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# Delineation of Water Sources for Public-Supply Wells in Three Fractured-Bedrock Aquifer Systems in Massachusetts

By FOREST P. LYFORD, CARL S. CARLSON, and BRUCE P. HANSEN

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## CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

### CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| acre | 0.4047 | hectare |
| cubic foot per day ($ft^3/d$) | 0.02832 | cubic meter per day |
| cubic foot per day per square foot ($ft^3/d/ft^2$) | 0.3048 | cubic meter per day per square meter |
| foot (ft) | 0.3048 | meters |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day |
| gallons (gal) | 3.78544 | liters |
| inch (in.) | 2.54 | centimeters |
| inches per year (in/yr) | 2.54 | centimeters per year |
| miles (mi) | 1.609 | kilometers |
| square miles ($mi^2$) | 2.590 | square kilometers |

### VERTICAL DATUM

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

### ABBREVIATIONS

| | |
|---|---|
| GPS | Geographic Positioning System |
| MassGIS | Massachusetts Geographic Information System |
| MDEP | Massachusetts Department of Environmental Protection |
| MDEM | Massachusetts Department of Environmental Management |
| PVC | Polyvinyl Chloride |
| USEPA | United States Environmental Protection Agency |
| USGS | United States Geological Survey |
| VCONT | Vertical hydraulic conductivity divided by thickness |

# Delineation of Water Sources for Public-Supply Wells in Three Fractured-Bedrock Aquifer Systems in Massachusetts

*By* Forest P. Lyford, Carl S. Carlson, *and* Bruce P. Hansen

## Abstract

Fractured-bedrock aquifer systems in West Newbury, Maynard, and Paxton, Massachusetts, were studied to advance methods of data collection and analysis for delineating contributing areas to public-supply wells completed in fractured rock and for determining the effects of pumping on streams and wetlands. Contributing areas, as defined for this study, include all areas through which ground water flows from recharge areas to wells.

In West Newbury, exploratory public-supply wells at two locations were completed in phyllite of the Eliot Formation. Aquifer testing indicated that subhorizontal and steeply dipping fractures that parallel two sets of foliation form elongated transmissive zones in the bedrock aquifer near the two well locations and also form a vertical hydraulic connection to surficial materials consisting of till at one location and marine clay at the other location. Recharge to bedrock is largely through a thin veneer of till over bedrock, but leakage through thick drumlin tills also recharges bedrock. Simulated contributing areas for the three supply wells pumped at a combined rate of 251 gallons per minute encompass about 1.3 square miles and extend to ground-water divides within most of a subbasin of the Artichoke River. Pumping likely would reduce streamflow in the Artichoke River subbasin by approximately the pumping rate. Pumping is likely to affect wetland areas underlain by till near the wells 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 in bedrock that is well connected vertically to surficial materials consisting of sandy till, lacustrine silts, sand and gravel, and wetland deposits. The simulated contributing area for the three supply wells pumped at a combined rate of 780 gallons per minute encompasses about 1.8 square miles of the Fort Pond Brook drainage area. Pumping likely would reduce streamflow in Fort Pond Brook by about the same amount as the pumping rate, and wetland-water levels within a 2,000-foot radius from the wells are likely to be lowered below the land surface by pumping.

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 feet is closely connected hydraulically to overlying till. Two deep wells, however, receive much of their water from fractures at depths below 500 feet. Ground-water flow in bedrock appears to be mostly through parting fractures along a foliation set that dips gently (10 degrees) eastward. These 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 gallons per minute encompass 3.0 square miles or more. Streamflow in the Blackstone River subbasin where the wells are located could be reduced by 70 to 90 gallons per minute; pumping would minimally affect wetland areas near the wells.

Activities that provided useful information for delineations of contributing areas to wells in fractured rock include characterization of ductile structures and fractures in bedrock outcrops and boreholes, long-term observation of water levels in wells completed in bedrock and surficial materials, extended aquifer tests of 7 days or more, and water-level observations during aquifer testing in residential supply wells and piezometers completed in surficial materials. Recharge rates and potential leakage rates from surficial materials to bedrock aquifers stressed by pumping are, in general, poorly defined and are major sources of uncertainty for accurate delineation of contributing areas to public-supply wells.

## INTRODUCTION

Delineating contributing areas to public-supply wells forms a critical component of state and federal strategies for protecting drinking-water supplies (U.S. Environmental Protection Agency, 1991). Identifying the source of water to a supply well allows for an assessment of the susceptibility or risk of contamination to the pumped water. The Massachusetts Department of Environmental Protection (MADEP) is required to delineate contributing areas to supply wells under 1986 Amendments of the Federal Safe Drinking Water Act. For wells in fractured-bedrock settings, MADEP guidelines for delineating zones of contribution may not be appropriate (Massachusetts Department of Environmental Protection, 1996). Also, the Massachusetts Department of Environmental Management (MADEM) is concerned about the effects of pumping from bedrock aquifers on streamflow and wetlands.

From 1999 to 2002, the U.S. Geological Survey (USGS), in cooperation with MADEP and MADEM, studied fractured-rock geohydrology for well sites in three Massachusetts towns. The study identified contributing areas to proposed and existing water-supply wells for use by MADEP to delineate wellhead-protection zones. The study also evaluated possible effects of pumping from bedrock wells on wetland water levels and streamflow to provide information to MADEM to address concerns by residents, environmental groups, and local conservation commissions about possible hydrologic responses to pumping. The MADEM also needs this information for review and analysis of interbasin water transfers that might affect surface water, wetlands, and ecosystems. The broad goals of the study were to define ground-water flow within the bedrock-aquifer systems, develop methods of data collection and analysis for delineating contributing areas to supply wells completed in fractured crystalline bedrock, and determine the effects of pumping these wells on streams and wetlands.

### Purpose and Scope

This report describes the geohydrology and presents an analysis of contributing areas to wells completed in bedrock, and provides an assessment of pumping effects on streamflow and wetlands for the Knowles and Andreas well sites in West Newbury, the Rockland Avenue well site in Maynard, and the Leicester well site in Paxton, Massachusetts (fig. 1). The report also includes a review of information sources and methods that were found to be useful for this study for delineating contributing areas and for determining responses to pumping from municipal water-supply wells in fractured bedrock.

For this report, the contributing area to a well or wells is defined as “the land area that has the same horizontal extent as that part of the aquifer, or adjacent areas, from which ground-water flow is diverted to the pumping well” (Morrissey, 1989, p. 8). The contributing area encompasses all of the flow paths to the well regardless of their vertical distribution. Also described here are areas contributing recharge to wells. Reilly and Pollock (1993, p. 2) define the area contributing recharge to a discharging well as “the surface area that delineates the location of the water entering the ground-water system at the water table that eventually flows to the well and discharges.” Because the names of the two types of areas are similar, the term “source area” is used in this report as a substitute for “area contributing recharge.” The two types of areas are shown schematically in figure 2.

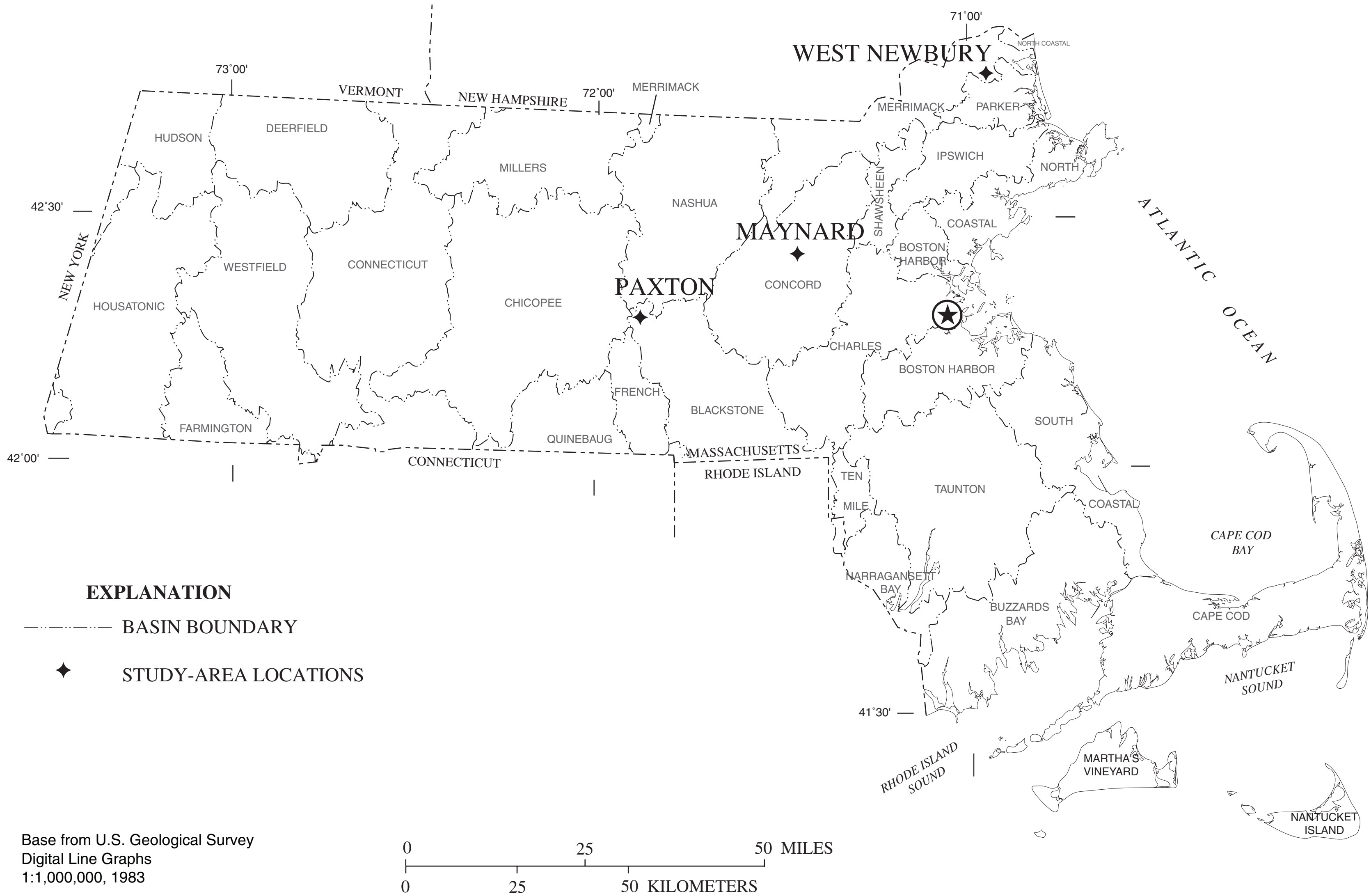



**Figure 1.** Locations of study areas in Massachusetts.

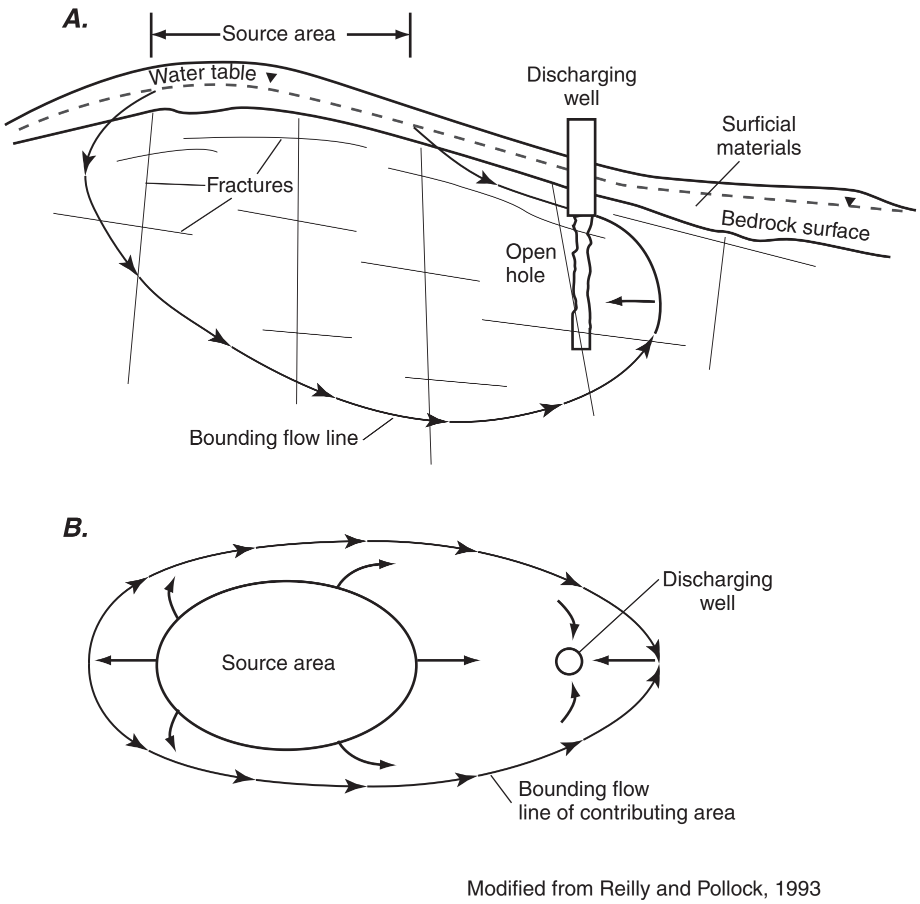



**Figure 2.** Source area and contributing area for a discharging well in a simplified hypothetical fractured-bedrock aquifer system: (*A*) cross-sectional view and (*B*) map view.


