## LEICESTER WELL SITE, PAXTON, MASSACHUSETTS

The Leicester public-supply well site in Paxton, MA, is about 4,000 ft east of Paxton Center and 3,000 ft west of Asnebumskit Hill and Little Asnebumskit Hill (fig. 39). The study area encompasses approximately 16 $mi^2$ and extends to streams, reservoirs, or presumed ground-water divides that could serve as boundaries for numerical modeling. Crocker Hill, near the center of the study area, marks the intersection of three major drainage basins: the Chicopee River to the west, the Nashua River to the north, and the Blackstone River to the southeast. The well site is in the headwaters of Kettle Brook in the Blackstone River Basin. Kettle Brook Reservoirs 3 and 4 (fig. 39) are part of the water-supply system for Worcester, MA. The well site is in a rural residential area where most homes obtain water from a Paxton public-supply system, but a few homes obtain water from private wells. Much of the land east of Grove Street near the wells includes open fields, forests, and wetlands and is restricted from development to protect water supplies (Frank Lyon, Leicester Water Department, written commun. 2001).

Wells at the site (fig. 40) include the rock-lined dug well 13 (Jim Dandy), which has supplied water intermittently since the late 1800s; well 14 (No. 1), a 150-ft deep rock well drilled in 1908; well 1 (No. 2), a 537-ft deep rock well drilled in 1948; well 19 (No. 3), a 700-ft deep rock well drilled in 1954; and well 15 (Pierce Spring), a circular rock-lined dug reservoir that collects water from wells 14 and 1 before distribution to a pipeline into Leicester. Well 15 reportedly receives 16 gal/min from ground-water sources other than wells 1 and 14 (table 12, at back of report). Water from well 19 flows directly to the water-supply pipeline. Well 14 is pumped continuously, and wells 1 and 19 are pumped intermittently. Typically, well 1 is pumped during the winter and spring, and well 19, because of a somewhat higher yield than well 1, is pumped during the summer and fall (Frank Lyon, oral commun., 2001).

Well yields reportedly fluctuate with season (Frank Lyon, oral commun., 2001). This characteristic of bedrock wells was supported by limited data collected during this study. For example, in February 2001, well 14 produced water at a steady rate of about 40 gal/min, but the rate declined to 23 gal/min by August. Water could be heard cascading into well 1 in February 2001, but no cascading water was apparent in August.

In the spring and summer of 2001, beaver dams flooded approximately 9 acres of land near the wells (fig. 40). Flow was observed in the spring and early summer of 2001 in channels that intermittently drain upland areas to the west and south near Wells 14 and 1. The water level in the beaver pond declined slowly during the summer and early autumn.

In the spring and early summer of 2001, the USGS installed 16 shallow piezometers for water-level observations and 2 stream-gaging stations (figs. 39 and 40; table 12). Also, three residential bedrock wells were selected for water-level observations during aquifer testing. Aquifer testing in August involved a 1-week-shutdown (recovery) period followed by continuous pumping in two wells. During aquifer testing, borehole geophysical logs were collected from well 19. Water-level and stream gaging continued until early winter to provide baseline information for hydrologic analysis. Stream discharges at the two stream-gaging stations were of limited use for this study and are not included in this report.

### Geology

The bedrock geology near the Leicester wells was mapped in the summer of 2001 as part of this study (Walsh, 2002). The following discussion of bedrock geology is from his report. Surficial materials in part of the study area were mapped by Stone (1980).

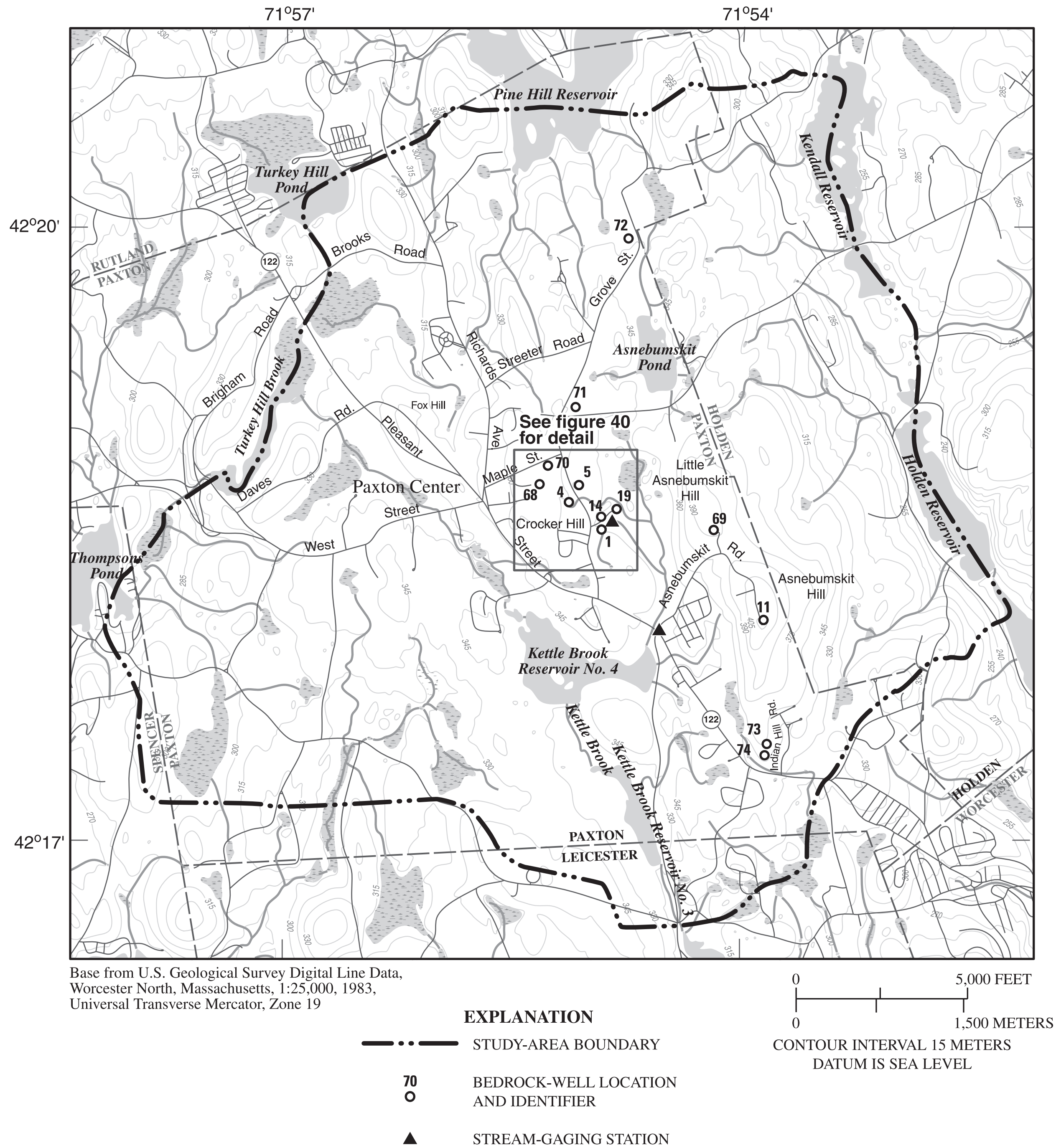



**Figure 39.** Location of the study area, selected bedrock wells, stream-gaging stations, Paxton study area, Massachusetts.

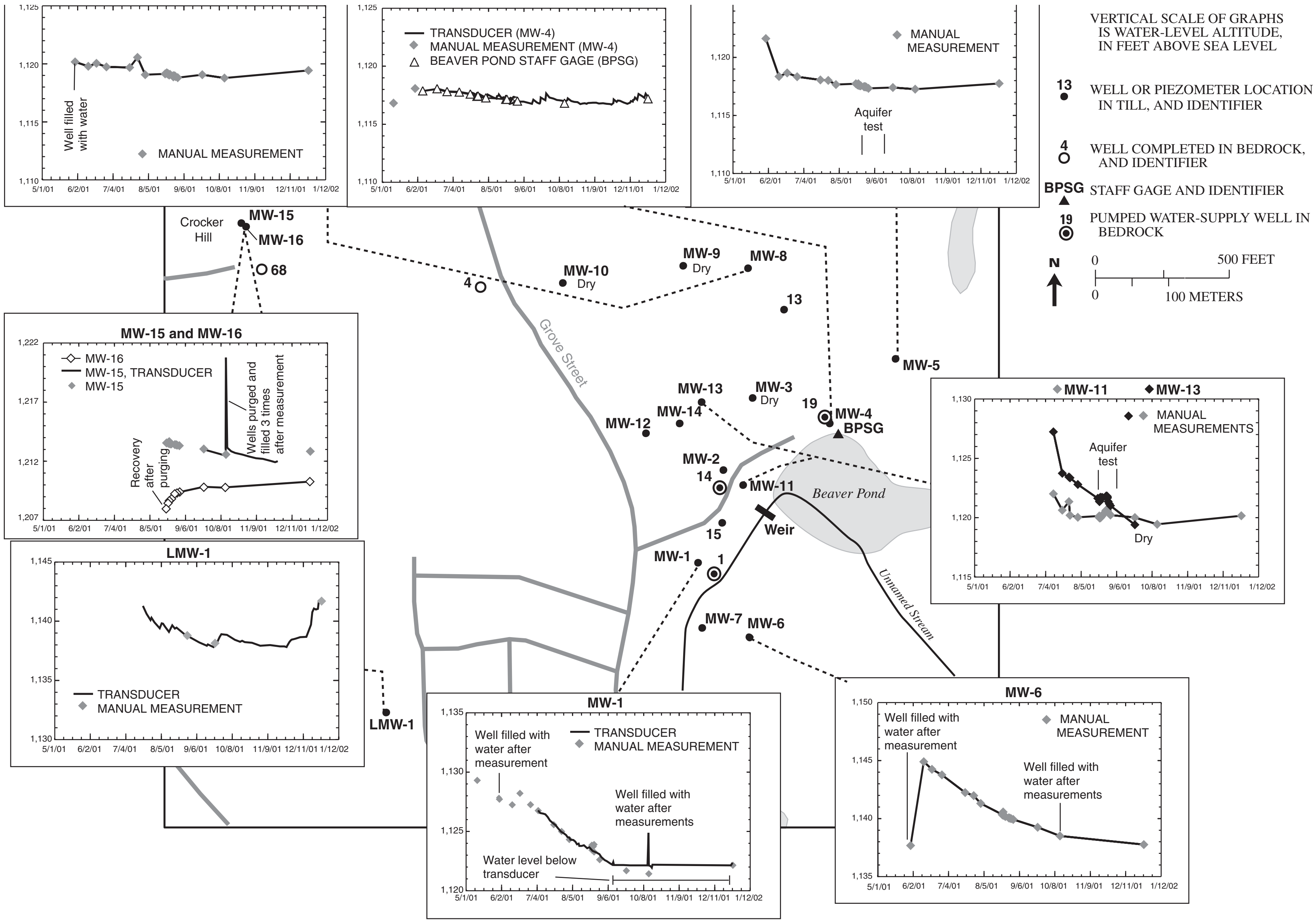



**Figure 40.** Water levels in selected piezometers and staff gage, May–December 2001, Paxton study area, Massachusetts.

### Bedrock

Bedrock in the study area consists mainly of granofels, schist, and quartzite of the Paxton and Littleton Formations (fig. 41). The Paxton Formation contains three distinct metasedimentary units: biotite and calc-silicate granofels, sulfidic schist, and sulfidic quartzite and schist (fig. 41). A distinguishing characteristic of the unit is the slabby outcrops and distinct partings along the foliation. The sulfidic quartzite and schist unit (Spqr) forms a resistant cap above the granofels unit (Sp) in the ridge formed by Little Asnebumskit Hill and Asnebumskit Hill. The Littleton Formation consists of interbedded biotite-muscovite-quartz schist and quartzite. The Littleton Formation is interpreted as an overturned syncline truncated along a thrust fault. Dikes and sills of biotite granite and granitic pegmatite intrude the metasedimentary rocks in the area.

The dominant planar ductile fabric is a second generation (S2) schistosity in metasedimentary rocks and a foliation that ranges from a cleavage to gneissosity in the granitic and pegmatitic rocks. The average strike and dip of S2 is 352°, 10° east (fig. 41). Parting along S2 surfaces is common in all rocks, particularly the Paxton Formation granofels (Sp).

The major fractures are along the S2 foliation. Fracture aperture is small, and the fractures are not filled with vein minerals. Mapping indicates that the fractures are regionally extensive but not well interconnected. Most of the fractures, other than those along the S2 foliation, dip steeper than 60°. The intrusive rocks are more fractured than the metasedimentary rocks. Rocks in the Paxton area are less fractured than rocks that were mapped in West Newbury and Maynard as part of this study. Principal strikes of steeply dipping fractures in intrusive rocks include 1°, 54°, and 68°. Principal trends of steeply dipping fractures in the metasedimentary rocks are tightly clustered at 281°, 296°, and 313°.

### Surficial Geologic Units

Surficial materials, where mapped east of Crocker Hill, consist predominantly of thin surface till, but in places include surface till over thicker drumlin till (Stone, 1980). Thin till is mapped on Asnebumskit and Little Asnebumskit Hills, where bedrock is exposed in many places (fig. 41). Till is interpreted as the main surficial geologic unit in unmapped areas west of Crocker Hill. Till thickness varies from zero in scattered rock outcrops to a maximum of 40 ft reported for well 70 (fig. 39). Near the Leicester wells, till is generally less than 25 ft thick (table 12) as indicated by refusal depths in piezometers. During installation of piezometers, till near the lowland area was less dense than the till on hill slopes and near hilltops. The piezometers in lowland areas also yielded water more readily than piezometers elsewhere.

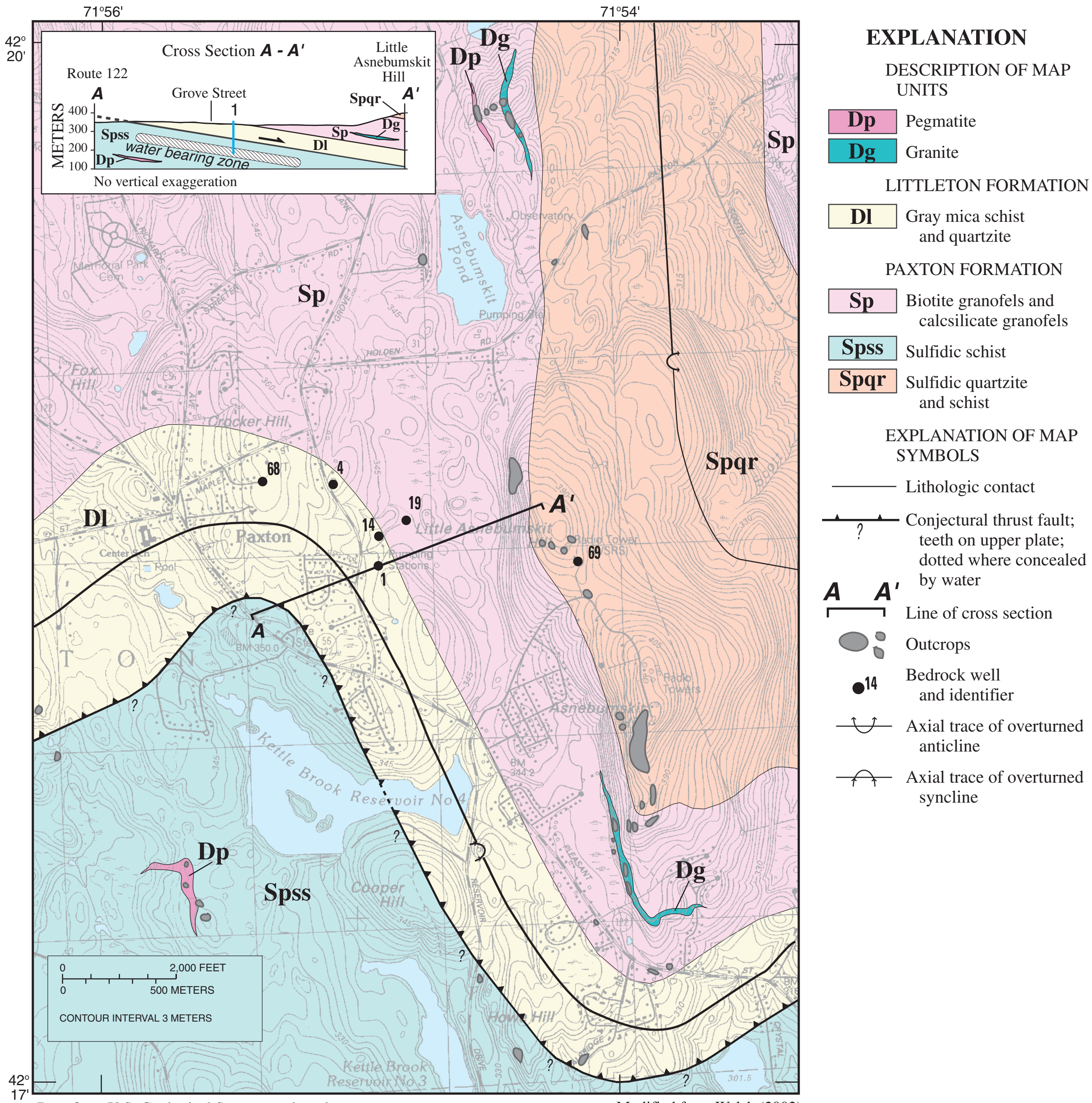
## Ground-Water-Flow Patterns and Water-Level Fluctuations

Water-level data for piezometers completed in till indicated that the water table parallels the land surface. Many ephemeral streams receive flow from shallow ground water when water levels are high in the late winter and spring. Some ground water in till on hills and near pumped wells, where steep vertical gradients are apparent from water-level data, leaks downward to recharge bedrock. Near wells 1, 19, and 68, water levels in deep bedrock are 100 ft or more below water levels in surficial materials; an unsaturated zone in bedrock is likely where bedrock water levels are below the base of surficial materials.

