Northwestern Lansdale Models

Local-scale models of ground-water flow in northwestern Lansdale are embedded within the regional-scale flow model of Senior and Goode (1999). This approach is used because the two local-scale models are linked by high-permeability beds that extend regionally and because streams traverse the local-scale model areas. This approach is computationally less efficient than separate local and regional models but allows ground-water fluxes between the local-scale model areas and the regional model to be automatically simulated. Furthermore, it allows a simultaneous calibration of the model using results from the two separate aquifer tests.

Aquifer tests were conducted at the J.W. Rex Co. property (Rex) in October 1997 and at the Keystone Hydraulics property (Keystone) in November 1997. Although these locations are far enough apart that the aquifer test at one did not appreciably affect water levels at the other during the tests, they are within a mile of each other and are nearly along strike. Calibrating a single model to both aquifer tests yields more representative hydraulic properties and facilitates simulation of flowpaths at the local as well as larger scale.

Aquifer-Test Results

Keystone Hydraulics site

One aquifer test was done at Keystone on November 18, 1987 (Senior and Goode, 1999). Well Mg-1610 was pumped for 8.05 hours at rates that ranged from 8.1 to 15 gal / min (0.51 to 0.95 L / sec) during the early part of the test. The pumping rate was stable at about 10 gal / min (0.63 L / sec) from 42 minutes after pumping started until the end of pumping. Water levels were measured in eight wells (fig. 16) with pressure transducers and electric tape. The configuration of wells included shallow [less than 100 ft (30m)] wells Mg-1611 and Mg-1620; intermediate-depth [up to 190 ft (60 m)] wells Mg-1610 (pumped well) and Mg-1619; and several deep [more than 270 ft (82 m)] open-hole wells (Mg-67, Mg-80, Mg-163, and Mg-164) (fig. 17). The observation wells were updip and along strike from the pumped well. Bedding at Keystone strikes about N57°E and dips about 8° to the northwest (Conger, 1999).

Positive drawdown during the aquifer test was measured in all wells but Mg-164 (fig. 16). Drawdown exceeded 0.3 ft (0.09 m) in three observation wells that were among the closest to and updip of the pumped well including Mg-1611, a shallow well within 25 ft (7.6 m) of the intermediate depth pumped well; Mg-80, an open-hole deep well with 138 ft (42 m) of casing and within 153 ft (46.6 m) of the pumped well; and Mg-1620, a shallow well within 365 ft (111m) of the pumped well. Well Mg-1611 is not open to the projected pumped interval. Large drawdown at this well may be caused by local high permeability outside the projected bed. Although the primary water-bearing zone in well Mg-80 is about 30 ft (9.1 m) below the projected dip of bedding through the pumped zone, aquifer interval-isolation testing indicated that this water-bearing zone in well Mg-80 may be hydraulically connected to shallower zones outside the borehole. Shallow well Mg-1620 intersects the projected dip of bedding through the pumped zone (fig. 17). Well Mg-1619 is at a similar distance from the pumped well as well Mg-1620 and is within 25 ft (7.6 m) of well Mg-1620, yet drawdown in well Mg-1619 is only 0.13 ft (0.04 m). Well Mg-1619 is open to beds that are projected to be below the pumped bed (fig. 17). Water levels in well Mg-163, approximately along strike with the pumped well, were drawn down by more than 0.14 ft (0.05 m), whereas water levels in well Mg-164, at a similar radial distance but further updip, were not affected by pumping.

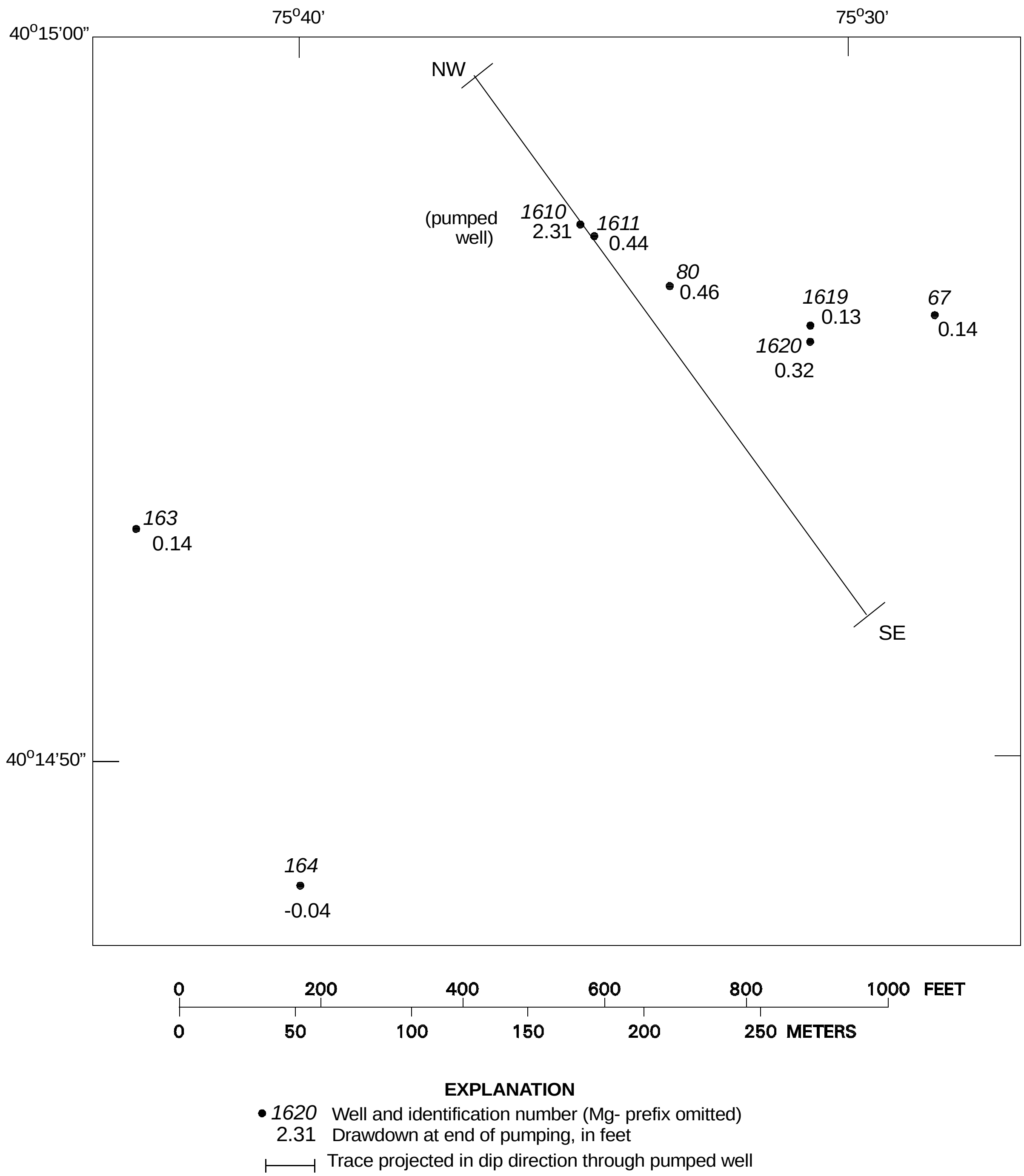

Figure 16.-- Well locations and drawdown at end of pumping well Mg-1610 at the Keystone Hydraulics property in northwestern Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours (from Senior and Goode, 1999).