## Acknowledgments

Several people assisted with coordination of field activities and data collection. They include: Joseph Cerutti and Ron Stalline (MADEP), Linda Marler (MADEM), Mike Gootee (Superintendent, West Newbury Water Department), Janet Tatarczuk (West Newbury Water Department), Walter Socolowski (Superintendent, Maynard Public Works), Frank Lyon (Superintendent, Leicester Water Supply District), Reider Bomengen and Theodore Morine (D.L. Maher Co., Inc.), and Robert Leitch (Dufresne-Henry, Inc.). Numerous well owners kindly provided access to their wells during aquifer testing. Borehole geophysical logs were collected for a well site in West Newbury by Frederick Paillet (USGS Geophysicist). Gregory Walsh (USGS Geologist) mapped the bedrock geology in the three study areas. Janet Stone, USGS, compiled surficial geologic maps and geologic sections for the West Newbury study area and assisted with interpretation of available geologic maps in the Maynard and Paxton study areas. The USGS personnel who assisted with data collection and data reduction include Jason Sorenson, Peter Church, Stacey Archfield, Elizabeth Farren, and Gene Parker.


## STUDY METHODS

Study methods included compilation of drillers' logs and well records that were available in local, state, and USGS files and reports, installation of small-diameter wells, manual installation of shallow drive points, geologic mapping, borehole geophysical logging, collection of streamflow and water-level data, and aquifer testing. Numerical models were used to delineate contributing areas to wells and determine the potential responses of streams and wetlands to pumping from fractured bedrock.

## Well Installation

Numerous small-diameter wells were installed in surficial materials at each of the well sites and used as piezometers during aquifer testing. For this report, the small-diameter wells will be called piezometers. The piezometers have an inside diameter of 0.085 ft (approximately 1 in.), and an outside diameter of about 0.11 ft. They were installed with a vibration or rapid-pulse hammering technique, sometimes referred to as the direct-push method. Many piezometers were installed to a refusal depth. In areas underlain by till, two or more attempts were made within a radius of 5 ft at some locations to penetrate to the estimated depth of the bedrock surface. If depths were similar after three tries, a piezometer was completed at the third location. Generally, penetration to or near the bedrock surface was successful at all well sites, including those where till was the principal lithology.

Most piezometers consisted of a steel point on 1 ft of blank steel pipe below a 5-ft screen. The screen consisted of 0.01-in. wide slots cut vertically with a laser in steel pipe (Pine and Swallow, Inc., written commun., 1999). Blank steel pipe was added in approximately 10-ft lengths and connected by welding a steel coupling. In areas of thin surficial materials, such as the Knowles site in West Newbury, the lower 1 ft of blank pipe was cut off and a steel point was inserted at the bottom of the screened interval so that the screen was at or near the bedrock surface. The piezometer typically extended 2 to 3 ft above the land surface and was equipped with a locking cover.

After installation, piezometers were developed by pumping with an inertia valve pump on the end of 1/2-in. polyethylene tubing. Where possible, a volume of 1 to 5 gal of water was pumped to ensure a good hydraulic connection with aquifer materials. The intrusion of marine clay through screen openings during installation complicated the development of several piezometers in West Newbury. The clay plug inside the piezometer was removed in short increments of 1 ft or less by insertion and removal of polyethylene tubing. Two piezometers in West Newbury recovered slowly after purging either because the screen was opposite low-permeability materials such as clay, or the clay in the screen openings was not removed during development. Several piezometers completed in till in Paxton were quickly evacuated by pumping and slowly yielded water. Attempts to develop these piezometers by adding water, surging, and removing water had little effect on their yields. The inability to improve yield probably reflects the low permeability of the till at this location. Although water levels recovered slowly after purging or adding water, the water levels measured after full recovery are most likely representative of actual water levels.

At the Maynard site, an alternative method was used to develop several piezometers where the large drawdown and the surging action of the inertia pump caused silt and fine sand to enter the well and fill the screen. These piezometers were developed by inserting polyethylene tubing to the level of the silt to circulate clean water from the surface to the bottom by using a hand pump. After removing the silt, water levels declined rapidly after filling the piezometer with water, and the piezometers remained hydraulically connected to the formation during aquifer testing.

Drive points consisting of either steel or PVC screen were installed manually in standing water on the edge of wetland areas before aquifer testing to monitor wetland-water levels. The drive points were installed about 1 ft below the wetland surface, and the screen extended above the surface into standing water.

## Geologic Mapping

Standard techniques were used to map bedrock geologic characteristics at each of the study areas. Features identified included rock outcrops, lithology, orientations of ductile structures (foliation and folds), and orientations of brittle structures (fractures and faults). Detailed descriptions of the bedrock for the three study areas are published separately (Walsh, 2001a; 2001b; 2002). The characteristics of surficial materials in the Maynard and Paxton areas were determined mainly from published maps (Hansen, 1956; Stone, 1980) and in the West Newbury area from unpublished maps available in USGS files (J.R. Stone, U.S. Geological Survey, written commun., 2000). Drillers' logs obtained from town and MADEM files and refusal depths for piezometers were used to estimate the thickness of surficial materials. In this report several terms that describe characteristics of fractured rock may not be familiar to some readers and are defined in the back of this report.

## Borehole Geophysics

Borehole geophysical data collected to determine depths and orientations of water-bearing fractures at the well sites studied included caliper, acoustic televiewer, and optical televiewer logs. A heat-pulse flowmeter also was used to identify water-bearing fractures at the Andreas well site in West Newbury (Frederick Paillet, U.S. Geological Survey, written commun., 1999; Paillet, 2001) and the Leicester well site in Paxton.

## Hydrologic Data Collection

Weirs were installed in streams at four locations in West Newbury, two locations in Maynard, and one location in Paxton. The 90-degree V-shaped notch was cut in sheet metal and attached to plywood that spanned the stream channel. At three locations in West Newbury, one location in Maynard, and one location in Paxton, the weirs were placed across open channels and secured with steel posts and reinforced with sand bags. At one location near West Newbury, the weir was secured by bolts to a cylindrical road culvert; and at one location near Maynard, the weir was secured to a rectangular rock-lined culvert under a former railroad. To monitor stream stage, a staff gage was installed at each of the sites, and a pressure transducer and digital recorder were placed in a vertical stand pipe secured to a steel rod, bridge abutment, or tree. Streamflow was estimated with the method described by Rantz and others (1982) for portable weirs.

At each of the study areas, ground-water levels were measured continuously for several months in selected wells equipped with pressure transducers and data recorders. The recorders were serviced periodically, typically every 2 months or less. Water levels also were measured periodically in selected wells by an electric sounder or steel tape.

Before aquifer testing in each study area, transducers and water-level recorders were installed in selected residential wells, bedrock test wells, and piezometers. During aquifer tests, water levels also were measured manually by electrical sounder or steel tape in numerous wells and piezometers. Water levels were measured in two wells at the Paxton site by pressurizing an airline with a tire pump and reading the water level directly from a pre-calibrated gage.

## Aquifer Testing

The aquifer testing by the towns and their contractors at the West Newbury (Knowles and Andreas) and Maynard (Rockland Avenue) sites determined the sustainable yield for wells in accordance with state guidelines for bedrock wells (Massachusetts Department of Environmental Protection, 1996). Under those guidelines, public-supply wells completed in bedrock are pumped for at least 10 days. These aquifer tests provided an opportunity for the USGS to collect information needed to accomplish the study objectives. Aquifer testing at the Paxton site, where wells have produced water for public supply for many years, was designed to accomplish only the objectives of this study and not to determine sustainable yield.

Contractors to the Towns of West Newbury and Maynard were principally responsible for collecting water-level data in pumped wells and selected observation wells completed in bedrock and surficial materials. Water levels were measured by USGS personnel in piezometers, in bedrock wells other than those measured by contractors, and in residential wells. Residential wells were selected to provide additional measuring points, to the extent possible, around the test sites. The USGS also measured stream stage.

At the Paxton site, pumping was nearly continuous during the study as part of normal operation to provide water for Leicester residents. Aquifer testing involved shutting off pumps for about a week, measuring recovery, restarting pumps, and measuring drawdown for another week.

## Positioning of Data-Collection Points and Location Identifiers

A geographic positioning system (GPS) was used to locate selected data-collection points near the well sites. Altitudes of measuring points for piezometers, observation wells, and stream gages were determined by means of standard leveling methods, or from topographic maps. Locations of residential wells used to map the bedrock surface at the West Newbury site were estimated from addresses and corresponding lot numbers shown on town property maps, locations of homes observed on orthophoto maps, and locations described on drillers' logs. The altitudes of residential wells at their estimated locations were determined from topographic maps. For most residential wells, these estimates are accurate to within 10 ft of actual altitudes.

Data-collection points for this study may have three identifiers, including a local number, a unique number for entry into USGS databases, and a shortened local number to facilite numbering on maps. The map number is used in this report to identify wells. It is either an abbreviated USGS number, or an abbreviated local number, such as for a production well. The local number was selected for some wells because those numbers would be easily recognized by local users of the information. An exception is the Paxton site where the abbreviated USGS number was used for production wells to reduce the possibility of confusion with local numbers (for example, a number 1 appeared for both numbering schemes but for different wells).

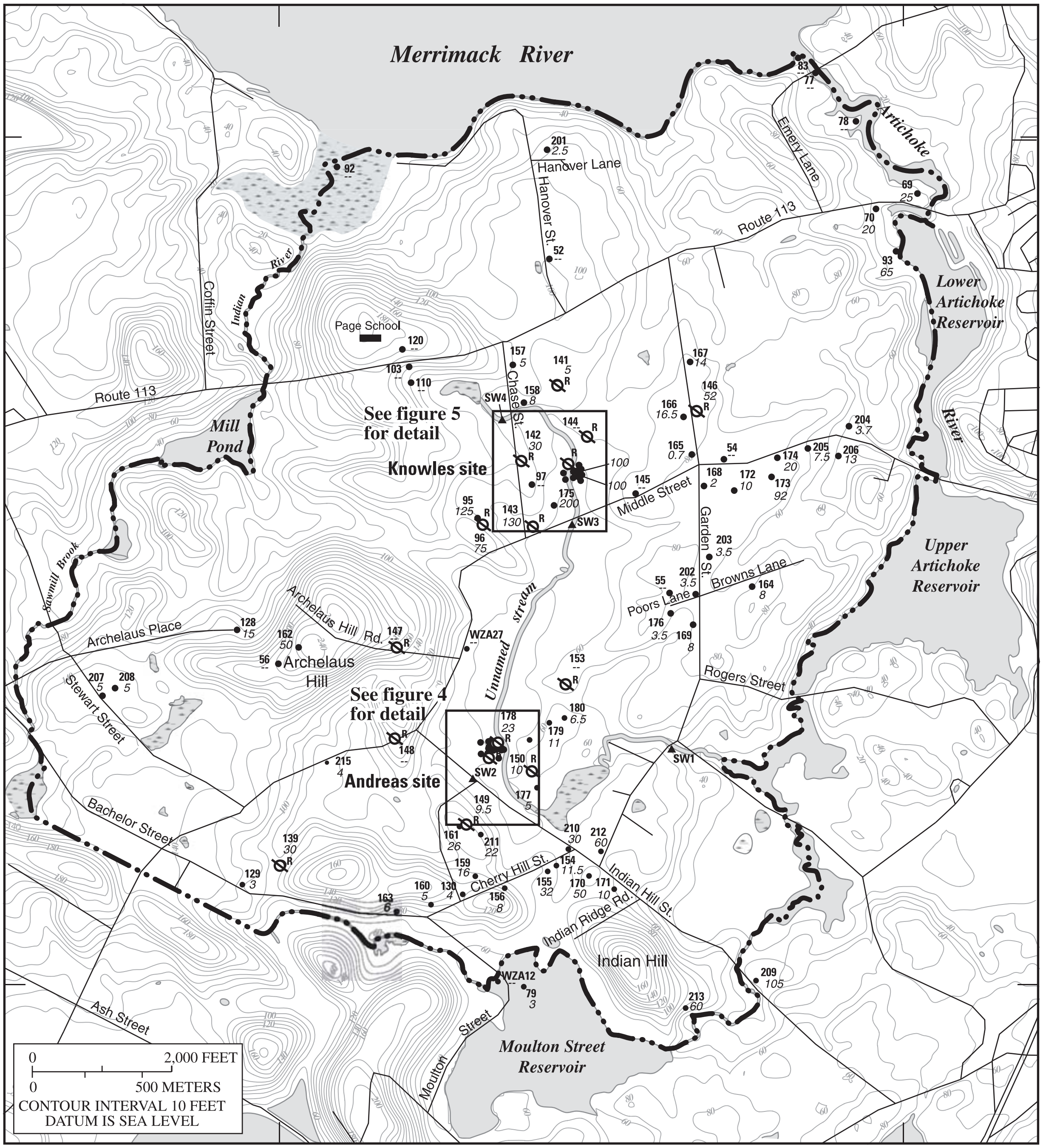
## Numerical Modeling

Finite-difference ground-water-flow modeling and particle tracking methods were used to determine the contributing areas to wells. Continuum or porous-media flow rather than flow through discrete fractures was considered reasonable for the modeled areas on the basis of criteria presented by Long and others (1982). They state that fractured rock behaves as porous media if (1) a small addition or subtraction of test volume does not change the equivalent permeability, and (2) the correct flux is computed when direction of a constant gradient is changed. The relatively large sizes of the model areas (several square miles) and the large number of water-bearing fractures within them satisfy these criteria. Tiedeman and others (1997), Lipfert and others (2001), Barton and others (1999), Starn (1997), and Lyford and others (1999) describe modeling studies of fractured-rock systems. The finite-difference ground-water-flow model used for this analysis was MODFLOW-96 (Harbaugh and McDonald, 1996), with particle tracking by the programs MODPATH and MODPATH-PLOT, version 3 (Pollock, 1994). Approved yields of wells used for the contributing-area analysis were provided by MADEP. For the Paxton study area, modeling indicated that the approved pumping rates based on reported yields could not be sustained, so the rates used for analysis of contributing areas were adjusted downward. All delineations of contributing areas were based on simulations of steady-state conditions. For particle tracking, particles were allowed to pass through weak sinks that remove only part of the water that flows into a model block. Source areas were delineated by forward tracking of particles as they started from the uppermost face of model blocks and moved to wells. Detailed site models are described for each of the study areas.