Water levels in piezometers completed in till on hilltops and hill slopes declined gradually during much of the observation period because of limited recharge (fig. 40). During this same period, water levels also fell below the bottom of the screen in several piezometers. Typically, wells completed in till are responsive to recharge from precipitation. This fact is apparent in water levels measured in observation well LMW-1 (fig. 40). Water levels in piezometers MW-4, MW-5, MW-8, and MW-11 near wetlands reflect the wetland water table, including the beaver pond, and they fluctuated less than 2 ft during the study. The water levels in well MW-4, which is screened at a depth of 18.1 to 23.1 ft below the land surface, are nearly identical to stage in the beaver pond measured at a nearby staff gage (fig. 40).

## Ground-Water Recharge

Ground-water-recharge rates to till may be limited mainly by precipitation minus evapotranspiration rates; and in places, by a shallow water table. Much of the recharge to till in upland areas may flow laterally and discharge to local drainages. Leakage rates from till to bedrock probably vary with the character of till.




Base from U.S. Geological Survey quadrangles, Paxton, 1979, and Worcester North, Massachusetts, 1974, 1:25,000

Modified from Walsh (2002)

**Figure 41.** Bedrock lithologic units, structural features, and a generalized geologic cross section, Paxton study area, Massachusetts.

A persistently shallow water table at piezometers MW-15 and MW-16 on Crocker Hill (fig. 40) and low yields indicate the presence of dense till and limited vertical leakage in that area. Leakage rates may be greater near pumping well 14 where water levels were several feet below the land surface during the observation period and where water levels responded to pumping, as discussed in the next section. Conceptually, leakage rates are greater in areas underlain only by surface till than in areas underlain by deeper drumlin till. Hydrologic data are insufficient to determine recharge rates to till and leakage rates to bedrock.

## Aquifer Testing and Observed Hydrologic Responses to Pumping

Aquifer testing included a recovery period of 7 days from August 20 to 27, 2001, followed by an extended pumping period. A trace of precipitation fell during the aquifer-test period. During the test period, water levels were declining in the region, as shown by the hydrograph for USGS observation well HRW-169 completed in till about 4 mi northeast of the well site (fig. 42). Pumping at well 19 was discontinued on August 20 after about 3 months of continuous pumping. A flowmeter indicated the well was producing about 60 gal/min when pumping ended. The pump was then removed to gain access to the well for water-level observations and borehole logging. The next day, August 21, pumping at well 14 was discontinued after several years of nearly continuous pumping (Frank Lyon, oral commun., 2001). Before shutdown, a flowmeter indicated the well was producing 23 gal/min, but a higher rate of 40 gal/min was measured on February 7, 2001. During the test, water levels were measured manually with a water-level indicator or steel tape in wells 14 and 19, 16 piezometers, and 3 residential wells. Pressure transducers and recorders also were used to monitor water levels in three piezometers and one bedrock well (fig. 40). Water levels in well 1 and in well 14 (when the water level was below a zone of cascading water at a depth of 60 ft) were measured by applying air pressure to an air line and reading depth to water directly from a pre-calibrated pressure gage. A staff gage in the beaver pond (BPSG) was read periodically.

After the 7-day-recovery period, the start of pumping at wells 1 and 14 was staggered by about 21 hours. Pumping at well 1 started on August 27, 2001. Flow was measured volumetrically at Pierce Spring (well 15). Flow that was diverted to a level about 6 ft above the water level in Pierce Spring may have caused the measured discharge rate to be somewhat lower than the rate for most of the time between measurements. Discharge and water-level data for well 1 show that a head rise of 6 ft at the discharge pipe can cause a reduced pumping rate of 3 to 4 gal/min. Pumping at well 14 started on August 28; discharge was read periodically from a meter.

The water level in well 14 recovered rapidly after pumping ceased and nearly stabilized after about 3 days. While the well was pumping and during early stages of recovery, water cascading into the well at a depth of about 60 ft prevented manual water-level measurements below that depth. Water was heard cascading into the well until the water level recovered to a depth of about 19 feet below the land surface, indicating a second major water-producing interval at that depth.

Recovery in wells 1 and 19 was slow, and water levels did not stabilize during the 7 days of recovery. Water levels in wells 1 and 19 closely paralleled each other during recovery and subsequent pumping. The water level in residential well 68 rose approximately 35 ft during the recovery period. This well reportedly yields about 7 gal/min. Water levels at wells 4 and 69 did not change when pumping ended. Well 4 is unused and apparently is completed in poorly transmissive bedrock. Its low transmissivity was apparent when 4 gal of water poured into the well caused the water level to rise suddenly about 3 ft with no discernible decline for the next half hour. Well 69 supplies water for radio station WSRS and reportedly yields 22 gal/min. The fairly high yield was confirmed by observed fluctuations of less than 1 ft during pumping cycles.

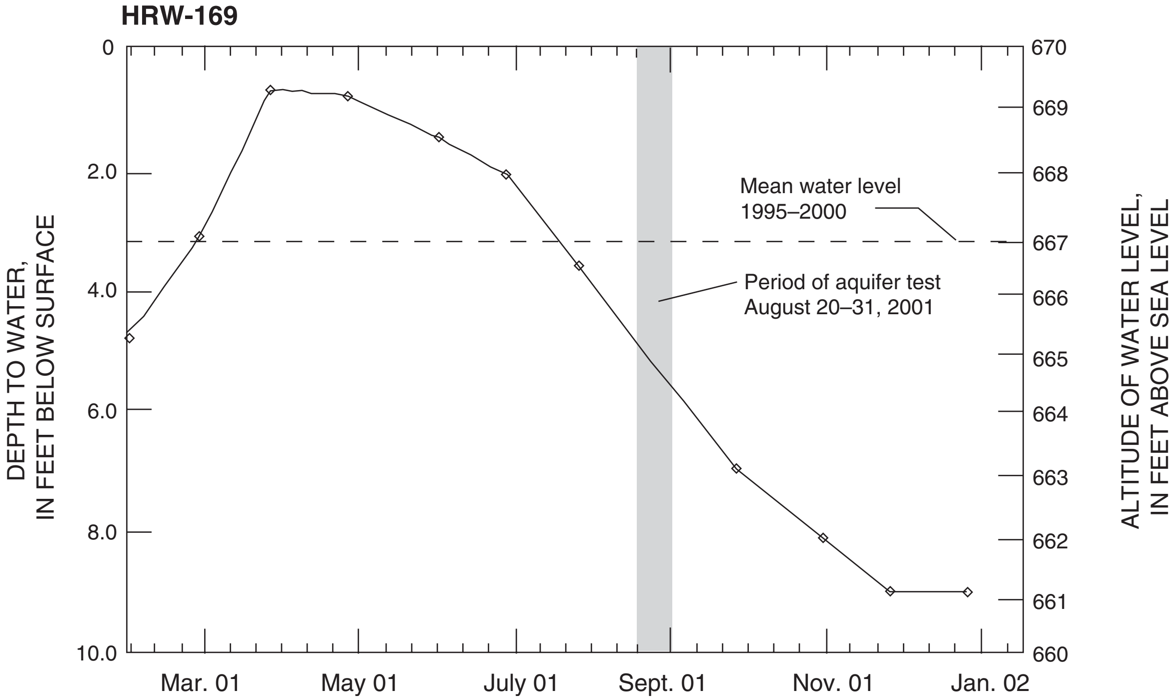



**Figure 42.** Graph showing water level in U.S. Geological Survey observation well HRW-169, January–December 2001, Holden, Massachusetts.

Water levels in piezometers MW-2, MW-11, MW-13, and MW-14 rose during the recovery period and declined during the subsequent pumping period, indicating a hydraulic connection to surficial materials near well 14. These responses for wells MW-11 and MW-13 are apparent on selected hydrographs shown on figure 40. The water level in well MW-2 (not shown on fig. 40) rose about 0.8 ft into the screened interval during the recovery period, and it fell below the screened interval approximately 2 hours after pumping started. Water levels in piezometers MW-1 and MW-4 near wells 1 and 19 did not respond to the aquifer test. A response in these piezometers is unlikely because water levels in the bedrock wells were well below the water table throughout the recovery period, and distances were too great to be affected by testing at well 14.

Borehole flow was measured in well 19 with a heat-pulse flowmeter during the recovery period and subsequent pumping period. One day after pumping ended in well 19, while the water level was recovering slowly, about 0.4 gal/min entered the well above a depth of 250 ft, flowed downward, and exited the well between depths of 250 to 300 ft. Concurrently, about 0.25 gal/min was entering the well at depths below 620 ft and exiting at about 500 ft. Borehole flow was too small to detect any flow from 300 to 500 ft and near the top of the water column where the well was filling at a rate of 0.015 gal/min, which is below the flow-detection limit of 0.02 gal/min. Also, a flow meter would not have detected flow that may have entered the well through the open hole above the water level. Several hours after pumping started in well 1, flow entered well 19 at depths above 100 ft (0.37 gal/min), at about 170 ft (0.05 gal/min), and at about 310 ft (0.49 gal/min). Flow exited the well at about 470 ft (0.08 gal/min) and at about 640 ft (0.84 gal/min). These borehole-flow data indicate that a transmissive zone below 640 ft provides a hydraulic connection between wells 1 and 19.

## Hydraulic Properties of Geologic Units

Water-level data during startup for the deep bedrock well 1 indicated no discernible vertical connection at the shallow bedrock well 14. A slow recovery during later stages of recovery in well 14 reflected resaturation of surficial materials near the well. Water-level rises in nearby piezometers also indicate resaturation of surficial materials. The hydraulic properties of bedrock will be discussed in the modeling section for the Paxton study.

Low yields and slow response of water levels in piezometers after purging and filling with water indicate that the hydraulic conductivity for till at this site probably is at the low end of a range of 0.0028 to 65 ft/d for surface and drumlin tills reported by Melvin and others (1992). An even slower recovery after purging or recession after filling piezometers MW-6, MW-15, and MW-16 indicates a lower hydraulic conductivity than at the other piezometers completed in till.

## Numerical Models

Geologic and hydrologic data from the Paxton study area support two contrasting conceptual models of ground-water flow. One conceptual model, a 2-layer model (fig. 43), includes a shallow flow system in till and shallow fractures in bedrock, supported by data from well 14, and also includes a deep flow system through subhorizontal fractures in the bedrock that are poorly connected vertically to the shallow system. A second conceptual model, a 5-layer model (fig. 43), invokes flow along schistosity partings in zones that dip at about 10° to the east. Rationale for the five layers is discussed in the section on horizontal and vertical discretization. A uniform strike was assumed for simplicity, but strike actually varies across the study area (Walsh, 2002). The till and wetland sediments at the surface are assumed to be extensions of the sloping layers in their outcrop areas. The models are useful for illustrating effects of alternative aquifer geometries.

Each model was calibrated to the extent possible with limited data by adjusting model characteristics and comparing simulated heads to measured heads for steady-state and transient conditions. The models demonstrate how contrasting conceptual models can affect estimates of contributing areas and effects of pumping on wetlands and streams. Because of limited data for calibration and the simplification of geologic features, actual contributing areas and pumping effects may be considerably different than those presented.

### Areal Extent and Boundary Conditions

The model area (fig. 44) covers about 16 $mi^2$. The boundaries of the models coincide approximately with surface-water bodies or wetlands in many areas. In these areas, constant heads were assigned to layers exposed at the land surface. Altitudes of the constant head blocks are estimated from topographic contours. Elsewhere, the edges of the models were extended to presumed ground-water divides, which are treated in the models as no-flow boundaries. Sloping layers in the 5-layer model extended to sea level, assuming limited ground-water flow below this altitude.

### Horizontal and Vertical Discretization

A finite-difference model grid of uniformly spaced square block 200-ft wide on a side was used for both models. For the 2-layer model, layer 1 approximately represents shallow bedrock and till, and layer 2 represents deep bedrock (fig. 44). A uniform thickness of 200 ft was assigned for layer 1, and a uniform thickness of 500 ft was assigned for layer 2. Layer 1 was simulated as unconfined, and layer 2 was simulated as confined but convertible to unconfined if the simulated head was below the top of the layer.

The 5-layer model consists of five sloping layers (fig. 43). A uniform strike of 352° and dip of 10° east for fractures along foliation present within a few thousand feet of the wells was assumed throughout the model area. The top, bottom, and thickness of each layer were based partly on well depths and results of borehole-flowmeter tests. The bottom of layer 1 was placed at the bottom of well 69. The bottom of layer 2 was placed at the bottom of well 14, and the bottom of layer 3 was placed 320 ft above the bottom of well 19, which is the bottom of layer 4 at that location. The hydraulic conductivity of layer 3 appears to be lower than the conductivity of layers 2 and 4 on the basis of borehole-flowmeter logs. The land-surface altitude forms the top where the layer intersects the land surface, and the minimum bottom altitude is sea level. For layer 5, the bottom is at sea level throughout its extent.

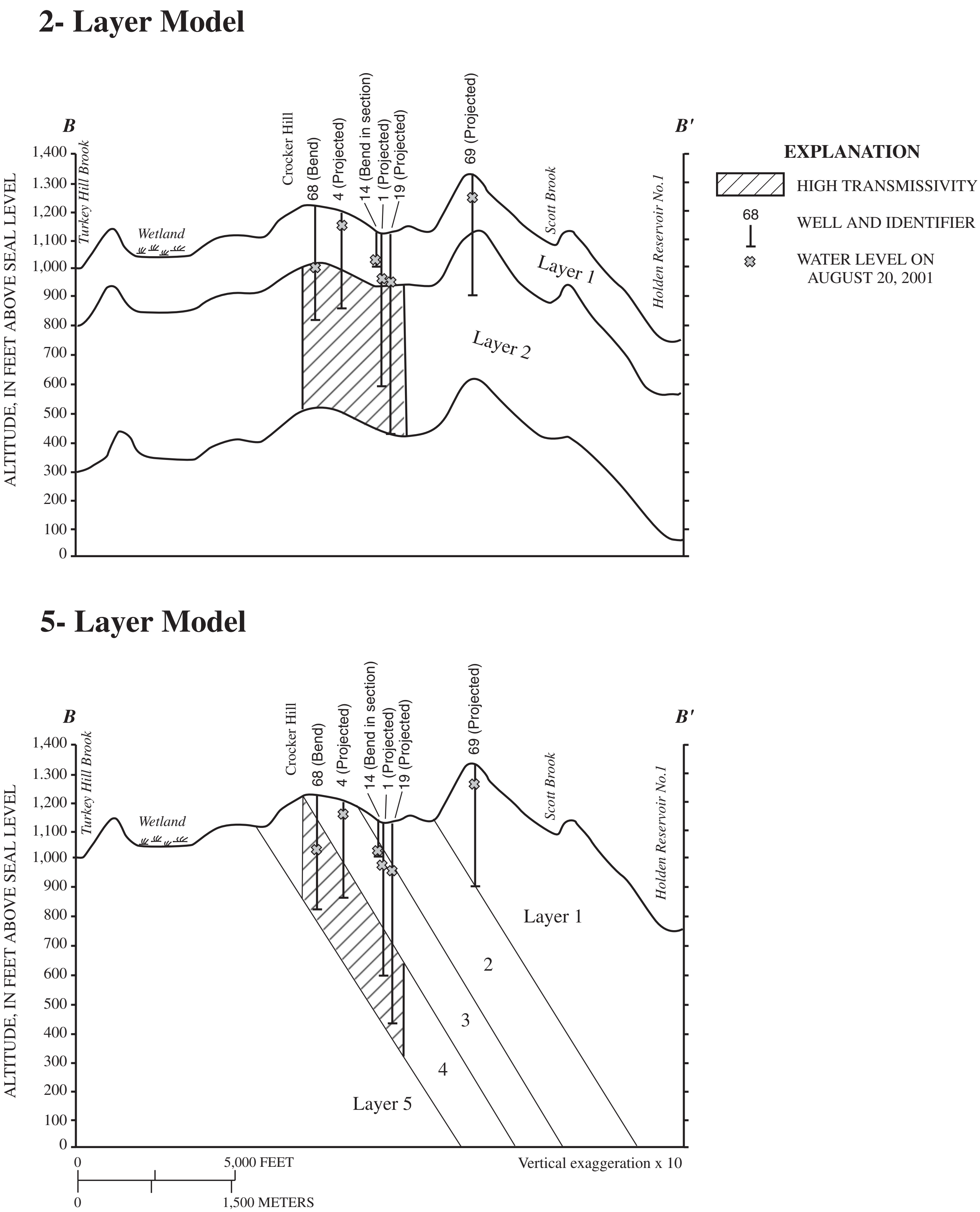



**Figure 43.** Cross sections showing model layers for the 2-layer and 5-layer models, Paxton study area, Massachusetts.

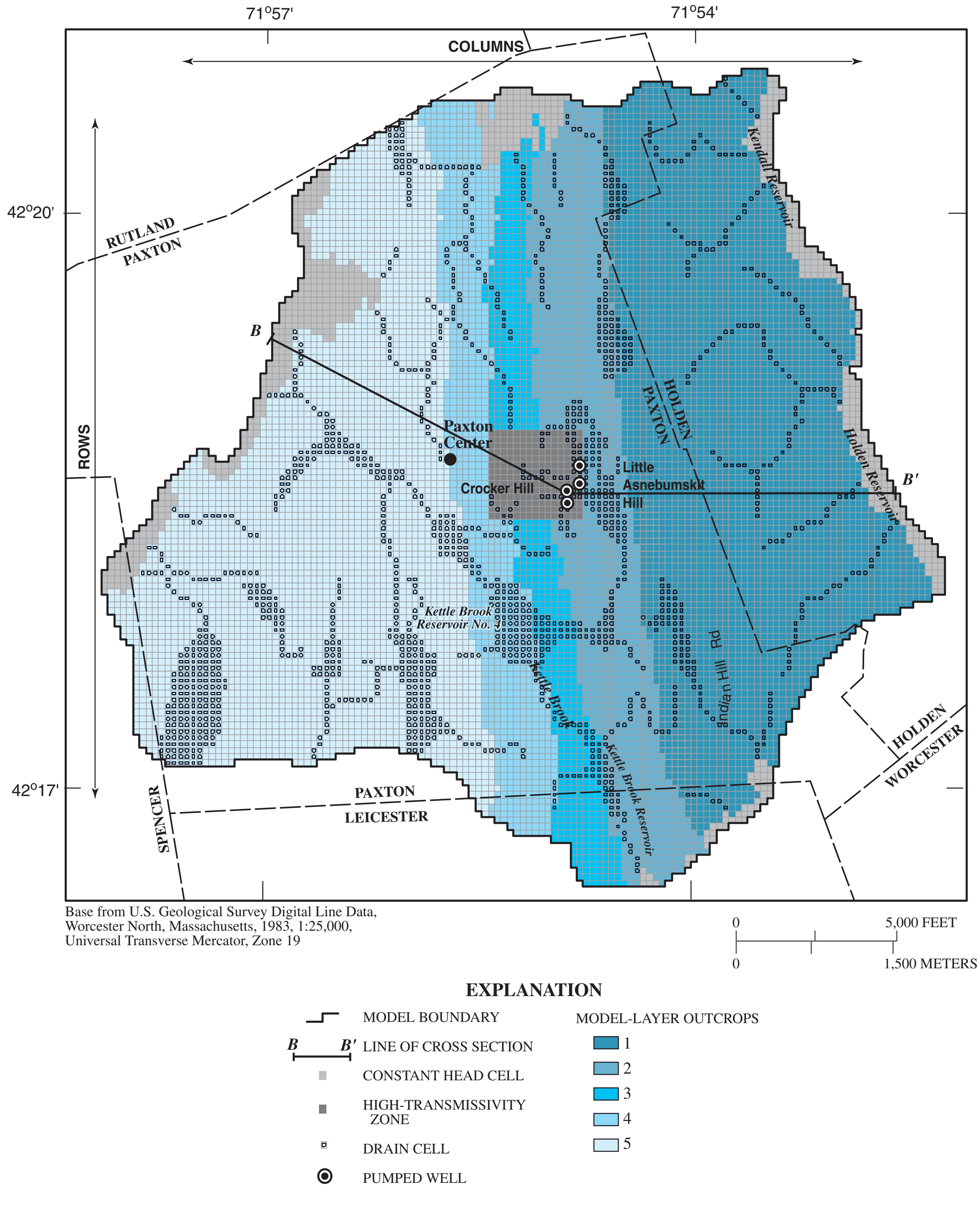



**Figure 44.** Model boundaries and zones, Paxton study area, Massachusetts.

## Model Stresses

Model stresses include drains at the land surface, wells, and recharge. Drains were placed at stream locations or along topographic depressions that are possible discharge areas for ground water. A large uniform conductance of 10,000 $ft^2/d$ was assigned so that aquifer properties, rather than the drain conductance, constrained flow into the drains. It is assumed that leakage rates from streams are negligible. Drain altitudes were held constant during simulation of the aquifer test.

