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

Case Study for Delineating a Contributing Area to a Well in a Fractured Siliciclastic-Bedrock Aquifer Near Lansdale, Pennsylvania

by Gary J. Barton, Dennis W. Risser, Daniel G. Galeone, and Daniel J. Goode

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In cooperation with the
PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION

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2003

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CONTENTS

CONTENTS—Continued

ILLUSTRATIONS

ILLUSTRATIONS—Continued

ILLUSTRATIONS—Continued

TABLES

CONVERSION FACTORS, DATUMS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
	Flow rate	
foot per year (ft / yr)	0.3048	meter per year
cubic foot per year (ft^3 / yr)	0.02832	cubic meter per year
gallon per minute (gal / min)	0.06309	liter per second
million gallons per day (Mgal / d)	43.81	liters per second
inch per year (in / yr)	25.4	millimeter per year
	Hydraulic conductivity	
foot per day (ft / d)	0.3048	meter per day
	Transmissivity	
foot squared per day (ft^2 / d)	0.09290	meter squared per day

Abbreviated water-quality unit used in report:
µS / cm, microsiemens per centimeter at 25 degrees Celsius

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

CASE STUDY FOR DELINEATING A CONTRIBUTING AREA TO A WELL IN A FRACTURED SILICICLASTIC-BEDROCK AQUIFER NEAR LANSDALE, PENNSYLVANIA

by Gary J. Barton, Dennis W. Risser, Daniel G. Galeone, and Daniel J. Goode

ABSTRACT

A supply well used by the North Penn Water Authority near Lansdale, Pa., was selected as a case study for delineating a contributing area in a fractured siliciclastic-bedrock aquifer. The study emphasized the importance of refining the understanding of factors that control ground-water movement to the well by conducting (1) geophysical logging and flow measurements, (2) ground-water level monitoring, (3) aquifer testing, and (4) geochemical sampling. This approach could be applicable for other wells in siliciclastic-bedrock terranes, especially those of Triassic age in southeastern Pennsylvania.

The principal methods for refining the understanding of hydrology at supply well MG-1125 were aquifer testing, water-level measurements, and geophysical logging. Results of two constant-discharge aquifer tests helped estimate the transmissivity of water-producing units and evaluate the anisotropy caused by dipping beds. Results from slug tests provided estimates of transmissivity that were used to evaluate the results from the constant-discharge aquifer tests. Slug tests also showed the wide distribution of transmissivity, indicating that ground-water velocities must vary considerably in the well field. Water-level monitoring in observation wells allowed maps of the potentiometric surface near the well field to be drawn. The measurements also showed that the hydraulic gradient can change abruptly in response to pumping from nearby supply wells. Water levels measured at a broader regional scale in an earlier study also provided a useful view of the potentiometric surface for purposes of delineating the contributing area. Geophysical logging and measurements of flow within wells showed that about 60 percent of water from supply well MG-1125 probably is contributed from relatively shallow water-producing fractures from 60 to 125 feet below land surface, but measurable amounts of water are contributed by fractures to a depth of 311 feet below land surface. Chemical samples supported the evidence that shallow fractures probably contribute significant amounts of water to well MG-1125. The large contribution of water from shallow fractures indicates that the area providing part of the recharge to the well is not far removed from the wellhead.

Preliminary delineations of the contributing area and the 100-day time-of travel area were computed from a water budget and time-of-travel equation. These delineations provided insight into the size (but not the shape) of the contributing areas. Three other approaches were used and results compared: (1) uniform-flow equation, (2) hydrogeologic mapping, and (3) numerical modeling. The uniform-flow equation predicted a contributing area that seemed unrealistic—extending far across the ground-water divide into an adjacent watershed. Hydrogeologic mapping, if used with the potentiometric surface and constrained by the water budget, produced a contributing area that was similar to that from numerical modeling. Numerical modeling allowed the incorporation of anisotropy caused by dipping water-producing units, differing transmissivity values of geologic units, and ground-water withdrawals from nearby supply wells. The numerical modeling showed that ground-water withdrawals from nearby supply wells affected the contributing area to supply well MG-1125 but had less effect on the 100-day time-of-travel area.

INTRODUCTION

The 1986 Amendments to the Safe Drinking Water Act required states to establish wellhead-protection (WHP) programs to protect ground water used for public supplies from possible contamination (U.S. Environmental Protection Agency, 1989). A critical element of every WHP program is the delineation of a wellhead-protection area, which is the surface area and subsurface volume of aquifer through which contaminants are reasonably likely to move toward and reach a water well (U.S. Environmental Protection Agency, 1987, p. 1-2). Many methods can be used to delineate the surface and subsurface parts of an aquifer contributing water to a well, but results can vary widely depending on the hydrogeologic setting in which they are applied. Recognizing this, the Pennsylvania Department of Environmental Protection (PaDEP) initiated this study in cooperation with the U.S. Geological Survey (USGS) to evaluate methods for delineating the contributing area for public-supply wells in different hydrogeologic settings throughout Pennsylvania.

The USGS evaluation of methods to delineate contributing areas to wells in valley-fill aquifers was reported in Risser and Madden (1994), and a strategy for delineating contributing areas to wells in fractured-bedrock aquifers was outlined in Risser and Barton (1995). The strategy for fractured-bedrock aquifers was developed from three hydrogeologic field studies at public-supply wells selected to represent the wide range of hydrogeologic settings encountered by communities establishing WHP programs. Field studies were conducted at wells in (1) fractured crystalline bedrock at Stewartstown (Barton and others, 1999), (2) fractured sandstone and shale near Lansdale (this report), and (3) karstic carbonate bedrock at Houserville (ongoing study) (fig. 1).

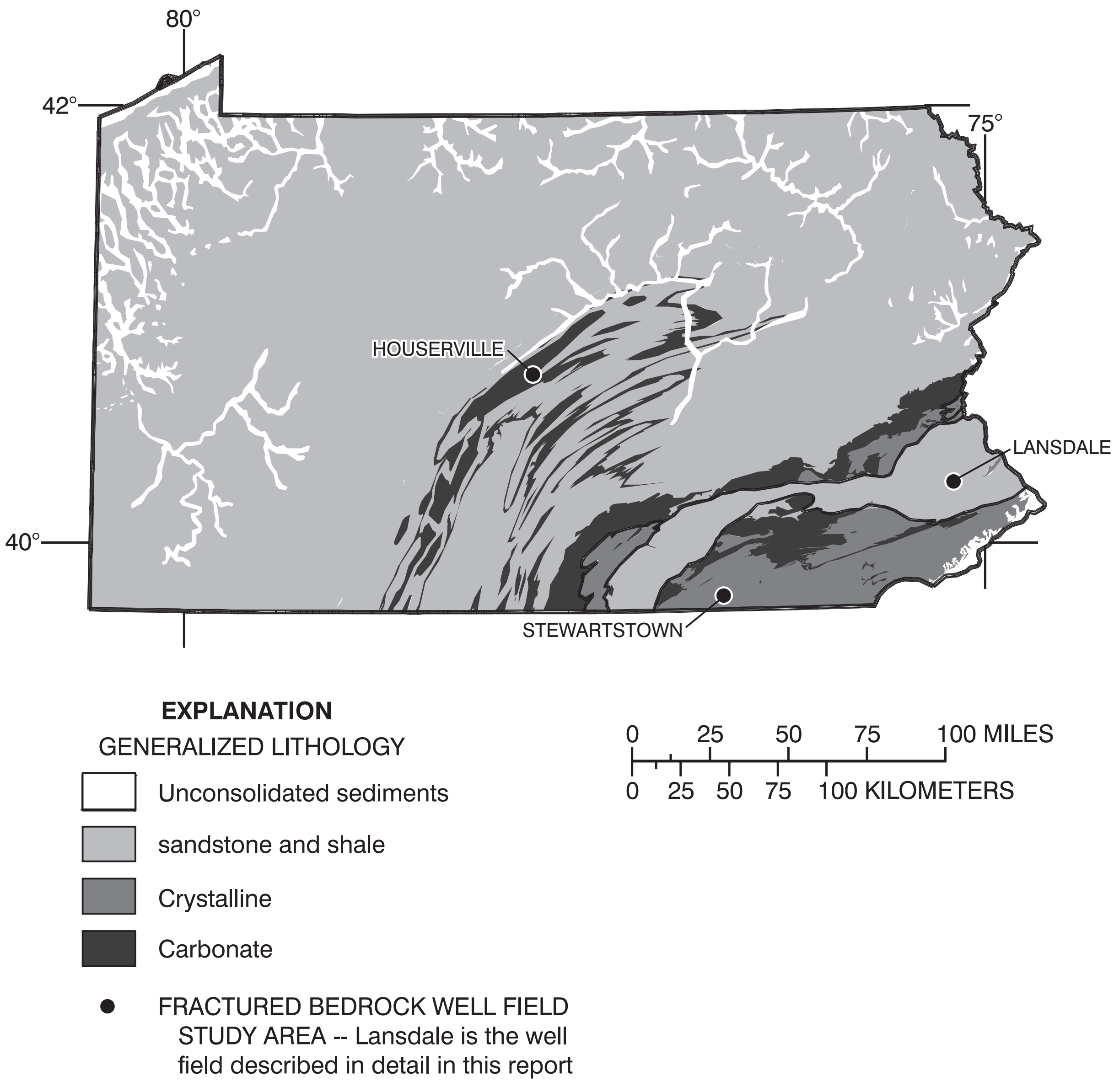


Figure 1. Generalized geology of Pennsylvania and location of fractured-bedrock study areas.

Purpose and Scope

This report describes the hydrogeologic field study of supply well MG-1125 (known locally as North Penn Water Authority well 61) near Lansdale, Pa. The study at supply well MG-1125 is presented as a case study to illustrate the strategy to delineate contributing areas as applied to wells in fractured siliciclastic-bedrock aquifers. The report also illustrates the differences in results from various methods to delineate contributing areas (U.S. Environmental Protection Agency, 1987). The study focused on the collection of hydrogeologic information and refinement of the hydrogeologic framework and conceptual model of the ground-water-flow system in the immediate vicinity of supply well MG-1125. Most of the investigations at the well were conducted during 1991. Some of the results from an investigation of regional hydrogeologic conditions of the Lansdale area reported in Senior and Goode (1999) also are presented in this report.

Supply well MG-1125 was selected for study because it represents hydrogeologic conditions characteristic of siliciclastic-bedrock aquifers of Triassic age in southeastern Pennsylvania. Siliciclastic-bedrock aquifers comprising conglomerate, sandstone, siltstone, mudstone, and shale crop out throughout about three-fourths of the Commonwealth. In southeastern Pennsylvania, withdrawals of ground water for community public supplies from the siliciclastic-bedrock aquifers of Triassic age averaged about 38 Mgal/d during 1993 and 1994, according to data from the USGS water-use database system.

Contributing Area and Related Terms

As used in this report, the aquifer volume through which water is drawn (or diverted) to a well is called the zone of diversion (fig. 2A). The projection of this aquifer volume to land surface defines the area of diversion to the well. The contributing area is the area of diversion and any adjacent areas that provide recharge to the aquifer within the zone of diversion. The contributing area may be coincident with the area of diversion, but it also can be much larger. For example, if it can be demonstrated that pumping from a well induces significant infiltration from a stream as shown in figure 2A, the contributing area to the well includes the watershed of the stream (fig. 2B). In such an instance, it may be impractical to implement a WHP program throughout the watershed, but the source of water from the stream needs to be recognized. The part of the area of diversion from which water will reach a well within a specified time is a time-of-travel area (fig. 2B). A time-of-travel area is always an area around the well that is less than or equal to the size of the area of diversion.

The area of diversion and contributing area as defined here relate to WHP Zones II and III in the Pennsylvania WHP and Source Water Protection programs (Commonwealth of Pennsylvania, 2000, p. 9). A hydrogeologically determined Zone II is equivalent to the area of diversion unless a radius of 0.5 mi is used instead. WHP Zone III equals those parts of the contributing area exclusive of the area of diversion. For example, in figure 2B, Zone III equals the watershed of the stream. The Pennsylvania WHP program Zone I is a circular area surrounding the well with a radius of 100 to 400 ft, determined on the basis of the volumetric flow to the well as described in Commonwealth of Pennsylvania (2001).

Strategy for Delineating the Contributing Area

Delineating a contributing area to a well completed in a fractured-bedrock aquifer is difficult because the hydrogeologic characteristics of fractured rocks are complex. Because of this complexity, a single method or technique to delineate a contributing area is not applicable for most wells completed in fractured-bedrock aquifers. Therefore, rather than presenting a method to delineate a contributing area, a strategy (fig. 3) for refining the understanding of boundary conditions and major heterogeneities that control ground-water movement and sources of water to a supply well was proposed by Risser and Barton (1995). The strategy consists of (1) developing an initial conceptual hydrogeologic model of the setting near the well field on the basis of a literature review, (2) developing a preliminary contributing-area delineation, (3) refining the initial conceptual hydrogeologic model by conducting field studies, and (4) refining the preliminary contributing-area delineation so that it reflects the refined conceptual hydrogeologic model. By use of such a strategy, the improved understanding of the ground-water-flow system should, in theory, lead to a technically defensible delineation of the contributing area. This report describes a case study illustrating that strategy in a fractured siliciclastic-bedrock aquifer.

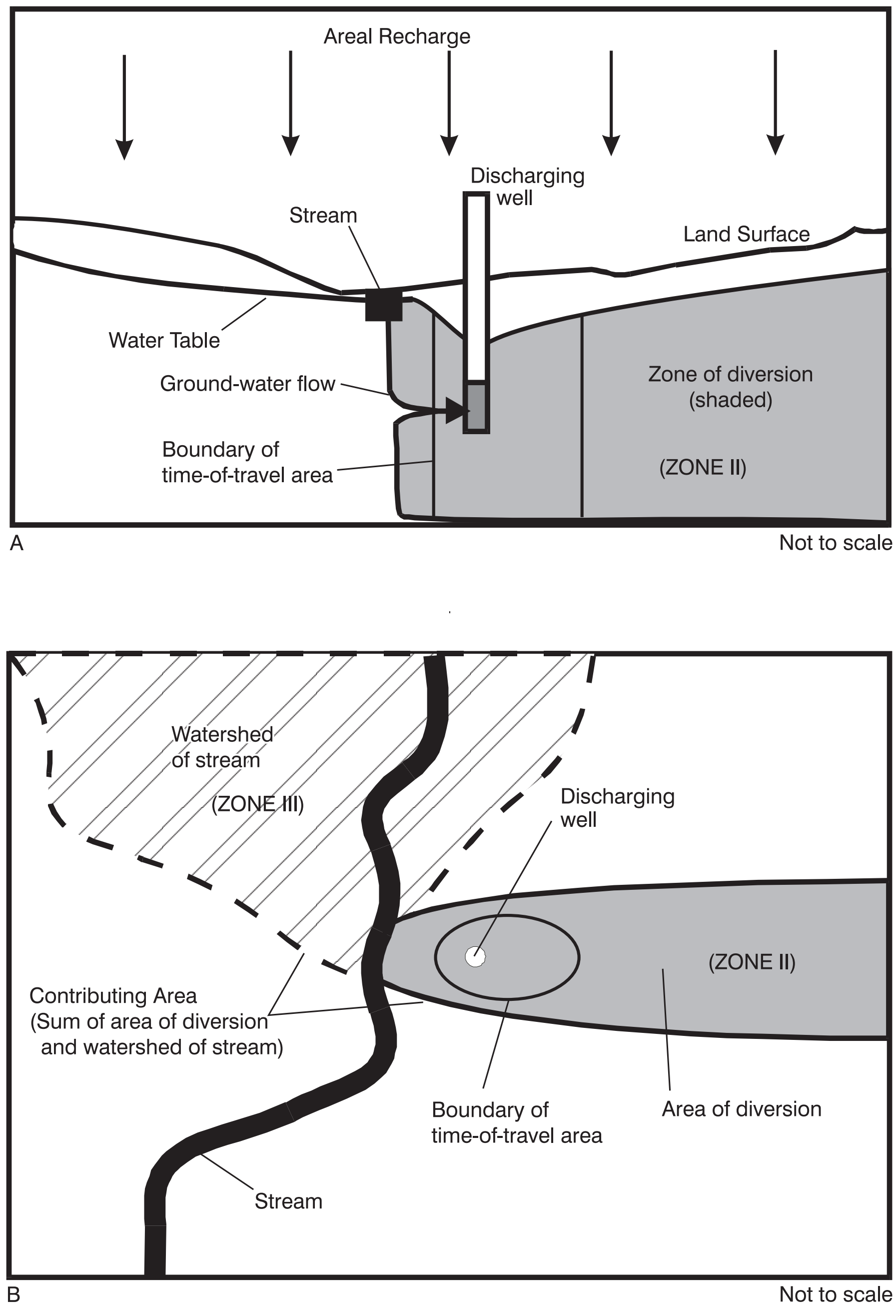


Figure 2. Area of diversion, contributing area, and time-of-travel area of a discharging well: (A) cross-sectional view, (B) map view. (Modified from Reilly and Pollock, 1993, fig. 2.)

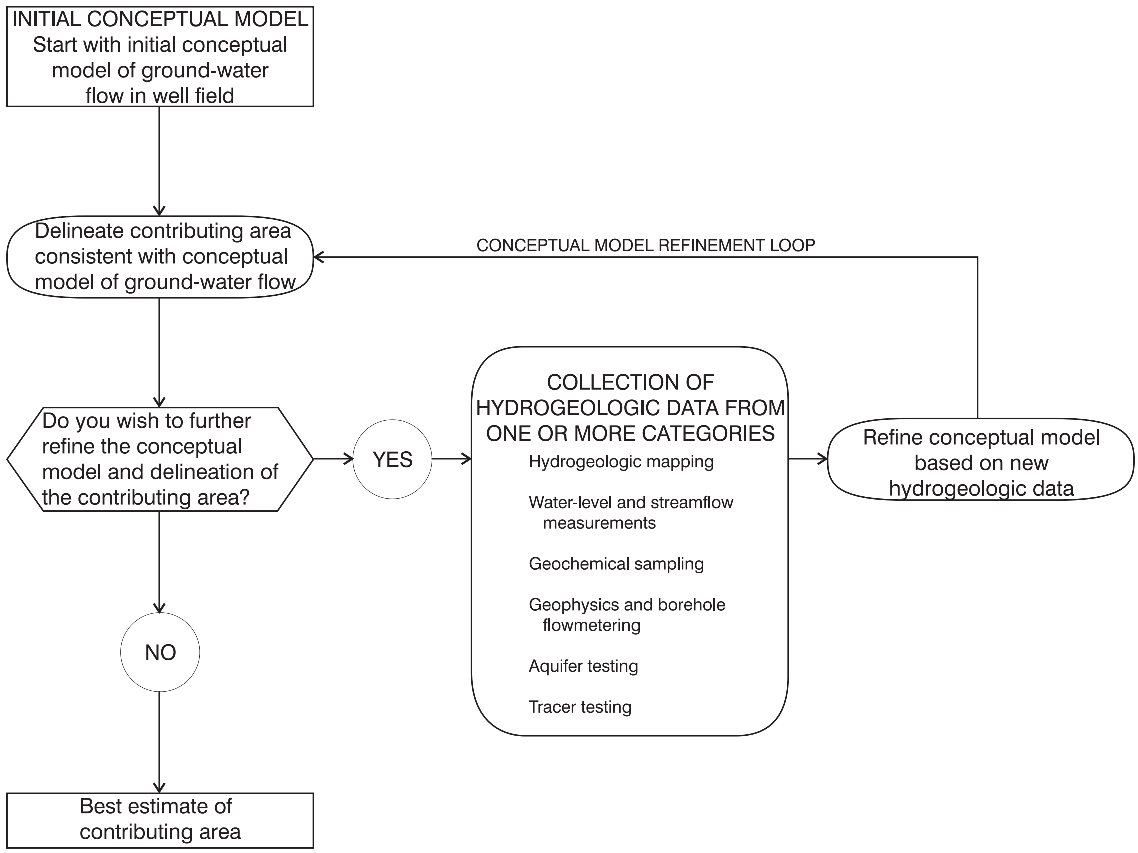


Figure 3. Overall strategy for delineating contributing areas in fractured crystalline-bedrock aquifers. (From Risser and Barton, 1995, fig. 4.)

Description of the Well Field

Supply well MG-1125 and four nearby observation wells are referred to in this study as the Hospital well field because of their location near North Penn Hospital. The Hospital well field is in the Gettysburg Newark Lowlands Section of the Piedmont Physiographic Province (Sevon, 2000) and is in the headwaters of the Neshaminy Creek Watershed (fig. 4). The well field and surrounding area are underlain by Triassic-age siliciclastic rocks of the Brunswick and Lockatong Formations. The undulating hills of low relief in this upland setting are characteristic of Triassic-age bedrock terrains of the Piedmont Physiographic Province.

The hospital well field is defined for this study as consisting of supply well MG-1125, owned and operated by North Penn Water Authority (NPWA), and four observation wells (fig. 4). Although not in service during this study (1991), supply well MG-1125 is equipped with a submersible pump and is connected to the municipal water-distribution system. Withdrawing water at an average rate not to exceed 200 gal/min is permissible (Gregory Cavallo, Delaware River Basin Commission, oral commun., 1999). Observation wells MG-1124 and MG-1126, owned by NPWA, are 940 ft southwest and 780 ft northeast from supply well MG-1125, respectively. To provide additional hydraulic information, observation well MG-1270 was drilled 620 ft southeast of supply well MG-1125 by USGS and a water-level recorder was placed on observation well MG-618 located 1,690 ft west of supply well MG-1125.