Steady-state numerical models that were used for delineation of contributing areas also were used to determine the potential effects of pumping from supply wells on wetland areas and streamflow. Streams and wetland areas were simulated as drains that were active only when simulated heads exceeded altitudes of drains. The potential effects of pumping on streamflow were determined for selected drainage basins within the model areas by comparing drain outflow for simulated steady-state nonpumping and pumping conditions. Simulated differences between the two conditions approximately represent the average effect of pumping, but effects could vary seasonally and yearly because of variations in ground-water recharge. A comparison of active drain locations for steady-state simulations of nonpumping and pumping conditions identified wetland areas that might be affected by pumping. The actual effects could include permanent drying of wetland areas or a reduction of the wet period for seasonal wetland areas.

# KNOWLES AND ANDREAS WELL SITES, WEST NEWBURY, MASSACHUSETTS

The Knowles and Andreas well sites are in West Newbury in northeastern Massachusetts (fig. 3). A drilling and testing program supported by the town identified these two sites as candidates for water-supply wells (D.L. Maher Co., 1999a; 1999b). Aquifer tests at the two well sites provided the well-yield data required by the State as part of the process for issuing a permit for a public-supply well. Hydrologic data collected by the USGS and town contractors (Reider Bomengen, D.L. Maher Co., written commun., 2000) during the tests were used to support numerical modeling. Records of wells used for this study are summarized in table 10 (at back of report), and locations are shown on figures 3, 4, and 5. Most of the hydrologic data presented here were collected from July 1999 to November 2000.




Base from U.S. Geological Survey,
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

**EXPLANATION**

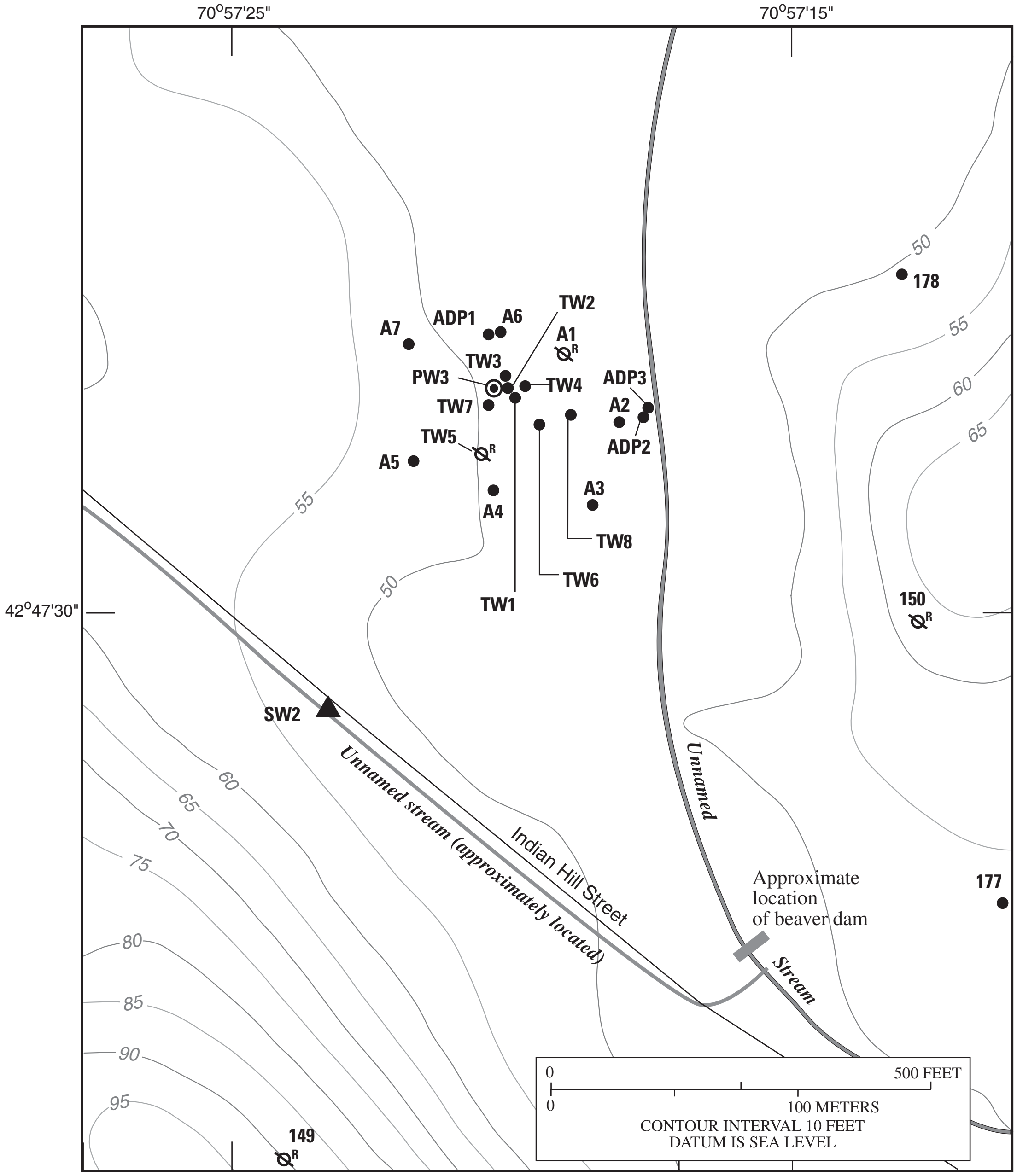
STUDY-AREA BOUNDARY

129 / 3 — WELL OR PIEZOMETER, IDENTIFIER AND REPORTED YIELD, IN GALLONS PER MINUTE—No data, --

149 R — WELL EQUIPPED WITH TRANSDUCER DURING AQUIFER TEST AND IDENTIFIER

SW1 — STREAM-GAGING STATION AND IDENTIFIER

**Figure 3.** Location of the West Newbury study area, Knowles and Andreas well sites, selected wells, reported yields from bedrock wells, and stream-gaging stations, West Newbury, Massachusetts.




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

**EXPLANATION**

178 ● WELL, PIEZOMETER, OR DRIVE-POINT LOCATION, AND IDENTIFIER

150 ⌀R WELL OR PIEZOMETER EQUIPPED WITH TRANSDUCER DURING AQUIFER TEST, AND IDENTIFIER

SW2 ▲ STREAM-GAGING STATION AND IDENTIFIER

PW3 ⊙ PUMPED WELL

**Figure 4.** Wells and stream-gaging stations near the Andreas well site, West Newbury study area, Massachusetts.

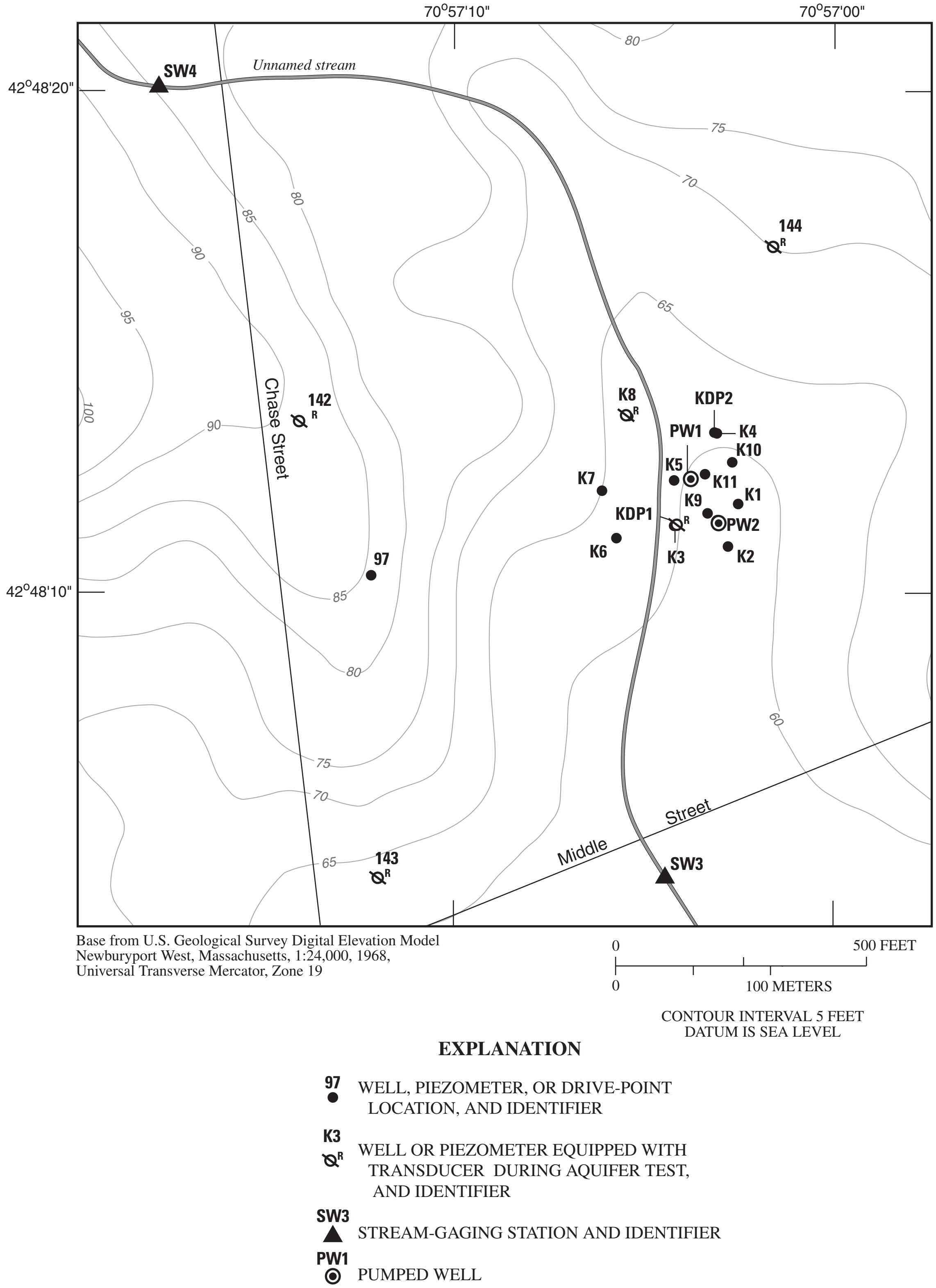



**Figure 5.** Wells and stream-gaging stations near the Knowles well site, West Newbury study area, Massachusetts.

The geographic extent of the study area around the Knowles and Andreas sites was determined on the basis of physiographic features beyond the area that is likely to be affected by pumping. These features also served as boundaries for numerical modeling. The study area shown in figure 3 is bordered on the north by the Merrimack River, on the east by the Artichoke River and associated water-supply reservoirs for the town of Newburyport, on the west by the Indian River and Sawmill Brook, and on the south by a segment drawn between tributaries of these two streams where ground-water flow is assumed to parallel the boundary. The study area is a rural setting where homes are widely spaced, and most residents obtain their water from private wells.

Hills formed as drumlins by continental glaciers are prominent topographic features within the study area; Archelaus Hill (fig. 3) is an example of this type of feature. An unnamed tributary of the Artichoke River flows southward through the approximate center of the study area and near both well sites before turning eastward near the Andreas well site. The drainage area of this tributary upstream from Garden Street is about 1.3 $mi^2$. Wetlands cover about 20 percent of this drainage area, as determined from available wetland maps in the Massachusetts Geographic Information System (MassGIS). Two wells at the Knowles site are on a nearly circular, about 200 ft wide hill that is surrounded by wetlands. One well at the Andreas site is on nearly flat ground and within 200 ft of extensive wetlands to the north and east. Data-collection points near the Andreas site are shown in figure 4 and near the Knowles well site in figure 5.

## Geology

The bedrock geology was mapped during June 2000 to identify characteristics of the bedrock that may affect ground-water flow (Walsh, 2001a). Additional information about the bedrock structures was provided by borehole geophysical surveys in the summer of 1999 (F.L. Paillet, written commun., 1999) and fall of 2000. The discussion of bedrock geology is based largely on the description by Walsh (2001a). His map and description of the geology expands on previous mapping by Shride (1976). Bedrock depths reported on drillers' logs were used to map the bedrock surface. A surficial map was compiled on the basis of unpublished information in USGS files (J.R. Stone, written commun., 2000).

### Bedrock

The Knowles and Andreas well sites are within phyllite rocks of the Silurian-age Eliot Formation (fig. 6), and are about 0.3–0.6 mi west of intrusive rocks of the Newburyport Complex. The Clinton–Newbury fault, a prominent geologic feature in northeastern Massachusetts that marks the boundary between two major geologic terrains, is about 0.5–1.5 mi south of the wells (Shride, 1976; Zen, 1983).

The Eliot Formation near the wells consists of slightly calcareous quartz-muscovite phyllite. Bedding is poorly developed and consists of alternating layers of phyllite and quartzose phyllite that are generally less than 5 cm thick. Solution cavities (vugs) are locally present in quartz-calcite veins that are oriented along schistosity, cleavage, and fracture planes. Trace amounts of pyrite are present in places.

The Newburyport Complex intrudes the Eliot Formation and consists of granodiorite to quartz monzonite. The degree of foliation in the Newburyport Complex increases southward toward the Clinton–Newbury fault. The Sharpners Pond Diorite is exposed south of the Clinton–Newbury fault but not near the wells. It consists of fine-grained biotite-hornblende diorite.