Model-simulated pumping wells were placed at locations of wells 14, 1, and 19 for simulation of steady-state conditions and for simulation of the aquifer test. For the 2-layer model, well 14 was placed in layer 1, and wells 1 and 19 were placed in layer 2. For the 5-layer model, well 14 was placed in layer 2, and wells 1 and 14 were placed in layer 4. Initial steady-state heads were simulated by pumping well 19 at a rate of 60 gal/min and well 14 at a rate of 23 gal/min, which were the pumping rates at the time the wells were shut down. The recovery and subsequent drawdown tests were simulated in seven stress periods that represent varying pumping rates (fig. 45).

Wells pumped for simulation of contributing areas included bedrock wells 14, 1, 19, and shallow well 13. The MADEP determined approvable yield rates for each well on the basis of historical records of maximum monthly usage (Joseph Cerutti, oral commun., 2001). The MADEP-approved yield rates are 50 gal/min for well 14; 86 gal/min for well 1; 91 gal/min for well 19; and 70 gal/min for well 13. These yields, however, caused model nodes to go dry at the locations of wells. To prevent well nodes from going dry during simulations, pumping rates were adjusted downward by 50 percent in all wells for both models. The reduction of the pumping rate at well 14 from 50 gal/min to 25 gal/min is reasonable considering the yield of 20–25 gal/min observed in August 2001 while the water level was at the pump level. Higher yields observed in the spring of 2001 indicate that the yield may change seasonally with recharge. Well 13 reportedly yields 70 gal/min but has not been tested to demonstrate that this yield can be sustained. Reported yields for wells 1 and 19 probably do not account for the interference effects between wells.

A recharge of 0.001 ft/d (4.4 in/yr) was applied to the uppermost active layer of the models over most of the model area. This rate was adjusted downward from an initial rate of 0.0021 ft/d (9 in/yr) that caused

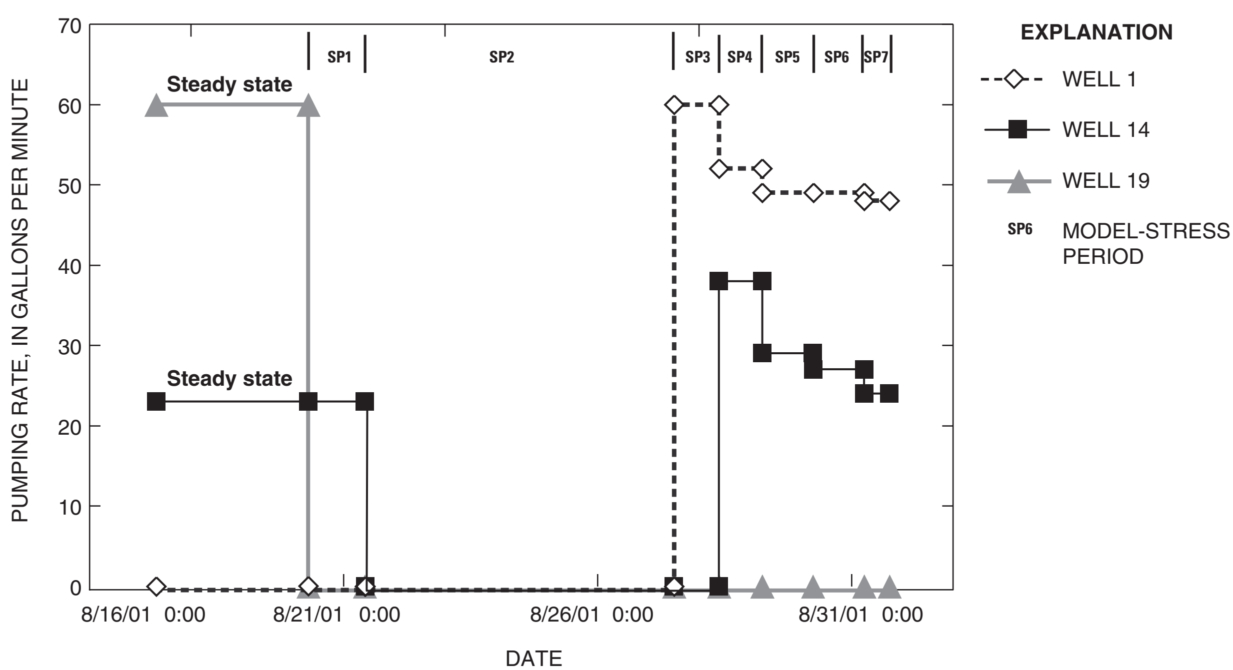



**Figure 45.** Observed pumping rates during aquifer testing and simulated stress periods, Paxton study area, Massachusetts.

heads to rise above the land surface in many areas. A higher rate of 0.0123 ft/d (54 in/yr) was assumed to be available for recharge in the lowland area near the wells because of runoff from upland areas. In the lowland area, 24 in/yr is available from infiltration of precipitation. If recharge in the upland area to the west is 4.4 in/yr, about 19.6 in/yr may flow to the valley as surface runoff. Some of the runoff flows directly to stream channels and may not be available for recharge.

For the models, it was assumed that 15 in/yr of upland runoff is available for recharge throughout the valley. Because the upland area is about twice the size of the valley area, 30 in/yr was assumed to be available for recharge, in addition to the 24 in/yr from infiltration of precipitation. Additional runoff from Little Asnebumskit Hill was not considered in the estimate because of the limited drainage area adjacent to the valley and the distance from the wells. Much of the recharge applied in the lowland area discharges to drains in the model. The same recharge rates were assumed for steady-state and transient simulations.

A recharge rate of 0.0034 ft/d (15 in/yr) was assumed on Asnebumskit and Little Asnebumskit Hills. A higher rate here was needed to simulate the observed head at well 69 and, conceptually, reflects a thinner and less dense till layer that results in infiltration rates greater than rates in other till-covered areas. This rate also was used for thin-till areas in the West Newbury study area.

### Hydraulic Properties

Hydraulic conductivities were initially estimated from aquifer-test results and adjusted during model calibration (table 8). For the 2-layer model (fig. 43), a hydraulic conductivity of 0.2 ft/d caused an initial head at well 14 that was slightly above a water-producing fracture at an altitude of about 1,060 ft. For the 5-layer model, a hydraulic conductivity value of 0.5 ft/d in layer 2 was needed to simulate a head at well 14 that was slightly above the level of the water-bearing fracture. The two values yield similar transmissivities near the well because the saturated thickness of layers near the well is greater for the 2-layer than for the 5-layer model. Hydraulic properties for layers 1, 3, and 5 in the 5-layer model are poorly constrained by available data; a uniform hydraulic conductivity value of 0.2 ft/d was selected for these layers.

A high-transmissivity zone surrounded by a low-transmissivity zone was hypothesized for the layer of each model that contained wells 1, 19, and 68 (fig. 44). A high-transmissivity zone was needed in the model to simulate the observed response at well 68, but the configuration and extent of the high-transmissivity zone could not be determined from the available data. For simplicity, a rectangular area that encompasses the three wells was assumed. The high-transmissivity zone shown in figure 44 was assigned a hydraulic conductivity value of 1.0 ft/d for both models. The surrounding low-transmissivity zone was assigned a hydraulic conductivity of 0.02 ft/d. These values reflect adjustments made during model calibration. The simulated thickness of 320 ft for layer 4 probably is much greater than the actual thickness of the water-producing zone at depth. Thus, the lower hydraulic conductivity value for layer 4 outside of the high-transmissivity zone than for other layers reflects a transmissivity (hydraulic conductivity times thickness) that is reasonable for a thinner water-producing layer. For example, a layer-4 thickness of 320 ft multiplied by a hydraulic conductivity of 0.02 ft/d yields the same transmissivity as a 32-ft-thick layer that has a hydraulic conductivity of 0.2 ft/d, which is the hydraulic conductivity assigned to adjoining layers (table 8). For the same reason, the actual hydraulic conductivity for the high-transmissivity zone may be greater than the 1 ft/d used in the model.

### Model-Simulated Heads

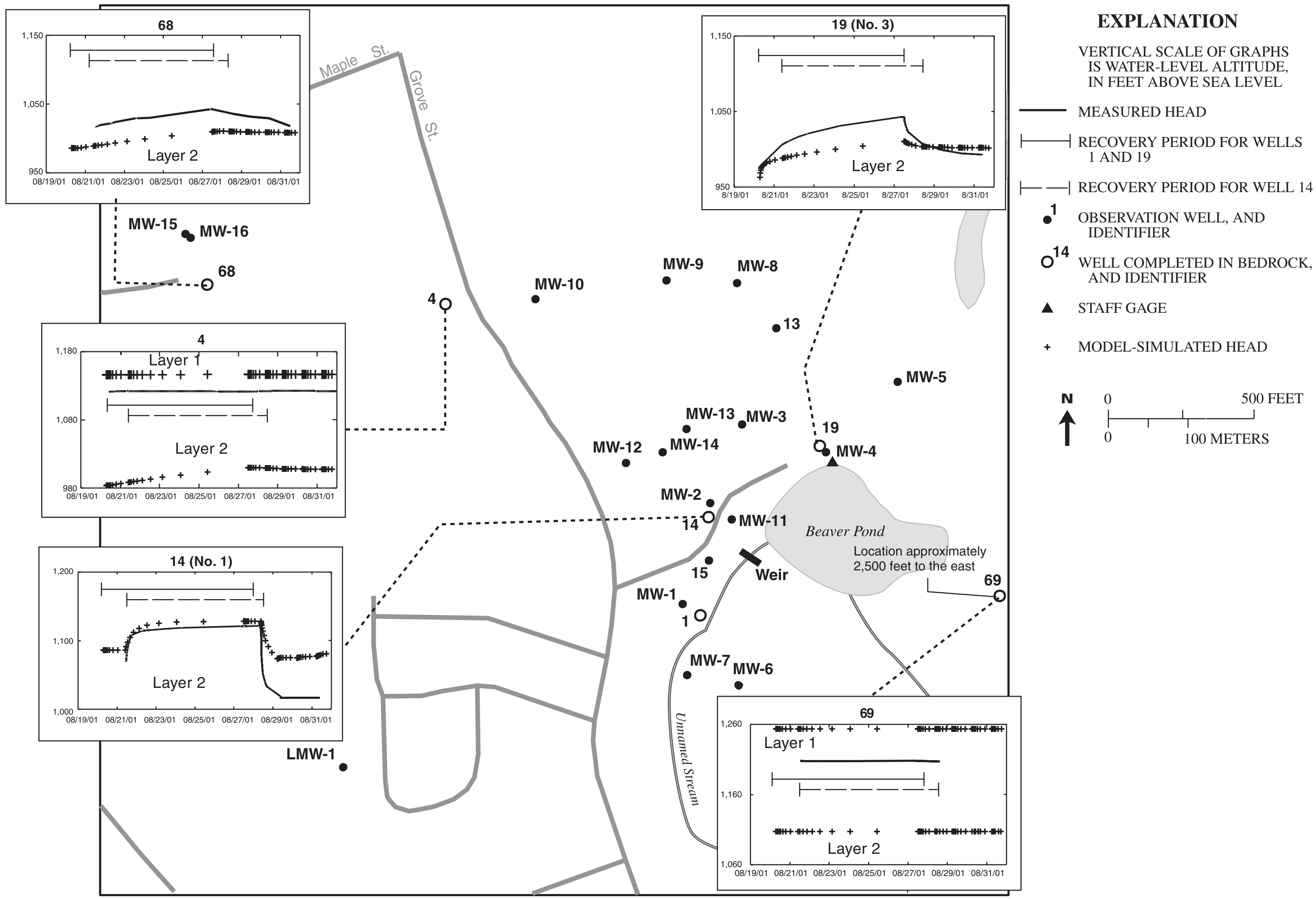
Generally, model-simulated heads for the aquifer-test period indicated that the 5-layer model more closely approximated heads than the 2-layer model. To observe the effects of different aquifer geometries on simulated contributing areas, the hydraulic properties for the 2-layer model were selected to be similar to properties in the 5-layer model. Further refinement of hydraulic properties for the 2-layer model by calibration was unnecessary for this study. Observed water levels in wells 4 and 69 were between simulated water levels for the layers in the 2-layer model (fig. 46). These levels are reasonable because both wells penetrate deeper than the bottom of layer 1 in the 2-layer model. Simulated heads that were below observed heads for these wells in the 5-layer model (fig. 47) were also considered reasonable, given the depths and possible producing intervals of the wells.

**Table 8.** Summary of properties for 2-layer and 5-layer models, Paxton study area, Massachusetts

[NA, not applicable; $day^{-1}$, 1/day; $ft^3/d$, cubic feet per day; ft, foot; ft/d, foot per day; $ft^2/d$, square feet per day; gal/min, gallons per minute; in/yr, inches per year; °, degree]