Supply-well MG-1125 and the four observation wells are drilled in siltstone and shale of the Brunswick and Lockatong Formations. Supply well MG-1125 is 400 ft deep. The observation wells range in depth from 310 to 400 ft (table 1). The observation wells are cased to depths of 19 to 47 ft below land surface and are completed as open holes below their surface casing.

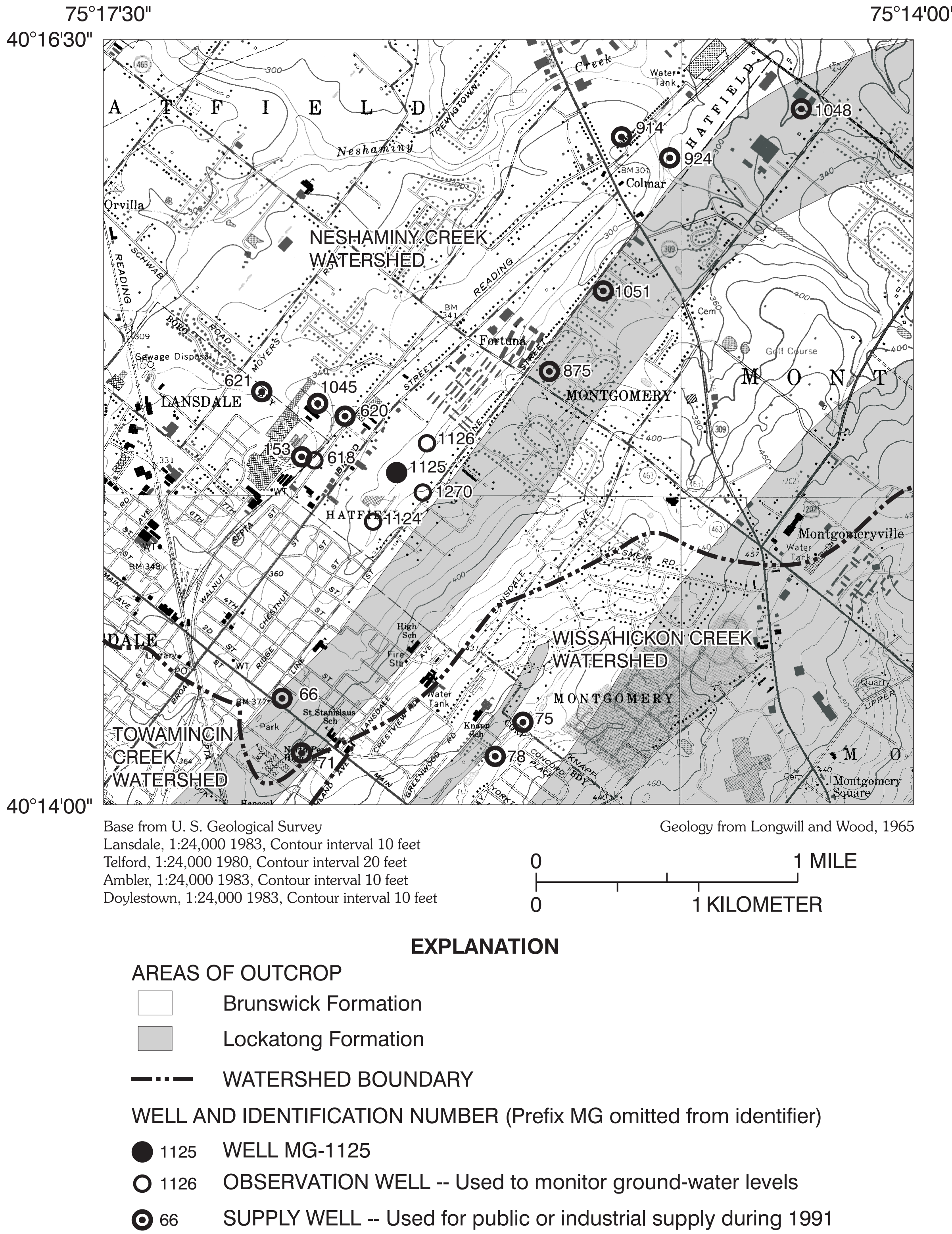


Figure 4. Location of supply well MG-1125, the four observation wells used in this study, and other nearby supply wells near Lansdale, Pa.

Table 1. *Record of public-supply, industrial, and observation wells in the study area near Lansdale, Pa.*

[Vertical Datum, NGVD 29; Horizontal Datum, NAD 27; Owner: AOTC, American Olean Tile Co.; NPWA, North Penn Water Authority; NWWA, North Wales Water Authority; NPH, North Penn Hospital; Use: N, industrial; O, observation; P, public water supply; Geophysical logs: C, caliper; D, driller's; E, electric; F, fluid conductivity; J, gamma ray; P, video; T, temperature; V, fluid velocity; ft, feet; in., inches; gal/min, gallons per minute; --, not known]

U.S. Geological Survey well identification number	Local well identifier	Latitude	Longitude	Driller	Owner	Date completed	Use	Altitude of land surface (ft)	Total depth below land surface (ft)	Casing		Depth to driller-reported water-bearing zone(s) (ft)	Reported yield (gal/min)	Geophysical logs
										Depth (ft)	Diameter (in.)			
MG-66	L-7	40°14′19″	75°14′28″	Bollinger	NPWA	1992	P	376.2	378	--	8	--	80	--
MG-71	L-12	40°14′09″	75°16′38″	Stothoff	NPWA	1938	P	406.8	285	43	8	--	120	--
MG-153	2	40°15′08″	75°16′37″	--	AOTC	1953	N	360	400	--	10	--	125	--
MG-618	Pit Well	40°15′07″	75°16′34″	Knieriem	NPWA	1958	O	364.77	343	47	6	--	30	C, E, F, J, V, T
MG-620	3	40°15′17″	75°16′26″	Stothoff	AOTC	1955	N	360	400	116	10	--	100	--
MG-621	4	40°15′21″	75°16′26″	Stothoff	AOTC	1957	N	340	400	63	10	--	--	--
MG-875	17	40°15′25″	75°15′40″	Miller	NWWA	1964	P	330	500	60	12	--	750	--
MG-914	NP-12	40°16′12″	75°15′18″	--	NPWA	1969	P	300	620	43	8	55, 100, 155, 210, 275, 300, 370	27	D
MG-924	NP-21	40°16′07″	75°15′03″	--	NPWA	1968	P	280	500	50	12	--	600	C, D, E, F, J, V
MG-1045	5	40°15′18″	75°16′35″	Stothoff	AOTC	1964	N	330	337	60	10	--	80	D
MG-1048	16	40°16′18″	75°14′28″	Book	NWWA	1981	P	300	502	60	12	--	1,000	--
MG-1051	22	40°15′41″	75°15′20″	Bollinger	NWWA	1969	P	310	500	--	8	--	400	--
MG-1124	NP-58	40°14′56″	75°16′20″	Bollinger	NPWA	1980	O	339.15	385	25	6	168, 179, 275	135	C, D, E, F, J, P, T, V
MG-1125	NP-61	40°15′04″	75°16′14″	Bollinger	NPWA	1980	P	331.03	400	60	10	55, 105, 207, 308, 335, 370	306	C, D, E, F, J, T, V
MG-1126	NP-62	40°15′10″	75°16′06″	Bollinger	NPWA	1980	O	327.38	310	19	6	70, 135, 225, 290, 302	157	C, D, E, F, J, P, T, V
MG-1270	NP-59	40°15′01″	75°16′06″	Bollinger	NPH	1991	O	340.50	320	19	6	--	--	C, D, E, F, J, T, V
MG-75	L-16	40°14′15″	75°15′41″	Stothoff	NPWA	1948	P	384	400	40	12	--	175	--
MG-78	L-19	40°14′07″	75°15′48″	Stothoff	NPWA	1951	P	375	430	41	12	--	173	--

Acknowledgments

This project would not have been possible without assistance from Harold Borchers at NPWA, who provided access to their wells, and Paul Greebe at North Penn Hospital, who allowed USGS to drill an observation well on their property. Appreciation also is extended to Ted Kline at North Wales Water Authority and Gilbert Fitzhugh at American Olean Tile Corporation for providing information on their supply wells.

DELINEATING THE CONTRIBUTING AREA

The contributing area to supply well MG-1125 was delineated according to the strategy as previously defined. Details of the four-step process are described in the following sections.

Initial Conceptual Hydrogeologic Model

An initial conceptual hydrogeologic model of the geologic framework, aquifer properties, and movement of ground water to supply well MG-1125 was developed from published information that describes general hydrogeologic conditions of the Triassic-bedrock aquifers of the Piedmont Physiographic Province in southeastern Pennsylvania. The principal sources of information were published reports by Greenman (1955), Rima (1965), Longwill and Wood (1965), McGreevy and Sloto (1977), Wood (1980), Michalski (1990), and Sloto and Schreffler (1994). The initial conceptual model is illustrated schematically in figure 5, and some information about aquifer characteristics of this conceptual model are summarized below.

Hydrogeologic Framework

The Triassic-age Brunswick and Lockatong Formations form the hydrogeologic framework at the Hospital well field. The Brunswick Formation consists of several thousand feet of non-marine, reddish brown mudstone, shale, and siltstone, which interfingers with the underlying Lockatong Formation (Longwill and Wood, 1965). The Lockatong Formation consists of thick-bedded argillite and mudstone and a few thin beds of shale. Beds in the Brunswick and Lockatong Formations are part of a homoclinal structure, striking NE-SW and dipping about 20° to the northwest. The more competent beds are fractured by bedding partings and high-angle joints that parallel the strike of the beds (Senior and Goode, 1999). The dipping fractured bedrock is thinly mantled with unconsolidated weathered rock that is generally less than 30 ft thick (McGreevy and Sloto, 1977, p. 11).

Layered siliciclastic rocks such as the Brunswick and Lockatong Formations at the hospital well field tend to produce a multi-aquifer, ground-water-flow system in which ground water moves predominantly through fractures. Shallow ground water typically is in the clayey regolith and fractures of the uppermost weathered bedrock under unconfined or semiconfined conditions (fig. 5). Deeper within unweathered bedrock, ground water flows through narrow secondary openings (fractures) under confined and semiconfined conditions. The very thin water-bearing zones in the Brunswick Formation consist of fractured sandstone confined between thick beds of less permeable shale and massive mudstone (fig. 6). The thickness of water-bearing zones ranges from a few inches to a few feet (Longwill and Wood, 1965) whereas the confining units generally are greater than 30 ft thick. Thus, the hydraulic connection between individual confined water-bearing units usually is poor. In addition, because the water-bearing beds commonly interfinger, pinch-out, or grade laterally into beds of lower permeability, the confined water-bearing zones are difficult to correlate or characterize as individual aquifers.

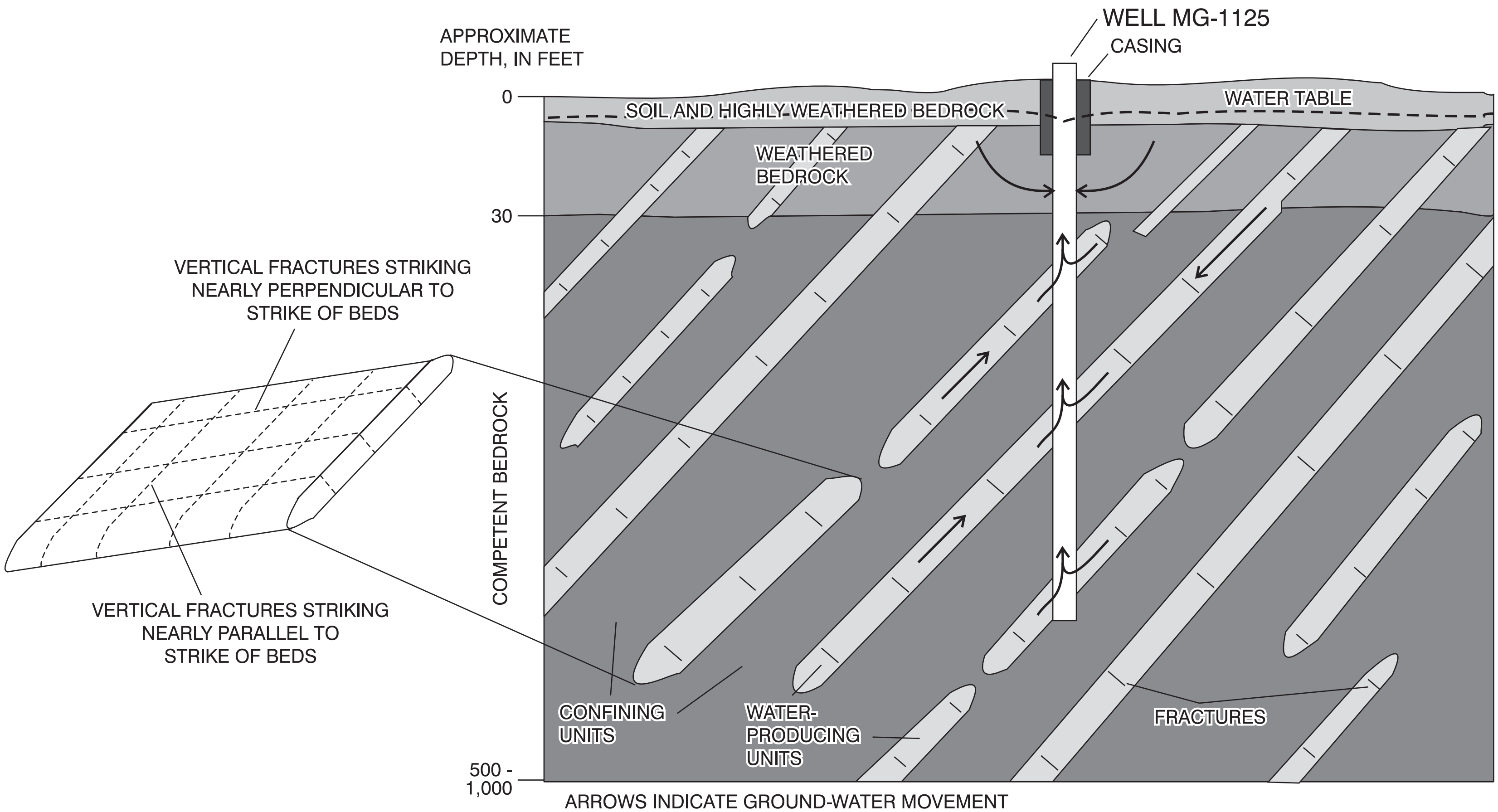


Figure 5. Initial conceptual model of ground-water flow in the vicinity of supply well MG-1125.

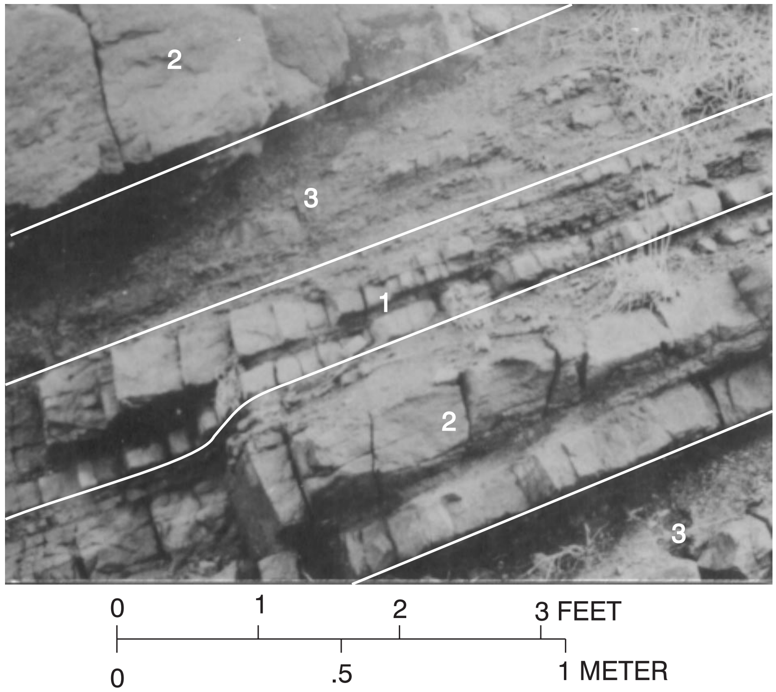


Figure 6. Sedimentary bedrock of Triassic age similar to that found in the Lansdale area showing (1) thin beds of highly fractured sandstone, (2) thicker sandstone beds where fractures are less well developed, and (3) interbeds of soft low-permeability shale (from Wood, 1980, fig. 2).

Aquifer Properties

The aquifer properties of the Brunswick and Lockatong Formations are controlled by the number, size, and degree of interconnection of water-bearing fractures within the bedrock. On the basis of drilling reports stored in the USGS National Water Information System database from 116 wells completed in the Brunswick Formation, the greatest density of water-bearing zones is between 30 and 100 ft below land surface. The density and number of water-bearing zones decrease with depth to 400 ft, although significant yields can be obtained at any depth where individual fractures are encountered.

Because of the complex hydrogeologic framework of multiple, dipping, fractured water-bearing zones, quantitative analysis of aquifer properties is difficult. However, aquifer tests do indicate that, because of the dipping beds, the transmissivity of the Brunswick Formation is highly anisotropic with the greater transmissivity value along the strike of water-bearing zones. Gerhart and Lazorchick (1988) estimated a 5:1 ratio of anisotropy for transmissivity along strike versus across strike in their model simulations of Triassic rocks in southeastern Pennsylvania.

Reported values of transmissivity of the Brunswick Formation in Montgomery and Berks Counties range from about 13 to 24,000 ft^2/d; the median is about 1,200 ft^2/d (Longwill and Wood, 1965). These values are one to two orders of magnitude larger than those reported for the Lockatong Formation.

Ground-water storage in the Brunswick and Lockatong Formations is small as indicated by the very low base flow of streams that drain these rocks. Gerhart and Lazorchick (1988) estimated a specific yield of 0.7 percent in their model simulations for Triassic-aged rocks. The porosity of the Brunswick and Lockatong Formations is very small because ground water flows predominantly through sparse fractures. Effective porosity proba-

bly does not exceed the 0.7-percent estimate for specific yield. A two-well tracer test of ground-water flow in a well field completed in similar rocks in New Jersey indicated that the effective porosity of the rocks was about 0.1 percent (Carleton and others, 1999, p. 61).

Boundary Conditions

The altitude of the water table and potentiometric surface at the hospital well field and throughout the Lansdale area is largely unknown. Most wells have open boreholes that penetrate multiple aquifers; thus, water levels in these wells are a composite of the hydraulic head of the water table and the multiple confined water-bearing zones. Prior to the development of ground-water resources in the Lansdale area during the early 1900s, the configuration of the water table probably was a subdued reflection of the surface topography.

Ground-water recharge to Triassic rocks ranges from about 6 to 10 in / yr on the basis of base-flow analysis at streamflow-gaging stations (Wood, 1980; Sloto and Schreffler, 1994). Recharge in the Lansdale area was estimated as 8.3 in / yr from calibration of a ground-water-flow model (Senior and Goode, 1999). Most shallow ground water in the hospital well field probably discharges to the West Branch of Neshaminy Creek and its tributaries or to wells. Ground-water flow in the confined water-bearing zones may move beneath small local streams and discharge instead to larger streams or supply wells.

The location and daily average rates of withdrawal by supply and industrial wells in the study area are shown in figure 4 and table 2. Supply well MG-1125 is permitted to pump at 200 gal / min (Gregory Cavallo, Delaware River Basin Commission, oral commun., 1999), but was not in operation at the time of this study in 1991. During 1991, there were nine public-supply wells within a 2-mi radius of supply well MG-1125 that had a combined average pumping rate of 851 gal / min. Four industrial wells, owned by American Olean Tile Company, had a combined average withdrawal rate of about 47 gal / min (fig. 4 and table 2).

Table 2. *Average ground-water withdrawals in 1991 from major supply wells in the study area near Lansdale, Pa.*

[NPWA, North Penn Water Authority; NWWA, North Wales Water Authority; AOTC, American Olean Tile Company; PaDEP, Pennsylvania Department of Environmental Protection]

U.S. Geological Survey well identification number	Owner	Local well identifier	Average well discharge (gallons per minute)	Approximate distance from supply well MG-1125 (feet)
MG-66	NPWA	L-7	[1] 39	5,200
MG-71	NPWA	L-12	[1] 39	6,000
MG-75	NPWA	L-16	[2] 35	5,800
MG-78	NPWA	L-19	[2] 63	6,400
MG-914	NPWA	NP-12	[1] 95	7,600
MG-924	NPWA	NP-21	[1] 81	7,600
MG-875	NWWA	17	[3] 76	3,100
MG-1048	NWWA	16	[3] 292	10,300
MG-1051	NWWA	22	[3] 84	5,100
MG-153	AOTC	2	[4] 13	2,100
MG-620	AOTC	3	[4] 9	1,500
MG-621	AOTC	4	[4] 13	3,400
MG-1045	AOTC	5	[4] 12	2,400

[1] Terry Gable, North Penn Water Authority, written commun., 1992.
[2] Tom Denslinger, Pennsylvania Department of Environmental Protection, written commun., 1999.
[3] Ted Kline, North Wales Water Authority, written commun., 1992.
[4] Gilbert Fitzhugh, American Olean Tile Company, written commun., 1992.