Ductile structures, formed during rock deformation under conditions of high temperature and pressure, include, in order of age: (1) a first generation bed-parallel schistosity (referred to as the S1 surface); (2) a second-generation planar fabric (S2) that varies from a cleavage to a schistosity in the Eliot Formation and a cleavage to gneissosity in the Newburyport Complex and Sharpners Pond Diorite; and (3) a weakly displayed third generation (S3) slip cleavage. The layer-parallel S1 schistosity is expressed by the planar alignment of metamorphic minerals, mostly muscovite, quartz, and chlorite. The orientation of S1 is subhorizontal to gently dipping throughout the area and is everywhere deformed by younger fabrics.

The S2 fabric consistently strikes northeast and dips steeply to the southeast and northwest. The average strike of the S2 fabric is 249°, and the average dip is 80° northwest. All rocks in the study area exhibit parting along S2 surfaces. Generally, the S2 foliation is more penetrative in the southern part of the map area near the Clinton–Newbury fault. Locally, in the southern part of the area, the S2 foliation is mylonitic.

Fractures are well connected in bedrock exposures. Most of the fractures observed in the study area dip steeply. The data might have a directional bias, however, because few of the rock exposures have vertical faces where shallow dipping fractures can be observed. Fractures in outcrops of the Eliot Formation near the wells strike predominantly northwest and dip steeply. Although the northwest direction is consistent, the strikes vary from outcrop to outcrop. Principal strikes in the Eliot Formation closest to the wells are 288°, 326°, and 34°. For the study area, principal strikes of fractures that transect the entire outcrop are 34° and 307°.

Borehole geophysical logs for several wells at the Andreas well site identified highly transmissive low-angle fractures generally less than 100 ft below the land surface and 50 ft below the bedrock surface within a cluster of bedrock test wells (wells TW1 to TW8, table 10) (F.L. Paillet, written commun., 1999; Paillet, 2001). These fractures dip to the northwest at about 8°. High-angle water-bearing fractures also are apparent at greater depths, generally 200 ft or more below the surface. The low-angle fractures near the top of the bedrock surface are much more transmissive than the high-angle fractures (F.L. Paillet, written commun., 1999). Water-bearing zones in the two Knowles site wells reported by drillers (wells PW1 and PW2, table 10) also were identified in borehole geophysical logs as nearly horizontal fractures, dipping to the north northwest at 9°. Interpreted water-bearing fractures at wells WZW-95 and WZW-96 also are low angle and dip to the west at 9°. The low-angle fractures appear to reflect partings along schistosity layers (the S1 surface).

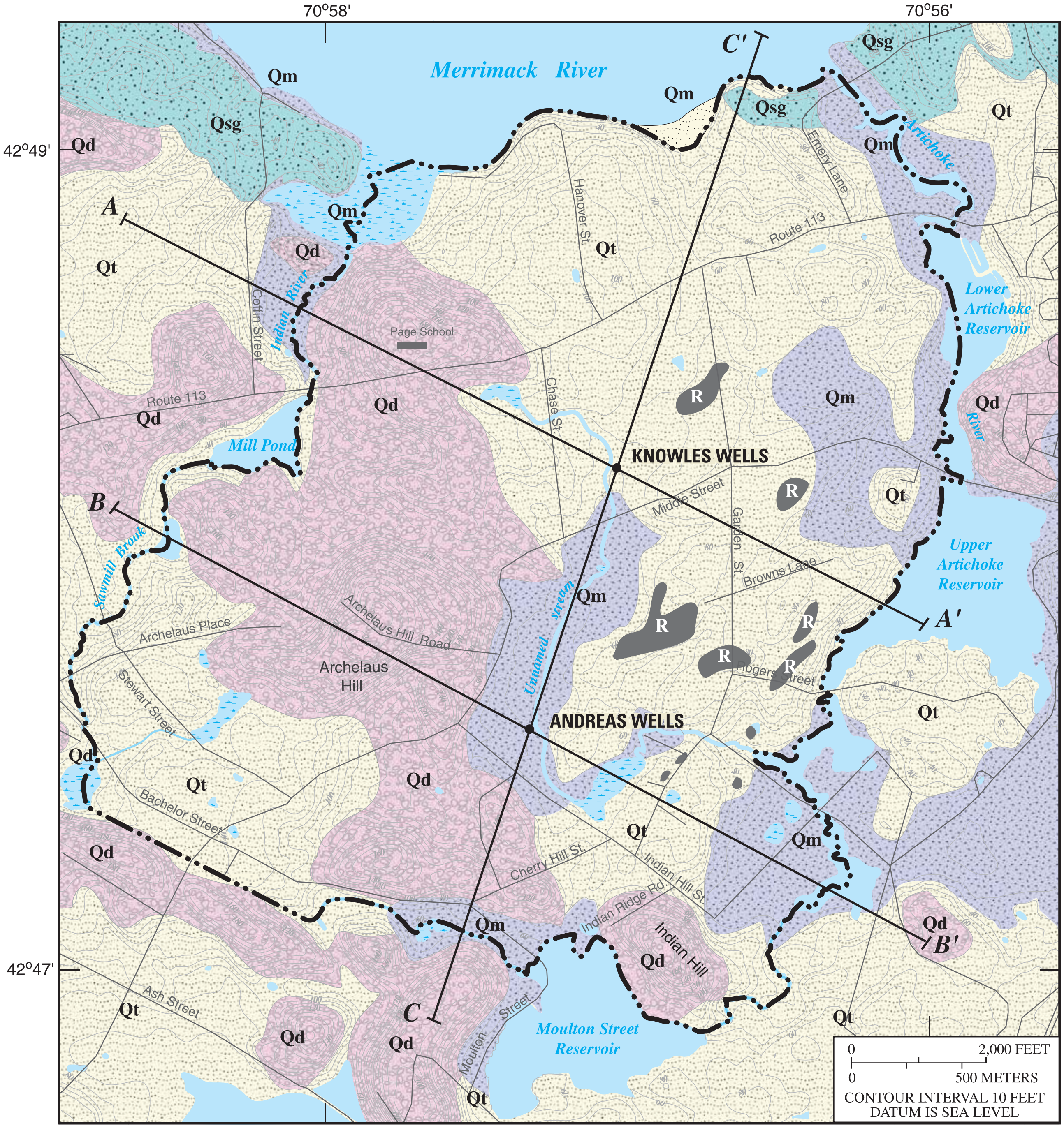
The bedrock surface closely parallels the land surface at a depth of less than 20 ft over most of the eastern half of the study area where till and wetland sediments overlie bedrock; and in several areas, bedrock is at or near the surface (fig. 7). Large thicknesses of till, exceeding 200 ft in places, overlie bedrock in drumlins on the west and south sides of the study area. Limited borehole information indicates bedrock troughs along the valleys of the Indian and Artichoke Rivers near their confluence with the Merrimack River. A depression buried below marine sediments and drumlins is apparent near the Andreas well site. This depression turns eastward in the area near Indian Hill and extends northward to the area near the confluence of the Indian and Merrimack Rivers. A seismic profile along the Merrimack River indicated that the bedrock surface is generally 60 ft or less below the river level between the Indian and Artichoke Rivers. A greater depth of about 100 ft was identified near the mouth of the Indian River (Sammel, 1962).

### Surficial Geologic Units

Surficial geologic units include thick till in drumlins, thin till over drumlin till or shallow bedrock, and marine silts and clays (figs. 7 and 8). Till in drumlins typically is greater than 15 ft thick and is denser than thin surface till because of compaction during the last period of glaciation (Melvin and others, 1992). Thin surface till was deposited mainly during melting of the last continental glacier (Wisconsinan glaciation). Surface till typically is thinner than 10 ft and is less compact than the thick till.

Sand and gravel deposits underlie a small part of the study area near the mouth of the Artichoke River (fig. 7). Several shallow water-supply wells for West Newbury are completed in this geologic unit.

Marine sediments, consisting mainly of silt and clay, were deposited where the weight of ice depressed the land surface below sea level and slowly rebounded to its present level after glacial retreat. The relative maximum sea level was at an altitude of about 100 ft (J.R. Stone, oral commun., 2000). Marine clays were deposited in the deeper water environments, typically below an altitude of about 70 ft. Marine sediments exceed 50 ft near the Andreas site (fig. 8) and near the mouth of Indian River. A silt layer observed in a hand-augured hole at about 1 ft below organic-rich wetland soils near the Knowles site also may have been deposited in a marine environment. Soft organic-rich wetland soils are less than 2 ft thick near the Andreas and Knowles sites, as determined from limited auguring by hand and ease of installing of drive points.




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

Geology by Janet Radway Stone, U.S. Geological Survey, 2000

**EXPLANATION**

MAP UNITS

**Qm** MARINE FINES—Consists mostly of silt- and clay-sized particles deposited in a marine environment

**Qsg** SAND AND GRAVEL—Coarse-grained materials deposited near melting ice. May extend beneath marine fines near the Artichoke River. Limited to northeast corner of study area

**Qt** SURFACE TILL—Assorted mixture of clay- to boulder-sized particles. Less compact and larger percentage of sand than thick till. Generally less than 15 feet thick

**Qd** THICK TILL—Assorted mixture of clay- to boulder-sized particles in drumlins. More compact and a larger percentage of fines than surface till. Generally greater than 15 feet thick. Typically includes a layer of surface till to a depth of 15 feet or less.