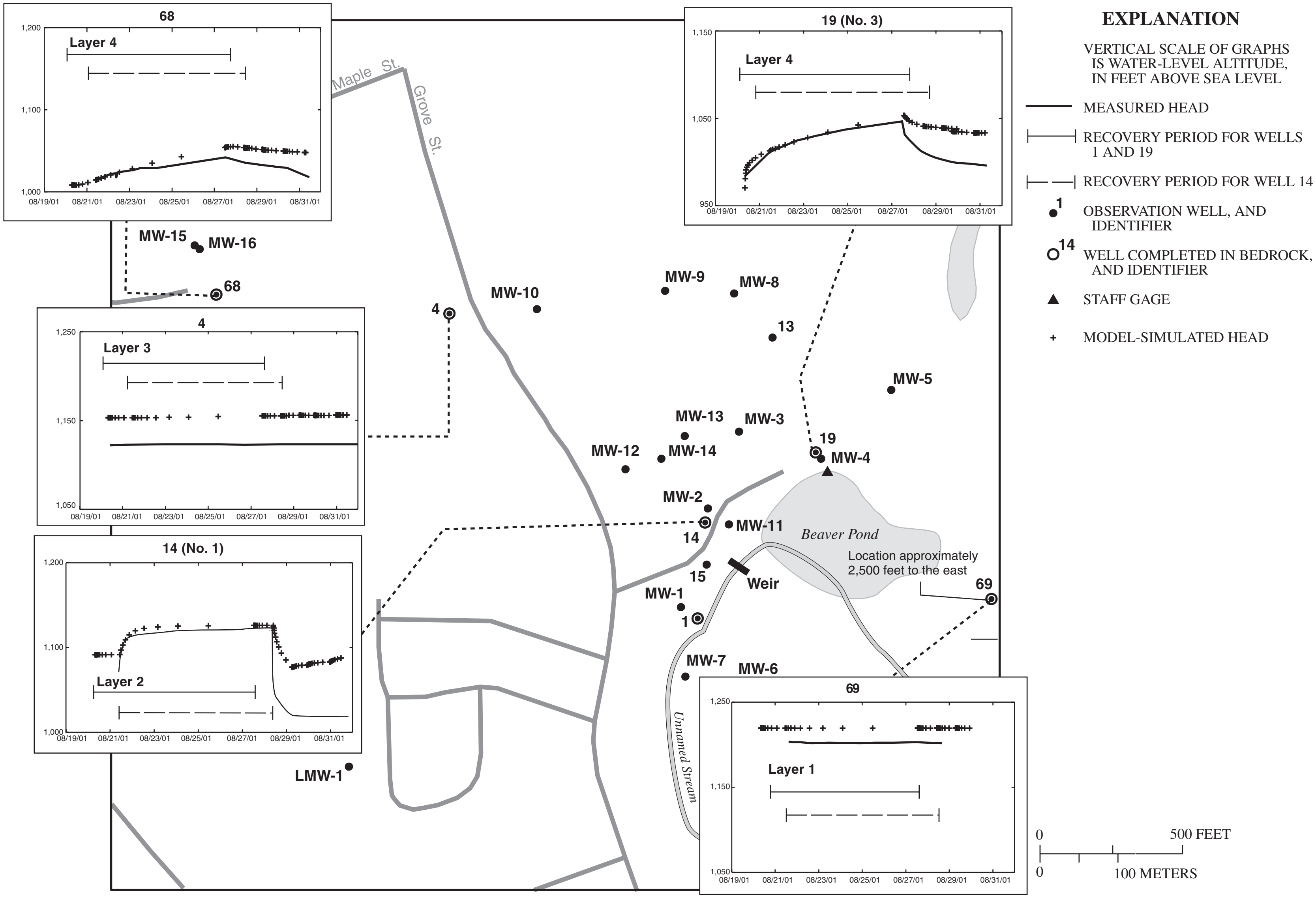
| Model property | 2-Layer model | 5-Layer model |
|---|---|---|
| **Top and bottom of layers** | | |
| Layer 1 | Bottom at 200 ft below the land surface | Top at land surface. Bottom dips to east at 10° |
| Layer 2 | Bottom at 700 ft below the land surface | Maximum thickness 740 ft. |
| Layer 3 | NA | Maximum thickness 460 ft. |
| Layer 4 | NA | Maximum thickness 320 ft. |
| Layer 5 | NA | Maximum thickness 1,100 ft. |
| **Hydraulic conductivity** | | |
| Layer 1 | 0.2 ft/d | 0.2 ft/day |
| Layer 2 | 0.02 ft/d (low transmissivity)<br>1.0 ft/d (high transmissivity) (model rows 59–70, columns 64–76) | 0.5 ft/day |
| Layer 3 | NA | 0.2 ft/day |
| Layer 4 | NA | 0.02 ft/d (low transmissivity)<br>1.0 ft/d (high transmissivity) (model rows 59–70, columns 64–76) |
| Layer 5 | NA | 0.2 ft/day |
| Vertical conductance | $2X10^{-6}$ $day^{-1}$ | $2X10^{-6}$ $day^{-1}$ (all layers) |
| **Storage coefficient** | | |
| Primary | 0.001 layer 1<br>0.0002 layer 2 | 0.05 layer 1<br>0.0002 layer 2<br>0.0001 layers 3,4,5 |
| Secondary | 0.0002 layer 2 | 0.001 layer 2<br>0.0001 layers (3,4,5) |
| Recharge (uppermost active layer) | Area: 0.001 ft/d (4.4 in/yr)<br>Wetland: 0.0123 ft/day (54 in/yr)<br>Asnebumskit Hill: 0.0034 ft/d (15 in/yr) | Area: 0.001 ft/day (4.4 in/yr)<br>Wetland: 0.0123 ft/day (54 in/yr)<br>Asnebumskit Hill: 0.0034 ft/d (15 in/yr) |
| Drain conductance | 10,000 $ft^2/d$ | 10,000 $ft^2/d$ |
| **Pumping rates** | | |
| Well 13 Approved: 13,476 $ft^3/d$ (70 gal/min) | 6,738 $ft^3/d$ (35 gal/min) (layer 1) | 6,738 $ft^3/d$ (35 gal/min) (layer 2) |
| Well 14 Approved: 9,626 $ft^3/d$ (50 gal/min) | 4,813 $ft^3/d$ (25 gal/min) (layer 1) | 4,813 $ft^3/d$ (25 gal/min) (layer 2) |
| Well 1 Approved: 16,556 $ft^3/d$ (86 gal/min) | 8,278 $ft^3/d$ (43 gal/min) (layer 2) | 8,278 $ft^3/d$ (43 gal/min) (layer 4) |
| Well 19 Approved: 17,519 $ft^3/d$ (91 gal/min) | 8,760 $ft^3/d$ (45 gal/min) (layer 2) | 8,760 $ft^3/d$ (45 gal/min) (layer 4) |

The starting heads, recovery trends, and drawdown trends at the location of well 14 are similar for the two models. Starting heads at wells 19 and 68 for the 2-layer model are appreciably lower than observed heads, and recovery and drawdown trends are not as closely simulated as for the 5-layer model. For both models, a relatively low VCONT value of $2x10^{-6}$ $day^{-1}$ was needed to simulate observed heads at depth. For comparison, a lower value of $1x10^{-9}$ $day^{-1}$ was reported by Lyford and others (1999) for poorly fractured diorite at a site in Maine. For both models, in deep wells simulated drawdowns were less than observed drawdowns after restarting wells. This condition could not be resolved during model calibration and may reflect inaccuracies in simulated pumping rates of a few gallons per minute before and after the shut-down period.




Base from U.S. Geological Survey Digital Line Data,
Worcester North, Massachusetts, 1983, 1:25,000,
Universal Transverse Mercator, Zone 19

**Figure 46.** Simulated heads for the 2-layer model and measured heads during aquifer testing, Paxton study area, Massachusetts.




Base from U.S. Geological Survey Digital Line Data,
Worcester North, Massachusetts, 1983, 1:25,000,
Universal Transverse Mercator, Zone 19

**Figure 47.** Simulated heads for the 5-layer model and measured heads during aquifer testing, Paxton study area, Massachusetts.

## Simulated Contributing Areas to Wells

The source areas and contributing areas to wells were considerably different for the two models (figs. 48 and 49). Examination of flow lines indicated that shallow wells 14 and 13 receive much of their water from the water table near the wells. Deep wells completed in layer 2 of the 2-layer model received all of their water by leakage from layer 1. Deep wells completed in layer 4 of the 5-layer model received their water from recharge in the outcrop area of layer 4 and from leakage from layers 3 and 5. The source area for wells in the 2-layer model was considerably larger than that for the 5-layer model. The difference may be attributed to lower leakage rates to deep bedrock for the 2-layer model than recharge rates in outcrop areas plus leakage rates for the 5-layer model.

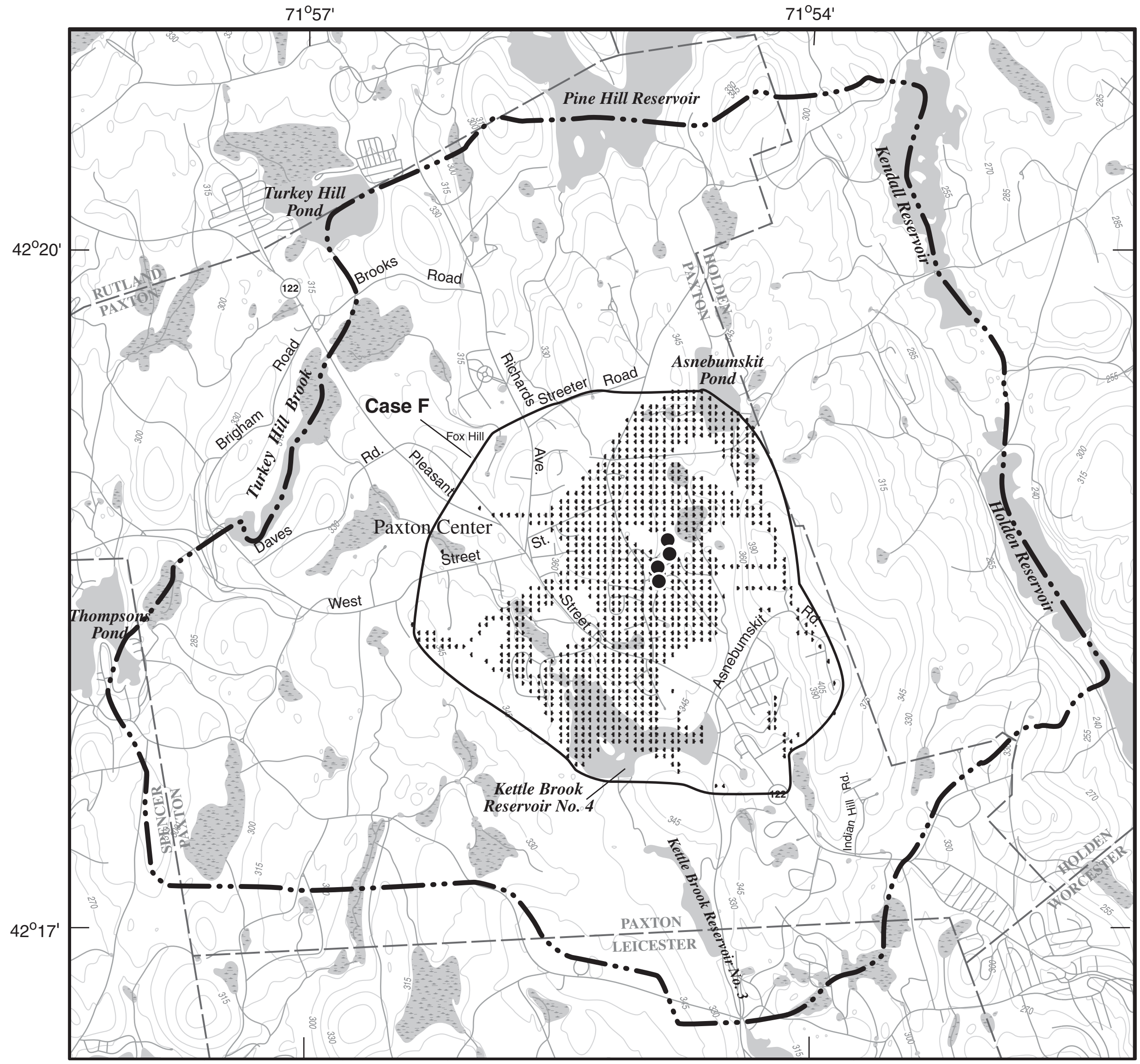
For the 2-layer model, some particles tracked from distant ground-water ridges to the wells (for example, Asnebumskit and Little Asnebumskit Hills). This process is consistent with theoretical flow patterns for upland basins presented by Toth (1963), but it may be less likely where heterogeneities and depths of ground-water flow are accounted for fully. This process was not apparent for the 5-layer model; however, some particles tracked from distant layer-4 outcrop areas to the south.

The contributing areas for both models encompass similar total areas, but the shapes of the areas are considerably different (figs. 48 and 49). For the 2-layer model, the contributing area covered about 3.3 $mi^2$ and extended to ground-water divides. A review of path lines shows that some particles tracked in one direction in layer 1, commonly parallel to the slope of the land surface, until they entered layer 2, where they then tracked in a different direction, sometimes opposite to the direction in layer 1. For the 5-layer model, particles from west of the wells tracked down dip through layer 3 beyond the wells and then reversed directions to the wells when they entered layer 4 by downward leakage. This caused a contributing area that extends considerably eastward beyond the area of the wells. The contributing area for the 5-layer model covers about 3.0 $mi^2$. For source areas in the southern part of the contributing area, particles tracked downdip from outcrop areas and then along strike to the wells. Distant sources for both models are questionable and difficult to validate on the basis of available information.

Conceptually, the contributing areas for deep wells are sensitive to vertical conductance. To test this concept, VCONT for all layers in both models was increased by a factor of 3 to $6x10^{-6}$ $day^{-1}$. This change caused steady-state heads for pumping conditions to rise about 70 ft in the 2-layer model and about 40 ft in the 5-layer model, well above observed heads in deep bedrock wells. Thus, the higher value of VCONT probably does not reflect actual values of vertical conductance. Head differences between layers 1 and 2 in the 2-layer model and layers 3 and 4 in the 5-layer model were reduced at the locations of wells 4 and 69. For the 2-layer model, the contributing area was reduced by about a factor of 2, and for the 5-layer model an extension of the contributing area to the south was eliminated. Although values of VCONT appear to be unrealistically high, this sensitivity test illustrates the importance of vertical hydraulic conductivity for estimating contributing areas to deep wells in poorly transmissive rocks.

Confirmation or refinement of VCONT values was not possible with the available aquifer-test data. An analysis of the time needed to detect a deviation from the Theis type curve (Cooper, 1963) indicated that leakage may not be apparent for at least 40 days of pumping. For this analysis, a vertical conductance of $2x10^{-6}$ $day^{-1}$, a transmissivity of 50 $ft^2/d$, and a storage coefficient of $2x10^{-4}$ were assumed. Regional head data and depth variations may be more useful for determining vertical conductance through model calibration in this geologic setting than determining vertical conductance with aquifer-test data.

The 5-layer model was used to determine if higher pumping rates could be sustained for two deep wells if water was removed from layers 3 and 4 at the locations of the wells. For this analysis, constant heads were placed at the approximate tops of layers 3 and 4 at the location of wells 1 and 19 to simulate reasonable upper-limit yields for these layers. Using this approach, the model generated a steady-state yield of 41 gal/min for well 1 compared to 43 gal/min for the original model, and 58 gal/min was simulated for well 19 rather than the 45 gal/min used in the original model. This analysis indicated that combined discharges for both wells could be somewhat greater than those used for the original model. Simulated yields totaled 44 gal/min from layer 3 and 55 gal/min from layer 4, but the contributing area was similar to the original model. The pumping rate was not increased substantially by including layer 3 as a direct source to the wells because water removed from layer 3 at the wells would otherwise have leaked downward and been a major source of water for layer 4.




Base from U.S. Geological Survey Digital Line Data,
Worcester North, Massachusetts, 1983, 1:25,000,
Universal Transverse Mercator, zone 19

0 — 5,000 FEET
0 — 1,500 METERS

CONTOUR INTERVAL 15 METERS
DATUM IS SEA LEVEL

**EXPLANATION**

STUDY-AREA BOUNDARY

CONTRIBUTING AREA
CASE F, 2-LAYER MODEL

SOURCE AREA

WELL

**Figure 48.** Simulated contributing areas to wells for the 2-layer model, Paxton study area, Massachusetts.

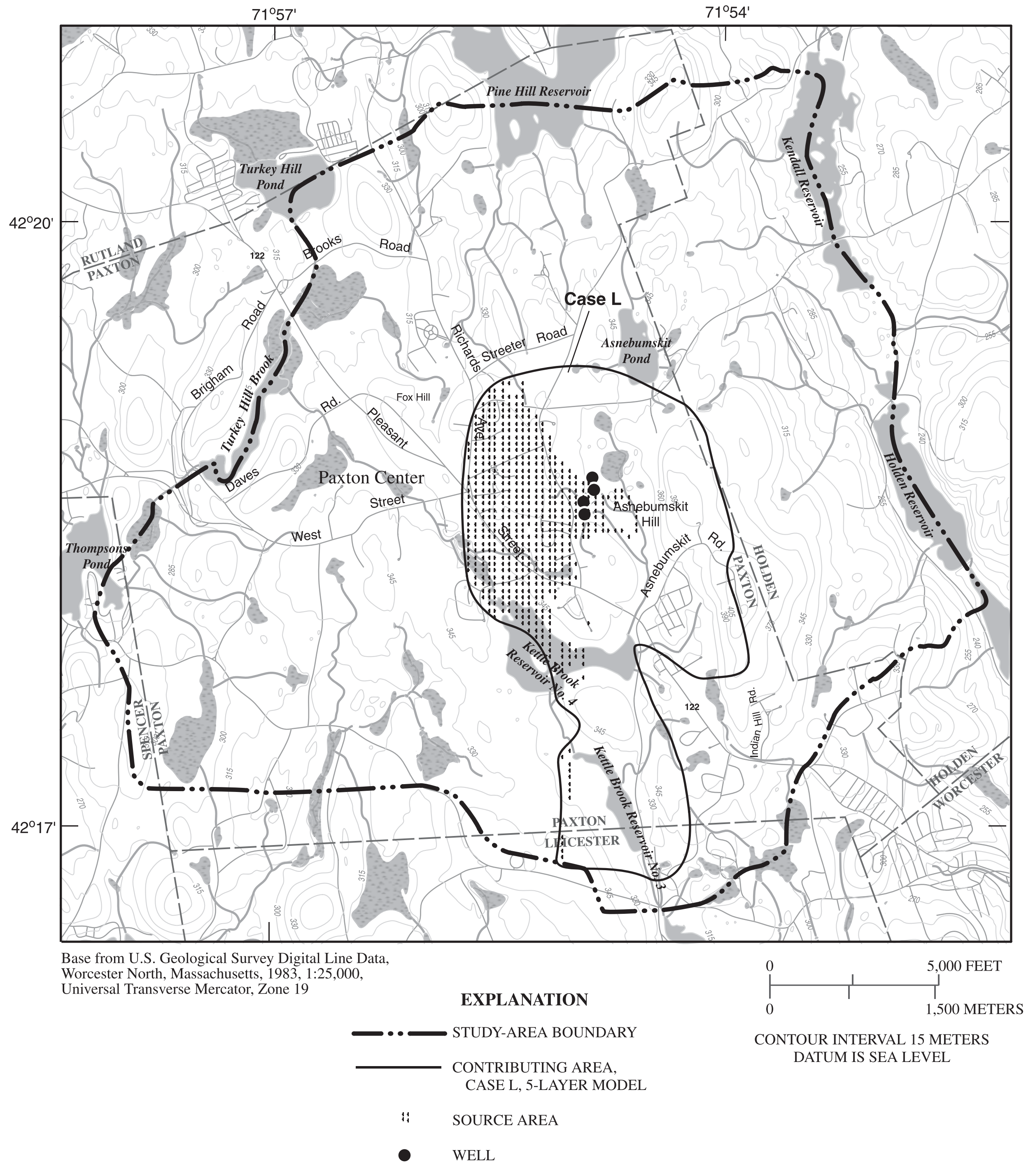



**Figure 49.** Simulated contributing areas to wells for the 5-layer model, Paxton study area, Massachusetts.

## Simulated Effects of Pumping on Streamflow and Wetlands

Simulated water budgets for nonpumping conditions and while pumping at rates used to simulate contributing areas (table 9) illustrated the collective effect of pumping on streamflow. Nearly all of the pumpage was water that otherwise would have flowed to drains; constant-head nodes on the edge of the model were minimally affected by pumping for both models. A simulated total pumping rate of 148 gal/min reduced flow in the headwater basin of Kettle Brook upstream from Route 122 by 90 gal/min for the 2-layer model and by 71 gal/min for the 5-layer model. Most of the remaining quantities pumped are diverted from headwaters of the Chicopee River Basin to the west.