Hydrogeologic Investigations at the Well Field

Hydrogeologic investigations were conducted at and in the vicinity of the hospital well field in 1991 to provide additional information about its hydrogeologic framework, boundary conditions, and aquifer properties. Additional information was incorporated into the conceptual hydrogeologic model to help refine delineations of the contributing area. Investigations included geologic and fracture-trace evaluation, borehole logging and flow measurements, ground-water level monitoring, aquifer testing, and geochemical sampling.

Geologic and Fracture-Trace Mapping

Geologic maps helped define the hydrogeologic framework at the well field. Geologic mapping (Longwill and Wood, 1965) indicates that mudstone, shale, and siltstone of the Brunswick Formation crop out at the hospital well field (fig. 4). However, good exposures of bedrock were not observed at the site because of the overlying regolith and urban development. Approximately 1,200 ft southeast of the well field, argillite and mudstone crop out in a 1,500-ft wide band. These rocks are shown by Longwill and Wood (1965) as a stringer of the main body of the Lockatong Formation, which crops out about 1 mi east of supply well MG-1125. Lyttle and Epstein (1987) map the argillite and mudstone as gray beds within the lower part of the Brunswick Group. The Lockatong Formation as mapped strikes about N. 40° E. and dips about 20° to the northwest near supply well MG-1125.

Geologic information from driller's logs provided information on the vertical dimension of the hydrogeologic framework. Driller's logs indicated that supply well MG-1125 penetrates red shale of the Brunswick Formation from land surface to a depth of about 230 ft and gray shale and argillite of the Lockatong Formation from 231 ft to the bottom of the hole at 400 ft below land surface (fig. 7). Observation wells MG-1124, MG-1126, and MG-1270 also penetrate the red shale of the Brunswick Formation and gray argillite of the Lockatong Formation. On the basis of the depth that each well encountered the Lockatong Formation, the geologic units strike N. 60° E. and dip about 10° to the northwest. Because the formations appear to interfinger, on the basis of the driller's logs, these estimates of strike and dip need to be refined by correlation of borehole geophysical logs.

Potential preferred avenues of ground-water flow to supply well MG-1125 were investigated on black and white, 1:24,000-scale aerial photographs by visually identifying linear traces that may indicate the presence of fractures. Because the well field is part of an area that has been heavily populated since the early 1900s, anthropogenic activities have largely covered any lineaments, such as soil tonal variations, that could be a surface expression of fracturing below land surface. Also, the anthropogenic activities have created lineaments that are related to buried sewers, pipelines, and roads. Therefore, lineaments reflecting geologic conditions could not be identified on aerial photos.

Borehole Geophysical Logging and Flow Measurements

Geophysical logging and measurements of vertical borehole flow were conducted in supply well MG-1125 and observation wells MG-618, MG-1124, MG-1126, and MG-1270. Geophysical logs were used to help (1) identify and correlate geologic units below land surface, (2) identify the water-producing fractures in each well, (3) determine the relative yield of water-producing fractures, and (4) determine hydraulic connections among wells when supply well MG-1125 is pumped.

Natural-gamma logs were useful for correlating geologic units because several units contained clay minerals that produced large emanations of natural-gamma radiation that were easy to identify. Caliper logs helped identify the location of fractures intercepted by the well, but not all fractures produced water. Inflections in fluid-temperature and fluid-resistivity logs showed fractures that produced water. Measurements of vertical flow within the borehole by the brine-tracing method (Patten and Bennett, 1962) quantified the rate to a detection limit of about 0.5 gal / min. Flow measurements made while simultaneously pumping water from that same well allowed the relative yield (fig. 7) and transmissivity of fractures to be estimated. Hydraulic connections between supply well MG-1125 and observation wells were determined by measuring flow in observation wells while pumping from supply well MG-1125.

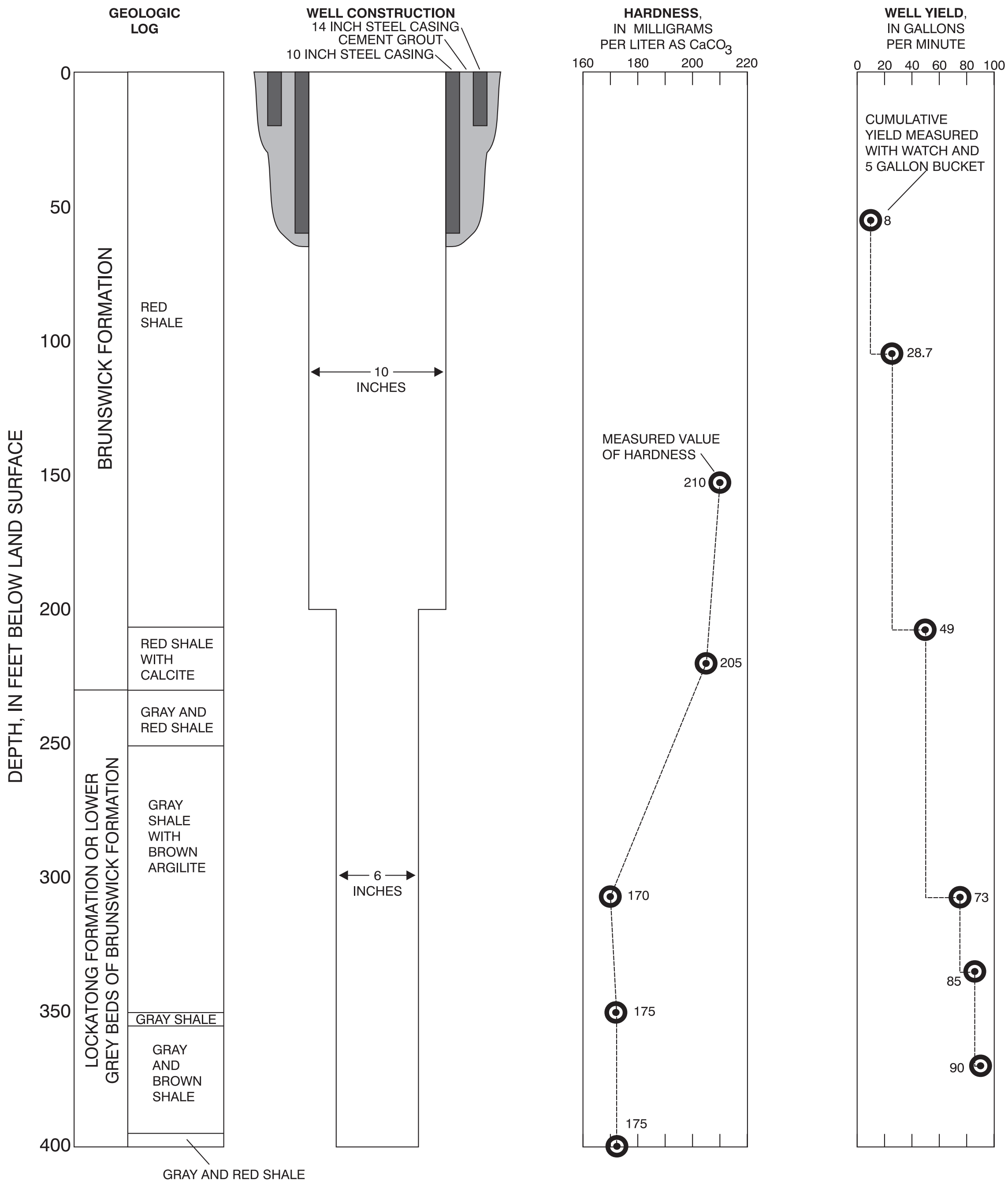


Figure 7. Driller’s logs of lithology, well construction, hardness of water, and well yield for well MG-1125. (Data from North Penn Water Authority.)

Correlation of Geologic Units

Natural-gamma logs were used to evaluate the subsurface geologic structure of the Brunswick and Lockatong Formations by correlation of thin, dark black shale beds, enriched with radioactive elements that intersect the supply well MG-1125 and the four observation wells in the subsurface. The correlation of beds with elevated gamma emissions is shown in figure 8. These beds emit natural-gamma radiation at a rate that is two to three orders-of-magnitude greater than the surrounding beds and, therefore, can easily be identified by use of the natural gamma-ray logging tool. The correlation shown in figure 8 clearly shows the relative stratigraphic sequence through which each well was drilled. Marker beds *B*, *C*, and *D* correlate between wells MG-1124, MG-1125, and MG-1270. Marker horizon *A* was found only in wells MG-618 and MG-1126; however, the driller's log of supply well MG-1125 describes a dark gray bed at a depth of 20 ft below land surface, which is probably marker horizon *A*. The base of the Brunswick Formation is about 20 ft above marker horizon *B* as determined from the change from predominantly red to gray shale.

The open interval of supply well MG-1125 is from 60 to 400 ft below land surface. The correlations show that observation well MG-618 is completed in the highest (youngest) strata, mostly above the strata open to supply well MG-1125. Thus, the hydraulic connection between MG-1125 and MG-618 is less direct than for the other observation wells that are completed in most of the same strata as supply-well MG-1125, between marker horizons *A* and *D*.

The correlation shown in figure 8 indicates that the rocks of the Brunswick and Lockatong Formations are striking N. 54° E. and dip 11° northwest. This is significantly different than the strike of the Lockatong outcrop of about N. 40° E. as shown on the map compiled by Longwill and Wood (1965). Supply well MG-1125 and the four observation wells are shown in a cross section oriented N. 36° W., perpendicular to the strike of beds (fig. 9).

From the record of borehole diameter shown on the caliper logs, locations where the borehole diameter is larger than the nominal diameter of the hole indicate possible locations where the well intersects fractures in the bedrock. The depth of the possible fractures interpreted from caliper logs are shown for each well in figure 9. The density of fractures appears to be lower in the Lockatong Formation than the Brunswick Formation. This could be a function of lithology or that the density of fractures decreases with depth. Wells drilled in the Brunswick Formation encountered 15 fractures in about 1,030 ft of rock; thus, one fracture was penetrated for about every 70 ft of depth drilled. In the Lockatong Formation, four fractures were identified in 570 ft of rock, which is an average of one fracture for about every 140 ft of depth drilled. The sparsity of fractures encountered in observation well MG-618 may indicate that the chance of penetrating water-bearing openings in the Brunswick Formation may be greatest between marker beds *A* and *B*.

The depth of water-bearing zones reported by the driller also are shown in figure 9. Note that many but not all fractures indicated by the caliper log correspond to water-bearing zones reported by the driller. This indicates that not all fractures yield water to the well.

Water-Producing Fractures

To help identify fractures that yield water, fluid-resistance, fluid-temperature, and brine-trace logging was conducted in wells MG-1124, MG-1270, MG-618, and MG-1126 during periods when supply well MG-1125 was not pumping. The logs show that ground water enters wells from fractured thin beds in a confined-aquifer system, flows upward in the wells, and exits into shallow water-bearing beds (fig. 10). Vertical-flow measurements, made by tracing the movement of injected brine slugs, show upward flow in boreholes at rates up to 8 gal / min. Vertical upward flow occurs in these boreholes because they penetrate multiple water-bearing zones and the hydraulic heads in deep zones are greater than heads near the water table. The maximum depth in each well where water flows from the well into water-bearing rocks (thieving zones in figure 10) ranges from 50 ft in MG-1124 to 116 ft in MG-1125. The deepest water-producing bed at a depth of 311 ft is in supply-well MG-1125 and produces 4 gal / min under non-pumping conditions. Zero to three confined water-producing beds were identified per borehole, and bed thickness ranges from less than 1 to 4 ft. Intervening confining beds have an average thickness of about 40-50 ft.

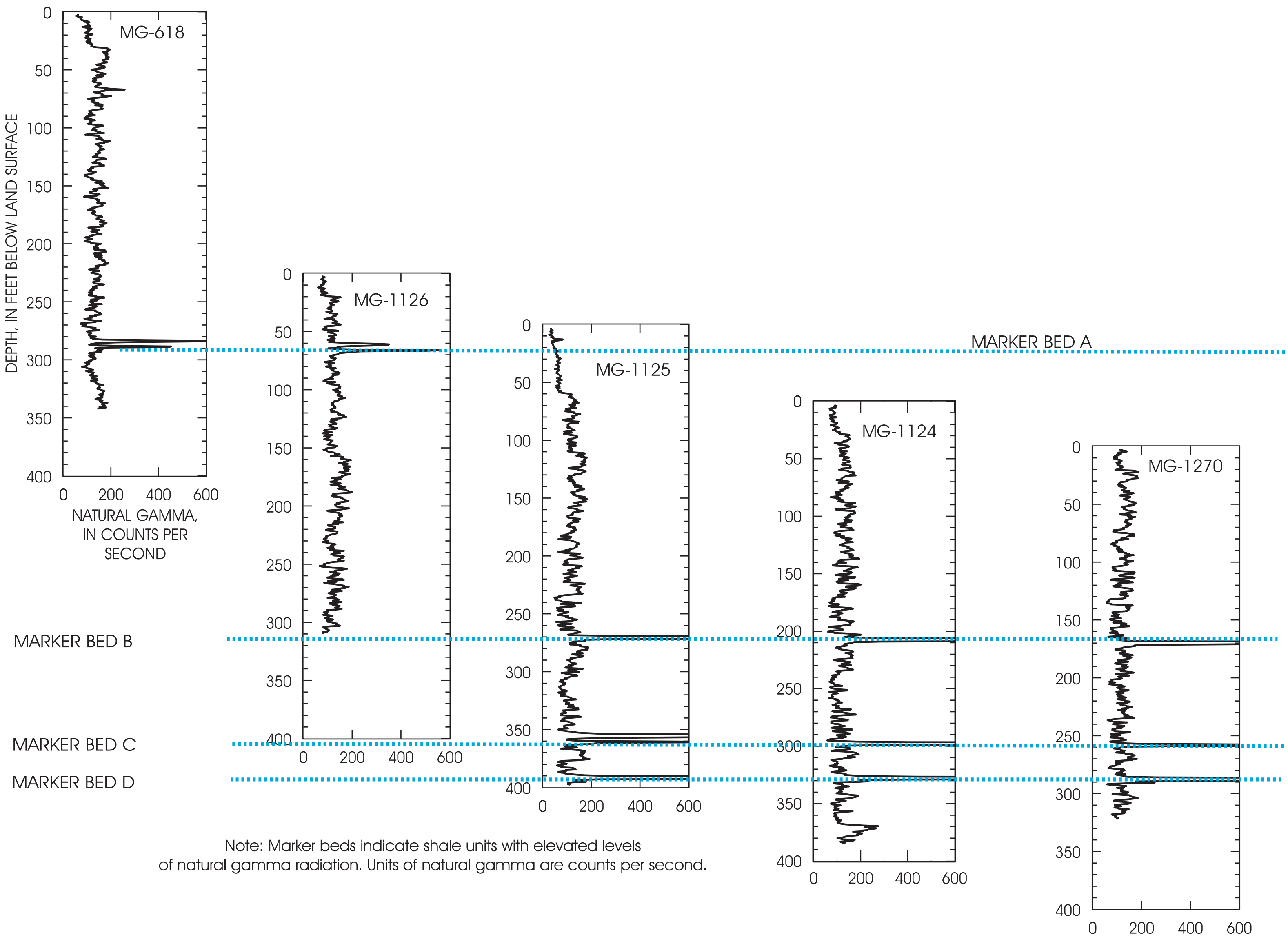


Figure 8. Stratigraphic correlation among wells on the basis of shale beds with elevated emissions of natural-gamma radiation.

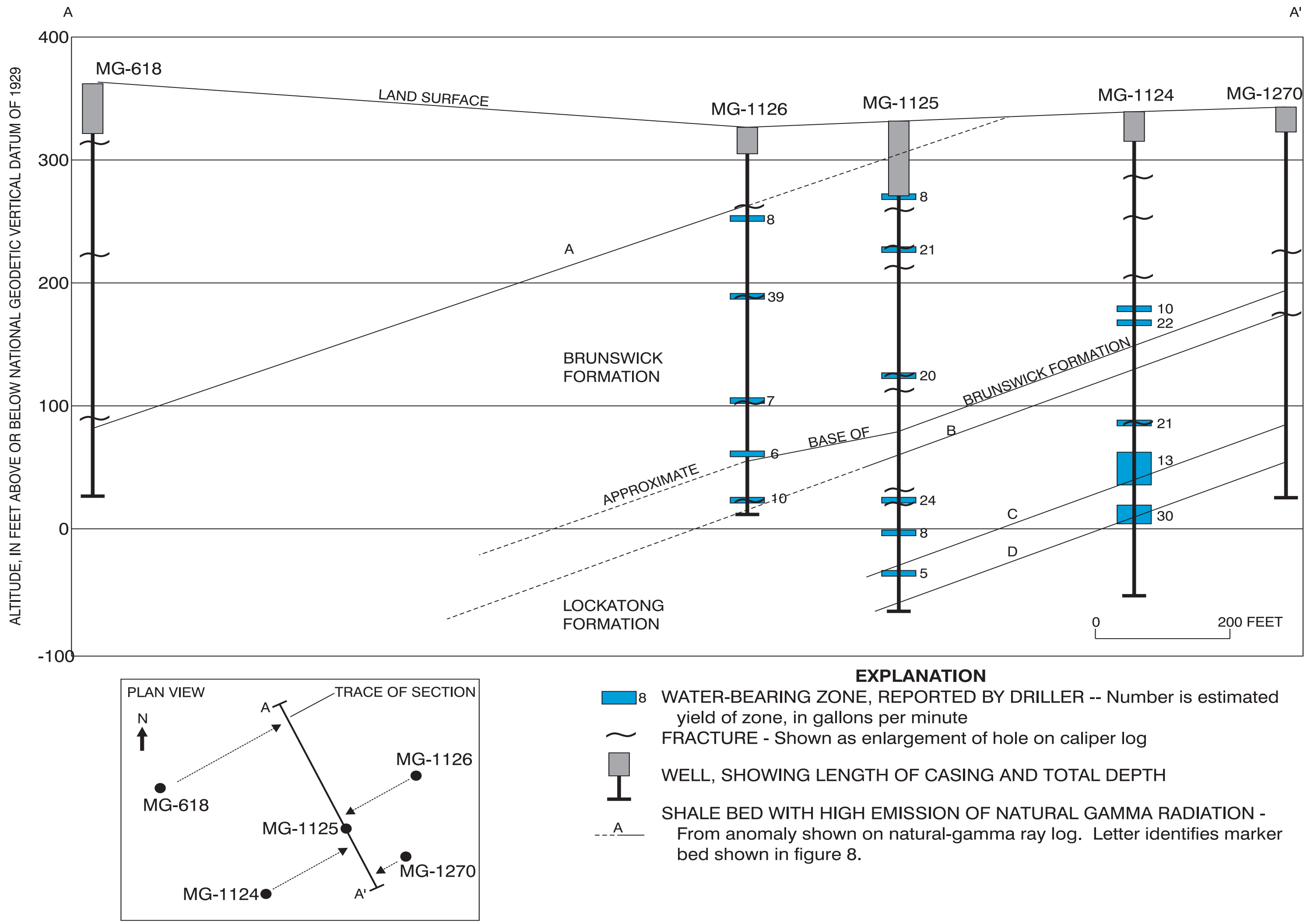


Figure 9. Northwest-southeast cross section trending N. 36° W., perpendicular to the strike of beds showing location of water-bearing zones reported during drilling and rock fractures determined from caliper logs.

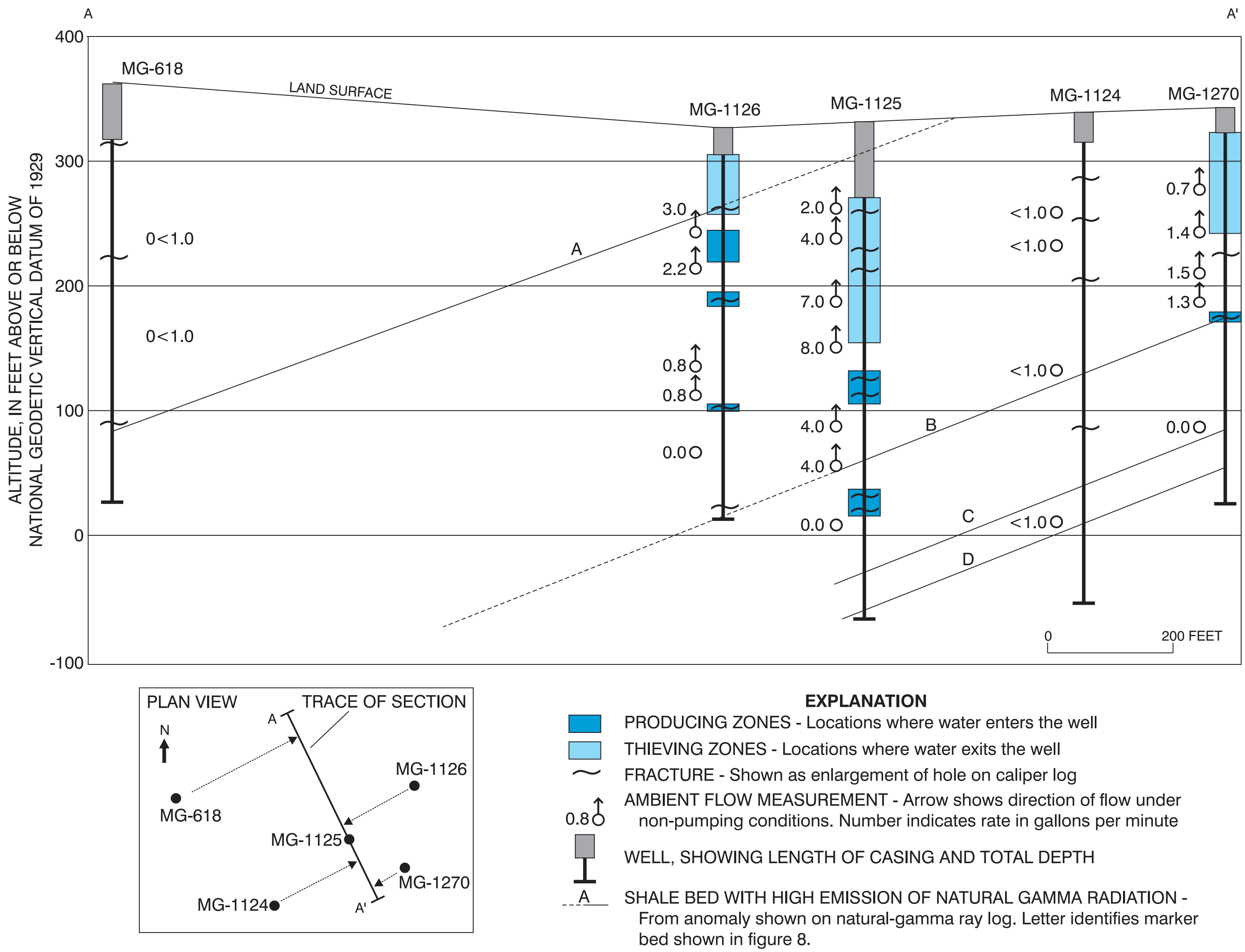


Figure 10. Northwest-southeast cross section trending N. 36° W., perpendicular to the strike of beds showing location of water-producing and thieving zones determined from brine-tracing under nonpumping conditions.