**R** ROCK—Bedrock exposed at land surface

STUDY-AREA BOUNDARY

A — A' LINE OF GEOLOGIC SECTION–See figure 8

LINE OF GEOLOGIC CONTACT

**Figure 7.** Surficial geologic units and locations of geologic cross sections, West Newbury study area, Massachusetts.

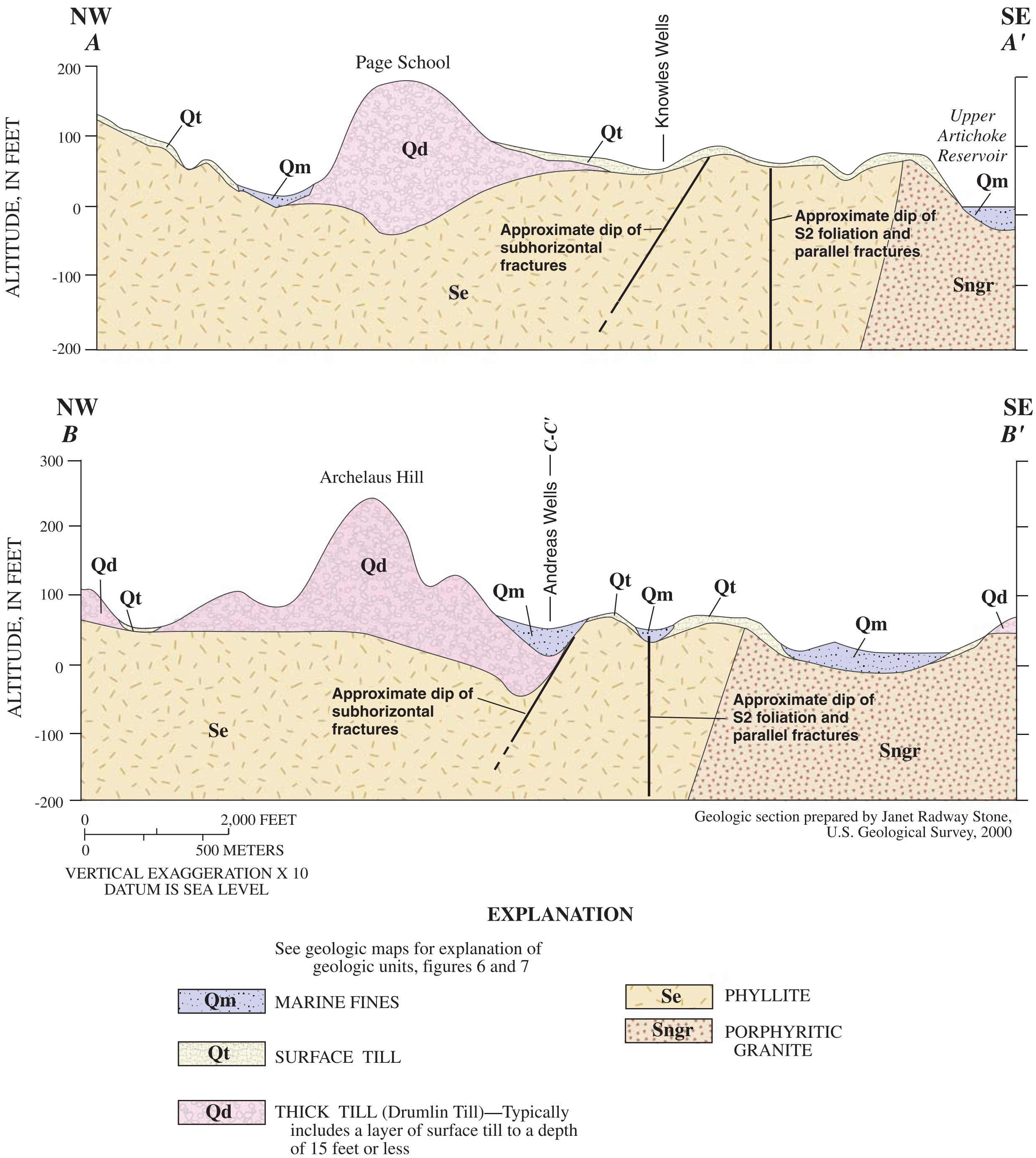



**Figure 8**. Geologic cross sections, West Newbury study area, Massachusetts.

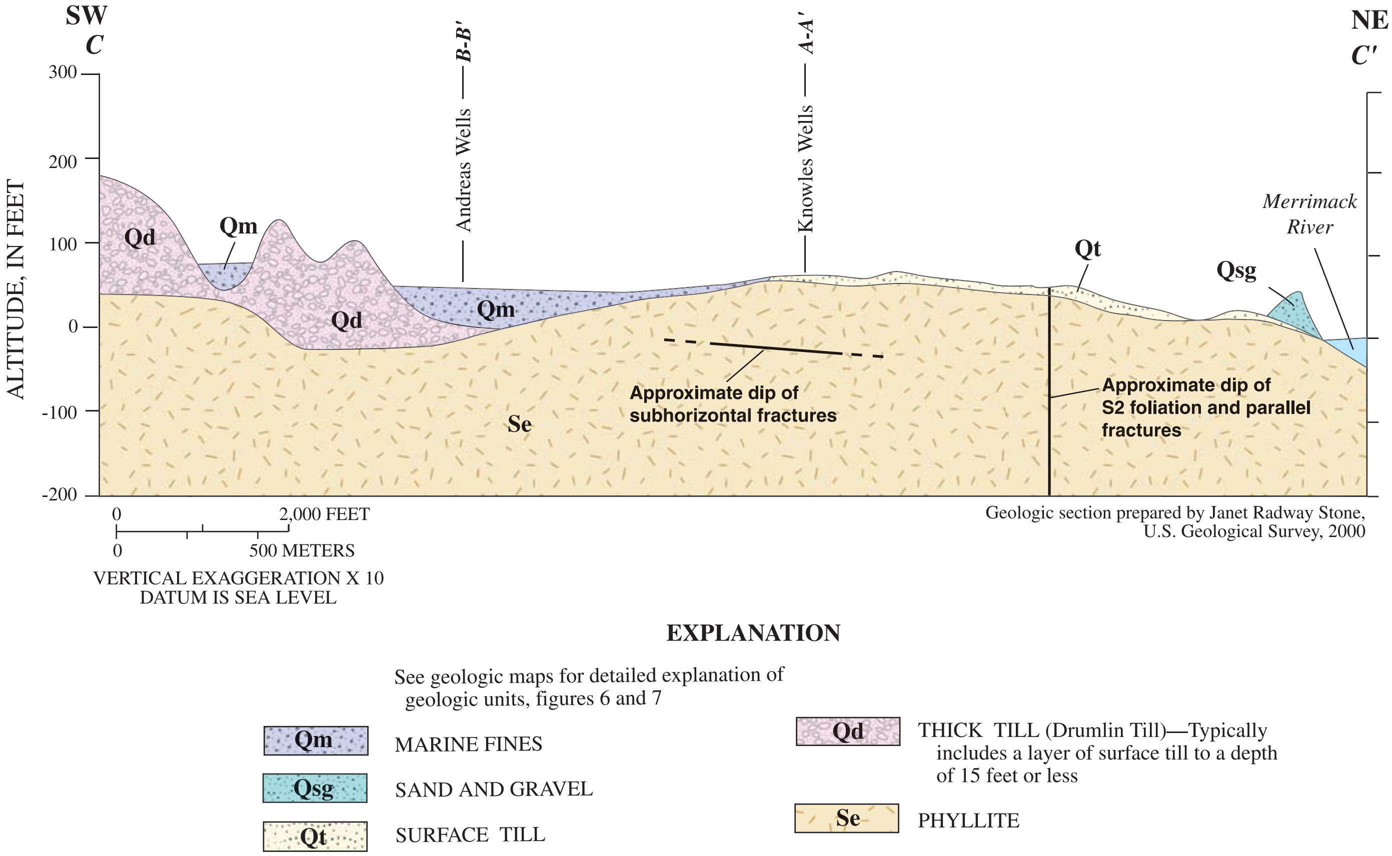
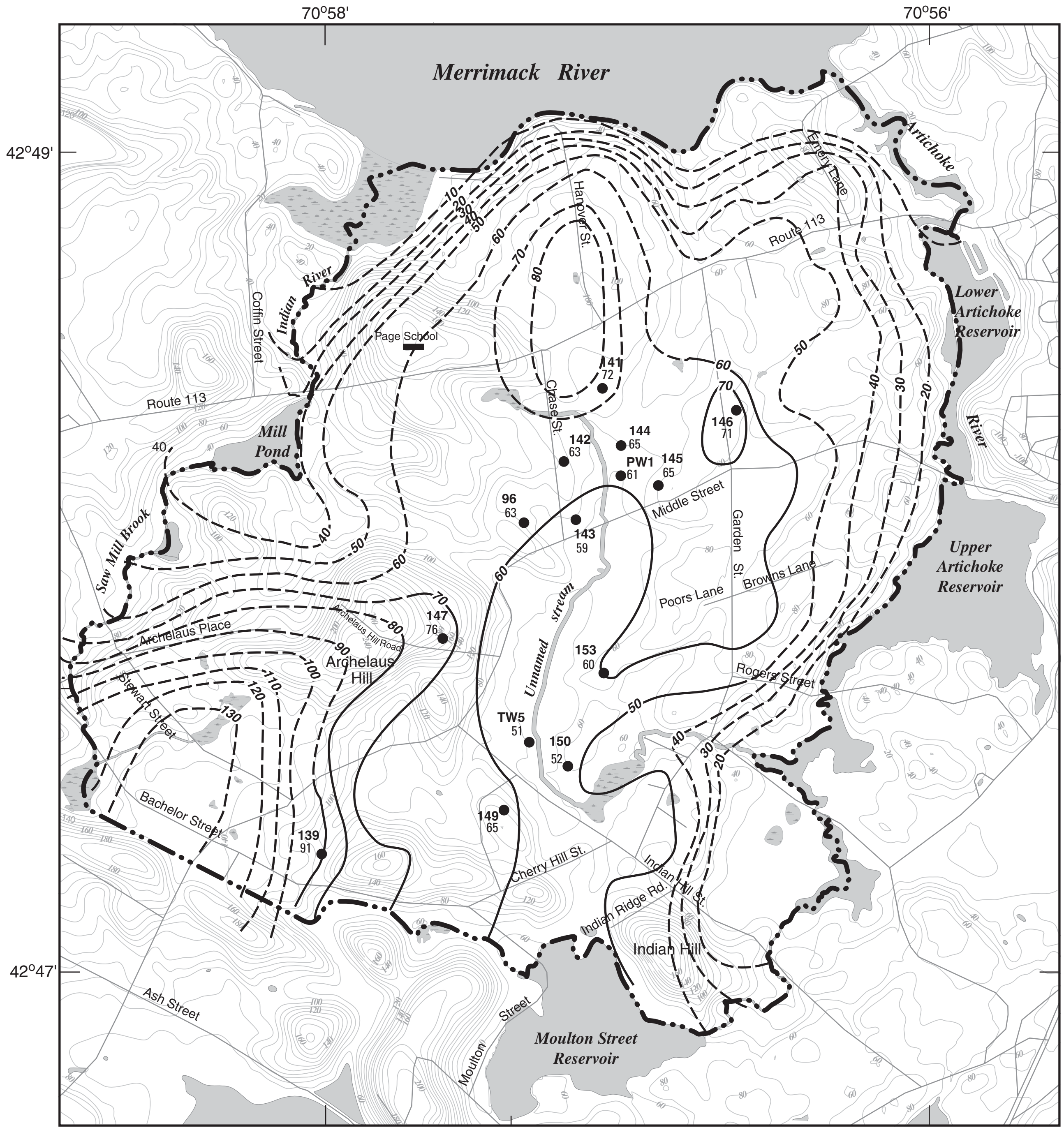



**Figure 8**. Geologic cross sections, West Newbury study area, Massachusetts—*Continued*.

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

A potentiometric surface map (fig. 9) was constructed from water levels measured in December 1999, land-surface altitudes at stream channels and wetlands, and depths to water reported by drillers. Ground-water flow in the bedrock at the scale of the study area is at right angles to the potentiometric contours. Principal ground-water-discharge areas are the Merrimack River, the Artichoke River and associated reservoirs on the east, the Indian River on the west, and the unnamed tributary and associated wetlands through the central part of the study area. Shallow ground water in drumlins flows in the general direction of the topographic slope toward drainage channels.

Flow patterns may change somewhat seasonally in response to water-level fluctuations, but general patterns should be similar from season to season. Because of the inferred steep hydraulic gradients near the Merrimack River, Artichoke Reservoirs, and Indian River, stage fluctuations in these surface-water features are not expected to alter water levels and flow patterns elsewhere in the ground-water system. During 1999–2000, water levels fluctuated over a range of about 8 ft in well 96, within a range of 2 ft in piezometer K8 in a wetland area near the Knowles site, and within a range of 2 ft in bedrock well TW5 at the Andreas site (fig. 10). Dug well 97 near the Knowles site was dry in August 1999; water levels fluctuated over a range of at least 10 ft during 1999–2000. Water levels in bedrock well 139 fluctuated over a range of about 4 ft during the observation period. The altitude of the water level and range of water-level fluctuations may partly reflect stage in a nearby stream.




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

0 2,000 FEET
0 500 METERS
CONTOUR INTERVAL 10 FEET
DATUM IS SEA LEVEL

**EXPLANATION**

STUDY-AREA BOUNDARY

149 52 WELL, WATER LEVEL, AND IDENTIFIER — Shows altitude of water level measured on December 9–10, 1999. Datum is sea level.

60 POTENTIOMETRIC CONTOUR—Shows estimated altitude at which water level would have stood in bedrock on December 9−10, 1999. Contour interval is 10 feet. Dashed where approximated

**Figure 9.** Water levels and estimated potentiometric surface for the bedrock aquifer, December 1999, West Newbury study area, Massachusetts.

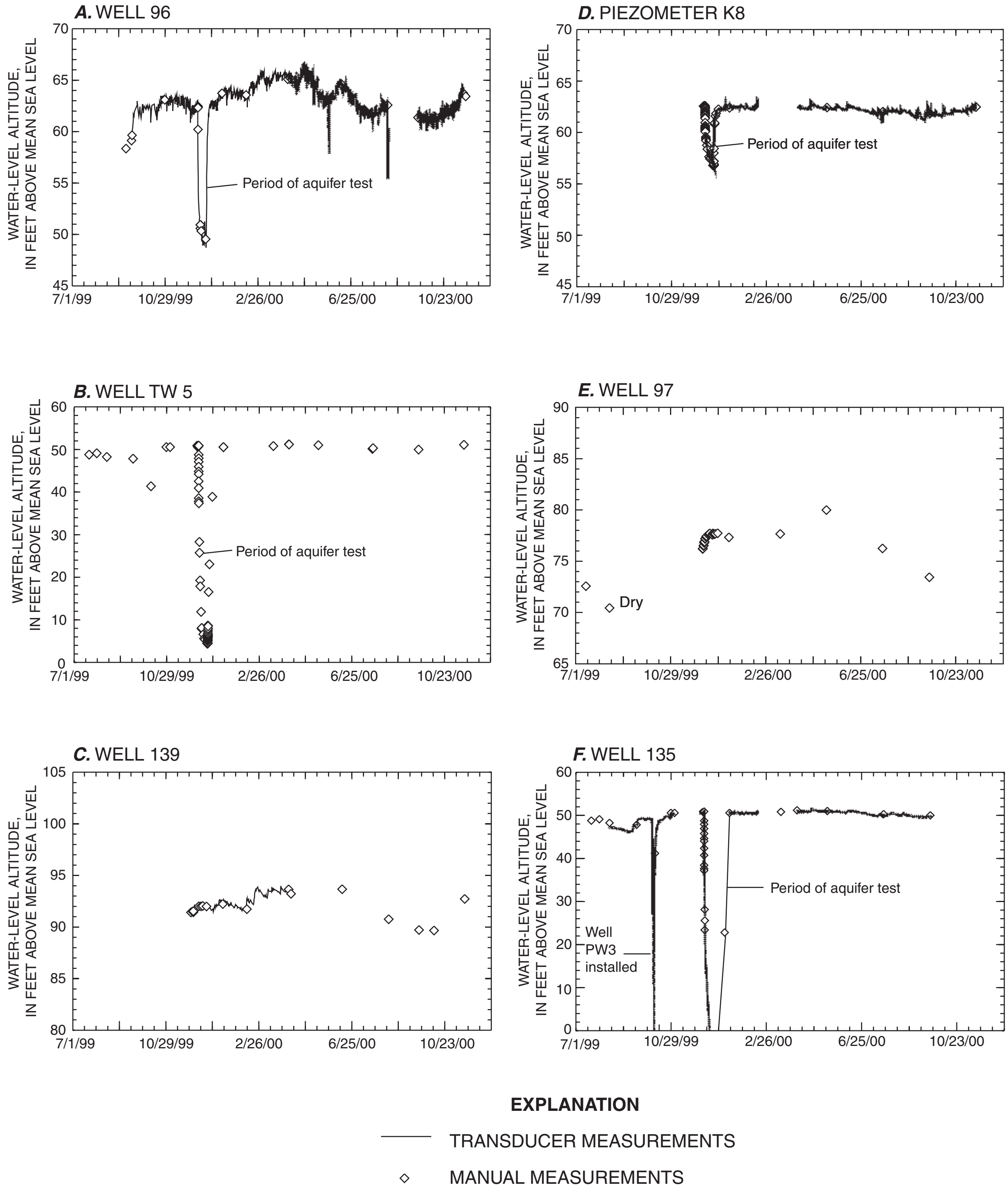



**Figure 10.** Water levels in wells 96, K8, TW5, 97, 139, and 135, July 1999 to November 2000, West Newbury study area, Massachusetts.

## Ground-Water Recharge

Recharge rates to the bedrock aquifer in the study area were estimated on the basis of surficial geology and previous estimates in other bedrock settings. Areas underlain by marine sediments are typically in lowland areas that are primarily areas of ground-water discharge. If pumping in these areas lowers the head below the surface, the bedrock might receive some recharge by leakage through these marine sediments, but the rates would be low because of the low vertical hydraulic conductivity of silts and clays that compose the sediments. Gerber and Hebson (1996) report a recharge rate through marine clay of 0.24 in/yr for a landfill in Maine. Potential leakage rates through marine clay under stressed conditions will be discussed later.