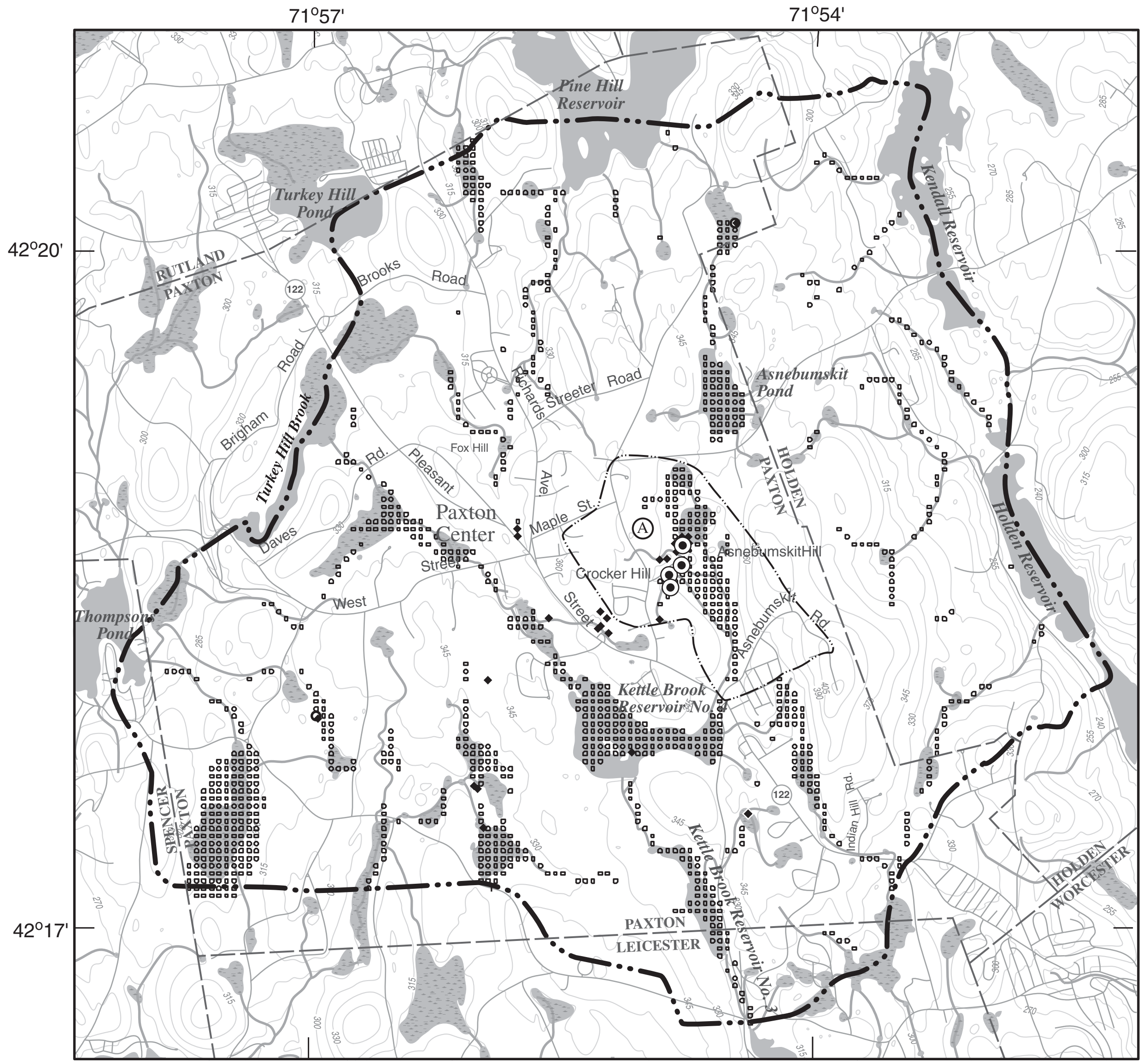
Drains that became inactive while pumping at 148 gal/min (figs. 50 and 51) were near shallow wells 14 and 13, and at considerable distance to the west and southwest for the 2-layer model and to the northwest and southwest in or near the outcrop of layer 4 for the 5-layer model. The effects of pumping on distant streams and wetlands simulated with drains probably would not be readily apparent because upland runoff would be much greater than the quantity diverted by pumping.

Fewer drain nodes were active for the 5-layer model than for the 2-layer model, particularly in outcrop areas of layers 1 and 5 (figs. 50 and 51). Relatively high simulated thicknesses and associated transmissivities for these layers caused most recharge in outcrop areas to flow to constant heads on the edge of the model area rather than to drains.

**Table 9.** Simulated volumetric budgets and flow to drains near Leicester wells for the 2-layer and 5-layer models, Paxton study area, Massachusetts

[NA, not applicable; $ft^3/d$, cubic feet per day; gal/min, gallons per minute]

| Subbasin and volumetric budget | 2-Layer model | | | | 5-Layer model | | | |
|---|---|---|---|---|---|---|---|---|
| | Non-pumping ($ft^3/d$) | Pumping ($ft^3/d$) | Difference | | Non-pumping ($ft^3/d$) | Pumping ($ft^3/d$) | Difference | |
| | | | $ft^3/d$ | gal/min | | | $ft^3/d$ | gal/min |
| **Flow to drains** | | | | | | | | |
| Subbasin A | 99,057 | 81,793 | 17,263 | 89.6 | 62,325 | 48,637 | 13,688 | 71.0 |
| Rest of model area | 356,497 | 345,665 | 10,832 | 56.2 | 265,288 | 251,547 | 13,740 | 71.3 |
| Total | 455,554 | 427,458 | 28,095 | 145.8 | 327,613 | 300,184 | 27,429 | 142.4 |
| **Total model volumetric budget** | | | | | | | | |
| IN: | | | | | | | | |
| Constant head | 3,305 | 3,328 | -24 | -0.1 | 33,445 | 33,629 | -184 | -1.0 |
| Wells | 0 | 0 | 0 | .0 | 0 | 0 | 0 | .0 |
| Drains | 0 | 0 | 0 | .0 | 0 | 0 | 0 | .0 |
| Recharge | 568,184 | 568,184 | 0 | .0 | 568,664 | 568,664 | 0 | .0 |
| Total in | 571,489 | 571,512 | -24 | -.1 | 602,109 | 602,293 | -184 | -1.0 |
| OUT: | | | | | | | | |
| Constant head | 115,941 | 115,432 | 509 | 2.6 | 274,440 | 273,582 | 858 | 4.5 |
| Wells | 0 | 28,589 | -28,589 | -148.4 | 0 | 28,589 | -28,589 | -148.4 |
| Drains | 455,554 | 427,458 | 28,095 | 145.8 | 327,613 | 300,184 | 27,429 | 142.4 |
| Recharge | 0 | 0 | 0 | .0 | 0 | 0 | 0 | .0 |
| Total out | 571,495 | 571,480 | 15 | .1 | 602,052 | 602,355 | -303 | -1.6 |
| IN–OUT | -6 | 33 | -39 | -.2 | 57 | -62 | 119 | .6 |
| Percent discrepancy | .00 | .01 | NA | NA | .01 | -.01 | NA | NA |
| Number of active drains | 1,103 | 1,074 | NA | NA | 679 | 639 | NA | NA |




Base from U.S. Geological Survey Digital Line Data,
Worcester North, Massachusetts, 1983, 1:25,000,
Universal Transverse Mercator, Zone 19

0 5,000 FEET
0 1,500 METERS
CONTOUR INTERVAL 15 METERS
DATUM IS SEA LEVEL

**EXPLANATION**

(A) SUBBASIN BOUNDARY AND IDENTIFIER

STUDY-AREA BOUNDARY

DRAIN CELL

- Active while pumping
- Inactive while pumping

PUMPED WELL

**Figure 50.** Drain cells inactivated by pumping from Leicester wells and subbasin boundary, 2-layer model, Paxton study area, Massachusetts.

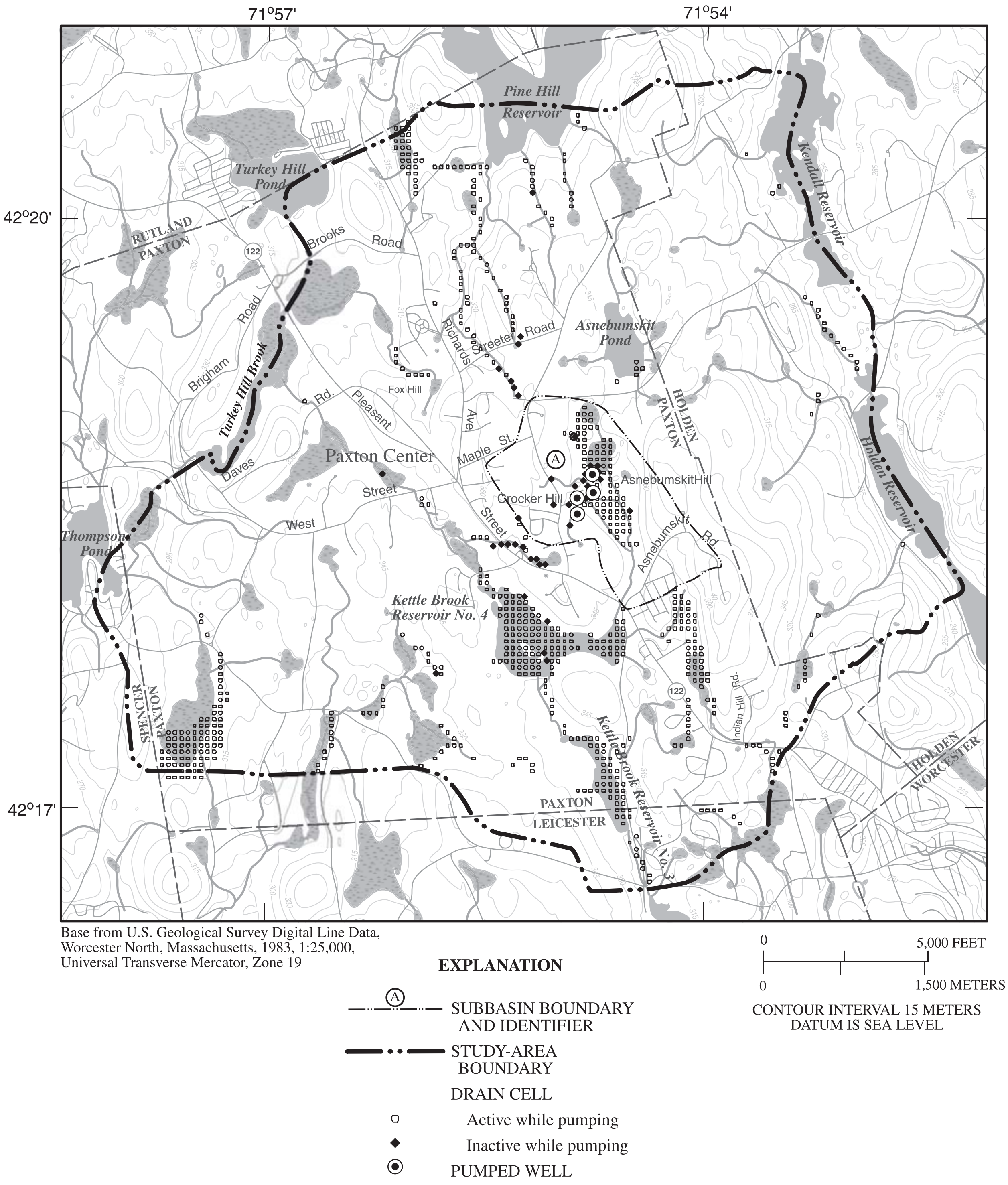



**Figure 51.** Drain cells inactivated by pumping from Leicester Wells and subbasin boundary, 5-layer model, Paxton study area, Massachusetts.

Additional layers in the model and the associated vertical and lateral anisotropy would have caused higher heads and more active drains in these areas. Closer simulation of heads in layers 1 and 5 probably would not have affected leakage to layer 4 and the size and shape of the contributing area.

## SUMMARY AND CONCLUSIONS

Fractured-bedrock aquifer systems in West Newbury, Maynard, and Paxton, MA, were studied to advance methods of data collection and analysis for delineating contributing areas to public-supply wells completed in fractured bedrock and for determining the effects of pumping on streams and wetlands. Contributing areas, as defined for this study, encompass areas contributing recharge to supply wells and areas through which ground water flows from recharge areas to wells. Study areas in the three towns represent contrasting hydrogeologic settings.

In West Newbury, exploratory public-supply wells at two locations were completed in phyllite of the Eliot Formation. Aquifer testing during this study indicated that subhorizontal and steeply dipping fractures that parallel two sets of foliation form elongated transmissive zones in the bedrock aquifer near the two wells and form a hydraulic connection vertically to surficial materials. Recharge to bedrock is largely through a thin veneer of till over bedrock, but leakage through thick drumlin tills also recharges bedrock. Conceptually, leakage rates to bedrock for pumping conditions are controlled mainly by the vertical hydraulic conductivity of till rather than the vertical hydraulic conductivity of bedrock because of an extensive network of high-angle fractures in bedrock. Simulated contributing areas for the three supply wells, pumped at a combined rate of 251 gal/min, encompass about 1.3 $mi^2$ and extend to ground-water divides within most of a subbasin of the Artichoke River. A sensitivity analysis indicates that reducing the recharge rate in thin till areas from 15 in/yr to a reasonable alternative value of 9 in/yr increases the contributing area to about 1.7 $mi^2$. Pumping likely would reduce streamflow in the Artichoke River Subbasin by approximately the pumping rate, but it would minimally affect streamflow in other basins. Wetland areas underlain by till near the wells are likely to be affected by pumping because of the vertical hydraulic connection to surficial materials.

In Maynard, three exploratory public-supply wells were completed in coarse-grained schist of the Nashoba Formation. Aquifer testing indicated that a dense network of fractures in bedrock forms a laterally extensive transmissive zone that is well connected vertically to surficial materials consisting of sandy till, lacustrine silts, sand and gravel, and wetland deposits. Potential leakage rates to bedrock under pumping conditions exceed potential recharge rates to the surficial materials near the transmissive zone. The simulated contributing area for the three supply wells pumped at a combined rate of 780 gal/min encompasses about 1.8 $mi^2$ of the Fort Pond Brook drainage area. Sensitivity analyses indicate that reducing the recharge rate from 24 in/yr to a plausible low extreme of 12 in/yr increases the size of the contributing area to about 2.3 $mi^2$. Streamflow in Fort Pond Brook on the north side of the study area would likely be reduced by about the same amount as the pumping rate. Simulation results also indicate that pumping is likely to lower wetland-water levels below the land surface within a 2,000-ft radius from the wells.

In Paxton, three existing supply wells are completed in granofels and schist of the Paxton and Littleton Formations. Aquifer testing demonstrated that a shallow bedrock well completed to a depth of 150 ft is connected hydraulically to overlying till. Two deep wells, however, receive much of their water from fractures at depths below 500 ft. Flow in bedrock appears to be mostly through parting fractures along a foliation that dips gently (10°) eastward. Parting fractures at depth are poorly connected vertically to shallow bedrock and till. Simulated contributing areas for the three bedrock supply wells and one dug well pumped at a combined rate of 148 gal/min extend beyond the surface-water basin for the 2-layer and 5-layer numerical models that reflect contrasting but plausible geometries of the aquifer system. The contributing area encompasses about 3.3 $mi^2$ for the 2-layer model and about 3.0 $mi^2$ for the 5-layer model. For this bedrock-aquifer system, vertical leakage is important for predicting the size and shape of the contributing area. Streamflow in the the Blackstone River Subbasin, where the wells are located, could be reduced by 70 to 90 gal/min. Most of the additional water pumped, largely from the deep bedrock wells, likely would be diverted from the Chicopee River Basin to the west.

Numerical modeling is considered essential for delineating contributing areas to wells completed in fractured-bedrock aquifers because of the many features that are not easily accounted for in simpler analytical approaches. Geologic mapping for this study, particularly the characterization of ductile structures that often control the distribution of fractures in the bedrock, provided useful supporting information for conceptual ground-water-flow models. Hydrologic data that support numerical modeling include:

- drawdown and recovery of water levels in the pumped well or wells and bedrock-test wells for extended, typically 10-day aquifer tests,
- drawdown and recovery of water levels in nearby residential-supply wells during aquifer testing,
- driller-reported yields, static water levels, water-producing zones, and depth to bedrock for production wells, test wells, and residential wells,
- drawdown and recovery data from multilevel or nests of piezometers completed in surficial materials near pumped wells,
- continuous records of water levels in ground-water-recharge areas for several months or years for one or more wells in bedrock and for one or more wells in surficial materials,
- borehole-geophysical logs for depths, orientations, yields, and transmissivity of water-bearing fractures, and
- streamflow near pumped wells during aquifer testing.

Recharge rates and potential leakage rates from surficial materials to bedrock aquifers stressed by pumping are generally poorly defined and are major sources of uncertainty for accurate delineation of contributing areas to public-supply wells.