Relative Yields of Water-Producing Fractures

Simultaneous pumping and measurement of flow in the well by brine-trace logging was conducted in supply well MG-1125 and observation wells MG-1124 and MG-1126 to determine which water-producing fractures contribute the largest quantities of water to each well. The method requires that flow measurements be conducted before pumping commenced in order to measure ambient flow. Flow was again measured while the well was pumped after such time that the water level in each well stabilized and flow to the well approached a pseudo-steady behavior. The difference between successive flow measurements determines the quantity of water yielded to the well between the depths of the two flow readings. Results show that most water is contributed from the Brunswick Formation between marker beds A and B (fig. 11). In supply well MG-1125, about 60 percent of the water probably is contributed from fractures from 60 to 125 feet below land surface and very little is contributed from the Lockatong Formation below marker bed B. The major water-producing interval in MG-1126 is between 110 and 180 ft below land surface. Most water contributed in this zone probably enters from the fracture at 140 ft below land surface.

Hydraulic Connections to Supply Well MG-1125

Geophysical logging also was conducted during constant-discharge aquifer tests at supply well MG-1125 on February 22 and October 3, 1991, to identify hydraulic connections between the supply well and observation wells MG-618, MG-1124, MG-1126, and MG-1270. During the aquifer test, withdrawals of 200 gal / min of water from supply well MG-1125 lowered the hydraulic head in water-producing fractures that were hydraulically connected to the supply well. These hydraulically connected fractures were identified by flow measurements in observation wells by use of the brine-tracing method. An increase in the quantity of flow exiting the well or decrease of inflow to the well measured across a known water-producing or thieving zone provided an indication that the zone was connected hydraulically to water-producing zones open to supply-well MG-1125. Only three water-producing zones in the observation wells could be shown to be connected hydraulically to the supply well—zones in MG-1126 at 72 and 140 ft below land surface and in MG-1270 at 169 ft below land surface (fig. 12). Fractures in observation well MG-1124 could not be shown to be connected hydraulically to supply well MG-1125 although some connection must exist because drawdown was measured in this well during the aquifer test.

Ground-Water Level Monitoring

To map the water-table surface and investigate hydraulic interconnections among wells, ground-water levels were measured. Water levels were monitored continuously in supply well MG-1125 and observation wells MG-618, MG-1124, MG-1126, and MG-1270 during all or parts of the period from February 1991 through January 1992. During periods unaffected by aquifer tests, ground-water levels ranged from less than 1 ft below land surface in April 1991 to as much as 40 ft below land surface in early October 1992.

Water-Level Fluctuations

Water levels fluctuate in response to recharge and nearby pumping. Typical water-level changes from July 15 through August 15, 1991 during a period of large ground-water withdrawals are shown in figure 13. Water levels in supply well MG-1125 and observation wells MG-1124, MG-1126, and MG-1270 generally show gradual declines when North Wales Water Authority supply well 17 (MG-875) is pumping and gradual increases when the pumping decreases or ceases. Other supply wells in the area (fig. 4) also affect water levels in these wells as indicated by water-level fluctuations in MG-1126 on July 25 and 29 that do not appear to correlate with pumping from North Wales Water Authority supply well 17. However, the effects of pumping from individual supply wells are difficult to sort out because of the large number of wells and varying pumping regimes. The influence of recharge from precipitation on water levels is difficult to determine because pumping from supply wells in the area usually decreases after precipitation is received because water use decreases.

Water levels in observation well MG-618 show a general decline during the period July 15-August 15, 1991, that differs from the fluctuations observed in the other wells (fig. 13). MG-618 does not seem to respond to ground-water withdrawals-from the same supply wells that influence levels in wells MG-1124, MG-1125, MG-1126, and MG-1270. Instead, water levels fluctuate in response to cyclic rates of ground-water withdrawals at the American Olean Tile Company (wells MG-153, MG-620,

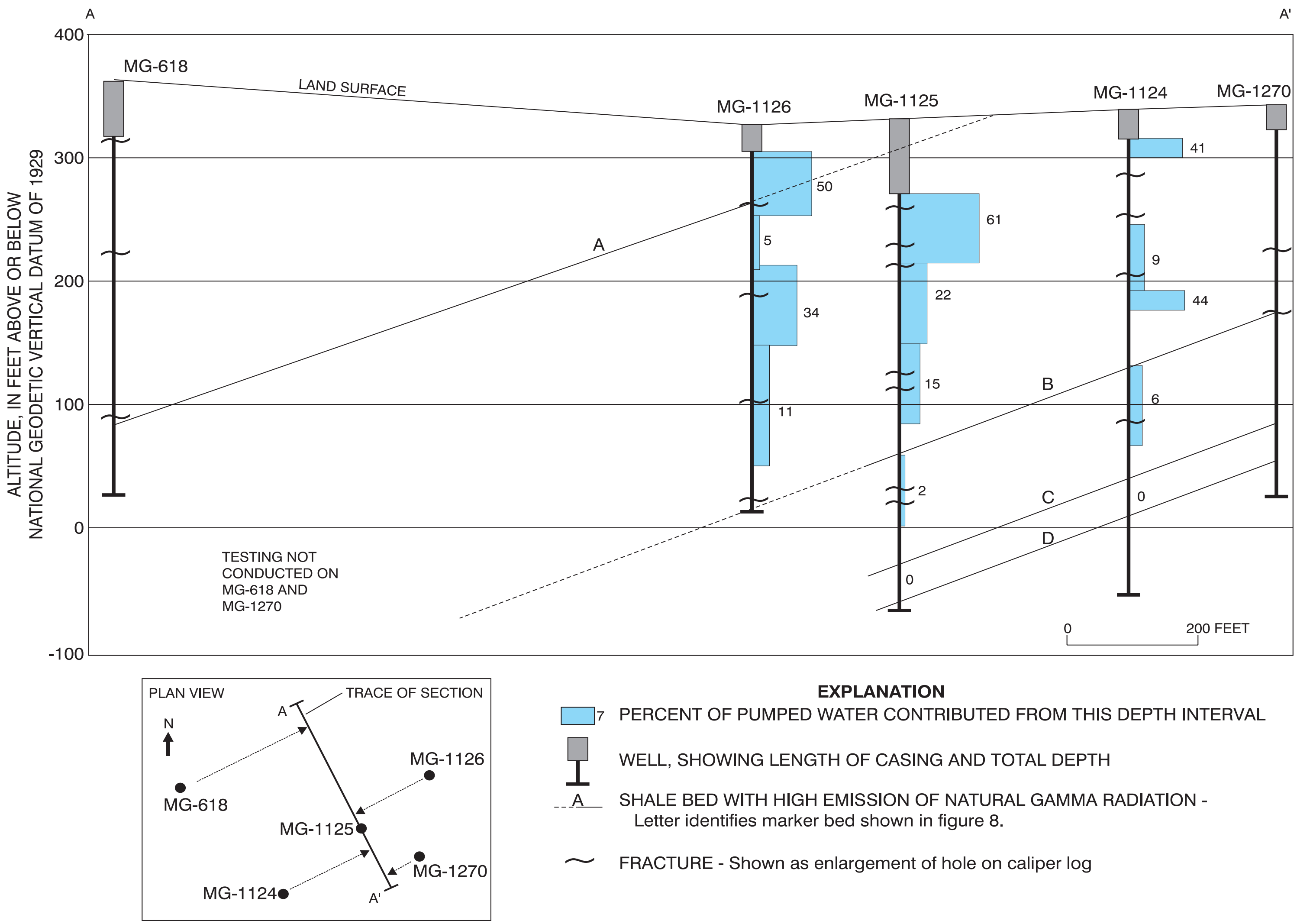


Figure 11. Northwest-southeast cross section trending N. 36° W., perpendicular to the strike of beds showing percentage of pumping contributed from different depth intervals as determined from pumping each well and simultaneously measuring borehole flow.

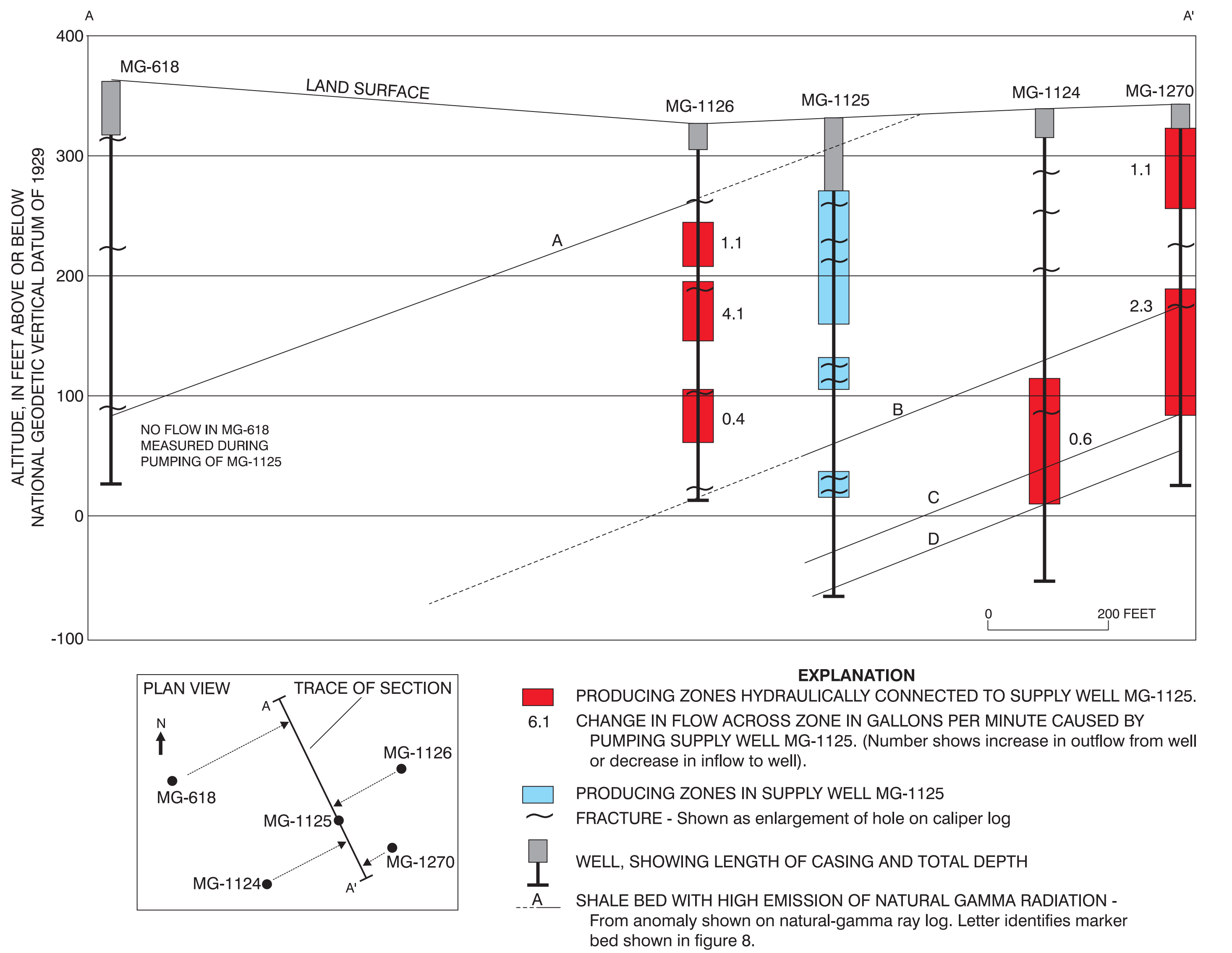


Figure 12. Northwest-southeast cross section trending N. 36° W., perpendicular to the strike of beds showing location of water-producing zones that are hydraulically connected as determined from brine-tracing while pumping supply-well MG-1125 at 200 gallons per minute.

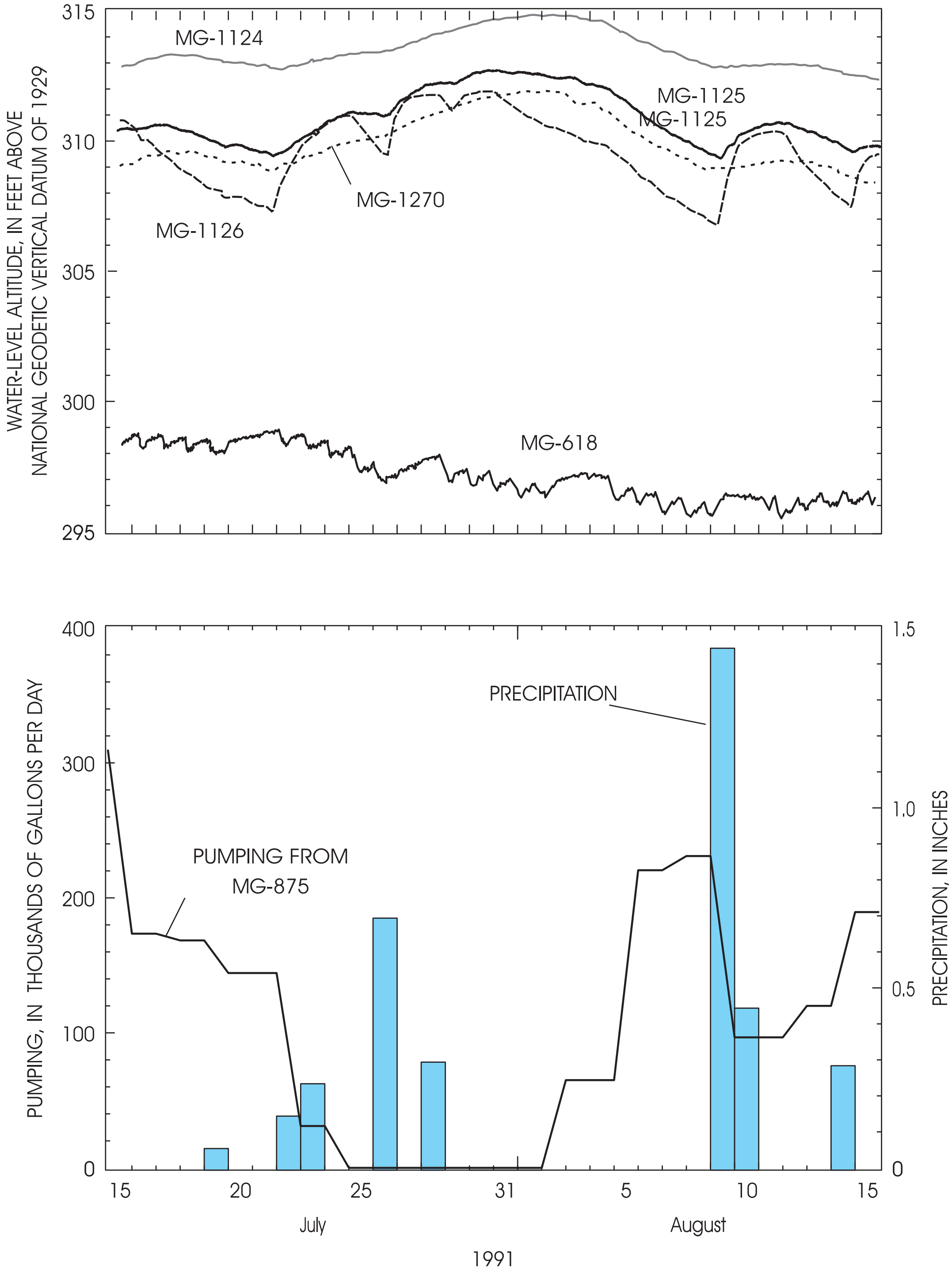


Figure 13. Water-level altitude in wells, precipitation, and daily pumping from supply well MG-875 (North Wales Water Authority Well 17) from July 15 through August 15, 1991.

MG-621, and MG-1045). Water levels in well MG-618 rise during weekends (for example, July 20-21, and July 28-29) when ground-water withdrawals at the factory decrease (fig. 13). The difference in water-level fluctuations between MG-618 and the other wells is consistent with evidence from stratigraphic correlations that show MG-618 is completed in geologic units that are stratigraphically higher than those penetrated by the other wells.

Potentiometric Surface

The potentiometric surface was contoured from water levels measured in supply well MG-1125 and observation wells MG-1124, MG-1126, and MG-1270 on August 5, 1991, when supply wells northeast of the well field were pumping large quantities of water (fig. 14). The local hydraulic gradient is generally to the northwest but may be to the northeast near wells MG-1125, MG-1126, and MG-1270. The few observation wells give a very local-scale view of the potentiometric surface.

During some periods, the water level in MG-1126 is lower than in MG-1270, and other times the reverse is true (fig. 13). These small changes in relative water levels caused by current recharge and pumping conditions could change the interpretation of the direction of the hydraulic gradient at the local scale, which would affect the determination of contributing area to the well. A more regional view is needed to show the configuration of the hydraulic gradient that is affected less by transient changes in water level caused by recharge or pumping.

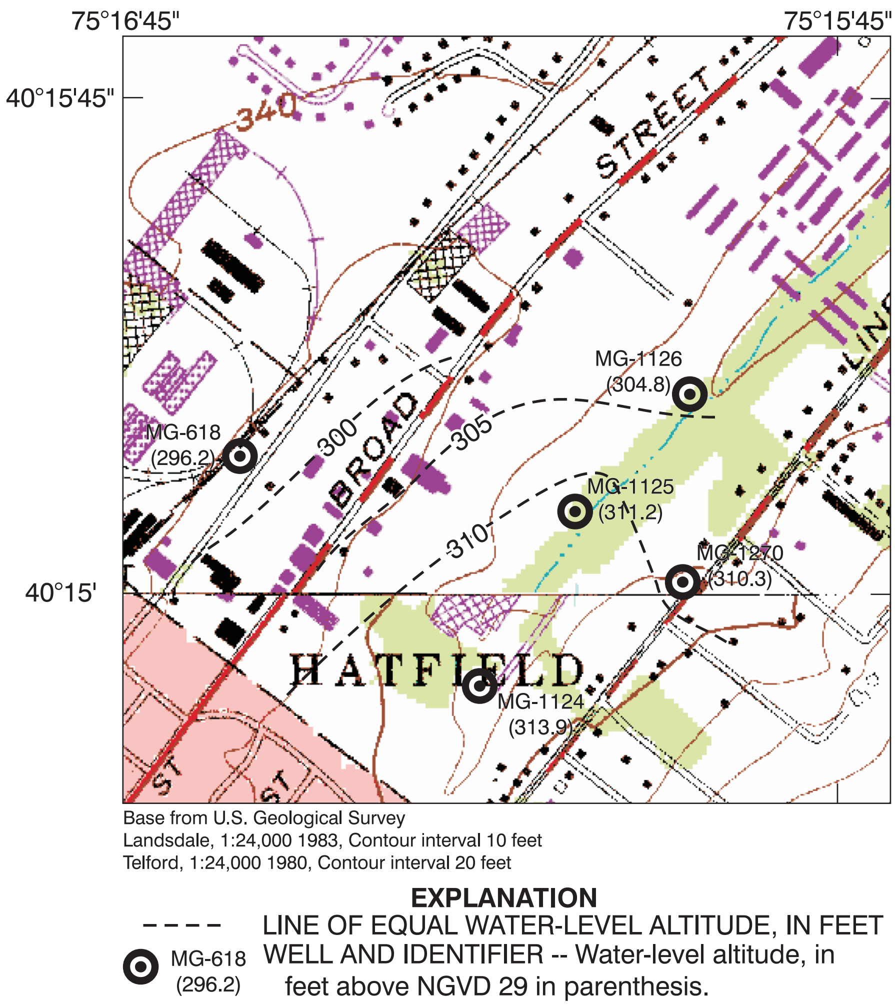


Figure 14. Altitude of the potentiometric surface in the hospital well field near Lansdale, Pa., on August 5, 1991.