Leakage rates to bedrock through thick till may also be low because of the presumed low hydraulic conductivity of the thick till. Conceptually, hydraulic gradients are downward through thick till, and leakage rates from till to bedrock may not vary appreciably with time if the thick till is mostly saturated. Additionally, if vertical gradients are steep, approaching 1:1, a lowering of the head in bedrock by pumping may not affect leakage rates appreciably. Gerber and Hebson (1996) report an average recharge rate of 3.2 in/yr for a drumlin in Maine. Simulated recharge rates for a drumlin area near Walpole, MA, ranged from 2 to 11 in/yr (ENSR Consulting and Engineering, 1992).

Recharge rates to bedrock in thin till areas are controlled by the infiltration rates for soils derived from till and by the hydraulic properties of the till that control leakage rates to bedrock. Where the head in bedrock is below the bedrock surface, the recharge rate to bedrock will be controlled either by vertical hydraulic conductivity of the till where leakage rates are less than the soil infiltration rates to till, or by the infiltration rate where leakage rates exceed infiltration rates. Recharge rates used for modeling of fractured-rock aquifer systems in the northeastern United States include: 9 in/yr (Barton and others, 1999); 10–20 in/yr (Lyford and others, 1999); 10.2–11.0 in/yr (Tiedeman and others, 1997); 13 in/yr (Starn, 1997); 8.45 in/yr (Wolcott and Snow, 1995). For Connecticut basins covered mostly by till, Mazzaferro and others (1979) estimate ground-water-runoff rates have a lower limit of 35 percent of total runoff. For West Newbury, where total runoff is about 24 in/yr, the result from the Connecticut study would indicate a recharge rate to till of about 8 in/yr. Analysis of long-term streamflow records for upland basins consisting mostly of till in southeastern, central, and western Massachusetts yielded larger recharge rates that ranged from 17.5 to 28.1 in/yr (Bent, 1995; 1999; 2001).

## Aquifer Testing and Observed Hydrologic Responses to Pumping

Aquifers were tested at the Knowles and Andreas sites during December 9–21, 1999, to provide the data needed by MADEP to determine an approvable yield. Streamflow at the start of the test was declining after a rain storm of about 1 in. on December 6–7, 1999. Air temperatures were generally above freezing during the test but were below freezing during most of the recovery period.

Well PW3 (fig. 4, table 10) at the Andreas site was pumped initially at a rate of 200 gal/min, starting on December 9, 1999. At the Knowles site, pumping at well PW1 began 20.5 hours later at a rate of 120 gal/min, and pumping at well PW2 began 130 minutes later at a rate of 120 gal/min, for a combined rate of 240 gal/min. The staggered start was to determine if pumping at the Andreas site affected water levels at the Knowles site and to determine water-level responses caused by pumping a single well at the Knowles site. The pumping rate at the Andreas site was reduced in three steps over an 8-day period to a final rate of 135 gal/min to maintain a water level in the pumped well above the major water-bearing fractures at a depth of about 55 ft below the land surface. The pumping rate at the Knowles site was reduced in two steps over a 6-day period to a final combined rate of 200 gal/min. Pumping at the Knowles site was interrupted for about 5 hours after 9 days of pumping because of power failure. The temporary shutdown is apparent on several of the water-level hydrographs. Water from the pumped well at the Andreas site was piped and discharged near the beaver dam (fig. 4). Water from the two pumped wells at the Knowles site was piped and discharged immediately downstream from the Middle Street weir (SW3) (fig. 5).

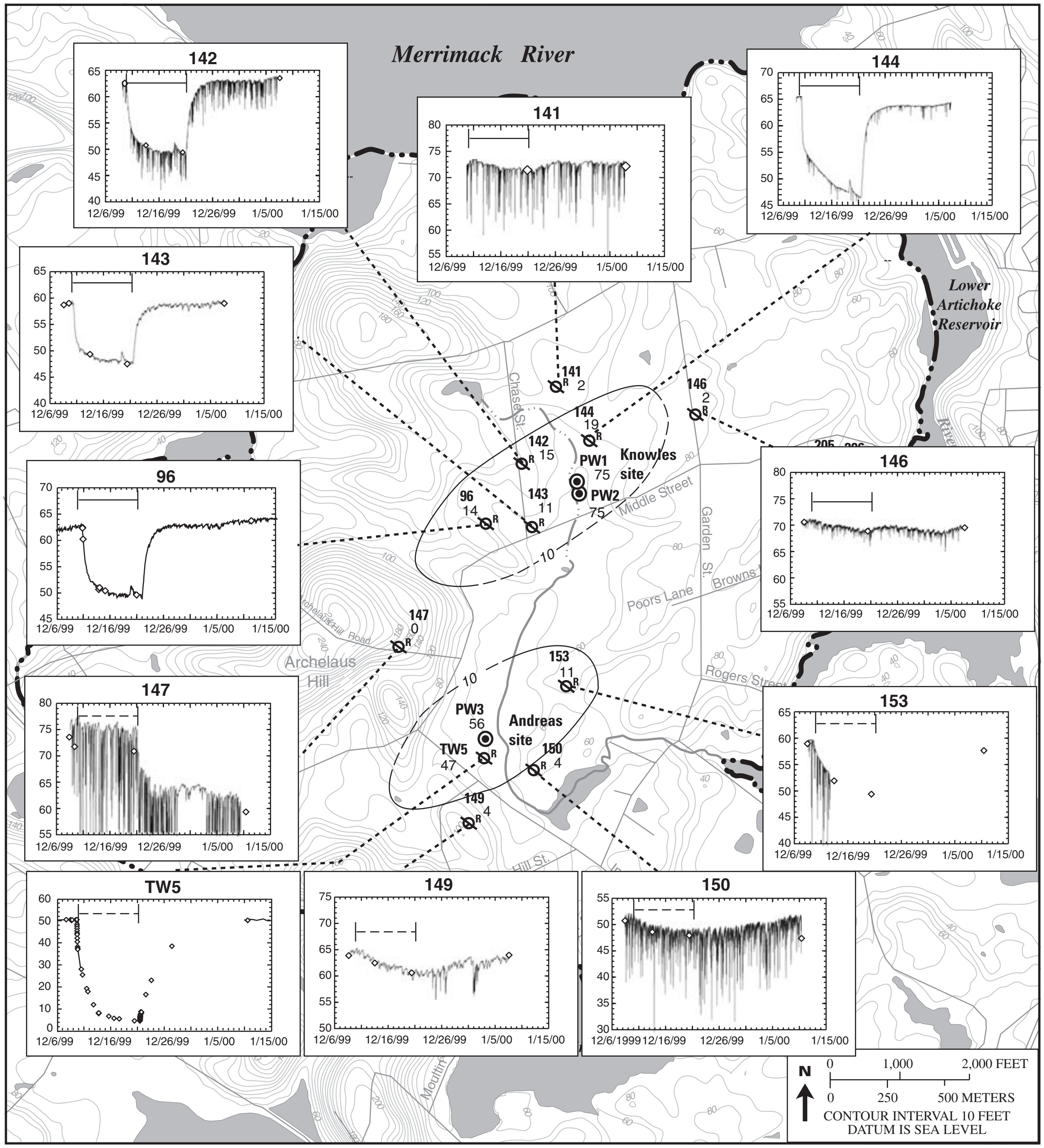
Water-level changes observed in residential wells during aquifer testing include short-term changes of a few minutes or tens of minutes, which were caused by cyclic pumping for residential use superimposed on long-term changes of several days caused by pumping and recovery at the Knowles and Andreas sites (fig. 11). The magnitude of drawdowns caused by cyclic pumping is related inversely to well yields reported by drillers (fig. 3; table 10). For example, pumping cycles at well 143, which has a reported yield of 130 gal/min, cause much less drawdown than pumping cycles in well 141, which has a reported yield of 5 gal/min. Short-term fluctuations in well 96, which was not pumped, and well 149, which was pumped infrequently, may reflect pumping from one or more nearby residential wells.

Water-level responses during the initial 20.5 hours of pumping at the Andreas site were not apparent in wells at the Knowles site nor in well 96 or in residential wells near the Knowles site. Water levels in three residential wells (149, 150, and 153) near the Andreas site responded to pumping (fig. 11). The response, if any, to pumping at a fourth residential well, well 147, on nearby Archelaus Hill was not obvious. The cause for a sudden decline in water level at this well about 1 day after pumping ended is not known, but probably did not relate to pumping from either well site. Responses to pumping were not apparent at a nearby dug well, well 148, nor in bedrock well 139 (fig. 3) about 3,500 ft southwest of the Andreas site. Two bedrock observation wells, TW1 and TW7 (hydrograph not included on fig. 11), both of which are cased to depths that are above the water-productive fractures near the bedrock surface (F.L. Paillet, written commun., 1999), had greater drawdowns than the other bedrock observation wells, which were cased to depths below these fractures. These differences are apparent on figure 12 for wells TW1 (casing above shallow fractures) and TW8 (casing below shallow fractures).

Generally, drawdowns at the end of the test did not correlate with distance from the pumped well, which is commonly observed in fractured aquifers where the hydraulic connections between fractures vary from well to well (Tiedeman and Hsieh, 2001). A drawdown of approximately 11 ft in well 153 near the end of the aquifer test, and limited drawdowns of 4 ft or less in wells 149 and 150, support an interpreted oblong cone of depression elongated northeast and southwest. This pattern of drawdown could result from a preferred orientation of high-angle transmissive fractures parallel to the S2 foliation or to a northeast strike of low-angle fractures that dip to the northwest. Other interpretations of drawdown distribution are possible. The heads at the end of the test indicated an upward hydraulic gradient from deep to shallow bedrock.

Water levels in five of the seven piezometers at the Andreas site responded nearly instantaneously to pumping. Water levels were lowered below the transducer level in piezometer A1 and below the bottom of piezometers A2 and A3 during the test (fig. 12) Throughout the test, the drawdown observed in piezometer A5 was larger than drawdown in nearby well TW5, and drawdown in piezometer A6 was larger than drawdown in nearby well TW3. Drawdowns observed in piezometers A5 and A6 were similar to drawdowns observed in wells TW1 and TW7 and probably reflect drawdown in the shallow fracture zone. Water-level data for piezometers A4 and A7, which were not developed well enough to form a good hydraulic connection to surficial materials after installation, are considered nonrepresentative of actual water levels and have been omitted. Water levels in wetland drivepoints ADP2 and ADP3 represent stage in the pond behind the beaver dam. At ADP1, fluctuations of 0.1 ft or less seem to reflect changes in stream stage rather than responses to pumping.

Water levels in several bedrock wells (96, 142, 143, 144) responded strongly to pumping at the Knowles site (fig. 11). Water levels at wells 141 and 146 may have changed slightly in response to pumping at the Knowles site, but drawdowns are less than 2 ft and are difficult to distinguish from background trends. Water-level responses, as shown by a 10-ft drawdown contour on figure 11, are interpreted to be greater along a transmissive zone that trends southwest to northeast than in areas outside this zone, such as at wells 141 and 146. The interpreted drawdown pattern may relate to low-angle transmissive fractures that dip to the northwest parallel to the S1 foliation, high-angle transmissive fractures along the S2 foliation, or a combination of the two. The extent of low-angle fractures and likely intersection of fractures with the bedrock surface to the south and southeast may affect the shape and extent of the drawdown cone south of the well.




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

**EXPLANATION**

VERTICAL SCALE OF GRAPHS IS WATER-LEVEL ALTITUDE, IN FEET ABOVE SEA LEVEL

STUDY-AREA BOUNDARY

TRANSDUCER MEASUREMENT—Individual points are manual measurements.

PUMPING PERIOD
- Knowles site
- Andreas site

149 4 R — WELL OR PIEZOMETER EQUIPPED WITH TRANSDUCER DURING AQUIFER TEST, IDENTIFIER, AND DRAWDOWN, IN FEET AT THE END OF AQUIFER TEST

PW3 — WELL PUMPED DURING AQUIFER TEST, AND IDENTIFIER

—10— INTERPRETED 10-FOOT-DRAWDOWN CONTOUR AT THE END OF AQUIFER TESTING—Dashed where inferred

**Figure 11.** Water levels in selected bedrock observation wells during aquifer testing, West Newbury study area, Massachusetts.