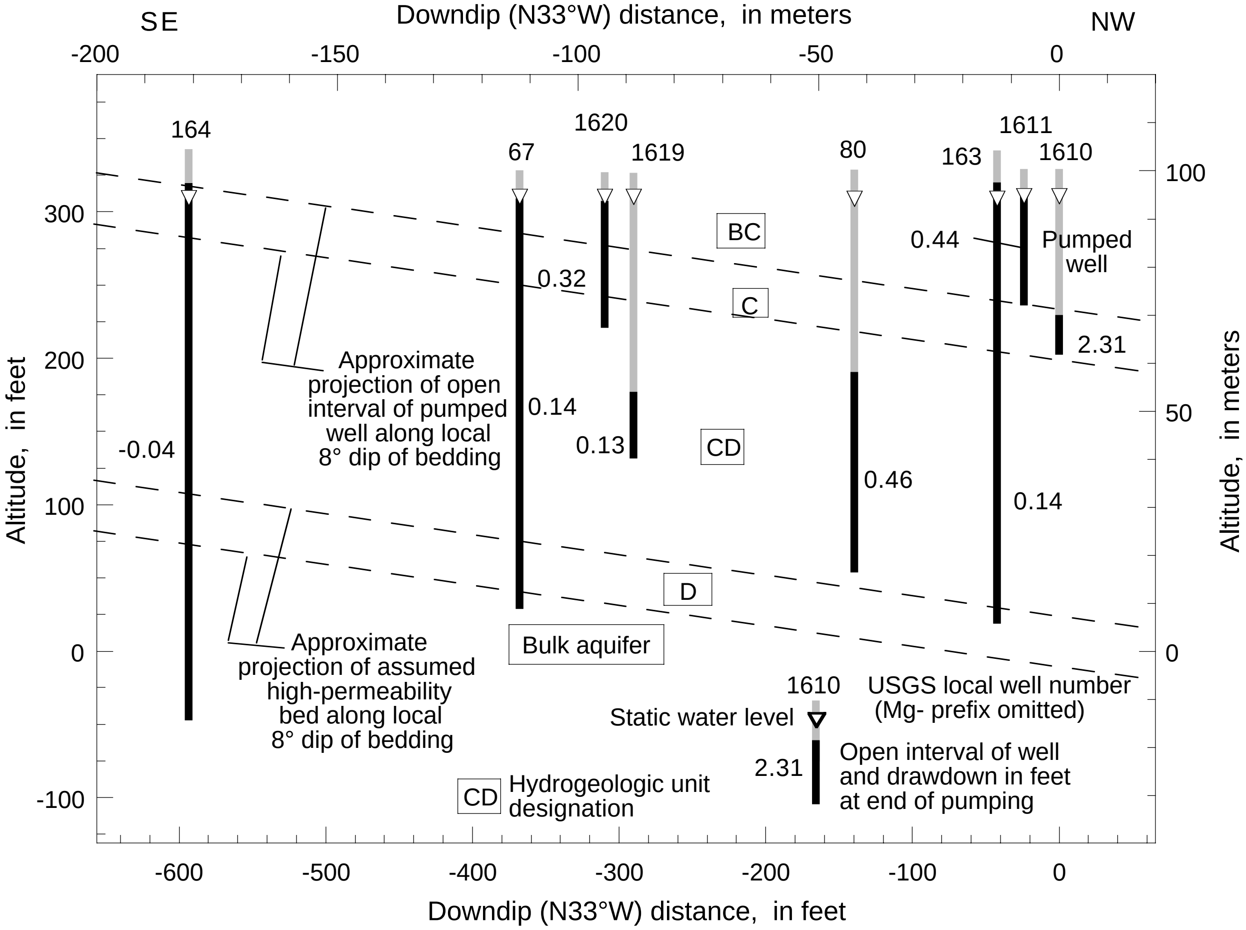

Figure 17.-- Cross-section of open intervals of wells, static depth to water, and drawdown at end of pumping at the Keystone Hydraulics property in northwestern Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours. Also shown is the conceptual model of dipping high-permeability (C, D) and low-permeability (BC, CD) beds. High and low-permeability beds stratigraphically below D are combined and designated “Bulk aquifer.” All wells are projected onto a vertical plane parallel to the dip direction (modified from Senior and Goode, 1999).

Measured water levels during the aquifer test illustrate the effect of pumping, including variable rates of pumping at the beginning of the test and fluctuations associated with regional water-level trends (fig. 18). Decreases in barometric pressure resulted in corresponding increases in water levels in wells during the aquifer test. Because the drawdowns resulting from pumping were small, Senior and Goode (1999) used analytical aquifer-test models to remove the effect of the barometric pressure changes prior to analysis of drawdown.

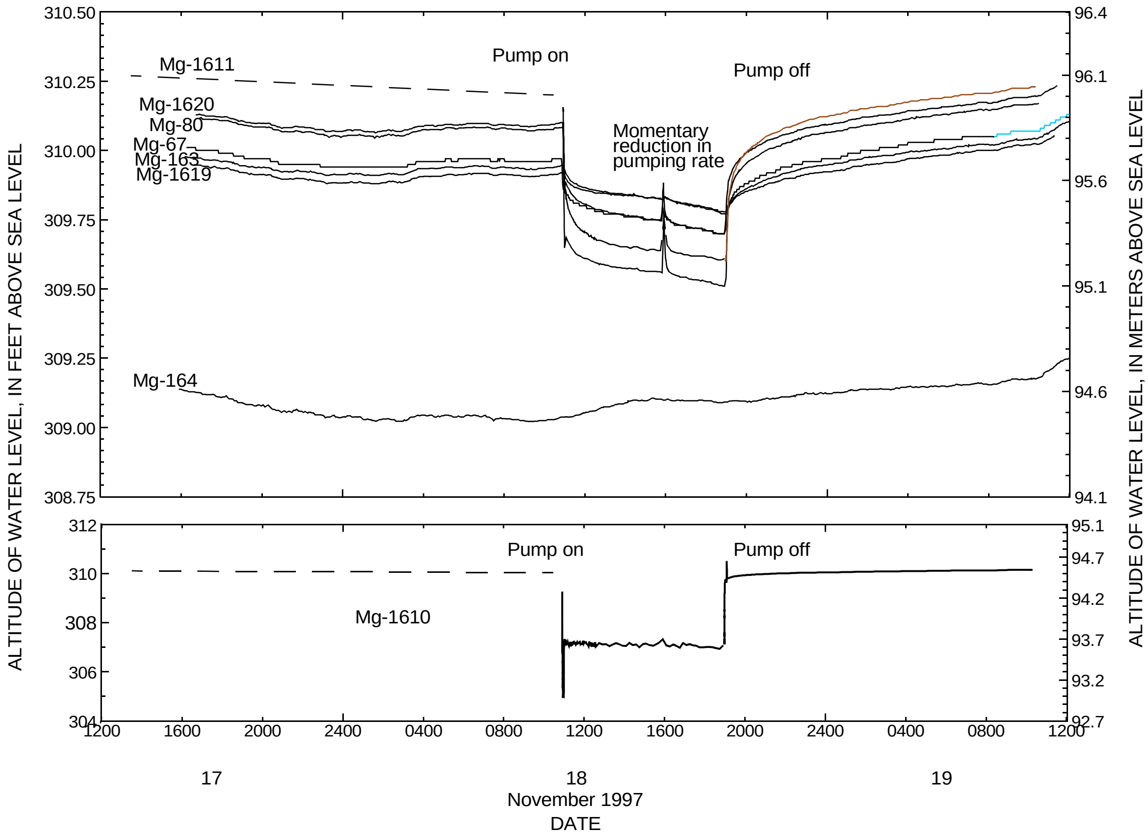

Figure 18.-- Measured water levels at the Keystone Hydraulics property in northwestern Lansdale, Pa., November 17-19, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours on November 18 (from Senior and Goode, 1999).

Senior and Goode (1999) selected drawdown in four observation wells for analysis using the anisotropic single-aquifer model of Papadopulos (1965). Of the six observation wells with positive drawdown, drawdown in two wells was not matched. Well Mg-1611 is very close to the pumping well but was drawn down less than more distant wells, and the well is not open to the projected pumped bed (fig. 17). Well Mg-1619 was drawn down less than half as much as the nearby well Mg-1620, and it also is not open to the projected pumped bed. Drawdown in these wells cannot be matched by a single-aquifer model because in such a model all observation wells are assumed to be completed within the pumped aquifer. Senior and Goode (1999) did not include these wells in their analysis in order to use the directional variability of drawdown in the pumped bed to estimate large-scale anisotropy. Well Mg-80 was included in the analysis even though it also is open to bedrock outside the projected pumped interval. The measured drawdown and aquifer-isolation test results suggest that this well is hydraulically connected to the pumped interval (Senior and Goode, 1999).

Senior and Goode (1999) matched drawdown in four observation wells using the single-aquifer anisotropic model of Papadopulos (1965) (fig. 19). The response of anisotropic aquifers to aquifer tests include larger drawdowns in one direction than in another for similar distances from the pumped well. The early-time part of the measured drawdown was not matched because the pumping rate was variable for about the first 42 minutes of pumping. The estimated hydraulic properties from this match were: T_{max} = 10,700 ft^2 / d (990 m^2 / d); T_{min} = 520 ft^2 / d (48 m^2 / d); horizontal angle of maximum T, θ_{max} = N51°W; and S = 3 x 10^{-5}. The non-directional geometric-mean transmissivity was 2,300 ft^2 / d (220 m^2 / d). These aquifer-test results from this match represent a preferred flow direction within the pumped bed that is oriented in the dip direction (about N33°W). Previous aquifer-test results in the similar Passaic Formation (Carleton and others, 1999) present a preferred flow direction oriented in the strike direction.

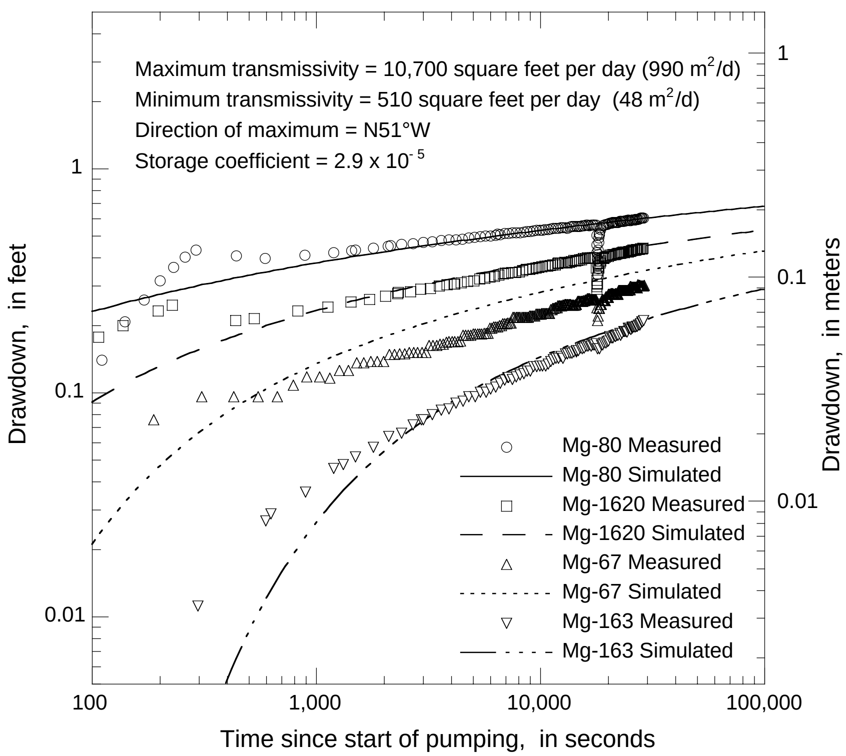

Figure 19.-- Measured and simulated drawdown, using anisotropic model of Papadopulos (1965), in wells Mg-67, Mg-80, Mg-163, and Mg-1620 at the Keystone Hydraulics property in north-western Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours (from Senior and Goode, 1999).