Water levels were measured on a regional basis in the Lansdale area on August 22-23, 1996, and the configuration of the potentiometric surface was mapped (Senior and others, 1998). Although ground-water withdrawals in the Lansdale area differed from 1991 to 1996, the regional configuration of the water table is probably more useful for estimating the contributing area to supply well MG-1125 than the shifting local gradient in the immediate vicinity of the well. The regional map (fig. 15) shows a potentiometric surface that slopes to the northwest. The hydraulic gradient southeast of supply-well MG-1125 where the Lockatong Formation crops out is steeper (0.025) than to the northwest (0.0091) where the Brunswick Formation crops out.

AQUIFER TESTING

Aquifer tests conducted or analyzed for this study include slug tests at five wells, a step-drawdown test, and two constant-discharge tests. Results were used to estimate aquifer transmissivity and provide insight into the hydrologic framework.

SLUG TESTS

Slug tests were conducted in supply-well MG-1125 and observation wells MG-618, MG-1124, MG-1126, and MG-1270 to estimate the transmissivity of the Brunswick and Lockatong Formations. The rise and fall of the water level in the wells caused by the sudden introduction of a displacement barrel ("slug") was analyzed by use of the method of Bouwer and Rice (1976). Water-level change in response to slug testing at each well is shown in figure 16.

Analysis of the data on figure 16 requires the identification of a straight-line segment of data on a semilog plot of water-level change as a function of time. The early-time data for wells MG-618, MG-1125, and MG-1270 are fairly linear, but the plots for wells MG-1124 and MG-1126 were curved throughout. Thus, transmissivity values computed for wells MG-1124 and MG-1126 are approximate. Because this analytical method is based on an assumption of radial flow to (or away from) the well, it is not surprising that ideal results were not obtained in wells completed in a fractured-bedrock aquifer.

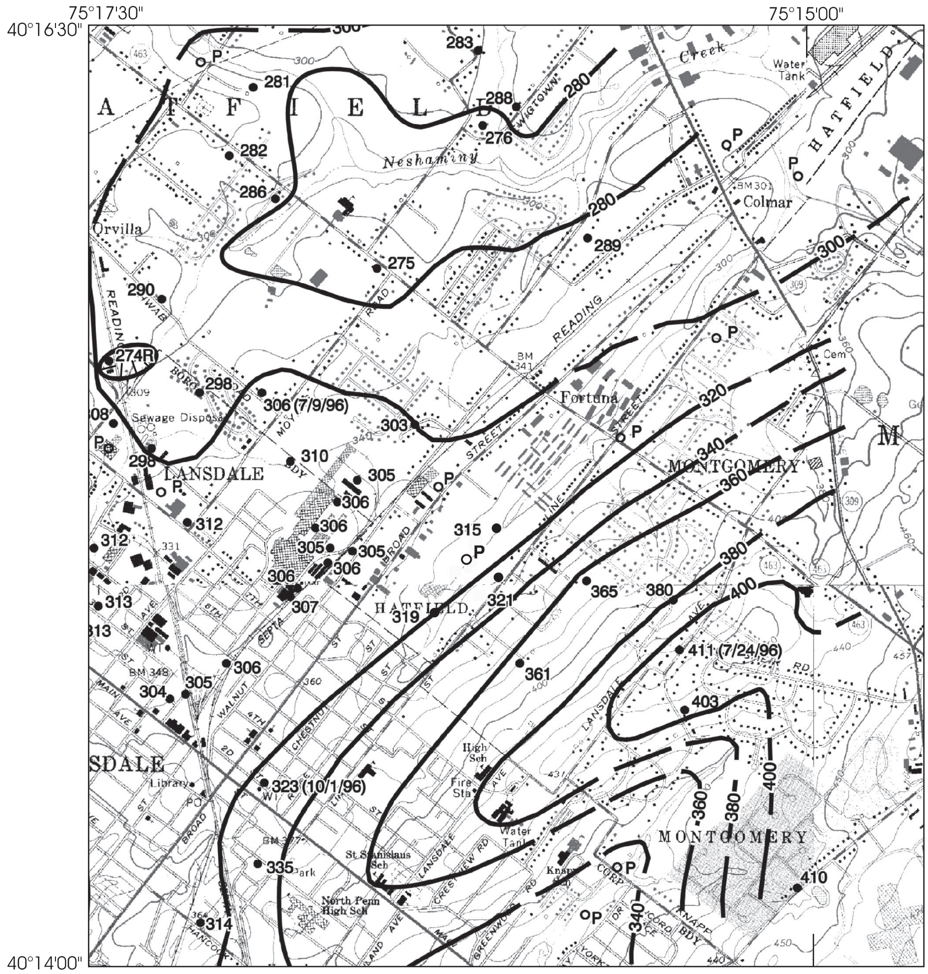
Transmissivity determined from the slug tests ranged from 19 to 1,700 ft^2/d (table 3). The relative difference in transmissivity among the wells is apparent from the water-level changes shown in figure 16. Wells in which the water level declined most quickly are completed in the most transmissive water-bearing zones. The water-level decline in supply well MG-1125 was fastest, and the decline in well MG-618 was slowest. Correspondingly, the transmissivity at well MG-1125 (1,700 ft^2/d) is greatest, and the value at well MG-618 (19 ft^2/d) is lowest of the five wells tested. The range of hydraulic conductivity at the well field is an indicator of the aquifer heterogeneity caused by an unequal distribution or density of water-bearing zones within the siltstone and shale.

STEP-DRAWDOWN TEST

A step-drawdown test was conducted at supply well MG-1125 on October 15, 1982 (Harry Borchers, North Penn Water Authority, written commun., 1991). The well was pumped at rates of 100, 203, and 305 gal/min. Calculations from the step-drawdown data show that well loss is a significant component of total drawdown in supply well MG-1125 when it is pumped at its permitted rate of 200 gal/min. When analyzed by the method of Bierschenk (1964), the step-drawdown data indicate that at least 67 percent of the drawdown in the well is caused by (nonlinear) turbulent flow in the well, aquifer, or both (fig. 17). Thus, the drawdown in supply well MG-1125 will be much greater than that observed in the aquifer near the well. The large component of nonlinear well loss supports the conceptual model of rapid movement of water near the well through fractures.

CONSTANT-DISCHARGE TESTS

Two constant-discharge aquifer tests were conducted at supply well MG-1125. The well was pumped for 72 hours in February 1991 and 48 hours in October 1991; during both tests, water was pumped at 203 gal/min and discharged to the public-water-supply system. During the 72-hour test in February, water levels were monitored in wells MG-1124, MG-1126, and MG-1125. Two additional observation wells, MG-1270 and MG-618 (up dip and down dip, respectively, of supply well MG-1125), were added for the 48-hour test in October to investigate anisotropy caused by the dipping geologic units. Ground-water levels were monitored prior to both tests and were approximately constant. Although the aquifer tests were conducted under contrasting hydrologic conditions (wet and dry seasons), the shape of draw-



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 10 feet

0 — 1 MILE
0 — 1 KILOMETER

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. Shape and altitude inferred from water levels measured in wells, topography, and elevations of streams. Altitudes of water levels in wells near streams may differ from altitude of water levels of streams because ground-water system is not always well connected to surface-water system. Losing reaches have been identified in some streams. Contour interval 20 feet. Vertical datum is National Geodetic Vertical Datum of 1929.

WATER-LEVEL MEASUREMENT SITES -- Symbol gives location of site. Number is altitude of water level, in feet above National Geodetic Vertical Datum of 1929. Water levels may reflect composite of potentiometric heads in wells with multiple yielding zones. Wells ranged from about 70 to 600 feet in depth.

●315 Altitude of static water level measured in a drilled well competed in bedrock. Date of observation in parenthesis ( ) if measured for a date other than August 22-23, 1996.

● 274R Altitude of water level measured in a recently pumped well or in a well known to be affected by nearby pumping.

○P Well known to be pumping for public supply or industrial uses during period of water-level measurements.

Figure 15. Altitude of the potentiometric surface near Lansdale, Pa., on August 22-23, 1996 (from Senior and others, 1998).

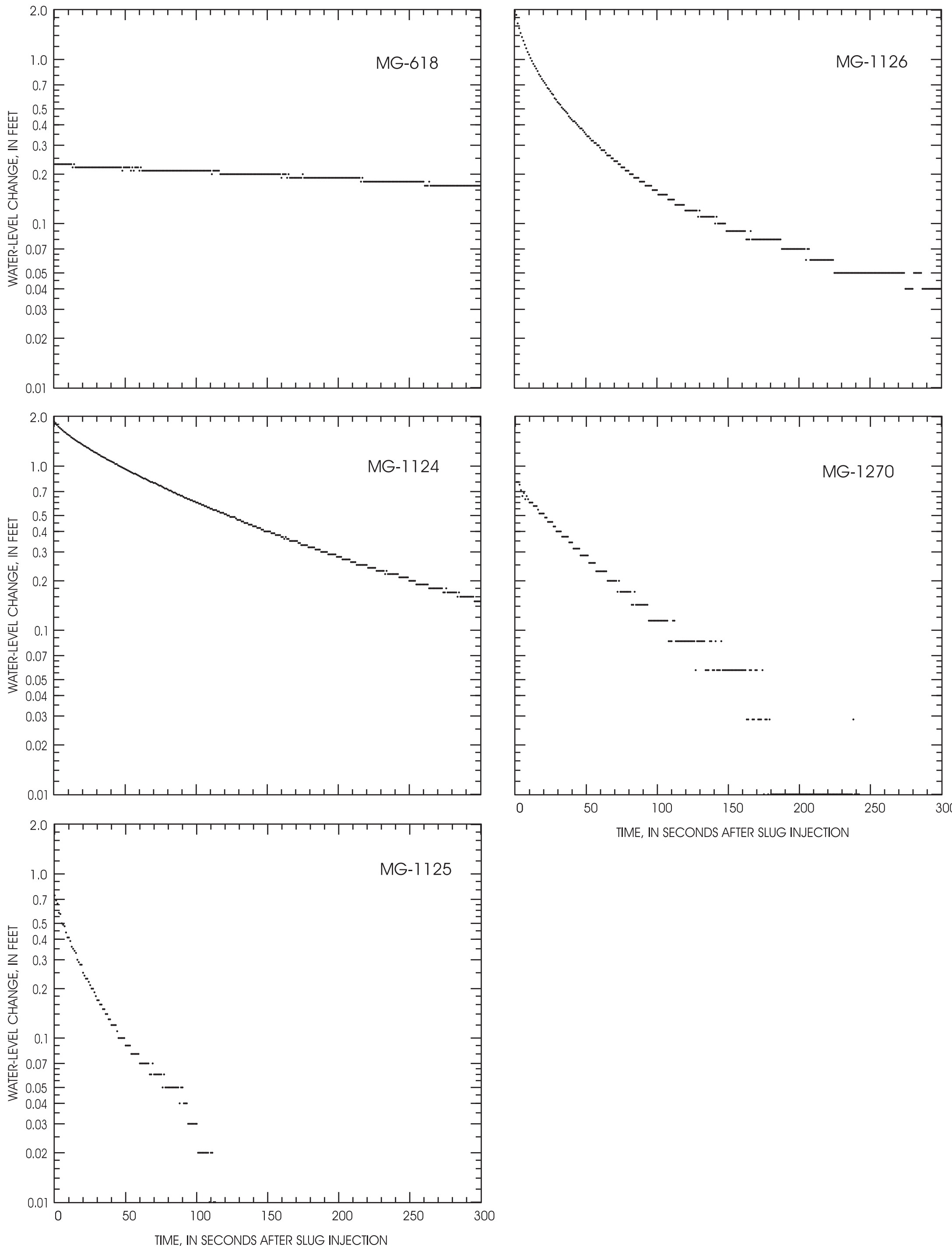


Figure 16. Water-level change in response to slug tests in supply well MG-1125 and observation wells MG-618, MG-1124, MG-1126, and MG-1270.

Table 3. *Summary of parameters used to determine transmissivity from the water-level response to slug tests*

Note: Parameter "H" (not shown) equals "D" for all wells.

Parameter (in feet except where noted)	Well MG-618	Well MG-1124	Well MG-1125	Well MG-1126	Well MG-1270
Well depth	343	385	400	310	320
Well radius "R_w"	.25	.25	.42	.25	.25
Casing length	47	25	60	19	19
Water level (feet below land surface)	65	4	3	3	31.5
Aquifer thickness "D"	278	381	397	307	289
Open interval "L"	278	360	340	291	289
Initial water level "y_o"	.21	.72	.41	.55	.20
Water level at later time "y_t"	.14	.32	.14	.22	.09
Time "t" (days)	.0039	.0012	.00032	.00052	.00046
Transmissivity (feet squared per day)	19	140	1,700	330	320

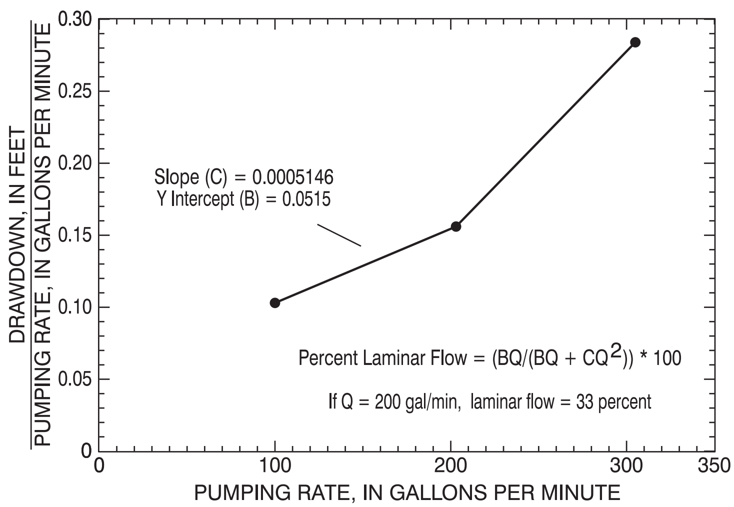


Figure 17. Step-drawdown test for pumping rates of 100, 203, and 305 gallons per minute from supply well MG-1125. (Data from North Penn Water Authority.)

down curves for both tests are similar (fig. 18). The aquifer tests do not show any recharge-boundary effect from the unnamed tributary near well MG-1125.

Because a large part of drawdown in MG-1125 is caused by well inefficiency, the Cooper and Jacob (1946) method was used to estimate transmissivity from water-level declines at the pumped well (fig. 19). A transmissivity of 1,300 ft2/d was estimated for both tests. The slope of the time-drawdown curves was similar for both tests, but total drawdown was about 4 ft greater during the 72-hour test conducted in February. The cause of the abrupt shift in water level between 200 and 1,000 minutes during the October test is unknown.

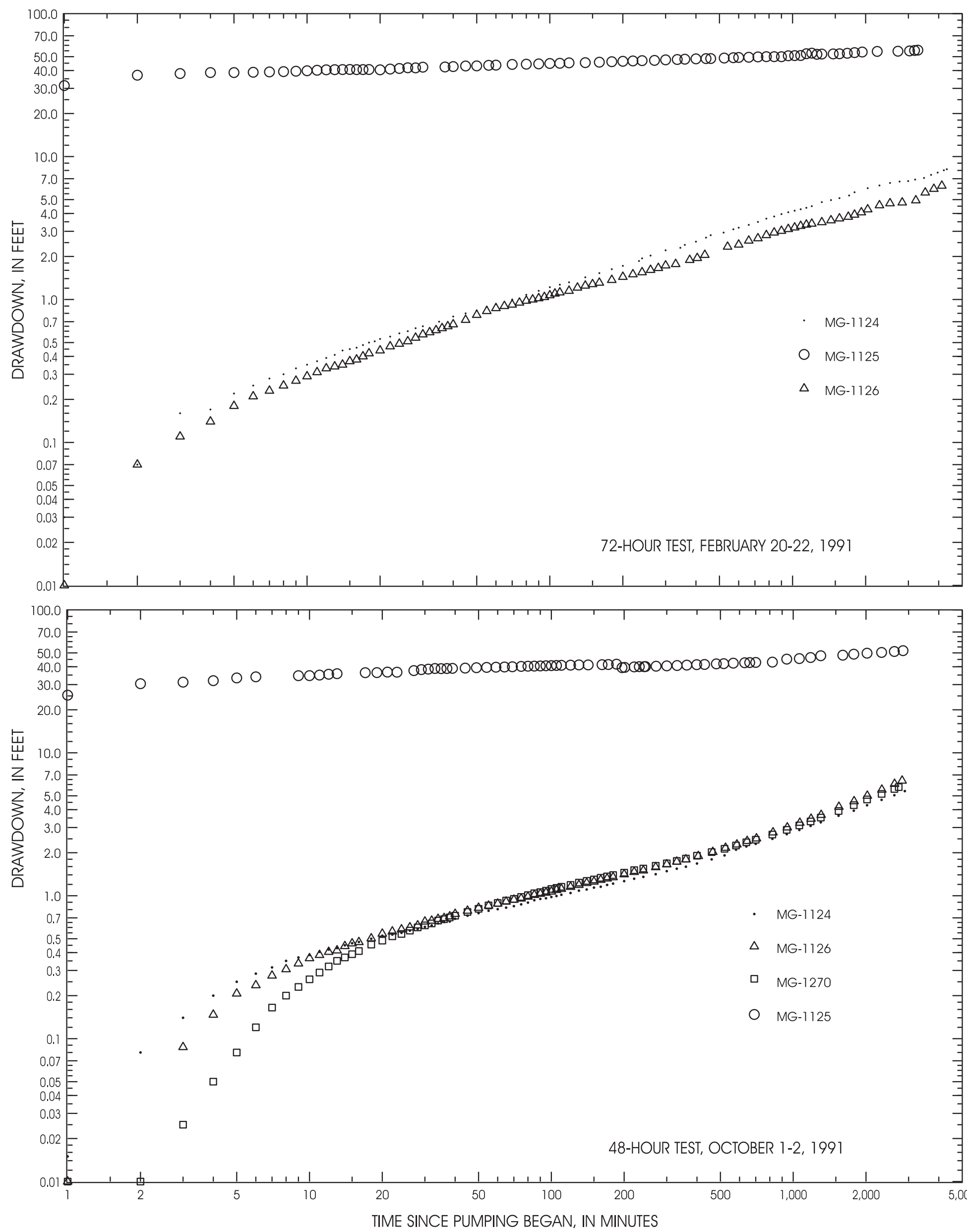


Figure 18. Drawdown in supply well MG-1125 (pumped well) and observation wells during a 72-hour aquifer test on February 20-22, 1991, and a 48-hour aquifer test on October 1-2, 1991.

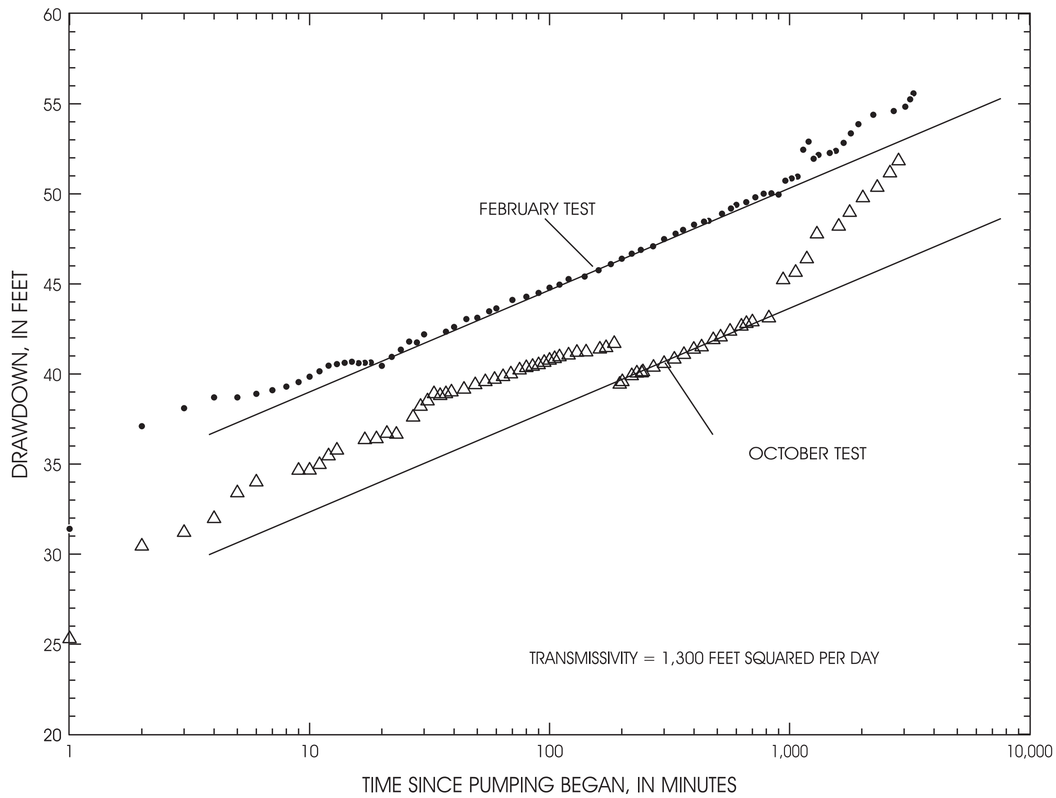


Figure 19. Drawdown in pumped well MG-1125 analyzed by the method of Cooper and Jacob (1946) for aquifer tests conducted during February and October 1991.

