was found to be contaminated with trichloroethylene (TCE), tetrachloroethylene (PCE), and other synthetic organic compounds (CH2MHill, 1991). Through additional sampling, an area of ground-water contamination was identified, and the site, known as North Penn Area 6, was placed on the National Priority List (NPL) by the U.S. Environmental Protection Agency (USEPA). The North Penn Area 6 site encompasses about 3 mi² (2.6 km²) and includes at least six sources of contamination on separately-owned properties largely within the borough of Lansdale (CH2M Hill, 1991). The site is located on the U.S. Geological Survey (USGS) Lansdale and Telford 7.5-minute topographic quadrangle maps (fig. 1, pl. 1).

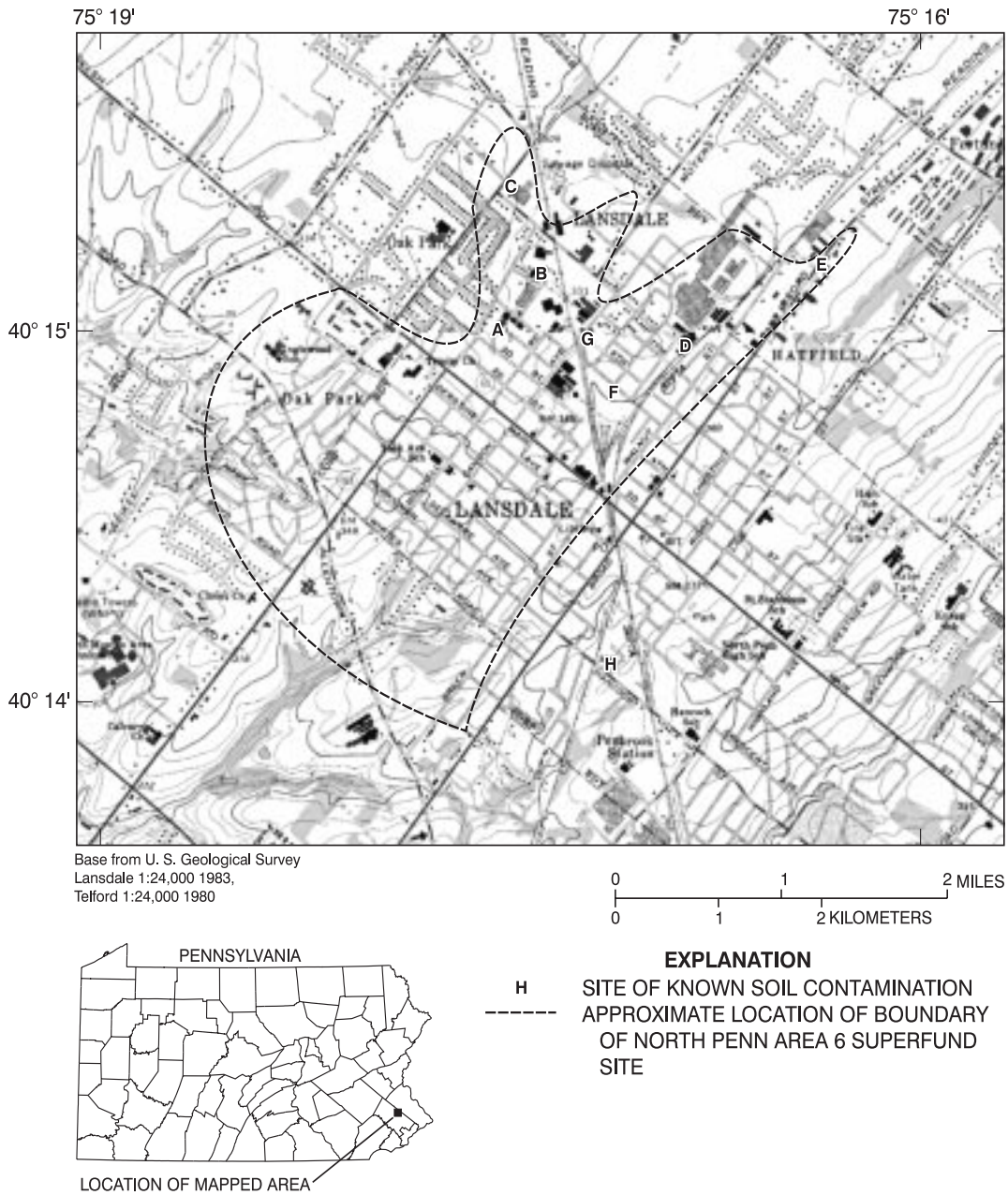


Figure 1. Location of North Penn Area 6 site, Lansdale, Pa.

Since 1995, abandonment of public-supply wells in favor of an alternative surface-water supply and closure of industrial facilities has changed the location and rate of ground-water withdrawals in Lansdale. The USEPA, concerned about contaminant migration, requested that the USGS determine the effects of these changes in water use on the direction of ground-water flow. In 1996, the USGS began a study to describe the ground-water system and simulate ground-water flow on a regional scale by use of a numerical model. This work was done to assist the USEPA in preparing a remedial investigation and feasibility study (RI/FS) of the North Penn Area 6 site.

The North Penn Area 6 site initially included about 26 industrial properties. Some industries in the area have operated since the 1940's, whereas others began operating as recently as the 1980's. Various solvents, degreasers, and other types of organic compounds were used by these industries and most commonly include PCE, TCE, and 1,1,1-trichloroethane (1,1,1-TCA). The organic compounds PCE and TCE may break down in microbially mediated reactions to form various additional compounds, including cis-1,2-dichloroethylene (cis-1,2-DCE) and vinyl chloride (VC) (Bouwer and others, 1981; Vogel and McCarty, 1985). The break-down compounds cis-1,2-DCE and VC also have been detected in ground water in Lansdale. Although most ground-water contamination in the Lansdale area is due to organic compounds, metals were used in some industrial processes, and chromium has been detected in ground water beneath at least one property.

In 1979, TCE was measured in concentrations greater than 4.5 µg/L in eight North Penn Water Authority (NPWA) public-supply wells in and near Lansdale. The USEPA maximum contaminant level to minimize health risks in drinking water is 5 µg/L for TCE. After the discovery of TCE in water from the public-supply wells, ground-water sampling and site assessments were conducted by USEPA and others. In 1986, the USEPA requested information about solvent use from 17 industries in the area, and in 1989, residential wells were sampled by CH2MHill (CH2MHill, 1991). The North Penn Area 6 site was placed on the NPL (commonly referred to as a Superfund site) in 1989. Environmental investigations by property owners, the Pennsylvania Department of Environmental Protection (PADEP) and by USEPA and its contractors indicate ground water beneath the Borough of Lansdale is contaminated with volatile organic compounds (VOC's). Concentrations of TCE as great as 9,240 µg/L were measured in water samples from public-supply wells (CH2MHill, 1991). VOC's also were detected in ground-water samples from industrial and domestic wells and in surface-water samples from a tributary to West Branch Neshaminy Creek (fig. 1). A RI/FS was initiated by the USEPA and its contractor, CH2MHill, in 1991. Since 1994, the USEPA through its contractor, Black & Veatch Waste Science, Inc. (B&V), and individual property owners have conducted soil sampling to determine the extent of contaminant sources (Black & Veatch Waste Science, Inc. 1994; Gregory Ham, U.S. Environmental Protection Agency, written commun., 1997); the USEPA also coordinated ground-water sampling in spring 1995, winter 1996, and fall 1997 to determine the extent of ground-water contamination. In consultation with USGS, 26 additional monitor wells were drilled by USEPA's contractor (B&V) in Lansdale during the summer of 1997; these and other wells were sampled in fall 1997. Concentrations of TCE as high as 13,000 µg/L were measured in shallow monitor wells during fall 1997 (Black & Veatch Waste Science, Inc., 1998).

Purpose and Scope

This report describes the ground-water system and presents results of numerical simulation of ground-water flow in the area of the North Penn Area 6 site, Lansdale, Pa. All hydrologic and geologic data collected by USGS during the 3-year (1996-99) investigation in and near Lansdale are summarized in this report; these data include geophysical logs and measurements of stream base flow, water levels in wells, chemical and physical properties of ground-water samples, and responses of water levels in wells to aquifer tests. Aquifer characteristics are defined. Ground-water flow directions, capture zones for streams and wells, and flowpaths from known sources of contamination in soil are presented for simulations under three different pumping conditions.

Previous Work

Ground-water studies in the Lansdale area have been prompted by concern about limited ground-water availability during periods of drought, by discovery of contaminated drinking water from public-supply wells, and by interest in commercial and industrial uses of the ground water. Rima (1955), Longwill and Wood (1965), and Newport (1971) provide well-characteristic and ground-water-quality data and a description of ground-water resources in Montgomery County, Pa., including the Lansdale area. Longwill and Wood (1965) compiled a geologic map, that in the Lansdale area, was based almost entirely on unpublished manuscripts by Dean B. McLaughlin. Lytle

and Epstein (1987) compiled a geologic map of the Newark $1^{\circ} \times 2^{\circ}$ quadrangle that updates and revises the geologic nomenclature for the area. Biesecker and others (1968) described the water resources of the Schuylkill River Basin, which drains part of the Lansdale area.

Investigations of ground-water contamination after 1979 by NPWA, USEPA, and others are summarized in a report to the USEPA by CH2MHill (1991). Sources of ground-water contamination in North Penn Area 6 site are identified additionally in another report to the USEPA by B&V (1994). Results of aquifer-interval isolation (packer) tests of two NPWA wells for hydraulic properties and water quality are given in Sutton (1983; 1984). Goode and Senior (1998) present a review of aquifer tests done in the Lansdale area from 1980 through 1995, including tests done in industrial-supply wells at manufacturing facilities, in public-supply wells, and in monitor wells at sites of known or suspected ground-water contamination.

Acknowledgments

The cooperation of well owners who made their wells accessible for water sampling, water-level measurements, and geophysical logging is greatly appreciated, especially those owners that allowed repeated sampling or continued monitoring of their wells. The well owners include North Penn Water Authority; J.W. Rex Company; John Evans & Sons Company; Philadelphia Toboggan Company; Rogers Mechanical; American Olean Tile; Dal Tile; North Penn Feed; Lehigh Valley Dairy; Merck, Sharpe and Dohme; Angelo Brugnoli; and residents in areas in and near Lansdale. Steve Siegfried, Craig Forwood, and Terry Gable of NPWA, Austin Race of Lehigh Valley Dairy, and Jason Szeftcak of Merck are recognized for providing information about aquifer tests and other hydrologic data, as well as assistance in conducting field work. The technical guidance and coordination by Gregory Ham and Kathy Davies of USEPA was essential to the study. The cooperation of USEPA's contractor, B&V, also was integral to geophysical logging of new monitor wells, disposal of wastewater from aquifer tests, and other aspects of the study. The cooperation of J.W. Rex's consultant, QSI, Inc., is also appreciated.

Roger Morin of USGS provided analyses of acoustic televiewer and other geophysical data for selected wells. Other USGS staff contributing to the project include Randall Conger, Kenneth Eden, Phillip Bird, Kevin Grazul, Robert Rossman, Nicholas Smith, and Cynthia Lesitsky. The assistance of student interns and volunteers at the USGS, including David Prieto, Valerie Holliday, Ben Skupp, and Carrie Stevenson, also is appreciated.

GEOLOGIC SETTING

The study area in and near Lansdale is in the Gettysburg-Newark Lowlands Section of the Piedmont Physiographic Province. The North Penn Area 6 site and surrounding area are underlain by sedimentary rocks of the Lockatong Formation and lower beds of the Brunswick Group of the Newark Supergroup (Lyttle and Epstein, 1987) (fig. 2). Sediments of the Newark Supergroup were deposited in a rift basin during the Triassic age (260 million years ago). Following deposition, sediments in the Newark Basin were buried, compacted, and faulted. 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 North Penn Area 6 site 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 (figs. 1 and 2).

Lithology

The Lockatong Formation consists of detrital sequences (cycles) of gray to black calcareous shale and siltstone, with some pyrite, and chemical sequences (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). Interbeds of reddish-brown, sandy siltstone have been mapped in the Lockatong Formation south of Lansdale (Lyttle and Epstein, 1987). The Lockatong Formation overlies the Stockton Formation, which consists of gray to reddish-brown sandstones, shales, and siltstones. Contacts between the Lockatong Formation and the overlying Brunswick Group are conformable and gradational, and the two formations may interfinger (Lyttle and Epstein, 1987). 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, with some fine-grained sandstones and siltstones. Bedding is irregular and wavy. Some beds are micaceous. Interbedded silt-shales and siltstones are moderately well sorted. Mudcracks, ripple marks, crossbeds, and burrows are common in all of the beds. The Brunswick Group rocks contain

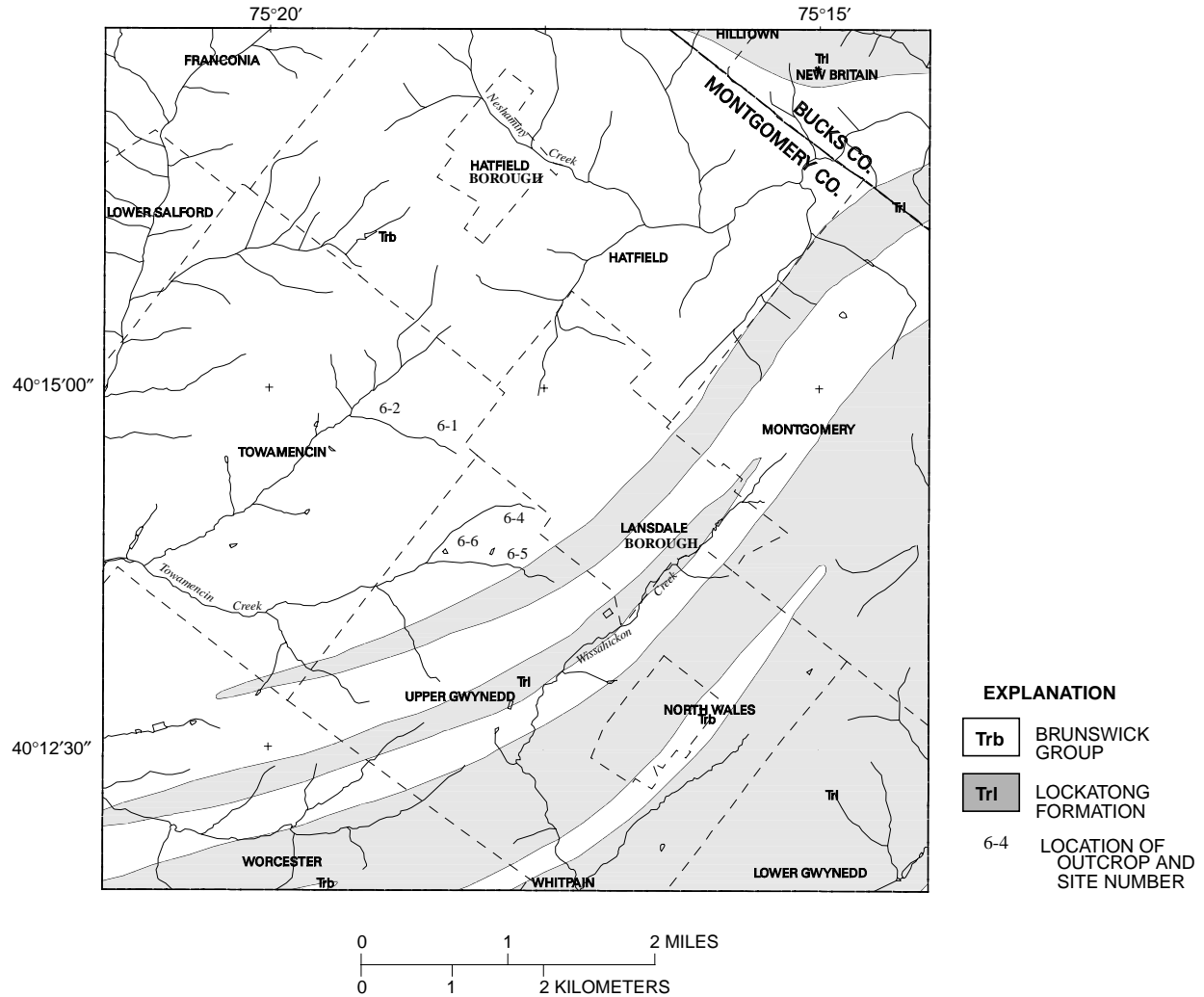


Figure 2. Bedrock geology in area of Lansdale, Pa.

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.

Examples of a driller's log describing lithology of the Triassic-age sedimentary rocks from well cuttings and corresponding geophysical logs are shown for well Mg-1604 in figure 3. Red-brown shale, red-brown sandstone, and gray shale are the most frequently reported rock types in drillers' logs for monitor wells drilled in 1997 (Black & Veatch Waste Science, Inc., written commun., 1997). The large gamma-activity near 80 ft is associated with dark gray shale in well Mg-1604. Increased resistance near 215 ft is associated with red-brown sandstone in the well (fig. 3).

Structure

Bedding in the Newark Basin generally strikes northeast and dips to the northwest. The regional homoclinal dip has been cut by normal and strike-slip faults and warped by transverse folds (Schlische, 1992). Many faults with small displacements have not been mapped. The beds of the Brunswick Group and Lockatong Formation generally strike northeast and dip shallowly to the northwest in the vicinity of the North Penn Area 6 site, with a gradual shift in strike from northeast in central Lansdale to east-northeast in the area south of Lansdale near North Wales (fig. 2) (Longwill and Wood, 1965).

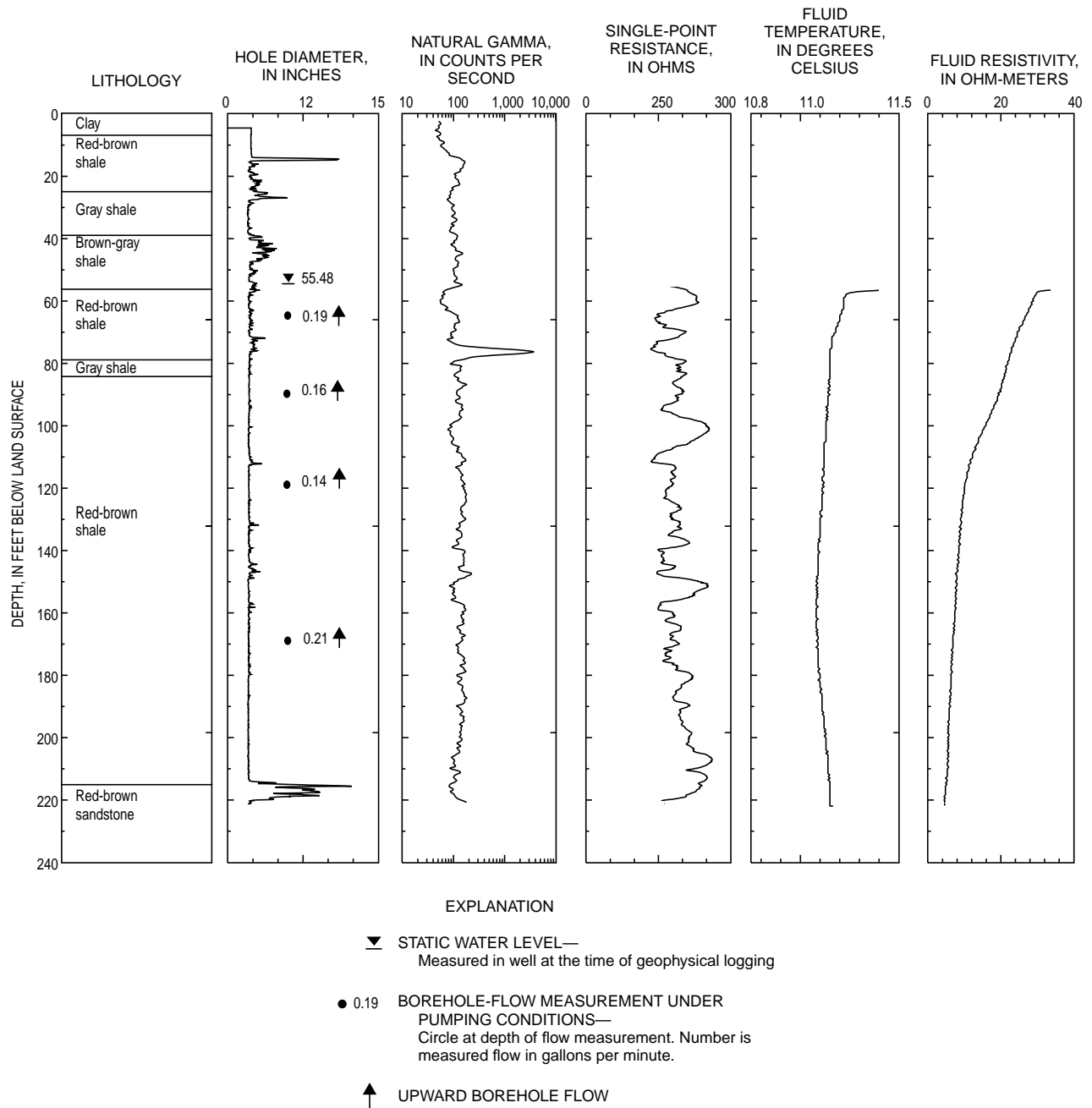


Figure 3. Lithology of well cuttings and geophysical logs for well Mg-1604 in Lansdale, Pa.

Thin shale marker beds in the Brunswick Group identified by elevated natural-gamma activity on geophysical logs can be correlated over distances of 1,000 ft or more (300 m or more). High natural-gamma activity typically is associated with thin gray shale beds. Correlation of natural-gamma activity in logs collected by USGS in and near Lansdale show that these shale beds strike 48° to 60° northeast and dip 6° to 30° northwest; the average dip is about 11° (fig. 4) (Conger, 1999). Examples of correlations of natural-gamma logs (fig. 5) from selected wells in central Lansdale Borough (near Third and Main Streets) indicate that bedding strikes about 56° northeast and dips about 7° northwest in that area.

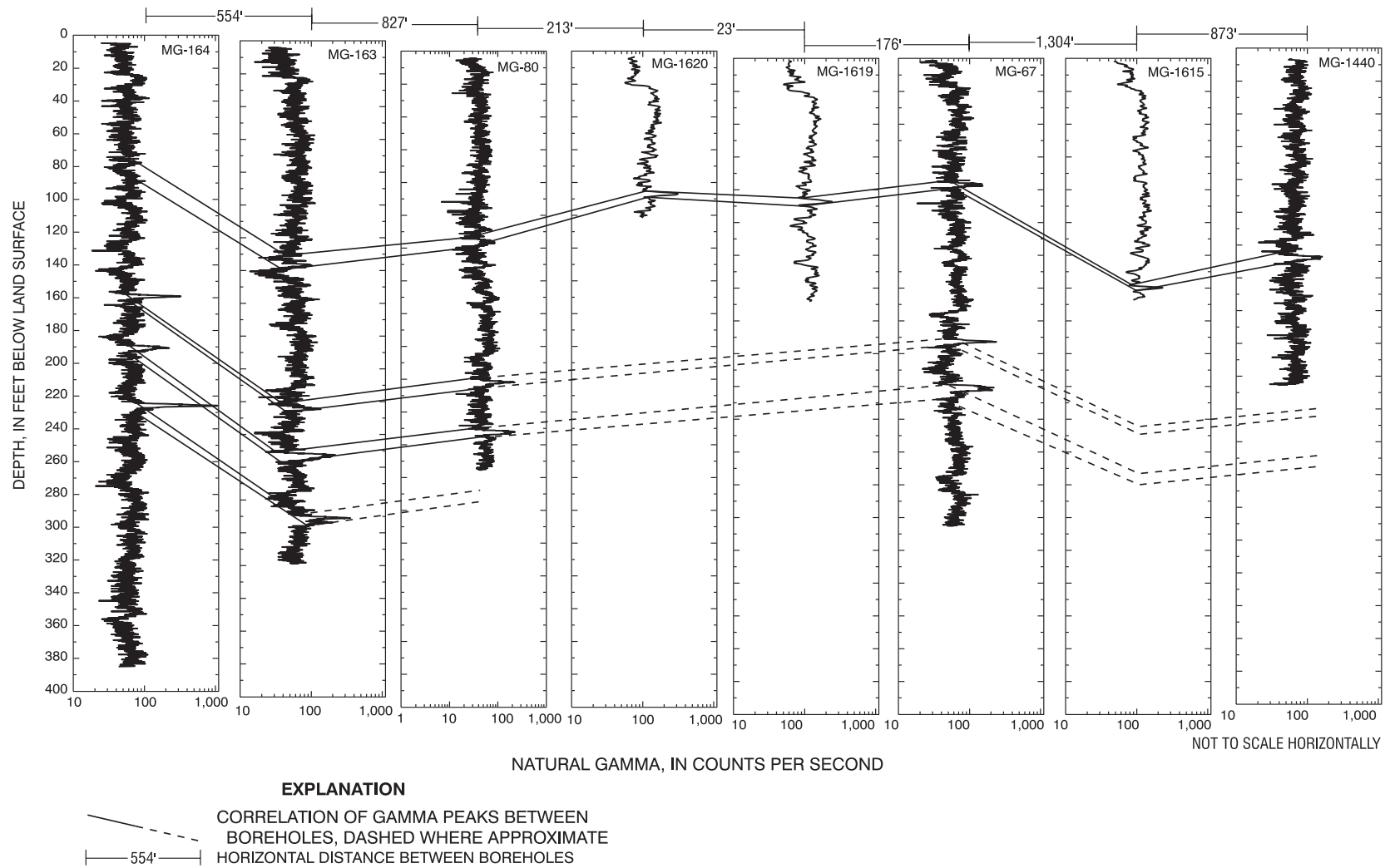


Figure 4. Natural-gamma-log correlations for wells Mg-164, Mg-163, Mg-80, Mg-1620, Mg-1619, Mg-67, Mg-1615, and Mg-1440 in Lansdale, Pa.

Fractures

Longwill and Wood (1965) noted the presence of well-developed fracture systems in many beds of the Brunswick Group. They observed that the strike of the fracture sets appears to be independent of bedding orientation; most fractures are nearly vertical and average about 6 in. (153 mm) apart. The width of fracture openings in individual beds varies. Greenleaf (1996) measured the orientation of more than 150 fractures at outcrops exposed in streams at four sites in the Lansdale area. The strike of fracture sets measured by Greenleaf (1996) commonly ranged from 60° to 70°, 45° to 50°, and 140° to 160°; many fractures are nearly orthogonal to bedding. High-angle fracture sets (vertical or near-vertical fractures) strike northeast to northwest and dip to the southeast and southwest, respectively. Plots of poles to fracture planes determined by Greenleaf (1996) are shown in figure 5. Low-angle fractures (bedding) strike northeast to southeast and dip to northwest and northeast, respectively (fig. 5). The pole of

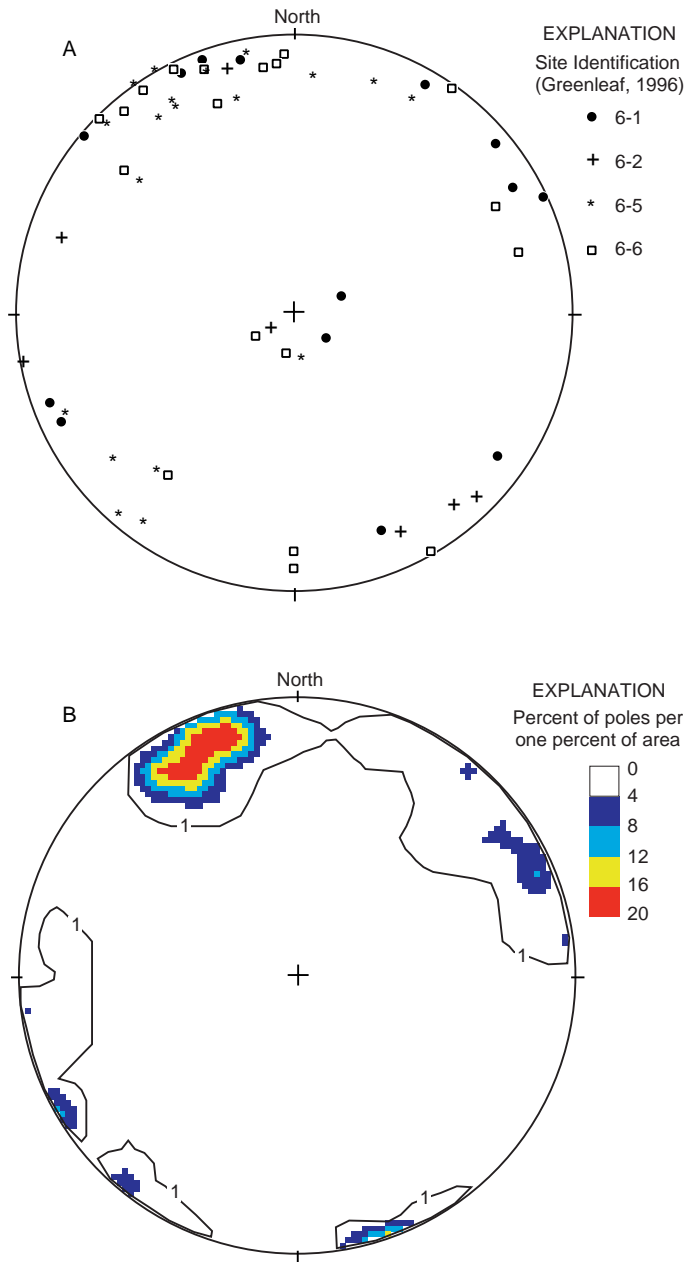


Figure 5. Equal-area, lower-hemisphere plots of poles to fracture planes determined from outcrop measurements at (A) four stream sites in and near Lansdale, Pa., and at (B) one stream site in Whites Road Park, Lansdale, Pa. (Greenleaf, 1996). Individual fracture plane poles are plotted for (A), and 86 fracture plane poles are contoured in (B). See figure 2 for location of stream sites.

each fracture plane is a line perpendicular to the fracture plane. The intersection of the fracture poles with an equal-area projection of a lower hemisphere (Ramsey, 1967) is shown in figure 5; horizontal and subhorizontal fractures are represented by points near the center of the circle, and near-vertical fractures plot near the perimeter of the circle.

Acoustic televiewer logs run in seven boreholes in and near Lansdale indicate many of the features identified appear to be bedding-plane partings that strike about 48° northeast and dip about 11° northwest (R. Morin, U.S. Geological Survey, written commun., 1998). Other features appear to be high-angle fractures that also strike to the northeast but dip to the southeast (fig. 6).

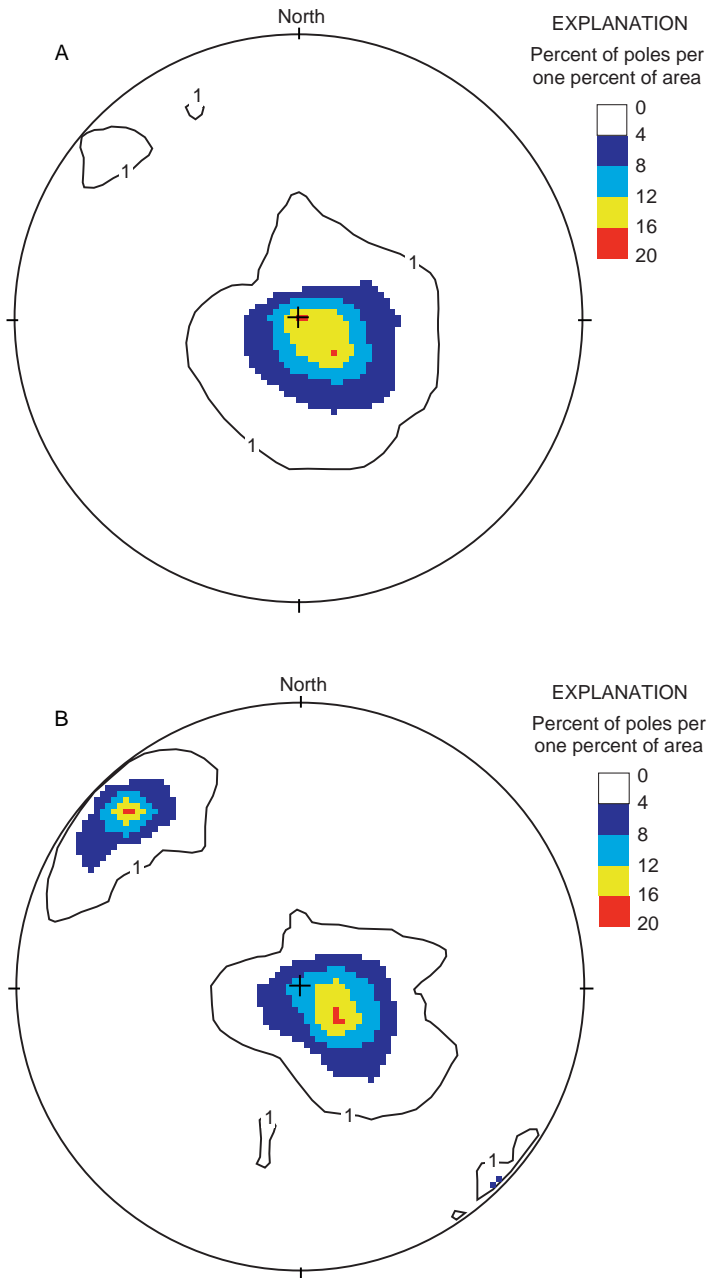


Figure 6. Equal-area, lower-hemisphere contours of poles to fracture planes measured by acoustic televiewer in wells in Lansdale, Pa., for (A) 698 fractures above 400 feet, and (B) 181 fractures below 400 feet below land surface.

GROUND-WATER SYSTEM

Ground water in the rocks underlying Lansdale and the North Penn Area 6 site originates from infiltration of local precipitation. After infiltrating through soil and saprolite (extensively weathered rock), the water moves through near-vertical and horizontal fractures in the shale and siltstone bedrock. Depth to bedrock is commonly less than 20 ft (6 m) below land surface. The soil, saprolite, and individual beds of the sedimentary bedrock form a layered aquifer, with varying degrees of hydraulic connection between the layers. Hydraulic properties of the soil, saprolite, and individual beds of the underlying sedimentary bedrock differ. Primary porosity, permeability, and storage in the Triassic-age sedimentary bedrock is very low.

Water in the shallowest part of the sedimentary-rock aquifer may be under unconfined (water table) or partially confined conditions; the unconfined part of the aquifer is thin and is difficult to delineate. In some areas, perched water is present at shallow depths [less than 50 ft (15 m)]; in the deeper part of the aquifer, water generally is confined or partially confined, resulting in artesian conditions.

Shallow and deep ground-water-flow systems may be present at the site. Water from the shallow system likely discharges locally to streams and leaks downward to the deep system. Deep and shallow ground water generally flows in a direction similar to the topographic gradient. Deep ground water discharges to streams and to pumping wells. The natural direction of shallow and deep ground-water flow is altered by pumping, and pumping from deep zones may induce downward flow from shallow zones. In the Triassic-age sedimentary rocks of the Brunswick Group and the Lockatong Formation, cones of depression caused by pumping have been observed to extend preferentially along strike of bedding planes or in the direction of fracture orientation (Longwill and Wood, 1965).

The conceptual model of the ground-water system in the study area consists of dipping, layered fractured rocks with ground-water flow within partings developed primarily along bedding planes. Vertical fractures generally do not cut extensively across beds but may provide local routes of ground-water flow or leakage between beds (fig. 7).

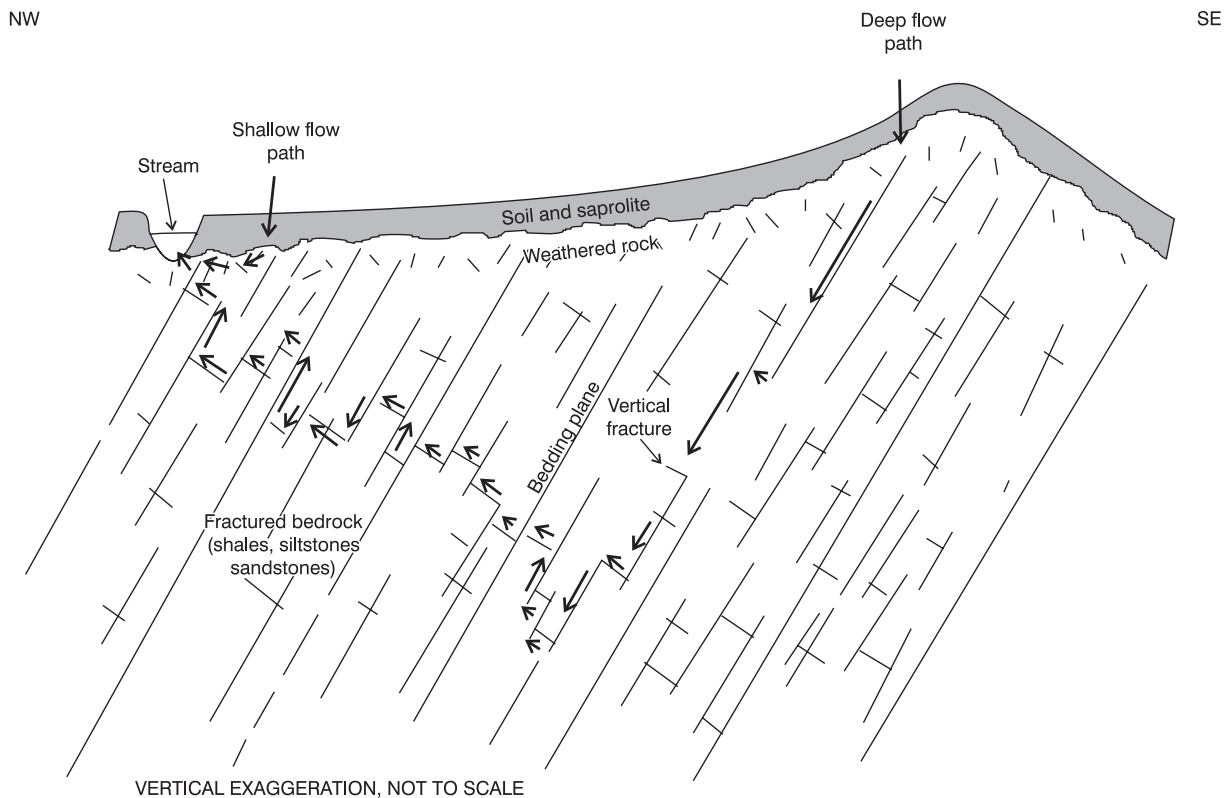


Figure 7. Conceptual ground-water flow system in a fractured sedimentary-rock aquifer with dipping beds.

Recharge

Recharge to areas underlain by shales, siltstones, and sandstones of the Newark Basin tends to be lower than recharge to other areas of the Piedmont in southeastern Pennsylvania. Recharge estimates to areas underlain by the Triassic sedimentary rocks of the Newark Basin range from 6 to 12 in. (153 to 305 mm) (Sloto and Schreffler, 1994). The permeability of soils, saprolite, and underlying bedrock of the Triassic sedimentary rocks of the Newark Basin probably is lower than in areas underlain by other rocks in the Piedmont.

Measurements of base flow (ground-water discharge to streams) commonly are used to estimate recharge. White and Sloto (1990) report that base flow in two areas underlain by Triassic sedimentary rocks in the Piedmont in southeastern Pennsylvania averaged 5.9 to 7.9 in. (150 to 200 mm) over a 13-year period from 1959 to 1972. In the Lansdale area, ground-water discharge to streams is reduced by ground-water pumping, therefore, recharge can be estimated by summing base flow and ground-water pumpage, as discussed in the section on “Numerical Simulation of Regional Ground-Water Flow.”

Water-Bearing Zones

Water-bearing zones in the shales, silstones, and sandstones underlying Lansdale are discrete fractures. These fractures have been identified in boreholes using drillers’ logs and (or) a combination of geophysical logs (caliper, fluid resistivity, and fluid temperature), heatpulse-flowmeter measurements, and borehole television surveys. The depth of water-bearing fractures determined by a series of flowmeter measurements in a borehole may differ from that reported from drillers’ logs, in part because of differences in pumping rates. Pumping rates during drilling, which typically are much higher than rates maintained during heatpulse-flowmeter measurements, can enhance development of water-bearing fractures at and above the depth of drilling and make the actual depth of water-bearing zones difficult to determine.

Fractures are identified from caliper logs, acoustic televiewer images, or borehole television surveys, and water-producing zones are identified using a combination of caliper logs, fluid-resistivity logs, and heatpulse-flowmeter measurements. Water-bearing fractures can produce or receive (thieve) water. Changes in slope with depth of the fluid-temperature or fluid-resistivity logs can indicate the presence of water-bearing fractures. From the heatpulse-flowmeter measurements, changes in vertical borehole flow can indicate the presence of water-bearing fractures. Where increases in flow rates are measured, fractures are contributing water to the well; where decreases in flow rates are measured, fractures are receiving water. Wells with intra-borehole flow must have both producing and receiving zones. Examples of geophysical logs that can be used identify water-bearing zones (fractures) in three wells with different flow patterns in Lansdale are shown in figures 8-10. Under nonpumping conditions, downward flow only was measured in well Mg-164 (fig. 8), upward flow only was measured in well Mg-69 (fig. 10), and upward and downward flow were measured in well Mg-68 (fig. 9). Both inflow at producing zones and outflow at receiving zones could be estimated from heatpulse-flowmeter measurements and geophysical logs for wells Mg-68 and Mg-69 (figs. 9 and 10); inflow only was determined for well Mg-164 (fig. 8). A complete description of borehole geophysical logs done by USGS in 62 wells in and near the North Penn Area 6 site, Lansdale, Pa., is given by Conger (1999).

Some fractures transmit more water than others. The relative productivity of fractures can be determined by use of the heatpulse flowmeter under pumping conditions. The transmissivity of water-bearing zones can be determined quantitatively using controlled tests, such as the aquifer-interval-isolation tests (packer tests) done by USGS on three wells in Lansdale and described in detail in the section on “Single-Well, Interval-Isolation Tests.” The flowmeter measurements probably show the location of only the most productive zones and may not detect all water-bearing zones. The drillers’ logs of monitor wells drilled in 1997 indicate many of the most productive zones in wells are associated with sandstone rather than shale beds (Black & Veatch Waste Science, Inc., 1998). In well Mg-1604 (fig. 3), the primary water-bearing fractures appear to be in the sandstone contact with the overlying shale near the bottom of the hole.

Thirty-one existing industrial, commercial, public-supply, and observation wells in and near Lansdale were included in analysis of heatpulse-flowmeter measurements. Twenty-eight monitor wells drilled in 1997 were excluded from this analysis because most were shallow [less than 150 ft (46 m)] in depth and many lacked heatpulse-flowmeter measurements under pumping conditions. The 31 wells ranged in depth from 144 to 1,027 ft (43.9 to 313 m); the median depth was 339 ft (103 m) and the average depth was 356 ft (108.5 m). Casing lengths ranged from 3.5 to 138 ft (1.1 to 42 m); the median length was 22 ft (6.7 m) and the average length was 34 ft (10.4 m)]. Heatpulse-flowmeter measurements for all wells are described by Conger (1999).

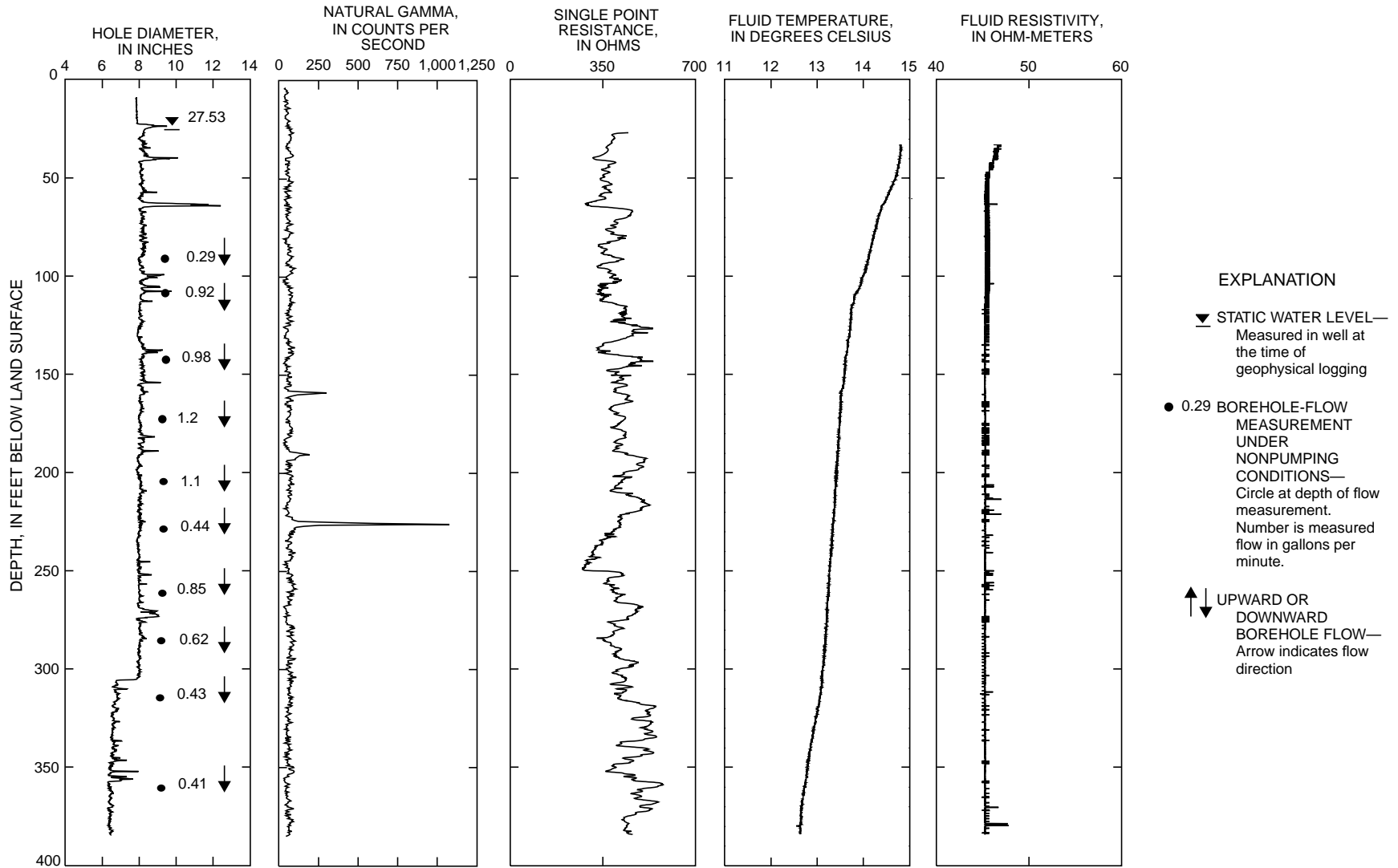


Figure 8. Geophysical logs of well Mg-164 in Lansdale, Pa.

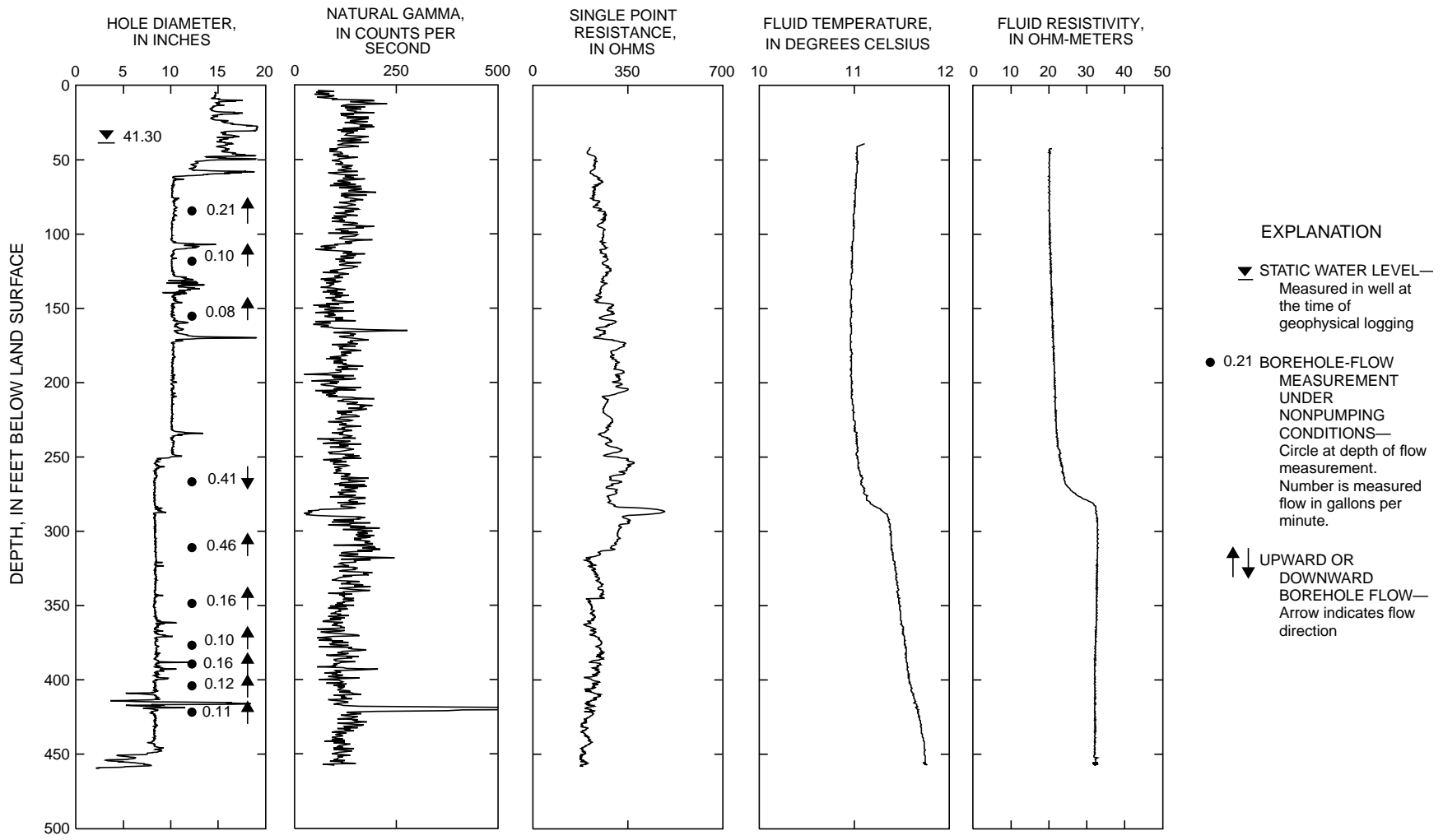


Figure 9. Geophysical logs of well Mg-68 in Lansdale, Pa.