Rex site

Aquifer and step tests at Rex were done by QST Environmental, Inc. (1998). Production well Mg-625 was pumped at a rate of about 30 gal / min for 60 hours from October 24-27, 1997, and then shut down for 13 hours. A step test was conducted at the beginning of the 60-hour pumping period. This well is normally pumped continuously for industrial water supply. Water levels in the pumped well and 10 other wells, including Mg-82, Mg-157, Mg-1441, Mg-624, Mg-1639, Mg-1640, Mg-1641, Mg-1615, Mg-1617, and Mg-1665 (fig. 20), were measured during the tests. Water-level changes were observed in all wells. Recovery at the end of the shutdown period was greatest [12 ft (3.7 m)] in observation well Mg-1639. Well Mg-1639 is the closest to the pumped well. Well Mg-1640 is within 10 ft (3 m) of well Mg-1639 but is shallower than well Mg-1639 and had much less recovery [3.0 ft (0.9 m)]. Aquifer interval-isolation tests indicate little hydraulic connection between well Mg-1639 and the screened interval of well Mg-1640 (QST Inc., 1998; Senior and Goode, 1999). The downward vertical flow observed during geophysical logging prior to the aquifer tests indicates that well Mg-1639 is directly influenced by pumping in production well Mg-625. Estimates of hydraulic properties were determined from analysis of drawdown data, assuming an isotropic aquifer. Transmissivity ranged from 160 to 665 ft^2/d (14.5 - 61.8 m^2/d) and storage ranged from about 2×10^{-5} to 4×10^{-3} (QST Environmental Inc., 1998). The transmissivity values from this test are similar to a value of 330 ft^2/d (31 m^2/d) estimated from an earlier test (Goode and Senior, 1998).

The extent of water-level changes in observation wells are controlled, in part, by the hydrostratigraphic locations of open intervals (fig. 21). Wells that are open to the same hydrostratigraphic horizon as the pumped interval have the largest water-level changes.

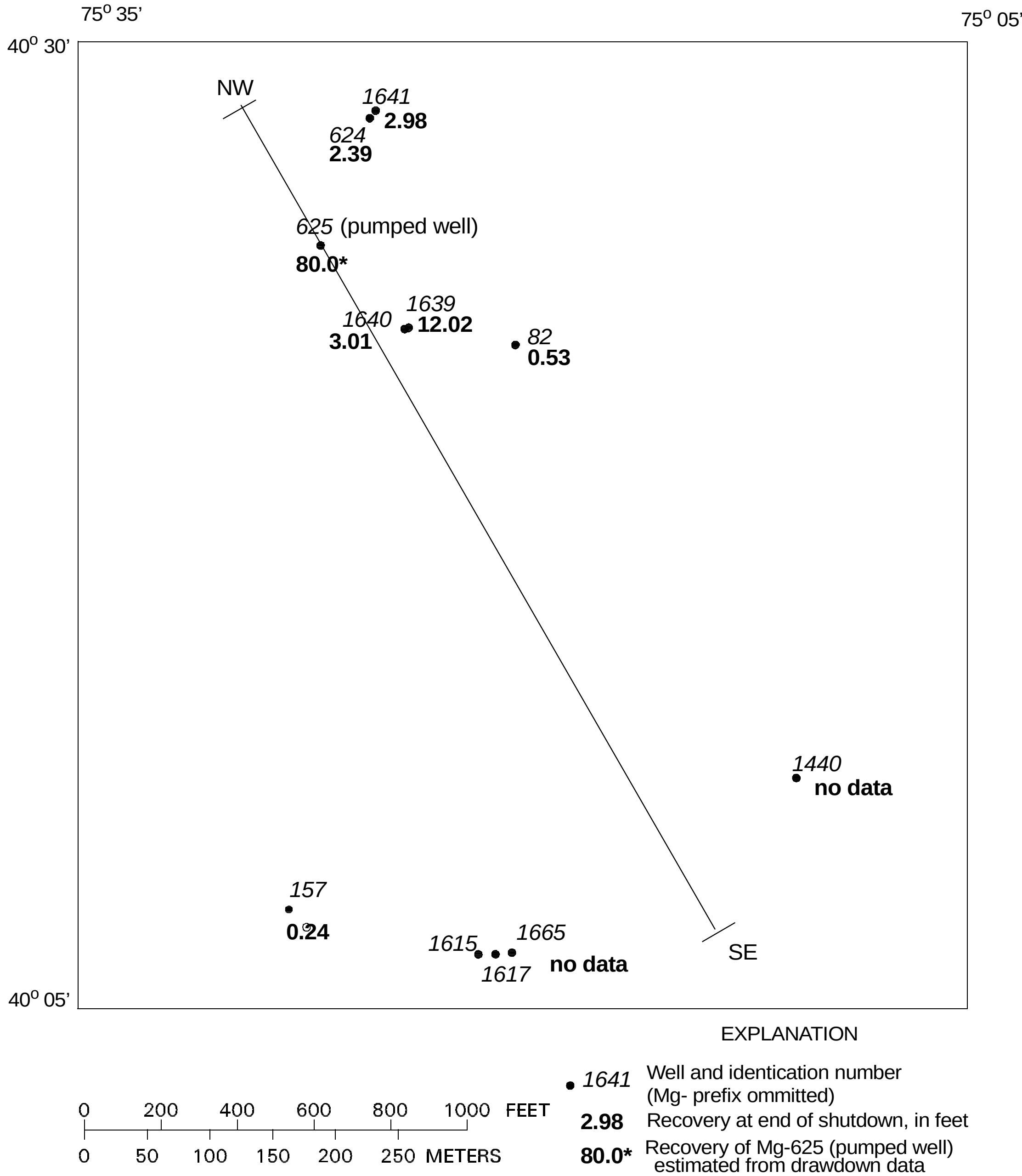

Figure 20.-- Well locations and recovery at end of shutdown of well Mg-625 at the J.W. Rex Co. property in northwestern Lansdale, Pa., October 27, 1997. Well Mg-625 normally pumped at a rate of 30 gallons per minute and was shutdown for 13 hours (water-level data from QST Environmental Inc., 1998).

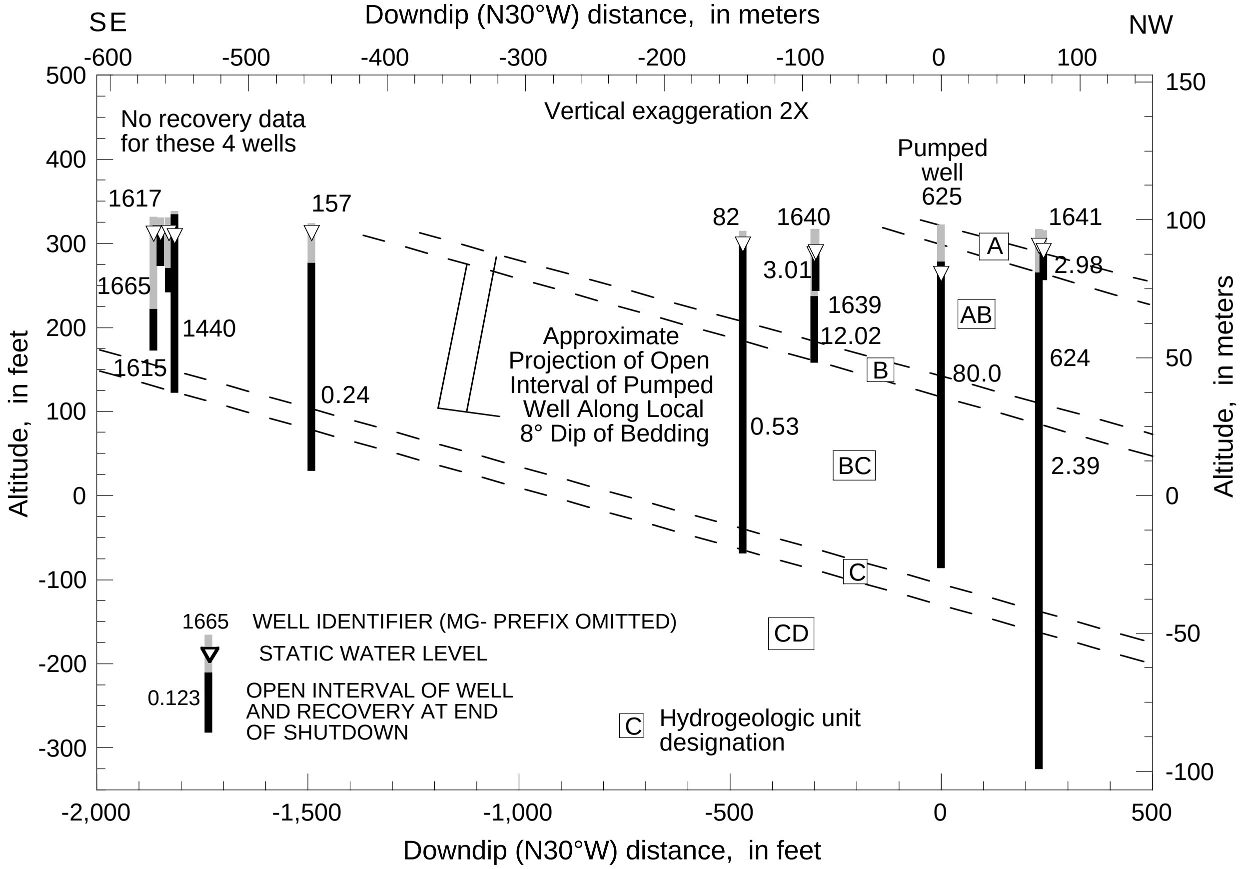

Figure 21.-- Cross-section of open intervals of wells, static water level, and recovery at end of shutdown at the J.W. Rex Co. property in northwestern Lansdale, Pa., October 27, 1997. Well Mg-625 normally pumped at a rate of 30 gallons per minute and was shutdown for 13 hours (water-level data from QST Environmental Inc., 1998). Also shown is the conceptual model of dipping high-permeability (A, B, C) and low-permeability (AB, BC, CD) beds. High and low-permeability beds stratigraphically above A are combined and designated “Bulk aquifer.” All wells are projected onto a vertical plane parallel to the dip direction.