Water-level declines at observation wells MG-1124, MG-1126, and MG-1270 were analyzed by use of the method of Theis (1935). The data generally match the Theis curve for approximately the first 100 minutes of pumping (fig. 20). Thereafter, the slope of the log-log drawdown curves are steeper than the Theis curve. The steeper slope on the drawdown curves is likely caused by a nearby flow boundary, possibly the contact with the less-permeable Lockatong Formation or termination of a water-producing fracture. Matching the Theis curve for the early-time data yields values of transmissivity of 10,700 ft^2/d for MG-1124, 9,500 ft^2/d for MG-1126, and 6,400 ft^2/d for MG-1270. During the 48-hour test, no drawdown was measurable in well MG-618, indicating that the sequence of tilted confining beds between MG-1125 and MG-618 impedes flow between these two wells.

The values of transmissivity determined from drawdown in the observation wells (6,400 to 10,700 ft^2/d) are much larger than both the transmissivity determined from drawdown in the pumped well MG-1125 (1,300 ft^2/d) and values from slug tests (19 to 1,700 ft^2/d). The large transmissivity values from the observation-well data may be a result of the wells not being connected hydraulically to all the water-producing fractures that are being stressed. An observation well that has a poor hydraulic connection to the pumping well will exhibit less drawdown than a comparable fully connected observation well at the same location. Thus, analysis of the poorly connected well using the Theis (1935) method will cause transmissivity to be overestimated. The transmissivity value of 1,300 ft^2/d from the pumped well (MG-1125) is probably the most reliable estimate for the Brunswick Formation in this area. This value agrees closely with slug-test data from that well (1,700 ft^2/d) and with the geometric-mean transmissivity of 1,075 ft^2/d used in a regional ground-water-flow model of the Lansdale area (Senior and Goode, 1999, p. 78).

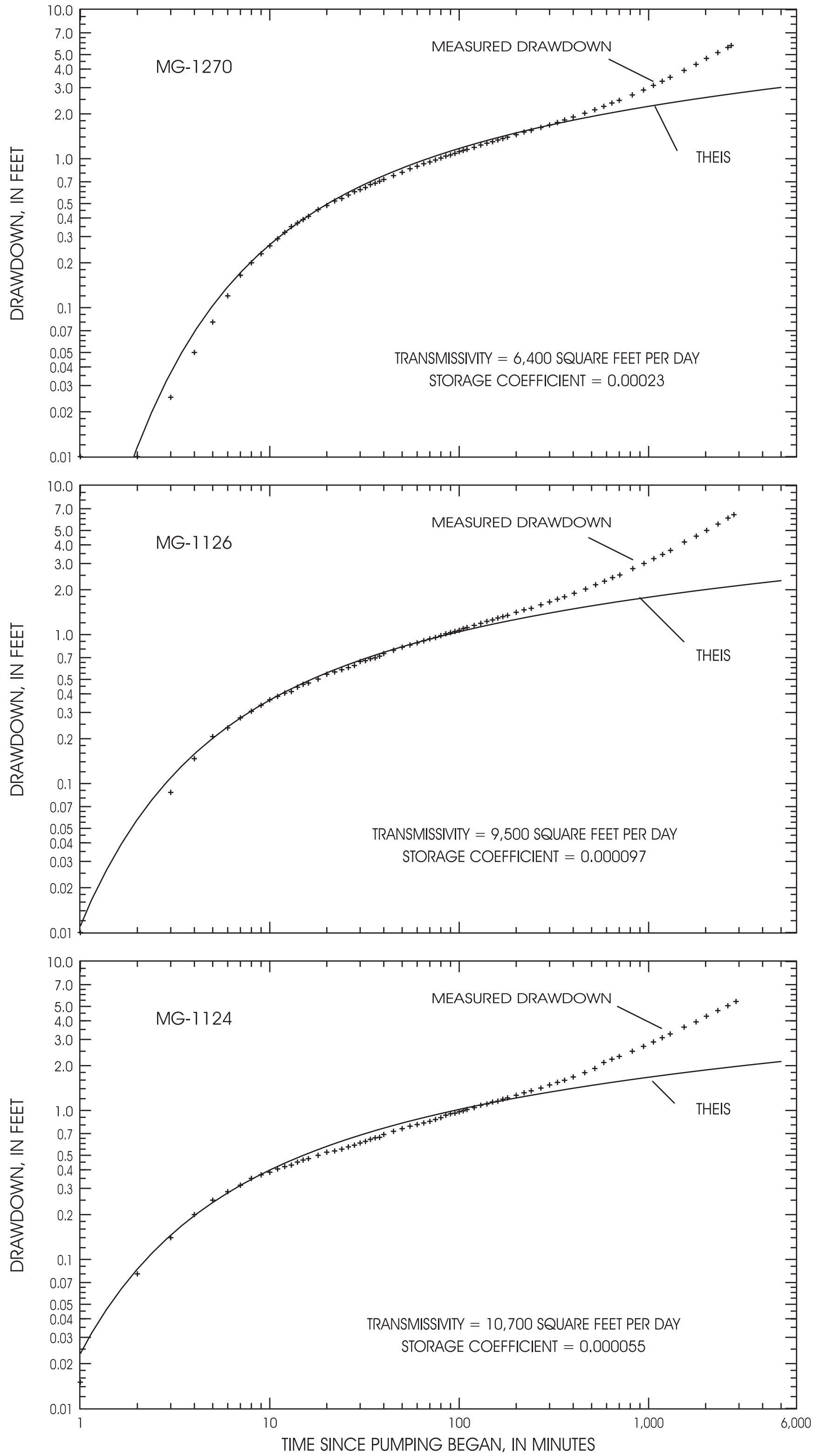


Figure 20. Match of Theis (1935) solution to drawdown in MG-1270, MG-1126, and MG-1124 caused by pumping from supply well MG-1125 during the 48-hour aquifer test, October, 1-2, 1991, Lansdale, Pa.

WATER CHEMISTRY

Water from supply well MG-1125 was sampled for tritium to estimate the time since the ground water was isolated from the atmosphere. Samples without detectable tritium indicate that the water may not be influenced by recent activities on the land surface. The water sample from supply well MG-1125 was collected on May 14, 1991, at a depth of 280 ft below land surface. At this depth, brine tracing measured upward ambient flow in the well. The sample should represent ground water from water-producing zones below 280 ft—most likely from the water-producing fracture identified at 311 ft below land surface. The sample contained 15 tritium units, which indicated that the water is less than 35 years old; thus, the prospect of very old water being contributed that is not affected by human activities is remote.

Measurements of specific conductance conducted during the aquifer test of supply well MG-1125 suggest the mixing of waters of different dissolved-solids concentration. The specific conductance of water discharged from supply well MG-1125 increased from 360 to 560 µS / cm during the 72-hour aquifer test in February 1991 (fig. 21). A very similar increase in specific conductance was measured during the 48-hour test in October 1991. The change in specific conductance could indicate mixing of waters from different water-bearing zones at different depths.

Measurements of specific conductance at depths between 20 and 150 ft below land surface in observation well MG-1126 during the February 1991 aquifer test (fig. 22) indicate that the specific conductance of the water is greatest in shallow water-bearing fractures (about 510 µS / cm at 65 ft). Water in the deeper water-bearing fractures generally is more dilute (420 µS / cm at 150 ft). The general observation that water contains more dissolved solids in shallower parts of the well is substantiated by water samples that were analyzed for hardness during the drilling of supply-well MG-1125 (fig. 7). Those samples showed that hardness was greatest at shallowest depths.

Increases in specific conductance observed in the discharge from supply well MG-1125 during both aquifer tests could be caused by capture of an increasing percentage of shallow ground water having a higher concentration of dissolved solids than water from deeper water-bearing fractures. Mixing of shallow and deeper water of different dissolved-solids concentration was observed in the borehole of observation well MG-1126. When water is discharged from supply well MG-1125 at 200 gal / min, some shallow ground water in a water-bearing fracture at about 60 ft below land surface enters into observation well MG-1126, moves downward within the borehole, and exits the borehole into a water-bearing fracture hydraulically connected to supply well MG-1125 at about

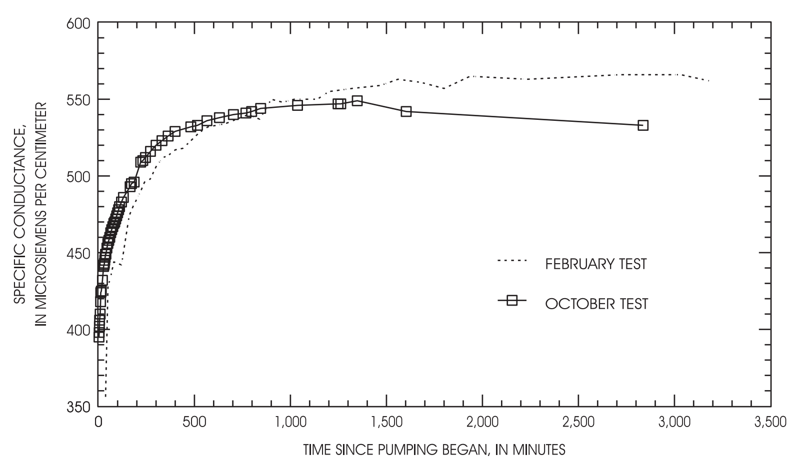


Figure 21. Change in specific conductance of water discharged from supply well MG-1125 during aquifer tests in February and October 1991.

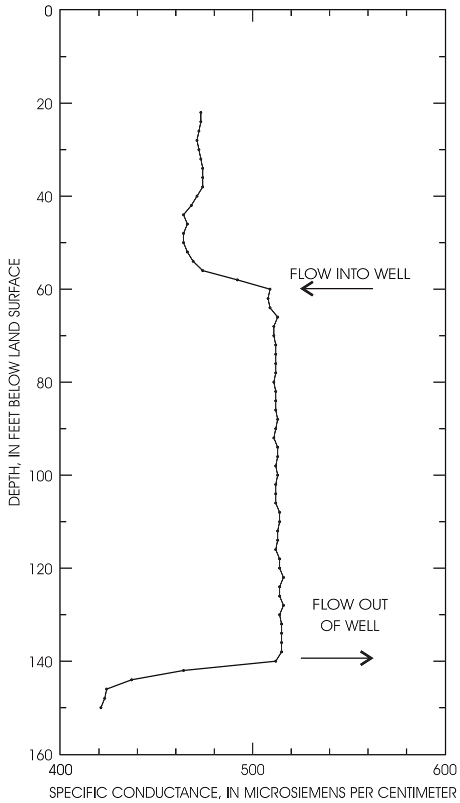


Figure 22. Specific conductance of water at various depths in observation well MG-1126 while pumping supply well MG-1125 at 200 gallons per minute during the aquifer test in February 1991.

145 ft below land surface. (This differs from the flow direction measured in the well when MG-1125 is not pumping as shown in figure 10.) Vertical movement of small amounts of ground water through wells with long open-hole intervals is one mechanism that could allow shallow and deeper waters to mix. However, the large change in specific conductance of water discharged from supply well MG-1125 suggests that as drawdown from the well increases, shallow ground water provides much of the water to the well, directly from shallow water-producing fractures or through downward leakage to deeper water-producing fractures.

REFINED CONCEPTUAL HYDROGEOLOGIC MODEL

Hydrogeologic testing at the well field provided information that helped refine the conceptual hydrogeologic model of ground-water flow to the supply well. The following are the major points of refinement:

1. Geophysical logging showed that ground water in the Lansdale area flows through thin, fractured, water-bearing beds that dip about 11° to the northwest. Supply well MG-1125 penetrates the Brunswick and Lockatong Formations and derives water primarily from about five thin water-producing fractures in the Brunswick Formation. Flow measurements within the well indicate that about 60 percent of the discharged water probably enters from fractures between 60 and 125 ft below land surface. Because some water is produced from these relatively shallow depths, the area contributing recharge is likely to be situated immediately surrounding the supply well. However, water-producing fractures in the competent bedrock were identified as deep as 311 ft below land surface in supply well MG-1125, and the driller reported water-bearing fractures as deep as 370 ft below land surface. Measuring vertical flow in observation wells while pumping supply well MG-1125 identified only three fractures that were hydraulically connected to the pumped well—at depths of 75 and 140 ft below land surface in MG-1126 and 169 ft below land surface in MG-1270. Other hydraulic connections that could not be identified with flow measurements must be present because drawdown was measured in MG-1124 when supply well MG-1125 was pumped.
2. Water-level monitoring showed that nearby supply and industrial wells cause water-level fluctuations that change the potentiometric surface in the vicinity of MG-1125. Ground-water withdrawals from these wells probably should be included in the analysis of contributing area because their use alters the hydraulic gradient.
3. Aquifer tests helped quantify the transmissivity of the water-bearing units. Slug tests indicated that transmissivity of the Brunswick Formation in the well field ranges from 19 to 1,700 ft^2/d. The nonuniform distribution of transmissivity throughout the well

field indicates that the geometry and interconnection of water-producing fractures probably vary considerably, water-producing fractures are not distributed evenly, and ground-water velocities must vary greatly throughout the well field. Constant-discharge aquifer tests indicated that the transmissivity of the Brunswick Formation at supply well MG-1125 is most likely about 1,300 ft^2/d. A boundary condition indicated on the time-drawdown curves could be caused by the less permeable Lockatong Formation. The spatial pattern of drawdown showed little evidence of anisotropy for wells completed in the same stratigraphic beds. The lack of drawdown measured at the observation well completed in beds that were stratigraphically higher than the pumped well indicates that anisotropy is caused by dipping beds of low permeability.

4. Tritium analysis of ground water from a depth of 280 ft below land surface in supply well MG-1125 indicated the ground water had been recharged less than 35 years before present. This finding supported the evidence from flowmetering that the major source of water contributed to the well was not deep, old ground water. Measurements of specific conductance of water discharged during the aquifer test at MG-1125 also indicated that shallow sources of water probably provided a significant quantity of water to the well.

CONTRIBUTING-AREA DELINEATIONS

This section describes results from approaches to delineate the contributing area to supply well MG-1125. Preliminary delineations were made with water budget and time-of-travel equations; three approaches to improve the delineations were illustrated and compared.

PRELIMINARY DELINEATIONS

A water budget and time-of-travel equation were used to provide preliminary delineations of the contributing area and 100-day time-of-travel area to supply well MG-1125. These are simple delineations that require little data and are based on assumptions that do not incorporate the hydrogeologic complexities identified in the conceptual model. Nevertheless, the delineations provide initial estimates of the aquifer surface area that might need protection. As with the preliminary delineations of contributing area at the Trouts Lane well field in Stewartstown (Barton and others, 1999), these circular areas are not consistent with our preliminary conceptual model. They do, however, provide insight into the size of the contributing area, even though its shape is not delineated accurately.

CONTRIBUTING AREA USING WATER BUDGET

A steady-state water budget provides the first approximation of the limits of aquifer surface area needed to provide recharge to supply well MG-1125. This can be computed from:

$$A = \frac{Q}{w} \qquad (1)$$

where A is the aquifer area needed to provide recharge, in square feet;
Q is pumping rate, in cubic feet per year; and
w is ground-water recharge rate, in feet per year.

According to this computation, if ground-water recharge is about 8 in/yr (0.67 ft/yr), a surface area of about 0.76 mi^2 is needed to capture enough recharge to provide 200 gal/min (14 million ft^3/yr) for supply well MG-1125. Recharge of 8 in/yr is a median within the range of recharge rates reported in the initial conceptual model. Recently, a ground-water recharge rate of 8.3 in/yr was estimated indirectly from regional ground-water-flow modeling in the Lansdale area by Senior and Goode (1999). The shape of the area that provides recharge to the well is not given from equation 1 but is shown in figure 23 as a circle with a radius of 2,590 ft surrounding well MG-1125. The circular area is unlikely to be the actual contributing area because it encloses nearby supply wells MG-53 and MG-620, which might also derive water from this area.

Note that the water-budget computation provides an estimate of the aquifer surface area providing recharge that moves to and reaches the well. For this preliminary estimate of contributing area, the area providing recharge and the contributing area are assumed to be coincident, although this is not always the case (Reilly and Pollock, 1993, fig. 1). Because driller’s logs, geophysical logs, and flowmeter surveys indicate that supply well MG-1125 produces much of its water from fractures between 60 and 125 ft below land surface, it is probably reasonable to assume that at least part of the area providing recharge surrounds the wellhead.

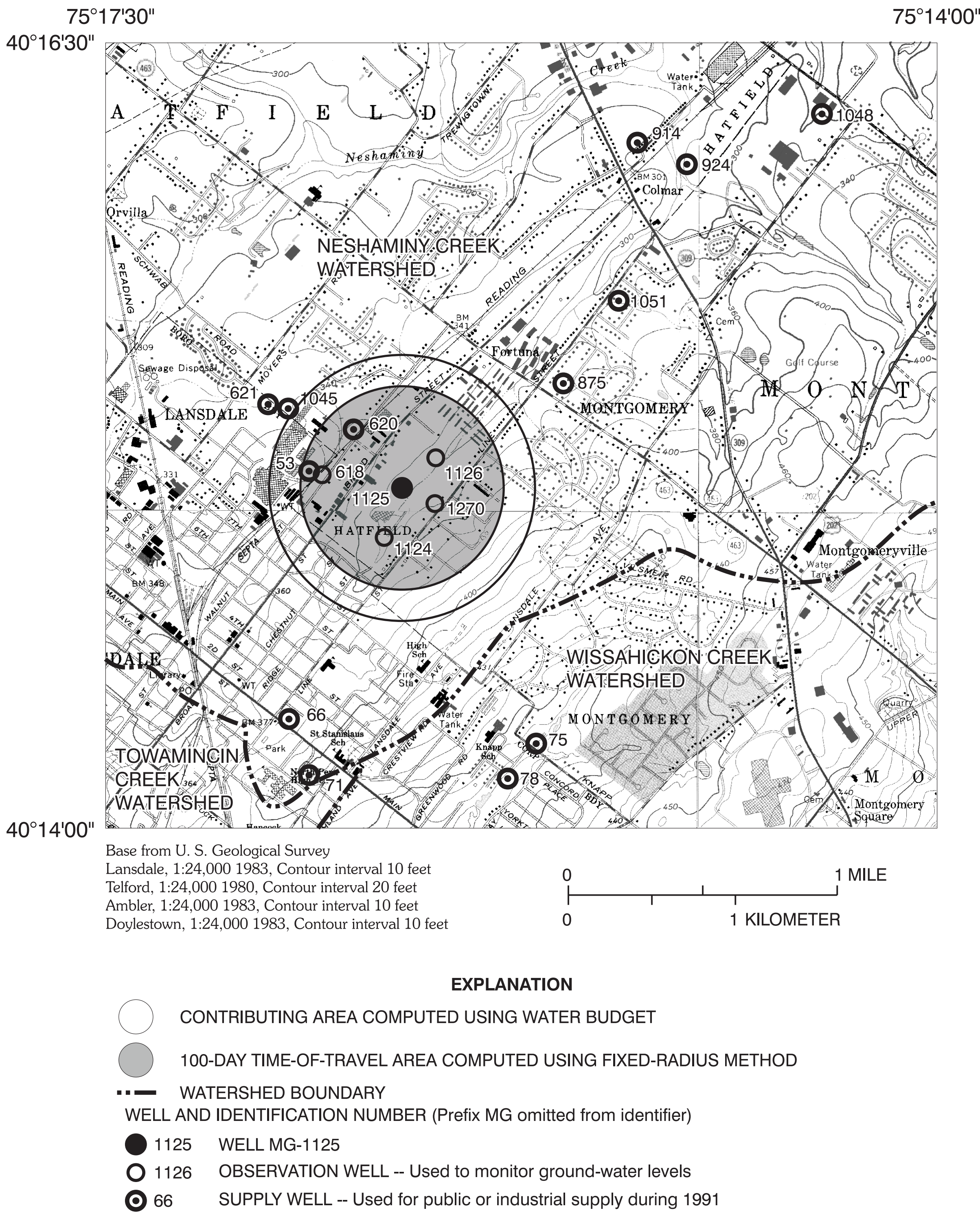


Figure 23. Delineation of contributing area and 100-day time-of-travel area for pumping 200 gallons per minute from supply well MG-1125 near Lansdale, Pa.

Time-of-Travel Area Using Fixed-Radius Method

An approximation of the radius of a 100-day time-of-travel area for a pumping rate of 200 gal / min was delineated by use of the fixed-radius (volumetric-flow) method (Risser and Madden, 1994, p. 26; U.S. Environmental Protection Agency, 1987, p. 4-6). The selection of 100 days for the traveltime criteria was arbitrary, but USEPA (1987, p. 2-18) indicates that most common bacteria will have difficulty surviving more than 100 days in ground water. The method gives the radius of an area that is assumed to be circular with its focus at the well:

$$R = \left[\frac{Qt}{\pi b\theta}\right]^{\frac{1}{2}} , \qquad (2)$$

where R is radius of time-of-travel area, in feet;
Q is pumping rate, in cubic feet per day;
t is traveltime of interest, in days;
b is aquifer thickness, in feet; and
θ is porosity of the aquifer.

Values of porosity (θ) and aquifer thickness (b) were estimated as 0.001 and 300 ft, respectively, from properties of the Brunswick and Lockatong Formations as described for the initial and refined conceptual models. The radius of the 100-day time-of-travel area computed by this method is about 2,000 ft, which defines a circle with an area of about 0.46 mi^2 (fig. 23). The 100-day time-of-travel area is about 60 percent of the contributing-area size as estimated from the water budget.