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# Tables 10–12

**Table 10.** Well records for the West Newbury study area, Massachusetts

[All depths in feet below land surface. **Map No.:** Shown on figures 5, 6, and 7. **S or T:** S, surveyed altitude; T, altitude from topographic map. **Reported yield:** well yield reported by drillers. **Water-level records:** Y indicates water-level data were collected by USGS, a number in the column is a driller-reported depth to water at the time drilled. **Remarks**: water-bearing zones are from drillers' logs unless otherwise indicated. USGS, U.S. Geological Survey; ft, feet; gal/min, gallons per minute; hrs, hours; >, actual value is greater than value shown; --, no data]

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pumping wells (PW) and bedrock test wells (TW)** | | | | | | | | | | | | | |
| PW1 | BRPW-1 | WZW-151 | 9/17/96 | 63.86 | 61.5 | S | 483.5 | 11 | 50.5 | 31.5–483.5 | >100 | Y | Water-bearing zones at 83–103, 108–109, 123–143, 223–243, and 392–395 ft. |
| PW2 | BRPW-2 | WZW-152 | 9/24/96 | 62.49 | 60.8 | S | 403 | 4 | 56.8 | 26.5–403 | >100 | Y | Water-bearing zone at 105–108 ft. |
| PW3 | BRPW-3 | WZW-182 | 10/05/99 | 52.23 | 51.1 | S | 503 | 38 | 13.1 | 53.7–503 | 300 | Y | Water-bearing zones at 55, 157–160, 217–218, and 486–510 ft. Zone at 55 ft yields 300 gal/min or more. |
| TW1 | TW #1 | WZW-131 | 1/27/97 | 51.66 | 50.7 | S | 303.5 | 30 | 20.7 | 50.5–303.5 | 150 | Y | Water-bearing zone from geophysical logging: 50 ft. |
| TW2 | TW #2 | WZW-132 | 1/30/97 | 50.99 | 50.4 | S | 363 | 30 | 20.4 | 57.5–363 | 45 | Y | Water-bearing zone from geophysical logging: 130–185, 160–190, 250–305 ft. |
| TW3 | TW #3 | WZW-133 | 2/04/97 | 51.98 | 50.7 | S | 363 | 32 | 18.7 | 62.5–363 | 30.45 | Y | Water-bearing zone from geophysical logging: 135–145, 260–280, 285–290, 305–310 ft. |
| TW4 | TW #4 | WZW-134 | 2/11/97 | 51.83 | 50.3 | S | 83 | 37 | 13.3 | 45.5–83 | 10 | Y | Logged depth was 123 ft. Water-bearing zone from geophysical logging: 46–55, 90–100 ft. |
| TW5 | TW #5 | WZW-135 | 2/10/97 | 52.81 | 51.9 | S | 403.5 | 44 | 7.9 | 65–403.5 | 25 | Y | Water-bearing zone from geophysical logging: 80–110, 210–225, 285–300, 395–405 ft. |
| TW6 | TW #6 | WZW-136 | 2/05/98 | 51.31 | 50.2 | S | 123 | 29 | 21.2 | 50.5–123 | 5 | Y | Water-bearing zone from geophysical logging: 65–70, 90–95 ft. |
| TW7 | TW #7 | WZW-137 | 7/27/98 | 52.25 | 51.5 | S | 300 | 37 | 14.5 | 58–300 | >200 | Y | Water-bearing zone from geophysical logging: 55–60, 220–275 ft. |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pumping wells (PW) and bedrock test wells (TW)—*Continued*** | | | | | | | | | | | | | |
| TW8 | TW #8 | WZW-138 | 7/30/98 | 51.15 | 50.1 | S | 260 | 25 | 25.1 | 57–260 | 75 | Y | Water-bearing zone from geophysical logging: 60–75, 75–85, 85–95, 135–145, 240–250, 275–280, 355–365 ft. |
| 139 | Thurlow (East) | WZW-139 | 6/05/97 | 96.50 | 95.0 | T | 423 | 4 | 91 | 12–423 | 30 | Y | -- |
| 95 | Dunn #1 | WZW-95 | 6/17/97 | 81.28 | 80.2 | S | 383.5 | 12 | 68.2 | 28.5–385.5 | 125 | Y | -- |
| 96 | Dunn #2 | WZW-96 | 6/20/97 | 85.69 | 85.2 | S | 403 | 28 | 57.2 | 40.5–403 | 75 | Y | -- |
| **Residential wells used for water-level monitoring** | | | | | | | | | | | | | |
| 141 | Cramphorn | WZW-141 | 11/19/91 | 85.00 | 85.0 | T | 500.0 | 19 | 66 | 29–500 | 5 | Y, 15 | Drawdown of 250 ft at 5 gal/min for 4 hrs. |
| 142 | Maio | WZW-142 | 10/10/85 | 92.88 | 91.9 | S | 420.0 | 20 | 71.9 | 35–420 | 30 | Y | -- |
| 143 | R. Knowles | WZW-143 | 3/03/86 | 63.21 | 61.0 | S | 280.0 | 8 | 53.0 | 32–280 | 130 | Y | -- |
| 144 | Marston | WZW-144 | -- | 75.08 | 73.2 | S | -- | -- | -- | -- | -- | Y | -- |
| 145 | Crowley | WZW-145 | -- | 95.00 | 95.0 | T | -- | -- | -- | -- | -- | Y | -- |
| 146 | Poore | WZW-146 | 7/23/98 | 85.25 | 83.4 | S | 305.0 | 10 | 73.4 | 45–305 | 52 | Y, 15 | Drawdown to 305 ft at 52 gal/min for 4 hrs. |
| 147 | Flinn | WZW-147 | -- | 147.00 | 147.0 | T | -- | -- | -- | -- | -- | Y | -- |
| 148 | Cawley | WZW-148 | -- | 110.00 | 110.0 | S | -- | -- | -- | -- | -- | Y | -- |
| 149 | Shade | WZW-149 | 2/09/96 | 93.43 | 92.0 | S | 505 | 71 | 21.0 | 95–505 | 9.5 | Y, 27.5 | Drawdown to 505 ft at 9.5 gal/min for 4 hrs. Water-bearing zones at 421–422, 472–473, and 487–488 ft. |
| 150 | Belanger | WZW-150 | 7/06/83 | 62.07 | 61.3 | S | 330.0 | 4.5 | 56.8 | 20–330 | 10 | Y | -- |
| 153 | J. Andreas | WZW-153 | -- | 72.71 | 71.9 | S | -- | -- | -- | -- | -- | Y | -- |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Piezometers and dug wells in surficial materials monitored during aquifer testing** | | | | | | | | | | | | | |
| A1 | A1 | WZW-183 | 12/02/99 | 52.29 | 49.0 | S | 49 | 49 | 0.0 | 43–48 | -- | Y | -- |
| A2 | A2 | WZW-184 | 12/03/99 | 51.11 | 48.9 | S | 28.8 | 29 | 19.9 | 22.8–27.8 | -- | Y | -- |
| A3 | A3 | WZW-185 | 12/03/99 | 51.63 | 49.4 | S | 34 | 34 | 15.4 | 28–33 | -- | Y | -- |
| A4 | A4 | WZW-186 | 12/03/99 | 54.02 | 50.9 | S | 49 | 49 | 1.9 | 43–48 | -- | Y | Well not fully developed or screened opposite poorly permeable sediments. |
| A5 | A5 | WZW-187 | 12/03/99 | 57.88 | 55.8 | S | 75 | 75 | -19.2 | 69–74 | -- | Y | -- |
| A6 | A6 | WZW-188 | 12/06/99 | 51.31 | 49.3 | S | 57 | 57 | -7.7 | 51–56 | -- | Y | -- |
| A7 | A7 | WZW-189 | 12/06/99 | 52.99 | 51.0 | S | 93 | 93 | -42.0 | 87–92 | -- | Y | Well not fully developed or screened opposite poorly permeable sediments. |
| K1 | K1 | WZW-190 | 12/01/99 | 68.03 | 66.0 | S | 4.3 | 4.3 | 61.7 | 0–4.3 | -- | Y | -- |
| K2 | K2 | WZW-191 | 12/01/99 | 60.60 | 58.6 | S | 9.0 | 9.0 | 49.6 | 4.0–9.0 | -- | Y | -- |
| K3 | K3 | WZW-192 | 12/01/99 | 61.76 | 59.8 | S | 10.0 | 10 | 49.8 | 5.0–10.0 | -- | Y | -- |
| K4 | K4 | WZW-193 | 12/01/99 | 63.05 | 61.0 | S | 10.0 | 10 | 51.0 | 5.0–10.0 | -- | Y | -- |
| K5 | K5 | WZW-194 | 12/01/99 | 62.90 | 61.0 | S | 9.0 | 9 | 52.0 | 4.0–9.0 | -- | Y | -- |
| K6 | K6 | WZW-195 | 12/02/99 | 63.20 | 61.1 | S | 10.0 | 10 | 51.1 | 5.0–10.0 | -- | Y | -- |
| K7 | K7 | WZW-196 | 12/02/99 | 64.20 | 61.4 | S | 4.3 | 4.3 | 57.1 | 0–4.3 | -- | Y | -- |
| K8 | K8 | WZW-197 | 12/02/99 | 64.35 | 62.3 | S | 11.5 | 11.5 | 50.8 | 6.5–11.5 | -- | Y | -- |
| K9 | K9 | WZW-198 | 12/02/99 | 65.63 | 61.9 | S | 6.5 | 6.5 | 55.4 | 1.5–6.5 | -- | Y | -- |
| K10 | K10 | WZW-199 | 12/02/99 | 66.18 | 64.0 | S | 8.0 | 8 | 56.0 | 3.0–8.0 | -- | Y | -- |
| K11 | K11 | WZW-200 | 12/02/99 | 66.89 | 64.8 | S | 12.5 | 12.5 | 52.3 | 7.5–12.5 | -- | Y | -- |
| 97 | Cemetery Well | WZW-97 | | 85.00 | 83.9 | S | 13.9 | -- | -- | -- | -- | Y | -- |
| ADP1 | ADP-1 | -- | 12/06/99 | 51.18 | 49.8 | S | 1 | -- | -- | 0–1 | -- | Y | Drive point in wetland. |
| ADP2 | ADP-2 | -- | 12/08/99 | 50.58 | 49.3 | S | 1 | -- | -- | 0–1 | -- | Y | Drive point in wetland. |
| ADP3 | ADP-3 | -- | 12/10/99 | 49.97 | 48.7 | S | 1 | -- | -- | 0–1 | -- | Y | Drive point in wetland. |
| KDP1 | KDP-1 | -- | 12/08/99 | 61.95 | 60.0 | S | 1 | -- | -- | 0–1 | -- | Y | Drive point in wetland. |
| KDP2 | KDP-2 | -- | 12/08/99 | 62.44 | 60.4 | S | 1 | -- | -- | 0–1 | -- | Y | Drive point in wetland. |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential and other wells used for bedrock-surface, well-yield, and water-level data** | | | | | | | | | | | | | |
| 52 | -- | WZW-52 | 1963 | -- | 100 | T | 19 | -- | -- | -- | -- | 15 | -- |
| 54 | -- | WZW-54 | 1963 | -- | 75 | T | 17 | -- | -- | -- | -- | 11 | -- |
| 55 | -- | WZW-55 | 1963 | -- | 85 | T | 16 | -- | -- | -- | -- | 8 | -- |
| 56 | -- | WZW-56 | 1963 | -- | 210 | T | 16 | -- | -- | -- | -- | 9 | -- |
| 69 | -- | WZW-69 | 1955 | -- | 12 | T | 30.5 | 30.5 | -18.5 | -- | 25 | -- | -- |
| 70 | -- | WZW-70 | 1955 | -- | 79 | T | 58 | 58.5 | 20.5 | -- | 20 | 3 | -- |
| 77 | -- | WZW-77 | 1964 | -- | 21 | T | 23 | 23 | -2 | -- | -- | 5 | -- |
| 78 | -- | WZW-78 | 1964 | -- | 10 | T | 27 | -- | -- | -- | -- | 5 | -- |
| 79 | -- | WZW-79 | 1964 | -- | 45 | T | 97 | 97 | -52 | -- | 3 | -- | Well site flooded by Moultin Street Reservoir. |
| 83 | -- | WZW-83 | 1964 | -- | 5 | T | 16 | 16 | -11 | -- | -- | 4 | -- |
| 92 | -- | WZW-92 | 1964 | -- | 8 | T | 76 | 76 | -68 | -- | -- | -- | -- |
| 93 | -- | WZW-93 | 1959 | -- | 100 | T | 52 | 52 | -42 | -- | 65 | -- | -- |
| 103 | -- | WZW-103 | 1974 | -- | 165 | T | 20 | -- | -- | -- | -- | 5 | -- |
| 110 | -- | WZW-110 | 1974 | -- | 150 | T | 27 | -- | -- | -- | -- | -- | Water level 2 ft above land surface |
| 120 | -- | WZW-120 | 1974 | -- | 165 | T | 38 | -- | -- | -- | -- | 6 | -- |
| 128 | -- | WZW-128 | 1963 | -- | 125 | T | 210 | 27 | 98 | -- | 15 | -- | -- |
| 129 | -- | WZW-129 | 1967 | -- | 133 | T | 107 | 15 | 118 | -- | 3 | -- | -- |
| 130 | -- | WZW-130 | 1969 | -- | 104 | T | 295 | 132 | -28 | -- | 4 | -- | -- |
| 154 | 37 Cherry Hill Street | WZW-154 | 6/28/94 | -- | 60 | T | 355 | 26 | 34 | 57–355 | 12 | 19 | Drawdown to 355 ft at 11.5 gal/min for 2.75 hrs. Water-bearing zones at 211–213 and 331–332 ft. |
| 155 | 35 Cherry Hill Street | WZW-155 | 6/22/94 | -- | 65 | T | 380 | 25 | 40 | 56–380 | 32 | -- | Drawdown to 380 ft at 32 gal/min for 2.25 hrs. Water-bearing zones at 172–173 and 362–363 ft. |
| 156 | 31 Cherry Hill Street | WZW-156 | 6/07/85 | -- | 100 | T | 305 | 50.5 | 49.5 | 73–305 | 8 | -- | -- |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential and other wells used for bedrock-surface, well-yield, and water-level data—*Continued*** | | | | | | | | | | | | | |
| 157 | 10 Chase Road | WZW-157 | 120/2/92 | -- | 100 | T | 600 | 15 | 85 | 30–600 | 5 | 10 | Drawdown of 420 ft at 5 gal/min for 4 hrs. |
| 158 | 14 Chase Road | WZW-158 | 9/07/90 | -- | 80 | T | 420 | 20 | 60 | 35–420 | 8 | 15 | Drawdown of 100 ft at 8 gal/min for 4 hrs. |
| 159 | 159 Cherry Hill Street | WZW-159 | 12/11/96 | -- | 95 | T | 555 | 51.5 | 43.5 | 72–555 | 16 | -- | -- |
| 160 | 4 Cherry Hill Street | WZW-160 | 7/19/94 | -- | 100 | T | 410 | 96 | 4 | 106–410 | 5 | 75 | Drawdown to 410 ft at 5 gal/min for 0.3 hrs. Water-bearing zone at 395–400 ft. |
| 161 | 33 Indian Hill/Cherry Hill Street | WZW-161 | 11/25/85 | -- | 100 | T | 330 | 79 | 21 | 109–330 | 26 | -- | -- |
| 162 | 18 Archelous Hill Road | WZW-162 | 10/07/85 | -- | 230 | T | 460 | 195 | 35 | 208–460 | 50 | -- | Depth to water 290 ft at 2 gal/min, 450 ft at 48 gal/min. |
| 163 | 210 Bachelor Street | WZW-163 | 3/12/87 | -- | 80 | T | 305 | 42 | 38 | 65–305 | 6 | -- | -- |
| 164 | 17 Browns Lane | WZW-164 | 11/3/83 | -- | 80 | T | 400 | 2 | 78 | 41–400 | 8 | 20 | -- |
| 165 | Garden Street | WZW-165 | 8/27/83 | -- | 83 | T | 605 | 4 | 79 | 20–605 | .7 | -- | -- |
| 166 | 43 Garden Street | WZW-166 | 3/05/85 | -- | 85 | T | 255 | 2 | 83 | 20–255 | 16.5 | -- | -- |
| 167 | 36 Garden Street | WZW-167 | 4/08/86 | -- | 82 | T | 305 | 3.5 | 78.5 | 20–305 | 14 | -- | -- |
| 168 | 80 Garden Street | WZW-168 | 9/15/93 | -- | 75 | T | 455 | 3.5 | 71.5 | 44–455 | 2 | 21 | Drawdown to 455 ft at 2 gal/min for 2.5 hrs. Water-bearing zone at 320–321 ft. |
| 169 | 113 Garden Street | WZW-169 | 9/24/92 | -- | 70 | T | 355 | 3 | 67 | 45–355 | 8 | -- | Drawdown to 355 ft at 8 gal/min for 2.5 hrs. Water-bearing zones at 234–235 and 328–329 ft. Water-bearing material reported as white quartz. |
| 170 | 55 Indian Hill Street | WZW-170 | 12/29/84 | -- | 71 | T | 255 | 15 | 56 | 34–255 | 50 | -- | -- |
| 171 | 59 Indian Hill Street | WZW-171 | 9/22/93 | -- | 61 | T | 605 | 8 | 53 | 40–605 | 10 | 15 | Drawdown of 180 ft at 10 gal/min for 1 hr. Water-bearing zone at 590–595 ft. |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential and other wells used for bedrock-surface, well-yield, and water-level data—*Continued*** | | | | | | | | | | | | | |
| 172 | 411 Middle Road | WZW-172 | 8/21/92 | -- | 75 | T | 420 | 5 | 70 | 30–420 | 10 | 15 | Drawdown of 150 ft at 6 gal/min for 4 hrs. Water-bearing zones at 340–360 and 400–420 ft. |
| 173 | 413 Middle Street | WZW-173 | 7/27/92 | -- | 75 | T | 405 | 2.5 | 72.5 | 42–405 | 92 | 21 | Drawdown 405 ft at 92 gal/min for 2.5 hrs. Water-bearing zone at 226–227 and 378–383 ft. Water-bearing material reported as white quartz. |
| 174 | 415 Middle Street | WZW-174 | 8/01/86 | -- | 72 | T | 405 | 13 | 59 | 34–405 | 20 | -- | -- |
| 175 | 350 Middle Street | WZW-175 | 9/17/82 | -- | 62 | T | 260 | 4 | 58 | 20–260 | 200 | -- | -- |
| 176 | 14 Poors Lane | WZW-176 | 1/22/86 | -- | 75 | T | 405 | 6.5 | 68.5 | 34–405 | 3.5 | 14 | -- |
| 177 | 1 Kelly Brook Road | WZW-177 | 5/15/84 | -- | 58 | T | 365 | 6 | 52 | 20–355 | 5 | -- | -- |
| 178 | 4 Kelly Brook Road | WZW-178 | 4/10/84 | -- | 61.00 | T | 305 | 7 | 54 | 20–305 | 23 | -- | -- |
| 179 | 6 Indian Head/ Kelly Brook | WZW-179 | 3/10/83 | -- | 61 | T | 305 | 8 | 53 | 20–305 | 11 | -- | -- |
| 180 | 9 Kelly Brook Road | WZW-180 | 4/10/85 | -- | 65 | T | 355 | 12.5 | 52.5 | 34–355 | 6.5 | -- | -- |
| 201 | Hanover Lane | WZW-201 | 7/09/85 | -- | 80 | T | 605 | 12.5 | 67.5 | -- | 2.5 | 14 | -- |
| 202 | Garden Street | WZW-202 | 10/07/93 | -- | 75 | T | 405 | 5 | 70 | 46–405 | 3.5 | 16 | Drawdown to 405 ft at 3.5 gal/min for 3 hrs. Water-bearing zone at 328–331 ft |
| 203 | 86 Garden Street | WZW-203 | 3/08/97 | -- | 75 | T | 305 | 3.5 | 71.5 | 46–305 | 3.5 | 6 | Drawdown to 305 ft at 3.5 gal/min for 4 hrs. Water-bearing zones at 89–90 ft and 277–280 ft. |
| 204 | Middle Street | WZW-204 | 10/28/89 | -- | 50 | T | 505 | 27 | 23 | 66–505 | 3.75 | -- | Water-bearing zone 482–483 ft. |
| 205 | Middle Street | WZW-205 | 10/26/89 | -- | 60 | T | 405 | 11.5 | 48.5 | 34–405 | 7.5 | 6.5 | Water-bearing zones at 282–283 and 390–391 ft. |