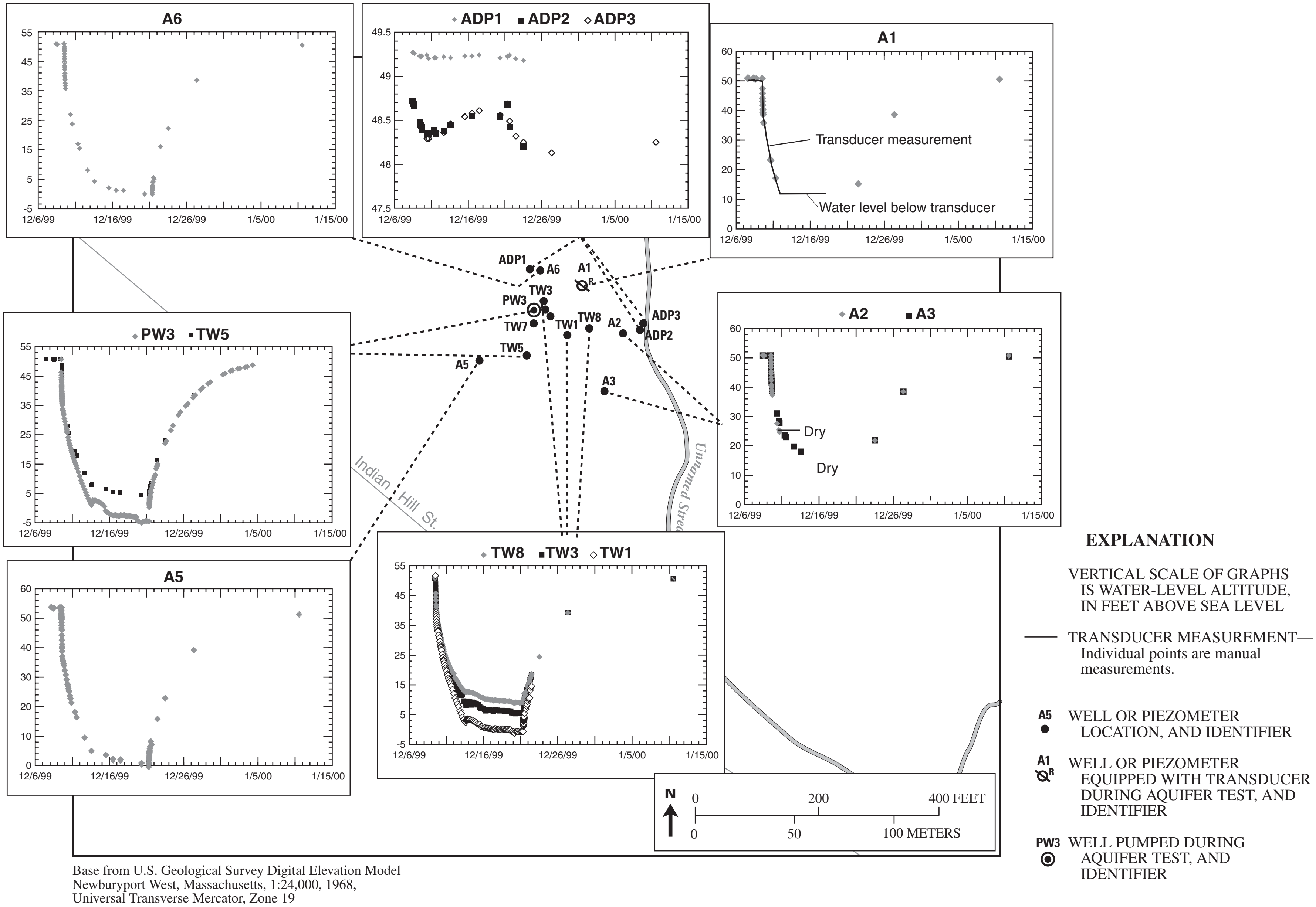



**Figure 12.** Water levels in selected wells and piezometers near the Andreas well site during aquifer testing, West Newbury study area, Massachusetts.

When plotted on a logarithmic scale (fig. 13), the shapes of drawdown curves for well 96, located 1,500 ft southwest, and well 144 located 600 ft northeast of the Knowles wells, provide insights on possible sources of water in the bedrock aquifer during pumping. At well 96, stabilization of drawdown after about 5 days of pumping and deviation from the Theis (1935) type curve indicate a steady source of water. Surficial materials at the well that are 28 ft thick and thicken westward are a likely source. At well 144, the drawdown curve has a shape that indicates delayed drainage (Neuman, 1973), possibly from thinly saturated surficial materials or shallow bedrock.

Water levels in 9 of 11 piezometers at the Knowles site responded within 30 minutes of the time that pumping began (fig. 14). Exceptions were at piezometer K1, which was dry before pumping, and at K7, which was less than 5 ft deep and had a water column of about 2 ft at the start of pumping. The water level in piezometer K7 began declining about 2 hours after pumping began. Water levels in all but piezometers K8 and K4 declined below the level of the screen during the test. The water level at K4 declined to near the bottom of the screen within 2 days and fluctuated somewhat for the remainder of the test. The persistence of water in the piezometer may have resulted from lateral flow into the piezometer at the top of the 5-ft screen and out near the bottom.

Wetland-drivepoint KDP2 was in standing water throughout the aquifer test, and the wetland-water level did not change discernably in response to pumping and precipitation. The wetland area near KDP2 appeared to receive water from upstream sources, and water flow on the wetland surface was observed throughout the test and recovery period. Wetland-drivepoint KDP1 was installed in standing water, but the water level fell about 1 ft below the land surface during the aquifer test. The water level recovered to the land surface when 0.7 in. of rain fell on December 20–21, 1999, and then continued a downward trend until the water level in nearby piezometer K3 had risen to the land surface 3 to 4 days after pumping ceased.

The observed water-level declines in several piezometers reflected a reduction in head near the bedrock surface and not dewatering of the surficial materials. Piezometers screened at the water table would reflect the extent of dewatering. For example, the decline of about 1 ft observed at drivepoint KDP1 indicates the magnitude of dewatering where water was not replenished by surface inflow. Drainage of surficial materials near KDP2 and nearby wetland areas was limited because water that leaked downward from the surface was replenished by surface water.

Pumping at the Knowles site rapidly affected streamflow at the Middle Street stream-gaging station (SW3) (fig. 15). For approximately 2 days before the test, the stream was gaining 100 gal/min between the weir at SW4 and the weir at SW3. After about 2 days of pumping and for the remainder of the test, the stream was losing about 20 to 30 gal/min between these two weirs. Streamflow gains were negligible for approximately 10 days after pumping ceased and eventually increased to about 80 to 100 gal/min in early January. The gradual increase probably reflects resaturation of till and wetland sediments at the water table, but storage of water as ice in streams and wetlands may also have delayed the recovery of streamflow. Pumping had no obvious effect on streamflow at the Chase Street and Indian Hill Street stream gages (SW4 and SW2) (fig. 15). Streamflow measured at the Garden Street stream gage (SW1) (fig. 15) included as much as 400 gal/min discharged from pumped wells during aquifer testing. This increase in flow was partly offset by reduced streamflow caused by pumping, so the effect of pumping discharge is not readily apparent.

## Hydraulic Properties of Geologic Units

Yields of bedrock wells reported by drillers vary widely from 0.7 gal/min to greater than 300 gal/min (table 10; fig. 3). These yields are indicators of the distribution of transmissivity in the upper 300 to 500 ft of bedrock, the depth range for most residential wells. The magnitude of water-level declines caused by cyclic pumping for residential use (fig. 11) is also an indicator of relative transmissivity. For example, drawdowns in residential wells 143 and 144 near the Knowles site indicate higher transmissivity than near well 141 where cyclic drawdowns are much greater.

The hydraulic properties of till have not been measured in the study area. Melvin and others (1992) report an average hydraulic conductivity of 2.7 ft/d for loose surface till and 0.06 ft/d for compact drumlin till derived from crystalline rocks in Connecticut. Horizontal hydraulic-conductivity values for surface and drumlin tills range from 0.0028 to 65 ft/d, and vertical hydraulic-conductivity values range from 0.013 to 96 ft/d. The specific yield averaged 0.28 for surface till and 0.04 for compact drumlin till (Melvin and others, 1992).

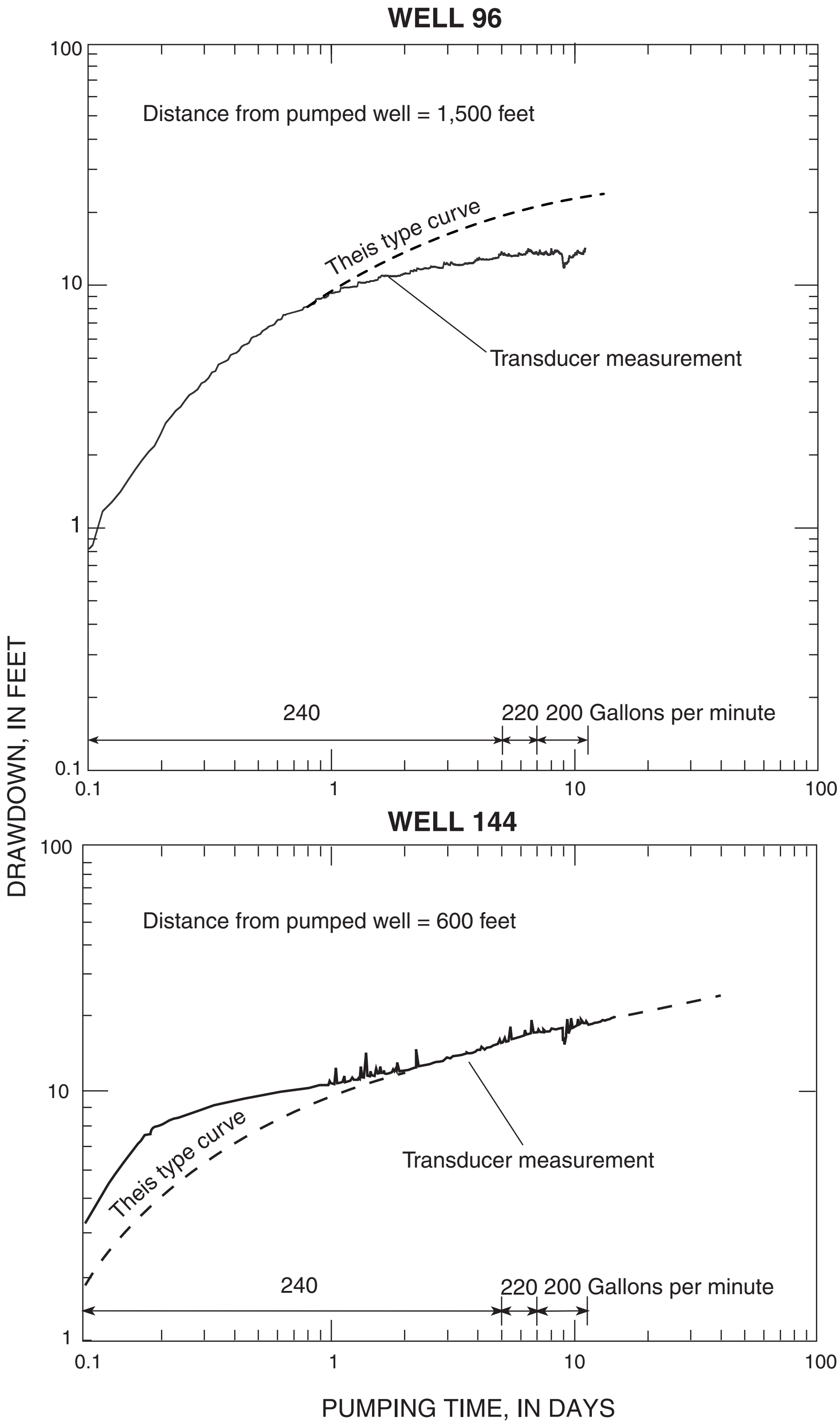



**Figure 13.** Logarithmic plots of drawdown with time compared to the Theis type curve for well 96 and well 144 West Newbury study area, Massachusetts.

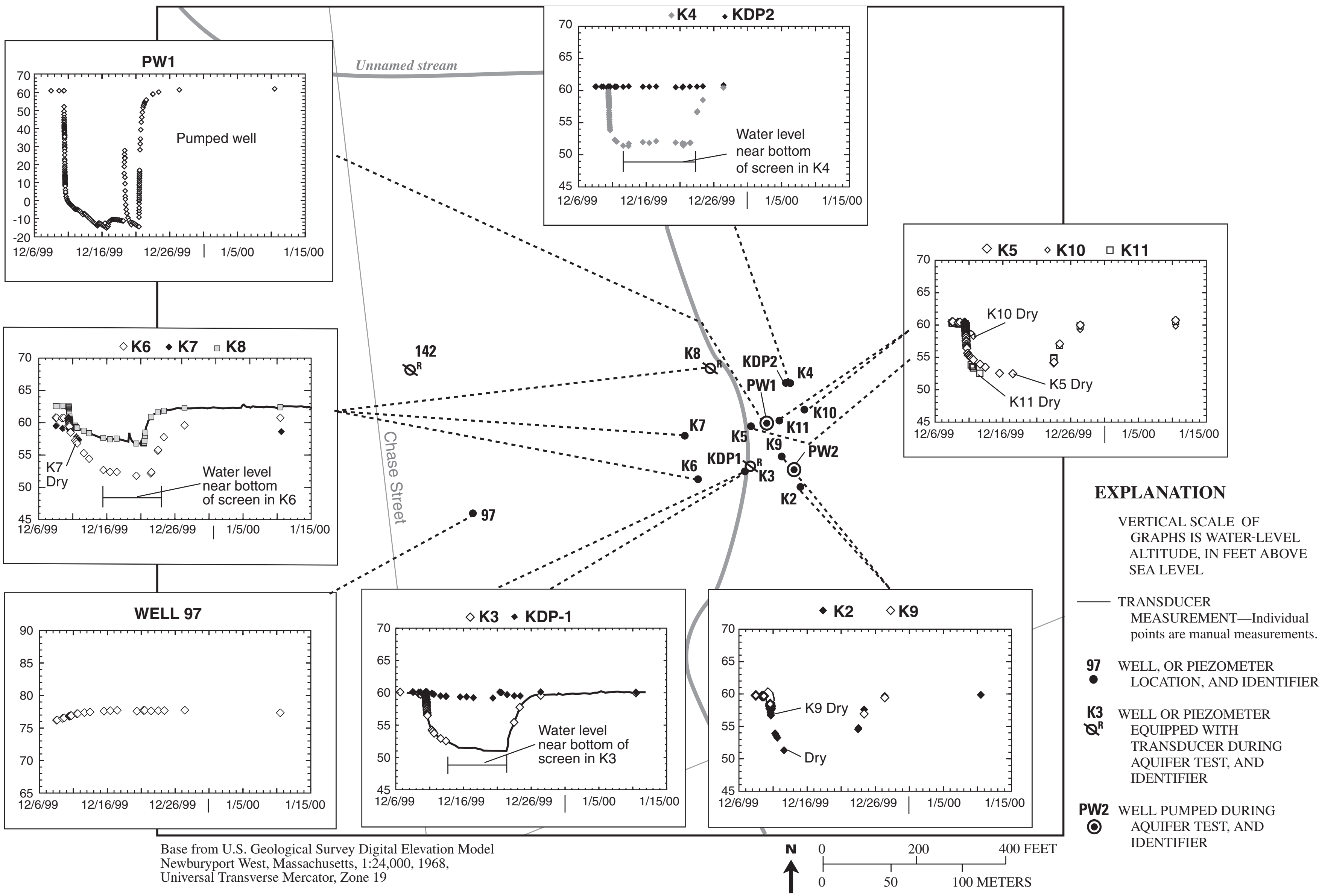



**Figure 14.** Water levels in selected wells and piezometers near the Knowles well site during aquifer testing, West Newbury study area, Massachusetts.