Refinements to Preliminary Delineations

Three approaches were used to refine the delineation of contributing area: (1) uniform-flow equation, (2) hydrogeologic mapping, and (3) numerical modeling. Results from these approaches are compared in this section.

Uniform-Flow Equation

The uniform-flow equation (Todd, 1980, p. 121) was used to estimate the contributing area for supply well MG-1125. The contributing area was delineated by computing the stagnation point and position of the outer bounding flow path as described in Risser and Madden (1994, p. 32) according to the following equations:

$$P = \frac{-Q}{2\pi Kbi} , \qquad (3)$$

$$L = 2\pi P \text{ , and} \qquad (4)$$

$$x = \frac{-y}{\tan\left(\frac{-y}{P}\right)} , \qquad (5)$$

where P is distance from the well to the stagnation point, in feet;
L is the width between the asymptotic limits separating flow to the well from flow that bypasses the well, in feet;
Q is pumping rate, in cubic feet per day;
K is hydraulic conductivity, in feet per day;
b is aquifer thickness, in feet;
i is uniform slope of the prepumping potentiometric surface, in feet per foot;
x is coordinate distance of a point on the limiting flow line parallel to the uniform flow; and
y is coordinate distance of a point on the limiting flow line perpendicular to the uniform flow.

All angles are in radians.

The contributing area is shown in figure 24 for a withdrawal rate of 200 gal / min, aquifer transmissivity (Kb) of 1,300 ft^2 / day, and ground-water gradient of 0.017. The transmissivity was estimated from drawdown in supply well MG-1125 during constant-discharge aquifer tests, and the gradient was determined as the average gradient of the potentiometric surface (fig. 15). The size of the contributing area shown in figure 24 is 0.53 mi^2, which is a surface area only large enough to capture about 70 percent of the recharge needed to supply 200 gal / min to supply well MG-1125 if recharge is 8 in / yr. Results of some computations from the uniform-flow equation are shown on page 36.

The uniform-flow method assumes a uniformly sloping water table, which was not observed at the site. The slope of the potentiometric surface was greater (0.025) in the upgradient area underlain by Lockatong Formation than in the area near supply well MG-1125 (0.0091) underlain by the more transmissive Brunswick Formation. Normally, one would terminate the upgradient extent of the delineation at the watershed divide, but to capture 200 gal / min, the contributing area

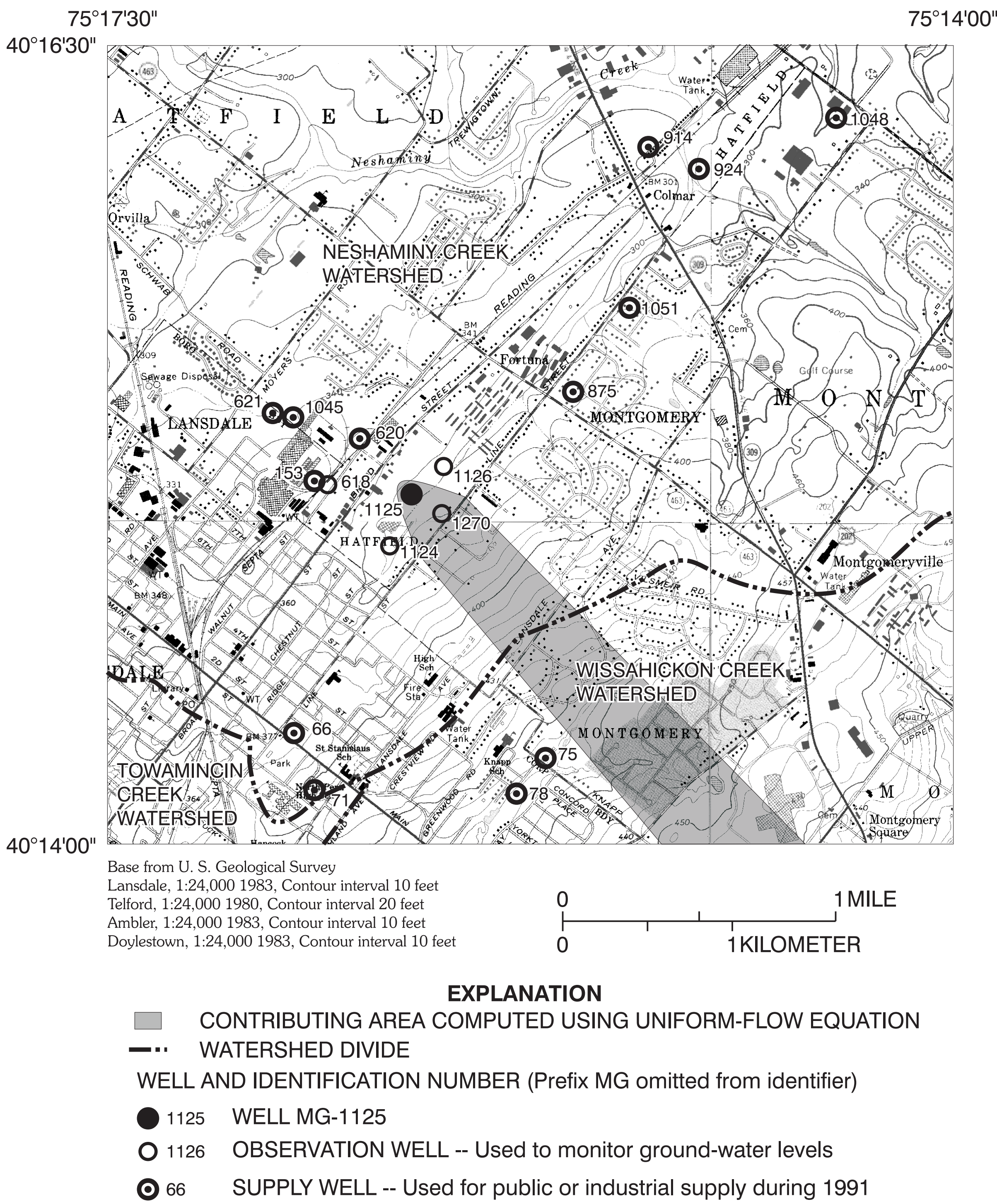


Figure 24. Contributing area for pumping 200 gallons per minute from supply well MG-1125 near Lansdale, Pa., estimated by use of the uniform-flow equation.

Distance upgradient (+) or downgradient (-) from supply well MG-1125, in feet (x coordinate in equation 5)	Width of contributing area, in feet (equals 2y in equation 5)
2,413	1,568
959	1,394
443	1,220
170	1,045
0 (at well)	871
-190	523
-277	0 (stagnation point)

must extend across the watershed divide and extend beyond the area that could be shown in figure 24. Although the pumping could cause the ground-water divide to shift, the contributing area for supply well MG-1125 extending such a great distance into the Wissahickon Creek Watershed is unlikely.

HYDROGEOLOGIC MAPPING

Hydrogeologic mapping is a method that uses geologic boundaries and hydrologic features such as streams to delineate the contributing area (U.S. Environmental Protection Agency, 1987, p. 4-19). The water-table configuration also can be used in this method to help define ground-water-flow paths and the contributing area.

One approach to hydrogeologic mapping as applied to supply well MG-1125 is shown schematically in figure 25. Investigations in the well field showed that water is contributed to the well in thin fractures within beds that dip about 11° to the northwest. If the open interval of the well from the base of the well casing at 60 ft below land surface to the deepest major water-producing fracture at 311 ft below land surface is projected updip to its intersection with land surface, that interval intersects from about 300 to 1,300 ft updip. The projected outcrop of these rocks can be extended along the northeast-southwest strike of the Lockatong Formation as shown in figure 26. To estimate the area capturing surface recharge, the outcrop is extended to the boundary of the Neshaminy Creek Watershed to the southwest and to the northeast until the area of outcrop captures enough recharge (assuming recharge is 8 in / yr) to equal the pumping rate of 200 gal / min from supply well MG-1125.

The area capturing recharge on the outcrop area as shown in figure 26 is surely in error because it overlays three large public-supply wells MG-924, MG-815, and MG-1051. This approach also assumes that ground-water movement to the well is constrained entirely to within the dipping layers of rock intersected by supply well MG-1125 and that movement of water across the dipping beds does not occur. An alternative hydrogeologic-

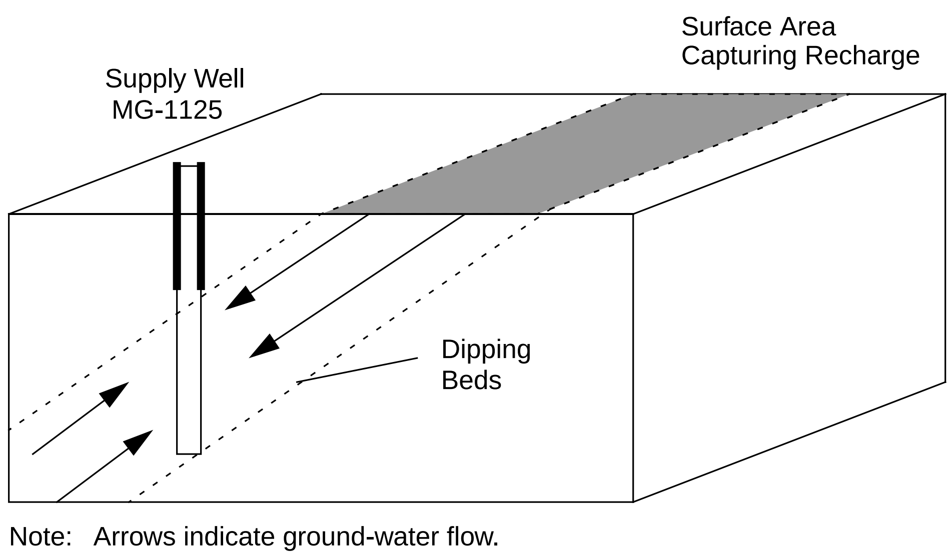
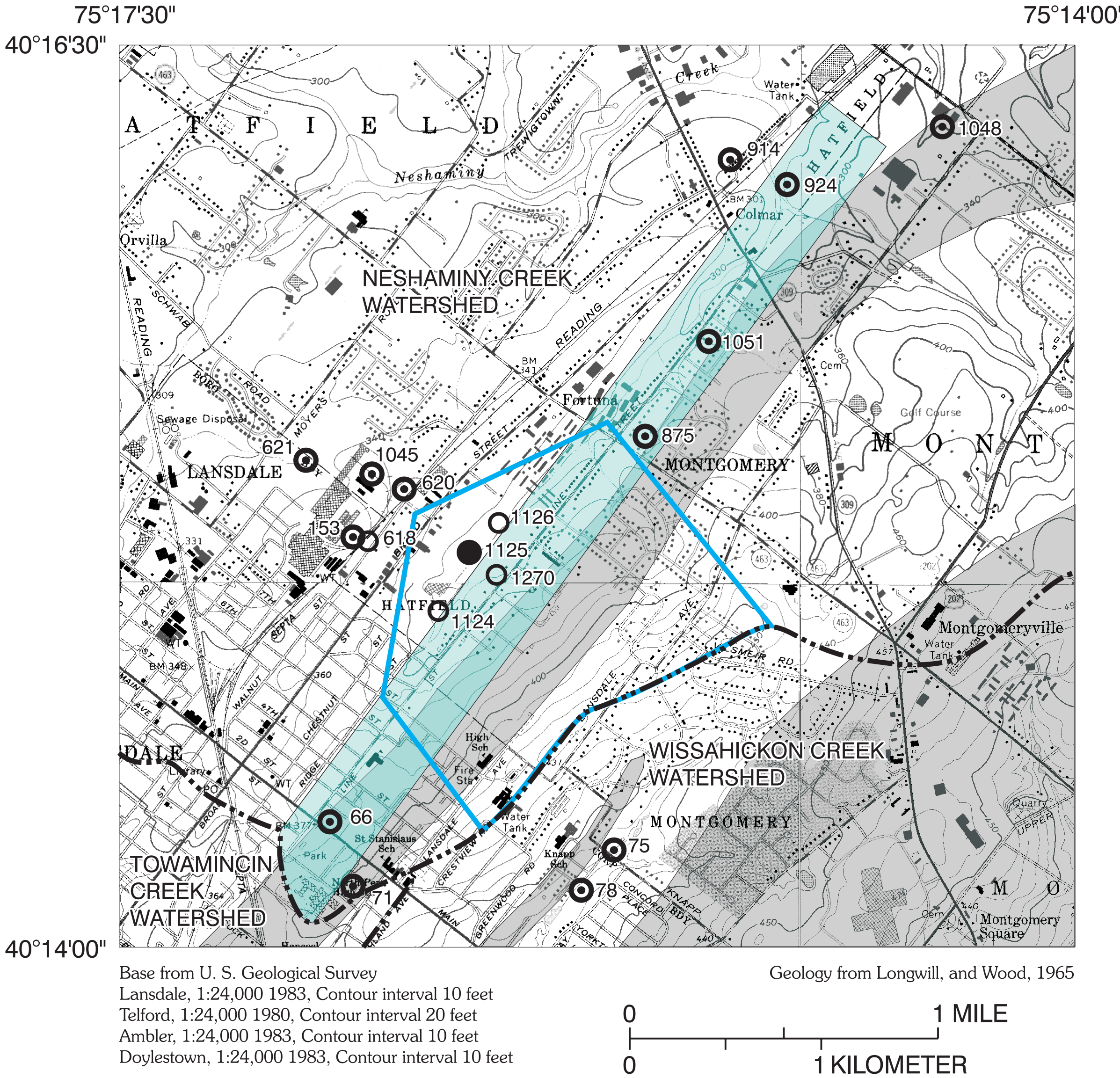


Figure 25. Potential surface area contributing recharge as determined from geologic structure.



EXPLANATION

AREAS OF OUTCROP

- Brunswick Formation
- Lockatong Formation
- AREA CAPTURING RECHARGE CONTRIBUTING TO WELL MG-1125 ESTIMATED FROM ROCK OUTCROP
- CONTRIBUTING AREA ESTIMATED FROM ROCK OUTCROP, POTENTIOMETRIC SURFACE, AND WATERSHED BOUNDARY
- WATERSHED BOUNDARY

WELL AND IDENTIFICATION NUMBER (Prefix MG omitted from identifier)

- 1125 WELL MG-1125
- 1126 OBSERVATION WELL -- Used to monitor ground-water levels
- 66 SUPPLY WELL -- Used for public or industrial supply during 1991

Figure 26. Contributing area for pumping 200 gallons per minute from supply well MG-1125 near Lansdale, Pa., estimated by hydrogeologic mapping.

mapping delineation, taking into account the potentiometric surface (fig. 15), also is shown in figure 26. This estimate assumes that ground-water recharged on the outcrop area of rocks intersected by supply well MG-1125 and the area upgradient from the outcrop to the ground-water divide, is captured by the well. This delineation is made by drawing a center line from supply well MG-1125 upgradient and approximately orthogonal to the potentiometric contours shown on figure 15 until the watershed boundary is reached. Then the lateral limits of the contributing area are sketched parallel to that center line and connected to a downgradient location that approximates the stagnation point. The area is sketched several times as the limits of the contributing area are adjusted until an area is found that captures enough recharge to equal the pumping rate of 200 gal / min from supply well MG-1125. The downgradient extent of the area of diversion is not readily estimated by use of this method. In this example, the area of diversion is assumed to extend about 1,200 ft downgradient, which is the distance downgradient at which the uppermost water-bearing zone in the well would lie at a depth at which fractures may be sparse (about 500 ft below land surface in this example).

Numerical Modeling

A 3-dimensional numerical ground-water-flow model of the Lansdale area, developed by Senior and Goode (1999, p. 68), was used to delineate a contributing area for supply well MG-1125. The model was developed to simulate regional ground-water flow to provide insight into possible pathways for contaminant movement from numerous potential sources in the Lansdale area. A detailed description of development and calibration of the model is given in Senior and Goode (1999, p. 68-78); items pertinent to simulating a contributing area to supply well MG-1125 are summarized in this section.

The ground-water-flow model employs a finite-difference computer code (McDonald and Harbaugh, 1988) with a particle-tracking program (Pollock, 1994) to simulate ground-water-flow paths. The Lansdale area was divided into a finite-difference grid that has 80 rows and 100 columns (fig. 27). Rows are aligned approximately along the regional strike (N. 45° E.) of geologic formations. The horizontal dimensions of the cells are 328 ft by 328 ft. The area was divided vertically into three layers (fig. 28). The geometry, boundary conditions, and hydraulic properties used in the model are summarized in table 4.

The model was calibrated by the use of parameter-estimation program MODFLOWP (Hill, 1992). MODFLOWP computed the optimum values of recharge rate, hydraulic conductivity, and horizontal anisotropy with respect to transmissivity for the model structure shown in figures 27 and 28. Optimal values of parameters were determined by minimizing the differences between simulated and observed water levels at 87 model cells and between simulated ground-water discharge to streams and measurements of stream base flow at five stream locations. The model indicated that the optimum anisotropy ratio of transmissivity along strike against across strike was 11 to 1.

The model was used to simulate the contributing area and 100-day time-of-travel area for supply well MG-1125 while pumping at a continuous rate of 200 gal / min (fig. 29). The simulation indicates that water will be captured from upgradient and from an elongated area parallel to the strike of the geologic formations (N. 45° E). A small area in Wissahickon Creek Watershed is included in the contributing area, because pumping probably caused the ground-water divide to shift. The 100-day time-of-travel area is simulated as a smaller elliptical shape through which ground water moves to the within 100 days. The elliptical shape of this area also is caused by the anisotropy.

The model also was used to simulate a contributing area for supply well MG-1125 that includes the influence of pumping from all supply wells that could be identified in the modeled area (fig. 30). Although both simulations show a contributing area with a similar “tear-drop” shape, pumping of the nearby supply wells squeezes the eastern part of the contributing area into a narrower area. Ground-water withdrawals from nearby supply wells MG-66, MG-71, MG-75, and MG-78 push the contributing area of MG-1125 to the north and withdrawals from MG-875 and MG-1051 push it to the south. Clearly, including withdrawals from nearby wells affects the determination of contributing area to MG-1125. However, note that the simulated 100-day time-of-travel area for supply well MG-1125 is changed only slightly by inclusion of nearby supply wells. This is because hydraulic gradients near supply well MG-1125 are affected very little by withdrawals from the nearby supply wells.

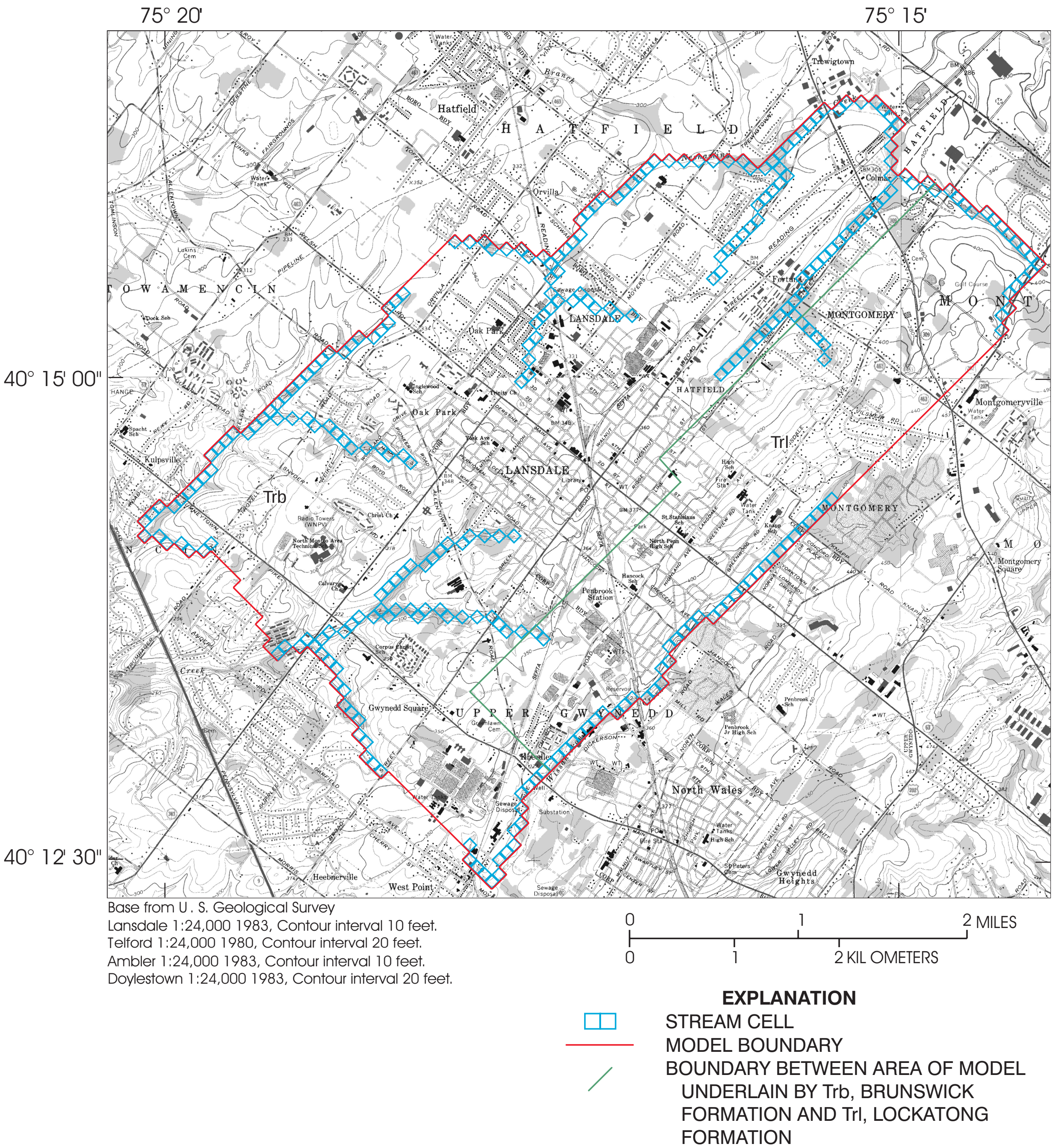


Figure 27. Model boundaries, finite-difference grid, and stream cells in and near Lansdale, Pa. (from Senior and Goode, 1999, fig. 52).