Water levels measured at Rex are influenced by pumping at well Mg-625 and at other nearby wells (fig. 22). Water levels recover most in well Mg-1639 and less in wells Mg-624 and Mg-1640 when Mg-625 is shutdown. The response of the water level in well Mg-1641 to pumping at Mg-625 is difficult to discern because of a greater response to pumping at a different well. This stronger influence is shown by the recovery of nearly 5 ft on October 25, 1997, while Mg-625 was pumping. The temporal pattern of this water-level change strongly indicates pumping effects and not recharge. Unfortunately, this other well was also apparently shutdown a few hours before Mg-625 on October 26, 1997. The magnitude of the water-level rise in Mg-1641 measured on October 26-27, 1997, is caused by shutdown of Mg-625 in addition to the other, unidentified well.

The shutdown of well Mg-625 is treated as negative pumping in the aquifer-test analysis. The water-level rise is computed as the water level after shutdown minus the water level at the time of shutdown. This approach assumes that the water levels are in equilibrium with pumping and other stresses and boundary conditions at the time of shutdown, and that the only factor causing water-level rise is the cessation of pumping. This assumption, while not perfectly met, is supported by the relatively constant water levels prior to shutdown on October 26, 1997 (fig. 22). The water-level rise for well Mg-1641 is computed by subtracting the water-level rise on October 25, 1997, during the apparent shutdown of a different pumping well, from the water-level rise on October 26-27, 1997, when both wells (Mg-625 and the unidentified well) are not pumping. These procedures yield the water-level rise and fall as a function of elapsed time since shutdown.

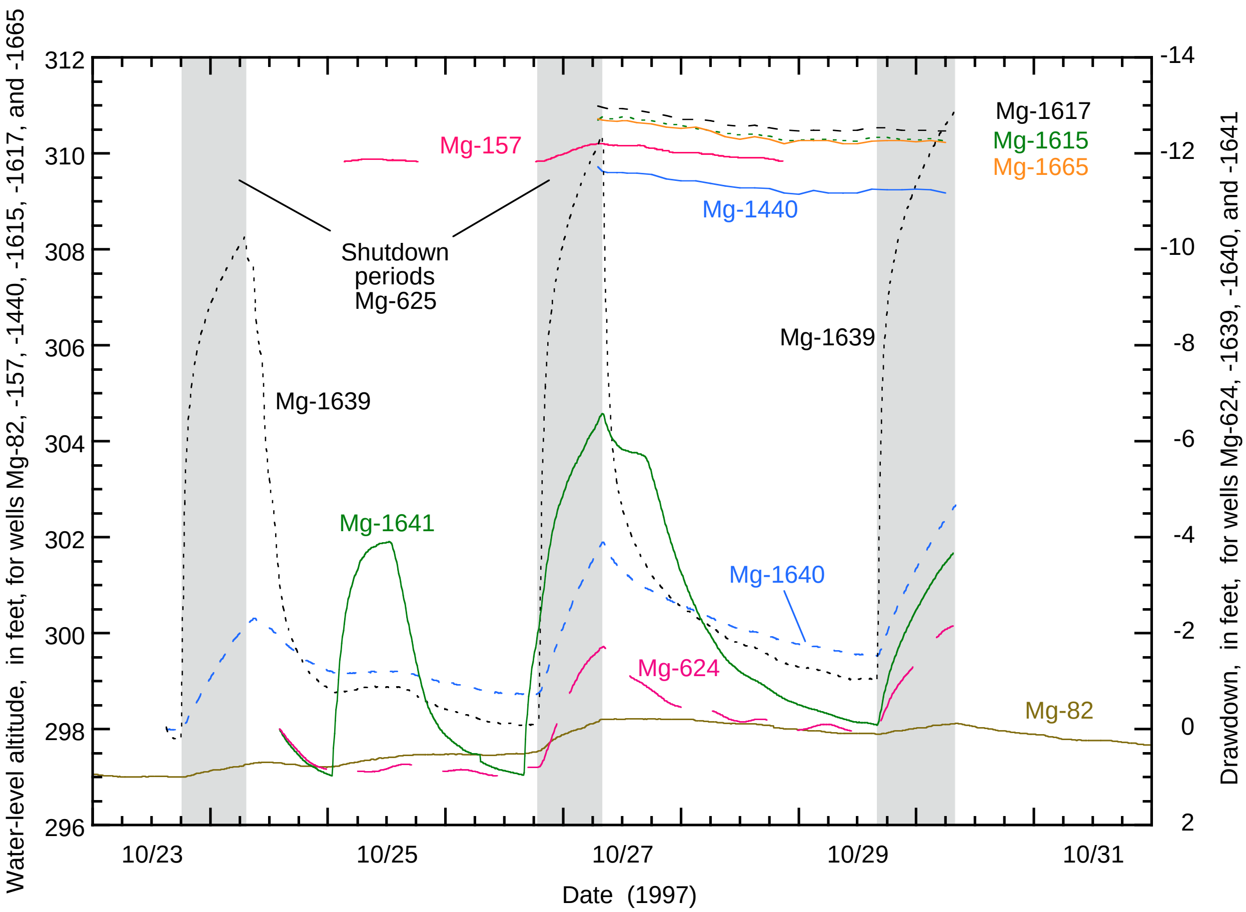

Figure 22.-- Measured water levels or drawdown in wells Mg-82, Mg-157, Mg-624, Mg-1440, Mg-1615, Mg-1617, Mg-1639, Mg-1640, Mg-1641, and Mg-1665 at the J.W. Rex Co. property in northwestern Lansdale, Pa., October 23-31, 1997. Well Mg-625 was pumped at a rate of 30 gallons per minute, except for the shutdown periods indicated (data from QST Environmental Inc., 1998).

Model Structure and Boundary Conditions

Local-scale models of ground-water flow in the northwestern part of Lansdale (fig. 23) are embedded within the regional-scale model. Most of the aquifer system of the regional-scale model is represented almost identically as done by Senior and Goode (1999). The top model layer represents soil and weathered bedrock and has uniform thickness of 19.7 ft (6 m). The bedrock aquifer is represented by two model layers, each 328 ft (100 m) thick. Most pumping and observation wells in the regional-scale model are located in the second model layer, as described by Senior and Goode (1999).

In the areas of Keystone and Rex, the horizontal grid spacing is reduced to allow simulation of dynamics of the local-scale flow system (see fig. 12 for example of grid spacing reduction near the pumped well). While the horizontal grid spacing is 328 ft (100 m) in the regional-scale model, the smallest horizontal spacing is 32.8 ft (10 m) at Keystone and 82 ft (25 m) at Rex. Because the local-scale models are embedded directly in the regional-scale model, regional fluxes are automatically simulated.

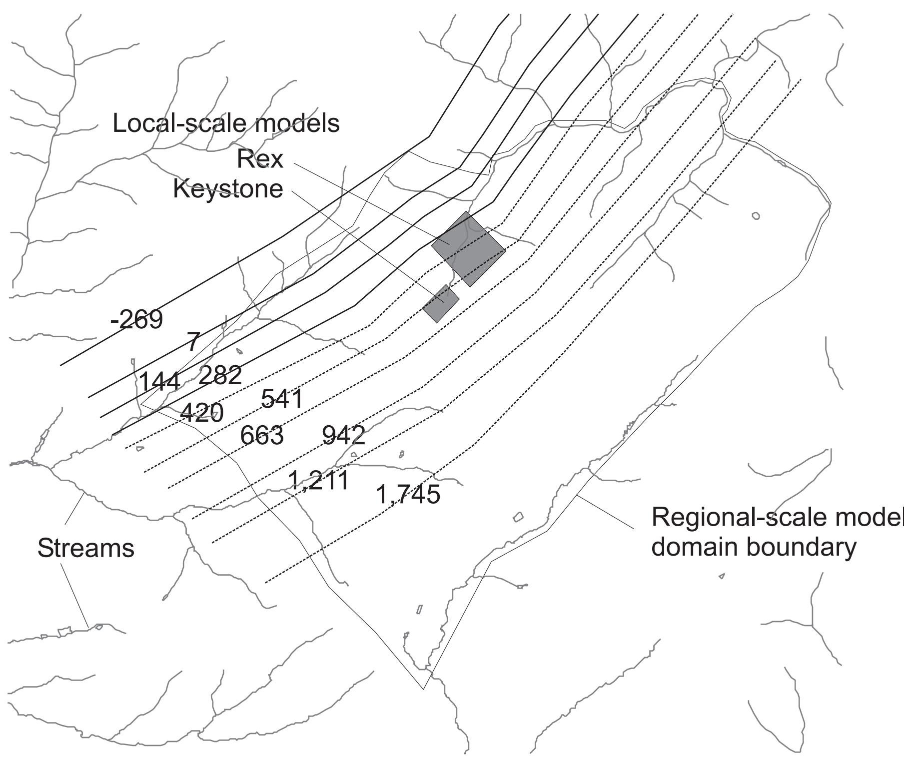

Figure 23.-- Location of the regional-scale model domain and the embedded local-scale models at the Keystone Hydraulics property (Keystone) and the J.W. Rex Co. property (Rex) in northwestern Lansdale, Pa. The contours are the elevation of the top of bed A, represented by model layer 4, taken from regional geologic maps and from local stratigraphic correlations of gamma logs (Conger, 1999).