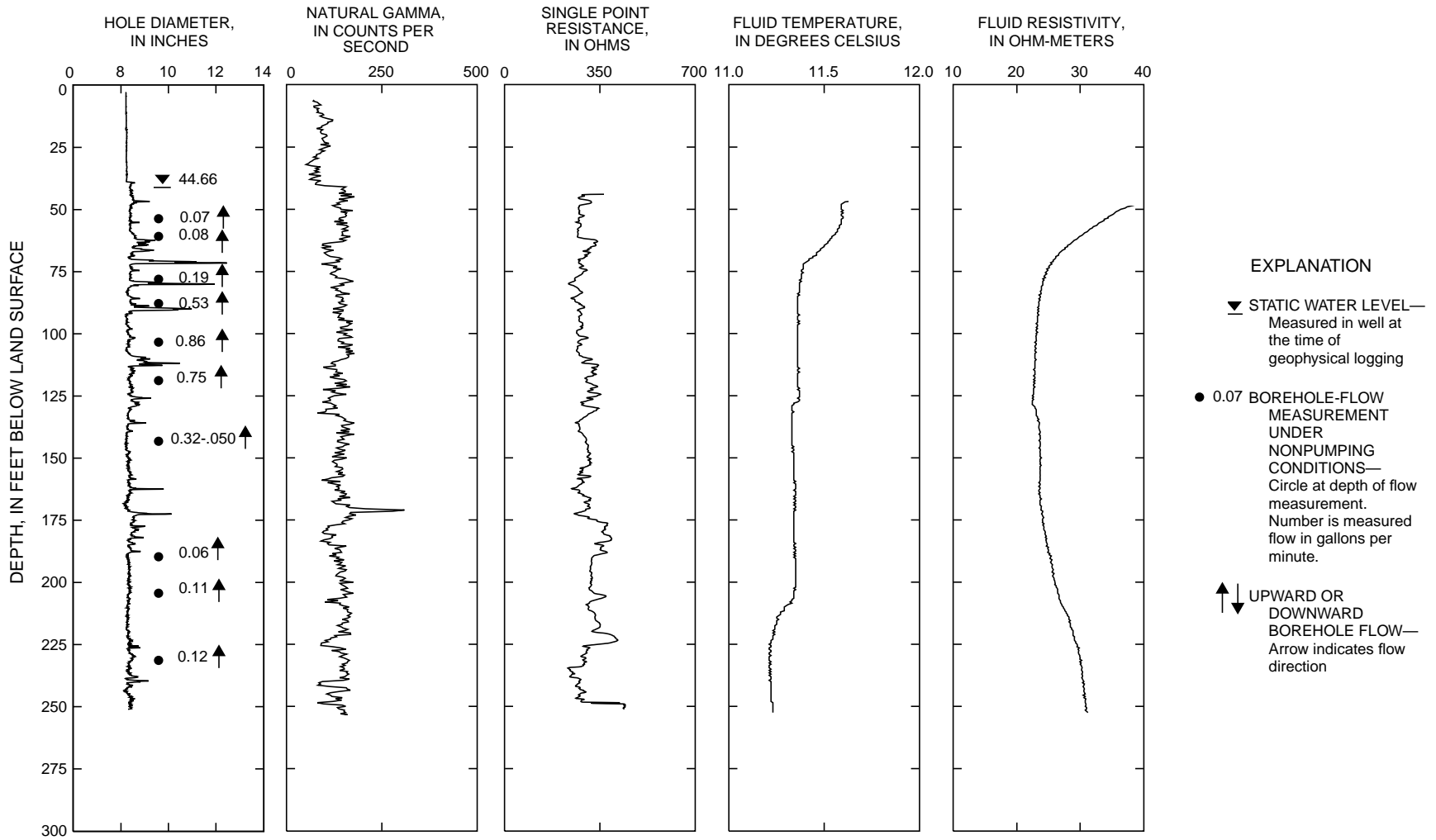


Figure 10. Geophysical logs of well Mg-69 in Lansdale, Pa.

Water-bearing zones (fractures) detected during heatpulse-flowmeter measurements in 31 wells logged in and near Lansdale are summarized in table 1. The greatest number of water-bearing zones detected per foot drilled were in the interval of 50-100 ft (15.2 - 30.5 m) below land surface, followed by the interval of 100-200 ft (30.5-61 m) below land surface. These two intervals contained about 67 percent of all water-bearing zones detected. The majority of the most productive zones detected in each well also were in the intervals of 50-100 ft (15.2-30.5 m) and 100-200 ft (30.5-61 m) below land surface; about 76 percent of the most productive zones were in these intervals.

Water-bearing zones at depths shallower than 50 ft (15.2 m) below land surface were detected less frequently than in the interval between 50-100 ft (15.2-30.5 m) below land surface (table 1). This result may reflect lower productivity in the 0- to 50-ft (15.2-30.5 m) interval, which is weathered and where potentially productive fractures may be partially closed with clay, but also may reflect the interval's smaller sample of open-hole footage because the upper part of the interval is unsaturated or cased off. The frequency of water-bearing zones detected appear to decrease with depth below 100 ft (30.5 m) and just one zone was detected below 500 ft (152.4 m) below land surface. However, because the amount of footage drilled below land surface also decreased with depth, these results could partly reflect the smaller sample of aquifer with depth.

Borehole television surveys and acoustic televiewer logs indicate most identified water-bearing fractures dip at shallow angles, similar to bedding. Examples of water-bearing near-horizontal (bedding-plane opening) and near-vertical fractures are shown in borehole television images of figures 8-10 well Mg-1444 (fig. 11). A plot of poles to fracture planes including water-bearing fractures for well Mg-67 is shown in figure 12. Points near the center of the plot represent low-angle features, such as bedding, and points near the perimeter of the plot represent high-angle features, such as near-vertical fractures that are approximately orthogonal to bedding. The orientation of water-bearing zones for well Mg-67, as interpreted from the acoustic televiewer log, is similar to bedding. Some features, such as the near-vertical water-bearing fracture at 72 ft in well Mg-67, are not detected from acoustic televiewer logs.

Table 1. Depth distribution of water-bearing zones determined from geophysical logging of 31 wells¹ in and near Lansdale, Pa.

[>, greater than]

	Depth interval, in feet below land surface							Total
	0-50	50-100	100-200	200-300	300-400	400-500	>500	
Number of wells drilled no deeper than this interval	0	0	5	9	9	4	4	31
Percentage of all wells drilled no deeper than this interval	0	0	16.1	29.0	29.0	12.9	12.9	99.9
Footage drilled in interval ²	857	1,419	2,946	2,271	1,351	612	752	10,208
Percentage of total footage drilled	8.4	13.9	28.9	22.2	13.2	6.0	7.4	100
Number of water-bearing zones in interval	7	32	42	19	6	3	1	110
Percentage in interval of total water-bearing zones	6.4	29.1	38.2	17.3	5.5	2.7	.9	100
Number of water-bearing zones per 100 feet drilled in interval	.8	2.3	1.4	.8	.4	.5	.1	6.3
Number of water-bearing zones determined to be most productive ³ for well in interval	2	9	13	4	0	0	0	28
Percentage in interval of total most productive ³ water-bearing zones for all wells	7.1	32.1	46.4	14.3	0	0	0	99.9
Number of water-bearing zones determined to be most productive ³ for well per 100 feet drilled in interval	.2	.6	.4	.2	0	0	0	.27

¹ Wells Mg-62, 64, 67, 68, 69, 72, 76, 79, 80, 81, 138, 143, 142, 154, 157, 163, 164, 498, 618, 623, 624, 704, 1128, 1284, 1440, 1441, 1443, 1444, 1445, 1446, and 1447 were included in analysis.

² Uncased or open-hole footage when logged.

³ Relative productivity of water-bearing zone determined by pumping well while measuring borehole flow with heatpulse flowmeter.

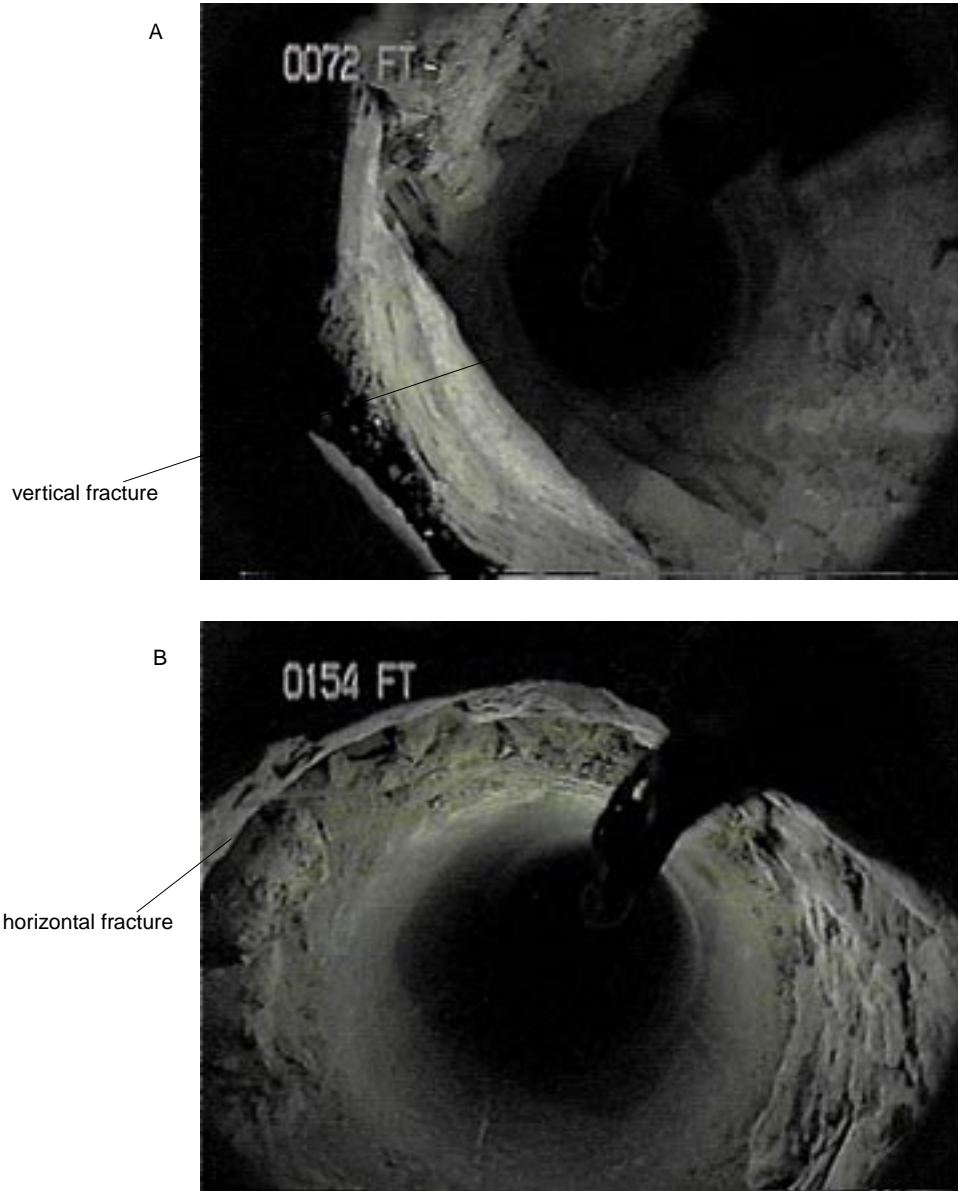


Figure 11. Borehole television image of (A) vertical fracture, and (B) horizontal fracture in well Mg-1444 in Lansdale, Pa.

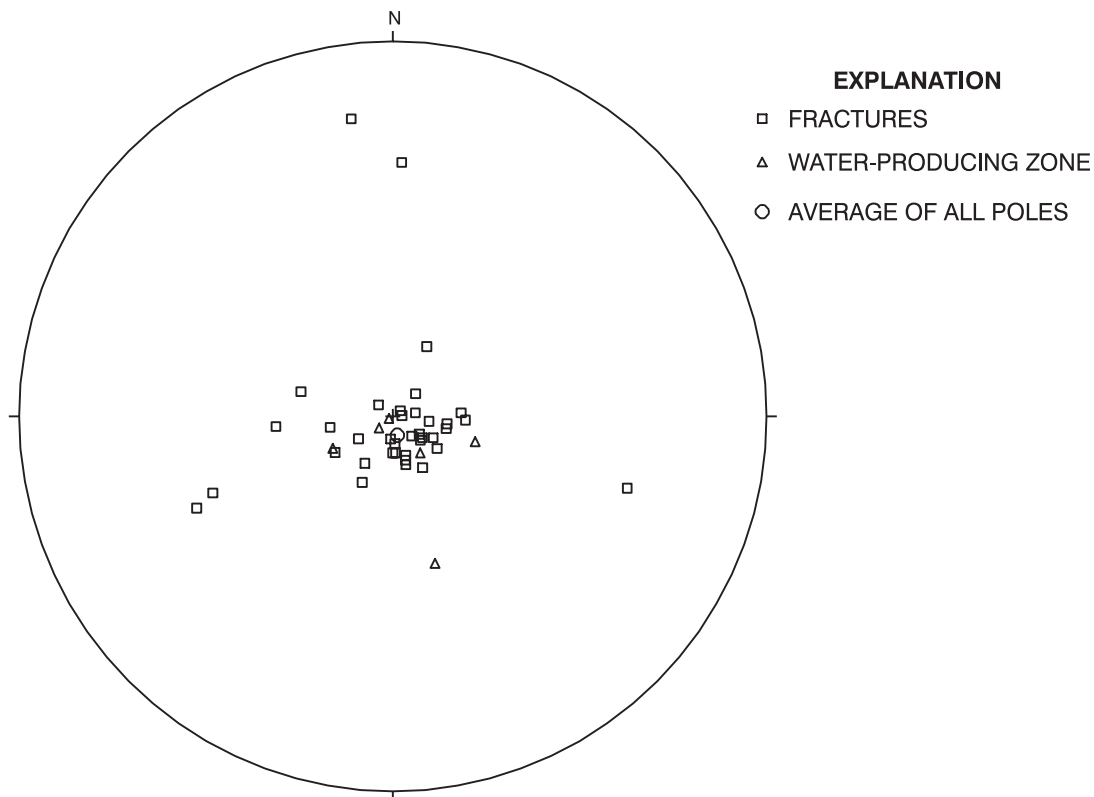


Figure 12. Equal-area, lower-hemisphere plot of poles to fracture planes measured by acoustic televiewer in well Mg-67 in Lansdale, Pa.

Water Levels

Water levels measured in wells in an unconfined aquifer indicate the level of the water table. In confined aquifers, water levels measured in wells indicate the level of a potentiometric surface. In the bedrock aquifer underlying Lansdale, water-bearing fractures in wells constructed as open holes typically have different potentiometric heads, and, therefore, water levels measured in wells constructed as open holes that intersect one or more water-bearing fractures represent composite heads. Water levels typically are measured as the depth to water from land surface and are expressed as the altitude of the water level above sea level. The altitude of the water table or potentiometric surface indicates potential energy (head). In pumped or recently pumped wells, observed water levels may be depressed by drawdown (including well loss) or slow recovery and do not necessarily reflect levels nearby but outside the well.

Water levels rise in response to recharge to the ground-water system from precipitation, and decline in response to discharge from the ground-water system to ground-water evapotranspiration, streams, and pumping. In southeastern Pennsylvania, where precipitation is distributed nearly evenly year-round, water levels generally rise during the late fall, winter, and early spring when soil-moisture deficits and ground-water evapotranspiration are at a minimum and recharge is at a maximum. The depth to water is least in the late winter and early spring when water levels rise because recharge rates are greater than discharge rates. Water levels generally decline during the late spring, summer, and early fall when soil-moisture deficits and ground-water evapotranspiration are at a maximum and recharge is at a minimum. The magnitude of seasonal fluctuations or shorter-term changes in water levels in response to recharge is related to aquifer porosity and storage. After recharge, the rise in water levels may be greater and sustained longer in aquifers with low permeability than in aquifers with high permeability.

Water levels were measured continuously during fall 1995 through spring 1998 in seven Lansdale area wells. During this same period, water levels in three other wells were measured for short (less than 1 year) periods. The wells were constructed as open holes, ranged in depth from 179 to 507 ft (54.6 to 154.5 m), were cased from 9 to 97 ft (2.7 to 29.6 m) below land surface, and had multiple water-bearing zones (table 2). Depth to water generally was smaller in wells near streams (discharge areas) than in wells in upland areas near divides or at distances away from streams (pl. 1, table 2). Under natural conditions, depth to water in a water-table aquifer is related to topography. Water levels generally are closest to land surface in valleys near streams (discharge areas) and deepest below land surface on hilltops (recharge areas).

Table 2. Well depth, casing length, depth to water, and change in water levels from January 1996 to January 1997 and from January 1997 to January 1998 for selected wells in and near Lansdale, Pa.

[ft bls, feet below land surface; ft, feet; --, no data]

U.S. Geological Survey local well number Mg-	Well depth (ft bls)	Casing length (ft)	Within 200 ft of stream	Depth to water on 1-23-96 to 1-24-96 (ft bls)	Depth to water on 1-7-97 (ft bls)	Depth to water on 1-13-98 (ft bls)	Change in water level 1996-97 (ft)	Change in water level 1997-98 (ft)
67	292	19	yes	14.71	10.81	15.44	3.90	-4.63
68	500	9	yes	--	40.90	44.68	--	-3.78
81	320	33	no	¹ 50.27	38.52	45.50	11.75	-6.98
82	350	18	yes	10.86	11.49	11.86	-.63	-.37
143	400	30	yes	3.85	--	--	--	--
152	203	22	no	--	47.97	56.19	--	-8.22
618	343	47	no	66.20	54.71	62.01	11.49	-7.3
623	507	97	no	² 21.24	19.91	23.53	1.33	-3.62
704	400	83	no	16.30	16.84	18.55	-.54	-1.71
Average							4.55	-4.10

¹ Measured on 1/18/96.

² Measured on 1/3/96.

In wells not affected by nearby pumping, rising water levels indicate recharge periods. The long-term (1995-98) response of water levels to recharge by precipitation is shown on figures 13 and 14. In southeastern Pennsylvania, the autumns of 1995 and 1997 were drought periods and water levels declined accordingly. The autumn of 1996 ended a year of higher-than-average precipitation. Ground-water levels were some of the highest on record in southeastern Pennsylvania in December 1996. Annual precipitation as measured at Allentown, Pa., a weather station about 20 mi (32 km), north of Lansdale, was 38.46 in. (977 mm) in 1995, 56.87 in. (1,444 mm) in 1996, and 38.49 in. (978 mm) in 1997. Normal annual precipitation (computed for a 30-year period, 1960-90) at Allentown, Pa., is 43.52 in. (1,105 mm) (National Oceanic and Atmospheric Administration 1995; 1996; 1997).

The range of seasonal fluctuation varied among the wells, reflecting the different hydrologic settings of the observation wells and possibly also spatial variability in recharge rates or storage characteristics of the aquifer. The range of fluctuations generally increased with depth to water (table 2). For example, the rise from October 1995 to May 1996 was about 20 ft (6.1 m) in well Mg-618 (fig. 14) but only about 6 ft (1.8 m) in well Mg-67 (fig. 13). The average change in water levels in six wells was 4.55 ft from January 1996 to January 1997 and was -4.10 ft from January 1997 to January 1998 (table 2), reflecting an increase in annual precipitation of 18.41 in. in 1996 and a decrease of 18.38 in. in 1997 compared to precipitation in the previous year of 1995 and 1996, respectively.

Water levels in most wells, except for Mg-1441 and Mg-618, appeared unaffected by local pumping. The weekly schedule of nearby industrial pumping is reflected in the rapid, periodic decline and recovery in measured water levels during the week and the rise in water levels (recovery) over weekends in well Mg-1441, such as March 31-April 1, April 7-8, April 14-15, April 21-22, and April 28-29, 1996 (fig. 15). Water levels in well Mg-618 also declined and recovered periodically (7-day cycle) in apparent response to industrial pumping, although to a lesser extent than in Mg-1441.

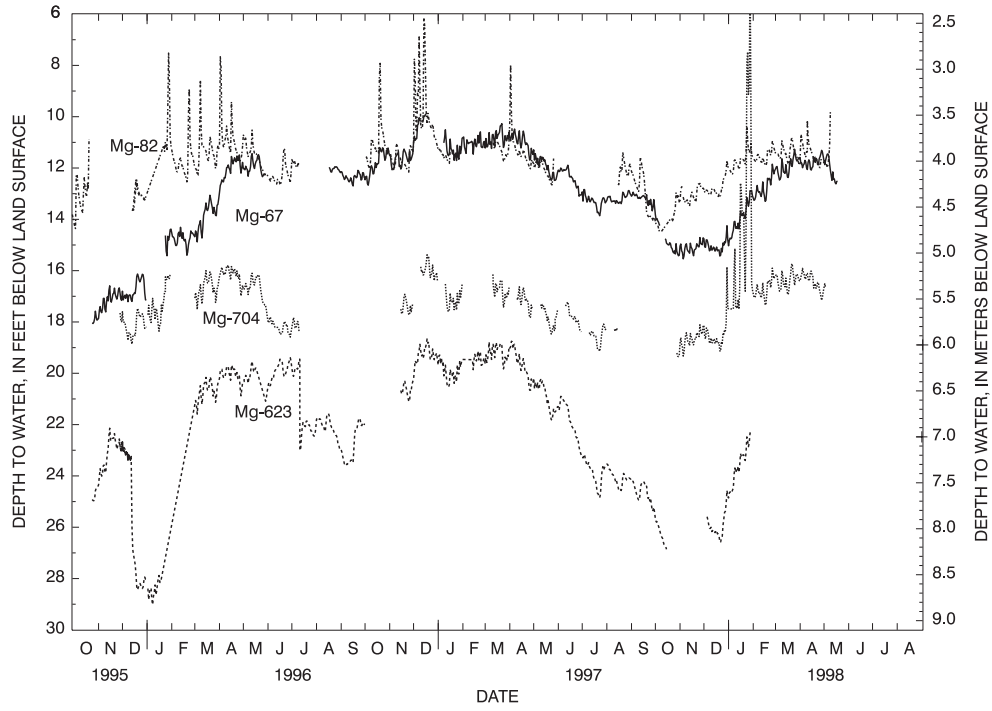


Figure 13. Long-term (annual or greater) water levels showing seasonal recharge in wells Mg-82, Mg-67, Mg-704, and Mg-623 in Lansdale, Pa.

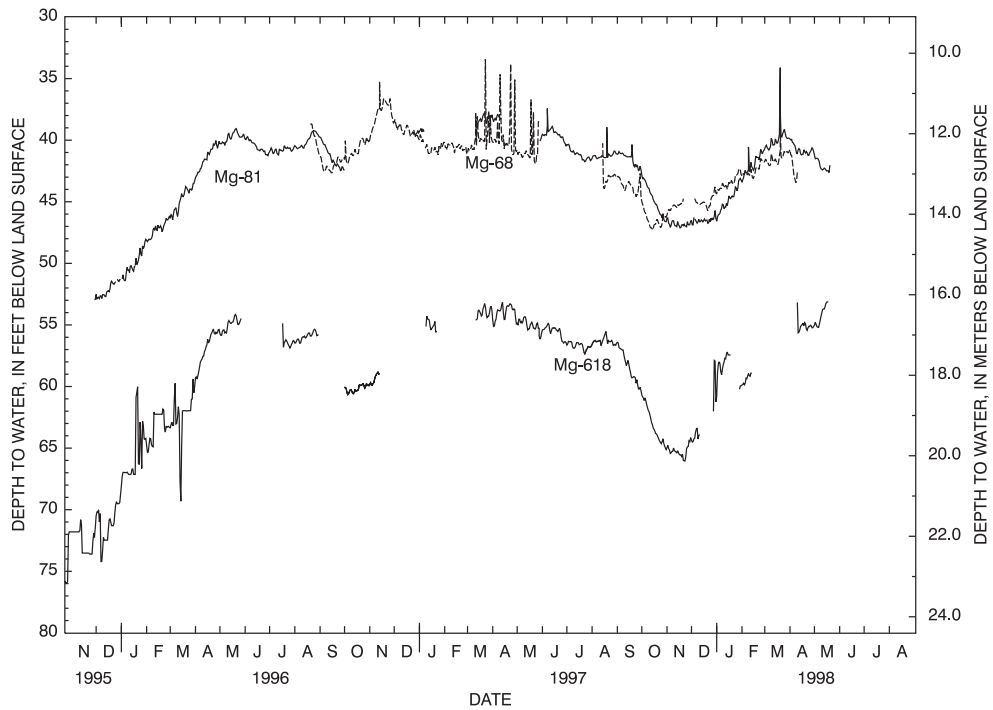


Figure 14. Long-term (annual or greater) water levels showing seasonal recharge in wells Mg-81, Mg-68, and Mg-618 in Lansdale, Pa.

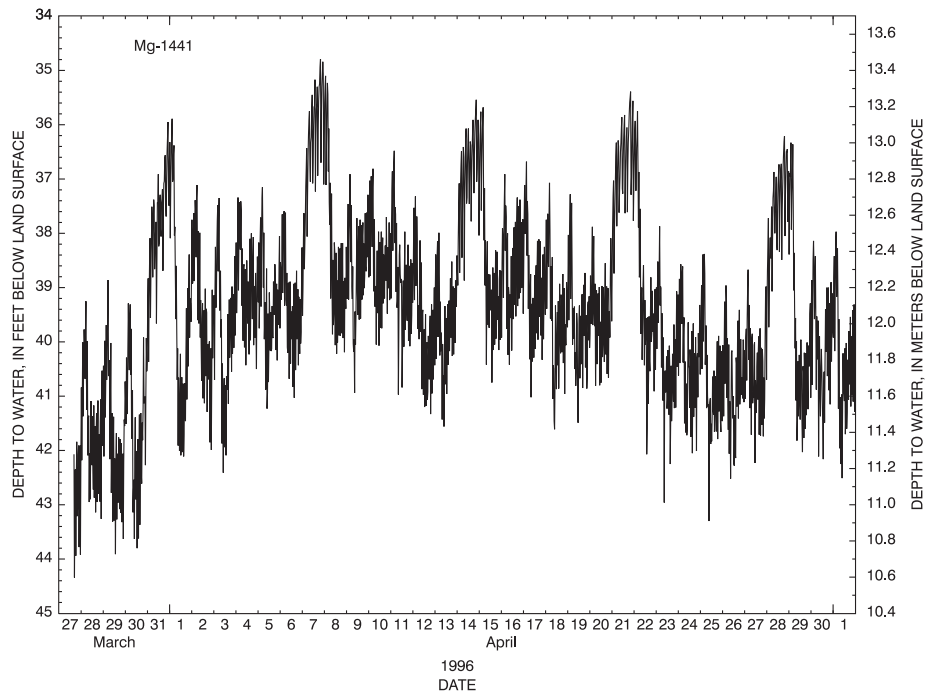


Figure 15. Water levels in well Mg-1441 showing response to nearby pumping in Lansdale, Pa., February-March 1996.

The short-term (few days or less) response to precipitation is shown in figure 16. In most wells monitored in the Lansdale area, the response is rapid (within a few hours of rainfall), indicating the rise in water levels probably is caused by an increase in hydrostatic pressure rather than physical infiltration of water. The rapid response of water levels to precipitation indicates these wells penetrate confined parts of the aquifer.

In confined ground-water systems, ground-water levels also can fluctuate with changes in earth tides and barometric pressure. The apparent effect of earth tides on water levels in well Mg-704 in Lansdale (fig. 17) indicates that the water-bearing zones of this well are confined or semiconfined. Earth tides are characterized by semi-diurnal fluctuations and are caused by the force of gravity exerted by the sun and moon on the earth and by centrifugal forces produced by the revolution of the earth and moon around their common center of gravity (Hsieh and others, 1987). Twice-daily peaks occur at low tide when the earth is compressed. The increased pressure results in a rise in water levels in wells completed in confined aquifers. Daily patterns as a result of earth tides similar to those in water levels of Mg-704 (fig. 17) were observed in water levels in most wells that were monitored in Lansdale. The effect of changes in barometric pressure on water levels in a well in Lansdale during November 1997 is shown in figure 18. Water levels rise in response to declines in barometric pressure and fall in response to increases in barometric pressure. This inverse response of water level to barometric pressure indicates that the water-bearing zones of the well in Lansdale (fig. 18) are under confined conditions. Similar responses to changes in barometric pressure were observed where measured in most wells in the Lansdale area.

Water levels in and near Lansdale were measured in more than 130 wells during 2 days in August 1996 and again in 80 wells during 2 days in January 1998 to prepare maps of the regional potentiometric surface. Because most water levels were measured in wells that were constructed as open holes and ranged in depth from 70 to 600 ft (21 to 183 m) in depth, water levels represent the composite head of multiple water-bearing zones. Vertical head differences between discrete water-bearing zones were less than 20 ft (6.1 m) in three wells tested using inflatable packers to

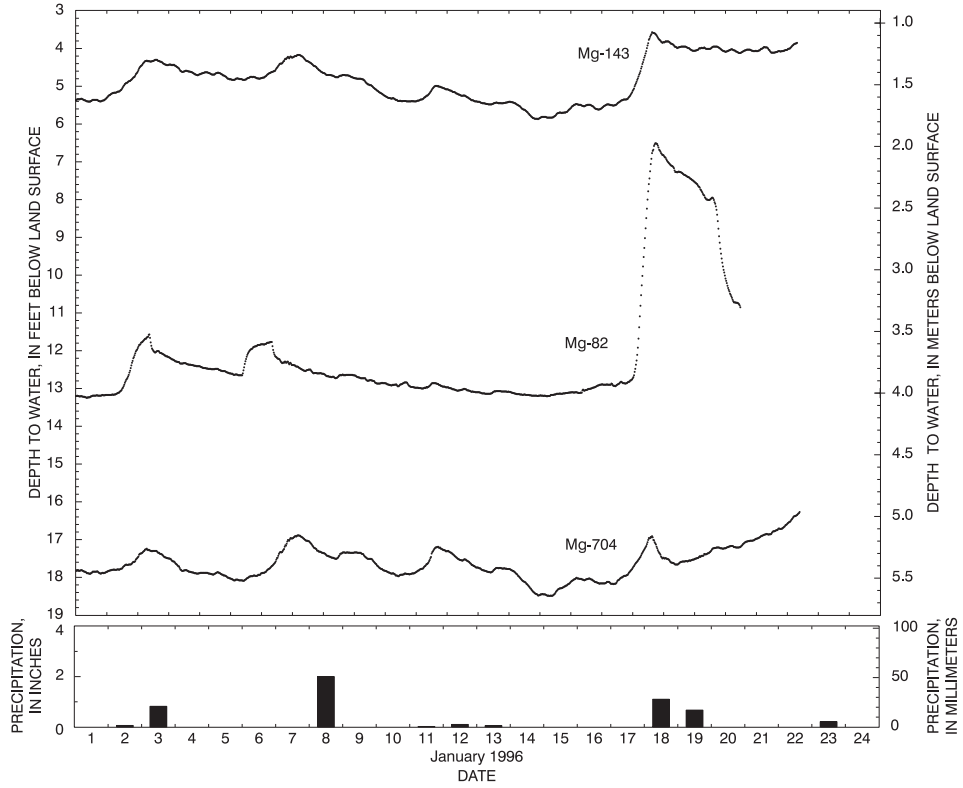


Figure 16. Short-term water-level response to precipitation in wells Mg-143, Mg-82, and Mg-67 in Lansdale, Pa., January 1996.

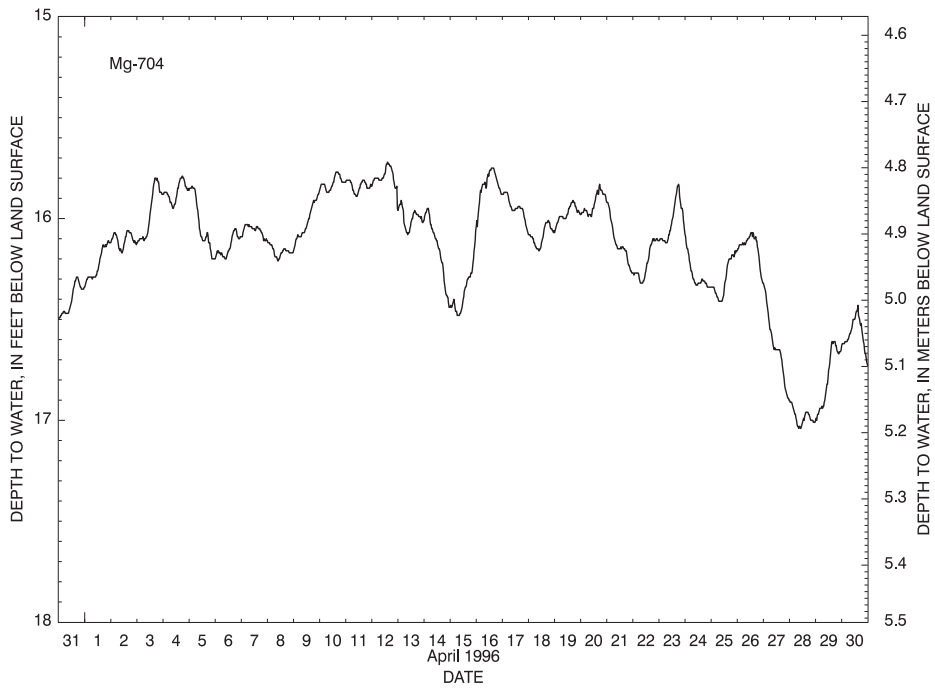


Figure 17. Water levels in well Mg-704 showing water-level response to earth tides in Lansdale, Pa., April 1996.

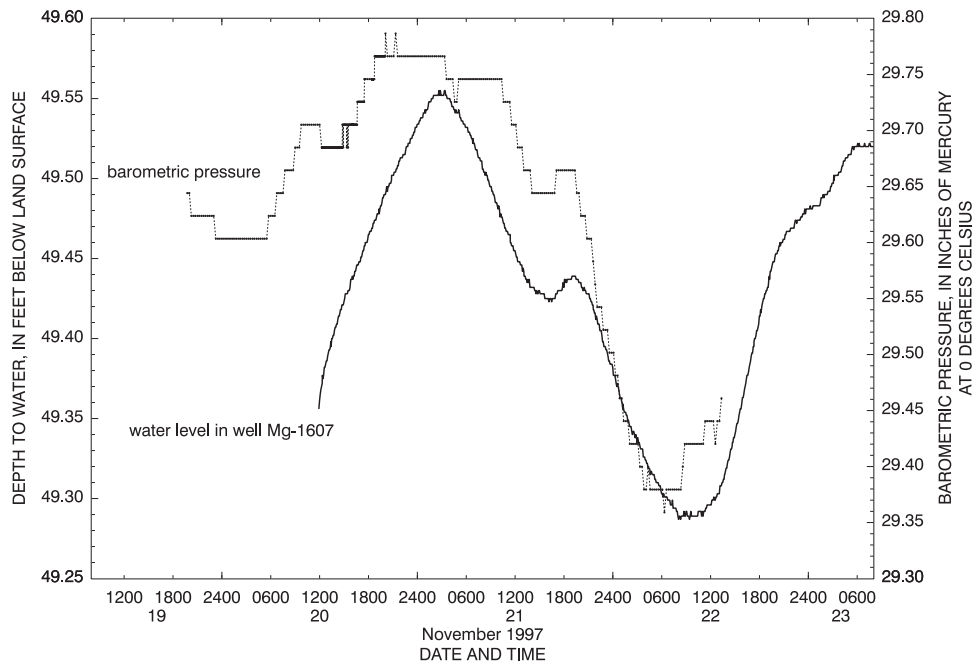
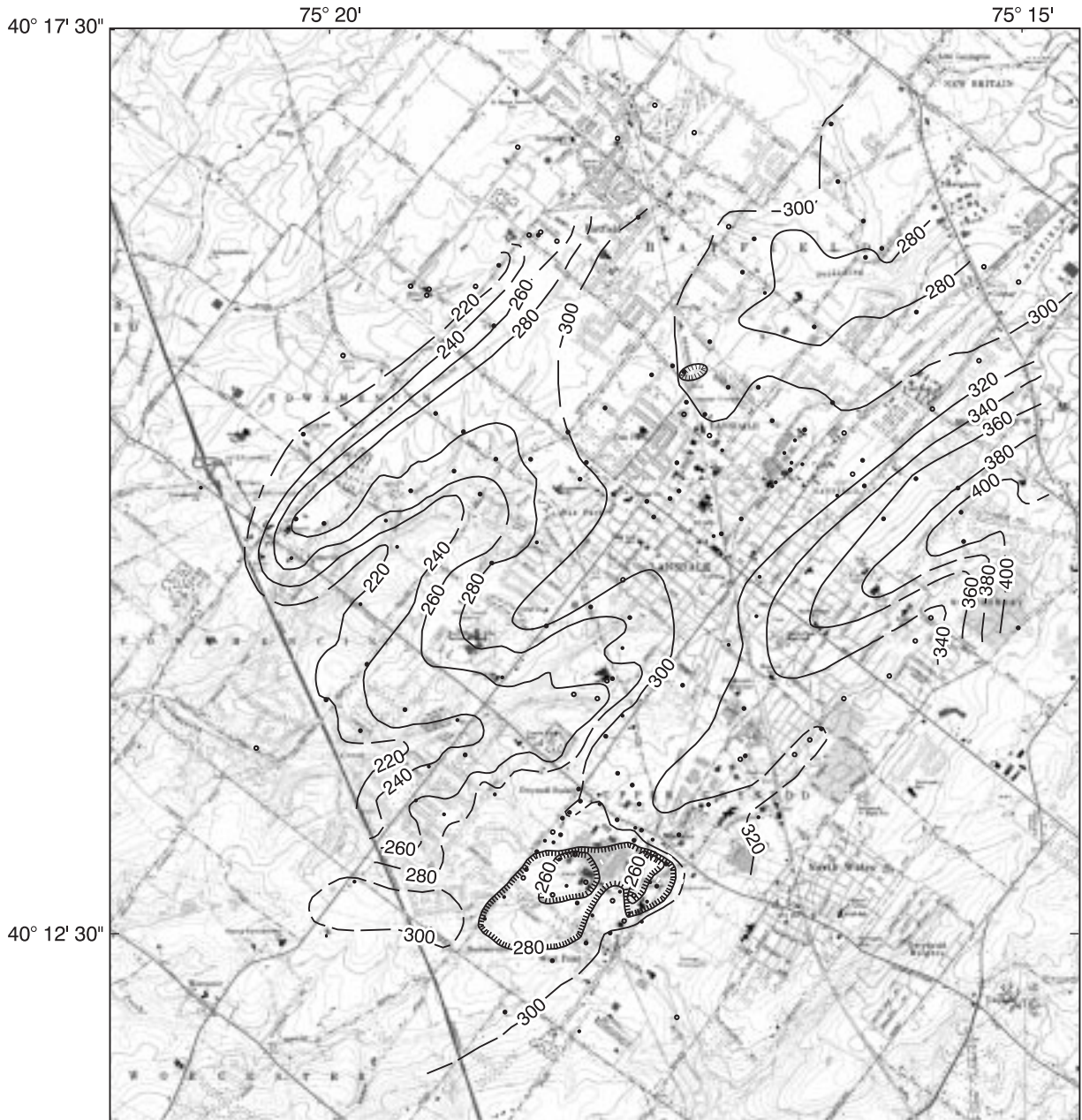


Figure 18. Water levels in well Mg-1607 showing response to barometric pressure, Lansdale, Pa., November 1997.

isolate zones, as discussed in the section on “Single-Well, Interval-Isolation Tests.” Assuming these wells are representative of other wells in the Lansdale area, the relative error in contouring composite heads on a 20-ft (6.1-m) interval should be small.

A map of water levels measured on August 22-23, 1996 (fig. 19; Senior and others, 1998), shows that water-level altitudes are highest under the small ridge east of Lansdale, underlain by the Lockatong Formation, and lowest along Towamencin Creek southwest of Lansdale. The contoured water-level altitudes, as mapped, represent only changes in a potentiometric surface in the horizontal direction. Although the contoured water levels in the semi-confined aquifer beneath Lansdale do not represent the water table, the surface is nevertheless similar to topography. Commonly, the water table closely replicates topography, especially in aquifers with low permeability and (or) storage. The shape of the contoured water-level surface differs from topography in the central part of the study area under Lansdale. In central Lansdale, the ground-water divide between the West Branch Neshaminy Creek Basin to the north and the Towamencin Creek Basin to the south is about 0.75 mi (0.47 km) north of the surface-water (topographic) divide. Also, the contoured water-level surface, which is nearly flat in the area of the ground-water divide, has a slope inverse to that of topography along an axis from the southeast to the northwest; changes in the permeability of the bedrock aquifer possibly influence the configuration of the water-level surface in this area. The shape of the contoured water-level surface also differs from topography in an area south of Lansdale, where industrial pumping has caused a cone of depression. A map of water levels measured January 13-14, 1998 (fig. 20), shows a general configuration similar to the map of water levels measured on August 1996, although water levels in January 1998 generally were several feet lower than in August 1996. A dry period of about 6 months preceded January 1998.



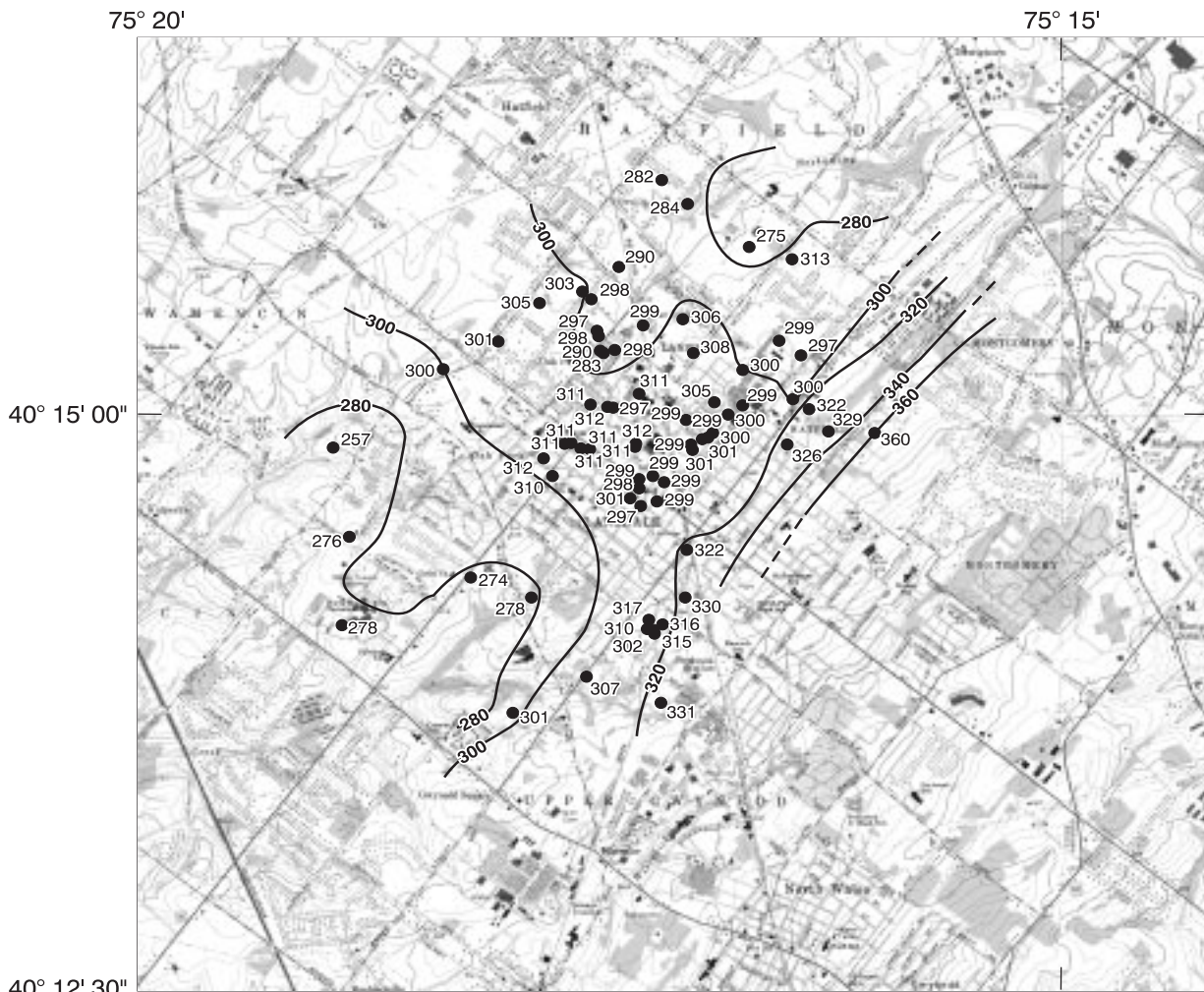
Base from U.S. Geological Survey
 Lansdale, 1:24,000 1983, Contour interval 10 feet
 Telford, 1:24,000 1980, Contour interval 20 feet
 Ambler, 1:24,000 1983, Contour interval 10 feet
 Doylestown, 1:24,000 1983, Contour interval 20 feet



EXPLANATION

- 300-- POTENTIOMETRIC CONTOUR -- Shows altitude of potentiometric surface as defined by measured water levels. Dashed where approximately located. Hachured contour indicates depression in potentiometric surface. Contour interval 20 feet. Datum is sea level.
- WATER-LEVEL MEASUREMENT SITES
- ⊕P WELL KNOWN TO BE PUMPING FOR PUBLIC SUPPLY OR INDUSTRIAL USES DURING PERIOD OF WATER-LEVEL MEASUREMENTS

Figure 19. Measured water levels and contoured water-level surface in and near Lansdale, Pa., August 22-23, 1996 (From Senior and others, 1998).



Base from U. S. Geological Survey
 Lansdale 1:24,000 1983, Contour interval 10 feet
 Telford 1:24,000 1980, Contour interval 20 feet
 Ambler 1:24,000 1983, Contour interval 10 feet
 Doylestown 1:24,000 1983 Contour interval 20 feet



EXPLANATION

- 300- POTENTIOMETRIC CONTOUR - Shows altitude of potentiometric surface as defined by measured water levels. Dashed where approximately located. Contour interval 20 feet. Datum is sea level.
- 331 LOCATION AND ALTITUDE OF STATIC WATER LEVEL MEASURED IN A DRILLED WELL COMPLETED IN BEDROCK - Altitude in feet above sea level.

Figure 20. Measured water levels and contoured water-level surface in and near Lansdale, Pa., January 13-14, 1998.

The water levels from January 1998 include measurements in vertically nested monitor wells and, therefore, includes data on differences in vertical heads. In most monitor-wells nests, the water-level altitude in the deepest well of the nest is higher than the water-level altitude in the shallowest well, indicating an upward vertical gradient. In a few well nests, the water-level altitude in the shallowest well of the nest is higher than water-level altitude in the deeper well, indicating a downward vertical gradient. In aquifer-interval-isolation tests done in three wells in Lansdale, water levels for different water-bearing zones were measured after inflation of straddle (set of two) packers. Water levels in the deepest zones were higher than levels in the shallower zones, but water levels in the shallowest zone were slightly lower than levels in the next deepest zone isolated. These observations, described in detail in the section “Single-Well, Interval-Isolation Tests,” indicate an upward vertical gradient from zones at depth and a smaller downward vertical gradient from the shallowest zone. Vertical hydraulic gradients are discussed in detail in the section on “Ground-Water Flow.”

Ground-Water Flow

Ground water flows from higher to lower head (water-level altitude), and therefore the general direction of horizontal ground-water flow can be estimated from a map of the water table or potentiometric surface. If there are no vertical head differences, then flow is strictly planar (two-dimensional). In isotropic aquifers, where hydraulic conductivity is independent of direction, the flow is parallel to hydraulic gradient. In anisotropic aquifers, where hydraulic conductivity depends on direction, the flow is at an angle (toward the direction of highest permeability) to the hydraulic gradient. The maps of water levels in August 1996 (fig. 19) and January 1998 (fig. 20) indicate that ground water generally flows from the small ridge east of Lansdale toward Lansdale, in the central part of the study area. From central Lansdale, a triple divide, ground water flows north, southwest, and south in directions similar to the topographic gradient toward three separate drainages.