**Table 10.** Well records for the West Newbury study area, Massachusetts—*Continued*

| Map No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measurement point (ft) | Altitude of land surface (ft) | S or T | Total depth (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) | Water-level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential and other wells used for bedrock-surface, well-yield, and water-level data—*Continued*** | | | | | | | | | | | | | |
| 206 | Middle Street | WZW-206 | 3/21/90 | -- | 48 | T | 355 | 0.5 | 47.5 | 40–355 | 13 | 10.5 | Drawdown to 355 ft at 13 gal/min for 2.5 hrs. Water-bearing zones at 102–103 and 342–345 ft. |
| 207 | 84 Stewart Street | WZW-207 | 1/02/96 | -- | 145 | T | 300 | 20 | 125 | 40–300 | 5 | 20 | Drawdown of 100 ft at 5 gal/min for 4 hrs. Water-bearing zone at 200–220 ft. |
| 208 | 80 Stewart Street | WZW-208 | 1/10/96 | -- | 145 | T | 500 | 30 | 115 | 50–500 | 5 | 40 | Drawdown 300 ft at 5 gal/min for 4 hrs. Water-bearing zone at 480–500 ft. |
| 209 | 132 Indian Hill Street | WZW-209 | 10/12/89 | -- | 35 | T | 280 | 10 | 25 | 42–280 | 105 | 9 | Water-bearing zone at 265–267 ft. |
| 210 | Corner of Indian Hill and Cherry Hill Streets | WZW-210 | 6/05/92 | -- | 60 | T | 425 | 25 | 35 | 40–425 | 30 | 7 | Drawdown 400 ft at 30 gal/min for 1 hr. Water-bearing zone at 380–385 ft. |
| 211 | 31 Indian Hill Street | WZW-211 | 8/23/91 | -- | 80 | T | 705 | 73 | 7 | 106–705 | 22 | 28 | Drawdown to 705 ft at 22 gal/min for 3.25 hrs. Water-bearing zones at 440–450 ft and 500–705 ft. |
| 212 | Indian Hill Street | WZW-212 | 9/11/96 | -- | 62 | T | 305 | 13 | 49 | -- | 60 | 11 | Drawdown to 305 ft at 60 gal/min for 4 hrs. Water-bearing zones at 138–140 ft and 278–283 ft. |
| 213 | 111 Indian Hill Street | WZW-213 | 8/28/90 | -- | 70 | T | 305 | 60 | 10 | -- | 60 | 25 | Drawdown 285 ft at 60 gal/min for 2 hrs. Water-bearing zone at 260–285 ft. 60 ft of till. |
| 215 | Middle Street | WZW-215 | 9/23/80 | -- | 75 | T | 355 | 9.5 | 65.5 | 315–355 | 4 | 9 | -- |
| WZA7 | -- | WZA-7 | 1963 | -- | 55 | T | 58 | 57.5 | -2.5 | -- | -- | -- | -- |
| WZA12 | -- | WZA-12 | 1963 | -- | 47 | T | 42 | 42 | 5 | -- | 4 | -- | Well site flooded by Moultin Street Reservoir. |

**Table 11.** Well records for the Rockland Avenue study area, Maynard, Massachusetts

[**Map No.:** Shown on figures 21 and 22. **S or T:** S, surveyed altitude; T, altitude from topographic map. NA, not applicable; No., number; USGS, U.S. Geological Survey; >, actual value is greater than value shown; --, data not available; ft, foot; gal/min, gallons per minute]

| Map. No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measure-ment point (ft) | Altitude of land surface (ft) | S or T | Total depth of borehole (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pumping wells and bedrock-test wells** | | | | | | | | | | | |
| RW1 | RW-1 | MKW-131 | 8-18-99 | 204.01 | 202.4 | S | 363 | 40 | 162.4 | 82–363 | 250 |
| RW2 | RW-2 | MKW-132 | 5-06-99 | 200.87 | 200.9 | S | 355 | 68 | 132.9 | 97–355 | 400 |
| RW3 | RW-3 | MKW-133 | 5-17-99 | 201.64 | 200.8 | S | 470 | 32 | 168.8 | 48–470 | 300 |
| RW4 | RW-4 | MKW-134 | 6-17-99 | 206.43 | 206.1 | S | 600 | 37 | 169.1 | 60–600 | 25 |
| RW5 | RW-5 | MKW-135 | 8-11-99 | 200.59 | 200.6 | S | 395 | 45 | 155.6 | 80–395 | 350 |
| RW6 | RW-6 | MKW-136 | 1-27-00 | 205.36 | 204.5 | S | 360 | 43 | 161.5 | 69–360 | >100 |
| **Residential wells used for water-level monitoring** | | | | | | | | | | | |
| 50 | Anderson Well | ACW-50 | -- | 202.84 | 201.4 | S | -- | -- | -- | -- | -- |
| 51 | Stone Well | ACW-51 | -- | 206.78 | 205.2 | S | -- | -- | -- | -- | -- |
| 66 | Redway Well | S3W-66 | -- | 209.69 | 208.1 | S | -- | -- | -- | -- | -- |
| 67 | Hammer Well | S3W-67 | -- | 204.66 | 202.2 | S | 15 | -- | -- | -- | -- |
| 68 | Scafidi Well | S3W-68 | -- | 221.44 | 220.4 | S | -- | -- | -- | -- | -- |
| 126 | Sweeney Well | MKW-126 | -- | 213.30 | 212.8 | S | -- | -- | -- | -- | -- |
| 127 | Ames Well | MKW-127 | -- | 230.88 | 229.7 | S | -- | -- | -- | -- | -- |
| 128 | Britton Well | MKW-128 | 7-22-88 | 212.90 | 212.6 | S | 180 | 30 | 182.6 | 50–180 | 30 |
| **Piezometers and dug wells in surficial materials** | | | | | | | | | | | |
| MW1 | MW-1 | MKW-120 | -- | 211.66 | 208.2 | S | 11.25 | -- | -- | -- | -- |
| MW2 | MW-2 | MKW-121 | -- | 206.60 | 203.4 | S | 9.6 | -- | -- | -- | -- |
| M1-20 | M1-20 | MKW-140 | 1-26-00 | 211.32 | 210.2 | S | 20.5 | 20.5 | 189.7 | 14.5–19.5 | -- |
| M2-67 | M2-67 | MKW-141 | 1-26-00 | 206.06 | 203.4 | S | 67 | 67 | 136.4 | 61–66 | -- |
| M3-9 | M3-9 | MKW-142 | 1-26-00 | 202.23 | 200.1 | S | 9 | -- | -- | 3–8 | -- |
| M3-73 | M3-73 | MKW-143 | 1-26-00 | 203.17 | 200.1 | S | 73.5 | 73.5 | 126.6 | 67.5–72.5 | -- |
| M4-19 | M4-19 | MKW-144 | 1-27-00 | 205.65 | 204.5 | S | 19 | -- | -- | 13–18 | -- |
| M4-38 | M4-38 | MKW-145 | 1-27-00 | 206.06 | 203.5 | S | 38.5 | 38.5 | 165.0 | 32.5–37.5 | -- |
| M5-18 | M5-18 | MKW-146 | 1-27-00 | 204.81 | 202.6 | S | 18 | -- | -- | 12–17 | -- |
| M5-51 | M5-51 | MKW-147 | 1-27-00 | 205.74 | 202.7 | S | 51.5 | 51.5 | 151.2 | 45.5–50.5 | -- |

**Table 11.** Well records for the Rockland Avenue study area, Maynard, Massachusetts—*Continued*

| Map. No. | Well No., name, or address | USGS No. | Date drilled | Altitude of measure-ment point (ft) | Altitude of land surface (ft) | S or T | Total depth of borehole (ft) | Depth to bedrock or refusal (ft) | Altitude of bedrock surface (ft) | Screened or open-hole interval (ft) | Reported yield (gal/min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M6-14 | M6-14 | MKW-148 | 1-27-00 | 203.72 | 201.6 | S | 14 | -- | -- | 8–13 | -- |
| M7-18 | M7-18 | ACW-70 | 1-27-00 | 201.22 | 199.2 | S | 18 | -- | -- | 12–17 | -- |
| M7-38 | M7-38 | ACW-71 | 2-03-00 | 202.42 | 199.3 | S | 38 | 38 | 161.3 | 32–37 | -- |
| M8-9 | M8-9 | MKW-151 | 1-27-00 | 200.10 | 198.1 | S | 9 | -- | -- | 3–8 | -- |
| M9-46 | M9-46 | MKW-152 | 1-28-00 | 203.26 | 199.6 | S | 46 | 46 | 153.6 | 40–45 | -- |
| M10-15 | M10-15 | MKW-153 | 1-28-00 | 208.12 | 205.9 | S | 15 | -- | -- | 9–14 | -- |
| M10-37 | M10-37 | MKW-154 | 1-28-00 | 209.15 | 205.8 | S | 37 | 37 | 168.8 | 31–36 | -- |
| M11-9 | M11-9 | MKW-155 | 1-28-00 | 200.61 | 198.3 | S | 9 | -- | -- | 3–8 | -- |
| M12-9 | M12-9 | MKW-156 | 1-28-00 | 200.29 | 198.1 | S | 9 | -- | -- | 3–8 | -- |
| M13-17 | M13-17 | MKW-157 | 1-28-00 | 206.87 | 204.8 | S | 17 | -- | -- | 11–16 | -- |
| M13-49 | M13-49 | MKW-158 | 1-28-00 | 207.39 | 204.7 | S | 49 | 49 | 155.7 | 43–48 | -- |
| M14-10 | M14-10 | ACW-72 | 1-28-00 | 200.90 | 198.8 | S | 10 | -- | -- | 4–9 | -- |
| M14-49 | M14-49 | ACW-73 | 1-28-00 | 202.33 | 198.8 | S | 49 | 49 | 149.8 | 43–48 | -- |
| RW3S | RW-3S | MKW-163 | 2-04-00 | 204.31 | 201.4 | S | 13 | -- | -- | 3–13 | -- |
| RW3D | RW-3D | MKW-164 | 2-04-00 | 204.26 | 201.8 | S | 36 | -- | -- | 31–36 | -- |
| RW5S | RW-5S | MKW-161 | 2-11-00 | 202.91 | 200.5 | S | 13 | -- | -- | 2–12 | -- |
| RW5D | RW-5D | MKW-162 | 2-10-00 | 202.15 | 200.2 | S | 42.5 | -- | -- | 32.5–42.5 | -- |
| 122 | Realty Trust North | MKW-122 | -- | 219.31 | 216.6 | S | 13.3 | -- | -- | -- | -- |
| 123 | Realty Trust South | MKW-123 | -- | 213.48 | 211.0 | T | 6.4 | -- | -- | -- | -- |
| 124 | Realty Trust Dug | MKW-124 | -- | 212.87 | 211.0 | T | 13.5 | -- | -- | -- | -- |
| 125 | Sweeney Observation Well | MKW-125 | -- | 213.39 | 211.1 | S | 14.8 | -- | -- | -- | -- |
| MDP1 | MDP-1 | NA | 3-03-00 | 202.53 | 199.7 | S | -- | -- | -- | 0–1 | -- |
| MDP2 | MDP-2 | NA | 3-03-00 | 200.84 | 197.6 | S | -- | -- | -- | 0–1 | -- |
| MDP3 | MDP-3 | NA | 3-03-00 | 201.08 | 197.0 | S | -- | -- | -- | 0–1 | -- |
| MDP4 | MDP-4 | NA | 3-14-00 | 205.26 | 202.1 | S | -- | -- | -- | 0–1 | -- |

**Table 12.** Well records for the Paxton study area, Massachusetts

[All depths in feet below land surface. **Map No.:** Shown on figures 39 and 40. **Altitude of land surface:** Determined from topographic maps. **Reported yield:** well yield reported by drillers. **Water-level records:** Y indicates water-level data were collected by USGS. USGS, U.S. Geological Survey; ft, foot; gal/min, gallons per minute; --, no data]

| Map No. | Well No. or name | USGS No. | Date drilled | Altitude of land surface | Meas-uring point height (ft) | Altitude of meas-urement point | Depth below land surface | Depth to bedrock or refusal | Screened or open hole nterval | Reported yield (gal/min) | Water level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Production wells and piezometers** | | | | | | | | | | | | |
| 14 | No. 1 | PBW-14 | 1908 | 1,127 | 0.25 | 1,127.3 | 150 | -- | -- | 50 | Y | Surface casing probably to 19 ft. Note in well house states depth is 127 ft |
| 1 | No. 2 | PBW-1 | 1948 | 1,130 | -5.00 | 1,125.0 | 537 | 16 | 24–537 | 100 | Y | |
| 19 | No. 3 | PBW-19 | 1955 | 1,119 | 0.00 | 1,119.0 | 700 | 18 | 29–700 | 120 | Y | Caliper log indicates bottom of steel casing at 39 ft. |
| 13 | Jim Dandy | PBW-13 | 1891 | 1,119 | 3.00 | 1,122.0 | 10 | 10 | -- | 70 | Y | Dug well |
| 15 | Pierce Spring | PBW-15 | 1890 | 1,127 | | 1,127.0 | 12 | -- | -- | 16 | Y | Dug well and cistern |
| MW-1 | MW-1 | PBW-57 | 5-11-01 | 1,132 | 2.05 | 1,134.1 | 11.8 | 11.8 | 5.8–10.8 | | Y | |
| MW-2 | MW-2 | PBW-58 | 5-11-01 | 1,127 | 2.31 | 1,129.3 | 8.5 | 8.5 | 2.5–7.5 | | Y | |
| MW-3 | MW-3 | PBW-59 | 5-11-01 | 1,132 | 2.02 | 1,134.0 | 7.1 | 7.1 | 1.1–6.1 | | Y | |
| MW-4 | MW-4 | PBW-60 | 5-11-01 | 1,119 | 2.01 | 1,121.0 | 24.1 | 24.1 | 18.1–23.1 | | Y | |
| MW-5 | MW-5 | PBW-61 | 5-11-01 | 1,126 | 1.98 | 1,128.0 | 12.9 | 12.9 | 6.9–11.9 | | Y | |
| MW-6 | MW-6 | PBW-62 | 5-11-01 | 1,150 | 1.90 | 1,151.9 | 13.2 | 13.2 | 7.2–12.2 | | Y | |
| MW-7 | MW-7 | PBW-63 | 5-11-01 | 1,138 | 2.07 | 1,140.1 | 7.6 | 7.6 | 1.6–6.6 | | Y | |
| MW-8 | MW-8 | PBW-64 | 5-11-01 | 1,121 | 1.98 | 1,123.0 | 12.5 | 12.5 | 6.5–11.5 | | Y | |
| MW-9 | MW-9 | PBW-65 | 5-11-01 | 1,139 | 2.04 | 1,141.0 | 13.2 | 13.2 | 7.2–12.2 | | Y | |
| MW-10 | MW-10 | PBW-66 | 5-11-01 | 1,171 | 2.04 | 1,173.0 | 10.3 | 10.3 | 4.3–9.3 | | Y | |
| MW-11 | MW-11 | PBW-51 | 7-11-01 | 1,123 | 2.20 | 1,125.2 | 14.5 | 14.5 | 8.5–13.5 | | Y | |
| MW-12 | MW-12 | PBW-52 | 7-11-01 | 1,145 | 1.99 | 1,147.0 | 14.8 | 14.8 | 8.8–13.8 | | Y | |
| MW-13 | MW-13 | PBW-53 | 7-11-01 | 1,133 | 2.63 | 1,135.6 | 13.6 | 13.6 | 7.6–12.6 | | Y | |
| MW-14 | MW-14 | PBW-54 | 7-11-01 | 1,132 | 1.97 | 1,134.0 | 16.8 | 16.8 | 10.8–15.8 | | Y | |
| MW-15 | MW-15 | PBW-55 | 7-11-01 | 1,219 | 2.46 | 1,221.5 | 9.3 | 9.3 | 3.3–8.3 | | Y | |
| MW-16 | MW-16 | PBW-56 | 7-11-01 | 1,219 | 2.16 | 1,221.2 | 23.5 | 23.5 | 17.5–22.5 | | Y | |
| LMW-1 | LMW-1 | PBW-67 | 1999 | 1,145 | 0.00 | 1,145.0 | 10.8 | -- | -- | | Y | Sounded depth |
| **Residential wells used for water-level monitoring** | | | | | | | | | | | | |
| 4 | Dado | PBW-4 | 9-1-48 | 1181 | -5.5 | 1,175.50 | 346 | 20 | 20–346 | -- | Y | Record from USGS files |
| 68 | Lederer | PBW-68 | 8-20-88 | 1,216 | 2.13 | 1,218.13 | 400 | -- | -- | 6.9 | Y | |
| 69 | WSRS/WTAG | PBW-69 | 5-03-48 | 1305 | 0 | 1,305.00 | 419 | -- | -- | 22 | Y | |