The vertical discretization also is changed at Keystone and Rex to incorporate more detailed hydrogeologic information from aquifer-isolation (packer) and aquifer-test results. On the basis of these results and borehole-logging information, a conceptual hydrogeologic cross-section at Keystone and Rex is constructed (fig. 24). Not all geologic beds observed are treated separately in this model. Rather, the major beds that control the hydraulic connections between the pumping and observation wells at these sites are included. The strike and dip of beds is taken from regional information and from the local correlations (Conger, 1999) of gamma logs (fig. 23).

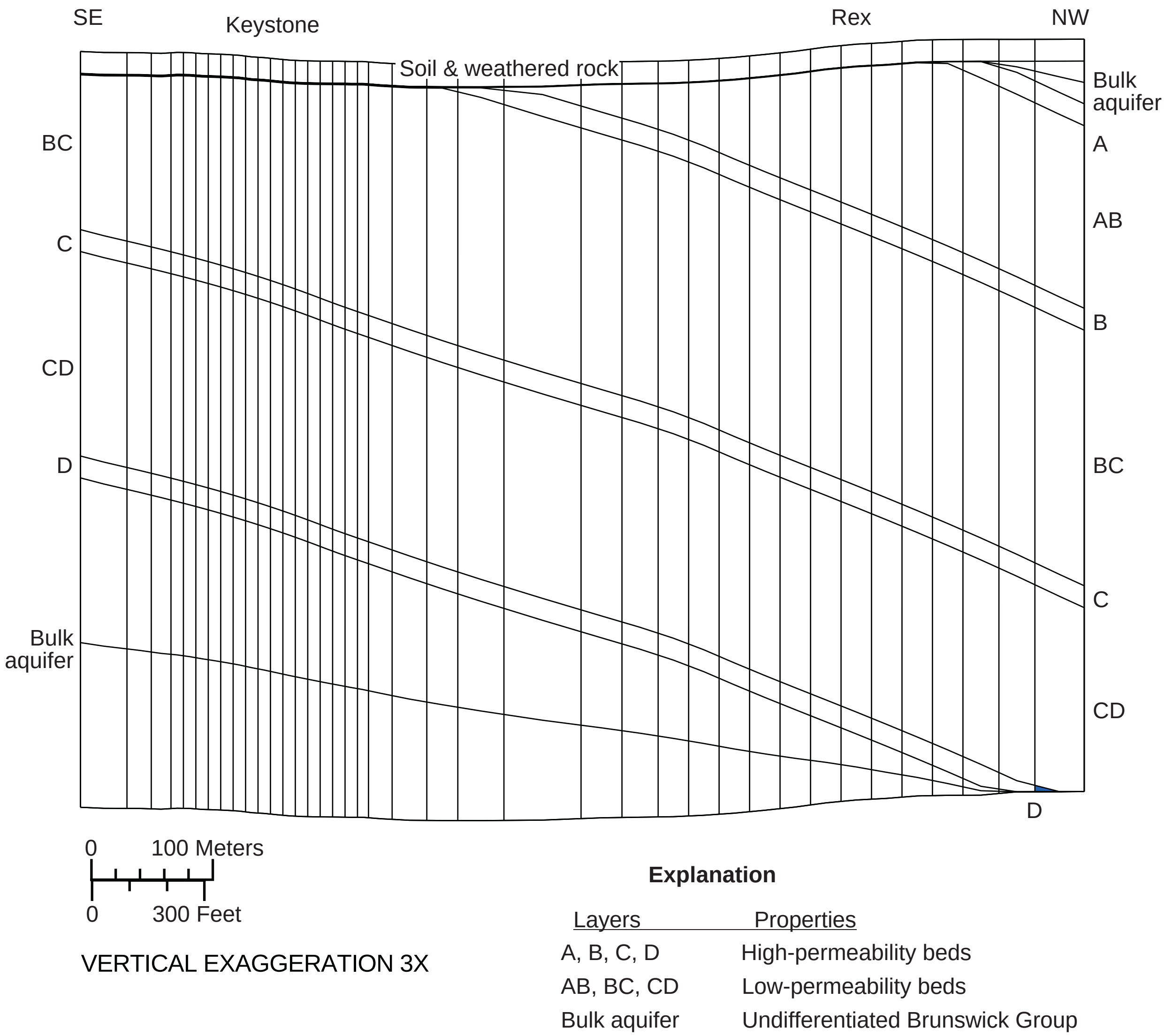

Figure 24.-- Hydrogeologic cross-section in the downdip direction in northwestern Lansdale. Assumed high-permeability beds are designated A-D. Assumed structural contours of the top of bed A are shown in figure 23.

In summary, the model structure is similar to the regional-scale model of Senior and Goode (1999) but with finer horizontal spacing and heterogeneous structure in the northwestern Lansdale area. The bedrock properties are the same as the regional-scale model outside the area of the dipping beds in northwestern Lansdale. Where the dipping beds occur between the bottom of the soil / weathered rock layer and at a depth of less than 676 ft (206 m), the homogeneous bedrock is replaced by dipping beds of alternating high and low hydraulic conductivity. Computations associated with mapping the dipping bed structure into the three-dimensional model grid are handled by a preprocessor using a programmed GIS (geographic information system) (Shapiro and others, 1997; Winston, 1999).

Aquifer-Test Simulation

The local-scale model, which is embedded in the regional-scale model, is calibrated by simulation of aquifer-test results at Keystone and Rex. Drawdown during pumping at Keystone is simulated, similar to the approach of Senior and Goode (1999). In this case, however, the local-scale numerical model is used instead of the analytical model used by Senior and Goode (1999). Water-level rise during shutdown of well Mg-625 is simulated at Rex. The MODFLOWP calibration procedure is applied simultaneously for the two separate aquifer tests (table 4). This procedure yields estimates of model parameters for the entire model using information from both tests. The calibration results for the two locations are shown separately below, but only one model, with one set of optimum parameters, is used by both simulations.

Table 4.-- Optimum and approximate, individual, 95-percent confidence-interval values for hydraulic conductivity and specific storage for calibrated simulation of ground-water flow in northwestern Lansdale, Pa.

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

Parameter	Units	Optimum value	Approximate, individual, 95-percent confidence interval: Lower value	Approximate, individual, 95-percent confidence interval: Upper value
Beds A & B hydraulic conductivity	ft/d	7.2	5.7	9.2
Beds A & B transmissivity[1]	ft^2/d	142	112	181
Beds C & D hydraulic conductivity	ft/d	36	15	82
Beds C & D transmissivity[1]	ft^2/d	709	295	1,610
Interbeds AB & BC hydraulic conductivity	ft/d	9.6×10^{-4}	1.5×10^{-4}	5.4×10^{-3}
Interbed CD hydraulic conductivity	ft/d	.26	.087	.78
Beds A & B specific storage	per foot	1.2×10^{-6}	9.3×10^{-7}	1.5×10^{-6}
Beds C & D specific storage	per foot	1.4×10^{-6}	1.4×10^{-7}	1.3×10^{-5}
Interbeds AB & BC specific storage	per foot	9.9×10^{-8}	1.8×10^{-8}	5.6×10^{-7}
Interbed CD specific storage	per foot	4.2×10^{-6}	6.4×10^{-7}	2.8×10^{-5}

[1] Transmissivity is product of hydraulic conductivity and bed thickness [19.7 ft (6 m)].

The estimated hydraulic parameters from this three-dimensional numerical model can be qualitatively compared to parameters identified previously using analytical models. The estimated transmissivity of each isotropic high-permeability bed at Keystone is 709 ft^2/d, and the sum of the transmissivities is about 1,420 ft^2/d. Senior and Goode (1999) used a single-layer anisotropic analytical model and estimated the equivalent isotropic transmissivity as 2,300 ft^2/d, about 60 percent higher. QST Environmental, Inc. (1998) estimated single-layer isotropic transmissivity at Rex of 160 to 665 ft^2/d. Goode and Senior (1998) estimated transmissivity as 320 ft^2/d from recovery of Mg-625 at Rex. The sum of the transmissivities of high-permeability beds A and B estimated here is about 280 ft^2/d.

The calibrated model can approximately simulate measured drawdown during the aquifer test at the Keystone site (fig. 25). Compared to the analytical model match using the anisotropic model by Senior and Goode (1999), this model does not match the measured drawdowns as well. The shape and relative magnitudes of drawdown at the four wells used in the analytical analysis (fig. 25 A) are reasonably matched, although the absolute drawdowns are off by up to 20 percent. The drawdown at the end of the test is matched for Mg-1619, but the simulated drawdown curve is steeper than that measured. Well Mg-1611, which is immediately adjacent to the pumped well, but shallow, is not matched. In the model, this well is located in a low-permeability interbed and is poorly connected to the pumped interval. The measured drawdown suggests a higher-permeability connection between this well and the pumped interval, which is not included in the model. However, if this well is moved downward to the pumped bed, drawdown would be higher than that measured. This match could be improved by adding more local heterogeneity to the model.