On a local or borehole scale, ground-water flow directions may appear to deviate from regional flow directions. These local-scale deviations may be the result of vertical gradients, nearby pumping, or natural flow through a complex network of fractures in the dipping-bed hydrogeologic system. Where differences in potentiometric head between zones of water-bearing fractures in a well are present, water in the well flows vertically from zones of high head to zones of low head. The well allows rapid flow between these different water-bearing zones, which under natural conditions are separated by layers of unfractured or low-permeability bedrock. Examples of downward and upward vertical borehole flow between producing and receiving fractures in wells in Lansdale are shown in figures 8 and 10, respectively.

Vertical flow in open-hole wells under nonpumping conditions was measured by use of a heatpulse flowmeter or brine-tracing techniques in 58 wells in the area of Lansdale. The wells included 31 available observation, industrial, commercial and public-supply wells that ranged in depth from 144 to 1,027 ft (43.9 to 313 m) and 27 monitor wells drilled in the summer of 1997 that ranged in depth from 49 to 385 ft (14.9 to 117.3 m). Of the 58 wells tested, upward borehole flow was measured in 35 wells, downward flow only was measured in 11 wells and inferred in 1 well (Mg-76), upward and downward flow were measured in 3 wells, and no detectable flow was measured in 8 wells (table 3; Conger, 1999). Measured upward flow rates ranged from 0.01 to 1.2 gal/min (0.038 to 4.54 L/min), and downward flow rates ranged from 0.02 to 12 gal/min (0.076 to 45.4 L/min). In wells with upward flow, water commonly exited the well in fractures at depths typically ranging from 30 to 70 ft (9.1 to 21.3 m) below land surface. In wells with downward flow, water commonly exited the well in fractures at depths greater than 100 ft (30 m) below land surface. The location of wells where flow was measured and direction of vertical flow in the well are shown in figure 21.

Table 3. Depth and direction of vertical flow and inferred depths of fractures with inflow and outflow in wells logged under nonpumping conditions in and near Lansdale, Pa. (Conger, 1999)

[ft bls; feet below land surface; gal/min, gallons per minute; --, not detected or measured; <, less than; >, greater than; -, not applicable]

U.S. Geological Survey local well number Mg-	Depth of well (ft bls)	Depth to water (ft bls)	Upward flow		Downward flow		No flow	Inflow	Outflow
			Range of depths with upward flow (ft bls)	Flow rate or range of flow rates (gal/min)	Range of depths with downward flow (ft bls)	Flow rate or range of flow rates (gal/min)	Depths with no flow detected (ft bls)	Depths of fractures with inflow ¹ (ft bls)	Depths of fractures with outflow ¹ (ft bls)
62	382	--	120-345	0.02	--	--	--	>345	<120
64	1,027	--	106-376	.06	--	--	--	>376, 111-115	<86
67	² 294	--	--	--	65-114	0.07	--	24, 54-58, 72-75, 114	>114
68	460	41.8	85-148	.11-.46	--	--	--	108-110, 169-171, 321-323, 361-371, >426	<70, 284-288
69	251	44.7	52-234	.06-.86	--	--	--	125-129, 158-162, 238-242	47, 67-72, 80, 90, 109-113, 208
72	298	--	--	--	165	12	--	71,79-86	250
76	367	--	--	--	--	--	--	51-100	232
79	284	--	--	--	68-150	.02	--	124	166
80	270	13.3	170-248	.16-.25	--	--	--	253-258	144-154
81	350	--	--	--	--	--	³ 230, 310	-	-
82	⁴ 375	--	56-70	.04	--	--	35	>70	--
138	424	39.6	265-401	.11-.19	53-150	.08-1.2	--	50-52, 421-423	82-86, 130-142, 157-175, 240, 391-399
143	392	--	--	--	--	--	² 130-350	-	-
152	196	49.4	55-186	.07-.25	--	--	--	63-68, >186	<63
154	183	51.2	85-140	.10-.18	--	--	60, 145-170	140-142	63-88
157	268	6.6	52-240	.12-.30	--	--	--	124-127, 187, >240	<52, 64-68, 92-97
163	318	25.4	37-300	.11-.30	--	--	--	>300	<37, 104-111, 234
164	385	27.5	--	--	92-332	.29-1.2	--	62-65, 99-113, 154, 245-257	222, 270-274, 300-348, >362
498	587	46.2	450-554	.08-.09	--	--	104-424	566-576	435-442
618	342	--	130-200	.01	--	--	315	--	--
624	633	--	66-322	.01	--	--	--	>322	<66
704	380	--	--	--	--	--	² 105-315	--	--
1128	486	18.3	--	--	42-264	0.10-1.3	--	33, 70	118-137, 172, 204, 215-231, >265
1284	442	9.4	88-426	.06-.40	--	--	--	292, 438	82, 90-92, 256
1440	208	--	--	--	64-118	.02	--	108	128
1441	178	--	--	--	100-130	.23-.44	--	85, 118	161
1443	339	42.1	68-332	.07-.24	--	--	--	332	<68, 175, 225
1444	294	--	69-270	.07-1.2	--	--	--	260-265, 270	70-73

Table 3. Depth and direction of vertical flow and inferred depths of fractures with inflow and outflow in wells logged under nonpumping conditions in and near Lansdale, Pa. (Conger, 1999)—Continued

U.S. Geological Survey local well number Mg-	Depth of well (ft bls)	Depth to water (ft bls)	Upward flow		Downward flow		No flow	Inflow	Outflow
			Range of depths with upward flow (ft bls)	Flow rate or range of flow rates (gal/min)	Range of depths with downward flow (ft bls)	Flow rate or range of flow rates (gal/min)	Depths with no flow detected (ft bls)	Depths of fractures with inflow ¹ (ft bls)	Depths of fractures with outflow ¹ (ft bls)
1445	204	44.1	--	--	98-130	0.02-.07	--	84	110-120, 130-150
1446	144	53.9	68-90	0.06-.10	104	.10	--	73, 76, 97-101	54-59, 122
1447	145	47.2	--	--	54-114	.19-.36	--	48-50, 68-71, 82	104-108, 127-130
1600	150	48.8	56-142	.11-1.2	--	--	--	147-149	50, 70
1601	100	55.4	80-92	.15-.36	--	--	65	84-90, 94-95	66-77
1602	131	55.1	81-123	.12-.96	--	--	66	115-116, 129	69-72
1603	98	64.7	--	--	70	.013	76, 86	65	73
1604	221	55.5	66-170	.14-.21	--	--	--	214-221	55-65
1605	95	60.8	--	--	--	--	73, 81, 88	-	-
1606	101	43.1	52-94	.07-.14	--	--	--	94-100	44-48
1607	161	42.2	64	.15	104-140	.10	--	73	52, 157-159
1608	307	39.7	--	--	--	--	240-288	-	-
1609	101	46.5	52-76	.10-.19	--	--	86	79-81	48
1610	122	13.6	46	.09	--	--	28, 74-110	49	30-40
1611	88	13.5	--	--	--	--	24-74	-	-
1612	384	49.8	66-360	.12-.73	--	--	--	310-312, 330-340, 370-382	50-54, 94-115
⁵ 1613	179	25.6	60-78	.11-.32	--	--	--	72-74, 94	40-55
1613	320	37.1	--	--	--	--	190-288	-	-
1614	121	50.5	58-100	.10-.22	--	--	--	102-120	50-56
1615	148	15.7	34-126	.07-.52	--	--	--	72-74, 119, 140-148	19-28, 40-55
1616	101	26.6	40-74	.06-.12	--	--	90	81	30-34, 51-53
1617	49	13.5	--	--	--	--	25, 36	-	-
1618	181	52.0	85	0.10	--	--	70, 110-170	92	75-78
1619	150	11.9	50-70	.08-.11	--	--	90-134	92	20-42
1620	101	12.2	90	.13	--	--	46-70	>92	76
1621	161	50.5	80-150	.08-.46	--	--	--	96, 114, 134, >150	50-68
1622	101	50.4	86	.08	--	--	63	>89	50-74
1623	101	49.0	64-92	.09-.13	--	--	--	>92	50-62
1624	101	38.7	--	--	--	--	48-90	-	-
1639	149	24.7	--	--	42-100	1.1-1.3	--	30-38	102-113
1640	66	23.3	27-40	.06-.09	--	--	50	42	23, 30

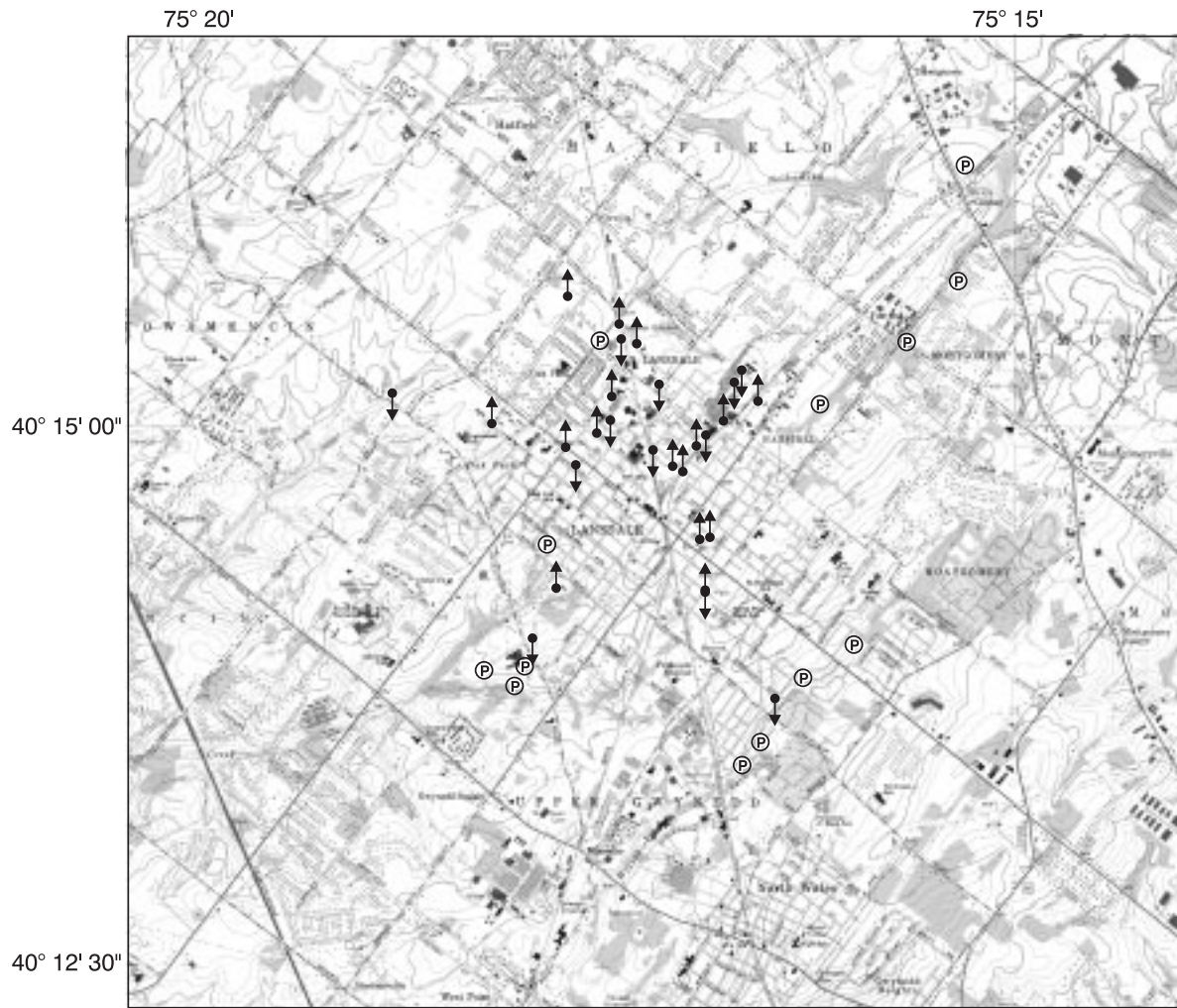
¹ Fracture depths were inferred from geophysical logs (Conger, 1999).

² Well was logged only to 120 ft bls because of obstruction at that depth.

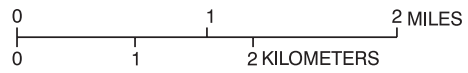
³ Brine tracing.

⁴ Only upper 92 feet of well Mg-82 was logged.

⁵ Well Mg-1613 deepened to 320 feet and reconstructed with 182 feet of casing.



Base from U. S. Geological Survey
 Lansdale 1:24,000 1983,
 Telford 1:24,000 1980,
 Ambler 1:24,000 1983,
 Doylestown 1:24,000 1983



EXPLANATION

- ↑ ● ↓ UPWARD DIRECTION OF BOREHOLE FLOW
- ↓ ● ↓ DOWNWARD DIRECTION OF BOREHOLE FLOW
- Ⓟ PUMPING WELL

Figure 21. Directions of vertical flow measured in wells logged in and near Lansdale, Pa.

Upward flow open-hole wells in the central part of the study area in Lansdale appear to conflict with downward vertical gradients typically associated with a recharge area. The area of Lansdale borough is considered a recharge area because of its relatively high topographic position and because water levels there are higher than water levels down slope from the borough. However, because beds dip in the area, upward flow at the borehole scale is possible if the deep water-bearing zones within underlying beds have a higher head than the shallow zones within overlying beds, as a result of recharge at an up-dip and up-slope (topographic) location (fig. 22). Thus, in this conceptual model of the flow system, topography (difference in elevation) is an important factor in determining ground-water flow gradients. Ground-water flow in bedrock is primarily along bedding planes, and water-bearing zones within beds are separated by layers of less permeable aquifer material. Because depth to bedrock commonly is shallow, recharge through soil and saprolite enters fractured bedrock near the land surface. The resulting potentiometric head is related to land-surface altitude near the recharge area. Remnant bedding structures in the saprolite also may preferentially direct recharge down dip. Although the flow path may be complex, the net regional flow direction generally is down the regional topographic gradient. A schematic showing relation of topography, bedding, and potentiometric head indicates that the head at deeper water-producing bedding-plane fractures is higher than shallow water-producing bedding-plane fractures except at the shallowest fractures near the water table (fig. 22). In aquifer tests where discrete water-producing zones were isolated by packers, the shallowest water-producing zone in a well had a higher head than the second deepest zone, indicating a downward gradient that is consistent with the direction of recharge in shallow depths of the aquifer. The tests are discussed in detail in the section “Single-Well, Interval-Isolation Tests.”

Downward flow in many wells in and near Lansdale is associated with proximity to a deep pumping well that results in a decrease in potentiometric head in the area of influence of the pumping well. The greatest downward flow rate of 12 gal/min (45.4 L/min) was measured in well Mg-72 (pl. 1). This well is influenced by nearby pumping of public-supply wells along Wissahickon Creek. Although no flow tests were done, downward flow in another well, Mg-76 (pl. 1), was inferred from its location near pumping wells along Wissahickon Creek and the discrete inflections in the fluid-temperature log at probable water-bearing zones (Conger, 1999).

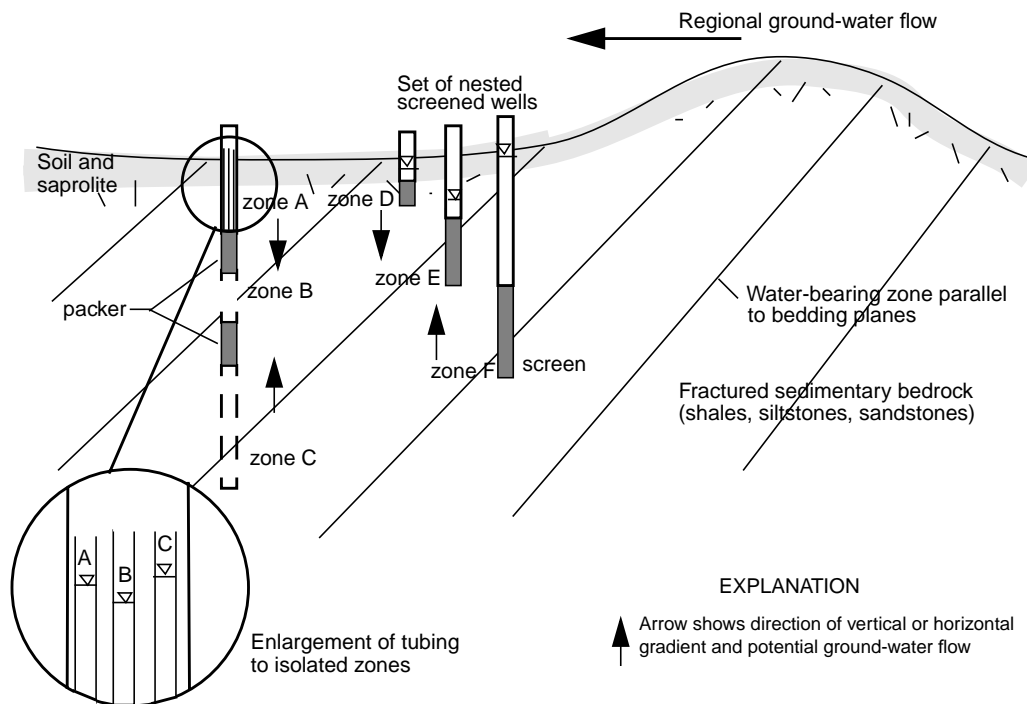


Figure 22. Conceptual ground-water flow system with wells open to different intervals in a fractured, sedimentary-rock aquifer with dipping beds.

Ground-Water/Surface-Water Relations

Streamflow is naturally composed of base flow and direct runoff. Anthropogenic withdrawals from and discharges to streams increase or decrease streamflow, respectively. Base flow is ground water discharged to streams. After rainfall or snowmelt, water of atmospheric origin that does not infiltrate or evaporate enters streams as direct runoff. Water that infiltrates is recharge. The proportion of streamflow that is base flow and direct runoff, as well as the relations between rainfall and runoff, depends on the hydrologic characteristics of a basin. Areas underlain by rocks with high permeability, such as carbonates, generally have more base flow and less direct runoff than areas underlain by rocks with low permeability, such as the Brunswick Group and Lockatong Formation (White and Sloto, 1990). Commonly, direct runoff of relatively high intensity is observed in small basins with steep slopes and low permeability soils and rocks compared to large basins with shallow slopes and high permeability rocks and soils. In urbanized areas, pavement or other impermeable land cover reduces natural infiltration and can increase the intensity and volume of direct runoff relative to undeveloped areas.

Base flow was measured seasonally at selected stream sites near Lansdale from spring 1995 through fall 1996 to provide an estimate of the quantity of ground water that discharges to streams (table 4, fig. 23). During this period,

Table 4. Streamflow measured at five sites in and near Lansdale, Pa., May 1995 to November 1996 (See figure 24 for locations of sites.)

[mi², square miles; ft³/s, cubic feet per second; in., inches; --, no data]

Site number	Site location	Drainage area ¹ (mi ²)	Streamflow, under base-flow conditions (ft ³ /s)					Estimated annual ² base flow in 1996 (in.)	
			Dates						
			5-9-95	1-31-96 to 2-8-96	5-23-96	8-30-96	11-13-96		Estimated mean ³ in 1996
SW-3	Tributary to W. Branch Neshaminy Creek at Cowpath Rd. near Kulp School	2.38	1.39	6.58	2.93	2.13	3.38	3.8	21.4
	Tributary to W. Branch Neshaminy Creek at Cowpath Rd. near Kulp School, corrected for Lansdale sewage discharge ⁴	2.38	⁵ -.31	.55	⁵ -.27	⁵ -.34	.45	.28	1.6
SW-10	Tributary to W. Branch Neshaminy Creek at Cowpath and Line Rds.	1.10	dry	.106	.0085	dry ⁶	.015	.03	.37
SW-13	Wissahickon Creek at Hancock St.		dry	.814	--	--	--	---	--
SW-13A	Wissahickon Creek at Wissahickon Ave.	2.45	--	--	.36	.07	.80	.51	3.2
SW-13A	Wissahickon Creek at Wissahickon Ave., corrected for industrial discharge ⁷	2.45	--	--	--	--	--	⁷ 4.8	⁷ 3.0
SW-17	Towamencin Creek at Sumneytown Rd.	2.06	.27	.875	.78	.40	1.37	.86	6.6
SW-17	Towamencin Creek at Sumneytown Rd., corrected for industrial discharge ⁸	2.06	--	--	--	--	--	⁸ 7.4	⁸ 5.7
SW-21	Tributary to Towamencin Creek at Troxell Rd.		.035	.306	--	--	--	--	--
SW-21A	Tributary to Towamencin Creek at Keeler Rd.	2.01		⁹ .70	.53	.10	1.40	.68	4.6

¹ Drainage area, as determined from surface topography may differ from actual stream capture zone.

² Estimated annual base was flow calculated from the estimated mean base flow for the surface drainage area.

³ Mean base flow was estimated from four seasonal measurements, assuming linear interpolation between measurements.

⁴ Daily values of sewage-plant discharge for date of streamflow measurement were provided by Lansdale Borough Sewage Treatment plant.

⁵ Negative values indicate that sewage plant discharge exceeds downstream streamflow; reach above site probably loses flow to ground water.

⁶ Flow was very low to dry; too small to measure.

⁷ Mean flow corrected by subtracting discharge of 20,500 gallons/day (260 days/year) from Precision Tube as reported to Pennsylvania Department of Environmental Protection (PADEP).

⁸ Mean flow corrected by subtracting discharge of 77,600 gallons/day from Lehigh Valley Dairy as reported to PADEP.

⁹ Estimated from sum of measurements at SW-21 and SW-20 (0.294 ft³/s) and SW-22 (0.10 ft³/s).

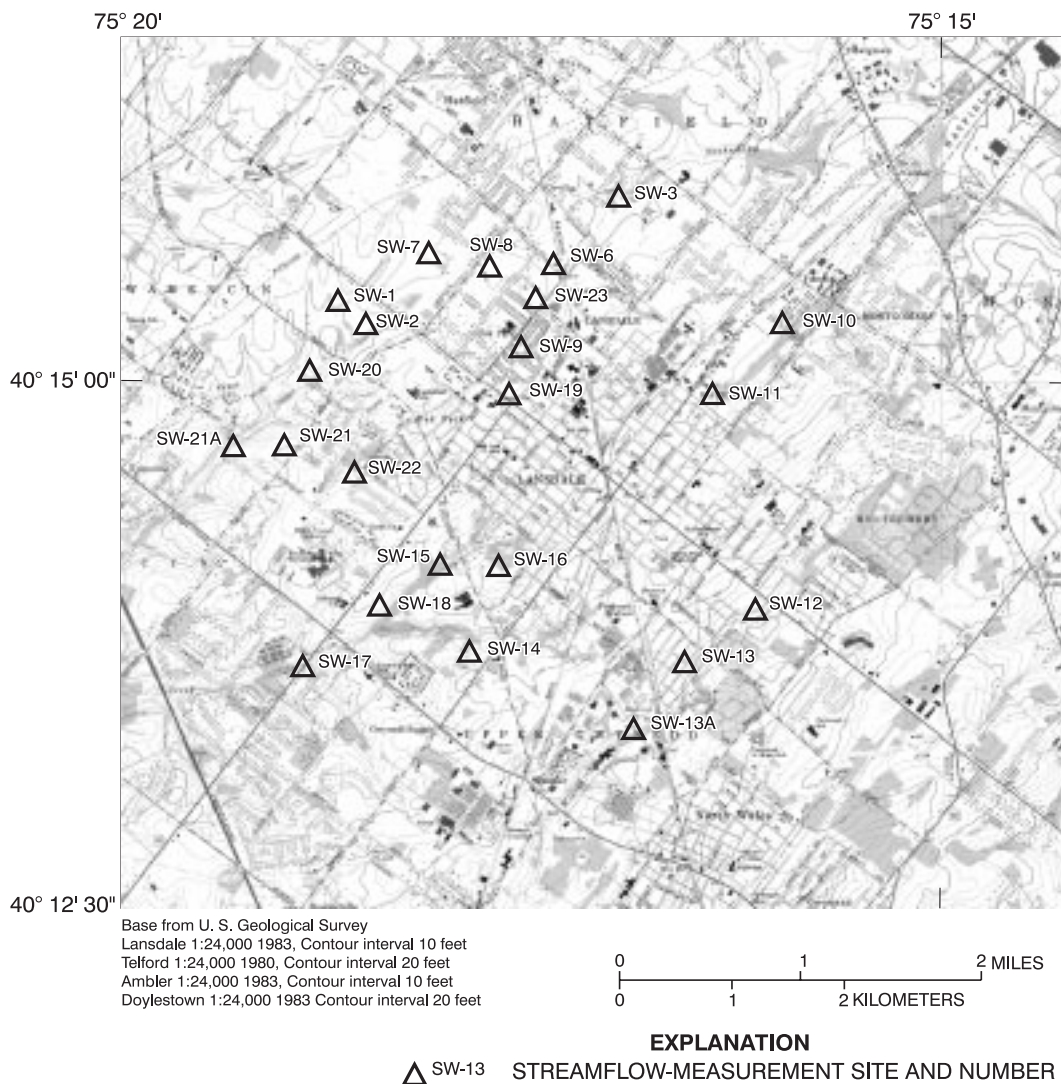


Figure 23. Location of streamflow-measurement sites in and near Lansdale, Pa.

some streams were dry, as a result of limited precipitation and lack of ground-water discharge. Estimated base-flow discharge to streams averaged about 3.2 in. (81 mm) over a 10-mi² (25.9-km²) area of Lansdale in 1996. This amount of base flow represents only part of recharge to the area. Base flow is an estimate of recharge minus possible losses to ground-water pumping, ground-water evapotranspiration, ground-water underflow to adjacent basins, and change in storage.

During May 1995, base flow at 23 stream sites and discharge from 1 pipe outfall was measured to provide data on gains and losses to streams (table 5). Where stream losses are noted between measurement sites (table 5, fig. 23), streamwater has infiltrated along the intervening reach to the ground-water system. In these areas, the potentiometric head of the ground-water system is lower than the water surface in the stream. The accuracy of the streamflow measurements should be considered in evaluating apparent gains or losses. The measurement error is estimated to be up to 10 percent.

Table 5. Streamflow at selected sites in and near Lansdale, Pa., under base-flow conditions, May 8-9, 1995, and during stormflow recession, May 10, 1995 (Site locations are shown on figure 23.)

[ft³/s, cubic feet per second; +, gain; -, loss; <, less than; μS/cm, microsiemens per centimeter; NA, not applicable]

Stream site	Method of measurement if other than standard ¹	Date	Discharge (ft ³ /s)	Gain/Loss (ft ³ /s)	Specific conductance (μS/cm)	Type of stream bottom
<u>Tributary to Towamencin Creek</u>						
SW-1		5-9-95	very low ²	NA	NA	
SW-2		5-9-95	dry	NA	NA	
SW-20	Flume	5-9-95	0.30	+0.30	320	
SW-22	Flume	5-9-95	.015	NA	390	bedrock
SW-21	Flume	5-9-95	.035	+.02	460	bedrock
<u>Towamencin Creek</u>						
SW-16		5-10-95	.28	NA	258	rocky/bedrock
SW-15		5-10-95	.74	+.046	235	rocky/bedrock
SW-18	Flume	5-9-95 ³	.057	NA	500	rocky/bedrock
SW-14		5-10-95	.85	NA	175	bedrock
SW-17		5-9-95	.27	NA	825	silt/rocky/bedrock
SW-17 (repeat)		5-10-95	.85	+.74	270	silt/rocky/bedrock
<u>Wissahickon Creek</u>						
SW-12		5-9-95	very low	NA	NA	rocky
SW-13		5-9-95	dry	<-.001	NA	rocky
<u>Tributary to W. Branch Neshaminy Creek near Line Rd.</u>						
SW-11		5-9-95	very low	<-.001	NA	clay
SW-10		5-10-95	dry	NA	NA	rocky
<u>Tributary to W. Branch Neshaminy Creek north of Moyers Rd.</u>						
SW-19	Flume	5-8-95	.063	NA	410	rocky
SW-9	Flume	5-8-95	.09	+.027	455	gravel
pipe from JW Rex		5-8-95	.067	NA	800	NA
SW-23		5-8-95	.112	NA	700	rocky
SW-7		5-9-95	seep	NA	NA	clay
SW-8		5-9-95	dry	<-.001	NA	rocky
SW-6		5-8-95	2.34	⁴ +2.10	850	silt/rocky
SW-3		5-8-95	1.39	-.95	770	silt/rocky
<u>Other tributaries to W. Branch Neshaminy Creek south of Moyers Rd.</u>						
SW-4		5-10-95	.025	NA	378	clay
SW-5		5-10-95	.051	NA	200	clay

¹ Standard method is based on measured flow velocities multiplied by cross-sectional area of stream channel.

² Very low flow was too small to measure.

³ Discharges in Towamencin Creek from 5-9-95 and 5-10-95 cannot be directly compared because precipitation during the night of 5-9-95 resulted in a change in conditions from base flow to recessions after a storm.

⁴ Discharge from the Lansdale Borough Sewage Treatment plant was estimated to range from 1.7 to 2.0 ft³/d at the time flow measured at SW-6 below plant discharge point.

The ground-water and surface-water systems are not well connected throughout the area of Lansdale. In some parts of the study area, water levels in wells near streams are similar to stream levels, indicating good hydraulic connection. However, in several locations where deep observation wells were drilled adjacent to streams, the observed water level in the wells was either higher (well Mg-930) or lower (wells Mg-68, Mg-1124, and Mg-1126) than the observed stream level (pl. 1). Where ground-water levels are higher than the stream, there is potential for upward flow or discharge to the stream. Where ground-water levels are lower than the stream, there is potential for infiltration of water from the stream to the ground-water system. Ground-water levels near streams may be lowered by nearby pumping. The connection between the stream and the ground-water system is affected by the permeability of materials of the streambed. Low permeability clays and weathered bedrock can reduce ground-water discharge to streams and infiltration from the stream to the ground-water system. In the Lansdale area, streambed materials consist of fractured bedrock in parts of the Towamencin and Wissahickon Creeks and clay and silt in most tributaries to West Branch Neshaminy Creek and other parts of the Towamencin and Wissahickon Creeks. Where streams are underlain solely by unweathered fractured bedrock, the upper part of the bedrock aquifer and the surface-water system probably are in direct hydraulic connection. Water in the deep parts of the aquifer may not discharge to the shallow, small, headwater streams that originate in the area of Lansdale but rather travel down-gradient to discharge to larger streams or pass into other basins as underflow.

Ground-Water Quality

The chemical composition of ground water is derived from the weathering of minerals and biologically mediated reactions in soils and aquifer materials. The quality of ground water can be affected by the introduction of synthetic organic compounds and pollutants, such as in the area of Lansdale where VOC's are ground-water contaminants (CH2MHill, 1991; Black & Veatch Waste Science, Inc., 1998). Chlorinated solvents PCE and TCE may degrade to VC by dehalogenation under reducing conditions (Bouwer and McCarty, 1983); VC may degrade to carbon dioxide under oxidizing conditions (McCarty and Semprini, 1994).

To assess general ground-water chemistry and determine the extent of reducing conditions favorable for degradation of chlorinated solvents, the USGS measured the water temperature, pH, specific conductance, alkalinity, and dissolved-oxygen concentration of water samples in the field during fall 1997. Measurements were made on water samples collected at a sampling port from pumping wells that were being sampled by USEPA's contractor, B&V, for VOC's and other constituents. The water temperature, pH, specific conductance, and alkalinity were measured by USGS by use of methods outlined in Wood (1976) and Wilde and Radtke (1998). Dissolved oxygen was measured by use of the azide modification of the Winkler titration method (American Public Health Association and others, 1976). The field analyses (tables 6 and 22) indicate that ground water in and near Lansdale generally has a near neutral pH and moderate alkalinity that probably represents dissolution of carbonate minerals in the Brunswick Group and Lockatong Formation. Many water samples were near saturation with respect to calcite, as calculated from calcium concentration, alkalinity, and pH. The median pH was 7.3, and the median alkalinity was 188 mg/L as CaCO₃ for wells sampled (table 6). Only two samples had alkalinity of less than 130 mg/L. Both samples were from shallow wells, suggesting that the water in the wells may have relatively short contact time with aquifer materials compared to water from deeper wells.

Table 6. Summary of chemical properties or constituents measured in the field for water samples from selected wells in and near Lansdale, Pa., fall 1997

[°C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; <, less than; CaCO₃, calcium carbonate]

Chemical property or constituent	Units	Number of wells	Minimum	10th percentile	Median	90th percentile	Maximum
Water temperature	°C	¹ 92	12.0	13	14.5	16.3	21.8
pH	units	¹ 92	5.6	7.0	7.3	7.7	8.2
Specific conductance	μS/cm	93	330	420	610	750	1,240
Dissolved oxygen	mg/L	² 91	<.1	.4	2.0	5.5	9.2
Alkalinity	mg/L as CaCO ₃	³ 82	54	150	190	230	320

¹ Missing value for sample from one well.

² Missing values for samples from two wells.

³ Missing values for samples from 10 wells.

A pH in the range of 5 to 9 is optimal for biodegradation of the chlorinated solvents (Wiedemeier and others, 1996, p. 2-22). All 39 wells sampled in the area of Lansdale in 1997 had water with a pH in the range of 5 to 9 (table 6). Alkalinity greater than twice the background alkalinity may indicate degradation of chlorinated solvents (Wiedemeier and others, 1996, p. 2-22). Background alkalinity is estimated to range from 150 to 200 mg/L as CaCO₃ in ground water in the Lansdale area.

The specific conductance, a measure of total dissolved ions, ranged between 333 and 1,286 µS/cm and was moderately correlated with alkalinity ($r=0.6$), suggesting that dissolved anions other than bicarbonate are present in ground water at concentrations large enough to affect conductance. These other anions include chloride, sulfate, and nitrate. In samples collected in fall 1997 (Black & Veatch Waste Science, Inc., 1998) from 39 (of 93) wells, concentrations of chloride ranged from about 5 to 196 mg/L, with a median of 49 mg/L; sulfate ranged from 17 to 193 mg/L, with a median of 38 mg/L; and nitrate concentrations ranged from less than 0.05 mg/L as N (reporting level) to 0.92 mg/L as N, with a median of 0.34 mg/L as N.

Chloride concentrations greater than twice the background concentration may indicate dechlorination of chlorinated solvents (Wiedemeier and others, 1996, p. 2-22). Chloride concentrations greater than 10 mg/L are greater than natural background, indicating an anthropogenic source of chloride. In the urbanized Lansdale area, almost all water samples contained more than 10 mg/L chloride, but determination of background chloride concentrations is difficult because of the several possible sources. Chloride can be introduced into the ground water by road salting, leaking sewage lines, septic systems, or by degradation (dehalogenation) of chlorinated organic solvents such as PCE and TCE. Sulfate concentrations less than 20 mg/L and nitrate concentrations less than 0.5 mg/L as N are thought to be consistent with reducing conditions favorable for degradation of chlorinated solvents (Wiedemeier and others, 1996, p. 2-22). Although most water from 39 wells sampled in 1997 in the Lansdale area contained less than 0.5 mg/L as N nitrate, most water samples also contained more than 20 mg/L sulfate.

Concentrations of dissolved oxygen ranged from less than 0.1 mg/L (reporting level) to 9.2 mg/L; the median concentration was 2 mg/L. The generally low but detectable concentrations of dissolved oxygen measured in well samples indicate some persistence of oxygen in ground water through the recharge process. Where dissolved oxygen is present near saturation concentrations of about 11 mg/L at 12°C (American Public Health Association and others, 1976, p. 446), there is rapid recharge and (or) lack of oxidation reactions along the recharge path. Generally, where dissolved oxygen is absent or is present at low concentrations, recharge is slow and (or) oxidation reactions along the recharge path or in the ground-water system are active. Reactions that consume oxygen include oxidation of natural and synthetic organic compounds; these reactions may be biologically mediated. Wiedemeier and others (1996, p. 2-22) have proposed that oxygen concentrations less than 0.5 mg/L indicate reducing conditions favorable for degradation of chlorinated solvents. About 18 percent (16 of 91) of the wells sampled in 1997 by B&V yielded water that contained concentrations less than or equal to 0.5 mg/L dissolved oxygen, and most of these wells (11) were in an area from 3rd to 9th Sts., west of Cannon St. in the northwestern part of Lansdale Borough (table 22, pl. 1). VC and cis-1,2-DCE, products of TCE and PCE degradation, also were measured in ground water in this area. The low concentrations of dissolved oxygen and detection of cis-1,2-DCE and VC in this area suggest past or ongoing degradation of chlorinated solvents.

ESTIMATION OF AQUIFER HYDRAULIC PROPERTIES

Hydraulic conductivity and storage are aquifer properties that may vary spatially because of geologic heterogeneity. Estimation of these properties allows quantitative prediction of the hydraulic response of the aquifer to recharge and pumping. Storage coefficients are important for understanding hydraulic response to transient stresses on aquifers. These properties can be estimated on a local scale by analysis of data from aquifer tests, such as single-well or multiple-well aquifer tests, or on a regional scale by a numerical simulation of ground-water flow by use of a computer-based model. The local scale ranges from tens of feet to hundreds of feet. The regional scale is characterized by lengths of hundreds to thousands of feet. Transmissivity, the hydraulic conductivity multiplied by the saturated thickness of the aquifer, represents a vertical average of hydraulic conductivities that may vary with depth. Most of the analytical techniques used to estimate the hydraulic properties of aquifers were developed for porous media, such as unconsolidated sediments. These techniques may provide reasonable estimates of hydraulic properties in fractured rocks, however, when the hydraulic response of the fractured-rock aquifers approximates porous media at the scale of interest. In this report, the regional-scale flow model assumes steady-state conditions, hence the storage coefficient cannot be estimated from it.

Aquifer Tests

As part of this study, several types of aquifer tests were conducted by the USGS and others in the Lansdale area since 1995. At each of three sites, both a single well, aquifer-interval-isolation test in one borehole and a multiple-well test (single pumping well and multiple observation wells) were done by USGS. At a fourth site (J.W. Rex), single-well, interval-isolation tests in two wells and a multi-well test were done by a private contractor for the property owner (QST Environmental, Inc., 1998). In addition, specific-capacity data are available for wells pumped during ground-water sampling done by the USEPA contractor (Lusheng Yan, Black & Veatch Waste Science, Inc., written commun., 1997). This report presents in detail the tests done by USGS and briefly discusses tests done by others.

In a review of aquifer-test data collected prior to this study (pre-1995), Goode and Senior (1998) summarized the range of estimated transmissivity and storage coefficients. Estimates of transmissivity ranged from 0 to about 5,400 ft²/d (0 to 500 m²/d); estimates from most tests ranged from 108 to 1,080 ft²/d (10 to 100 m²/d). Estimates of storage coefficients ranged from 0.00001 to 0.26; most estimates ranged from 0.0001 to 0.007.

Single-Well, Interval-Isolation Tests

Water enters open-hole wells through discrete openings or zones in fractured-rock aquifers. Most ground-water flow and contaminant movement at the site is through distinct water-bearing zones consisting of one or more fracture(s), and the hydraulic and chemical characteristics of each water-bearing zone can differ. By isolating these discrete zones with inflatable packers, hydraulic properties of individual zones and the extent of vertical hydraulic connection between zones can be determined. This determination provides data on the vertical distribution of hydraulic properties.

The USGS performed single-well, aquifer-interval-isolation tests in three wells known to yield water containing VOC's and near known sources of soil contamination. The wells were Mg-80 (at Keystone Hydraulics), Mg-1443 (at Philadelphia Toboggan), and Mg-1444 (at Rogers Mechanical) (pl. 1). The objectives of the single-well, interval-isolation tests were to (1) provide information on hydraulic heads and specific capacities of discrete vertical intervals and the hydraulic connection between intervals, and (2) provide water samples from discrete water-bearing zones to allow the USEPA to characterize the vertical extent of contamination in each well. Similar single-well, aquifer-interval-isolation tests were done in two wells, Mg-624 and Mg-1639, at the J.W. Rex property by QST Environmental, Inc.

Packers were set to isolate selected water-bearing (producing or receiving) zones. The number and depths of intervals to be tested in each open-hole well were based on an analysis of the borehole geophysical logs. A straddle packer was used to isolate three intervals and a single packer was used to isolate two intervals in the open-hole wells. When inflated, the rubber bladder of each packer acts as a plug sealing off 4 ft (1.2 m) of the borehole between two zones. Water levels in each isolated zone were measured before and after packer inflation by use of electric tapes. The reference measuring point for water levels and all logged depths was land surface. When possible, water levels also

were measured during pumping by use of pressure transducers; drawdowns were recorded at a specified change in water level [0.1 ft (.03 m)]. Pumping duration was approximately 1 to 2 hours; rates ranged from about 0.2 to 4 gal/min (0.76 to 15 L/min) for each test.

Specific capacity and transmissivity for each isolated zone were calculated. These results are compared to additional data, where available, on specific capacities of the open-hole wells determined from pumping rates and drawdowns during pumping for open-hole tests (Conger, 1999; Black & Veatch Waste Science Inc., 1998). The transmissivity (T) was calculated by use of the Thiem equation (Bear, 1979), assuming steady-state conditions, as follows:

$$T = \frac{Q}{2\pi\Delta h} \ln \frac{R}{r_w}, \quad (1)$$

where Q is pumping rate,

Δh is change in head,

R is radius of influence of pumping, and

r_w is radius of well.

For analysis of data from single-well, interval-isolation tests at the three wells (Mg-80, Mg-1443, and Mg-1444), R was assumed to equal 328 ft (100 m). This method of estimating transmissivity is similar to that used by Shapiro and Hsieh (1998) for short-term, low-injection-rate, single-well, interval-isolation tests in low-permeability fractured rocks. For the tests by Shapiro and Hsieh (1998), R was assumed to equal 9.8 ft (3 m). The rate and duration of pumping of tests for the present study were greater than in the tests by Shapiro and Hsieh (1998), and it is reasonable to assume that R would be greater than 9.8 ft (3 m).

Single-well, interval-isolation aquifer tests at three wells in Lansdale (Mg-80, Mg-1444, Mg-1443) generally indicate that (1) discrete water-bearing openings are not well connected in the vertical direction and (2) specific capacity and estimated transmissivity ranged over two to three orders of magnitude in the water-bearing zones tested. No relation between depth and specific capacity or estimated transmissivity was noted in the results of tests of isolated zones in the three wells. Evidence for limited vertical hydraulic connection between water-bearing openings includes differences in static potentiometric head up to 15 ft (46 m) over 300 vertical ft (91 m) and typically small drawdown in zones adjacent to the isolated pumped zone.

The chemical and physical properties of borehole discharge were measured at various times during pumping by the USGS by the use of temperature-compensated pH and specific-conductance meters. After physical and chemical properties stabilized or after three test-interval volumes of borehole water were pumped, water samples for measurement of pH, specific conductance, temperature, and dissolved oxygen concentration were collected. Samples for VOC analysis then were collected by the USGS and forwarded to USEPA's contractor, B&V, for analysis. In single-well, aquifer-interval-isolation tests by QST Environmental, Inc., in wells Mg-624 and Mg-1639, the USGS measured chemical and physical properties and QST Environmental, Inc., collected samples for VOC analysis. The pH and specific conductance were measured by methods outlined in Wood (1976). Dissolved oxygen was measured by use of the azide modification of the Winkler titration method (American Public Health Association and others, 1976).

Well Mg-80

The open-hole well is about 270 ft (82.3 m) in depth with a few feet of soft sediment at the bottom of the well. An 8-in. (0.2-m) diameter casing extends to a depth of 138 ft bls (42.1 m). Geophysical logging (Conger, 1999) indicated water-bearing zones at 144-154 ft bls (43.4-46.9 m) and 253-258 ft bls (77.1-78.6 m) (fig. 24). Under non-pumping conditions, upward flow in the borehole was measured with inflow from fractures at 253-258 ft bls (77.1-78.6 m) and outflow through fractures at 144-154 ft bls (43.4-46.9 m). The flow pattern indicated a difference in hydraulic heads in the well. When the open-hole well was pumped at a rate of about 1 gal/min (3.785 L/min) in summer 1996, the fractures at 144-154 ft bls (43.4-46.9 m) produced most of the fluid.

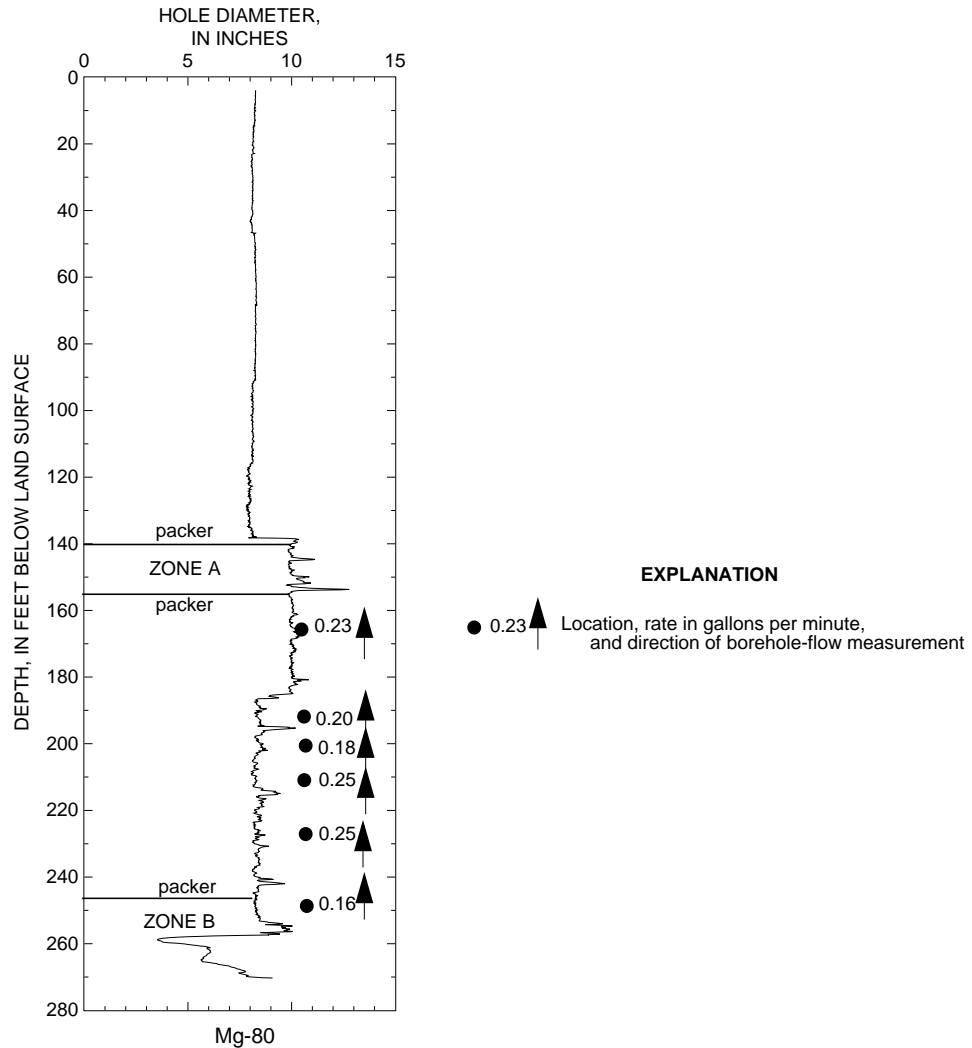


Figure 24. Depth of packers for aquifer-interval-isolation tests and direction of nonpumping flow in well Mg-80 in Lansdale, Pa.

Tests in well Mg-80 were conducted on March 24-27, 1997. Packers isolated two intervals (fig. 24) for testing, including below 246 ft bls (75 m) (zone B) and 142-157 ft bls (43.3-47.8 m) (zone A). Depth to water in the open borehole was 12.43 ft bls (3.79 m). After packer inflation, water levels were measured above, in, and for zone A below the isolated intervals. Water levels in isolated intervals stabilized in about 15 minutes after packer inflation. In test of zone A, the isolated interval was pumped at about 2 gal/min (7.6 L/min), and drawdown was observed in all three intervals (fig. 25, table 7). The observed drawdowns indicate either the packers did not isolate the interval (seal the borehole) effectively or the intervals are connected outside of the well. In the test of zone B, a single packer was placed at 246 ft bls (75 m) and the pump was placed below the packer. Drawdown was observed only in the pumped zone (fig. 26, table 7). These results indicate that the zone below 246 ft bls (75 m) is hydraulically isolated from water-bearing zones above that depth. In the test of zone A, a straddle packer with a 15-ft (4.6-m) spacing between center of packers was used to isolate the interval of 142-157 ft bls (43.3-47.8 m). The water level in the isolated interval was slightly higher than in the upper or lower intervals after packer inflation (table 7).