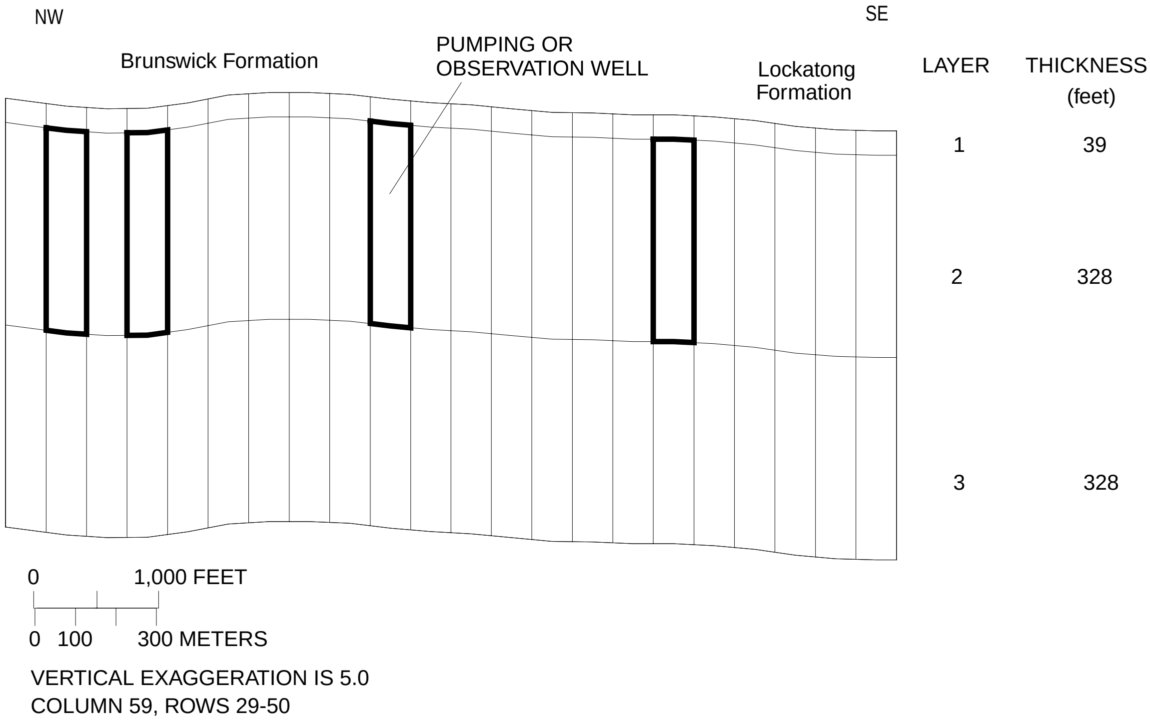
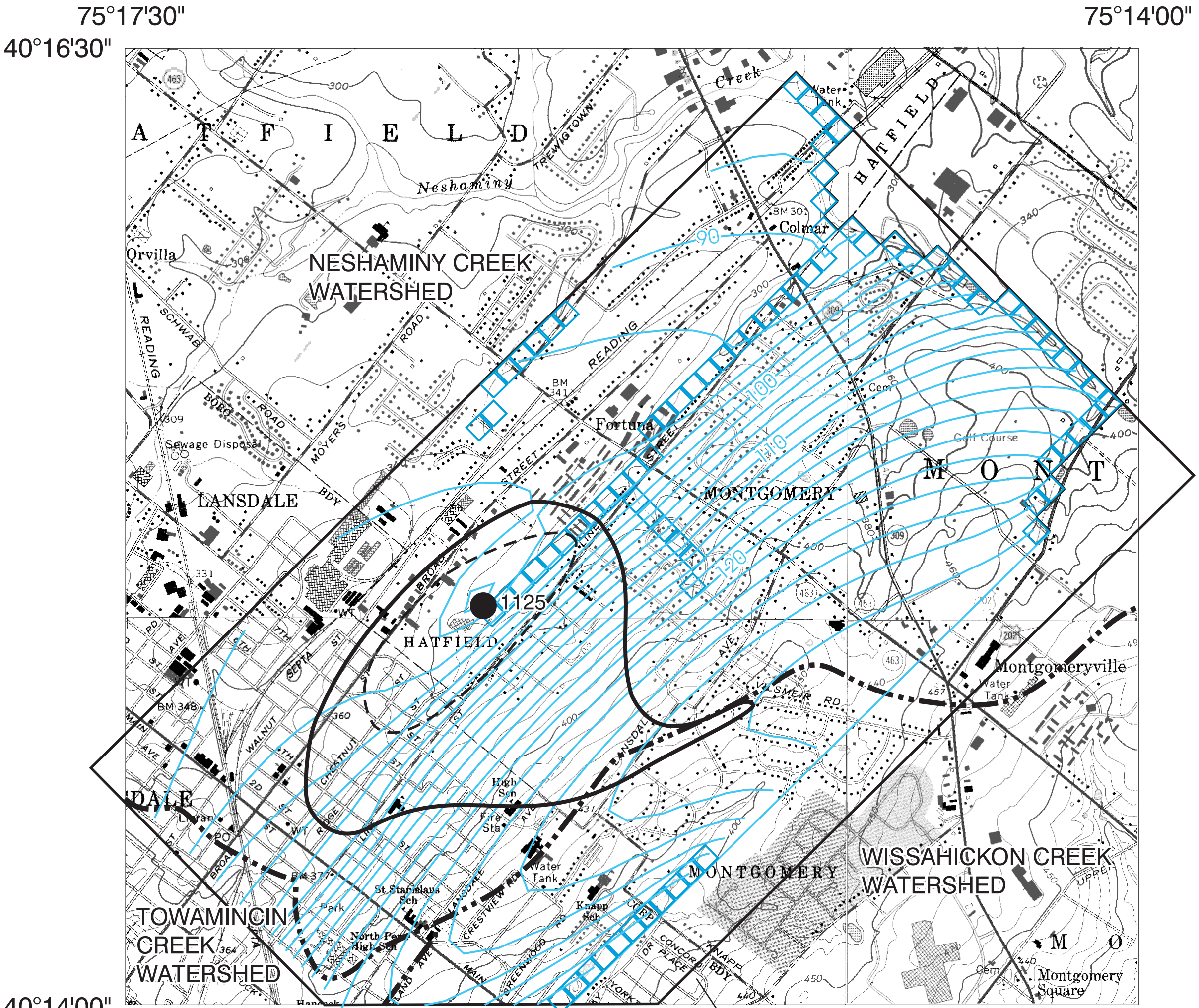


Figure 28. Model structure showing thickness of three layers and location of pumping or observation well in middle layer for simulation of ground-water flow in and near Lansdale, Pa. (From Senior and Goode, 1999, fig. 53.)

Table 4. *Summary of parameters in the ground-water-flow model of the Lansdale, Pa., area*

[ft, feet; ft/d, feet per day; in/yr, inches per year; gal/min, gallons per minute]

MODEL GEOMETRY	
Grid	Constant-spaced, finite-difference grid contains 80 rows and 100 columns. Horizontal cell-face dimensions are 328 × 328 ft.
Layers	Three layers—Layer 1 is 39 ft thick. Layers 2 and 3 are each 328 ft thick. The bottom of layer 1 is 39 ft below land surface everywhere. The bottom of layer 2 is 367 ft below land surface everywhere. The bottom of layer 3 is 695 ft below land surface everywhere. All layers are simulated as confined aquifers.
BOUNDARY CONDITIONS	
Base and lateral boundaries of model	The base of the model is simulated by no-flow cells located 695 ft below land surface. No-flow cells also surround the active model cells laterally.
Streams	Streams are simulated by use of head-dependent flux stream cells. Stream stage was set to elevations determined from 7.5 minute topographic maps. Bottom of stream was set 3 ft below river stage. Hydraulic conductivity of the streambed was set to 0.161 ft / d.
Recharge	Recharge is simulated as a constant flux of 8.3 in / yr to layer 1 throughout the modeled area.
Well	Supply well MG-1125 is simulated by withdrawing a constant flux of 200 gal / min from the cell at layer 1, row 47, column 59.
HYDRAULIC PROPERTIES	
Horizontal hydraulic conductivity	The horizontal hydraulic conductivity (along a row) is 0.161 ft / d everywhere in layer 1. It is 5.35 ft / d for the Brunswick Formation and 1.12 ft / d for the Lockatong Formation where they occur in layers 2 and 3.
Horizontal anisotropy	Ratio of hydraulic conductivity along a row to along a column is 11 to 1.
Vertical hydraulic conductivity	Equal to the horizontal hydraulic conductivity.
Porosity	0.001 for all layers



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 10 feet

ENLARGEMENT OF NORTHEAST QUARTER OF MODEL AREA SHOWN IN FIGURE 28.

0 — 1 MILE

0 — 1 KILOMETER

EXPLANATION

RIVER CELL

90 POTENTIOMETRIC CONTOUR - Shows altitude of water level simulated in layer 2 of regional model, in meters above National Geodetic Vertical Datum of 1929.

CONTRIBUTING AREA BOUNDARY - Area where ground water is diverted to well MG-1125, simulated in regional model.

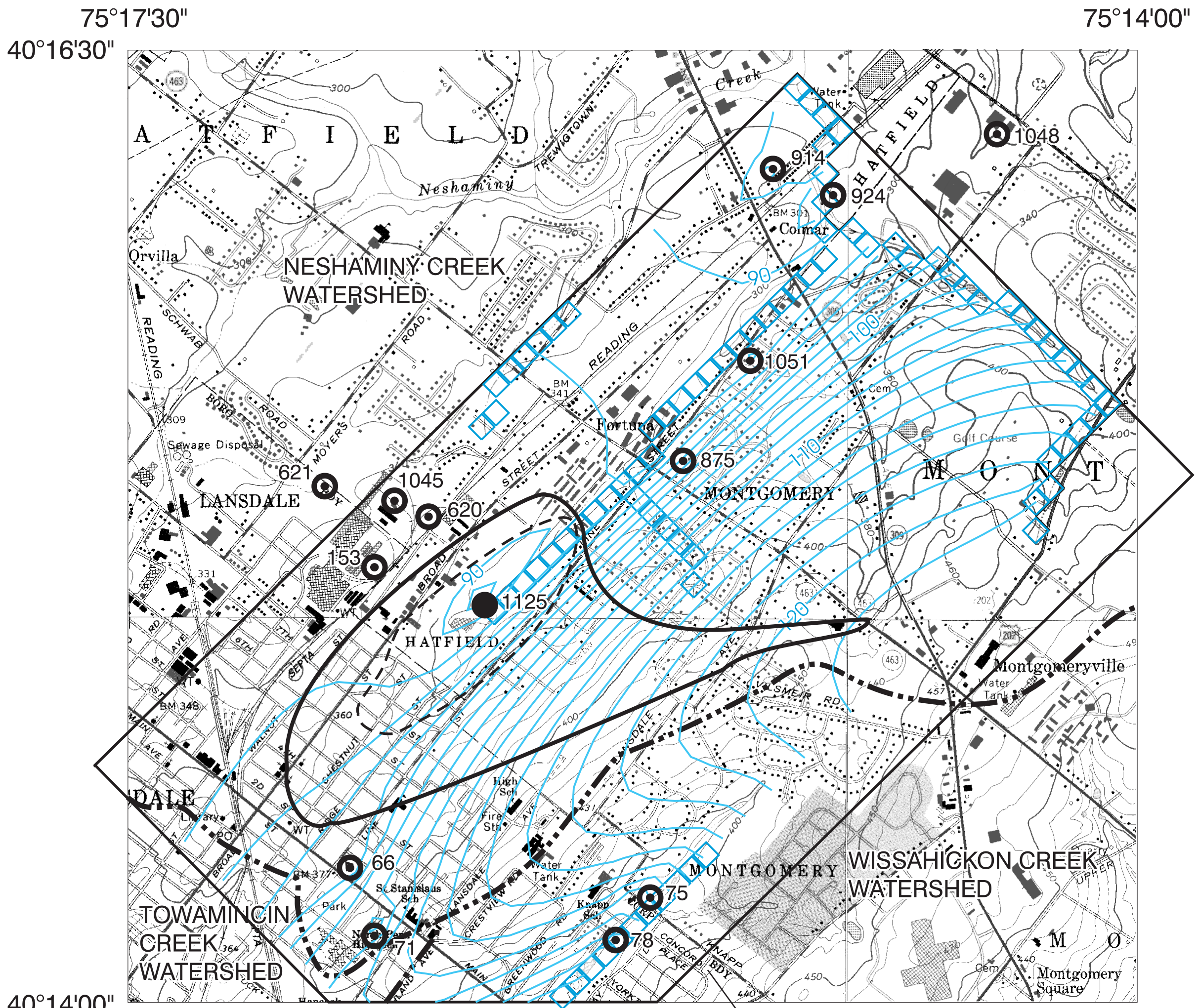
TIME OF TRAVEL AREA BOUNDARY - Extent where ground water is diverted to well in 100 days, simulated in regional model.

DRAINAGE BASIN BOUNDARY

WELL AND IDENTIFICATION NUMBER (Prefix MG omitted from identifier)

1125 WELL MG-1125

Figure 29. Contributing area and 100-day time-of-travel area for pumping 200 gallons per minute from supply well MG-1125 near Lansdale, Pa., estimated by use of a numerical ground-water-flow model.



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 10 feet

ENLARGEMENT OF NORTHEAST QUARTER OF MODEL AREA SHOWN IN FIGURE 28.

0 1 MILE

0 1 KILOMETER

EXPLANATION

RIVER CELL

POTENTIOMETRIC CONTOUR - Shows altitude of water level simulated in layer 2 of regional model, in meters above National Geodetic Vertical Datum of 1929. (—90—)

CONTRIBUTING AREA BOUNDARY - Area where ground water is diverted to well MG-1125, simulated in regional model

TIME OF TRAVEL AREA BOUNDARY - Extent where ground water is diverted to well in 100 days, simulated in regional model

DRAINAGE BASIN BOUNDARY

WELL AND IDENTIFICATION NUMBER (Prefix MG omitted from identifier)

1125 WELL MG-1125

1048 SUPPLY WELL - Used for public or industrial supply during 1991

Figure 30. Contributing area and 100-day time-of-travel area for pumping 200 gallons per minute from supply well MG-1125, with additional pumping from other nearby supply wells near Lansdale, Pa., estimated by use of a numerical ground-water-flow model.

Comparison of Delineation Methods

A time-of-travel equation was used to make a preliminary delineation of the contributing area for supply well MG-1125. Three other methods (uniform-flow equation, hydrogeologic mapping, and numerical modeling) were used to refine the contributing area determined from the water budget. The fixed-radius method, on the basis of a volumetric-flow computation, was used to estimate a 100-day time-of-travel area that was refined with the numerical model. These methods have differing data requirements that are summarized in table 5.

In general, methods that allow the most complete representation of hydrogeologic framework and boundary conditions will provide the most accurate delineations of contributing area. For wells that obtain water from shallow fractures (such as supply well MG-1125), the water budget provides a good method to estimate the size but not the shape of the area contributing recharge to the well. The uniform-flow method should provide a more realistic shape of the contributing area by allowing the sloping water-table surface to be incorporated. However, for supply well MG-1125, the uniform-flow equation delineated a long-narrow area of diversion that extended far across the ground-water divide. Sketching the limiting flow lines to supply well MG-1125 by the use of geologic outcrops and a potentiometric-surface map refines the delineation of the contributing area but does not include the relative influence of anisotropy on the contributing area caused by dipping geologic beds. Numerical modeling is the best method used in this study because it allows the incorporation of geologic units of differing hydraulic properties and irregular boundary conditions in the vicinity of supply well MG-1125. In this study, anisotropy caused by the dipping beds was simulated with a hydraulic conductivity eleven times greater along the strike of beds than across them. The main disadvantage to modeling is that model construction and calibration are time-consuming processes.

The ground-water model at this fractured-bedrock site could be refined to incorporate a more realistic dipping-bed geometry, which would probably result in a better delineation of contributing area. Most of the hydrologic investigations conducted at the well field provided information on the hydrologic framework and aquifer properties at a scale more detailed than was used in the ground-water modeling presented in the report. However, such detailed modeling is probably beyond the budget constraints of most actual wellhead-protection projects in Pennsylvania.

Table 5. *Comparison of minimum data requirements for each delineation method*

[N/A, not applicable]

Delineation method	Data needed						
	Pumpring rate	Estimate of recharge rate	Aquifer thickness	Effective porosity	Hydraulic conductivity	Water-table map	Topographic and geologic maps
Water budget	Required	Required	N/A	N/A	N/A	N/A	N/A
Fixed radius (volumetric flow equation)	Required	N/A	Required	Required	N/A	N/A	N/A
Uniform-flow equation	Required	Suggested	Required	N/A	Required	Slope of prepumping water table is required.	N/A
Hydrogeologic mapping	Suggested	Suggested	N/A	N/A	N/A	Required	Required
Numerical modeling	Required	Required	Required	Required for time-of-travel boundary.	Required	Suggested for calibration	Suggested

SUMMARY

Delineating a contributing area to a supply well completed in a fractured-bedrock aquifer near Lansdale, Pa., was approached by use of a strategy that focused on refining the understanding of factors that control ground-water movement and water sources to the well. The strategy consists of developing an initial conceptual hydrogeologic model, refining the initial model by conducting field studies, and revising the contributing-area delineation so it reflects the refined conceptual model. The improved understanding of the ground-water-flow system led to a more defensible delineation of the contributing area.

An initial conceptual hydrogeologic model was developed on the basis of information from a review of literature pertaining to siliciclastic-rock terranes in the Mesozoic Lowlands Section of the Piedmont Physiographic Province. Ground water in such terranes occurs and moves through fractures in the dipping bedrock of the Brunswick and Lockatong Formations that is thinly mantled with soil and weathered rock.

The principal methods of refining the understanding of hydrology at supply well MG-1125 in Lansdale were aquifer tests, water-level measurements, and geophysical logging. Results of two constant-discharge aquifer tests helped estimate the transmissivity of water-producing fractures. Results from slug tests provided estimates of transmissivity that were used to help evaluate the results from constant-discharge aquifer tests. Slug tests also showed the variable distribution of transmissivity, indicating that ground-water velocities vary considerably in the well field. Water-level monitoring in observation wells allowed maps of the potentiometric surface near the well field to be drawn. The measurements also showed that the hydraulic gradient can change abruptly in response to pumping from nearby supply wells. Water levels measured at a broader regional scale provided a more useful view of the potentiometric surface for purposes of delineating the contributing area. Geophysical logging and measurements of flow within wells showed that about 60 percent of water from supply well MG-1125 probably is contributed from relatively shallow water-producing fractures from 60 to 125 ft below land surface, but measurable amounts of water are contributed by fractures to a depth of 311 ft below land surface. The large contribution of water from shallow fractures indicates that the area providing at least some of the recharge to the well is not far removed from the wellhead. Chemical samples supported the evidence that shallow ground water of relatively young age is contributed to the well. Correlation of geophysical logs indicated that the Brunswick and Lockatong Formations strike N. 54° E. in the vicinity of supply well MG-1125. This result differs from the strike of the Lockatong (about N. 40° E.) shown on geologic maps (Longwill and Wood, 1965). The reason for this discrepancy is not known.

Preliminary delineations of the contributing area and the 100-day time-of travel area were computed from a water budget and time-of-travel equation. Assumptions inherent in the method were not consistent with the conceptual hydrogeologic model; however, the steady-state water budget provided a first approximation of the maximum size of the contributing area. Three other approaches were used and results compared: (1) uniform-flow equation, (2) hydrogeologic mapping, and (3) numerical modeling. Contributing-area shapes differed for the three methods because each method allowed only certain complexities of the hydrogeologic system to be included. Even the numerical model was a very simplified approximation of this fractured siliciclastic-bedrock aquifer.

The uniform-flow equation predicted a contributing area that seemed unrealistic—extending far across the ground-water divide into an adjacent watershed. Hydrogeologic mapping, if used with the potentiometric surface and constrained by the water budget, produced a contributing area that was generally similar to that from numerical modeling. A major limitation of the hydrogeologic-mapping method is that although geologic structure and the potentiometric surface are used in the analysis, professional judgement is relied on to ascertain the relative influence of each on the contributing area. Numerical modeling allowed the incorporation of aniso-tropy caused by dipping water-producing units, differing transmissivity values for geologic units, and ground-water withdrawals from nearby supply wells. The numerical modeling showed that ground-water withdrawals from nearby supply wells affected the shape of the contributing area to supply well MG-1125 but had little effect on the 100-day time-of-travel area.

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