The calibrated model can also approximately simulate measured water-level recovery during the shutdown test at Rex (fig. 26). The match is best for Mg-1639, which recovered the most. The differences between the measured and simulated recovery are most evident for wells that have smaller recovery. The shapes and relative magnitude of recovery in Mg-624 and Mg-1641 are matched well, but the absolute magnitudes are too low in the model. The slope of the recovery curves at Rex are steeper than the drawdown curves at Keystone, indicating a difference in hydraulic properties at the two locations.

The hydraulic conductivities estimated by local-scale model calibration in the northwestern Lansdale area include alternating beds of high and low hydraulic conductivity (table 4). Water levels change the most in wells open to high-permeability beds that also intersect the pumped well. Water levels generally do not change as much in wells that are open to beds above or below the pumped bed, in particular if the well is isolated by more than one intervening low-permeability bed. The storage coefficients are generally low, reflecting the confined conditions in the bedrock aquifer.

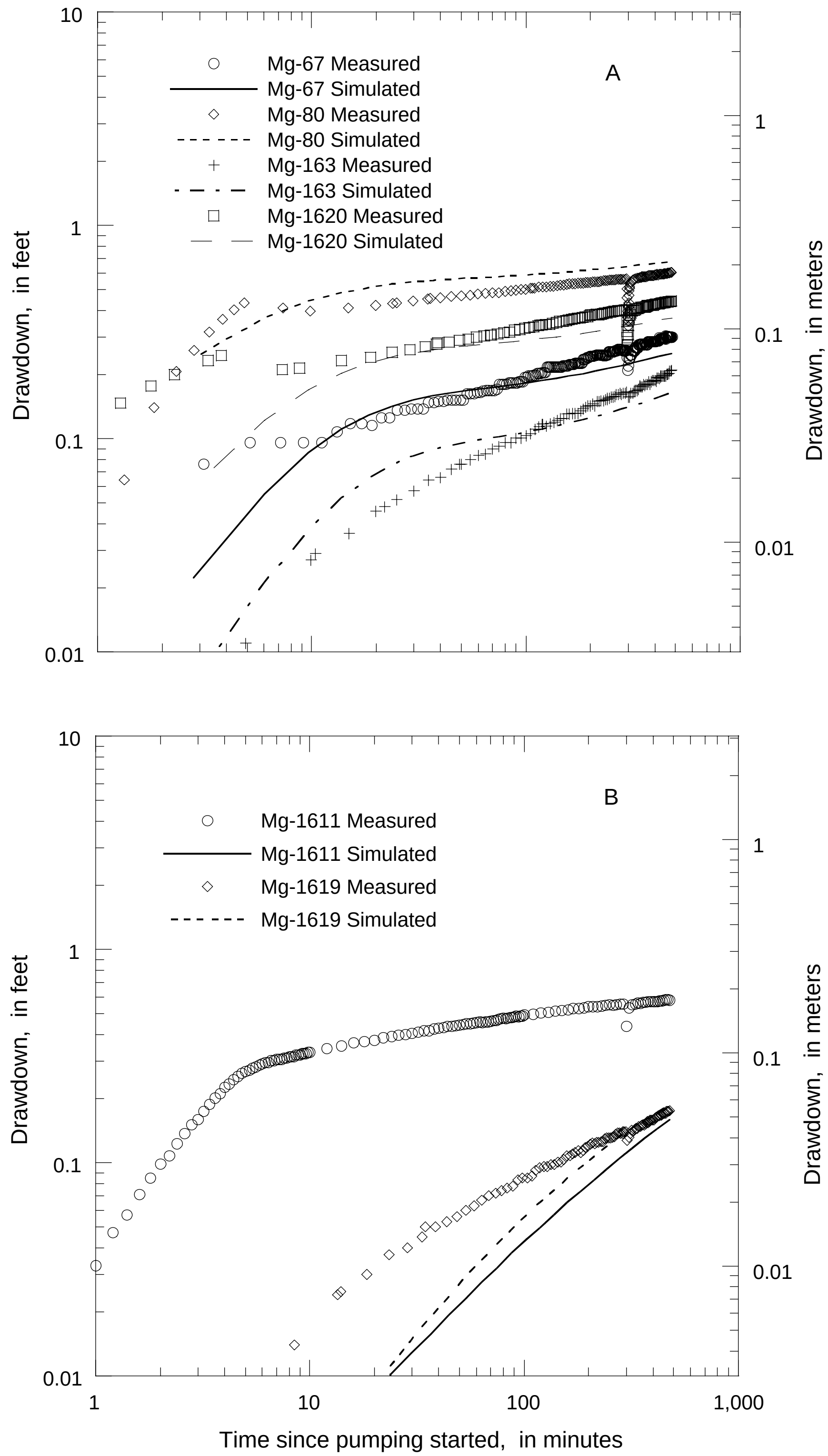

Figure 25.-- Measured and simulated drawdown in wells (A) Mg-67, Mg-80, Mg-163, Mg-1620, and (B) Mg-1611 and Mg-1619 at the Keystone Hydraulic property in northwestern Lansdale, Pa., November 18, 1997. Well Mg-1610 was pumped at a rate of 10 gallons per minute for 8.05 hours.

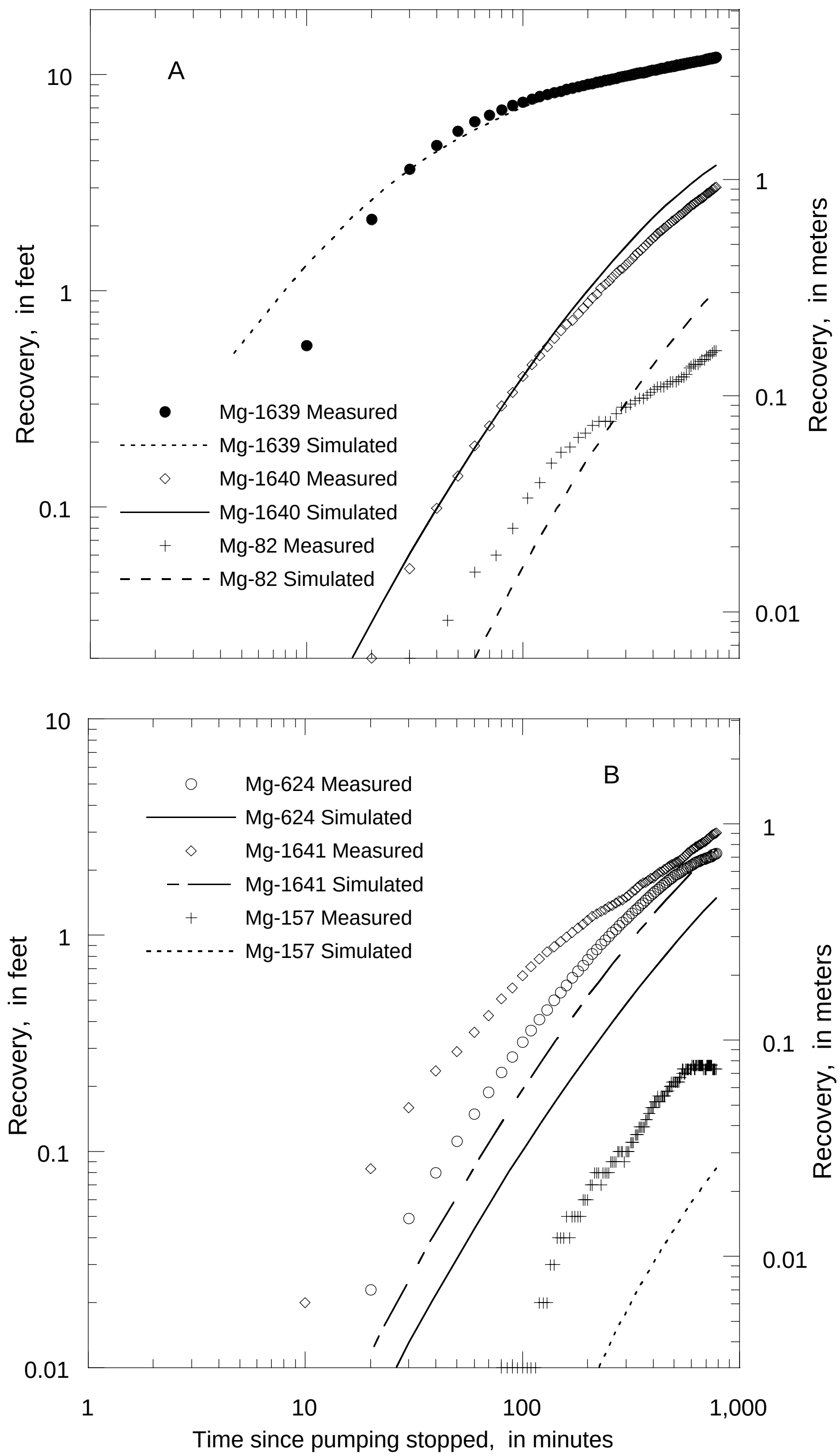

Figure 26.-- Measured and simulated water-level recovery in wells (A) Mg-82, Mg-1639, Mg-1640, and (B) Mg-157, Mg-624, and Mg-1641 at the J.W. Rex Co. property in northwestern Lansdale, Pa., October 26-27, 1997. Well Mg-625 was shutdown after pumping for 60 hours at a rate of 30 gallons per minute.