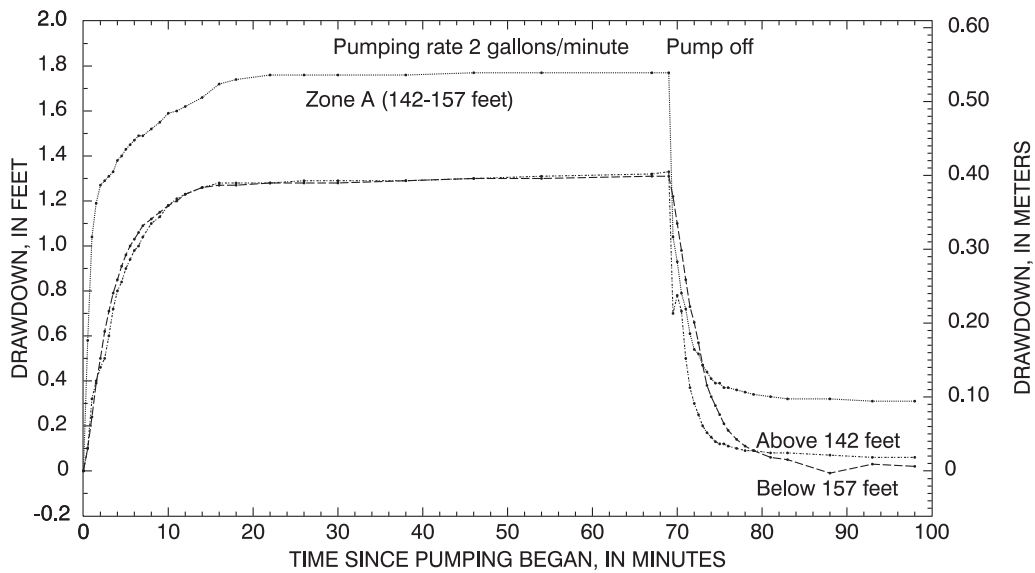


Figure 25. Drawdown as a function of time in aquifer-interval-isolation test of zone A in well Mg-80 in Lansdale, Pa., March 26, 1997.

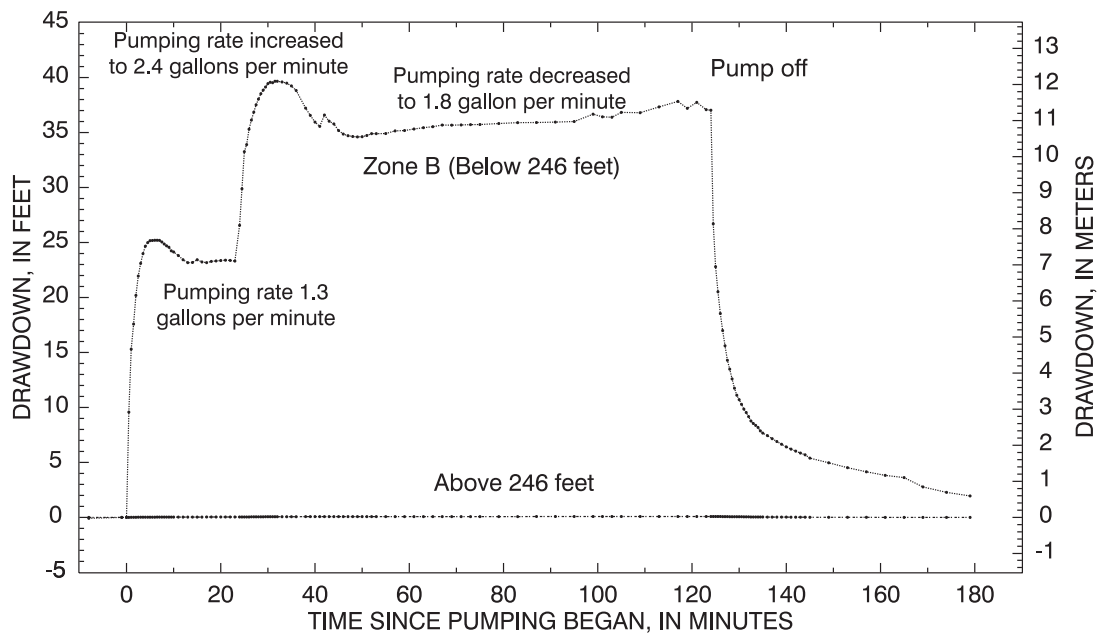


Figure 26. Drawdown as a function of time in aquifer-interval-isolation test of zone B in well Mg-80 in Lansdale, Pa., March 27, 1997.

The interval between 142-157 ft bls (43.3-47.8 m) has a greater specific capacity than the interval below 246 ft bls (75 m). These specific-capacity measurements are consistent with the heatpulse-flowmeter measurements that indicated fractures in the upper zone produced most water when the open well was pumped (Conger, 1999). The calculated specific capacity for the zone A (table 7) in this borehole probably is greater than actual specific capacity for the zone because of contribution from other intervals. The sum of specific capacities determined for isolated zones A and B is similar or somewhat less than the specific capacity determined for the open-hole tests (table 7).

Table 7. Depths, water levels, specific capacity, and transmissivity of aquifer intervals isolated by packers and of the open hole for well Mg-80 in Lansdale, Pa., March 1997, May 1996, and September 1997

[ft bls, feet below land surface; ft, feet; gal/min, gallons per minute; min, minutes; (gal/min)/ft, gallons per minute per foot; ft²/d, square feet per day; NA, not applicable]

Depth of isolated intervals (ft bls)	Date of test	Pre-pumping depth to water in interval ¹ (ft bls)	Depth to water in interval at end of test ² (ft bls)	Drawdown at end of test (ft)	Pumping rate (gal/min)	Pumping duration (min)	Specific capacity [(gal/min)/ft]	Transmissivity ³ (ft ² /d)
<u>Zone A (142-157 ft bls)</u>								
Open hole	3-26-97	12.43	NA	NA	NA	NA	NA	NA
Above 142	3-26-97	11.93	13.26	1.33	NA	NA	NA	NA
142-157 (pumped)	3-26-97	11.88	13.65	1.77	2	69	⁴ 1.13	⁵ 238
Below 157	3-26-97	12.03	13.34	1.31	NA	NA	NA	NA
<u>Zone B (below 246 ft bls)</u>								
Above 246	3-27-97	12.11	12.19	.08	NA	NA	NA	NA
Below 246 (pumped)	3-27-97	12.07	49.10	37.03	1.8	124	.037	10.2
Sum of specific capacities or transmissivities for intervals tested							1.17	248
<u>Open-hole tests</u>								
Open hole	5-23-97	13.29	13.8	.51	1	79	1.96	413
Open hole	9-30-97	15.2	25.78	10.58	12	65	1.13	239

¹ Stabilized water levels after packers were inflated.

² Depth to water at end of pumping at a constant rate before the pump was shut off.

³ Calculated using Thiem equation, assuming a radius of influence, r_0 , of 328 feet (100 meters).

⁴ Measured specific capacity for zone greater than actual specific capacity because of contributions of flow from other intervals.

⁵ Calculated transmissivity for zone greater than actual transmissivity because of contributions of flow from other intervals.

Well Mg-1443

The caliper log indicated fractures at 35-41 ft bls (10.7-12.5 m), 104-106 ft bls (31.7-32.3 m), 175-178 ft bls (53.3-54.3 m), and 289-291 ft bls (88.1-88.7 m) in the 339-ft (103.3-m) deep, 8-in.- (0.2 m) diameter borehole (fig. 27). When the open-hole well was pumped at a rate of about 1 gal/min (3.785 L/min) in summer 1996, the fractures at 289-291 ft bls (88.1-88.7 m) appeared to produce most of the water and fractures at 104-106 ft bls (31.7-32.3 m) produced the second greatest amount (Conger, 1999). Under nonpumping conditions in summer 1996, minor upward flow was measured between the depths of 332 ft bls (101.2 m) and 68 ft bls (20.7 m) (Conger, 1999). This flow pattern indicates a difference in hydraulic heads between water-bearing zones in the borehole.

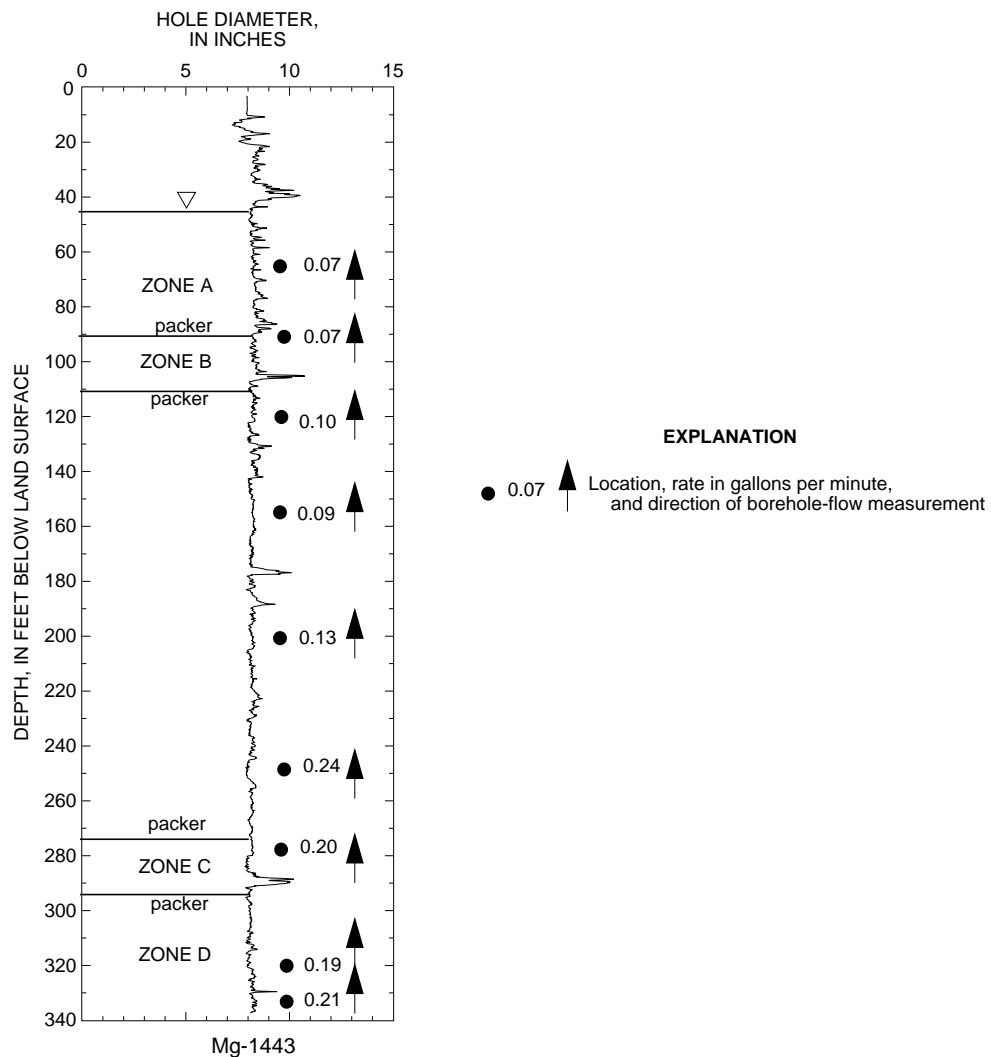


Figure 27. Depth of packers for aquifer-interval-isolation tests and direction of nonpumping flow in well Mg-1443 in Lansdale, Pa.

Tests in well Mg-1443 were conducted on April 9-11, 1997. On the basis of results of geophysical logging, four intervals were selected for testing (fig. 27) including below 296 ft bls (90.2 m) (zone D); 276-296 ft bls (84.1-90.2 m) (zone C); 90.5-110.5 ft bls (27.6-33.7 m) (zone B); and above 90.5 ft bls (27.6 m) (zone A).

In the test of zone A, the pre-pumping level in the pumped zone was about 2.4 ft (0.73 m) higher than the level in the interval immediately below (90.5-110.5 ft), indicating a downward vertical gradient between these intervals. The pre-pumping level in zone A was about 1 ft (0.3 m) lower than the interval below 110.5 ft, indicating an upward gradient between these intervals. Because testing of zone A was done soon after testing of zone B, water levels may not have fully recovered from the test of zone B. When zone A was pumped, drawdown was measured in the interval between 90.5 and 110.5 ft (27.6-33.7 m) but not in the interval below 110.5 ft (33.7 m) (fig. 28).

In the test of zone B, the pre-pumping water level in the isolated interval was almost equal to the level in the overlying interval and 0.52 ft (0.16 m) lower than the level in the underlying interval zone; the latter head difference was similar to the head difference [0.36 ft (0.11 m)] between the isolated zone C and the interval above zone C (table 8). When zone B was pumped, no drawdown was measured in the underlying interval, and about 1 ft (0.3 m) of drawdown was measured in the overlying interval (fig. 29), indicating some hydraulic connection between zone B and the interval above zone B.

In the test of zone C, the water level in the isolated interval before pumping was 4.79 ft (1.46 m) lower than the level in the underlying interval and 0.56 ft (0.17 m) higher than the level in the overlying interval, also indicating an upward vertical gradient. When pumped, small but measurable drawdown in intervals above and below zone C were observed (fig. 30), suggesting an incomplete seal by packers or hydraulic connection outside the borehole.

In the test of zone D, the water level in the isolated interval before pumping was 9.07 ft (2.76 m) higher than in the interval above 296 ft bls (90.2 m), indicating an upward vertical gradient. When zone D was pumped at a rate of about 0.2 gal/min (0.76 L/min), a large drawdown was observed in the pumped interval and very little drawdown was observed in the overlying interval (fig. 31). Zone D appeared to be hydraulically isolated from other intervals and to produce little water. Thus, water-bearing zones near the bottom of the well appear hydraulically isolated from the water-bearing zones near the top of the well.

The calculated specific capacities for zones A and C are lower than the specific capacity of zone B (table 8), which is consistent with the relative yields of these zones determined by heatpulse-flowmeter measurements while pumping (Conger, 1999). The specific capacity of zone D determined from the isolated-interval tests is probably higher than the actual specific capacity. In addition to the apparent hydraulic connection between zone D and adjacent intervals, the short duration of pumping and variable pumping rates may have affected the test. Specific capacity commonly tends to decrease with increases in pumping time. The sum of specific capacities of individual isolated zones is greater than the specific capacity determined for the open borehole in summer 1996 (Conger, 1999), possibly because of the over-estimated specific capacity of zone D (table 8).

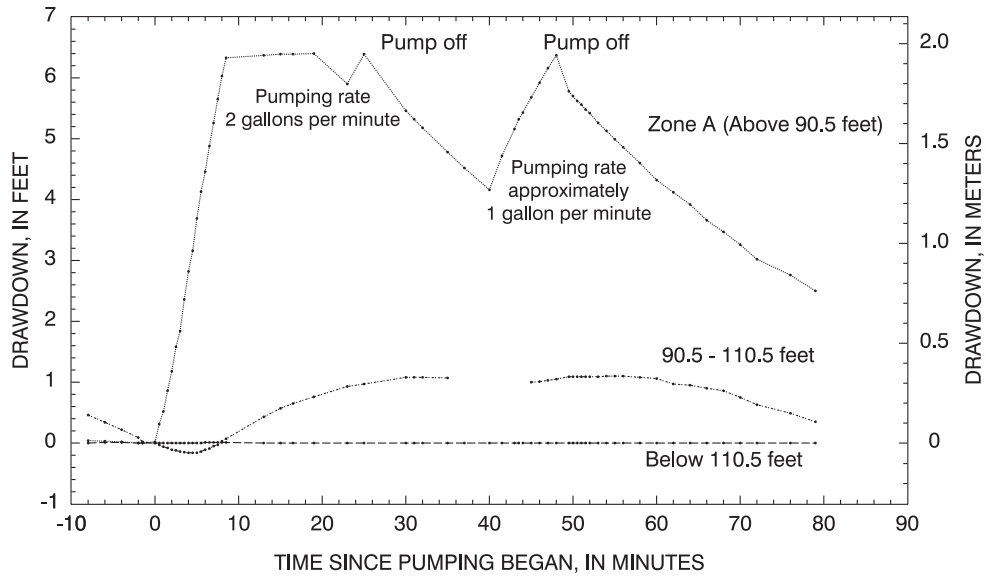


Figure 28. Drawdown as a function of time in aquifer-interval-isolation test of zone A of borehole Mg-1443 in Lansdale, Pa., April 11, 1997.

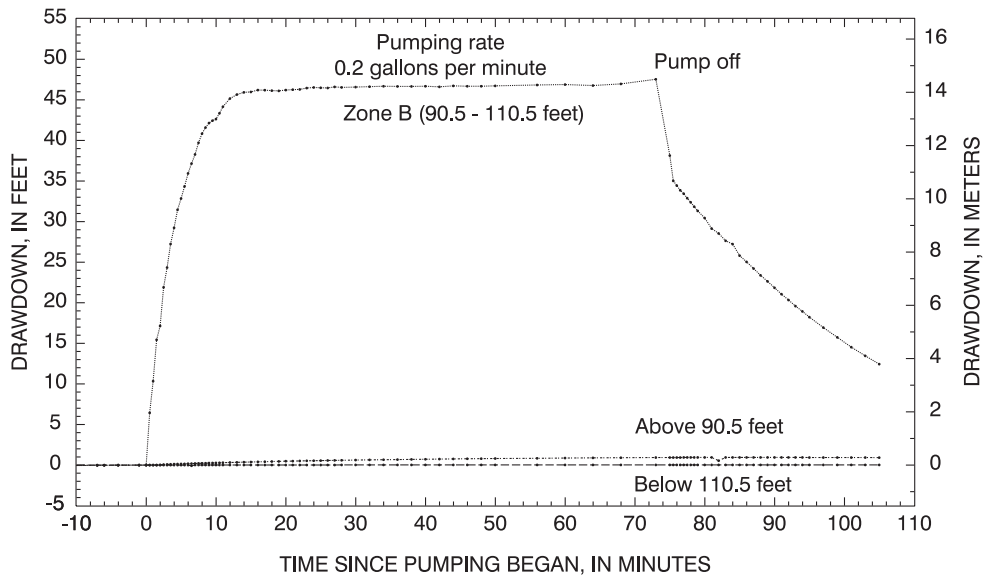


Figure 29. Drawdown as a function of time in aquifer interval-isolation test of zone B of borehole Mg-1443 in Lansdale, Pa., April 11, 1997.

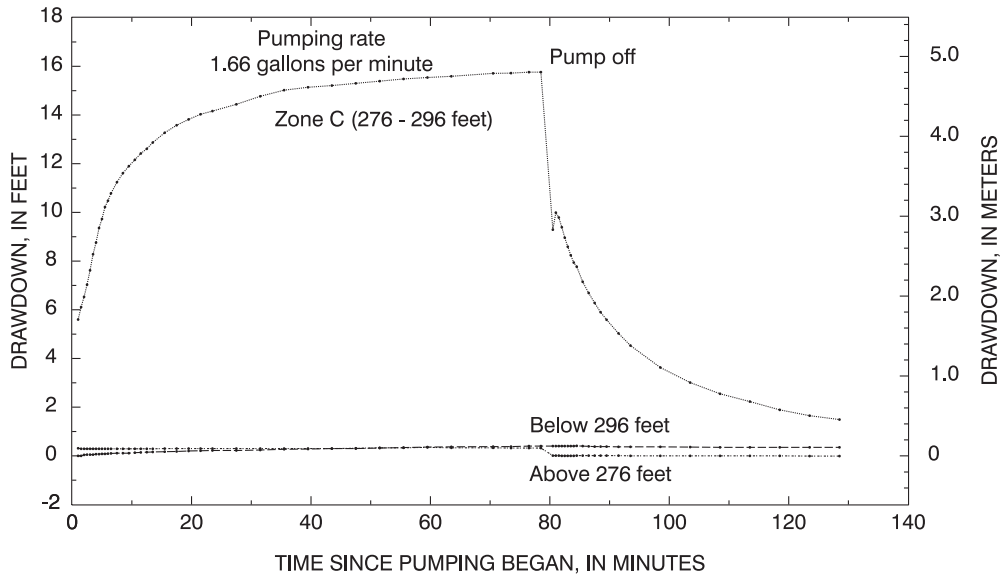


Figure 30. Drawdown as a function of time in aquifer-interval-isolation test of zone C of borehole Mg-1443 in Lansdale, Pa., April 10, 1997.

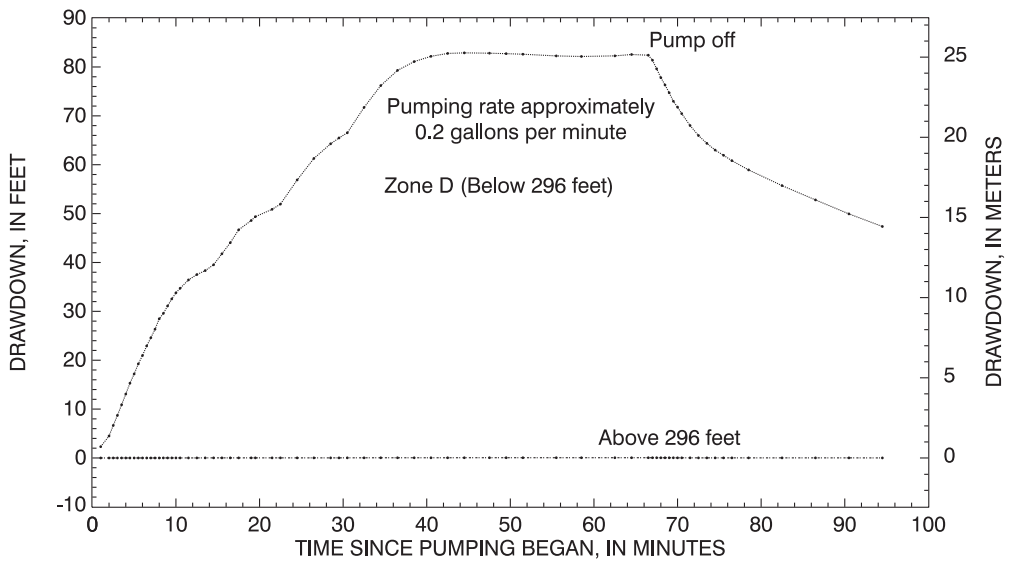


Figure 31. Drawdown as a function of time in aquifer-interval-isolation test of zone D of borehole Mg-1443 in Lansdale, Pa., April 9, 1997.

Table 8. Depths, water levels, specific capacity, and transmissivity of aquifer intervals isolated by packers and of the open hole for well Mg-1443 in Lansdale, Pa., April 1997, May 1996, and October 1997

[ft bls, feet below land surface; ft, feet; gal/min, gallons per minute; min, minutes; (gal/min)/ft, gallons per minute per foot; NA, not applicable]

Depth of isolated interval (ft bls)	Date of test	Pre-pumping depth to water in zone ¹ (ft bls)	Depth to water in zone at end of test ² (ft bls)	Drawdown at end of test (ft)	Pumping rate (gal/min)	Pumping duration (min)	Specific capacity [(gal/min)/ft]	Transmissivity ³ (ft ² /d)
Zone A (above 90.5 ft bls)								
Above 90.5 (pumped)	4-11-97	42.90	49.27	6.37	⁴ 1	21	⁵ 0.16	⁶ 34.4
90.5 - 110.5	4-11-97	45.29	46.34	1.05	NA	NA	NA	NA
Below 110.5	4-11-97	41.91	41.91	0	NA	NA	NA	NA
Zone B (90.5-110.5 ft bls)								
Above 90.5	4-11-97	42.39	43.32	.93	NA	NA	NA	NA
90.5 - 110.5 (pumped)	4-11-97	42.41	89.95	47.54	.2	73	.004	.86
Below 110.5	4-11-97	41.89	41.91	.02	NA	NA	NA	NA
Zone C (276-296 ft bls)								
Above 276	4-10-97	42.40	42.72	.32	NA	NA	NA	NA
276 - 296 (pumped)	4-10-97	42.04	57.80	15.76	1.7	78.5	.108	22.6
Below 296	4-10-97	37.25	37.65	.40	NA	NA	NA	NA
Zone D (below 296 ft bls)								
Above 296	4-9-97	41.95	42.00	.05	NA	NA	NA	NA
Below 296 (pumped)	4-9-97	32.88	115.43	82.55	.2	65	.002	.54
Sum of specific capacities or transmissivities for zones tested							.274	58.4
Open hole tests								
Open hole	5-22-97	42.09	47.35	⁷ 5.26	1	98	.19	39.8
Open hole	10-23-97	51.61	94.2	42.59	5.5	150	.13	26.9

¹ Stabilized water levels after packers were inflated.

² Depth to water at end of pumping at a constant rate before pump was shut off.

³ Calculated using Thiem equation, assuming radius of influence, r_0 , is 328 feet (100 meters).

⁴ Estimated time-weighted average of variable pumping rates ranging from 0.18 to 2.2 gallons/minute.

⁵ Calculated specific capacity for zone greater than actual specific capacity because of contributions of flow from other intervals, short duration of pumping, and variable pumping rates.

⁶ Calculated transmissivity for zone greater than actual transmissivity because of contributions of flow from other intervals, short duration of pumping, and variable pumping rates.

⁷ Drawdown did not stabilize during this test.

Well Mg-1444

Logging of well Mg-1444 identified producing fractures and vertical hydraulic head differences (Conger, 1999). The caliper log indicated major fractures at 70-72 ft bls (21.3-21.9 m), 138-141 ft bls (42.1-43 m), 153 ft bls (46.6 m), 260-265 ft bls (79.2-80.8 m) and numerous minor fractures along the open interval of the 294-ft (89.6-m) deep, 6-in.- (0.15 m) diameter borehole (fig. 32). During heatpulse-flowmeter measurements of the borehole under nonpumping conditions in summer 1996, upward borehole flow of about 1 gal/min (3.785 L/min) was measured, with inflow through fractures below 270 ft bls (82.3 m), at 260-265 ft bls (79.2-80.8 m), and possibly at 138-141 ft bls (42.1-43 m), and outflow through fractures at 70-72 ft bls (21.3-21.9 m). The observed upward flow indicated a difference in hydraulic heads in the borehole.

Tests in well Mg-1444 were conducted on April 3-7, 1997. On the basis of results of geophysical logging, five intervals were selected for testing (fig. 32) including below 268 ft bls (81.7 m) (zone E); 248-269 ft bls (75.6-82 m) (zone D); 136.5-157.5 ft bls (41.6-48 m) (zone C); 64-85 ft bls (19.5-25.9 m) (zone B); and above 64 ft bls (19.5 m) (zone A).

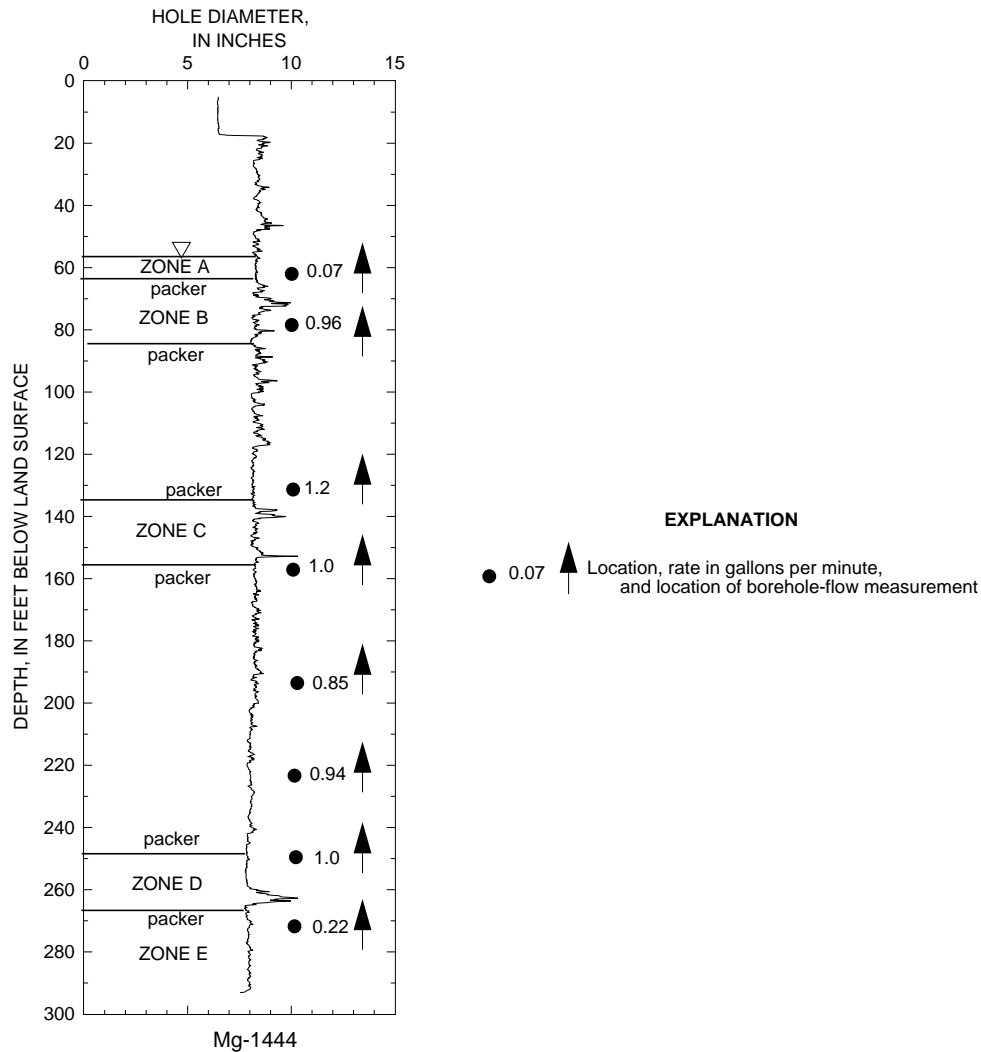


Figure 32. Depth of packers for aquifer-interval-isolation tests and direction of nonpumping flow in well Mg-1444 in Lansdale, Pa.

In the test of zone A, the pre-pumping water level in zone A was 0.28 ft (0.9 m) above the level in the interval between 64-85 ft bls (19.5-25.9 m) and 14.1 ft bls (4.30 m) lower than in the interval below 85 ft bls (25.9 m), similar to head differences measured in the test of zone B. Pumping of zone E was short in duration and at small, variable rates because the zone produced little water and dewatered rapidly. Little drawdown was measured in the interval immediately underlying zone E, and no drawdown was measured in the interval below 85 ft bls (25.9 m) (**fig. 33**).

In the test of zone B, the pre-pumping water level in zone B was 1.01 ft (0.31 m) lower than the level in the overlying interval and 12.12 ft (3.69 m) lower than the level in the underlying interval; these head differences indicate a downward vertical gradient from above and upward vertical gradient from below the isolated interval. Geophysical logging indicated fractures at 70-72 ft bls (21.3-21.9 m) were receiving, consistent with the lower heads measured in zone B compared to adjacent intervals. When zone B was pumped, gradual drawdown of up to 3 ft (0.91 m) in the interval above zone B and minor drawdown in the interval below zone B were measured (**fig. 34**). These results indicate leakage around packers or hydraulic connection outside the borehole between the zone B and the overlying interval and near hydraulic isolation between zone B and the underlying interval.

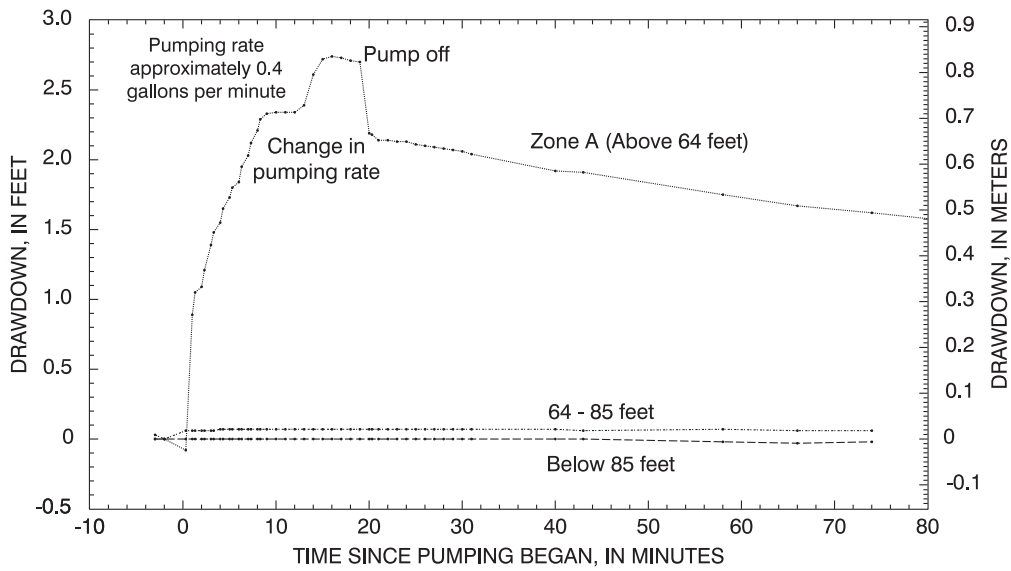


Figure 33. Drawdown as a function of time in aquifer-interval isolation test of zone A of borehole Mg-1444 in Lansdale, Pa., April 7, 1997.

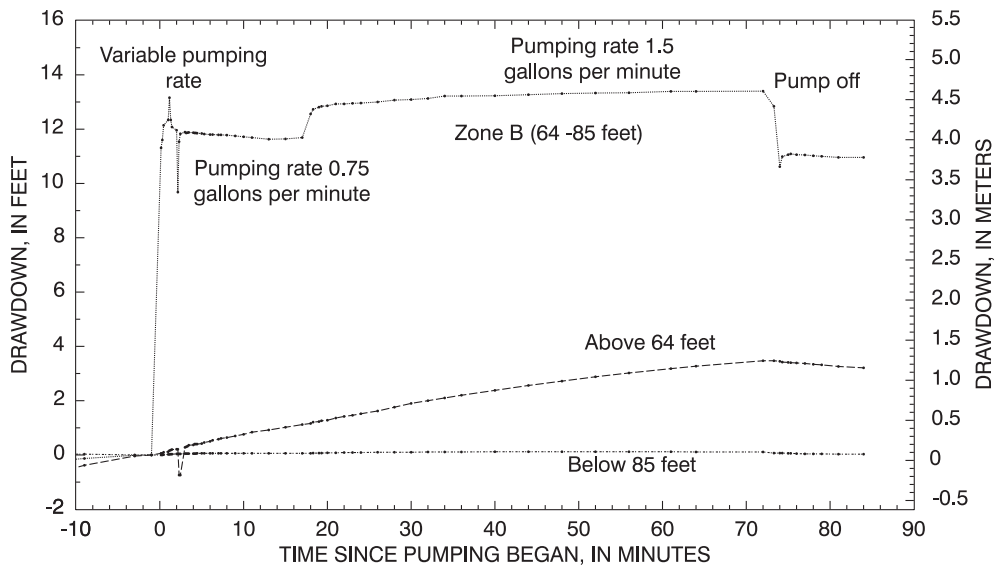


Figure 34. Drawdown as a function of time in aquifer-interval isolation test of zone B of borehole Mg-1444 in Lansdale, Pa., April 4, 1997.

In the test of zone C, the pre-pumping water level in zone C was 16.71 ft (5.09 m) higher than the level in the overlying interval and 1.06 ft (0.32 m) lower than the level in the underlying interval. These head differences are consistent with the upward flow measured with the heatpulse-flowmeter at 160 ft bls (48.8 m) and 130 ft bls (39.6 m) in summer 1996 (Conger, 1999). When zone C was pumped, very little drawdown was measured in the interval above zone C and virtually no drawdown was measured in the interval below zone C (fig. 35), suggesting hydraulic isolation between these intervals.

In the test of zone D, the pre-pumping water level in the isolated interval was 15.35 ft (4.68 m) higher than in the level in the overlying interval and 0.88 ft (0.27 m) higher than the level in the underlying interval. These head differences indicate upward and downward vertical gradients between zone D and adjacent intervals. The upward vertical gradient is consistent with the upward flow measured earlier with the heatpulse flowmeter at and above 256 ft bls (78 m) (Conger, 1999). Drawdown of more than 2 ft (0.61 m) was measured in the interval below zone D when zone D was pumped (fig. 36). These results suggest leakage around packers or a hydraulic connection outside the borehole between the isolated zone D and the underlying interval. In the test of zone D, little drawdown measured in the overlying interval indicates that zone D and the overlying interval were hydraulically isolated.

In the test of zone E, the pre-pumping water level in zone E was 6.45 ft (1.97 m) lower than the level in the overlying interval. Although upward flow was observed during heatpulse-flowmeter measurements in summer 1996, the observed head differences for zone E in April 1997 indicate a downward vertical gradient between the isolated interval and the overlying interval. Drawdown of less than 1 ft was measured in the interval above zone E during pumping of zone E (fig. 37, table 9), suggesting either leakage around packers or a hydraulic connection outside the borehole similar to the test results of zone D.

The total specific capacity of 0.89 (gal/min)/ft [11.1 (L/min)/m] determined from the interval-isolation tests was less than the specific capacity of 1.56 (gal/min)/ft [19.4 (L/min)/m] determined from an open-hole test (table 9). Results of heatpulse-flowmeter measurements in summer 1996 suggest that the zone between 248-269 ft bls (75.6-82 m) is the most productive (Conger, 1999), which is consistent with the results of the interval-isolation tests.

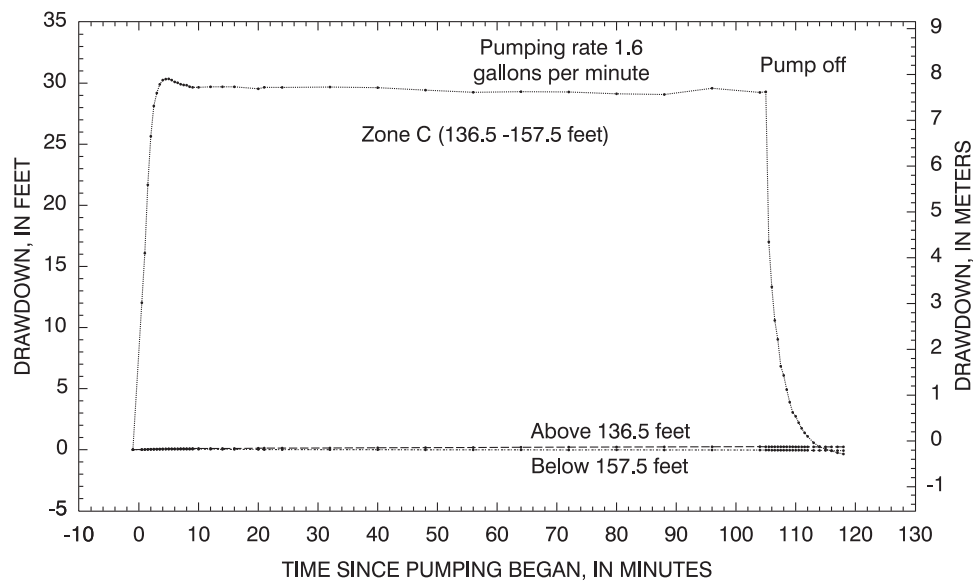


Figure 35. Drawdown as a function of time in aquifer-interval-isolation test of zone C of borehole Mg-1444 in Lansdale, Pa., April 4, 1997.

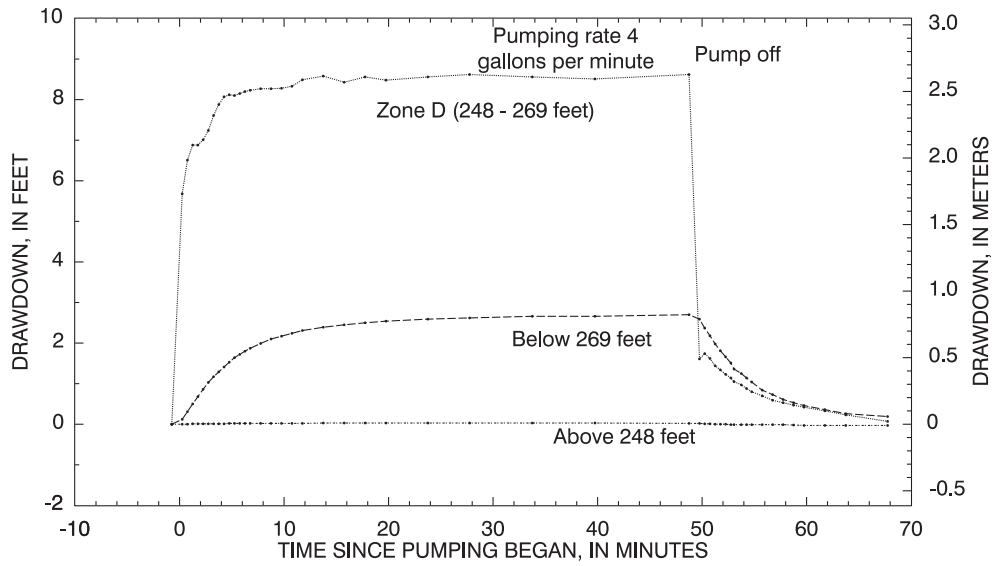


Figure 36. Drawdown as a function of time in aquifer-interval-isolation test of zone D of borehole Mg-1444 in Lansdale, Pa., April 3, 1997.

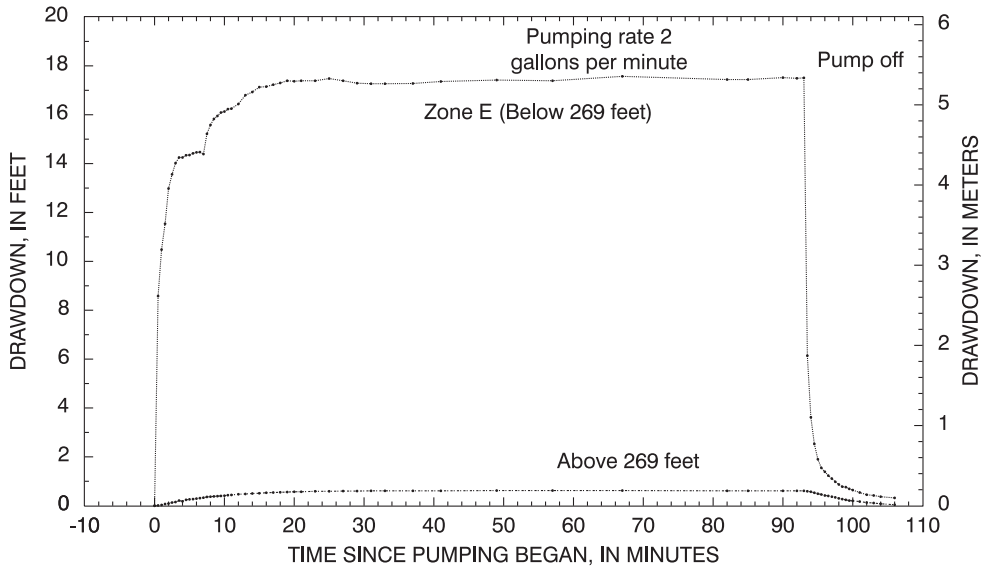


Figure 37. Drawdown as a function of time in aquifer-interval-isolation test of zone E of borehole Mg-1444 in Lansdale, Pa., April 3, 1997.

Table 9. Depths, water levels, specific capacity, and transmissivity of aquifer intervals isolated by packers and of the open hole for well Mg-1444 in Lansdale, Pa., April 1997 and October 1997

[ft bls, feet below land surface; ft, feet; gal/min, gallons per minute; min, minutes; (gal/min)/ft, gallons per minute per foot; ft²/d, square feet per day; NA, not applicable]

Depth of isolated zone in borehole (ft bls)	Date of test	Pre-pumping depth to water in interval ¹ (ft bls)	Depth to water in interval at end of test ² (ft bls)	Drawdown (ft)	Pumping rate (gal/min)	Pumping duration (min)	Specific capacity [(gal/min)/ft]	Transmissivity ³ (ft ² /d)
<u>Zone A (above 64 ft bls)</u>								
Above 64 (pumped)	4-7-97	56.34	59.04	2.7	0.4	19	0.15	32.5
64-85	4-7-97	56.62	57.32	.7	NA	NA	NA	NA
Below 64	4-7-97	42.52	42.52	0	NA	NA	NA	NA
<u>Zone B (64-85 ft bls)</u>								
Above 64	4-4-97	54.31	57.78	3.47	NA	NA	NA	NA
64-85 (pumped)	4-4-97	55.32	68.72	13.40	1.5	72	⁴ .11	⁵ 24.1
Below 85	4-4-97	43.20	43.31	.11	NA	NA	NA	NA
<u>Zone C (136.5-157.5 ft bls)</u>								
Above 136.5	4-4-97	58.15	58.38	.24	NA	NA	NA	NA
136.5-157.5 (pumped)	4-4-97	41.44	70.73	29.29	1.67	105	.057	12.5
Below 157.5	4-4-97	40.38	40.36	-.02	NA	NA	NA	NA
<u>Zone D (248-269 ft bls)</u>								
Above 248	4-3-97	54.58	54.60	.02	NA	NA	NA	NA
248 - 269 (pumped)	4-3-97	39.23	47.85	8.62	4	49	.46	102
Below 269	4-3-97	40.11	42.81	2.7	NA	n	NA	NA
<u>Zone E (below 268 ft bls)</u>								
Above 268	4-3-97	41.54	42.12	.61	NA	NA	NA	NA
Below 268 (pumped)	4-3-97	47.99	65.50	17.51	2	93	.11	25.1
Sum of specific capacities or transmissivities for zones tested							.89	196
<u>Open-hole tests</u>								
Open hole	10-1-97	58.8	65.85	7.05	11	130	1.56	342

¹ Stabilized water levels after packers were inflated.

² Depth to water at end of pumping at a constant rate before pump was shut off.

³ Calculated using Thiem equation, assuming radius of influence, r_0 , is 328 feet (100 meters).

⁴ Calculated specific capacity for zone greater than actual specific capacity because of contributions of flow from other intervals.

⁵ Calculated transmissivity for zone greater than actual transmissivity because of contributions of flow from other intervals.

Wells Mg-624 and MG-1639

Aquifer-isolation tests were done in wells Mg-624 and Mg-1639 on the J.W. Rex property in Lansdale by QST Environmental, Inc., during late August and early September 1997. Well Mg-624 is about 633 ft (193 m) deep and well Mg-1639 was about 150 ft (46 m) deep at the time of testing. Intervals for testing were selected on the basis of a review of geophysical logs done by USGS. Three intervals in well Mg-624 and four intervals in well Mg-1639 were tested.

The aquifer-interval-isolation tests in well Mg-624 indicated the tested intervals had relatively low permeability (table 10). The sum of transmissivities for tested zones was about 9.2 ft²/d, similar to a value of about 6 ft²/d reported for an earlier aquifer test of the well (Goode and Senior, 1998). In the test of zones A and B [116-146 ft (35.3-44.5 m) and 185-215 ft (56.3-65.5 m)], water levels in isolated intervals indicated a downward vertical gradient. In the test of zone C [290-320 ft (88.4-97.5 m)], water levels in the isolated intervals indicated a small

Table 10. Summary of aquifer-isolation tests of wells Mg-624 and Mg-1639, Lansdale, Pa., August and September 1997. Data from QST Environmental, Inc. (1998)

[ft bls, feet below land surface; ft/d, feet per day; ft²/d, square feet per day; --, no data]

U.S. Geological Survey local well number Mg-	Pumped interval	Depths of isolated intervals (ft bls)	Date of test	Pre-pumping depth to water (ft bls)	Pumping depth to water (ft bls)	Hydraulic conductivity ¹ (ft/d)	Transmissivity ² (ft ² /d)
624	Zone A	Above 116	9-2-97	12.34	36.61	0.13	3.9
		116-146	9-2-97	12.98	111.68		
		Below 146	9-2-97	13.06	28.20		
624	Zone B	Above 185	9-2-97	15.65	55.21	.006	.18
		185-215	9-2-97	15.85	197.27		
		Below 215	9-2-97	17.34	21.54		
624	Zone C	Above 290	9-3-97	12.7	30.7	.17	5.1
		290-320	9-3-97	12.6	150.7		
		Below 320	9-3-97	12.2	17.6		
624	Sum of zones tested					.306	9.2
1639	Zone A	0-40	8-28-97	24.78	32.39	--	--
		Below 40	8-28-97	26.00	34.00		
1639	Zone B	Above 40	8-28-97	25.30	25.96	--	--
		40-60	8-28-97	24.89	28.62		
		Below 60	8-28-97	29.60	30.90		
1639	Zone C	Above 80	8-28-97	23.98	24.51	.03	.6
		80-100	8-28-97	26.61	59.74		
		Below 100	8-28-97	26.47	51.47		
1639	Zone D	Above 100	8-29-97	24.29	24.98	.001	.02
		100-120	8-29-97	27.51	103.27		
		Below 120	8-29-97	27.28	96.30		

¹ Determined from analysis of slug tests (QST Environmental, Inc. 1998).

² Calculated by multiplying thickness of isolated interval (20 or 30 feet) by hydraulic conductivity for interval.

upward vertical gradient. The upward vertical gradient is consistent with measurements of upward flow at very low rates (less than 0.01 gal/min) at depths of 66, 100, 214, and 322 ft (20, 30, 65, and 98 m) in well Mg-624 during logging in September 1995 (Conger, 1999). Pumping in well Mg-624 produced little to no drawdown in the nearby shallow [50 ft (15 m)] well Mg-1641, indicating the tested zones are hydraulically isolated from the shallow interval open to well Mg-1641. However, pumping in the three tested zones resulted in drawdown in adjacent intervals in well Mg-624, indicating leakage around packers or hydraulic connection outside of the borehole.