**Table 12.** Well records for the Paxton study area, Massachusetts—*Continued*

| Map No. | Well No. or name | USGS No. | Date drilled | Altitude of land surface | Meas-uring point height (ft) | Altitude of meas-urement point | Depth below land surface | Depth to bedrock or refusal | Screened or open hole nterval | Reported yield (gal/min) | Water level records | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential and other wells used for bedrock-surface, well-yield, and water-level data** | | | | | | | | | | | | |
| 5 | -- | PBW-5 | 1942 | 1,170 | -- | -- | 180 | -- | -- | 3.5 | N | Could not locate well in 2001. |
| 11 | -- | PBW-11 | 1947 | 1,390 | -- | -- | 253 | -- | -- | 6 | N | Depth to water 67 ft when drilled. |
| 70 | -- | PBW-70 | 12-07-90 | 1,200 | -- | -- | 440 | 40 | -- | 25 | N | Depth to water 198 ft when drilled. Water-bearing zone from 425–435 ft. |
| 71 | -- | PBW-71 | 11-02-94 | 1,160 | -- | -- | 500 | 20 | -- | 0.75 | N | Depth to water 30 ft when drilled. Water-bearing zone 300–320 ft. |
| 72 | -- | PBW-72 | 4-10-96 | 1,170 | -- | -- | 325 | 12 | -- | 8 | N | Depth to water 8 ft when drilled. Water-bearing zone from 200–210 ft. Address confirmed. |
| 73 | -- | PBW-73 | 7-05-00 | 1,165 | -- | -- | 605 | 10 | -- | 25 | N | Depth to water 40 ft when drilled. Water-bearing zone from 590–595 ft. Precise location could not be determined. |
| 74 | -- | PBW-74 | 11-02-00 | 1,150 | -- | -- | 575 | 15 | -- | 50 | N | Depth to water 40 ft when drilled. Water-bearing zone from 535–555 ft. Precise location could not be determined. |

# Appendix 1. Considerations for Determining Contributing Areas to Wells and Aquifer-System Responses to Pumping in Crystalline Bedrock

Contributing areas to wells are commonly delineated by applying analytical methods that require generalization of aquifer-system characteristics (Massachusetts Department of Environmental Protection, 1996). They are also delineated by applying numerical modeling programs like MODFLOW 2000 (Harbaugh and others, 2000) that can account for system complexities, such as vertical and lateral variations in hydraulic properties of geologic materials and lateral variations in recharge rates. Because of the 3-dimensional nature of fractured-rock systems and the many factors that affect ground-water-flow patterns that are not easily generalized in these systems, numerical modeling that includes particle tracking is the preferred method of analysis (Bair and Roadcap, 1992; Franke and others, 1998; Lipfert and others, 2001). A minimal dataset for simulating contributing areas and predicting wetland and streamflow responses to pumping includes the following:

1. A surficial geologic map that shows the distribution of till and stratified deposits for estimating recharge rates, possible leakage zones, and leakage rates from the water table to bedrock. Surficial geological information is available through MassGIS for most of Massachusetts.
2. Drawdown for the pumped well or wells during an extended aquifer test of at least 10 days to estimate transmissivity near the well and to qualitatively assess leakage.
3. Altitudes for wetlands and surface-water bodies, which strongly affect the positions of ground-water divides. Altitude data are available through MassGIS for most of Massachusetts.

Water-level data for the pumped well alone will not identify transmissive zones that can cause elongation of contributing areas in some settings. Also, an apparent leakage response may be misinterpreted from drawdown data for a single well in bedrock. Additional data may be needed for some settings where contributing areas must be accurately delineated and wetland and streamflow responses must be confidently predicted. Estimates of aquifer-system characteristics such as recharge, hydraulic conductivity of surficial materials, and storage properties of bedrock and surficial materials, can be obtained from published sources, many of which are cited in this report.

## Information Sources and Data-Collection Methods

Several types of information are needed to determine confidently contributing areas and the effects of pumping on streams and wetlands. Information needed includes water-level data, transmissivity, bedrock surface, recharge rates, leakage rates, and storage properties.

### Water-Level Data

Drillers' logs often provide useful head data reported as static water levels. Drillers' logs for many residential wells are available through MADEM and town departments of public health. Residential wells are often easily accessed for water-level measurements after removing a steel cover. Because pumps in residential wells cycle regularly, several measurements over a period of 15 to 30 minutes may be needed to insure that measured water levels reflect static conditions.

Water-level data collected during testing of public-supply wells for sustainable yield are essential for model calibration. Water-level data can be collected from existing test wells, pumped wells, and nearby residential wells. Pressure transducers and recorders are recommended for residential wells because of frequent cycling of the pump for domestic water use.

Piezometers for observing pumping responses in surficial materials are readily installed manually or by machine-mounted, direct-push methods. Drilling equipment mounted on small all-terrain vehicles can be transported to many locations that are inaccessible to conventional auger rigs. The appropriate number of piezometers depends on the complexity of site conditions and budgetary constraints. Suggestions for designing a network of piezometers to determine the vertical hydraulic conductivity of surficial materials are given in a later section titled Recharge and Leakage Rates.

Water-level data collected for a year or more are often useful for calibrating models to cycles of ground-water recharge. Calibration of models for at least one annual cycle of recharge can refine estimates of recharge, storage properties, and seasonal sustainable yields, including the effects of drought. Water levels in wells located in recharge areas, such as hilltops, typically fluctuate over a wider range and are more sensitive to aquifer transmissivity, storage properties, and recharge rates. Water levels in recharge areas, therefore, are often more useful for model calibration than water levels in wells located in or near ground-water-discharge areas. Storage properties determined by calibration to long-term water levels are typically more reliable for simulating responses to seasonal recharge cycles than storage properties determined from short-term aquifer tests.

### Transmissivity of Geologic Units

Well yields reported by drillers and plotted on maps can provide a qualitative basis for determining transmissivity distribution within the region of public-supply wells. Water-level data collected during aquifer testing, which is generally required to estimate the sustainable yield of a well, will provide the most reliable estimates of transmissivity by applying standard analytical methods or by model calibration. Surficial geologic maps, where available, provide information that can be used to delineate transmissivity zones in surficial materials. Geologists can predict the vertical distribution of surficial materials by applying depositional models for glacially derived sediments. Bedrock geologic maps will be increasingly useful as knowledge expands on the relation of transmissivity to lithology and structural features. For this study, characteristics of ductile features, mainly foliation, supported conceptual ground-water-flow models. Borehole-flowmeter tests in a well for unpumped and pumped conditions can yield useful transmissivity values for fractures or depth intervals locally (Paillet, 2000; 2001).

### Bedrock Surface

Detailed information about the configuration of the bedrock surface was of limited value for accomplishing the goals for the three study areas. In other locations where the water table falls below the bedrock surface and the hydraulic properties of surficial materials contrast strongly with the properties of bedrock, the configuration of the bedrock surface may be important for accurate simulation of contributing areas and responses to pumping. Bedrock depths are generally reported on drillers' logs, and surficial and bedrock geologic maps often identify areas where bedrock is at or near the surface. Bedrock-surface data also can be obtained by applying several surface geophysical methods, including seismic refraction, seismic reflection, and ground-penetrating radar.

### Recharge and Leakage Rates

Recharge rates are poorly defined for most upland settings. An important conceptual consideration is that recharge rates may increase in areas where pumping lowers hydraulic head seasonally or perennially below the land surface. Where the head in bedrock is below the surface, recharge rates to bedrock are controlled by leakage rates from surficial materials to rock or by infiltration rates of precipitation where leakage rates exceed potential infiltration rates. In areas where infiltration and leakage rates potentially exceed precipitation rates, such as areas covered by sand and gravel, regional runoff data presented by Lyford and Cohen (1988) and Randall (1996) are useful for preliminary estimates of recharge rates.

The transfer of water in extensive wetlands from ground-water-discharge areas to recharge areas near wells may affect the size of contributing areas near wells; however, transfer processes for water in wetlands are poorly understood. Conceptually, the rate of water transfer could change appreciably with ground-water discharge and evapotranspiration rates.

Leakage rates from surficial materials to bedrock are likely to be greater from sand, gravel, silt, and thin surface till than from thick drumlin till and lacustrine or marine clays. Leakage rates to bedrock and between bedrock horizons also are likely to be greater where high-angle fractures are well distributed, such as along foliation, than where horizontal fractures predominate or where fractures are limited. Values of vertical hydraulic conductivity or vertical conductance are needed to predict the effects of pumping on wetlands and leakage rates from surficial materials to bedrock and between horizons in bedrock. For particularly leaky aquifer systems such as Maynard, standard analytical methods or numerical model calibration can determine leakage properties from water-level responses in bedrock-observation wells. Water-level measurements in piezometers or wells at multiple depths provide additional data for determining leakage rates and are needed where leakage rates cannot be determined reliably from drawdown data in bedrock. In aquifer systems such as the Paxton area, where geologic units are poorly connected vertically, aquifer tests of several days or even weeks may not be long enough to determine leakage rates. In these types of systems, longer-term regional head data at multiple depths may be essential for estimating vertical conductance through model calibration.

Water-level data from a network of piezometers can be used to compute the vertical hydraulic conductivity values needed to determine leakage rates and to predict possible effects of pumping on wetlands and the water table. A reasonable goal for aquifer testing at bedrock sites is to observe water levels in a network of multilevel piezometers or nests of individual piezometers completed at different depths. Reasonable locations for piezometers are near the pumping well or wells, near at least one bedrock observation well, if available, and at three locations near wetlands to assess drawdown distribution, vertical gradients, and lateral variations in vertical hydraulic conductivity. The piezometers should have short screens of 1 ft or less to monitor water levels at a point and should be completed at three levels: at or close to the water table, at the bottom of the aquifer, and at an intermediate depth. Methods described by Neuman and Witherspoon (1972) and Wolff and Papadopulos (1972) can be used to compute a vertical hydraulic diffusivity (vertical hydraulic conductivity divided by the specific storage of the confining layer) from water-level responses observed in the piezometers during aquifer testing. Specific storage values that are available in the several reports, such as Wolff (1970b) and Wolff and Papadopulos (1972), can be used to compute vertical hydraulic conductivity from the calculated vertical diffusivity values.

### Storage Properties

Storage properties of geologic materials are needed to simulate changes in contributing areas and changes in wetting and drying cycles in wetlands with seasonal recharge cycles. The specific yield of bedrock and surficial materials generally is more important for transient simulation of recharge cycles than the compressive storage properties of bedrock. Analyses of aquifer-test data typically underestimate specific-yield values, particularly in till-covered upland settings where gravity drainage is slow. Where surficial materials are perennially saturated, specific-yield values reported in the literature may be adequate. Where the water level is lowered into bedrock either by reduced recharge or by pumping, a specific yield for bedrock also is needed, but literature-reported values are sparse. Water-level records for surficial materials and bedrock for at least one year could produce reasonable estimates of aquifer-system specific yields through model calibration. Wells on hills, where the water table drops seasonally below the bedrock surface, would be more useful for estimating long-term specific yields than wells on hill slopes and in valleys where water levels remain above the bedrock surface.

## Transient Simulation of Contributing Areas

The MADEP guidelines say that contributing areas to wells (well-head protection zones) should be determined for the end of a transient 180-day period of no recharge from precipitation (Massachusetts Department of Environmental Protection, 1996). The possible effects of an extended period of no recharge on contributing areas were determined with the numerical models for the three study areas. For the analysis, steady-state heads for average recharge conditions while pumping at approved rates (or adjusted rates for the Paxton site) were used as starting heads for a 180-day, transient-stress period of no recharge while continuing to pump at those rates. The resulting heads after the 180 days were used to identify ground-water divides and likely bounding flow paths that define the contributing area for the condition of no recharge. This approach is commonly used to define wellhead protection zones for public-supply wells in Massachusetts (Joseph Cerutti, oral commun., 2002).

The storage properties used to simulate aquifer tests were also used to simulate the 180-day period of no recharge. For the Paxton site, the storage coefficient of the upper layer in the 2-layer model was adusted upward to better reflect storage properties of wetland sediments near shallow wells and to prevent the shallow wells from going dry. Other model properties were not adjusted.

For West Newbury (the Case K model), water levels declined more than 100 ft in places after 180 days, and ground-water-flow paths extended to model boundaries over most of the model area. An extensive area in layer 1 became dry, including the area near the Andres site. For this reason, the pumped well at the Andreas site was placed in layer 2 so it would remain active for the 180 days. The large drawdowns and expansion of the contributing area are considered unreasonable on the basis of water-level data for the site and water-level records for till and bedrock wells in other settings. It is likely that thick till, some of the thin till, and wetland sediments would have sustained recharge to bedrock by leakage and gravity drainage.

The existing data were not adequate, however, for refinement of leakage and storage properties; results of the transient-contributing-area analysis, therefore, are inconclusive.

For Maynard (the Case L model), water-level declines were generally less than 10 ft in layer 1, which are reasonable for this aquifer system. The simulated potentiometric surface for layer 2 at the end of the 180 days indicated an expanded Case L contributing area and a shape and size similar to the steady-state contributing area for the reduced recharge condition (Case G) (fig. 37). The similarity to the contributing area for Case G has no obvious hydrologic basis and is considered coincidental.

For Paxton, only the 2-layer model was used to evaluate possible effects of an extended dry period. Drawdowns were generally less than 12 ft in layer 1, except near the pumped wells placed in layer 1, where drawdowns of about 40 ft were simulated. The extent of the contributing area is controlled mostly by pumping from deep wells in layer 2. Heads in layer 2 at the end of 180 days indicated that ground-water divides were largely unchanged from steady-state conditions. This result is reasonable because the extent of the contributing area is controlled mainly by leakage from layer 1, and leakage was not appreciably reduced during the 180 days.

This exercise illustrates the importance of storage and leakage properties for determining the effects of transient conditions on contributing areas to wells. The results for the West Newbury site were inconclusive because storage and leakage are poorly defined. The storage and leakage properties for the Maynard site are better defined, and simulated heads are reasonable. Although the simulated contributing area expanded during the 180 days and flow was reversed near the divides, the distance that water traveled during the period of flow reversal was likely to be short because of low hydraulic gradients near the divide. During wet periods, the divides would shift closer to the pumped wells, and flow would again reverse near the divides away from wells. The net effect is little or no change in the contributing area from average conditions. Reilly and Pollock (1995) demonstrated that half-year cyclic changes in recharge generally caused minor differences in contributing areas and flow paths from average conditions. For aquifer systems like the Paxton study area where drawdown cones are extensive and the size of the contributing area is controlled largely by leakage rates, a drought of 180 days may have a limited effect on contributing areas.

## Streamflow and Wetland Responses to Pumping

Pumping inevitably reduces streamflow in the area contributing recharge to wells. Where the bedrock aquifer is well connected to surficial materials, such as for the West Newbury and Maynard sites, streamflow is likely to be affected near the wells. For wells that receive water from deep fractures that are not well connected vertically to surficial materials, such as the deep wells at Paxton, streamflow reductions caused by pumping may be spread over a large area and not be discernable in individual streams. Streamflow reduction caused by steady pumping is likely to be the same in dry periods as in wet periods, unless the pumped well is near headwaters where streamflow normally ceases or declines below projected pumping rates.

For this study, steady-state simulation of wetland areas as drains was useful for identifying areas where water levels may drop below the land surface during all or part of a wetland wetting and drying cycle. Conceptually, pumping can permanently lower the water table or reduce the time each year that water is at the surface. Transient simulation of wetlands would be appropriate where changes in the duration of wetting and drying cycles are a concern.

Pumping will affect wetland-water levels if leakage rates from surficial materials, including wetland sediments, near pumped wells exceed inflow rates from precipitation or inflow by runoff from adjoining areas. Values of vertical hydraulic conductivity and potential inflow rates to wetlands are needed to predict changes in wetland-water levels. Inflow rates can generally be estimated from regional precipitation and runoff data.

# Appendix 2. Definitions of Geologic Terms

The following geologic terms and their definitions are from Bates and Jackson (1987), unless otherwise indicated.

**Amphibolite:** A crystalloblastic (metamorphic) rock consisting mainly of amphibole (mostly dark minerals) and plagioclase (feldspar) with little or no quartz.

**Cleavage:** The property or tendency of a rock to split along secondary, aligned fractures or other closely spaced, planar structures or textures, produced by deformation or metamorphism.

**Diorite:** A plutonic rock (formed at considerable depth by crystallization of magma). intermediate in composition between acidic and basic, characteristically composed of dark-colored amphibole.

**Dip:** The angle that a structural surface makes with the horizontal, measured perpendicular to the strike of the structure and in the vertical plane.

**Fabric:** The complete spatial and geometrical configuration of all those components that make up a deformed rock.

**Fault:** A fracture or zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

**Foliation:** A general term for a planar arrangement of textural or structural features in any type of rock.

**Fracture:** A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress.

**Gneiss:** A foliated rock formed by regional metamorphism.

**Gneissosity:** Gneissic structure (the coarse textural lineation or banding of the constituent minerals into alternating silicic and mafic layers).

**Granodiorite:** A group of coarse-grained plutonic rocks containing quartz, plagioclase, and potassium feldspar.

**Granofels:** A field name for a medium- to coarse-grained metamorphic rock with little or no foliation or lineation.

**Joint:** A surface of fracture or parting in a rock, without displacement.

**Mylonitic structure:** A structure produced by intense microbrecciation (breaking of rock into fragments) and shearing.

**Pegmatite:** An exceptionally coarse-grained igneous rock.

**Penetrative fabric:** A fabric everywhere developed throughout a rock mass (Suppe, 1985).

**Phyllite:** A metamorphosed rock, intermediate in grade between slate and mica schist.

**Quartz monzonite:** A granitic rock consisting mostly of quartz and feldspar.

**Quartzite:** A metamorphic rock consisting mostly of quartz and formed by recrystallization of sandstone or chert by metamorphism.

**S1 foliation:** The oldest recognized generation of foliation (Suppe, 1985).

**S2 foliation:** A second generation of foliation (Suppe, 1985).

**Schist:** A strongly foliated crystalline rock, formed by metamorphism.

**Schistosity:** The foliation in schist or other coarse-grained, crystalline rock due to the parallel, planar arrangement of mineral grains, usually mica.

**Slip cleavage:** A type of cleavage that is superposed on slaty cleavage or schistosity, and is characterized by finite spacing of cleavage planes between which occur thin, tabular bodies of rock displaying a crenulated cross-lamination.

**Strike:** The direction or trend taken by a structural surface as it intersects the horizontal.

**Trend:** A general term for the direction or bearing of the outcrop of a geological feature of any dimension.