Effect of Pumping on Ground-Water Flowpaths

Steady-state-flow fields are simulated to determine the effects of pumping on ground-water flowpaths. The first scenario is for 1997 pumping conditions, which include continuous pumping in northwestern Lansdale at the J.W. Rex Co. production well. The second and third scenarios include additional pumping at a rate of 10 gal/min (gallons per minute) at wells Mg-1610 and Mg-1620, respectively. In areas where bedding is explicitly represented by the model, well pumpage is evenly distributed among high-permeability beds (table 5) intersected by the well. The pumped layers for wells Mg-625, Mg-1610, and Mg-1620 are the same as used in the analysis of the aquifer-test results.

Table 5.-- Annual average pumping rates for wells in and near Lansdale, Pa. during 1997.
[USGS, U.S. Geological Survey; --, not numbered]

USGS local well number Mg-	Owner	Owner well number	Model cells			Pumping rate (gal/min)
			Layer(s)	Row	Column	
625	J.W. Rex Co.	1	6	17	64	30.0
1610	Keystone Hydraulics	1-I	8	33	43	[1]10.0
1620	Keystone Hydraulics	2-S	8	44	46	[2]10.0
498	North Penn Water Authority	L-23	2,4,6,8	11	32	25.0
593	North Penn Water Authority	L-25	6,8,10,11	17	29	34.1
69	North Penn Water Authority	L-10	8,10,11	52	27	68.1
914	North Penn Water Authority	NP-12	10,11	55	101	54.9
566	Lehigh Valley Dairy	5	11	57	19	64.4
59	Lehigh Valley Dairy	3	11	57	19	44.4
1418	Ziegler	--	10,11	57	80	4.4
140	Lehigh Valley Dairy	4	11	59	17	92.5
1125	North Penn Water Authority	NP-61	11	60	77	71.5
875	North Wales Water Authority	NW-17	11	62	88	71.0
1051	North Wales Water Authority	NW-22	11	62	94	136.3
1198	Merck & Co.	PW9	11	65	5	26.1
125	Merck & Co.	PW2	11	71	3	[3]94.1
130	Merck & Co.	PW7	11	73	10	91.0
171	Precision Tube	1	11	73	23	6.4
204	Precision Tube	2	11	73	24	6.4
126	Merck & Co.	PW3	11	75	6	96.7
77	North Penn Water Authority	L-18	11	76	36	67.2
75	North Penn Water Authority	L-16	11	76	72	43.5
124	Merck & Co.	PW1	11	76	3	48.4
202	North Penn Water Authority	L-22	11	76	27	37.6
76	North Penn Water Authority	L-17	11	77	29	40.4
73	North Penn Water Authority	L-14	11	77	55	38.5
78	North Penn Water Authority	L-19	11	77	62	31.9

[1] Pumping included only for scenario “Mg-1610”.
[2] Pumping included only for scenario “Mg-1620”.
[3] Pumping rate at cell is (rate at PW2) + [(rate at PW8) / 2],

The hydraulic conductivity for the upper two interbeds is adjusted for the flowpath simulations. Simulations with the calibrated bed parameters (table 4) yield water levels too high where interbeds AB and BC are present in the model. These beds have very low hydraulic conductivity in the calibrated model, reflecting conditions at Rex. Use of these values, however, for interbeds that extend throughout the entire regional model causes a hydraulic barrier to flow that is inconsistent with observed water levels. For the flowpath simulations here, the hydraulic conductivity of interbeds is increased by two orders of magnitude. This hydraulic-conductivity parameter has the largest relative confidence interval, indicating that it is the least constrained by the measurements. Conceptually, this increase reflects the limited extent of low-hydraulic-conductivity parts of the interbed, or localized fracturing of the interbeds. With this increase, these units still have the lowest hydraulic conductivity in the model.

Pumping well Mg-625 under 1997 Conditions

The simulated contributing area of well Mg-625 is an area of about 3,000,000 ft^2 (fig. 27). Recharge at the well and in an area south of the well is simulated as flowing into the well. A thin region of capture also occurs to the northwest and north and extends more than 3,300 ft from the pumped well. These results reflect the location of the well near the ground-water divide between recharge flowing northeast into tributaries of the Neshaminy Creek and recharge flowing southwest towards tributaries of the Towamencin Creek. These results suggest that pumping at Mg-625 is effective in capturing water infiltrating at Rex south of the pumping well, but that infiltration falling on parts of the property to the north may not be captured by Mg-625 (see fig. 4 for locations). Recharge located downgradient from the pumped well, within about 150 ft of the well, is not captured by the well.

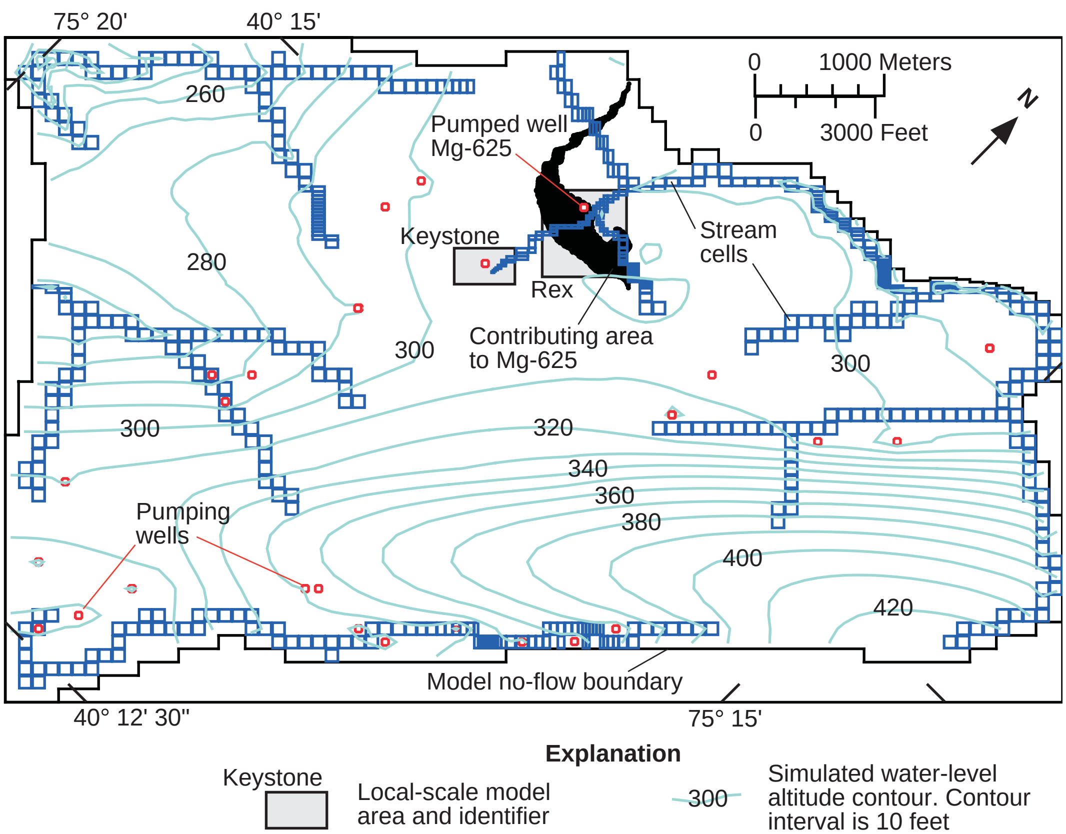

Figure 27.-- Simulated water levels in the upper part of the bedrock aquifer in Lansdale, Pa,. and vicinity for 1997 conditions and contributing area for well Mg-625 pumping at a rate of 30 gallons per minute.

The shape and location of the contributing area is determined by regional flow patterns and the geologic structure of beds of high and low hydraulic conductivity in the vicinity of the pumping well. To illustrate the role of geologic structure, the contributing area simulated with the model developed here is compared to the contributing area simulated using the regional-scale model of Senior and Goode (1999). The size of the contributing areas is identical because the same pumping rate and recharge rate are used. The regional-scale model includes anisotropy to approximate the effects of dipping beds but does not include individual high- or low-permeability beds. Compared to the contributing area simulated with the local-scale model, the regional-scale model contributing area has a larger extent in the strike direction, the direction of preferred flow in the anisotropic model (fig. 28). In the regional-scale model, which used a horizontal grid cell size of 328 ft (100 m), recharge on the surface within about 600 ft of the pumping well is captured. In contrast, the local-scale model, with finer resolution and explicit dipping beds, indicates that recharge as close as a few tens of feet in the downgradient direction (north) will not contribute to the well. The contributing areas to alternative pumping wells, located more to the north or in shallow layers, also could be simulated using this model to compare the effectiveness of capturing recharge in areas that do not contribute to Mg-625.