The aquifer-interval-isolation tests in well Mg-1639 indicated the deeper two tested intervals had relatively low permeability (table 10). The upper two intervals tested recovered too quickly from the slug test for analysis and no estimates of permeability were made (QST Environmental, Inc., 1998). Pumping in the upper intervals tested [above 40 ft (12 m) and 40-60 ft (12-18m)] resulted in drawdown in the adjacent shallow monitoring well (Mg-1640) and in the adjacent shallow zone but little to no drawdown in the deeper intervals. Thus, the shallow intervals of well Mg-1639 appear to be hydraulically isolated from the deep zones of the well. Water levels in the isolated intervals of well Mg-1639 indicate a downward vertical gradient. Downward flow was measured during geophysical logging of the well (Conger, 1999).

Chemical and physical properties of water

Chemical and physical properties and selected results of VOC analysis of water samples collected at the end of pumping of each isolated zone of wells Mg-80, Mg-1443, and Mg-1444 are summarized in table 11. Selected water-quality data from the aquifer-interval-isolation tests done by QST Environmental, Inc., in wells Mg-624 and Mg-1639 also are presented in table 11. For each pumped zone, the chemical and physical properties stabilized after about 20 to 40 minutes of pumping.

Comparison of the data for each isolated zone indicates the chemical and physical properties of the water differed slightly within the boreholes and differed to a greater extent between boreholes. Minor differences in chemical and properties of water from isolated zones may indicate hydraulic connection between zones, either by vertical flow between water-bearing zones in the borehole or through fracture networks outside the borehole. Upward flow was observed in wells Mg-1443 and Mg-1444, downward borehole flow was observed in well Mg-80 and Mg-1639, and upward and downward vertical gradients were measured in well Mg-624 (Conger, 1999; QST Environmental, Inc., 1998). Differences in properties measured in water from upper (shallow) and lower (deep) zones of wells Mg-1443, Mg-1444, and Mg-1639 included (1) the water temperature in the upper zones tended to be higher than that in the lower zones; (2) water temperature in zones with relatively high productivity generally was lower than in other zones of the borehole; and (3) the dissolved oxygen concentration commonly was higher, the pH lower, and the specific conductance was lower in water from the uppermost zone than in water from the lower zones. The water in upper zones commonly was more oxygenated and more dilute at the time of sampling compared to water from lower zones, suggesting that water in the upper zone had greater or more recent contact or exchange with the atmosphere and less contact time with aquifer materials than water in the lower zones. Wells Mg-80 and Mg-624 have deeper casing than the other wells and, thus, lack an upper zone open to shallow ground water. As such, water temperature, pH, specific conductance, and dissolved oxygen concentration varied little with depth in tested zones of these wells.

In comparison of chemical and physical properties of water from wells Mg-80, Mg-1443, Mg-1444, Mg-624 and Mg-1639, the water from wells Mg-1444 and Mg-624 had the highest pH (was the most basic), the water from Mg-80 contained the lowest concentration of dissolved oxygen (less than 0.1 mg/L), and the water from wells Mg-1443 and Mg-624 had the lowest specific conductance (table 11). Differences in the specific conductance of water from the five wells also were indicated by the fluid-resistivity logs (Conger, 1999). Fluid resistivity is the inverse of fluid conductivity. The differences in properties of water from these wells may be related to the residence time of ground water in the vicinity of the wells, differences in aquifer mineralogy, and (or) differences in compounds introduced by human activities in recharge areas of the wells. Ground water with a short residence time generally is more similar chemically to recharge water (dilute, oxygenated, and acidic) than ground water with a long residence time.

The concentrations of VOC's also differed between the isolated intervals of the boreholes (table 11). For intervals isolated in well Mg-80, the highest concentrations of PCE and TCE were measured in the upper (shallow) zone and the highest concentrations of VC was measured in the lower (deep) zone. Because PCE and TCE are the

Table 11. Physical properties and concentrations of selected volatile organic compounds in samples collected from isolated intervals at the end of pumping in wells Mg-80, Mg-1443, and Mg-1444 in Lansdale, Pa., March 26-April 11, 1997, and in wells Mg-624 and Mg-1639, August 28 - September 2, 1997

[ft bls, feet below land surface; °C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; μg/L, micrograms per liter; PCE, tetrachloroethylene; TCE, trichloroethylene; DCE, dichloroethylene; VC, vinyl chloride; <, less than; ND, not detected; --, no data]

Well and interval sampled	Depth of interval sampled (ft bls)	Temperature (°C)	Specific conductance (μS/cm)	pH (units)	Dissolved oxygen (mg/L)	Compound concentration ¹ (μg/L)				
						PCE	TCE	1,2-cis-DCE	VC	Toluene
Mg-80 - Zone A	142-157	12.7	600	6.86	<0.1	10.5	19.6	24.0	10.5	0.6
Mg-80 - Zone B	Below 246	12.7	² 600	6.79	<.1	ND	ND	5.2	57.2	ND
Mg-1443 - Zone A	Above 90.5	19.0	372	5.97	³ 10.3	408	3,550	512	2.6	8.9
Mg-1443 - Zone B	90.5-110.5	19.9	405	6.10	5.7	510	3,680	524	ND	14.4
Mg-1443 - Zone C	276-296	14.8	427	7.03	1.6	199	1,670	167	ND	.6
Mg-1443 - Zone D	Below 296	16.4	386	6.74	1.4	208	3,350	265	ND	13.6
Mg-1444 - Zone A	Above 64	19.9	445	7.35	6.3	11.4	1,220	.4	ND	33.7
Mg-1444 - Zone B	64-85	14.8	586	7.61	--	1.7	141	ND	ND	1.8
Mg-1444 - Zone C	136.5-157.5	15.4	625	7.58	1.1	.1	.6	ND	ND	.7
Mg-1444 - Zone D	248-269	14.0	600	7.58	2.0	ND	.5	ND	ND	.4
Mg-1444 - Zone E	Below 268	14.9	590	7.57	1.2	ND	1.2	ND	ND	.6
Mg-624 - Zone A	116-146	15.3	429	8.03	2.5	<1	7	4	<1	--
Mg-624 - Zone B	185-215	15.6	431	8.07	3.4	<1	2	4	<1	--
Mg-624 - Zone C	290-320	13.6	426	7.39	<.1	<1	<1	1	<1	--
Mg-1639 - Zone A	0-40	14.7	941	6.80	1.8	350	660	620	20	--
Mg-1639 - Zone B	40-60	15.3	950	6.80	.7	350	700	630	20	--
Mg-1639 - Zone C	80-100	15.2	976	6.91	.25	500	890	650	20	--
Mg-1639 - Zone D	100-120	14.2	1,017	6.88	.4	420	780	660	20	--

¹ VOC analytical results for Mg-80, Mg-1443, Mg-1444 from Black & Veatch Waste Science, Inc. (1998) and for Mg-624, Mg-1639 from QST Environmental, Inc. (1998).

² At beginning of pumping; probe fouled at end of pumping.

³ Sample aerated during pumping; reported concentration in sample probably higher than in unaerated ground water from zone.

primary contaminants at the site, these results suggest the upper zone draws water that may be close to contaminant sources near land surface as contaminated water moves deeper into the aquifer under flow or density gradients. VC at this site was likely formed during the chemical breakdown of PCE and TCE.

In samples from well Mg-1443, concentrations of PCE and cis-1,2-DCE were higher in the shallow zones than in the deep zones (table 8), suggesting the upper zones may be closest to contaminant sources near land surface. TCE and toluene concentrations in three of the four zones sampled in well Mg-1443 were similar, perhaps indicating greater areal and depth extent of contamination than that of the other VOC's detected. Zone D (276-296 ft bls) was the least contaminated but most productive zone of the well. This relation indicates that although fractures may provide preferential pathways for contaminants, increased flow through fractures may result in dilution of contaminants. Upward flow and upward vertical flow gradients were measured at all but the shallowest depths tested. A small downward vertical flow gradient was measured between the shallowest zone tested (zone A) and the underlying zone (zone B), indicating potential for transport of contamination from the shallowest zone to receiving fractures at 104-106 ft bls (31.7-32.3 m).

In samples from well Mg-1444, concentrations of PCE, TCE, and toluene were much greater in the shallowest zone than in the other zones sampled, indicating proximity to a contaminant source near the surface. Because a downward vertical flow gradient was measured from the shallowest zone tested (zone E) to the underlying zone (zone D), movement of contamination in the borehole from above 64 ft (19.5 m) to receiving water-bearing fractures at 70-72 ft bls (21.3-21.9 m) is possible. However, upward flow was measured in well Mg-1444 at depths below 72 ft (21.9 m) (Conger, 1999), indicating that under nonpumping conditions, the contaminants near the upper zones of the well are not moving to depths below 72 ft (21.9 m) in the borehole.

In samples from well Mg-624, only low concentrations of VOC's were detected. The concentrations of TCE and its breakdown product, cis-1,2-DCE, were greater in samples from the upper two zones than the deepest zone tested, suggesting a contaminant source near the surface. An upward vertical flow gradient was observed from the lower zone to the intermediate zone tested, indicating little potential for downward migration in the borehole over that interval.

In samples from well Mg-1639, relatively high concentrations of PCE, TCE, and cis-1,2-DCE were measured in water from all four zones tested. Concentrations of these compounds were higher in the lower two zones than in the upper two zones. VC was present in the same concentrations in all zones. Cross-contamination between zones in and outside of the borehole may explain the similar concentrations of contaminants in the four zones. Downward vertical flow gradients were noted between zones in this well.

Multiple-Well Tests

Aquifer tests involving 1 pumped well and 6 to 10 observation wells were done by USGS at 3 sites in November 1997. The pumped wells were Mg-1610 at Keystone Hydraulics property, Mg-1609 at John Evans Co. property, and Mg-1600 at Rogers Mechanical property (pl. 1). Information about the pumped and observation wells and the aquifer tests is summarized in table 12. Another aquifer test was done at the J.W. Rex property by QST Environmental, Inc., during which well Mg-625 was pumped. The tests were done in areas of known soil and groundwater contamination. The observation wells were oriented at various screened-depth intervals in both dip and strike directions from the pumped well and include open-hole wells and wells constructed in 1997. Wells constructed in 1997 generally have about 20-ft (6.1-m) of screen open to one water-production zone. The tests were done, in part, to determine the relation between transmissivity and aquifer-bed orientation. Information about vertical and horizontal transmissivity also was obtained.

At each site, one well of a nest was pumped. The pumped wells ranged in depth from about 100-150 ft (30.5-45.7 m) and were deeper than the companion monitor wells in the nests. New monitor-well nests were installed during summer 1997. Each well in a nest was constructed to be open to one water-bearing zone. Water levels in other monitor wells and in unused, deep, open-hole wells at or near the sites were measured before, during, and after the test by use of pressure transducers or floats and digital shaft encoders. Water levels were checked periodically by use of an electric tape to verify transducer and float readings. Barometric pressure was measured by use of a transducer during tests at Rogers Mechanical (pumped well Mg-1600) and John Evans (pumped well Mg-1609) at a nearby site in Warminster Township, Bucks County, Pa., about 10 mi (16.1 km) of Lansdale. Wells were pumped by use of a 0.5 horse-power submersible pump at rates of 8 - 10 gal/min (30.3 - 37.9 L/min) for about 8 hours. All pumped water was passed through granulated activated carbon to remove contaminants and then discharged to sanitary sewers. Pumping rates during the first 10-60 minutes tended to be variable and higher than later, stable pumping rates because of adjustments required to avoid exceeding the flow capacity of the carbon-filtration tanks. Drawdown of water levels during pumping and recovery after pumping ceased was measured at each site. For tests at two sites, Rogers Mechanical (pumped well Mg-1600) and John Evans (pumped well Mg-1609), recovery coincided with periods of rainfall that affected the cause and rate of rise in water levels.

Table 12. Well characteristics and locations and pumping data for aquifer tests done in Lansdale, Pa., November 1997

[P, pumped well; O, observation well; ft, feet; in., inches; ft bls, feet below land surface; ft asl, feet above sea level; gal/min, gallons per minute]

U.S. Geological Survey local well number Mg-	Site well name ¹	Well status	Well depth (ft)	Casing depth (ft)	Well diameter (in.)	Depth to water before test (ft bls)	Drawdown at end of test (ft)	Altitude of land surface (ft asl)	Location relative to pumped well	
									Radial distance (ft)	Direction ² (degrees)
Rogers Mechanical site - date: 11-13-97, start time: 12:21, duration: 6.15 hours, stable pumping rate: 8.1 gal/min										
1600	Rog 3I	P	150	130	6	50.8	3.94	365.7	--	--
1605	Rog 1S	O	95	15	6	66.5	-.03	380.5	410.55	116.83
1604	Rog 1D	O	221	210	6	67.5	-.07	380.7	417.83	117.02
1603	Rog 2S	O	98	15	6	74.8	-.10	376.0	307.49	158.04
1602	Rog2I	O	131	110	6	61.7	.71	376.0	313.17	159.64
1601	Rog 3S	O	100	18	6	65.1	-.06	365.5	12.01	41.83
1444	TA-1	O	294	17	6	58.6	-.06	367.0	210.75	195.32
Keystone Hydraulics site - date: 11-18-97, start time: 10:55, duration: 8.05 hours, stable pumping rate: 10.0 gal/min										
1610	Key 1I	P	122	100	6	16.6	2.31	326.7	--	--
1611	Key 1S	O	88	15	6	16.4	.44	326.6	25.15	126.41
80	KH1	O	270	138	8	15.9	.46	326.0	153.01	122.69
1620	Key 2S	O	101	20	6	14.3	.32	324.4	364.26	115.27
1619	Key 2I	O	190	150	6	14.2	.13	324.1	354.69	111.89
67	L-8	O	294	19	8	15.3	.14	325.4	516.12	102.42
163	RY2	O	318	22	8	29.2	.14	339.2	759.97	233.81
164	RY2	O	385	23	8	31.0	-.04	340.1	1,013.51	201.17
John Evans site - date: 11-21-97, start time:10:10, duration: 7.93 hours, stable pumping rate: 9.1 gal/min										
1609	Ev2S	P	101	19	10	55.6	3.56	352.4	--	--
1533	JE-1	O	63	14	6	55.5	.71	352.3	15.76	86.67
1624	Ev 1S	O	101	19	6	45.5	-.08	347.9	549.25	305.56
1666	Ev 1I	O	150	110	6	51.3	.37	348.3	520.69	305.61
1606	PhT 1S	O	101	15.5	6	51.2	.41	349.0	496.90	222.91
1607	PhT 1I	O	161	153	6	49.4	-.04	348.0	506.05	229.21
1608	PhT 1D	O	307	220	6	51.3	.23	348.5	501.64	225.77
1443	PTC	O	339	10	8	52.6	.13	351.1	206.17	232.52
152	PW1	O	196	22	12	57.8	.52	354.1	194.75	37.42
1445	AOmwl	O	204	21	5	61.8	.13	357.9	910.35	42.07
618	NPP	O	343	29	6	66.0	-.08	360.4	1,298.65	53.83

¹ Name given by Black & Veatch Waste Science, Inc.

² Due north is 0 degrees, due east is 90 degrees, due south is 180 degrees, due west is 270 degrees.

Method of aquifer-test analysis

The general approach for analyzing the aquifer-test data for this study was to match the measured drawdown with simulated drawdown using analytical models. These simple models treat the aquifer system as homogeneous and of infinite horizontal extent. Three models were used, including: (1) an isotropic single-aquifer model (Theis, 1935); (2) an anisotropic single-aquifer model (Papadopoulos, 1965); and (3) an isotropic two-aquifer model (Neuman and Witherspoon, 1969). The fit between measured and simulated drawdown was judged by visual inspection of the log-log graph of drawdown as a function of time since the start of pumping. The model parameters are adjusted such that an optimum fit was achieved.

The Theis (1935) model assumes all wells fully penetrate a confined aquifer in which the transmissivity (T) is independent of direction. The model parameters are transmissivity and storage coefficient (S). Simulated drawdown depends on the radial distance from the pumped well (r) and time elapsed since pumping began (t). The aquifer in the conceptual model corresponds to the network of fractures that are the most permeable and provide most of the flow to the pumped well. Low-permeability parts of the aquifer system, for example, large blocks of unfractured rock, are not explicitly included in the model. Furthermore, wells that are isolated from the pumped aquifer by low-permeability barriers to flow are not included in the model. For example, a well may be open to productive fractures, but those fractures may be isolated from the pumped aquifer by intervening beds of relatively unfractured low-permeability beds. The response of such a well cannot be simulated by use of the simple Theis single-aquifer model.

The anisotropic model (Papadopoulos, 1965) is similar to the Theis model, except that transmissivity depends on direction. Directional transmissivity is an ellipse characterized by three parameters. The three parameters are the transmissivity in the direction of maximum transmissivity (T_{\max}), the transmissivity in the direction of minimum transmissivity (T_{\min}), and the direction of maximum transmissivity, which is specified by the angle between north and the direction of maximum transmissivity (θ_{\max}). In addition to depending on r and t , drawdown at an observation well depends on the angle of the line joining the pumped and observation well (θ_{obs}). This model can approximate the apparent large-scale anisotropy often observed in dipping Triassic formations (Vecchioli, 1967; Carleton and others, 1999). As a single-aquifer model, however, this model cannot simulate drawdown in wells in low-permeability blocks or isolated wells, as described in the previous paragraph.

The isotropic two-aquifer model (Neuman and Witherspoon, 1969) assumes two semi-confined isotropic infinite aquifers separated by a confining unit. Only horizontal flow is considered in each of the aquifers, whereas only vertical flow is considered in the confining unit. The pumping well penetrates only one of the aquifers, and each observation well is assumed to fully penetrate either the pumped or unpumped aquifer. For the case considered here, no observation wells are located in the aquitard. The parameters for the isotropic two-aquifer model are transmissivity (T_1) and storage coefficient (S_1) in the pumped aquifer; transmissivity (T_2) and storage coefficient (S_2) in the unpumped aquifer; and thickness (B), vertical hydraulic conductivity (K_v), and specific storage (S_s) of the aquitard. This model can approximate water levels in wells that penetrate (1) a network of fractures hydraulically connected with the pumped well and (2) a second network of high-permeability fractures that are separated from the pumped aquifer by intervening low-permeability parts of the formation. As with the Theis and anisotropic models, wells that are completed in low-permeability parts of the formation (other than the intervening aquitard) cannot be simulated by use of this model.

The models used to simulate drawdown are simplifications of natural conditions. The models do not incorporate several known and unknown complexities that affect measured drawdown. Ground-water flow in the fractured rocks is through a complex network of interconnected fractures. The models are used to approximate the response of the system in the relatively well-connected network of fractures that most-readily contributes water to the pumped well. The typically small drawdown measured in wells that are not well-connected to the primary water-producing fracture network cannot be simulated by use of these models, except to the extent that a connection can be approximated by an infinite, homogeneous confining unit in the case of the two-aquifer model. The uniform parameters (T and S) determined from aquifer tests are effective values at the scale of the well field. Using these effective values, the simulated drawdown most closely matches measured drawdown during the test.

The approach of estimating a few large-scale effective parameters is consistent with the goal of developing a model of regional flow in the formations underlying Lansdale. Regional models, however, cannot fully describe local details of flow in heterogeneous formations. More complex models could be used to more closely simulate the aquifer-test data and describe local flow characteristics. For example, transmissivity could vary in space, having

different values in separate zones. In this case, each transmissivity value in each zone would be a separate model parameter. Although such a model may provide a better match between measured and simulated drawdowns, the reliability of each parameter (each zone's transmissivity in the example) decreases sharply as the number of parameters increases. Furthermore, the parameters become non-unique; several different combinations of parameters yield virtually the same match between measured and simulated drawdown. The parameters estimated from these simple models are relatively well-constrained by the measured drawdown, but the field situation is considerably more complex than these conceptual models imply.

Effects of heterogeneity and limited vertical hydraulic conductivity were observed in all three tests. At the Rogers Mechanical site, the water levels in only one observation well responded to pumping. Water levels in other wells, closer to the pumping well but open to parts of the formation above the pumped beds, did not respond, indicating limited hydraulic connection across beds. An anisotropic flow model in a single confined aquifer is used to analyze the drawdown at the Keystone Hydraulics site. However, this analysis included only the four observation wells with largest drawdown. Lower drawdown at several other observation wells does not match this model. Conceptually, these observation wells are located outside the high-permeability pumped beds and their response is muted by the limited cross-bed hydraulic conductivity. Finally, the test at the John Evans site is analyzed by use of a two-aquifer model. In this case, one observation well was located in a relatively moderate-permeability 'aquifer,' but the drawdown was significantly reduced because of intervening low-permeability parts of the formation. Here again, no drawdown because of pumping was measured at several observation wells indicating low hydraulic conductivity connections between these wells and the pumping well. The variability of the extent of response to pumping at all three sites underscores the heterogeneity of three-dimensional hydraulic conductivity in these fractured-rock formations. These results are consistent with a multi-aquifer conceptual model of the ground-water system in which flow is primarily in zones oriented parallel to bedding.

Rogers Mechanical site

One aquifer test was done at this site on November 13, 1997. Well Mg-1600 was pumped for 6.15 hours at rates that ranged from 7.9 to 14.7 gal/min (0.5 to 0.93 L/sec) during the early part of the test. The pumping rate was stable at about 8.1 gal/min (0.51 L/sec) from 7 minutes after pumping started to the end of pumping. Water levels were measured in seven wells (fig. 38) by use of pressure transducers and electric tapes. Barometric pressure at a nearby site also was recorded with a transducer. The configuration of wells included the shallow [less than 100-ft (30-m) deep] wells, Mg-1601, Mg-1603, and Mg-1605; the intermediate-depth [about 150-ft (46-m) deep] wells, Mg-1600 (pumped well) and Mg-1602; deep [222 ft (67.7 m)] well Mg-1604; and an open-hole well [open from 18 to 294 ft (5.5 to 89.6-m)], Mg-1444 (fig. 39; table 12).

Positive drawdown during the aquifer test was measured in the pumped well (Mg-1600) and observation well Mg-1602 (figs. 38 and 39). The effect of variable pumping rate during the early part of the aquifer test also is reflected in the hydrographs of water levels in the pumped well and the observation well Mg-1602. Drawdown in the remaining wells was negative, indicating the water level in those wells rose during the aquifer test. The intermediate-depth observation well (Mg-1602) that responded to pumping is open to a slightly shallower depth in the formation as the pumped well (table 11). Because the local dip is relatively shallow (10°), the open interval of Mg-1602 is open to the same beds as the open interval of the pumped well (fig. 39). Several wells that did not respond to pumping are located closer to the pumped well than well Mg-1602. Measured water levels during the aquifer test illustrate the lack of apparent hydraulic connection between the pumped well and all but one of the observation wells (fig. 40). Because only one observation well had positive drawdown during the aquifer test, the Theis model is used for data analysis.

Drawdown during the later part of the aquifer test in the pumped well (Mg-1600) and in the single observation well (Mg-1602) that responded to pumping can be matched by use of the single-aquifer isotropic model of Theis (1935) (fig. 41). Measured drawdown during the early part of the test is not matched because the pumping rate was elevated for about the first 5 minutes of pumping. The estimated hydraulic properties from this match are $T = 600 \text{ ft}^2/\text{d}$ ($56 \text{ m}^2/\text{d}$) and $S = 3 \times 10^{-5}$ (table 13).

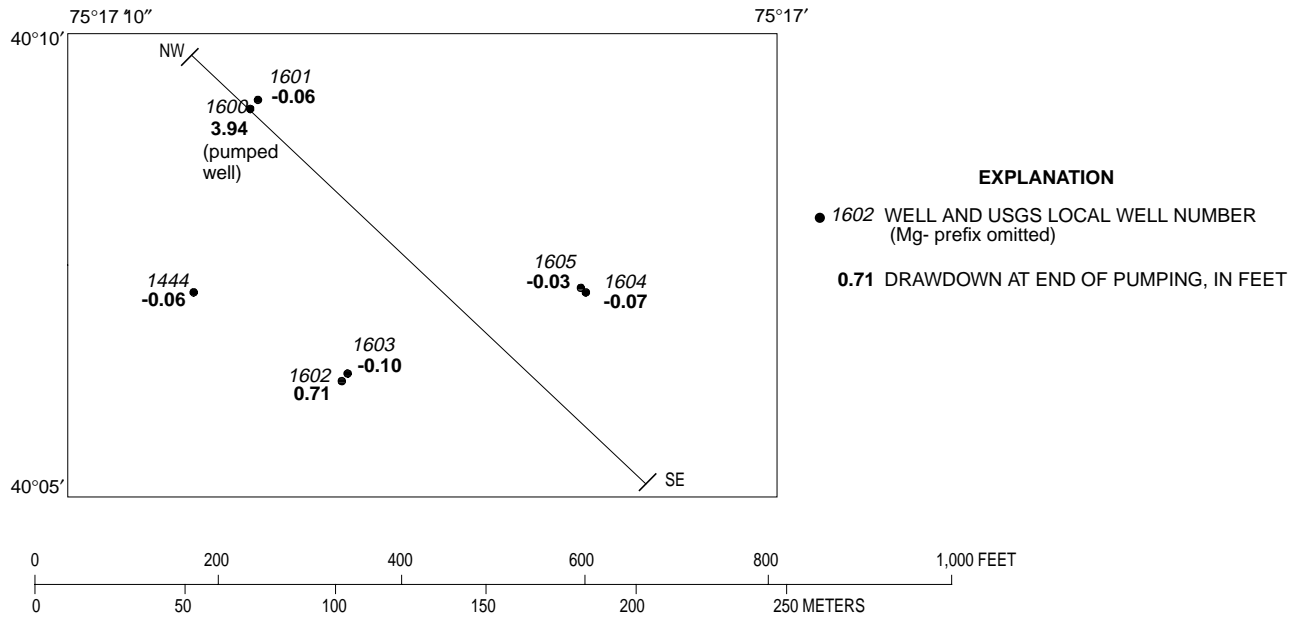


Figure 38. Well locations and drawdown at end of pumping well Mg-1600 at the Rogers Mechanical site in Lansdale, Pa., November 13, 1997. Well Mg-1600 was pumped at a rate of about 8.1 gallons per minute for 6.15 hours.

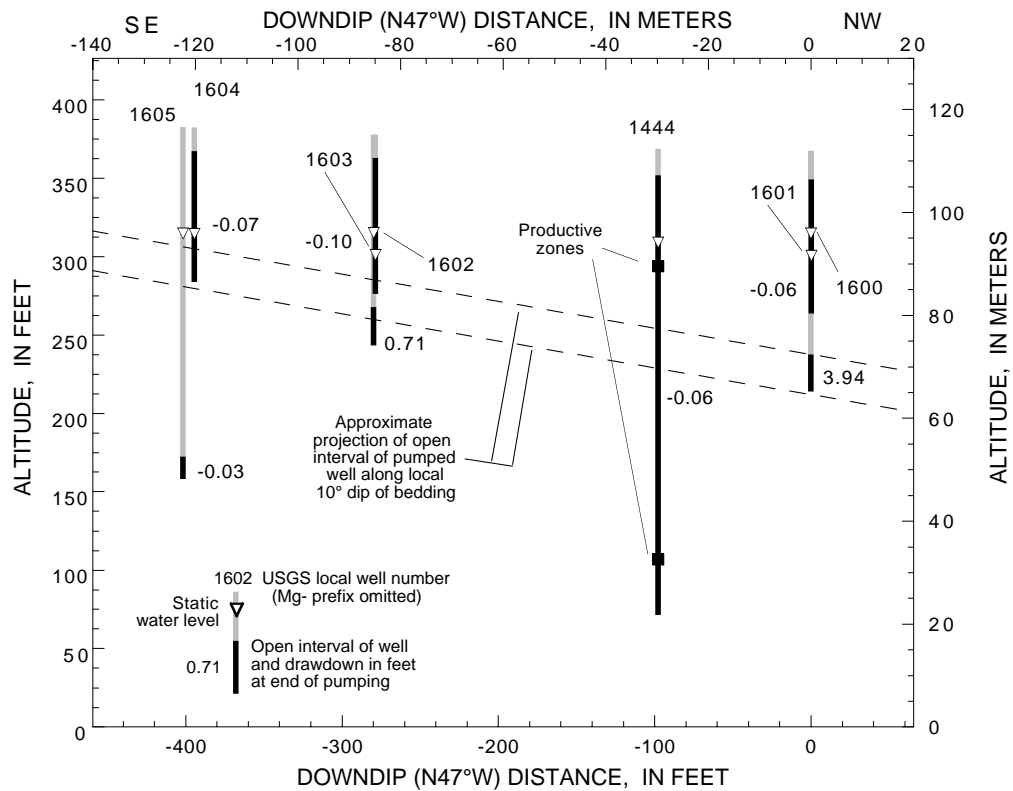


Figure 39. Open intervals of wells, static water level, and drawdown at end of pumping at the Rogers Mechanical site in Lansdale, Pa., November 13, 1997. Well Mg-1600 was pumped at a rate of about 8.1 gallons per minute for 6.15 hours. All wells are projected onto a vertical plane parallel to the dip direction.

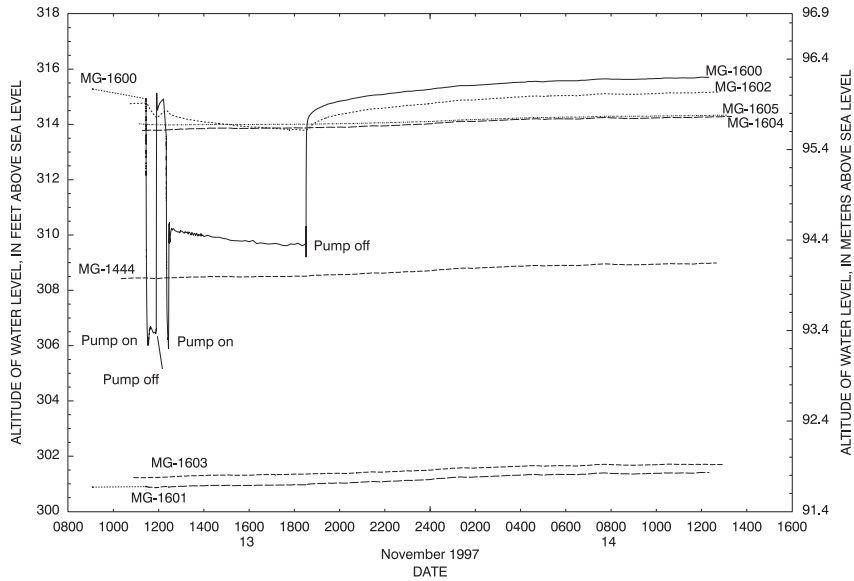


Figure 40. Measured water levels at the Rogers Mechanical site in Lansdale, Pa., November 13-14, 1997. Well Mg-1600 was pumped at a rate of about 8.1 gallons per minute for 6.15 hours on November 13.

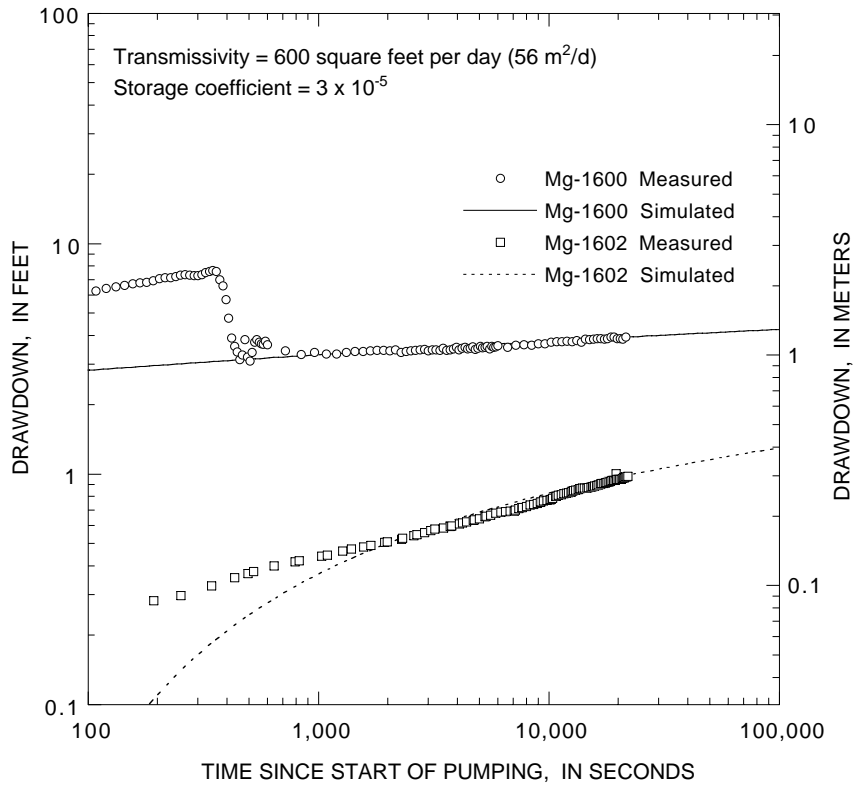


Figure 41. Measured and simulated drawdown in wells Mg-1600 and Mg-1602 at the Rogers Mechanical site in Lansdale, Pa., November 13, 1997. Well Mg-1600 was pumped at a rate of about 8.1 gallons per minute for 6.15 hours. Simulated drawdown is from the isotropic single-aquifer model of Theis (1935) using hydraulic properties of $T = 600 \text{ ft}^2/\text{d}$ ($56 \text{ m}^2/\text{d}$) and $S = 3 \times 10^{-5}$.

Table 13. Summary of estimated hydraulic properties determined from analyses of multiple-well aquifer tests in Lansdale, Pa.

[T, transmissivity; K, hydraulic conductivity; ft²/d, square feet per day; ft/d, feet per day; S, storage; S_s, specific storage; /ft, per foot; θ, angle]

Site	Conceptual model	Estimated hydraulic properties			
		Transmissivity (ft ² /d) or vertical hydraulic conductivity (ft/d)		Storage (dimensionless) or Specific storage (ft)	
Rogers Mechanical	isotropic aquifer	T	600	S	3×10^{-5}
Keystone Hydraulics	anisotropic aquifer	T _{max} (θ _{max} = N. 51° W.)	10,700	S	3×10^{-5}
		T _{min} (θ _{min} = N. 39° E.)	520		
		(T _{max} T _{min}) ^{1/2}	2,300		
John Evans	isotropic two-aquifer	T ₁ (lower pumped aquifer)	1,300	S ₁	8×10^{-5}
		T ₂ (upper aquifer)	15	S ₂	8×10^{-5}
		K _v (aquitard)	0.044	S _s	1×10^{-6}
J. W. Rex	isotropic aquifer	T	¹ 160 - 665	S	² 2×10^{-5} - 1×10^{-3}

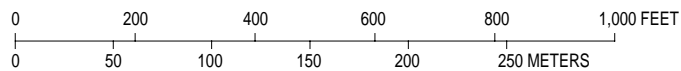
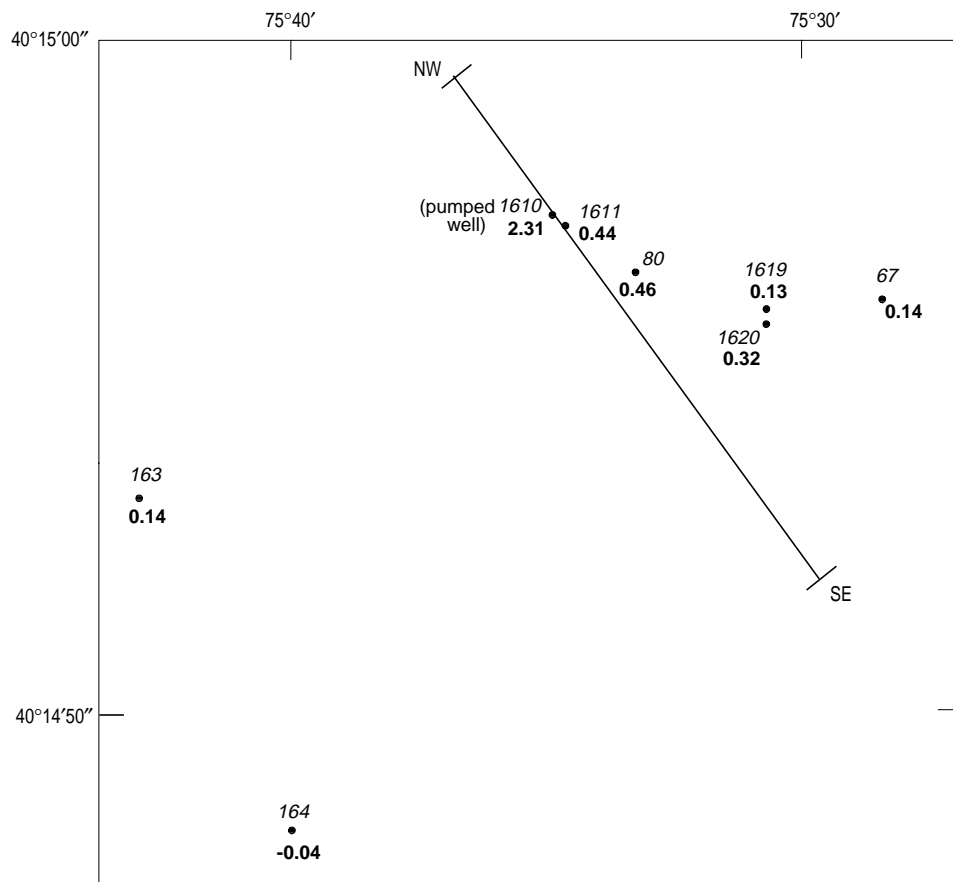
¹ Range of transmissivity values determined by QST Environmental, Inc. (1998).

² Range of storage values determined by QST Environmental, Inc. (1998).

Keystone Hydraulics site

One aquifer test was done at this site on November 18, 1987. Well Mg-1610 was pumped for 8.05 hours at rates that ranged from 8.1 to 15 gal/min (0.51 to 0.95 L/sec) during the early part of the test. The pumping rate was stable at about 10 gal/min (0.63 L/sec) from 42 minutes after pumping started until the end of pumping. Water levels were measured in eight wells (fig. 42) by use of pressure transducers and electric tape. The configuration of wells included shallow [less than 100 ft (30 m)] wells Mg-1611 and Mg-1620; intermediate-depth wells [up to 190 ft (60 m)] wells Mg-1610 (pumped well) and Mg-1619; and several deep [more than 270 ft (82 m)] open-hole wells (Mg-67, Mg-80, Mg-163, and Mg-164) (fig. 43). The observation wells were updip and along strike from the pumped well. Bedding at the Keystone Hydraulics site strikes about N. 57° E. and dips about 8° to the northwest (Conger, 1999).

Positive drawdown during the aquifer test was measured in all wells but Mg-164 (fig. 42). Drawdown exceeded 0.3 ft (0.09 m) in three observation wells that were among the closest to and updip of the pumped well (table 12) including Mg-1611, a shallow well within 25 ft (7.6 m) of the intermediate depth pumped well; Mg-80, an open-hole deep well with 138 ft (42 m) of casing and within 153 ft (46.6 m) of the pumped well; and Mg-1620, a shallow well within 365 ft (111 m) of the pumped well. Well Mg-1611 is not open to the projected pumped interval. Although the primary water-bearing zone in well Mg-80 is about 30 ft (9.1 m) below the projected dip of bedding through the pumped zone, aquifer interval-isolation testing indicated this water-bearing zone in well Mg-80 may be hydraulically connected to shallower zones outside the borehole. Shallow well Mg-1620 intersects the projected dip of bedding through the pumped zone (fig. 43). Well Mg-1619 is at a similar distance from the pumped well as well Mg-1620 and is within 25 ft (7.6 m) of well Mg-1620, yet drawdown in well Mg-1619 is only 0.14 ft (0.04 m). Well Mg-1619 is open to beds that are projected to be below the pumped bed (fig. 43). Water levels in well Mg-163, approximately along strike with the pumped well, were drawn down by over 0.18 ft (0.05 m), whereas water levels in well Mg-164, at a similar radial distance but more updip, were not affected by pumping.



EXPLANATION

- 1620 WELL AND USGS LOCAL NUMBER (Mg-prefix omitted)
 2.31 DRAWDOWN AT END OF PUMPING, IN FEET

Figure 42. Well locations and drawdown at end of pumping well Mg-1610 at the Keystone Hydraulics site in Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours.

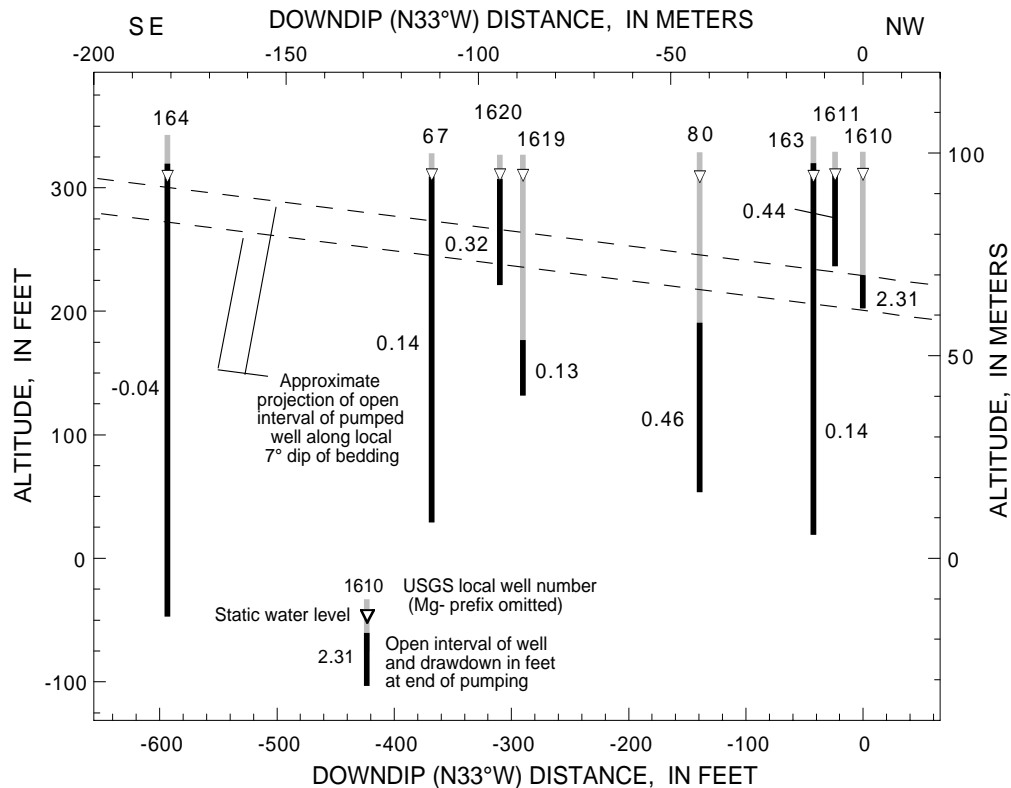


Figure 43. Open intervals of wells, static depth to water, and drawdown at end of pumping at the Keystone Hydraulics site in Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours. All wells are projected onto a vertical plane parallel to the dip direction.

Measured water levels during the aquifer test illustrate the effect of pumping, including variable pumping rates at the beginning of the test and fluctuations associated with regional water-level trends (fig. 44). Decreases in barometric pressure resulted in corresponding increases in water levels in wells during the aquifer test. Because the drawdowns resulting from pumping were small, the effect of the barometric-pressure changes was removed prior to analysis of drawdown by use of analytical aquifer-test models. By matching water-level trends in each observation well before and after pumping with the trends in a well unaffected by pumping (well Mg-164), a linear estimation can be made of water levels in the observation wells had pumping not occurred. Drawdown is computed as the difference between this predicted 'nonpumping' water level and the measured water level. This correction removes the effects of barometric-pressure fluctuations and other regional trends from the measured drawdown to the extent that those trends at each observation well are the same as the trends at the unaffected well (Mg-164).

Drawdown in four observation wells is selected for analysis by use of the single-aquifer anisotropic model of Papadopoulos (1965). Of the six observation wells with positive drawdown, two wells are not matched. Well Mg-1611 is very close to the pumping well but was drawdown less than more distant wells, and the well is not open to the projected pumped bed (fig. 43). Well Mg-1619 was drawdown less than half as much as the nearby well Mg-1620, and it also is not open to the projected pumped bed. Drawdown in these wells cannot be matched by a single-aquifer model because in such a model all observation wells are assumed to be located in the pumped aquifer. These wells are not included in the analysis here in order to use the directional variability of drawdown in the pumped bed to estimate large-scale anisotropy. Well Mg-80 is included in the analysis even though it also is open outside the projected pumped interval. The measured drawdown and aquifer-isolation test results suggest it is hydraulically connected to the pumped interval, as discussed above.

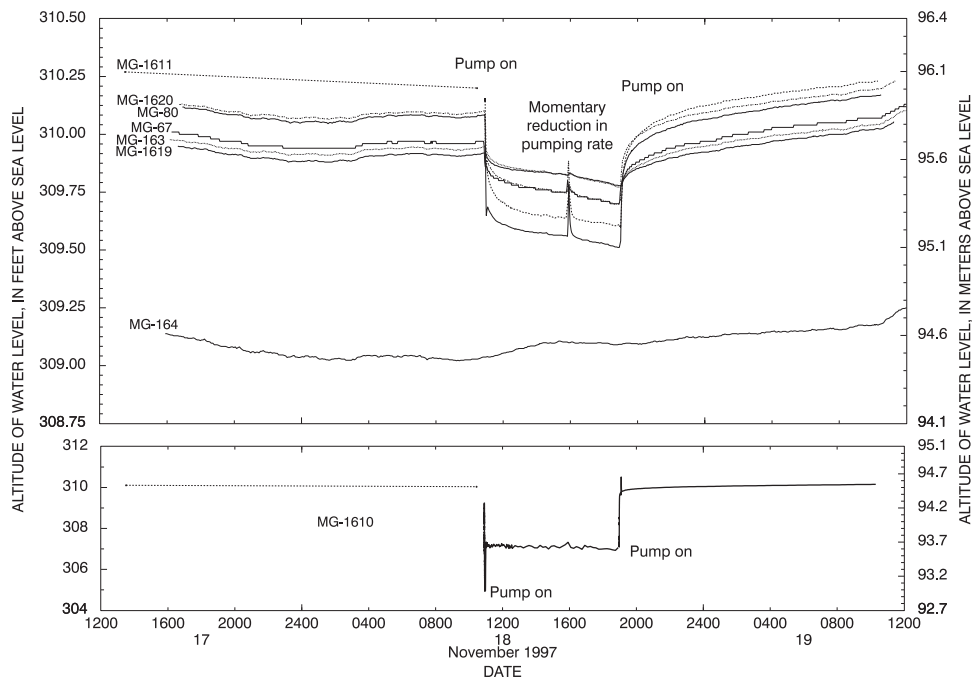


Figure 44. Measured water levels at the Keystone Hydraulics site in Lansdale, Pa., November 17-19, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours on November 18.

Drawdown in four observation wells can be matched by use of the single-aquifer anisotropic model of Papadopoulos (1965) (fig. 45). The response of anisotropic aquifers to aquifer tests include larger drawdowns in one direction than in another for similar distances from the pumped well. The early-time part of the measured drawdown is not matched because the pumping rate was variable for about the first 42 minutes of pumping. The estimated hydraulic properties from this match are: $T_{\max} = 10,700 \text{ ft}^2/\text{d}$ ($990 \text{ m}^2/\text{d}$); $T_{\min} = 520 \text{ ft}^2/\text{d}$ ($48 \text{ m}^2/\text{d}$); $\theta_{\max} = \text{N. } 51^\circ \text{ W.}$; and $S = 3 \times 10^{-5}$ (table 13). The non-directional geometric-mean transmissivity is $2,300 \text{ ft}^2/\text{d}$ ($220 \text{ m}^2/\text{d}$). These aquifer-test results from this match represent a preferred flow direction within the pumped bed that is oriented in the dip direction (about N. 33° W.). Previous aquifer test results in similar formations (Morin and others, 1997; Welty and Carleton, 1996) present a preferred flow direction oriented in the strike direction.

The difference between the isotropic and anisotropic model match is illustrated by comparing figure 45 to a similar plot using the isotropic Theis model with the nondirectional geometric-mean transmissivity (fig. 46). The isotropic model does not simulate the observed directional dependence of drawdown. Drawdowns at the observation wells estimated by the isotropic model are a function of distance from the pumped well only and more similar in magnitude than those estimated by the anisotropic model. Drawdown simulated by the anisotropic model in two wells (Mg-80 and Mg-1620) updip of the pumped well is greater than drawdown simulated by the isotropic model. Conversely for a well (Mg-163) along strike of the pumped well, drawdown simulated by the anisotropic model is less than drawdown simulated by the isotropic model. Differences in drawdown simulated by the two models are relatively small for well Mg-67, which is oriented between the strike and dip directions.

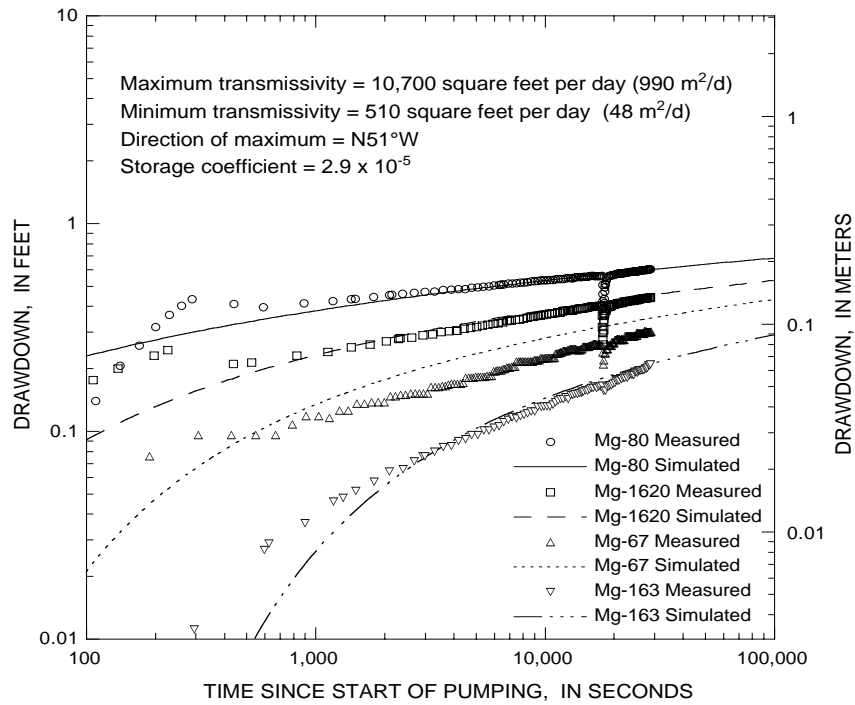


Figure 45. Measured and simulated drawdown, using anisotropic model of Papadopoulos (1965), in wells Mg-67, Mg-80, Mg-163, and Mg-1620 at the Keystone Hydraulics site in Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours.

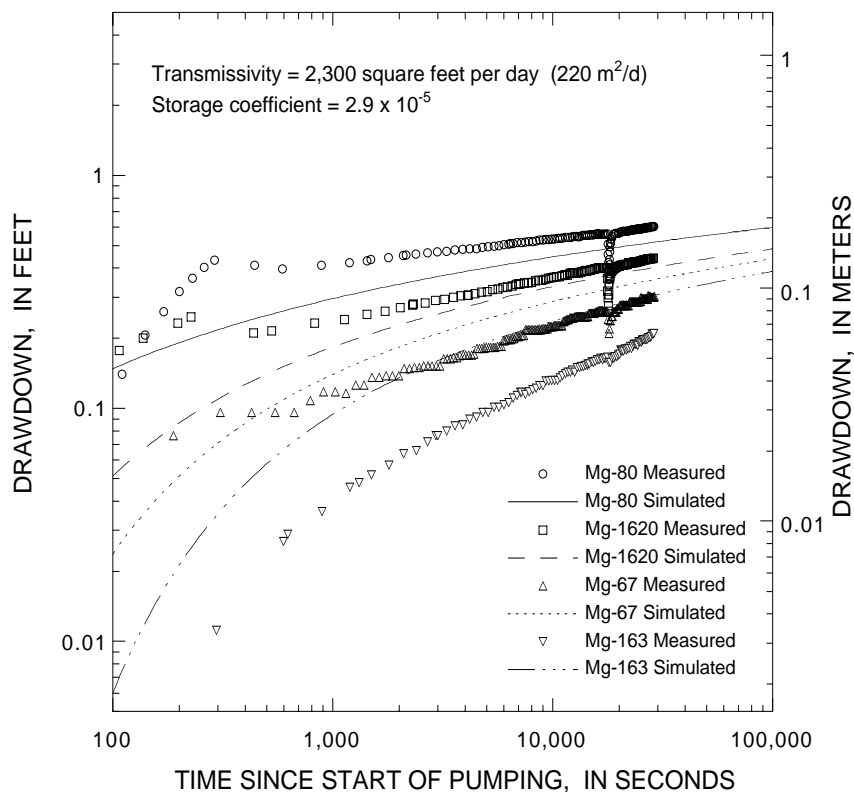
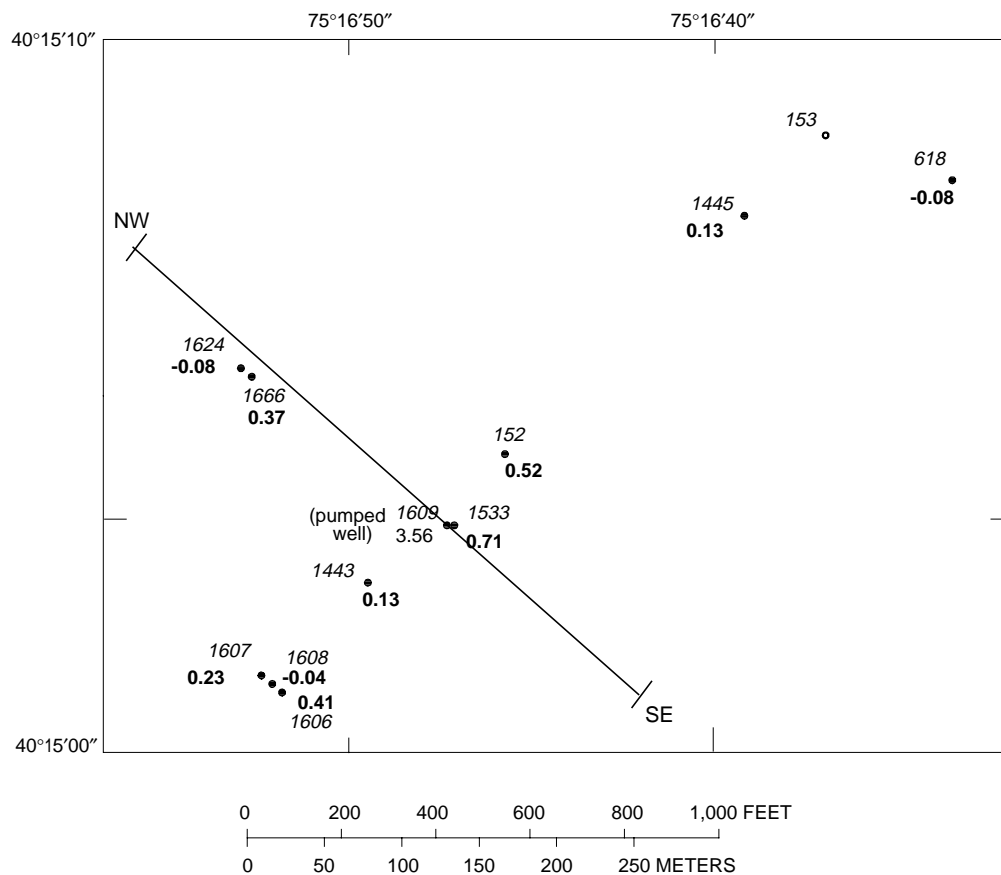


Figure 46. Measured and simulated drawdown, using isotropic model of Theis (1935), in wells Mg-67, Mg-80, Mg-163, and Mg-1620 at the Keystone Hydraulics site in Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours.

John Evans site

One aquifer test was done at this site on November 21, 1997. Well Mg-1609 was pumped for 7.93 hours at rates that ranged from 6 to 10 gal/min (0.38 to 0.63 L/sec) during the early part of the test. The pumping rate was stable at about 9.1 gal/min (0.57 L/sec) from 35 minutes after pumping started until the end of pumping. Water levels were measured in 11 wells (fig. 47) by use of pressure transducers and electric tapes. Barometric pressure at a nearby site also was recorded with a transducer. The well configuration included shallow [about 100 ft (30 m) or less in depth] wells Mg-1533, Mg-1606, Mg-1609 (pumped well), and Mg-1624; an open-hole well (Mg-142) with intermediate [less than about 200 ft (61 m)] and shallow water-bearing zones; intermediate wells Mg-1607, Mg-1666, and Mg-1445; deep [about 300 ft (91 m)] well Mg-1608; and two deep open-hole wells, Mg-618 and Mg-1443, open to a large part of the formation (figs. 48 and 49; table 12). Bedding strikes about N. 45° E. and dips about 12° NW. in the vicinity of the site (Conger, 1999).



EXPLANATION

- 1533 USGS WELL NUMBER (Mg- prefix omitted)
- 0.71 DRAWDOWN AT END OF PUMPING, IN FEET
- WELL USED FOR OBSERVATION DURING AQUIFER TEST
- PRODUCTION WELL THAT WAS PUMPING INTERMITTENTLY DURING AQUIFER TEST

Figure 47. Well locations and drawdown at end of pumping well Mg-1609 at the John Evans site in Lansdale, Pa., November 21, 1997. Well Mg-1609 was pumped at a rate of 9.1 gallons per minute for 7.93 hours.

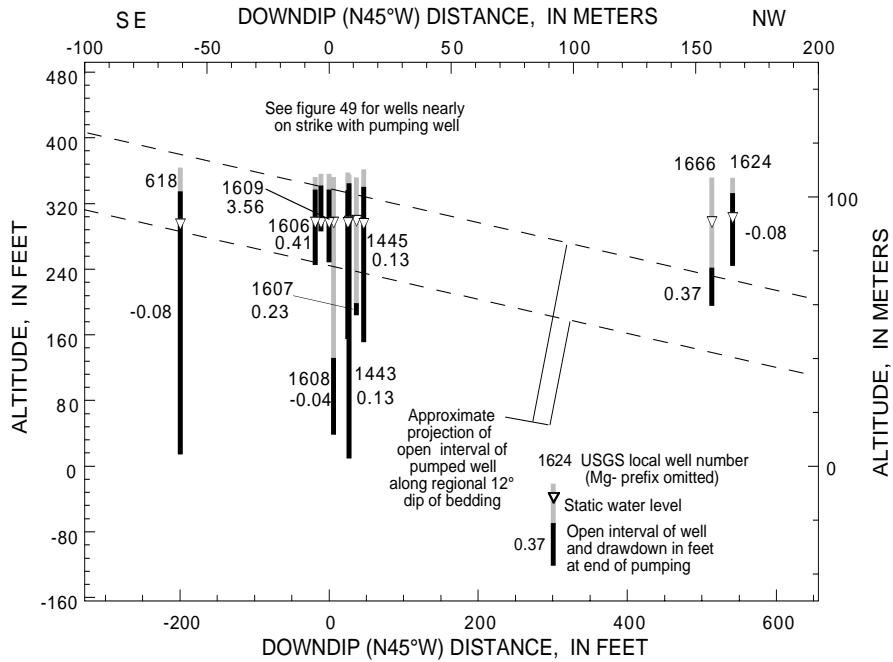


Figure 48. Open intervals of wells, static depth to water, and drawdown at end of pumping at the John Evans site in Lansdale, Pa., November 21, 1997. Well Mg-1609 was pumped at a rate of 9.1 gallons per minute for 7.93 hours. All wells are projected onto a vertical plane parallel to the dip direction.

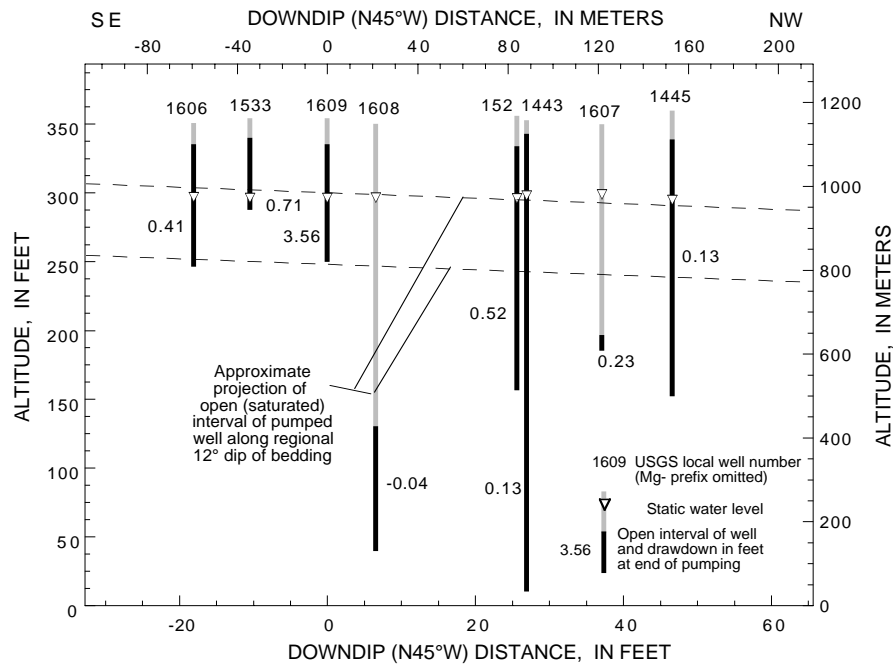


Figure 49. Open intervals of wells nearly on strike with the pumped well, static depth to water, and drawdown at end of pumping at the John Evans site in Lansdale, Pa., November 21, 1997. Well Mg-1609 was pumped at a rate of 9.1 gallons per minute for 7.93 hours. All wells are projected onto a vertical plane parallel to the dip direction.

Positive drawdown during the aquifer test was measured in the pumped well and in 7 of the 10 observation wells (fig. 47). Negative drawdown was measured in observation wells Mg-618, Mg-1607, and Mg-1624. Drawdown exceeded 0.3 ft (0.1 m) in four observation wells: Mg-1533, a shallow well adjacent to the shallow pumping well (fig. 49); Mg-152, the next closest observation well that is open to shallow and intermediate depths; Mg-1606, a shallow well relatively far from the pumping well but along strike; and Mg-1666, an intermediate depth well that is down-dip of the pumped well but open to the same beds (fig. 48). Well Mg-1443 is about the same distance from the pumped well as well Mg-152, in the opposite direction along strike, and is open to a large part of the formation. Measured drawdown in well Mg-1443 was less than 0.16 ft (0.05 m), which is less than one-third the drawdown at Mg-152. Drawdown in shallow well Mg-1624 was negative, whereas drawdown in the adjacent intermediate well Mg-1666 was over 0.3 ft (0.1 m). These differences in drawdown are consistent with the projection of the pumped beds through the open interval of well Mg-1666 but below that of well Mg-1624 (fig. 48).

Measured water levels during the aquifer test illustrate the effect of pumping, including variable pumping rates at the beginning of the test and fluctuations associated with regional water-level trends (fig. 50). The initial pumping rate was up to about 1 gal/min (0.06 L/sec) greater than the long-term average rate, as evidenced by greater drawdown in the pumped well during the first 15 minutes of the test. The water levels in well Mg-1607 (figs. 49 and 50) are representative of the other two observation wells (Mg-618 and Mg-1624) that did not respond to pumping. The water level in well Mg-1607 did respond to changes in barometric pressure (fig. 18) and rose about 0.04 ft (0.01 m) over the pumping period of the test. Water levels in well Mg-1445 apparently responded to pumping in well Mg-1609 but also

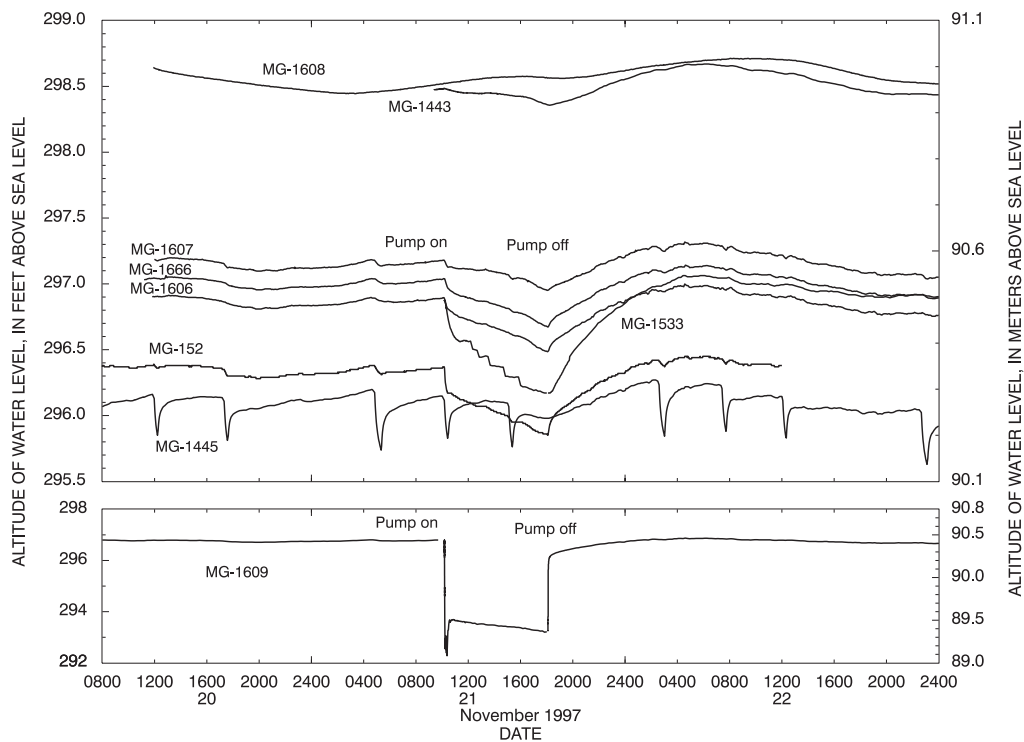


Figure 50. Measured water levels at the John Evans site in Lansdale, Pa., November 20-22, 1997. Well Mg-1609 was pumped at a rate of 9.1 gallons per minute for 7.93 hours on November 21.

responded strongly to other pumping in the area. Other pumping also resulted in minor water-level changes in the other observation wells. For wells included in the aquifer-test analysis, drawdown was not corrected for the apparently small effects of barometric-pressure decrease or other pumping wells. The recovery of water levels in the pumped well is similar to that reported for many pumping tests in the Lansdale area (Goode and Senior, 1998). A very rapid recovery of more than 75 percent of the drawdown at the end of pumping was followed by a much more gradual recovery to the static water level.

Drawdown in four observation wells was matched by use of the two-aquifer model of Neuman and Witherspoon (1969) to estimate hydraulic properties (fig. 51). These four wells had the largest measured drawdowns. The two-aquifer model matches the measured drawdown in these four wells better than either the isotropic Theis model or the anisotropic single-aquifer model (Papadopoulos, 1965). Smaller drawdown at several other observation wells could not be matched by use of this conceptual model. The estimated hydraulic properties from this match are $T_1 = 1,300 \text{ ft}^2/\text{d}$ ($122 \text{ m}^2/\text{d}$), $S_1 = 8 \times 10^{-5}$ for the pumped 'aquifer' or network of fractures; $T_2 = 15 \text{ ft}^2/\text{d}$ ($1.4 \text{ m}^2/\text{d}$), $S_2 = 8 \times 10^{-5}$ for the unpumped 'aquifer'; and $K_v = 0.044 \text{ ft/d}$ (0.013 m/d), and $S_s = 1 \times 10^{-6} / \text{ft}$ ($3 \times 10^{-6} / \text{m}$) for the 'aquitard' (table 13). These results are consistent with the results of aquifer interval-isolation tests in that the vertical hydraulic conductivity is very low for bedrock between high-permeability zones oriented along bedding.

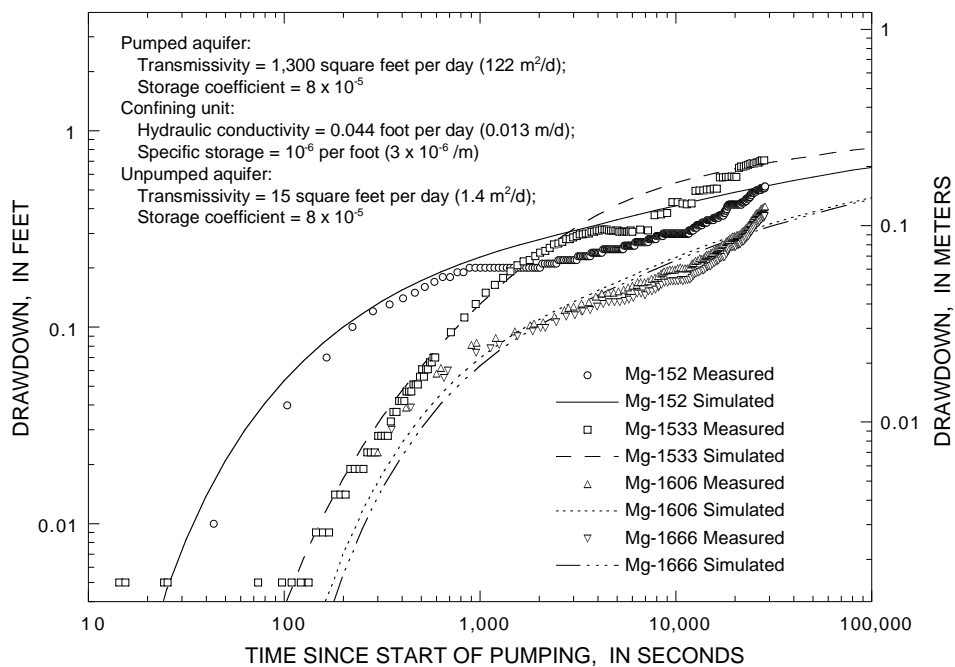


Figure 51. Measured and simulated drawdown, using two-aquifer model of Neuman and Witherspoon (1969), in wells Mg-67, Mg-80, Mg-163 and Mg-1666 at the John Evans site in Lansdale, Pa., November 21, 1997. Well Mg-1609 was pumped at a rate of 9.1 gallons per minute for 7.93 hours.

J.W. Rex site

An aquifer test at the J.W. Rex property was done by QST Environmental, Inc. (1998). Production well Mg-625 was pumped at a rate of about 40 gal/min for about 56 hours from October 24-27, 1997. Water levels in the pumped well and 10 other wells, including Mg-82, Mg-157, Mg-1441, Mg-624, Mg-1639, Mg-1640, Mg-1641, Mg-1615, Mg-1617, and Mg-1665 (pl. 1), were measured during the test. Drawdown was observed in all wells. Drawdown was greatest [11.4 ft (3.5 m)] in observation well Mg-1639. Well Mg-1639 is the closest to the pumped well. Well Mg-1640 is within 10 ft (3 m) of well Mg-1639 but is shallower than well Mg-1639 and had much less drawdown [2.4 ft (0.7m)]. The downward vertical flow observed during geophysical logging prior to the aquifer tests indicates well Mg-1639 is directly influenced by pumping in production well Mg-625. Estimates of hydraulic properties were determined from analysis of drawdown data assuming an isotropic aquifer. Transmissivity ranged from 160 to 665 ft²/d (14.5 - 61.8 m²/d) and storage ranged from about 2×10^{-5} to 4×10^{-3} (QST Environmental Inc., 1998) (table 13). The transmissivities from this test are similar to a transmissivity of 330 ft²/d (31 m²/d) estimated from an earlier test (Goode and Senior, 1998).

Chemical measurements during aquifer tests

Water samples were collected during the aquifer tests to determine chemical and physical properties and the concentration of VOC's at various times while pumping. Field measurements, including temperature, pH, specific conductance, and dissolved oxygen, were made by the USGS. Samples for VOC analysis were collected by the USGS and sent by B&V to a USEPA laboratory.

The measurements of pH, dissolved oxygen, and specific conductance and concentrations of VOC's generally remained relatively stable during the aquifer tests of the three wells (table 14). PCE, TCE, and cis-1,2-DCE concentrations increased slightly in samples collected during the test of well Mg-1610 (table 14), suggesting that increasingly contaminated water from elsewhere on the site may have been drawn toward the pumped well. The dissolved oxygen concentration in the last sample collected during the test of well Mg-1610 was more than 3 mg/L lower than the earlier samples from the well. Slight increases in PCE, TCE, 1,1-DCE, and cis-1,2-DCE concentrations also were measured in samples from the test of well Mg-1609 at John Evans site.

Numerical Simulation of Regional Ground-Water Flow

A three-dimensional finite-difference numerical model, MODFLOW (McDonald and Harbaugh, 1988), was used to simulate regional steady-state flow. The model was calibrated using an automatic, nonlinear optimization program, MODFLOWP (Hill, 1992), that minimizes the differences between measured and simulated hydraulic heads and streamflow. MODPATH (Pollock, 1994), a particle-tracking module linked to MODFLOW, was used to calculate and display ground-water-flow pathlines from the output of the flow model.

Model and Model Assumptions

The model structure is based on a simplified conceptualization of the ground-water flow system. The weathered and fractured-rock formations were modeled as equivalent porous media, such as unconsolidated granular deposits. Thus, it is assumed that ground-water flow can be described by use of a three-dimensional flow equation based on Darcy's Law. In this approach, the hydraulic conductivities used in the model represent the bulk properties of the fractured-rock formations. Water flux, which may pass through only a small fraction of the rock mass occupied by fractures, is simulated as distributed throughout the formations. The model cannot simulate localized ground-water flow controlled by a few, discrete permeable fractures or fracture zones. The model is assumed to approximately represent regional-flow conditions that are controlled by a large number of fractures or fracture zones distributed throughout the region.

Table 14. Field measurements of physical and chemical properties and concentrations of selected volatile organic compounds in water samples collected during aquifer tests of wells Mg-1600, Mg-1610, and Mg-1609 in Lansdale, Pa., November 13-21, 1997

[µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; DCE, dichloroethylene; PCE, tetrachloroethylene; TCA, trichloroethane; TCE, trichloroethylene; --, not detected]

Cumulative pumped volume (gallons)	Time of sample	Physical or chemical property				Volatile organic compounds (µg/L)									
		Temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH	Acetone	Carbon disulfide	Carbon tetrachloride	Chloroform	1,1-DCE	cis-1,2-DCE	trans-1,2-DCE	PCE	1,1,1-TCA	TCE
<u>Test of well Mg-1600, Rogers Mechanical site¹</u>															
845	14:00	12.4	627	1.0	7.09	2.2	0.1	0.06	0.1	--	0.08	--	0.2	--	1.4
925	14:10	12.5	625	1.0	7.20	--	--	.07	.1	--	.2	--	.2	0.2	2.2
1,330	15:00	12.0	628	1.0	7.40	2.7	.5	.06	.1	--	.08	--	.2	--	1.5
2,060	16:30	12.0	625	1.2	7.52	2.3	.08	.06	.1	--	.1	0.1	.2	--	1.8
2,790	18:00	12.3	627	1.4	7.51	5.0	.1	.07	.1	--	.3	.06	.2	--	4.0
<u>Test of well Mg-1610, Keystone Hydraulics site²</u>															
920	12:20	12.9	687	4.7	6.94	5.0	--	--	.4	0.9	67.0	.4	37	.6	63.6
1,620	13:30	13.0	686	4.8	6.87	2.1	--	--	.4	.8	68.8	.3	40.7	.6	64.0
2,820	15:30	12.6	689	4.9	6.70	3.2	.04	--	.4	.8	75.1	.5	46	.6	69.7
4,670	18:35	11.5	694	1.4	6.80	1.3	100	--	.4	.8	77.2	.4	51.6	.6	72.6
<u>Test of well Mg-1609, John Evans site³</u>															
820	11:40	15.0	673	2.4	7.04	4.7	.4	11.8	1.0	3.4	35.6	.5	78	.9	418
1,370	12:40	14.5	674	2.1	7.16	1.2	--	13.1	1.1	4.7	40.0	.5	90	1.2	526
3,000	15:40	14.5	683	2.1	7.51	3.7	.2	12.6	1.2	5.2	48	.4	100	1.4	544
4,190	17:50	14.5	686	2.4	7.14	3.4	.06	11.7	1.1	5.8	46	.8	97	1.3	530

¹ November 13, 1997.

² November 18, 1997.

³ November 21, 1997.

The model grid is aligned parallel to the regional strike of the dipping sedimentary beds (45° NE.) and corresponds to the assumed major axis of anisotropy of horizontal hydraulic conductivity (fig. 52). The assumed minor axis of anisotropy, therefore, is oriented in the dip direction. Cell dimensions of the horizontal model grid were 328-ft × 328-ft (100-m × 100-m). Lateral boundaries of the model were defined as zero-flux (no flow) cells that include streams (discharge boundaries) and topographic divides that were assumed to be ground-water divides (fig. 52). Definition of the lateral boundaries was based in part on a map of water levels in the area (Senior and others, 1998). The bottom layer of the model also was defined as a no-flow boundary. The top layer of the model was defined as a constant flux boundary, where the flux equals the recharge rate.

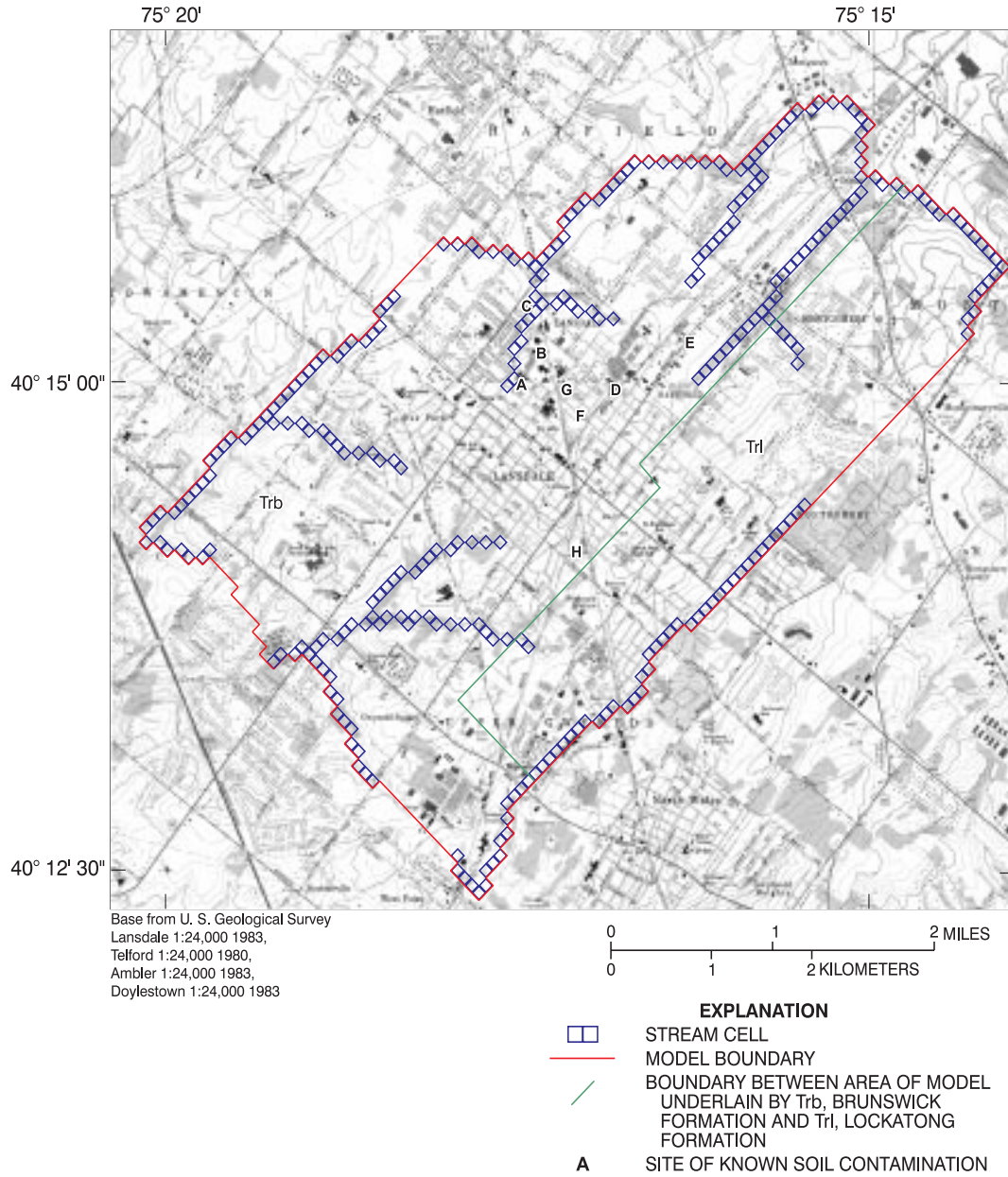


Figure 52. Boundaries and stream cells of model grid and selected areas of soil contamination in and near Lansdale, Pa.

Three model layers represent the shallow [0-40 ft (0-12 m)], intermediate [40-367 ft (12-112 m)], and deep [367-696 ft (112-212 m)] parts of the aquifer (fig. 53). The 40-ft (12-m) thick top layer (1) represents the shallow-flow system, and the 367-ft (100-m) thick second (2) and third (3) model layers represent the deep-flow system (fig. 53). The altitude of the top surface of the model was derived from digital-elevation-model data with 100-ft (30-m) grid spacing. Pumping wells fully penetrate the intermediate layer of the simulated aquifer (fig. 53).

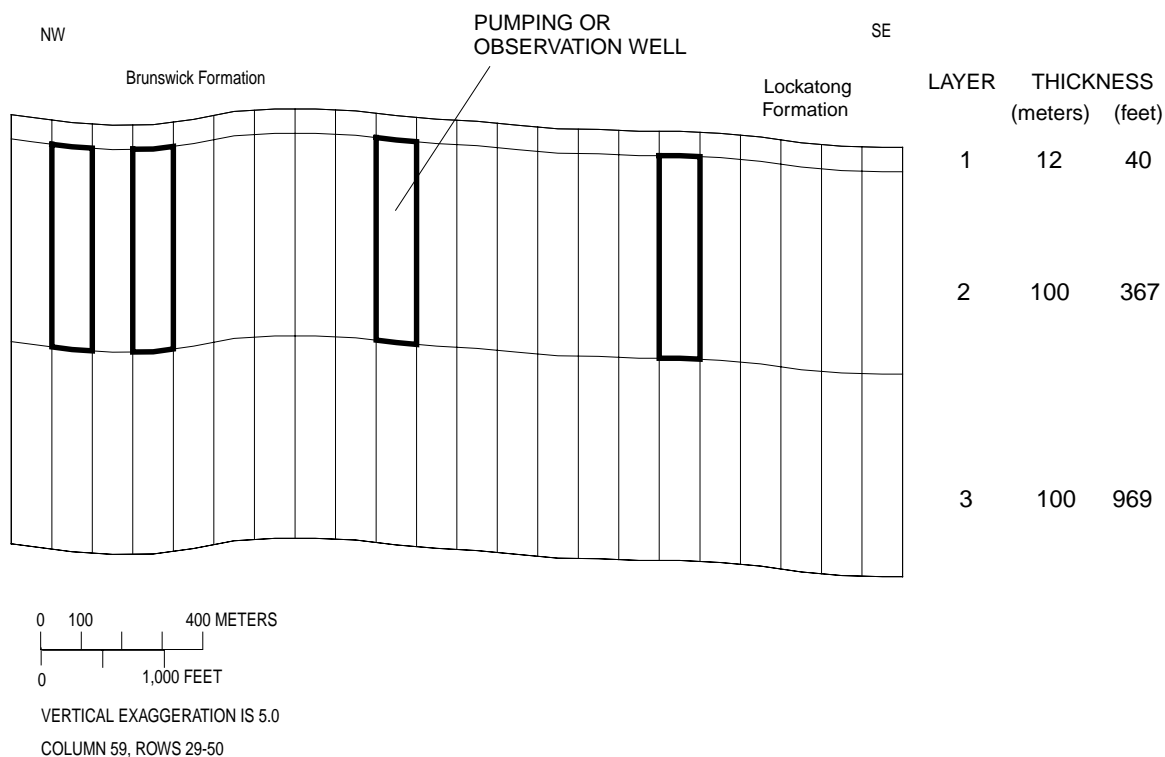


Figure 53. Model structure showing thickness of three layers and location of pumping or observation well in middle layer for simulation of ground-water flow in and near Lansdale, Pa.

The entire thickness of each model layer is assumed to be saturated. This approximation means that the transmissivity (T) of the top model layer is assumed to be independent of the computed hydraulic head. The calibration model MODFLOWP requires this approximation. The model results are relatively insensitive to minor changes in the transmissivity of the top layer because most flow is in the deeper parts of the ground-water system. Where not affected by pumping, the depth to water in the study area commonly is less than 50 ft (15 m) and was less than 30 ft (9 m) in about half of the wells measured in August 1996 (Senior and others, 1998).

Initial transmissivity estimates were determined from analyses of aquifer tests in and near Lansdale (this report; Goode and Senior, 1998). Analysis of some aquifer tests provided estimates of hydraulic conductivity (K), which can be multiplied by saturated thickness to obtain T . Because most tested wells are completed at depths within the intermediate layer [from 40 to 367 ft (12 to 112 m) below land surface], transmissivity estimates from aquifer tests pertain to this layer. Most pumping also is within this layer. The aquifer system also initially was assigned anisotropic properties on the basis of other earlier work (Longwill and Wood, 1965; Goode and others, 1997). The deep layer is assigned the same transmissivity as the intermediate layer. The hydraulic conductivity is assumed to be zero below the bottom of deep model layer, based on a review of data indicating that most water-bearing zones are at

depths less than 700 ft (210 m) and because hydraulic conductivity is thought to decrease with depth (Lewis-Brown and Jacobsen, 1995). Areas underlain by the Lockatong Formation were differentiated from areas underlain by the Brunswick Group, in accordance with relatively low transmissivity of the Lockatong Formation (Longwill and Wood, 1965). This zonation of hydraulic properties is described in more detail in the section, "Calibration of Numerical Model."

The vertical hydraulic conductivity is assumed to be equal to the horizontal hydraulic conductivity. Aquifer-interval-isolation tests suggest substantial vertical anisotropy at the borehole scale with the horizontal hydraulic conductivity much higher than the vertical hydraulic conductivity. However, model calibration tests indicate that the observed heads in the intermediate model layer and the observed streamflow are insensitive to the vertical hydraulic conductivity. Furthermore, if the vertical anisotropy is assumed to be uniform throughout the aquifer system, calibration tests indicate that minimum model error is obtained with very high vertical hydraulic conductivity. Vertical fractures may not be located near some of the tested wells but may serve to connect beds at the regional scale. Open boreholes also act as high-permeability connections across bedding. The regional-scale model cannot simulate local-scale vertical flow controlled by a local network of fractures and fracture zones.

The components of the water balance for the saturated zone that are included in the model are (1) uniform recharge to the water table, (2) discharge to pumping wells, and (3) discharge to and infiltration from streams. The steady-state assumption implies that these fluxes are in equilibrium and that hydraulic head is not changing in time. In reality, these fluxes, particularly pumping rates and recharge, are changing in time, and hydraulic head changes in response to these fluctuations. The steady-state model corresponds to the average flow conditions for the month of interest and approximates the average fluxes and hydraulic head during that period. Thus, the steady-state model cannot simulate instantaneous flow conditions.

Recharge to the saturated zone is assumed to be spatially uniform because detailed spatial information on factors affecting infiltration are not available for the area of Lansdale. On average, recharge to the water table is precipitation minus surface runoff and evapotranspiration. Areal recharge enters through the top model layer, and the magnitude of recharge is determined from calibration.

The pumping rates used in the model represent annual-average rates (Pennsylvania Department of Environmental Protection, State Water Plan Division, written commun., 1995), except for some NPWA wells (table 15). NPWA wells are assigned the average pumping rate for the month of interest, if monthly data are available.

Streams are in the shallow top layer of the model, and the aquifer discharges to the stream if the hydraulic head in a model cell is higher than the hydraulic head of the stream in that cell. Streamflow can enter the aquifer if the stream's hydraulic head is higher than the head in the aquifer, provided the stream is flowing. Stream hydraulic heads are estimated from topographic information.

Calibration of Numerical Model

The numerical model is calibrated by use of MODFLOWP (Hill, 1992), a parameter-estimation program that minimizes model error. Model error is defined as the sum of squared, weighted residuals, where residuals are the differences between measured and simulated hydraulic head and streamflow. Values for aquifer discharge to streams are derived from five measurements of base flow made at five locations from May 1995 through November 1996 (table 4). Eighty-seven model cells contain observation wells in which water levels were measured in August 1996. Because few data are available for comparison of measured to simulated heads in the shallow and deep layers, the calibration of the model is relatively insensitive to changes in hydraulic conductivity in these layers.

For model calibration, average pumping rates in August 1996 are assigned to NWPA wells and annual pumping rates in 1995 are assigned to the remaining wells (table 15). On the basis of available information, pumping rates in 1996 were similar to those in 1995.

The MODFLOWP program calculates optimum values of model parameters, such as recharge rate and hydraulic conductivity, for a particular model structure. The model structure includes all quantitative information that establishes the functional relation between model parameters and predicted heads and streamflow. Although properties of model cells can be specified individually, the approach is to group cells with similar properties into zones with uniform parameters. This approach (using zones) significantly reduces the number of model parameters

Table 15. Annual average pumping rates for wells in and near Lansdale, Pa., during model-calibration period (1996), 1994, and 1997

[--, not numbered; gal/min, gallons per minute]

U.S. Geological Survey local well number Mg-	Owner	Owner well number	Model cell ¹		Pumping rate (gal/min)		
			Row	Column	Calibration period	1994	1997
498	North Penn Water Authority	L-23	28	39	0	18.7	25.0
143	North Penn Water Authority	L-21	30	31	0	37.4	0
593	North Penn Water Authority	L-25	30	36	0	32.7	34.1
625	J.W. Rex Co.	1	31	52	49.7	49.7	49.7
704	North Penn Water Authority	L-26	32	57	0	29.9	0
67	North Penn Water Authority	L-8	36	45	0	60.0	0
621	American Olean Tile Co.	4	38	58	0	10.0	0
69	North Penn Water Authority	L-10	39	35	36.1	63.3	68.1
1045	American Olean Tile Co.	5	41	59	0	13.4	0
620	American Olean Tile Co.	3	42	61	0	10.6	0
914	North Penn Water Authority	NP-12	42	84	59.6	60.6	54.9
566	Lehigh Valley Dairy	5	43	23	64.4	64.4	64.4
153	American Olean Tile Co.	2	42	56	0	19.8	0
59	Lehigh Valley Dairy	3	44	26	44.4	44.4	44.4
1418	Ziegler	--	44	62	4.4	4.4	4.4
140	Lehigh Valley Dairy	4	45	24	92.5	92.5	92.5
924	North Penn Water Authority	NP-21	45	85	0	65.3	0
1125	North Penn Water Authority	NP-61	47	59	125.3	125.3	125.3
875	North Wales Water Authority	NW-17	48	70	71.0	71.0	71.0
1051	North Wales Water Authority	NW-22	48	77	136.3	136.3	136.3
1198	Merck & Co.	PW9	52	11	26.1	26.1	26.1
125	Merck & Co.	PW2	58	10	² 94.1	² 94.1	² 94.1
130	Merck & Co.	PW7	60	17	91.0	91.0	91.0
171	Precision Tube	1	60	30	6.4	6.4	6.4
204	Precision Tube	2	60	31	6.4	6.4	6.4
126	Merck & Co.	PW3	62	13	96.7	96.7	96.7
169	Leeds & Northrup Co.	1	63	20	0	10.6	0
223	Leeds & Northrup Co.	2	63	24	0	11.6	0
77	North Penn Water Authority	L-18	63	42	70.5	71.0	67.2
75	North Penn Water Authority	L-16	63	54	43.7	32.7	43.5
124	Merck & Co.	PW1	64	10	48.4	48.4	48.4
202	North Penn Water Authority	L-22	64	34	42.9	34.1	37.6
76	North Penn Water Authority	L-17	64	36	41.8	25.1	40.4
73	North Penn Water Authority	L-14	64	47	40.6	27.9	38.5
78	North Penn Water Authority	L-19	64	51	37.3	35.0	31.9

¹ All pumping wells are simulated as fully penetrating the middle layer (40 to 367 feet below land surface) of the model.

² Pumping rate at cell is (rate at PW2) + [(rate at PW8)/2].

and improves the reliability of parameter estimates. Zones are determined on the basis of hydrogeologic information. Model parameters are calibrated for several different structures, and the results of these calibrations are compared to identify a calibrated model appropriate for predictive simulation.

Two hydrogeologic zones are delineated from regional geologic mapping. Zone B represents the northwestern area of the model underlain by the Brunswick Group (Trb) (fig. 52). Zone L represents the southeastern area of the model underlain by the Lockatong Formation (Trl). Model parameters for the hydraulic conductivity of the Brunswick and Lockatong zones are designated KB and KL, respectively. Homogeneous hydraulic conductivity is specified by assigning one parameter with the same value of hydraulic conductivity for both of these zones (KB = KL). In some cases, model layer 1, representing saprolite and weathered bedrock, is assigned a value of hydraulic conductivity that differs from that assigned to model layers 2 and 3. In these cases, the model parameter corresponding to the uniform isotropic hydraulic conductivity of layer 1 is designated KW.

Anisotropy of hydraulic conductivity is included in some model structures. Anisotropy refers to a dependence of hydraulic conductivity on direction. Preliminary model evaluation indicated the simulated water levels at the observation well locations, and simulated streamflow, are relatively insensitive to vertical anisotropy. Hence, only horizontal anisotropy is included. The top layer of the model is assumed to be isotropic in all cases because extensive fracture features are less likely to be important in highly weathered rock and saprolite and because preliminary model evaluation indicated the simulated water levels in layer 2, the layer with the most observed data, are not sensitive to the horizontal anisotropy of model layer 1. The model parameter describing the horizontal anisotropy of model layers 2 and 3 is designated ANI23. The parameter is the hydraulic conductivity in the dip direction (y direction in model) divided by the hydraulic conductivity in the strike direction (x direction in model) (or $ANI23 = K_y/K_x$). In anisotropic cases, the hydraulic conductivity parameters KB and KL are the hydraulic conductivities in the strike direction and $KB = KB_x$ and $KL = KL_x$. The hydraulic conductivity in the dip direction is the value in the strike direction multiplied by ANI23. Another model parameter estimated by calibration is the uniform recharge rate, designated R.

Several alternative model structures for hydraulic-conductivity parameters were considered to evaluate the relation between model structure and calibration error (table 16). The structures varied by including one effective layer (cases 1t and 2t) or three effective layers (case 3t), one horizontal zone (case 1t) or two horizontal zones (cases 2t and 3t), and isotropy (cases with 1t.iso, 2t.iso, 3t.iso) or anisotropy (1t.ani, 2t.ani, 3t.ani) (table 16). In case 1t.iso, the hydraulic conductivity is assumed to be isotropic and uniform throughout the entire model domain. In case 1t.ani, the

Table 16. Hydraulic conductivity, anisotropic ratios of hydraulic conductivity, recharge rates, and calibration errors for calibrated cases of different model structures used for simulation of ground-water flow in and near Lansdale, Pa.

[KB, hydraulic conductivity of Brunswick zone; KL, hydraulic conductivity of Lockatong zone; KW, hydraulic conductivity of model layer 1 representing saprolite and weathered bedrock; ANI23, anisotropy ratio of model layers 2 and 3; R, recharge; SSR, sum of squared, weighted residuals; ft/d, feet per day; ft², square feet]

Case	Model parameter					Calibration error
	KB (ft/d)	KL (ft/d)	KW (ft/d)	ANI23	R (ft/d)	SSR (ft ²)
1t.iso	2.53	=KB ¹	=KB	ONE ²	0.0019	91,280
1t.ani	3.31	=KB	=KB	0.04	.0018	25,190
2t.iso	4.56	0.22	=KB	ONE	.0020	86,110
2t.ani	4.69	1.05	=KB	.041	.0019	16,360
3t.iso	11.4	.19	0.013	ONE	.0017	50,910
3t.ani	5.35	1.12	.161	.090	.0019	16,360

¹ =KB not estimated; set equal to KB.

² ONE not estimated; set equal to 1.0.

hydraulic conductivity also is assumed to be uniform throughout the entire model domain, but horizontal anisotropy is included to allow the optimal hydraulic conductivity in the dip direction to differ from the optimal hydraulic conductivity in the strike direction. In case 2t.iso, different hydraulic conductivities are assigned to the Brunswick and Lockatong zones. Hydraulic conductivities in both zones are assumed to be uniform with depth and isotropic. In case 2t.ani, different hydraulic conductivities are assigned to the Brunswick and Lockatong zones and horizontal anisotropy is included for model layers 2 and 3, which represent unweathered bedrock. Because of limitations in the input structure of MODFLOW, the anisotropy ratios of the Brunswick and Lockatong zones are assumed to be identical. In cases 3t.iso and 3t.ani, a separate model parameter represents the uniform isotropic hydraulic conductivity of model layer 1, which represents saprolite and weathered bedrock. Case 3t.iso assumes that hydraulic conductivity of layer 1 and the Brunswick and Lockatong zones are isotropic, whereas case 3t.ani includes one parameter for the horizontal anisotropy of both the Brunswick and Lockatong zones in model layers 2 and 3.

The calibrated model parameters for several alternative model structures are listed in table 16. These optimum values yield simulated hydraulic head and streamflow for each model structure that best match the measured water levels and streamflow. Changes in the model structure, for example, changing which cells represent the Brunswick Group and which represent the Lockatong Formation, would result in different optimum model parameter values. The model error excludes the contribution from the computed streamflow that corresponds to the measurement at SW-13. In the model, the stream is dry or virtually dry in all simulations.