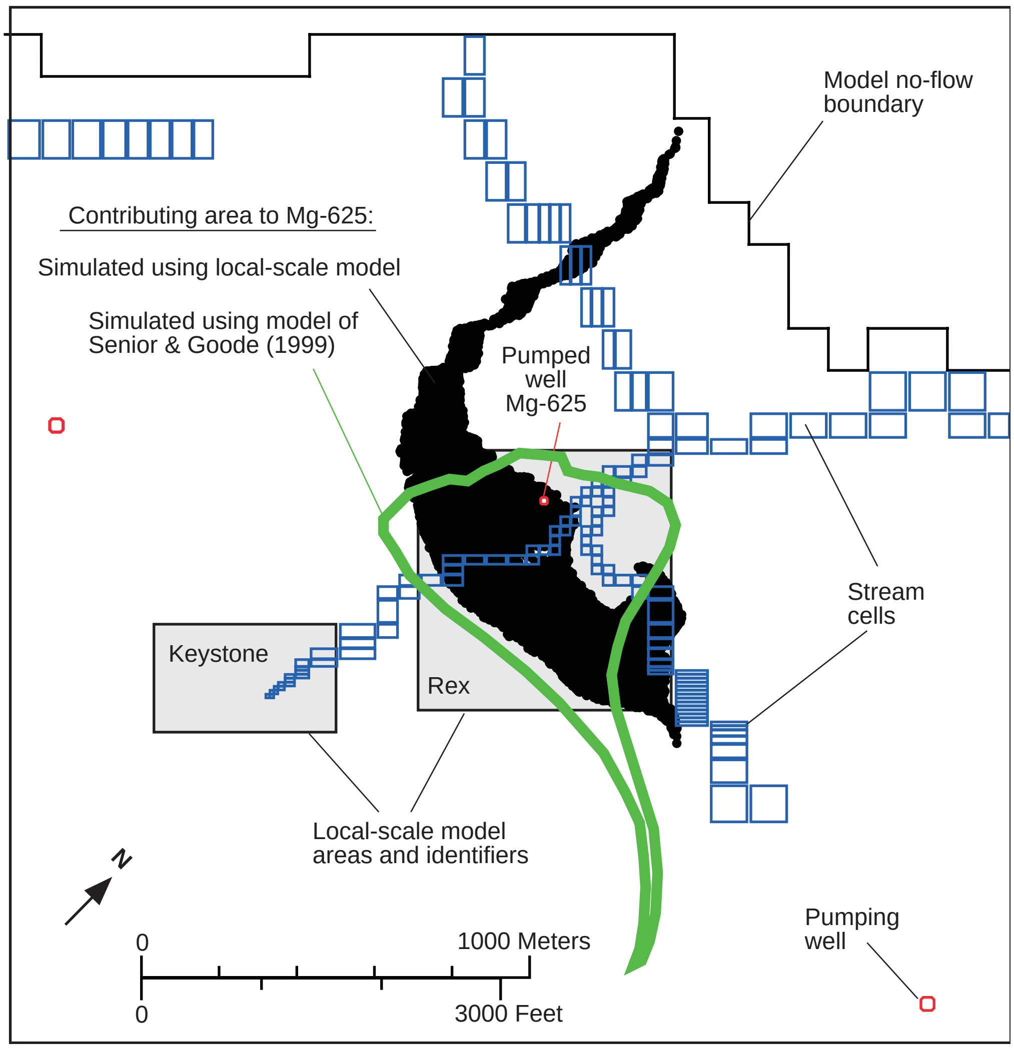

Figure 28.-- Contributing areas for well Mg-625 pumping at a rate of 30 gallons per minute in Lansdale, Pa., for 1997 conditions simulated using the local-scale model developed here and the regional-scale model of Senior and Goode (1999). See figures 27 and 4 for locations.

Additional pumping at well Mg-1610

The simulated contributing area of well Mg-1610 is an area of about 1,000,000 ft^2 (fig. 29). The contributing area includes the land surface at the well location and extends about 1,500 ft east in the upgradient direction. This pumping well is located southwest of the simulated ground-water divide, hence the contributing area is somewhat simpler than that for well Mg-625. These results suggest that infiltrating water northeast and east of the pumping well at the Keystone property would contribute to Mg-1610.

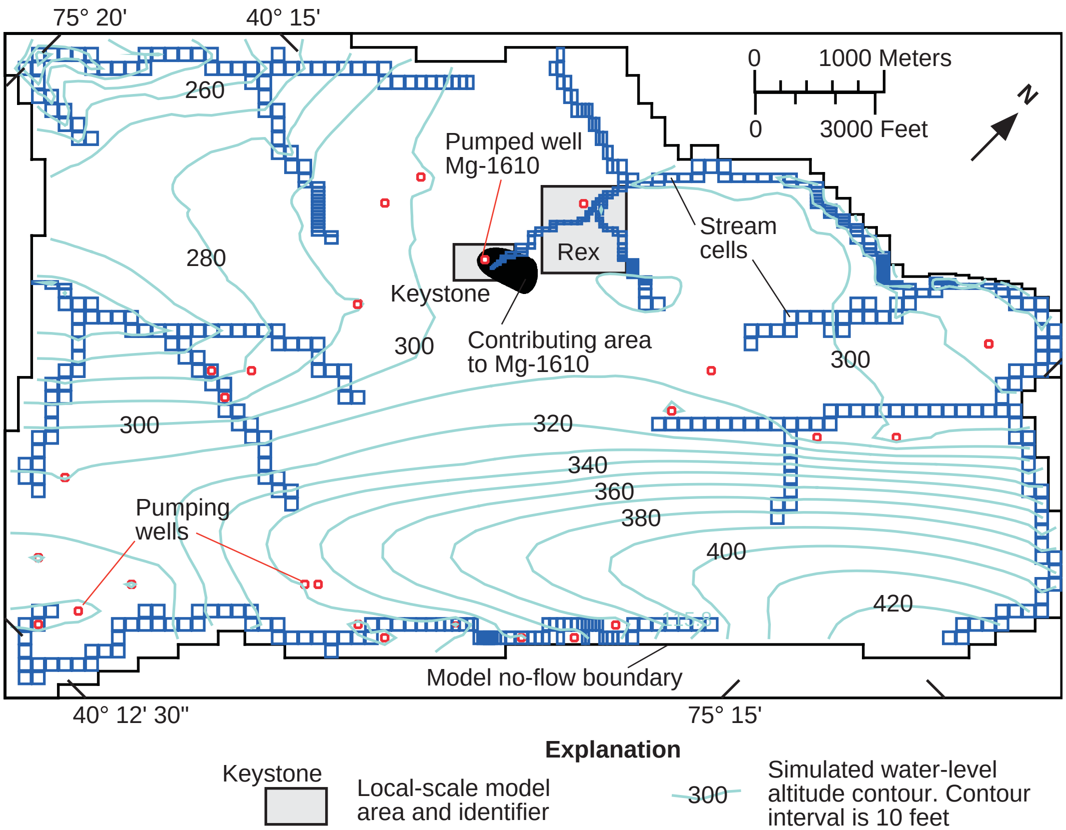

Figure 29.-- Simulated water levels in the upper part of the bedrock aquifer in Lansdale, Pa,. and vicinity, and contributing area for well Mg-1610 pumping at a rate of 10 gallons per minute.

Additional pumping at well Mg-1620

The simulated contributing area of well Mg-1620 is an area of about 1,000,000 ft^2 (fig. 30). The contributing area is very similar to that for well Mg-1610, which is deeper than Mg-1620, but which is open to the same high-permeability bed. The contributing area for Mg-1620 is shifted to the east and south, relative to the contributing area for Mg-1610.

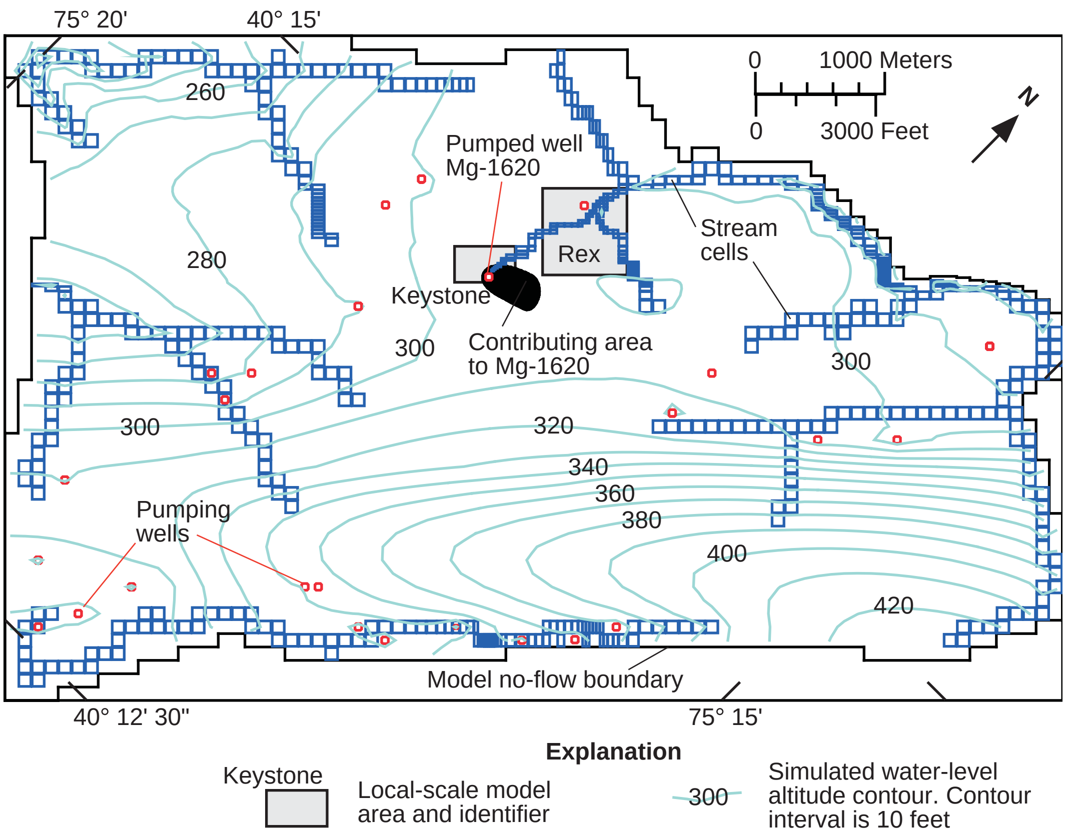

Figure 30.-- Simulated water levels in the upper part of the bedrock aquifer in Lansdale, Pa., and vicinity, and contributing area for well Mg-1620 pumping at a rate of 10 gallons per minute.