The overall model error (sum of squared, weighted residuals, SSR) decreases as the number of model parameters is increased. From these results, the incorporation of regional horizontal anisotropy is judged to be an important model feature. Separation of the model zones corresponding to the Brunswick Group and the Lockatong Formation also substantially reduces model error and yields different hydraulic conductivities for these zones. Separation of the hydraulic conductivity of the saprolite and weathered zone (model layer 1) yields no appreciable decrease in the model error (difference between cases 2t.ani and 3t.ani, table 16). However, the optimum hydraulic conductivity for model layer 1 is significantly lower than the hydraulic conductivities of the underlying unweathered rock, in agreement with previous observations of relative hydraulic conductivities in these Triassic rocks (Longwill and Wood, 1965). Therefore, the model structure “3t.ani” is chosen for further evaluation and predictive simulation. Because the shared model parameters of structures “3t.ani” and “2t.ani” are similar, simulated water levels and ground-water fluxes should be similar with either set of estimated parameters.

All the high-permeability bed-oriented features contributing to aquifer transmissivity are included into model layers 2 and 3. The actual aquifers may contain many more permeable zones in the top 656 ft (200 m) of unweathered rock, but that level of detail is not included in this regional-flow model. The two-aquifer model used to analyze the aquifer test of well Mg-1609 at the John Evans site identified two aquifers differing in permeability, the pumped aquifer and an overlying unpumped aquifer, separated by a low-permeability bed. Both low-permeability and high-permeability parts of the formation are included within the unweathered bedrock of model layers 2 and 3. In the analysis of the aquifer test at the John Evans site, the transmissivity of the overlying unpumped aquifer is less than that of the pumped aquifer. Although the shallow observation well in the test at the John Evans site is deeper than the thickness of model layer 1, the relation of low-permeability aquifer materials above high-permeability aquifer materials is similar to the relation between model layer 1 and the underlying model layers 2 and 3. The top model layer corresponds to the saprolite and weathered zone lying above the upper aquifer at the John Evans site.

Calibration Errors

The calibrated flow model describes the regional-scale average flow conditions during August 1996 (fig. 54). The contour map of hydraulic head in the intermediate model layer (2) is similar to the contour map of observed water levels in bedrock wells (fig. 19). These similarities include steep head gradients in the Lockatong Formation, a “flat” potentiometric surface underlying the borough of Lansdale, and flow generally away from Lansdale towards regional stream-discharge areas. Pumping has a strong influence on water levels, particularly in the southern part of the modeled area, where public supply and industrial pumping rates are high.

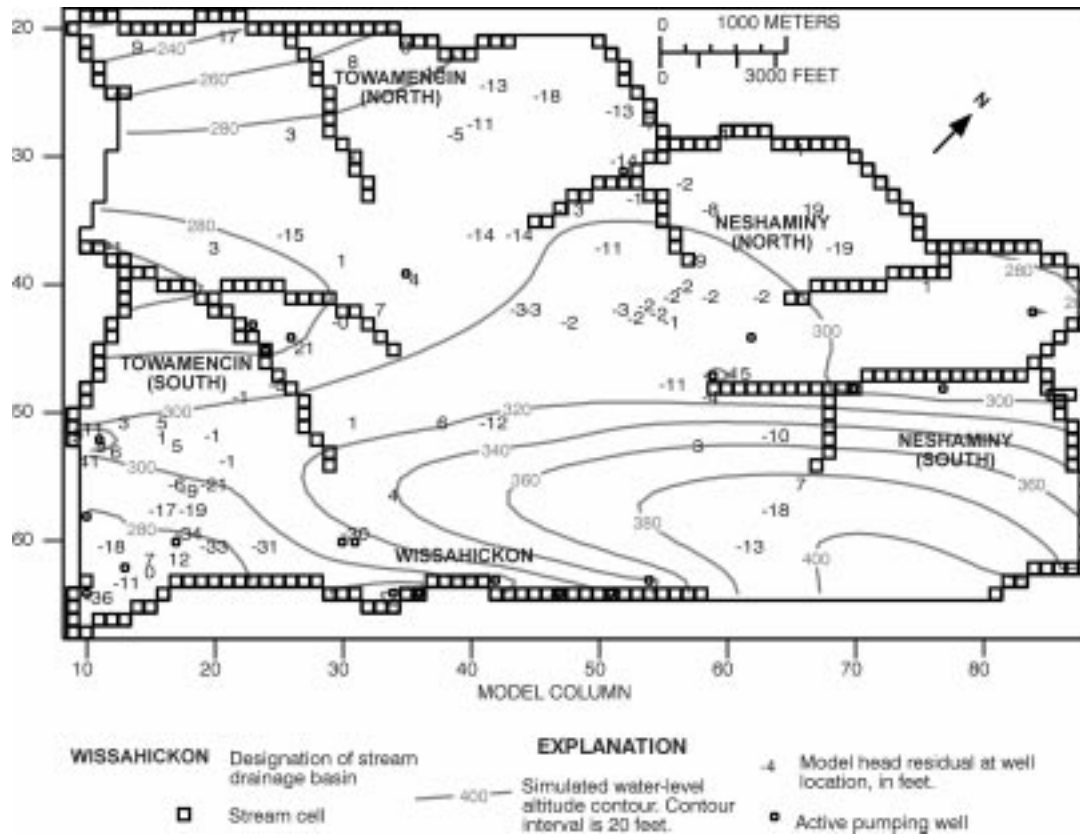


Figure 54. Simulated hydraulic head in model layer 2 representing the upper 328 feet of unweathered, fractured bedrock in and near Lansdale, Pa., and model head residual. The model head residual is the simulated hydraulic head minus the observed hydraulic head.

The root mean square residual for hydraulic head is 13 ft (4.0 m); ground-water-level differences are from -14 to +7 ft (-4 to +2 m) near the center of the model in the area of Lansdale. Maximum head residuals of -36 ft and +41 ft (-11 to +12 m) occur near the southern boundary (bottom left boundary, fig. 54), an area of intense industrial pumping that is outside the main area of interest for this study. These larger residuals may represent the inaccuracy of the regional-scale model in simulating local-scale effects of large pumping wells in this area.

Another feature of the measured water levels that is not reproduced by the model is the local water-level high in the area of the Keystone site (potential source location A), located in the central part of the model where the residuals are about -14 ft (-4 m) at three locations. A uniform transmissivity for the Brunswick Group is used in the model, but these relatively high water levels may be the result of lower permeability at this location or nearby than elsewhere in the modeled area underlain by the Brunswick Group. However, aquifer tests done in 1997 for this study and done prior to 1995 (Goode and Senior, 1998) indicate transmissivity at the Keystone Hydraulics site is higher than at several other locations in the modeled area.

Simulated streamflow agrees reasonably well with four of the observed values, but the optimized model does not include any net streamflow for the stream segments corresponding to the measurement at the site SW-13, Wissahickon Creek near Hancock Street (table 17). All the model structures tested simulated near-zero streamflow for the model stream cells corresponding to site SW-13. This stream is along the southeastern boundary of the modeled area and has been known to go dry during periods of low rainfall. The streamflow residuals are multiplied by a constant weight of 465 ft $/(ft^3/s)$ [0.058 m $/(m^3/d)$] to account for the difference in units and measurement errors between head and streamflow (see Hill, 1992, p. 38). The chosen weight value yields weighted residuals for

Table 17. Measured and simulated streamflow for calibrated numerical model of ground-water flow in and near Lansdale, Pa.

[ft³/s, cubic feet per second; ft, feet]

Site number	Model cell ¹		Streamflow			
	Row	Column	Simulated (ft ³ /s)	Measured ² (ft ³ /s)	Calculated residual (ft ³ /s)	Weighted residual ³ (ft)
SW-21, tributary to Towamencin Creek at Troxell Rd.	19	22	0.459	0.411	0.048	22
SW-3, tributary to W. Branch Neshaminy Creek at Cowpath Rd near Kulp Rd.	29	66	.126	.098	.028	13
SW-10, tributary to W.Branch Neshaminy Creek near Line & Cowpath Rd.	48	69	0	.022	-.022	-10
SW-13, Wissahickon Creek at Hancock St. (and at Wissahickon Ave.)	64	29	⁴ 0	.170		
SW-17, Towamencin Creek at Sumneytown Pike	39	15	.807	.762	.044	20

¹ All stream cells are in the top layer (1) of the model.

² Measured streamflow estimated from five base-flow measurements May 1995 through November 1996; flow was weighted at SW-21 by 70 percent and at both SW-3 and SW-13 by 50 percent to account for reduced amount of contributing areas in these streams at the boundaries of the model.

³ Weight is 465 feet per cubic feet per second for all flux measurements.

⁴ The measurement was not used in the model calibration procedure because all cells of the stream were dry during parameter-estimation iterations (Hill, 1992).

streamflow that are in the same range as head residuals. A smaller weight value would reduce the weighted residuals and the importance of the streamflow measurements in the overall parameter estimation, whereas a larger weight value would increase the importance of streamflow measurements relative to head measurements.

The accuracy of the nonlinear regression methods used here for estimating model parameters is based, in part, on the assumption of normally distributed, independent residuals. Hill (1992) proposes a hypothesis test of normality and independence of weighted residuals. This test compares the correlation coefficient between the ordered weighted residuals and order statistics from the normal distribution. For case “3t.ani,” this correlation coefficient is 0.978. This value is slightly greater than the critical value (0.977) for the 0.10 significance level, indicating the residuals are nearly normally distributed and independent. This suggests the optimum parameters for this model are accurately identified by use of these procedures.

Estimated Large-Scale Hydraulic Conductivity and Recharge

The calibrated model parameters are estimates of the large-scale hydraulic properties controlling ground-water flow in and near Lansdale. Calibrated parameters and estimated confidence intervals are shown in table 18. The confidence intervals correspond to plus and minus two standard deviations from the estimated value. These confidence intervals are based on the assumption that the optimization model is linear near the calibrated parameters. Furthermore, these confidence intervals represent only the uncertainty in the parameter in question under the condition that all other model parameters are held constant. The modified Beale’s measure is computed to examine nonlinearity in the optimization model (Cooley and Naff, 1990). For case 3t.ani, this measure is 19.1, which indicates the model is highly nonlinear. The model is nonlinear if the modified Beale’s measure is greater than 0.43, and it is effectively linear if the measure is less than 0.04. Examination of the output of program BEALEP (Hill, 1994) indicates parameter KW, the hydraulic conductivity of the top model layer, contributes most to the nonlinearity. To test the effect of this parameter on the model nonlinearity, parameter KW is set to its optimal value, 0.16 ft/d (0.049 m/d), and removed from the parameter estimation. For this test case without estimation of parameter KW, the modified Beale’s measure is 0.04 and indicates the model is effectively linear. This implies the linear confidence intervals on the other four parameters may be meaningful, even though the measure indicates the model is highly nonlinear with all parameters included.

Table 18. Optimum and approximate, individual, 95-percent confidence-interval values for hydraulic conductivity, anisotropic ratio, and recharge or calibrated simulation of ground-water flow in and near Lansdale, Pa.

[KB, hydraulic conductivity of Brunswick zone; KL, hydraulic conductivity of Locketong zone; KW, hydraulic conductivity of model layer 1 representing saprolite and weathered bedrock; ANI23, anisotropy ratio of model layers 2 and 3; R, recharge; ft/d, feet per day; -, dimensionless; in/yr, inches per year]

Parameter	Units	Optimum value	Approximate, individual, 95-percent confidence interval	
			Lower value	Upper value
KB	ft/d	5.35	4.04	7.05
KL	ft/d	1.12	.89	1.40
KW	ft/d	.16	.01	2.00
ANI23	-	.090	.060	.119
R	in/yr	8.3	7.9	8.8

The approximate, individual, 95-percent confidence intervals show the hydraulic conductivities of the Brunswick and Locketong zones are relatively tightly constrained in the optimum model but the hydraulic conductivity of the weathered zone is poorly described. This poor description is probably the result of a lack of water-level data in the top layer of the model. Only two measurements are assigned to that layer. Recharge also is tightly constrained, because streamflow observations are used in the calibration and the specified pumping constitutes a large percentage of the water balance.

The transmissivity of the weathered zone (layer 1) is estimated as $0.16 \text{ ft/d (hydraulic conductivity)} \times 40 \text{ ft (layer thickness)} = 6.4 \text{ ft}^2/\text{d}$ ($0.59 \text{ m}^2/\text{d}$). The transmissivity of the underlying Brunswick Group (layers 2 and 3) in the strike direction is estimated as $5.35 \text{ ft/d} \times 656 \text{ ft} = 3,510 \text{ ft}^2/\text{d}$ ($326 \text{ m}^2/\text{d}$). The transmissivity of the Brunswick Group in the dip direction is estimated as $3,510 \text{ ft}^2/\text{d} \times 0.090 = 316 \text{ ft}^2/\text{d}$ ($29 \text{ m}^2/\text{d}$). The geometric mean (square root of the product) of the directional transmissivities corresponds to the “effective” isotropic transmissivity controlling drawdown because of pumping (Kruseman and de Ridder, 1990, p. 134). For the Brunswick Group, the geometric mean transmissivity is about $1,050 \text{ ft}^2/\text{d}$ ($97 \text{ m}^2/\text{d}$). The transmissivity of the unweathered part of the Locketong Formation is similarly estimated as $732 \text{ ft}^2/\text{d}$ ($68 \text{ m}^2/\text{d}$) in the strike direction and $64 \text{ ft}^2/\text{d}$ ($6 \text{ m}^2/\text{d}$) in the dip direction, with a geometric mean of $215 \text{ ft}^2/\text{d}$ ($20 \text{ m}^2/\text{d}$). Most water moving horizontally through the model does so in layers 2 and 3, representing unweathered fractured rock. The transmissivity of the zone representing the Brunswick Group is higher than that of the Locketong Formation zone.

The calibrated recharge rate is 8.3 in/yr (212 mm/yr). This value is somewhat higher than regional estimates of recharge from long-term-average base flow to streams overlying the Brunswick Group and Locketong Formation (White and Sloto, 1990). The streamflow measurements and assumed pumping rates strongly control the estimated recharge rate. Lower estimated recharge would be obtained by use of lower pumping rates and lower streamflow measurements. Lower streamflow or pumping rates used for calibration also would lead to lower estimated hydraulic conductivity and transmissivity. It is not known how the observed streamflow compares to long-term streamflow because long-term measurements are not available for these streams.

EFFECT OF PUMPING ON GROUND-WATER FLOW

The effect that pumping has on ground-water flow in the Lansdale area is described at local and regional scales. Local-scale effects are identified primarily from borehole logging and aquifer-test data. Regional-scale effects are identified from simulation of regional ground-water flow under different pumping scenarios.

Local Ground-Water Flow

Local ground-water flow on a scale that ranges from within a single borehole to distances of 1,000 ft (300 m) or more can be affected by pumping. Effects of pumping within a borehole include change in the rates or directions of flow in and near the borehole. In Lansdale, such changes were observed while measuring vertical flow with a heatpulse flowmeter in a pumping well (Conger, 1999). Nearby pumping can have a similar effect of changing the rate or direction of borehole flow in a nonpumping well, if that well is hydraulically connected to the pumping well. For example, water levels in well Mg-1441 fluctuated rapidly (fig. 13) in response to nearby pumping. The downward borehole flow measured in well Mg-1441 reflects the difference in depths between the producing fracture at 108 ft (32.9 m) and the receiving fracture at 128 ft (39 m), which apparently is hydraulically connected to the pumping well.

Drawdown and changes in ground-water flow on a local scale near a pumping well can be highly variable because of aquifer heterogeneity. Results of aquifer tests indicate transmissivity differs in both vertical and horizontal directions. The extent of hydraulic connection between water-bearing fractures is not necessarily related to distance but may be related to geologic structure. For example, wells with water-bearing zones located in the projected bed of the pumped interval responded to pumping in aquifer tests described in the section, "Multiple-Well Tests."

Regional Ground-Water Flow Under Different Pumping Conditions

The calibrated flow model is used to simulate ground-water flow and hydraulic heads under three scenarios with different pumping conditions. The first scenario, no pumping, represents unstressed ground-water conditions with all recharge to the saturated zone discharging to streams as base flow. The second scenario, 1994, represents periods with high pumping rates in the Lansdale area. The third scenario, 1997, represents periods with moderate to high pumping rates that are less than those in the 1994 scenario, particularly for wells in the Borough of Lansdale. Between 1994 and 1997, several public-supply wells were removed from service because a surface-water supply became available to NPWA, and several industrial wells were shut down because of plant closure. It is assumed that the flow in a semi-confined aquifer system responds relatively quickly to changes in pumping rates; hence, a steady-state model is used.

Particle tracking using MODPATH (Pollock, 1994) illustrates the paths of ground-water flow simulated by the numerical flow model. On the basis of the calibrated anisotropic transmissivities and vertical hydraulic conductivity and the computed three-dimensional hydraulic gradients, particles of water are tracked through the flow system from recharge to discharge locations in streams or wells. Particles are introduced at the center of each model cell at the top of the modeled domain, which represents recharge across the water table. Maps of capture zones for streams and wells are generated by assigning a discharge location (color coded in figure) to each cell. However, not all of the recharge in that cell necessarily discharges to the same location. This procedure can yield discontinuous colors for cells at the boundaries between different capture zones. Recharge along a ground-water divide may flow deep through the system, beneath the three-dimensional capture zone of a nearby stream, and discharge to a more-distant regional boundary. A more-detailed delineation of capture zones could be generated by tracking more than one particle for each recharge cell, but this level of detail is considered to be unwarranted, given the uncertainties in model parameters and boundary conditions. Individual flowpaths were tracked from areas of known soil contamination (table 19).

Table 19. Selected sites and main volatile organic compounds where soil contamination or probable sources of ground-water contamination have been identified in Lansdale, Pa. [Source of data: Black & Veatch Waste Science, Inc. 1994; Greg Ham, U.S. Environmental Protection Agency, written commun., 1997]

[TCE, trichloroethylene; PCE, tetrachloroethylene; VC, vinyl chloride]

Site code	Site name	Primary volatile organic compound(s) on site
A	Keystone Hydraulics	TCE, PCE, VC
B	Westside Industries	TCE, VC
C	J.W. Rex Co.	TCE, PCE, VC
D	John Evans and Sons	TCE, PCE
E	Royal Cleaners	PCE
F	Electra Products	PCE
G	Precision Rebuilding	TCE
H	Rogers Mechanical ¹	TCE

¹ Formerly the Tate Andale property.

No Pumping

The no-pumping scenario corresponds to natural flow conditions in the absence of pumping (fig. 55). It is unlikely that ground-water pumping will cease in the Lansdale area, but this scenario serves as a base case to which alternative pumping conditions can be compared. This limiting-case scenario illustrates the maximum increases in stream discharge possible through reduction in pumping rates.

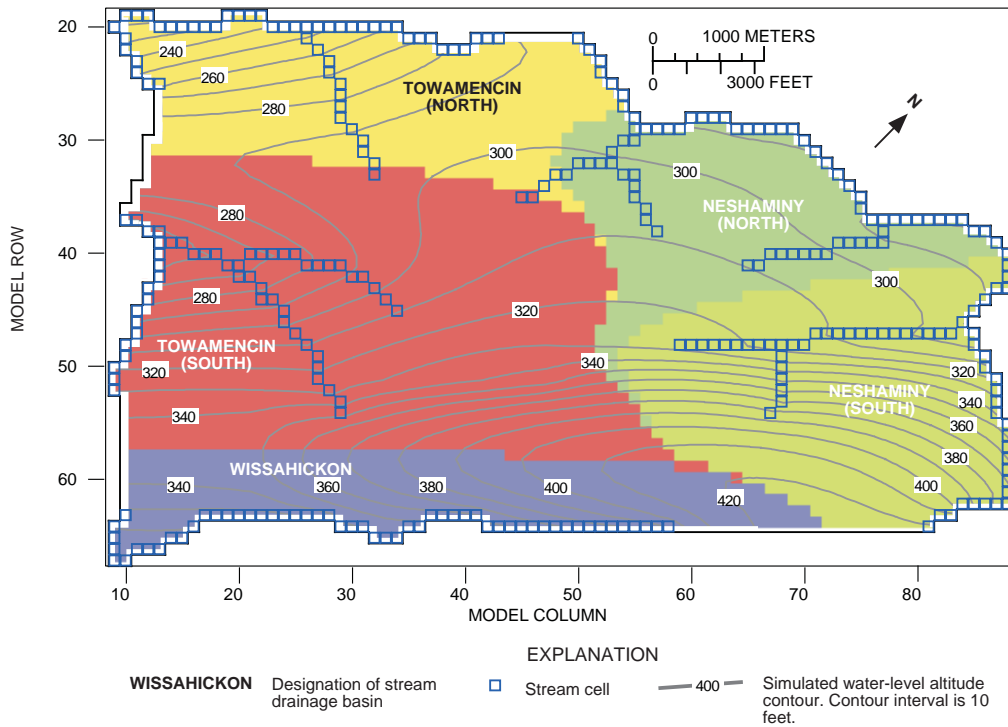


Figure 55. Simulated hydraulic head in model layer 2 representing the upper 328 feet of unweathered, fractured bedrock in and near Lansdale, Pa., and stream capture zones for “No Pumping” scenario. Simulated recharge within a colored capture zone discharges to the indicated stream.

In the no-pumping scenario, all discharge from the aquifer system is to streams (table 20). The sum of discharge from the ground-water system to the stream cells that correspond to the different stream segments in table 20 correspond to the ground-water base flow contributed to these streams from the modeled area. Over one-half of the discharge from the aquifer system is to the Towamencin Creek. The surface-drainage-basin area for the Towamencin Creek occupies a large part of the modeled area. In addition, the streambed altitudes along the Towamencin Creek are much lower than the altitudes along other creeks. Discharge to the West Branch Neshaminy Creek is approximately 35 percent of the total discharge, and discharge to the Wissahickon Creek is about 13 percent of total discharge. The relatively low discharge to Wissahickon Creek is partly the result of relatively low permeability of the Lockatong Formation.

Table 20. Simulated ground-water discharges to wells and the Towamencin, West Branch Neshaminy, and Wissahickon Creek stream segments in and near Lansdale, Pa., under no-pumping, 1994, and 1997 conditions

[ft³/s, cubic feet per second; %, percent]

Discharge location	No pumping		1994		1996 (Calibration)		1997	
	(ft ³ /s)	%	(ft ³ /s)	%	(ft ³ /s)	%	(ft ³ /s)	%
Towamencin (N)	1.23	17	1.02	14	1.16	16	1.10	15
Towamencin (S)	2.51	35	1.37	19	1.55	22	1.54	22
Neshaminy (N)	1.07	15	.57	8	.80	11	.78	11
Neshaminy (S)	1.43	20	.55	8	.69	10	.74	10
Wissahickon	.90	13	0	0	0	0	0	0
Wells	0	0	3.66	51	2.96	41	3.00	42

1994 Conditions

The 1994 scenario is representative of conditions of intensive ground-water pumping in the Lansdale area. Pumping rates were relatively high during and prior to 1994 (table 4). Ground-water use has decreased since 1994 because use of surface water from outside the local area has increased and because industrial water use has decreased. Although surface water requires filtration treatment, local ground water is contaminated and, hence, also requires treatment. The cost of ground-water treatment has made use of surface-water resources more economically attractive. Wells pumping in 1994 included well Mg-67 (NPWA well L-8), which is near a known source of contamination and was pumped to help limit the spread of ground-water contamination in the area and protect other downgradient public-supply wells, and four industrial wells (Mg-153, Mg-620, Mg-621, and Mg-1045) at a manufacturing facility.

Simulation of intensive pumping of ground water in the area of Lansdale in the 1994 scenario has a major effect on the regional water balance (table 20) and flowpaths (fig. 56). Slightly more than one-half of recharge to the aquifer system is captured by wells. Streamflow is decreased throughout the entire modeled area, and all the ground water that discharges to the Wissahickon Creek under no-pumping conditions is captured by wells.

Numerical simulation using the calibrated-model parameters and 1994 pumping rates indicates that well Mg-67 (NPWA well L-8) may have captured ground water that recharged in an area that includes sources of soil contamination shown as sites A and B in figure 15. Simulated recharge from site C is captured by the adjacent industrial pumping well Mg-625. Simulated ground-water recharge near site D is captured by industrial wells Mg-153 and Mg-1045. Public-supply well Mg-69 (NPWA well L-10) may have captured water from areas of soil contamination shown as sites F and G (fig. 15). Simulated recharge from site H discharges to industrial pumping well Mg-140.

Some ground water recharged near soil-contamination site E (fig. 15) flows near well Mg-1418 and is partly drawn toward industrial well Mg-620. However, the anisotropy of the calibrated model contributes to the model result that flowpaths from source E flow primarily in the strike direction. A fraction of recharge in the area of site E is captured by public-supply well Mg-1125 (NPWA well NP-61) (fig. 56).

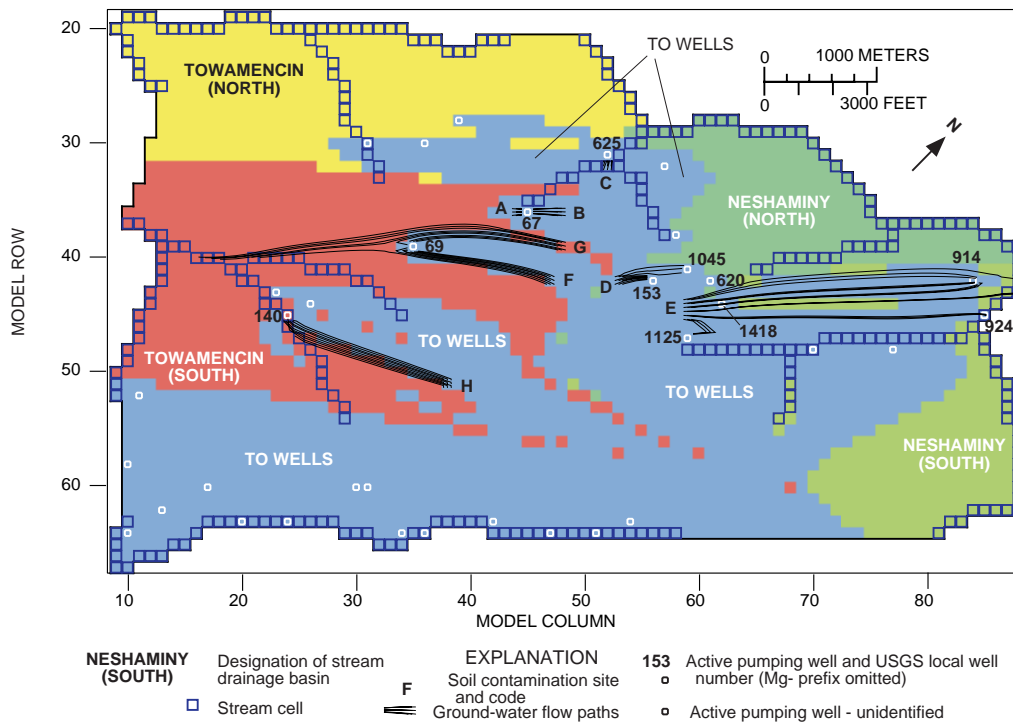


Figure 56. Simulated stream and well capture zones and flowpaths from potential source areas in Lansdale, Pa., and vicinity for “1994” scenario. Potential source areas are designated by letter. See table 19 for site names. Simulated recharge within a colored capture zone discharges to the indicated stream or pumping wells.

To illustrate the sensitivity of flowpaths to the hydraulic properties of the model layers, the 1994 pumping scenario was simulated with modified hydraulic properties. The anisotropy ratio ANI23 was changed from 0.09 to 0.119 (an increase of about 30 percent), and the hydraulic conductivity of the top model layer, representing overburden and weathered rock, was changed from 0.16 to 1.97 ft/d (0.049 to 0.6 m/d) (an increase of slightly more than one order of magnitude). These parameter values are near the limit of the linear, independent confidence intervals (table 7). The selection of these particular parameter changes is somewhat arbitrary but is meant to illustrate the sensitivity of flowpaths to these two model parameters. All other model parameters are identical to the calibrated-model values. These changes in the hydraulic properties result in readily apparent changes in flowpaths (fig. 57). Compared to the flow paths from the calibrated-model simulation, these flowpaths span more of the dip direction, because of the increased hydraulic conductivity in the dip direction. A fraction of the flowpaths from source E are captured by pumping at industrial well Mg-620, whereas none of the flowpaths from source E were captured by this well for the calibrated-model simulation. Public-supply well Mg-67 captures flowpaths from sources A and B, as in the calibrated-model simulation, but also captures at least some of the flowpaths from sources D and G. These results illustrate that simulated flowpaths are sensitive to changes in model parameters that are within the linear confidence intervals.

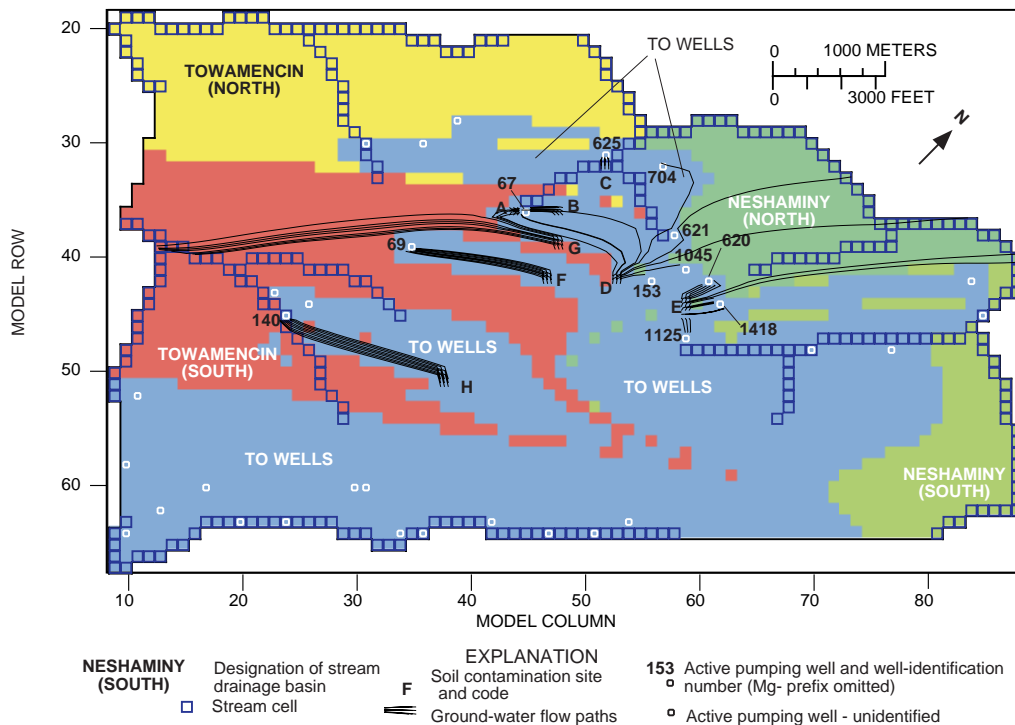


Figure 57. Simulated stream and well capture zones and flowpaths from potential source areas in Lansdale, Pa., and vicinity for 1994 scenario with modified anisotropy ratio (from 0.09 to 0.119) and layer 1 hydraulic conductivity [0.16 to 1.97 feet/day (0.049 to 0.6 meters/day)]. Potential source sites are designated by letter. See table 19 for sites names. Simulated recharge within a colored capture zone discharges to the indicated stream or pumping wells.

1997 Conditions

In fall 1995, the pump in public-supply well Mg-67 (NPWA well L-8) malfunctioned and pumping of the well ceased. In April 1996, manufacturing at an industrial facility ended, and pumping at three of four industrial wells (Mg-620, Mg-621, and Mg-1045) was stopped and greatly reduced in the remaining production well (Mg-153). Other wells in the area continued to be pumped at rates similar to historical rates (table 15). Overall pumping is a smaller fraction of average recharge (average ground-water discharge) in 1997 than in 1994 (table 20). Flowpaths and capture zones for the 1996 simulation are shown in figure 58.

The directions of ground-water flow, as simulated by the model (fig. 58), reflect the changes in the pumping regime. Well Mg-67 is not pumping and does not capture ground water that recharged near sites A and B. The capture zones for public-supply wells Mg-593 (NPWA well L-25) and Mg-69 (NPWA well L-10) shift towards contamination sources A and B, although the simulated flowpaths from these sources discharge to the Towamencin Creek. Ground water recharged near site D is no longer captured by industrial wells at the manufacturing facility, as discussed in section “1994 Conditions,” but moves to the west and southwest. Ground water recharged near site E no longer moves toward industrial wells at the manufacturing facility but instead moves to the northeast flowing directly by well Mg-1418. Other flowpaths from source E are intercepted to a smaller degree than in 1994 by public-supply well Mg-1125 (NP-61). As shown in the section on “1994 Conditions,” the uncertainty in hydraulic properties causes uncertainty in flowpaths. Simulations using other values of hydraulic properties within the linear confidence intervals

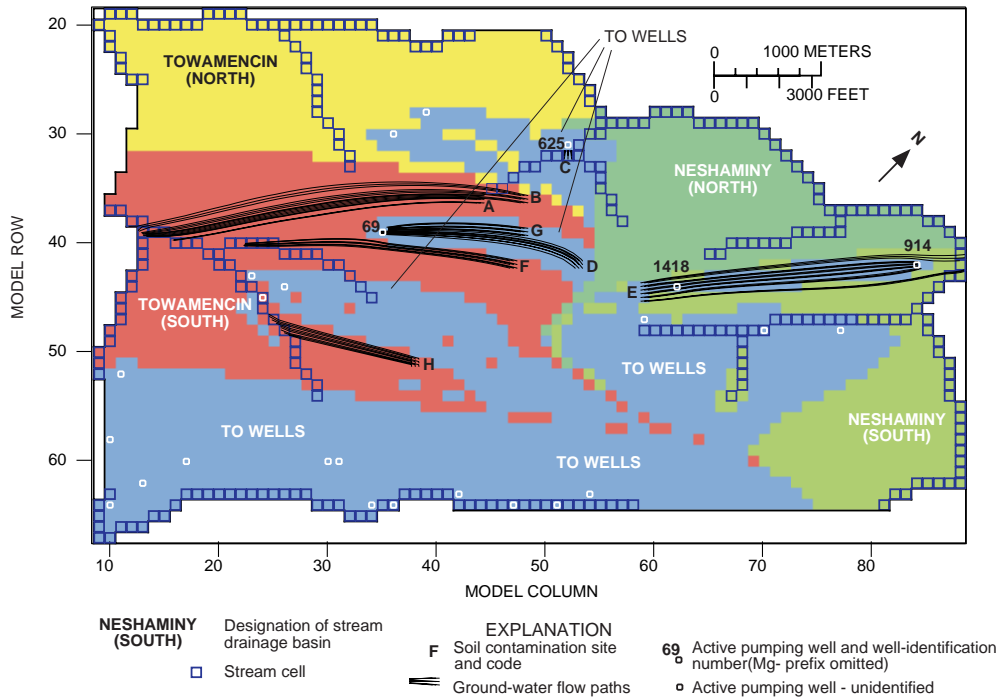


Figure 58. Simulated stream and well captures zones from potential source areas in Lansdale, Pa., and vicinity for 1997 scenario. Potential source areas are designated by letter. See table 19 for site names. Simulated recharge within a colored capture zone discharges to the indicated stream or pumping wells.

could yield different flowpaths. The flowpath for recharge from sites F and H discharges to streams under 1997 conditions rather than to wells as under 1994 conditions. Simulated recharge from site C discharges to the same locations under 1997 conditions as under 1994 conditions.

Relation Between Simulated Ground-Water Flow Directions and Ground-Water Contamination

Contaminants dissolved in ground water generally travel in the direction of ground-water flow. The rate of contaminant transport can be less than that of ground water because of degradation reactions or adsorption on surfaces within the aquifer. Diffusion of contaminants from high-permeability fractures into low-permeability rock matrix also can retard migration. Contaminants with a density different than water can move in directions other than that of ground-water flow in response to gravity. In addition, chemical gradients can differ from hydraulic gradients.

Changes in measured concentrations of some contaminants in samples from wells have corresponded to changes in pumpage in the Lansdale area. Concentrations of TCE and PCE measured in water from selected wells sampled in 1995, 1996, and 1997 are listed in table 21 (Black & Veatch Waste Science, Inc., 1998). Since 1995, concentrations of PCE decreased in samples from industrial wells Mg-153 and Mg-620 and observation well Mg-618 and increased in samples from well Mg-1418. Industrial wells Mg-153, Mg-620, Mg-621, and Mg-1045 were pumping during sampling in 1995 and 1996. PCE is the main contaminant detected in soils at site E, whereas TCE and PCE have been detected at elevated concentrations in soils at site D (Black & Veatch Waste Science, Inc., 1994). Site D may be a source for TCE contamination observed in wells at the manufacturing facility.

Table 21. Concentrations of trichloroethylene and tetrachloroethylene in water samples from selected wells in and near Lansdale, Pa., spring 1995, winter 1996, and fall 1997

[µg/L, micrograms per liter; --, no data; ND, not detected]

U.S. Geological Survey local well number Mg-	Owner	Owner well name	Trichloroethylene (µg/L)			Tetrachloroethylene (µg/L)		
			1995	1996	1997	1995	1996	1997
67	North Penn Water Authority	L-8	390	1,680	84.6	72	35.4	31
69	North Penn Water Authority	L-10	25	27.8	32.3	17	21.2	25.7
593	North Penn Water Authority	L-25	17	20	11.3	2	3.7	ND
1418	Ziegler & Sons	1	--	ND	ND	--	.3	128
618	North Penn Feed	--	22	13.3	8.5	130	90	7.6
153	American Olean Tile Co.	PW2	120	96.3	183	130	102	17.4
620	American Olean Tile Co.	PW3	28	27.4	77	110	186	37
621	American Olean Tile Co.	PW4	2	4.6	8.5	ND	.4	.5
1045	American Olean Tile Co.	PW5	17	30.1	--	4	6.5	--

If site E were the source of PCE detected in samples from these wells, the trend in concentrations of PCE in samples from wells Mg-620 and Mg-1418 is consistent with predicted ground-water flow directions. The simulation of flow under reduced 1997 pumping conditions (fig. 58) indicates the contaminants from site E would migrate almost directly to the northeast towards well Mg-1418 and beyond. Under the more intensive 1994 pumping conditions, transport is still in the same general direction, but several flowpaths are diverted from site E north and south towards other nearby pumping wells (fig. 56). The simulations illustrate changes in pumping rates at wells near source E can change flow directions from source E. Because of the uncertainty in the model parameters, and because the model is calibrated to regional hydraulic heads and streamflow, the actual flowpaths probably are more complex than the simulated flowpaths. When modeling steady-state ground-water flow directions, it is assumed the boundary conditions and recharge are constant during the entire time required for movement of water (and possibly contaminants) from the source area to the discharge boundary or pumping well.

Some public-supply wells, including Mg-69 (NPWA L-10) and Mg-593 (NPWA L-25) are equipped with air strippers, and in 1995, water from these wells was slightly contaminated (table 21). Since 1995, concentrations of contaminants have increased in water from well Mg-69 (table 21). The increase in TCE and PCE concentrations in well Mg-69 is consistent with simulated ground-water flow directions that show, in 1997, well Mg-69 captured ground water recharged near source G. Under increased 1994 pumping conditions, recharge near source G was captured by well Mg-67 (fig. 56). Although the model indicates the public-supply well Mg-593 should also capture more contaminants under 1997 pumping conditions, the sampling data from 1995 through 1997 do not show an increase in contamination (table 21).

Traveltime of ground-water flow paths cannot be simulated without specifying effective porosity values. To date (1998), these values have not been measured in the Lansdale area. However, the relatively rapid changes in measured concentrations of contaminants in ground water indicate the effective porosity is low in the formations that underlie the Lansdale area.

SUMMARY AND CONCLUSIONS

Ground water in the area of Lansdale, Pa., is used for drinking water and for industrial and commercial supply, and is known to be contaminated with volatile organic compounds that were used at several industrial facilities. An area in Lansdale and vicinity was placed on the National Priority List by the USEPA and is designated the North Penn Area 6 site. The USGS provided technical assistance to USEPA through this study to describe the ground-water flow system and evaluate the effects of changes in the well pumpage on ground-water flow directions as wells shut down in Lansdale during the 1990's. The USGS collected hydrologic data from 1995 to 1998 to characterize the ground-water flow system. These data included water-level and streamflow measurements, geophysical logs, selected chemical measurements of ground-water samples, and water-level response to pumping during aquifer tests. Using these data, a conceptual model of the ground-water system was developed and ground-water flow under various pumping scenarios was simulated.

The Lansdale area is underlain by Triassic-age fractured shales, siltstones, and sandstones of the Brunswick Group and Lockatong Formation. These rocks generally strike northeast and dip at angles less than 30 degrees to the northwest, as indicated by correlation of natural-gamma logs and in agreement with reported attitudes in literature. The Borough of Lansdale is on an upland area that forms a divide between three streams—Towamencin Creek to the southwest, Wissahickon Creek to the southeast, and Neshaminy Creek to the north. The bedrock aquifer is recharged by precipitation. Except perhaps at very shallow depths [less than 50 ft (15 m)], most of the aquifer is under confined or semi-confined conditions.

Water levels were measured near-continuously at seven wells from fall 1995 to spring 1998. Water levels were observed to respond to earth tides and changes in barometric pressure. Water levels generally declined in 1995 and 1997, years with less-than-normal precipitation, and rose in 1996, a year with greater-than-normal precipitation. Water levels in 100- to 500-ft (30.5- to 152-m) deep wells distributed throughout the area were measured in August 22-23, 1996, and January 12-13, 1998, to estimate the potentiometric surface of the bedrock aquifer in the region. The potentiometric surface estimated from these levels reflects land-surface topography, although the ground-water divide lies north of the topographic divide in the Borough of Lansdale.

Streamflow was measured periodically at five sites during 1995-96 to provide an estimate of annual base flow. The amount of annual recharge that discharged to streams averaged about 3.2 in. (81 mm) over a 10-mi² (25.9-km²) area of Lansdale in 1996. Streamflow measurements at about 20 sites in May 1995 indicated the upper reaches of Wissahickon Creek and a tributary to West Branch Neshaminy Creek were dry, discharge from the Lansdale sewage treatment plant contributed most of the flow in another tributary to West Branch Neshaminy Creek, and Towamencin Creek has a higher base flow relative to the surface-drainage area than the other streams.

Geophysical logs were run in 31 observation, industrial, water supply, and commercial wells and 27 monitor wells newly drilled in 1997 to determine distribution of water-bearing zones, directions of borehole flow, attitude of beds from stratigraphic correlation of natural-gamma logs, and attitude of water-bearing fractures. Wells ranged in depth from 49 to 1,027 ft (14.9 to 313 m). Water-bearing zones were most frequently detected in the interval from 50 to 300 ft (15 to 91.4 m) below land surface. Upward flow under nonpumping conditions was measured in 35 of 58 wells. Downward flow was measured in 11 wells and inferred in 1 well, and many of these were near pumping wells. Upward and downward flow was measured in three wells. No flow was detected in eight wells. Many water-bearing fractures were oriented in attitudes similar to that of bedding, which generally strikes to the northeast and dips to the northwest in the area.

Single-well, aquifer-interval-isolation tests (packer tests) were done by USGS at three wells in spring 1997 in Lansdale. The aquifer-interval-isolation tests indicate discrete water-bearing openings generally are not well connected in the vertical direction. Evidence for limited vertical hydraulic connection between water-bearing openings includes differences in static potentiometric head up to 15 ft (46 m) over 300 vertical ft (91 m) and typically small drawdown in zones adjacent to the isolated pumped zone. Estimated values for transmissivity (T) ranged from 0.54 to 240 ft²/d (0.05 to 22 m²/d) for tests of isolated intervals and ranged up to two orders of magnitude within a single well. No relation between depth and specific capacity or estimated transmissivity was noted in the results of tests of isolated zones in the three wells. The chemical composition of water from isolated intervals generally differed at least slightly. In tests of two of three wells, concentrations of manmade VOC's were highest in the shallowest zones tested.

Multiple-well aquifer tests were done at three sites in fall 1997. Effects of heterogeneity and limited vertical permeability were observed in all tests. The variability of the extent of response to pumping at all three sites underscores the heterogeneity of three-dimensional hydraulic conductivity in the fractured-rock formations. Estimated values of transmissivity determined from analyses of multiple-well tests, assuming isotropic radial flow, ranged from 210 to 2,300 ft²/d (20 to 210 m²/d). For analyses considering anisotropic response, a 20-fold difference was determined in directional transmissivity. The maximum transmissivity was 10,700 ft²/d (990 m²/d) in the dip direction and the minimum transmissivity was 520 ft²/d (48 m²/d) in the strike direction. Preferred horizontal flow in the strike direction was not observed for these tests because analyses were limited to wells open to pumped intervals, as projected along bedding. These results are consistent with a multiple-aquifer conceptual model of the ground-water system in which flow is primarily in zones oriented parallel to the dipping bedding.

Ground-water flow under steady-state conditions was simulated by use of a numerical model (MODFLOW). The model was oriented parallel to regional strike and consisted of three layers to represent saprolite and weathered rock near the surface and intermediate and deep zones of unweathered rock. The hydraulic properties of the model were subdivided laterally on the basis of geologic mapping of the Lockatong Formation and Brunswick Group. The model was calibrated against measured water levels (1996) and base flow estimated from seasonal measurements (1995-96) by use of a parameter-estimation program (MODFLOWP). Calibration yielded a regional anisotropy ratio of 11 to 1; preferred permeability was in the strike direction. Calibrated values were 8.3 in. (212 mm) for recharge, 5.35, 1.12, and 0.16 ft/d (1.63, 0.34, and 0.049 m/d) for the maximum hydraulic conductivity of the Brunswick Group, Lockatong Formation, and weathered layer, respectively. Discharge was much greater to the Towamencin Creek than to the West Branch Neshaminy and Wissahickon Creeks.

The calibrated ground-water flow model was used to simulate ground-water flow during periods of relatively high pumpage (1994) and relatively low pumpage (1997). Ground-water flowpaths originating from recharge near known areas of soil contamination were simulated. Pumping public-supply well Mg-67 (NPWA well L-8) and industrial wells Mg-153, Mg-620, Mg-621, and Mg-1045 captured ground water from several of these sources in the 1994 scenario. Because pumping at these wells ceased by 1997, ground water from those sources were no longer captured at those wells. Greater amounts of contaminated ground water moved away from Lansdale to surrounding areas under pumping conditions in 1997 than in 1994. Relatively small changes in the uncertain hydraulic properties of the model will result in changes in the simulated discharge paths of ground water from source areas.

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Table 22. *Description of wells and measured water levels in and near Lansdale, Pa.*

U.S. Geological Survey well number: 2-, 3-, or 4-digit number assigned by USGS that follows a 2-letter abbreviation for county (Mg- for Montgomery County).

Primary use of site: O, observation; P, public supply; T, institutional; U, unused; W, withdrawal.

Primary use of water: H, domestic; N, industrial; P, public supply; T, institutional; U, unused; Z, other miscellaneous.

Depth to water-bearing zones generally reported from driller's logs.

ft, feet

bls, below land surface

in., inches

gal/min, gallons per minute

(gal/min)/ft, gallons per minute per foot

--, no data

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.

U.S. Geological Survey local well number Mg-	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)	
	Site well number	Latitude (degrees)								Longitude (degrees)
59	3	401356	0751804	Lehigh Valley Farms	0303	1934	W	N	320	198
62	L-3	401428	0751653	North Penn Water Authority	-204	1903	P	U	365.1	385
64	L-5	401428	0751654	North Penn Water Authority	-204	1910	P	U	363.6	1,100
67	L-8	401456	0751728	North Penn Water Authority	0514	1923	W	P	325.4	292
68	L-9	401415	0751749	North Penn Water Authority	0514	1927	W	P	321.7	500
69	L-10	401428	0751754	North Penn Water Authority	0226	1935	W	P	329.8	265
72	L-13	401338	0751627	North Penn Water Authority	0226	1941	W	P	355.1	306
73	L-14	401356	0751559	North Penn Water Authority	0226	1944	W	P	371.4	325
75	L-16	401415	0751541	North Penn Water Authority	0226	1948	W	P	384	400
76	L-17	401334	0751633	North Penn Water Authority	0226	1949	W	P	350	388
77	L-18	401348	0751619	North Penn Water Authority	0226	1951	W	P	353.8	404
78	L-19	401407	0751548	North Penn Water Authority	0226	1951	W	P	375	430
79	PP	401446	0751711	Lansdale Electric	0503	--	W	N	348	279
80	KH	401457	0751733	Lansdale Borough	0514	1928	W	N	326	320
81	LB6	401441	0751713	Lansdale Borough	0514	1936	W	N	343	350
82	LB5	401523	0751719	Lansdale Borough	0514	1933	W	Z	310.4	375
89	1	401341	0751657	Lansdale Tube Co.	-221	1949	U	N	382	698
90	2	401337	0751700	Lansdale Tube Co.	-221	1951	U	N	375	500
123	B	401247	0751803	Merck & Co.	0514	1942	U	U	354.46	527
124	1	401234	0751753	Merck & Co.	0462	1948	W	N	329	300
125	2	401247	0751810	Merck & Co.	0462	1948	W	N	362	300
126	3	401243	0751749	Merck & Co.	0462	1948	W	N	338	420
128	5	401311	0751805	Merck & Co.	0462	1948	W	N	352	440
130	7	401256	0751743	Merck & Co.	0462	1949	W	N	339	300
134	-	401516	0751716	Kendik Rubber & Plastics	0313	1920	W	N	323	85
135	3	401331	0751706	Lansdale Tube Co.	-221	1953	W	N	370	500
138	-	401415	0751654	Santerian	--	--	W	N	378.6	424
140	4	401348	0751805	Lehigh Valley Farms	0226	1954	W	N	275	237
143	L-21	401439	0751831	Lansdale Borough	0226	1953	W	P	295	400
147	4	401336	0751654	Lansdale Tube Co.	-221	1953	W	N	370	500
150	--	401456	0751734	J W Rex Inc.	0514	1954	W	N	320	403

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing										
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number	Mg-
30	8	--	53.0	06-25-46	53	3.8	22.5	--	59	
30	6	--	76.0	08-06-54	8	--	--	--	62	
			43.2	01-13-98						
6	8	--	83.0	11-04-54	8	--	--	--	64	
19	8	--	132	03-01-47	57	--	--	--	67	
			12.1	08-23-96						
			14.2	01-13-98						
9	14	--	83.0	01-31-47	79	--	--	--	68	
			39.7	08-23-96						
			44.2	01-13-98						
40	8	--	73.0	01-31-47	39	--	--	--	69	
44	12	--	42.0	03-01-47	128	--	--	240/248/260	72	
			35.4	08-23-96						
45	10	--	46.0	03-01-47	300	3.3	70	276/295	73	
40	12	--	57.0	09-17-48	175	1.4	24	--	75	
37	12	--	23.0	07-18-49	355	3.8	49.5	-	76	
40	10	--	30.0	07-03-51	328	2.7	51.5	--	77	
41	12	--	122	09-27-51	173	--	48	--	78	
7	6	--	109	01-14-54	20	--	1	--	79	
			50.2	01-13-98						
138	8	--	60	1946	80	7.5	--	--	80	
			13.3	08-23-96						
			15.2	01-13-98						
33	8	--	45.0	1946	80	11	--	--	81	
			39.2	08-23-96						
			46.0	01-13-98						
18	8	--	20.0	1947	--	--	--	--	82	
			12.3	08-23-96						
			12.1	01-13-98						
40	8	--	50.0	09-20-49	96	.65	48.0	--	89	
46	8	--	57.0	01-17-51	165	1.3	49	--	90	
32	10	--	34	05-14-51	15	--	--	--	123	
--	12	--	22.5	03-22-48	357	2.7	50	--	124	
12	12	--	30	06-07-48	142	.92	48	--	125	
--	12	--	167	05-14-51	290	1.8	50	--	126	
--	12	--	58	11-03-53	395	2.7	48	--	128	
16	12	--	66	11-03-53	289	1.7	46	--	130	
--	6	--	--	--	--	--	--	--	134	
--	6	--	85.0	08-17-53	150	1.6	--	--	135	
22	10	--	43.2	08-23-96	--	--	--	--	138	
			48.8	01-13-98						
30	8	--	17.2	02-25-59	200	1.5	--	--	140	
30	12	--	8.00	06-09-54	250	--	--	--	143	
			5.68	08-23-96						
--	8	--	85.0	08-26-54	150	1.9	--	--	147	
43	8	--	70.0	08-05-54	58	.72	42	--	150	

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Site well number	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)
		Latitude (degrees)	Longitude (degrees)							
151	5	401332	0751652	Lansdale Tube Co.	-221	1954	W	N	365	500
152	AO1	401501	0751646	American Olean Tile Co.	--	1929	W	N	354.1	203
153	AO2	401508	0751637	American Olean Tile Co.	--	1953	W	N	358	400
154	--	401447	0751702	Arcadia Hosiery	-410	1934	W	N	355.5	193
157	WV1	401508	0751726	Lewis Fabrication Co.	0514	1950	W	N	318.9	285
161	--	401451	0751741	Rybond Inc.	0514	--	U	N	340	201
162	--	401451	0751744	Rybond Inc.	0514	1935	U	N	340	761
163	--	401453	0751744	Rybond Inc.	0514	1947	U	N	339.2	318
164	RY4	401448	0751740	Rybond Inc.	0514	1947	W	N	340.1	405
169	3	401252	0751721	Leeds & Northrup Co.	0249	1954	U	U	336	175
171	1	401328	0751701	Precision Tube Co.	-221	1952	W	N	366	500
202	L-22	401329	0751640	North Penn Water Authority	0226	1955	W	P	352	647
204	2	401328	0751704	Precision Tube Co.	-221	1955	W	N	365	500
223	2	401304	0751710	Leeds & Northrup Co.	0249	1955	W	N	332	350
498	L-23	401501	0751811	North Penn Water Authority	0226	1957	W	P	342.6	587
566	LVPW5	401349	0751815	Lehigh Valley Farms	0514	1960	W	N	280	330
593	L-25	401449	0751814	North Penn Water Authority	0561	1958	W	P	322.4	492
618	Pit Well	401507	0751634	Glenn Rigley, North Penn Pet FoodSupply	0708	1958	O	U	364.77	343
620	AO3	401517	0751626	American Olean Tile Co.	0226	1955	W	N	360	400
621	AO4	401522	0751651	American Olean Tile Co.	0226	1957	W	N	327.3	400
623	L-24	401536	0751744	North Penn Water Authority	0226	1957	U	P	328	507
624	2D	401528	0751724	J W Rex Inc.	0514	1958	U	N	312.1	633
625	1	401525	0751725	J W Rex Inc.	0514	1955	W	N	317.7	400
626	3	401607	0751923	Hatfield Packing Co.	0514	1981	W	N	300	550
630	--	401516	0752011	Christopher Dock Mennonite School	0121	1959	W	T	290	130
704	L-26	401530	0751709	North Penn Water Authority	0514	1961	W	P	316.4	400
875	17	401525	0751540	North Wales Water Authority	0512	1964	W	P	330	500

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
78	8	--	100	11-06-54	185	2.3	30	--	151
22	12	--	98	05-__-54	60	1.0	1	--	152
			48.7	08-23-96					
			55.1	01-13-98					
--	10	--	101	01-__-54	125	5.0	.3	--	153
30	6	--	85.0	1934	20	--	--	--	154
			50.0	08-23-96					
			57.0	01-13-98					
47	8	--	50	06-__-50	115	5.8	48	--	157
			6.72	08-23-96					
			8.16	01-13-98					
30	6	--	125	02-22-54	21	2.1	1.5	--	161
30	10	--	--	--	30	.15	1.5	--	162
22	8	--	38.7	06-13-89	15	.75	1.5	--	163
			25.8	08-23-96					
			28.2	01-13-98					
23	8	--	29.0	08-23-96	18	--	--	--	164
			29.0	08-23-96					
			30.2	01-13-98					
9	4	--	--	--	--	--	--	--	169
68	8	--	117	10-12-54	--	--	--	--	171
			27.1	08-23-96					
--	12	--	54.0	01-19-54	282	--	--	--	202
66	8	--	52.0	05-19-55	190	8.6	50	--	204
--	10	--	49.0	08-__-55	316	3.9	48	--	223
97	12	--	77	09-18-57	90	--	--	--	498
			22.2	08-23-96					
45	10	--	15.0	03-17-60	226	1.5	21	--	566
76	8	--	111	09-__-59	200	1.1	48	68/80/100/167/193/300/425/471	593
47	6	--	65.0	06-20-91	30	--	--	--	618
			55.7	08-23-96					
116	10	--	93.8	03-28-58	100	--	--	--	620
63	10	--	51	07-06-57	106	3.7	--	--	621
			17.5	08-23-96					
			18.9	01-13-98					
97	10	--	41	12-18-62	200	--	--	--	623
			22.2	08-23-96					
			23.4	01-13-98					
52	8	--	105	1958	9	--	--	--	624
			11.7	08-23-96					
			8.93	01-13-98					
44	8	--	54	06-__-60	186	--	--	--	625
40	--	--	67	06-24-81	30	--	--	--	626
--	--	--	52	08-10-59	60	--	--	--	630
			58.2	08-23-96					
83	10	--	25.0	12-07-61	136	1.0	40	--	704
			18.2	08-23-96					
			17.6	01-13-98					
60	12	--	--	--	750	13	168	--	875

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)	
	Site well number	Latitude (degrees)								Longitude (degrees)
876	1	401612	0751442	AEL Industries Inc.	--	1961	W	N	314	300
884	4	401310	0751817	Merck & Co.	0509	1965	O	U	353.55	600
914	NP-12c	401612	0751518	North Penn Water Authority	0514	1969	W	P	304	620
924	NP-21	401607	0751503	North Penn Water Authority	0413	1968	W	P	280	500
930	NP-25b	401339	0751906	Multicon Corp.	0514	--	U	U	238	--
991	8	401243	0751824	Merck & Co.	0248	1978	W	N	360	610
1014	10	401625	0751708	Hatfield Borough	0514	1979	W	P	300	305
1045	5	401518	0751634	American Olean Tile Co.	0226	1964	W	N	345.9	337
1051	22	401541	0751520	North Wales Water Authority	0514	1969	W	P	310	500
1124	NP-58	401456	0751619	North Penn Water Authority	0514	1980	O	P	339.15	385
1125	NP-61	401503	0751617	North Penn Water Authority	0514	1980	W	P	331.03	400
1126	NP-62	401508	0751610	North Penn Water Authority	0514	1980	O	P	327.38	310
1128	NP-70	401508	0751846	North Penn Water Authority	0330	1987	W	P	284.3	500
1169	--	401345	0751701	Zenith	--	--	O	U	370	69
1179	R-2	401623	0751829	Rosenbergers Dairies	0121	1977	W	N	367	572
1198	9	401304	0751824	Merck & Co.	0904	1985	W	N	342	300
1199	11	401248	0751836	Merck & Co.	1253	1988	W	N	355	303
1270	--	401501	0751605	North Penn Hospital	0514	1991	O	U	340.5	320
1284	NP-68	401659	0751624	North Penn Water Authority	0330	1986	W	P	307	448
1418	1	401517	0751613	M H Zeigler & Sons	--	1948	W	N	327	160
1423	12	401256	0751815	Merck & Co.	1862	1994	W	N	358	450
1424	13	401241	0751758	Merck & Co.	1862	1993	W	N	342	450
1440	--	401511	0751709	Crystal Soap	--	--	U	U	333.8	207
1441	LV3	401355	0751757	Lehigh Valley Farms	0188	1988	O	U	313	179
1442	LB3	401443	0751710	Lansdale Borough	0188	1989	O	U	346.8	84.8
1443	--	401459	0751649	Philadelphia Toboggan Co.	--	1996	U	N	351.1	239

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									U.S. Geological Survey local well number Mg-
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	
--	10	--	20.0	1961	300	7.1	18	--	876
--	10	--	92.7	02-22-66	130	--	--	--	884
43	8	--	23.0	07-__-69	27	1.9	--	55/100/155/210/275/300/370	914
50	12	--	7.3	02-11-68	602	5.4	75	--	924
--	--	--	-1.0 -.84	06-20-96 08-23-96	--	--	--	--	930
33	12	--	--	--	200	1.0	--	--	991
58	8	--	9	11-20-79	200	--	--	--	1014
60	10	--	74 41.1 46.0	04-07-64 08-23-96 01-13-98	80	.50	72	--	1045
--	8	--	27	1969	400	--	--	--	1051
25	6	--	6.92 11.6 19.1	02-15-91 08-23-96 01-13-98	107	2.9	.25	168/179/275	1124
58	10	--	16.8	06-14-91	200	4.9	5	55/105/207/308/335/370	1125
19	6	--	4.88 12.3 5.68	02-15-91 08-23-96 01-13-98	157	9.4	.25	70/135/225/290/302	1126
12	8	--	19.8 19.6 19.5	05-01-87 08-23-96 01-14-98	92	--	--	78/95/125/140/295/405	1128
--	6	--	45.9 37.3 38.7	06-12-89 08-23-96 01-14-98	--	--	--	--	1169
46	8	--	117 117	08-01-96 08-23-96	--	--	--	--	1179
31	6	--	30	09-19-88	77	.38	216	61/89/158/278/285	1198
30	8	--	87	10-01-97	184	2.9	48	75/95/114/135/148/207/215	1199
19	6	--	31.5 19.1 11.0 11.6	07-15-91 08-23-96 01-13-98 01-17-98	--	--	--	--	1270
82	10	--	9.37	07-29-91	68	1.2	48	13/70/90/190/230/260/365	1284
20	--	--	--	--	--	--	--	--	1418
80	8	--	66	02-15-94	72	2.0	54	114/193/201	1423
80	8	--	89.7	02-08-94	125	1.9	54	82/100/121/191/216	1424
3.5	6	--	26.4 22.2 27.2	06-21-95 08-23-96 01-13-98	--	--	--	50/73/102/127	1440
19.8	6	--	41.9 50.0 45.8	06-27-95 08-22-96 01-14-98	25	.19	.5	153/161	1441
--	2	?-85	55.7 41.7 49.3	08-30-95 08-23-96 01-13-98	.5	.02	.5	69	1442
10	8	--	42.6 43.0 48.7	05-22-96 08-23-96 01-13-98	--	--	--	--	1443

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Site well number	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)
		Latitude (degrees)	Longitude (degrees)							
1444	--	401407	0751708	Rogers Mechanical	--	1996	T	U	367	294
1445	MW-3	401514	0751639	American Olean Tile	0188	1989	T	U	346.3	204
1446	MW-1	401506	0751639	American Olean Tile	0188	1989	T	U	357.9	144
1447	MW-2	401511	0751642	American Olean Tile	0188	1989	T	U	349.6	145
1448	--	401317	0751812	AMOCO	0512	1990	O	U	333	72
1449	--	401446	0751937	Hopwood, Ann	0121	1971	U	H	265	115
1450	RW-24	401405	0751753	Martin, Marion	--	--	W	H	338	--
1451	--	401329	0751901	Usic, Rudy	0121	1985	W	H	290	125
1452	--	401412	0751826	Kiely, Robert	--	--	W	H	330	410
1453	--	401504	0751905	Weiss, Terry	--	--	W	H	275	217
1454	--	401517	0751902	Stark, Russell	--	--	U	H	298	23.8
1455	--	401337	0751802	Tryson, Richard	0512	1977	W	H	336	223
1456	--	401445	0752003	Trongone, Art	0512	1975	W	H	311	305
1457	--	401358	0751946	Thompson, Ray	0512	1964	W	H	281	--
1458	--	401346	0752001	Walton, Ray	--	--	W	H	269	87.6
1459	--	401418	0751946	Caserta, Richard	--	1927	W	H	275	100
1460	--	401526	0751620	Stuart, Richard	0512	1976	W	H	342.7	243
1461	--	401557	0751549	Kreider, Earl	0121	1984	W	H	309	260
1462	--	401440	0751527	Folger, Peter	--	--	U	H	434	--
1463	--	401603	0751653	Lund Brothers	0512	1985	W	H	297.2	202
1464	--	401612	0751847	Dyer, Fred	0514	1992	W	H	330	276
1465	--	401628	0751746	George Didden Greenhouses	0982	1991	W	I	331	400

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing			Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
Depth (ft)	Diameter (in.)	Screened interval (ft)							
18	6	--	49.8 53.3 56.9	05-30-96 08-23-96 01-13-98	--	--	--	--	1444
21	6	--	41.1 40.5	06-17-96 08-23-96	0.250	--	--	117	1445
19	6	--	54.9 53.1 60.2	06-14-96 08-23-96 01-13-98	3.0	0.07	0.5	127	1446
19	6	--	44.9 44.4 50.2	06-18-96 08-23-96 01-13-98	20	.23	.5	87/130	1447
--	6	--	36.1 36.7	06-20-96 08-23-96	--	--	--	--	1448
30	6	--	10.9 10.9	06-21-96 08-23-96	55	--	--	--	1449
--	--	--	52.9 60.5	06-21-96 01-14-98	--	--	--	--	1450
30	6	--	39.7 39.0	06-25-96 08-23-98	8	--	.25	60/95/105	1451
--	6	--	41.6 30.1	06-25-96 08-23-96	--	--	--	--	1452
--	6	--	12.8 8.89	06-28-96 08-23-96	--	--	--	--	1453
--	--	--	14.2 13.7	06-28-96 08-23-96	--	--	--	--	1454
30	6	--	34.5 35.0	06-28-96 08-23-96	15	--	--	--	1455
71	6	--	18.1 18.2	07-02-96 08-23-96	10	--	--	295	1456
--	6	--	41.6 41.2	07-05-96 08-23-96	--	--	--	--	1457
--	6	--	53.2 50.9	07-05-96 08-23-96	--	--	--	--	1458
--	6	--	54.4 49.0	07-05-96 08-23-96	--	--	--	--	1459
40	6	--	40.3 40.0 44.1	06-21-96 08-23-96 01-14-98	17	--	--	221/232	1460
41	6	--	19.5 19.9	06-21-96 08-23-96	40	--	.33	155/175/185/245	1461
--	--	--	29.8 31.0	06-25-96 08-23-96	--	--	--	--	1462
51	6	--	11.1 12.1 12.8	07-02-96 08-23-96 01-14-98	60	--	--	130/150/180/190	1463
42	6	--	75.1 115	07-02-96 08-23-96	40	--	--	160/215	1464
80	6	--	29.5 30.8	07-02-96 08-23-96	80	.22	.75	135/200/330	1465

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Site well number	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)
		Latitude (degrees)	Longitude (degrees)							
1466	--	401610	0751702	Steinmetz, Paul	0121	1974	W	H	315	120
1467	--	401546	0751715	Todorow, Stephen	--	1948	W	H	304.6	43
1468	--	401552	0751630	Ammendola, Frank	0512	1973	W	H	318	138
1469	--	401532	0751654	Fifield, Robert	0313	1950	W	H	325	100
1470	--	401456	0751925	Trumpp, Andrew	--	--	U	I	286	20.6
1471	--	401314	0751923	Slater, John	0121	1982	W	H	291	240
1472	--	401337	0751947	Gilbert, G.	0121	--	W	H	268	--
1473	--	401247	0751949	Taggart, Howard	0512	1986	W	H	320	--
1474	--	401523	0751914	Detweiler, Earl	0121	1973	W	H	322	140
1475	--	401316	0751849	Cunningham, Ralph	--	1965	W	H	303	105
1476	--	401325	0751917	Doorley, James	0982	1957	W	H	263	85
1477	--	401342	0751754	Martin, Tom	--	1950	W	H	325	160
1478	--	401418	0751808	Minucci, Neil	0121	1988	W	H	318	220
1479	--	401344	0751928	Kibblehouse, Janet	--	1967	W	H	283	--
1480	--	401457	0751530	Matchett, Carol	--	--	W	H	402	--
1481	--	401354	0751846	Calvary Baptist Church	--	1960	U	T	297	300
1482	--	401309	0751909	Gehman, Robert	0313	1957	W	H	322	114
1483	--	401525	0751759	Hutkowski, Kim	--	1954	W	H	348.1	--
1484	2	401537	0751727	Trotter Soft Pretzels	0121	1987	W	N	307.9	420
1485	--	401455	0751856	Santoro, Benny	--	--	W	H	287	--
1486	--	401552	0751848	Baum Meat Packing	--	--	W	S	342	--
1487	--	401507	0751809	Rossi, Joseph	0121	--	W	H	340	--
1488	--	401457	0752056	Towamencin Mennonite Church	0121	1977	W	T	254	300
1489	--	401437	0751931	Rittenhouse, Ronald	0188	1979	W	H	260	120
1490	--	401432	0751851	Terchek, Bob	--	1958	W	H	313	130

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
43	6	--	33.2	07-02-96	11	--	--	75/110	1466
			33.3	08-23-96					
			32.8	01-14-98					
--	6	--	15.8	07-09-96	--	--	--	--	1467
			15.8	08-23-96					
			16.0	01-14-98					
41	6	--	44.1	07-09-96	25	--	--	135	1468
			43.3	08-23-96					
			44.4	01-14-98					
20	6	--	18.9	07-09-96	15	--	--	60	1469
--	--	--	6.54	07-05-96	--	--	--	--	1470
			7.86	08-23-96					
67	6	--	31.0	07-08-96	11	--	--	115/221	1471
			31.3	08-23-96					
--	6	--	31.0	07-09-96	--	--	--	--	1472
			32.6	08-23-96					
--	6	--	10.8	07-09-96	--	--	--	--	1473
			11.9	08-23-96					
34	6	--	35.0	07-09-96	11	--	2	95/128	1474
			34.5	08-23-96					
25	6	--	18.1		30	--	--	--	1475
			18.4	08-23-96					
40	6	--	19.5	07-11-96	--	--	--	--	1476
			19.3	08-23-96					
--	6	--	21.5	07-12-96	--	--	--	--	1477
			21.7	08-23-96					
			24.1	01-14-98					
--	6	--	38.9	07-12-96	8	--	--	--	1478
--	6	--	35.1	07-15-96	--	--	--	--	1479
--	--	--	21.5	07-12-96	--	--	--	--	1480
			21.6	08-23-96					
--	6	--	26.7	07-16-96	--	--	--	--	1481
			26.5	08-23-96					
--	6	--	49.4	07-19-96	--	--	--	--	1482
			49.1	08-23-96					
--	6	--	40.0	07-23-96	--	--	--	--	1483
			40.0	08-23-96					
			47.3	01-14-98					
70	6	--	46.7	07-23-96	12	--	.25	180/230/367	1484
			33.6	08-23-96					
			9.29	01-13-98					
			9.60	01-14-98					
--	6	--	30.1	07-15-96	--	--	--	--	1485
--	6	--	83.3	06-08-96	--	--	--	--	1486
			83.3	08-23-96					
--	6	--	37.7	07-17-96	--	--	--	--	1487
36	6	--	52.1	07-17-96	17	--	2	145/230/285	1488
21.4	6	--	37.7	07-17-96	30	.36	.50	80/85/110	1489
--	6	--	32.7	07-19-96	--	--	--	--	1490

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Site well number	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)
		Latitude (degrees)	Longitude (degrees)							
1491	--	401508	0751833	Rittenhouse, Samuel	--	1966	W	H	323	137
1492	--	401448	0752014	Ellis, Edwin	--	--	W	H	311	100
1493	--	401434	0752016	Teti, Anthony	--	--	W	H	280	--
1494	--	401517	0751817	Plains Mennonite Church	--	--	W	T	328	--
1495	--	401158	0751812	Moyer, Edward	--	1963	W	H	353	145
1496	--	401204	0751844	Faust, Winifred	--	1949	W	H	302	120
1497	--	401352	0751727	Clark, Peter	--	--	U	U	347	125
1498	--	401448	0751601	Tolscik, Rihard	--	--	W	H	382	--
1499	--	401539	0751730	Abendschein, Ron	--	1959	U	H	308.5	84
1500	--	401627	0751610	Gadaleta, Sue	--	1949	W	H	299	--
1501	--	401450	0751528	Maerz, Ralph	--	--	U	H	430	--
1502	--	401615	0751609	Verna, Jim	--	1970	W	H	292	72
1503	--	401548	0751618	Jagger, Walter	--	--	W	H	318	35
1504	--	401238	0751847	Soley, James	--	--	U	S	342	16
1505	--	401309	0751654	Huey, William	--	--	U	U	351	79.6
1506	--	401501	0751548	Drissel, C. Daniel	--	--	W	H	374.2	--
1507	--	401233	0751915	Bollinger, Robert	--	--	W	H	333	140
1508	--	401640	0751622	Heinzmann, Erich	--	1966	W	H	320	--
1509	--	401618	0751602	Kerr, Kim & Dan	--	--	W	H	302	90
1510	--	401621	0751656	Luzi, John	--	--	W	H	307	--
1511	--	401412	0751504	Czerpak, S. R.	--	--	W	H	422	175
1533	--	401459	0751647	John Evans	--	--	O	U	352.3	--
1537	N1	401319	0751750	Merck & Co.	1253	1988	O	U	353.48	77
1538	N2	401313	0751747	Merck & Co.	1253	1988	O	U	364.56	78
1539	N3	401303	0751730	Merck & Co.	0514	1989	O	U	332	96
1540	N4	401313	0751717	Merck & Co.	1862	1991	O	U	335.65	84
1541	N5	401253	0751735	Merck & Co.	1253	1988	O	U	328.09	128
1542	N6	401234	0751746	Merck & Co.	1862	1991	O	U	329.57	99

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
130	6	--	30.1	07-19-96	--	--	--	--	1491
--	6	--	29.9	07-23-96	--	--	--	--	1492
--	--	--	7.92	07-23-96	--	--	--	--	1493
--	--	--	27.5	07-25-96	--	--	--	--	1494
--	6	--	38.9	07-30-96	--	--	--	--	1495
--	--	--	39.4	08-23-96	--	--	--	--	1496
--	--	--	6.89	07-30-96	--	--	--	--	1496
--	6	--	36.1	08-09-96	--	--	--	--	1497
--	--	--	36.4	08-23-96	--	--	--	--	1497
--	--	--	39.9	01-14-98	--	--	--	--	1497
--	6	--	17.4	07-24-96	--	--	--	--	1498
--	--	--	21.3	08-23-96	--	--	--	--	1498
40	6	--	7.29	07-24-96	22	--	--	--	1499
--	--	--	7.56	08-23-96	--	--	--	--	1499
--	--	--	5.85	01-17-98	--	--	--	--	1499
--	6	--	15.6	07-24-96	--	--	--	--	1500
--	--	--	16.1	08-23-96	--	--	--	--	1500
--	--	--	19.8	07-24-96	--	--	--	--	1501
--	6	--	15.5	07-25-96	--	--	--	--	1502
--	--	--	15.7	08-23-96	--	--	--	--	1502
--	--	--	5.34	07-25-96	--	--	--	--	1503
--	--	--	5.36	08-23-96	--	--	--	--	1503
--	--	--	5.42	01-14-98	--	--	--	--	1503
--	48	--	1.22	07-26-96	--	--	--	--	1504
--	--	--	1.52	08-23-96	--	--	--	--	1504
--	6	--	22.1	07-26-96	--	--	--	--	1595
--	--	--	23.5	08-23-96	--	--	--	--	1595
--	--	--	7.48	07-30-96	--	--	--	--	1506
--	--	--	9.44	08-23-96	--	--	--	--	1506
--	--	--	8.10	01-14-98	--	--	--	--	1506
--	6	--	28.8	07-31-96	--	--	--	--	1507
--	--	--	31.3	08-23-96	--	--	--	--	1507
--	6	--	28.7	08-01-96	--	--	--	--	1508
--	--	--	28.4	08-23-96	--	--	--	--	1508
--	6	--	13.0	08-01-96	--	--	--	--	1509
--	--	--	14.0	08-23-96	--	--	--	--	1509
--	--	--	24.6	08-01-96	--	--	--	--	1510
--	--	--	25.8	08-23-96	--	--	--	--	1510
--	--	--	11.8	08-02-96	--	--	--	--	1511
--	--	--	12.3	08-23-96	--	--	--	--	1511
--	--	--	46.5	08-23-96	--	--	--	--	1533
--	--	--	46.5	08-23-96	--	--	--	--	1533
--	--	--	52.9	01-13-98	--	--	--	--	1533
67	2	67-77	50.6	09-10-96	10	--	--	73	1537
68	2	68-78	46.8	08-22-96	3.5	--	--	71	1538
86	2	86-96	23	09-10-96	45	--	--	56/85	1539
74	2	74-84	17.8	08-22-96	20	--	1	77	1540
118	2	118-128	69.6	09-11-96	--	--	--	104/122	1541
89	2	89-99	29.6	08-22-96	60	--	--	55/67/75/90	1542

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)	
	Site well number	Latitude (degrees)								Longitude (degrees)
1543	N7	401246	0751739	Merck & Co.	1253	1988	O	U	321.07	124
1544	N8	401230	0751759	Merck & Co.	1253	1988	O	U	328.3	98
1545	N9	401221	0751824	Merck & Co.	1862	1991	O	U	331.02	95
1546	N10	401227	0751810	Merck & Co.	0514	1989	O	U	338	110
1547	N11	401236	0751807	Merck & Co.	1253	1988	O	U	337.69	92
1548	N12	401235	0751853	Merck & Co.	0514	1989	O	U	334.71	96
1549	N12D	401235	0751853	Merck & Co.	0514	1989	O	U	335.62	338
1550	N13	401242	0751845	Merck & Co.	0514	1989	O	U	346.41	101
1551	N16	401301	0751828	Merck & Co.	0514	1989	O	U	327.03	100
1552	N17	401308	0751820	Merck & Co.	1253	1988	O	U	343.06	78
1553	N19	401323	0751756	Merck & Co.	0514	1988	O	U	337.38	94
1554	N20	401314	0751812	Merck & Co.	1253	1988	O	U	345.51	84
1555	N20D	401314	0751811	Merck & Co.	0514	1989	O	U	346.31	289
1556	N21	401308	0751756	Merck & Co.	1253	1988	O	U	365.43	118
1557	N22	401304	0751746	Merck & Co.	1253	1988	O	U	354	98
1558	N22D	401304	0751746	Merck & Co.	0514	1989	O	U	354.83	363
1559	N23	401301	0751741	Merck & Co.	1253	1988	O	U	336.12	93
1560	N24	401301	0751749	Merck & Co.	1253	1988	O	U	359.2	100
1561	N25	401244	0751755	Merck & Co.	1253	1988	O	U	345.08	124
1562	N26	401251	0751835	Merck & Co.	1253	1988	O	U	347.2	94
1563	N28	401257	0751831	Merck & Co.	1253	1988	O	U	334.5	105
1564	N29	401303	0751820	Merck & Co.	1253	1988	O	U	340.57	86
1565	N30	401300	0751824	Merck & Co.	1253	1988	O	U	335.79	117
1566	3-85	401313	0751804	Merck & Co.	0904	1985	O	U	343.54	100
1567	4-85	401247	0751742	Merck & Co.	0904	1985	O	U	326.96	129
1568	6-85	401246	0751818	Merck & Co.	0904	1985	O	U	354.68	119
1569	7-85	401241	0751743	Merck & Co.	0904	1985	O	U	328.09	300
1570	9-85	401255	0751821	Merck & Co.	0904	1985	O	U	346.4	107
1571	10-85	401305	0751748	Merck & Co.	0904	1985	O	U	359.5	80
1572	11-85	401240	0751814	Merck & Co.	0904	1985	O	U	350.21	109
1600	3I	401409	0751707	Rogers Mechanical	1960	1997	O	U	365.7	152
1601	3S	401409	0751707	Rogers Mechanical	1960	1997	O	U	365.5	100
1602	2I	401406	0751706	Rogers Mechanical	1960	1997	O	U	376	129
1603	2S	401406	0751706	Rogers Mechanical	1960	1997	O	U	376	98
1604	1D	401407	0751703	Rogers Mechanical	1960	1997	O	U	380.7	222
1605	1S	401407	0751703	Rogers Mechanical	1960	1997	O	U	380.5	95
1606	1S	401456	0751652	Philadelphia Toboggan Co.	1960	1997	O	U	349	100
1607	1I	401457	0751652	Philadelphia Toboggan Co.	1960	1997	O	U	348	163

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
114	2	114-124	53.8	08-22-96	--	--	--	50/63/80/85/90/98/110	1543
88	2	88-98	25.4	08-22-96	6	--	--	96	1544
75	2	75-95	41.2	08-22-96	1	--	--	55	1545
100	2	100-110	53	09-09-96	1	--	--	70	1546
82	2	82-92	56.7	08-22-96	--	--	--	--	1547
86	2	86-96	58.5	08-22-96	1	--	--	51/96	1548
308	2	308-338	67.9	08-22-96	1	--	--	50/95/140/195/295/318/313	1549
91	2	91-101	73.8	08-22-96	1	--	--	90	1550
90	2	90-100	39.8	08-22-96	1	--	--	76	1551
68	2	68-78	45.9	08-22-96	1	--	--	73/81	1552
84	2	84-94	33.8	08-22-96	2	--	--	79/90	1553
64	2	64-84	45.3	08-22-96	20	--	--	80	1554
289	2	269-289	50.6	08-22-96	80	--	--	70/115/270	1555
108	2	108-118	65.9	08-22-96	1	--	--	--	1556
88	2	88-98	49.1	08-22-96	3	--	--	64/98	1557
323	2	323-363	61.7	08-22-96	2.5	--	--	10/19/62/75/260/330/356	1558
83	2	83-93	29.4	08-22-96	1.5	--	--	--	1559
90	2	90-100	58.1	08-22-96	3	--	--	95	1560
114	2	114-124	57.8	08-22-96	1	--	--	73	1561
84	2	84-94	71.5	08-22-96	--	--	--	--	1562
95	2	95-105	54.9	08-22-96	2	--	--	98	1563
76	2	76-86	46.8	09-11-96	15	--	--	82	1564
107	2	107-117	46.3	08-22-96	19	--	--	108/116	1565
90	2	90-100	48.7	08-22-96	60	--	--	94/181/203/207/230	1566
119	2	119-129	66.8	09-11-96	73	--	--	130/150/233/240	1567
47	6	--	106	09-11-96	3	--	--	99/112	1568
28	6	--	53.6	08-22-96	15	--	--	58/87	1569
97	2	97-107	89.6	08-22-96	36	--	--	105/208/245/252	1570
70	2	70-80	58.8	09-11-96	10	--	--	70/115/178	1571
99	2	99-109	75.9	08-22-96	65	--	--	40/50/70/130/180/195/201/220	1572
132	6	132-152	50.0	04-23-97	--	--	--	--	1600
			49.0	01-13-98					
18	6	--	55.4	05-12-97	--	--	--	--	1601
			63.1	01-13-98					
109	6	119-129	56.2	04-23-97	10	--	--	--	1602
			59.9	01-13-98					
15	6	--	64.7	05-12-97	--	--	--	--	1603
			73.0	01-13-98					
212	6	212-222	56.5	04-24-97	--	--	--	--	1604
			65.4	01-13-98					
15	6	--	62.4	05-12-97	--	--	--	--	1605
			66.0	01-13-98					
15	6	--	43.1	05-21-97	--	--	--	--	1606
			49.7	01-13-98					
153	6	153-163	43.2	05-13-97	--	--	--	--	1607
			48.9	01-13-98					

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Site well number	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)
		Latitude (degrees)	Longitude (degrees)							
1608	1D	401456	0751652	Philadelphia Toboggan Co.	1960	1997	O	U	348.5	307
1609	2S	401500	0751647	John Evans & Sons	1960	1997	O	U	352.4	100
1610	1I	401457	0751735	Keystone Hydraulics	1960	1997	O	U	326.7	120
1611	1S	401457	0751735	Keystone Hydraulics	1960	1997	O	U	326.6	88
1612	1D	401448	0751705	Electra Products	1960	1997	O	U	354.7	386
1613	1D	401456	0751710	Precision Products	1960	1997	O	U	339.7	320
1614	1S	401448	0751705	Electra Products	1960	1997	O	U	355.1	120
1615	1I	401507	0751719	Westside Industries	1960	1997	O	U	326.7	150
1616	1S	401457	0751710	Precision Products	1960	1997	O	U	339.5	100
1617	1VS	401507	0751719	Westside Industries	1960	1997	O	U	326.1	49
1618	1I	401522	0751614	Lansdale Warehouse	1960	1997	O	U	352.7	180
1619	2I	401456	0751731	Keystone Hydraulics	1960	1997	O	U	324.1	190
1620	2S	401456	0751731	Keystone Hydraulics	1960	1997	O	U	324.4	100
1621	1I	401510	0751617	Royal Dry Cleaners	1960	1997	O	U	353.5	150
1622	1S	401522	0751614	Lansdale Warehouse	1960	1997	O	U	328	100
1623	1S	401510	0751617	Royal Dry Cleaners	1960	1997	O	U	352.5	100
1624	1S	401503	0751652	Evans & Sons	1960	1997	O	U	347.9	102
1639	3I	401523	0751722	J W Rex Inc.	0188	1997	O	U	312.3	150
1640	3S	401523	0751723	J W Rex Inc.	0188	1997	O	U	312.6	65
1641	2S	401526	0751725	J W Rex Inc.	0188	1997	O	U	310.7	50
1645	AMW8	401355	0751803	Lehigh Valley Farms	--	--	O	U	311.4	71
1646	RW-7	401538	0751730	Pellak, David	--	--	W	H	312	--
1647	RW-4	401535	0751736	Darde, Robert	--	--	W	H	324	--
1648	RW-17	401532	0751649	Valleley, Paul	--	--	W	H	327	100
1649	RW-12	401516	0751704	Mancuso, Joseph	--	--	W	H	326	90
1650	RW-20	401407	0751800	Shank, Thomas	--	1952	W	H	320	143
1651	RW-10	401521	0751620	Diver, William	--	--	W	H	344	140
1652	RW-21	401354	0751747	Kurz, Charles	--	--	W	H	320	200
1653	1	401537	0751727	Trotter Soft Pretzels	--	--	W	N	308	--

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	U.S. Geological Survey local well number Mg-
220	6	--	39.7	05-13-97	--	--	--	--	1608
			47.1	01-13-98					
23.5	10	--	46.4	05-16-97	--	--	--	--	1609
			53.2	01-13-98					
100	6	100-120	14.7	05-21-97	--	--	--	--	1610
			15.3	01-13-98					
15	6	--	13.5	05-27-97	--	--	--	--	1611
			15.2	01-13-98					
306	6	306-386	50.6	05-29-97	--	--	--	--	1612
			53.3	01-13-98					
182	6	--	38.6	06-24-97	--	--	--	--	1613
			42.9	01-13-98					
20	6	--	50.6	06-10-97	--	--	--	--	1614
			56.6	01-13-98					
110	6	110-150	16.4	06-24-97	--	--	--	--	1615
			14.7	01-13-98					
20	6	--	26.6	06-26-97	--	--	--	--	1616
			27.9	01-13-98					
20	6	--	13.5	06-26-97	--	--	--	--	1617
			14.3	01-13-98					
160	6	160-180	53.0	07-10-97	--	--	--	--	1618
			55.8	01-13-98					
150	6	150-190	12.9	06-30-97	--	--	--	--	1619
			12.9	01-13-98					
20	6	--	12.1	07-10-97	--	--	--	--	1620
			13.1	01-13-98					
130	6	130-150	51.6	07-17-97	--	--	--	--	1621
			53.4	01-13-98					
20	6	--	50.4	07-17-97	--	--	--	--	1622
			54.3	01-13-98					
20	6	--	49.0	08-01-97	--	--	--	--	1623
			54.8	01-13-98					
18.5	6	--	38.7	08-29-97	10	--	--	--	1624
			43.2	01-13-98					
80	6	80-150	24.7	08-25-97	30	0.24	--	--	1639
			29.5	01-13-98					
23	6	--	23.3	08-25-97	3	07	--	26/42/57	1640
			22.8	01-13-98					
18	6	--	22.5	08-25-97	20	.65	--	28/31/38	1641
			13.6	01-13-98					
--	--	--	37.0	03-20-95	--	--	--	--	1645
--	6	--	--	--	--	--	--	--	1646
--	6	--	--	--	--	--	--	--	1647
--	6	--	--	--	--	--	--	--	1648
--	6	--	--	--	--	--	--	--	1649
127	6	--	75	01-02-82	--	--	--	--	1650
--	4	--	--	--	--	--	--	--	1651
--	8	--	--	--	--	--	--	--	1652
--	--	--	--	--	--	--	--	--	1653

Table 22. Description of wells and measured water levels in and near Lansdale, Pa.—Continued

U.S. Geological Survey local well number Mg-	Location		Owner	Driller license number	Year drilled	Primary use of site	Primary use of water	Altitude of land surface (ft)	Depth of well (ft bls)	
	Site well number	Latitude (degrees)								Longitude (degrees)
1654	N34D	401259	0751829	Merck & Co.	0514	1989	O	U	328.61	288
1655	PZS2	401256	0751813	Merck & Co.	--	1988	O	U	360	--
1656	N32S	401245	0751750	Merck & Co.	0514	1989	O	U	340.54	338
1657	RW-25	401543	0751734	Eyre, Howard	--	--	U	H	317.5	--
1658	1-85	401237	0751807	Merck & Co.	0904	1985	O	U	341.34	53
1659	PW-10	401245	0751752	Merck & Co.	0904	1985	O	U	337.1	300
1660	N14	401248	0751843	Merck & Co.	1253	1988	O	U	346.3	79
1661	13	401607	0751503	AEL Inc.	--	1980	O	U	288.8	46
1662	16	401602	0751437	AEL Inc.	--	1980	O	U	319.8	52
1663	LB2	401438	0751709	Lansdale Borough	0188	1989	O	U	347.6	31
1664	LB1	401441	0751704	Lansdale Borough	0188	1989	O	U	352.6	153
1665	IS	401507	0751720	Westside Industries	1960	1997	O	U	326.1	80
1666	II	401503	0751653	Evans & Sons	1960	1997	O	U	348.3	150
1667	RC	401514	0751616	Royal Dry Cleaners	--	--	W	N	353	240
1668	RD	401515	0751614	Debarth, Robert	--	--	W	H	318	400
1670	RW-27	401526	0751626	Debarth, Robert	--	--	W	H	340	--
1671	RW-26	401541	0751613	Elker, Robert	--	--	W	H	320	--
1701	14	401237	0751807	Merck & Co.	0198	1997	W	N	338	269
1702	15	401246	0751739	Merck & Co.	0198	1997	W	N	321	300

Table 22. Description of wells and measured water levels in the area of Lansdale, Pa.—Continued

Casing									U.S. Geological Survey local well number Mg-
Depth (ft)	Diameter (in.)	Screened interval (ft)	Depth to water (ft bls)	Date water level measured	Reported yield (gal/min)	Specific capacity [(gal/min)/ft]	Pumping period (hours)	Depth to water-bearing zones (ft bls)	
259	2	259-288	50	11-14-89	--	--	--	260/280	1654
--	--	--	--	--	--	--	--	--	1655
318	2	318-338	132	11-29-89	152	--	--	320	1656
--	6	--	--	--	--	--	--	--	1657
34	6	--	55.2	09-13-85	9	--	--	74/92/108/254/287	1658
24	6	--	54.9	09-28-88	60	2.2	6.5	80/130/150/217/240/270	1659
69	2	69-79	--	--	--	--	--	52/63/75	1660
10	2	--	2.42	04-08-80	--	--	--	--	1661
9	2	--	13.4	04-08-80	--	--	--	--	1662
11	2	11-31	4 3.62	1995 01-13-98	5	.19	.5	14	1663
20	2	20-153	52.6 54.6	1995 01-13-98	1	.01	.5	136	1664
60	6	60-80	14.3	01-13-98	10	1.4	1	40/57	1665
110	6	110-150	48.8	01-13-98	30	--	--	75/90/125/130	1666
--	--	--	--	--	--	--	--	--	1667
--	--	--	--	--	--	--	--	--	1668
--	--	--	--	--	--	--	--	--	1670
--	--	--	--	--	--	--	--	--	1671
30	8	--	77	10-02-97	28	.38	48	77/97/117/202/270	1701
35	8	--	82	10-10-97	110	1.2	48	65/73/84/93/189/208/260	1702

Table 23. Physical and chemical constituents measured in the field for water samples from wells in and near Lansdale, Pa.

[°C, degree Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, missing data]

U.S. Geological Survey well number Mg-	Date	Temperature (°C)	Specific Conductance (µS/cm)	pH (units)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO ₃)
59	09-17-97	17.1	593	7.77	7.4	170
62	09-08-97	15.7	684	6.93	4.0	249
64	09-10-97	15.4	624	7.19	1.6	224
67	10-08-97	14.0	680	7.00	.6	197
68	09-29-97	14.0	684	7.02	2.2	210
72	09-02-97	14.3	560	7.35	4.6	--
76	10-28-97	13.0	548	7.31	1.6	--
77	10-28-97	13.0	533	7.03	2.0	--
79	10-02-97	14.5	505	7.61	5.0	192
80	09-30-97	15.0	669	6.73	.0	191
81	09-19-97	15.4	504	7.60	1.0	180
82	09-18-97	15.2	984	7.38	4.2	226
89	04-09-53	10.6	--	--	--	--
134	10-29-97	13.7	629	7.55	--	204
138	09-04-97	16.3	534	--	2.0	--
140	09-17-97	14.5	544	7.62	5.2	168
152	09-24-97	15.2	806	6.84	5.5	229
153	09-24-97	13.7	589	7.08	3.1	246
157	09-15-97	16.0	696	7.37	.2	230
163	09-12-97	16.5	713	7.21	3.2	192
164	09-17-97	16.0	691	7.42	2.4	192
202	10-28-97	12.5	563	7.60	1.8	--
223	08--55	--	380	8.10	--	--
498	10-28-97	13.0	550	7.13	4.9	196
566	09-17-97	13.7	619	7.68	2.4	168
593	10-28-97	13.0	537	7.19	5.1	148
618	09-05-97	15.3	564	7.24	6.2	204
620	09-24-97	13.4	613	7.24	--	186
621	09-24-97	13.1	625	7.18	.8	153
623	09-03-97	--	390	7.38	2.5	186
624	10-21-97	13.5	416	7.43	.7	166
630	03-31-59	13.0	360	--	--	--
704	09-09-97	13.9	834	7.22	2.0	196
875	10-31-97	14.0	513	7.64	.3	152
1014	10-28-97	12.5	552	7.17	.8	--
1124	02-22-97	11.4	523	--	--	--
1125	10-28-97	12.5	428	7.57	4.0	152
1126	02-22-97	11.1	473	--	--	--
1418	10-29-97	14.3	602	7.57	<.1	188
1440	09-11-97	14.5	691	7.27	.2	192
1441	06-16-97	14.6	627	7.75	2.2	176
1442	09-22-97	12.0	563	7.58	3.4	222
1443	10-23-97	14.6	451	7.51	1.7	156
1444	10-01-97	14.0	586	7.26	1.2	182
1450	10-14-97	12.5	625	7.13	2.0	184
1460	10-22-97	12.8	542	7.61	3.8	200

Table 23. Physical and chemical constituents measured in the field for water samples from wells in and near Lansdale, Pa.—Continued

[°C, degree Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; mg/L, milligrams per liter; --, missing data]

U.S. Geological Survey well number Mg-	Date	Temperature (°C)	Specific Conductance ($\mu\text{S}/\text{cm}$)	pH (units)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)
1463	10-08-97	14.5	429	7.42	0.2	--
1484	10-31-97	14.2	393	7.60	.3	142
1499	09-30-97	16.0	437	7.26	1.7	--
1506	10-31-97	13.8	518	7.82	2.2	188
1533	10-09-97	16.7	634	7.07	3.4	194
1600	10-17-97	14.6	623	7.52	1.0	182
1601	10-17-97	14.6	664	7.29	3.2	256
1602	10-16-97	14.8	593	7.50	1.2	208
1603	10-16-97	17.2	758	7.35	5.4	316
1604	10-15-97	13.0	586	7.24	1.6	186
1605	10-15-97	13.0	389	8.24	8.7	138
1606	10-23-97	14.8	602	7.71	.4	176
1607	10-24-97	13.5	647	7.00	3.0	197
1608	10-24-97	14.0	352	7.67	.5	161
1609	10-09-97	16.4	694	7.40	1.8	216
1610	10-06-97	14.0	682	7.02	.5	181
1611	10-06-97	18.8	633	7.23	1.3	179
1612	09-25-97	14.6	337	7.88	.4	158
1613	09-26-97	15.4	700	7.26	1.0	157
1614	10-02-97	14.6	599	7.35	3.8	228
1615	10-30-97	14.5	607	7.41	.3	200
1616	09-26-97	15.3	772	7.08	3.8	220
1617	10-30-97	16.0	755	7.12	2.4	280
1618	10-22-97	12.9	560	7.48	3.8	188
1619	10-07-97	14.0	661	7.13	1.2	208
1620	10-07-97	14.5	828	6.96	.7	234
1621	10-27-97	13.5	567	7.57	1.1	151
1622	10-22-97	13.8	623	7.38	3.1	252
1623	10-27-97	13.5	804	7.00	3.6	185
1624	10-14-97	16.0	674	7.16	5.0	212
1639	10-20-97	14.6	1236	7.16	.2	254
1640	10-20-97	14.6	725	6.84	6.0	228
1641	10-21-97	13.0	539	6.22	.5	175
1645	09-16-97	18.5	627	7.56	2.0	174
1646	09-30-97	15.0	421	7.21	.7	--
1647	09-30-97	15.5	639	7.17	4.8	136
1648	10-01-97	14.0	639	7.04	1.3	--
1649	10-01-97	13.0	558	7.01	4.0	157
1650	10-01-97	12.5	644	7.07	1.7	--
1651	10-08-97	13.7	563	7.17	9.2	--
1652	10-14-97	13.0	548	7.32	3.0	189
1653	10-31-97	14.9	1,131	7.21	4.8	226
1657	10-29-97	13.1	345	6.29	8.1	54
1663	09-23-97	18.0	333	5.63	.5	63
1664	09-22-97	21.8	540	7.95	5.6	180
1665	10-30-97	15.9	697	7.10	.2	304

Table 23. Physical and chemical constituents measured in the field for water samples from wells in and near Lansdale, Pa.—Continued

[°C, degree Celsius; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; mg/L, milligrams per liter; --, missing data]

U.S. Geological Survey well number Mg-	Date	Temperature (°C)	Specific Conductance ($\mu\text{S}/\text{cm}$)	pH (units)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO_3)
1666	10-14-97	15.0	650	7.00	0.7	187
1667	10-27-97	15.0	576	7.29	8.2	164
1668	10-27-97	15.5	749	7.10	2.0	168
1670	10-22-97	14.2	616	7.51	2.0	186
1671	10-29-97	14.8	421	7.75	6.1	144