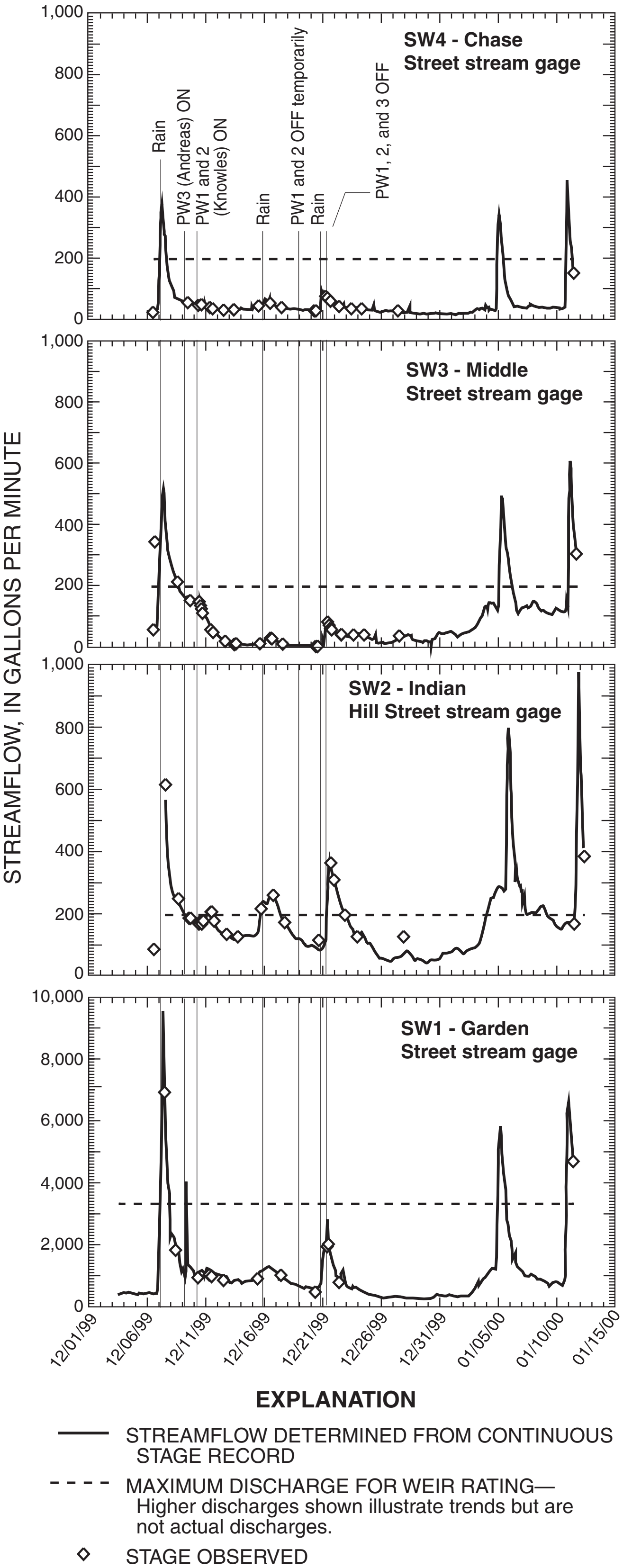



**Figure 15.** Streamflow hydrographs during aquifer testing, West Newbury study area, Massachusetts.

An upper limit for the vertical hydraulic conductivity of drumlin till can be estimated assuming that a water table persists near the surface of the drumlin. Continuous streamflow at the Chase Street stream gage (SW4) during 2000 supports the concept of a persistent shallow water table in the drumlin till underlying the drainage area of this stream. If 24 in/yr is an upper limit for the amount of water available for recharge, then the leakage rate must be less than 24 in/yr. By assuming a maximum possible vertical hydraulic gradient of 1.0 and a maximum potential recharge rate of 24 in/yr, Darcy's Law yields a maximum vertical hydraulic conductivity of about 0.006 ft/d. For comparison, a study of the hydrology of a drumlin in Walpole, MA, identified vertical gradients of 0.1 to 0.9, a horizontal hydraulic conductivity for till of 0.075 ft/d, and a vertical hydraulic conductivity one tenth of the horizontal (0.0075 ft/d) (ENSR Consulting and Engineering, 1992).

Sand and gravel deposits in the study area are limited to an area near the northern end of the Artichoke River. Because of their limited distribution, these deposits would have a negligible effect on ground-water flow in the study area. No estimates of their hydraulic properties are needed for this study.

The hydraulic properties of marine silts and clays have not been measured in the study area. Nielsen and others (1995) report a possible range of hydraulic conductivity from $4 \times 10^{-5}$ to $1 \times 10^{-3}$ ft/d. A vertical hydraulic conductivity of $2.7 \times 10^{-5}$ ft/d was estimated for a thick section of marine clay near Saco, Maine (Nielsen and others, 1995). Randall and others (1988) report an average hydraulic conductivity for marine silty clay of $6 \times 10^{-4}$ ft/d. The hydraulic properties of wetland deposits have not been measured but are assumed to be comparable to surface till.

Water-level and streamflow data collected during aquifer testing can be used to bracket values of vertical hydraulic conductivity of surficial materials near the Knowles site. During aquifer testing, surface-water inflow to the area of the Knowles wells exceeded surface-water outflow by 3,800 to 5,800 $ft^3/d$ (20 to 30 gal/min), as determined from streamflow measurement at SW3 and SW4. During the test, the persistence of water at or near the surface in two wetland drive points indicated vertical hydraulic gradients at piezometers of about 1:1. For an estimated wetland area of about 400,000 $ft^2$ upstream from Middle Street, a vertical hydraulic gradient of 1, and a leakage rate of 3,800 to 5,800 $ft^3/d$, Darcy's Law yields a vertical hydraulic conductivity of between 0.0095 and 0.015 ft/d. These values may be lower than actual values because leakage of the inflow volume may be distributed over an area considerably smaller than the entire wetland area, and the vertical gradient caused by pumping may vary across the area. Nevertheless, the range of vertical hydraulic conductivity values is reasonable for silty materials (Heath, 1989).

Reported storage coefficients for confined fractured-rock aquifers range from $2x10^{-4}$ to $6x10^{-6}$ (Randall, 1988; Tiedeman and Hsieh, 2001; Paillet, 2001). Gburek and others (1999) report specific yields of 0.005 for highly fractured rock, 0.001 for moderately fractured rock, and $1x10^{-4}$ for poorly fractured rock. Randall (1966) reports a general gravity yield of 0.005 for crystalline rocks. A storage coefficient of $9x10^{-4}$ was derived from the Theis formula, which was used to analyze the latter part of the drawdown curve for well 144 (fig. 13). The derived coefficient is comparable to the specific-yield value given by Gburek and others (1999) for moderately fractured rock.

## Numerical Model

A numerical model was developed to delineate contributing areas, estimate the effects of pumping on streamflow and wetlands, and to test hypotheses pertaining to the study. Applications other than these may not be appropriate for the model described.

The West Newbury model was calibrated to an extent considered sufficient to accomplish the goals of the study. Calibration data included water levels measured in December 1999 in 14 wells before aquifer testing, and water levels measured during aquifer testing and recovery. The general approach for model calibration was to simulate average (steady state) conditions reflected in the water levels measured in December 1999. Water-level data from USGS observation wells in Haverhill and Newbury, MA (fig. 16), support the assumption that water-level data collected in December represent average conditions. Water levels in the Haverhill observation well (HLW-23) were somewhat lower than normal, and water levels at the Newbury observation well (NIW-27) were about normal. Water levels that remained steady and near average indicate that the recharge rate was near average for the simulation period. Head data from the steady-state simulation, which reflected average water levels in wells, were then used as heads at the start of transient simulation of the aquifer test. Comparisons of drawdown/recovery patterns and drawdown at the end of pumping were used to qualitatively assess the ability of the model to simulate pumping stress.

### Areal Extent and Boundary Conditions

The modeled area extends from the Artichoke River on the east to the Indian River and Saw Mill Brook on the west and from the Merrimack River on the north to a tributary of the Artichoke River on the south (fig. 17). These features are beyond the likely contributing areas to both well fields. Perennial parts of these river systems, including reservoirs, were modeled as constant heads placed in the upper layer of the model at altitudes determined from a topographic map. Map altitudes are assumed to represent average stages of streams and surface-water bodies. A part of the southern boundary between perennial reaches of streams is assumed to parallel a flow line and is treated as a no-flow boundary.

### Horizontal and Vertical Discretization

The finite-difference grid consists of uniformly spaced square blocks 200 ft wide on a side (fig. 17). The grid is oriented so that rows are approximately parallel to a prominent foliation (S2 surfaces) to test possible effects of anisotropy on ground-water flow and contributing areas to wells. The model was initially designed with three layers to represent surficial materials, upper transmissive bedrock, and lower, less transmissive bedrock. This design, however, was unstable numerically in areas where thin till is typically unsaturated or thinly saturated. To minimize numerical instabilities, the model was modified to include two layers, one that simulated the upper 50 ft of bedrock (layer 1) and one that simulated the lower 400 ft of bedrock (layer 2) (fig. 18). Both layers were simulated as confined that converted to unconfined where the simulated head was below the top. This approach constrained transmissivity to an upper limit defined by the thickness of the bedrock aquifer. The transmissivity changed with saturated thickness if the simulated head was below the top of the layer. The surficial materials were simulated indirectly as sources of recharge and as sources of water from storage for transient simulations. Recharge rates and storage properties in the upper layer were varied areally, depending on the character of the surficial materials.

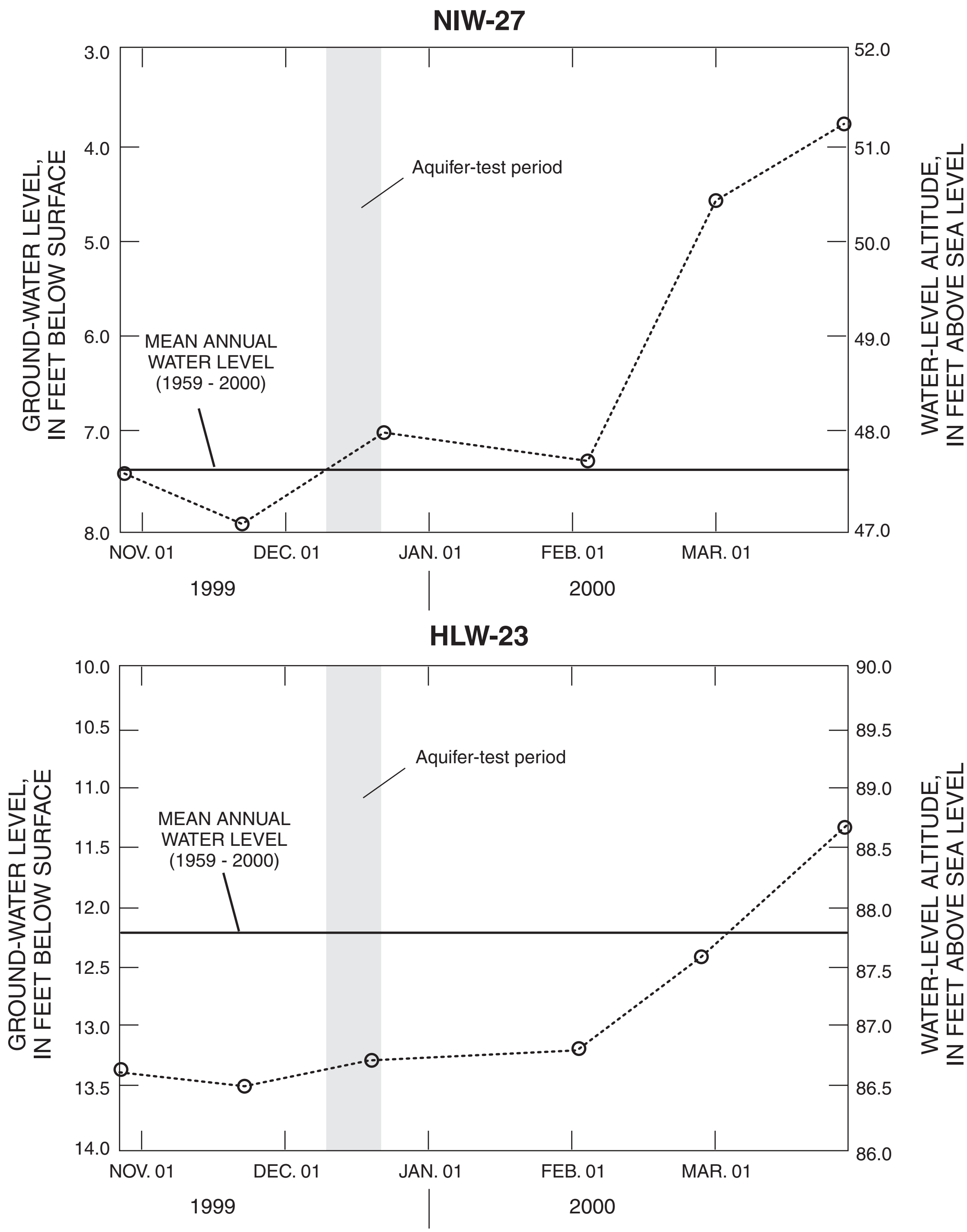



**Figure 16.** Water levels in U.S. Geological Survey observation wells NIW-27 and HLW-23 during October 1999 to April 2000 and mean water levels for the period of record, Newbury and Haverhill, Massachusetts.

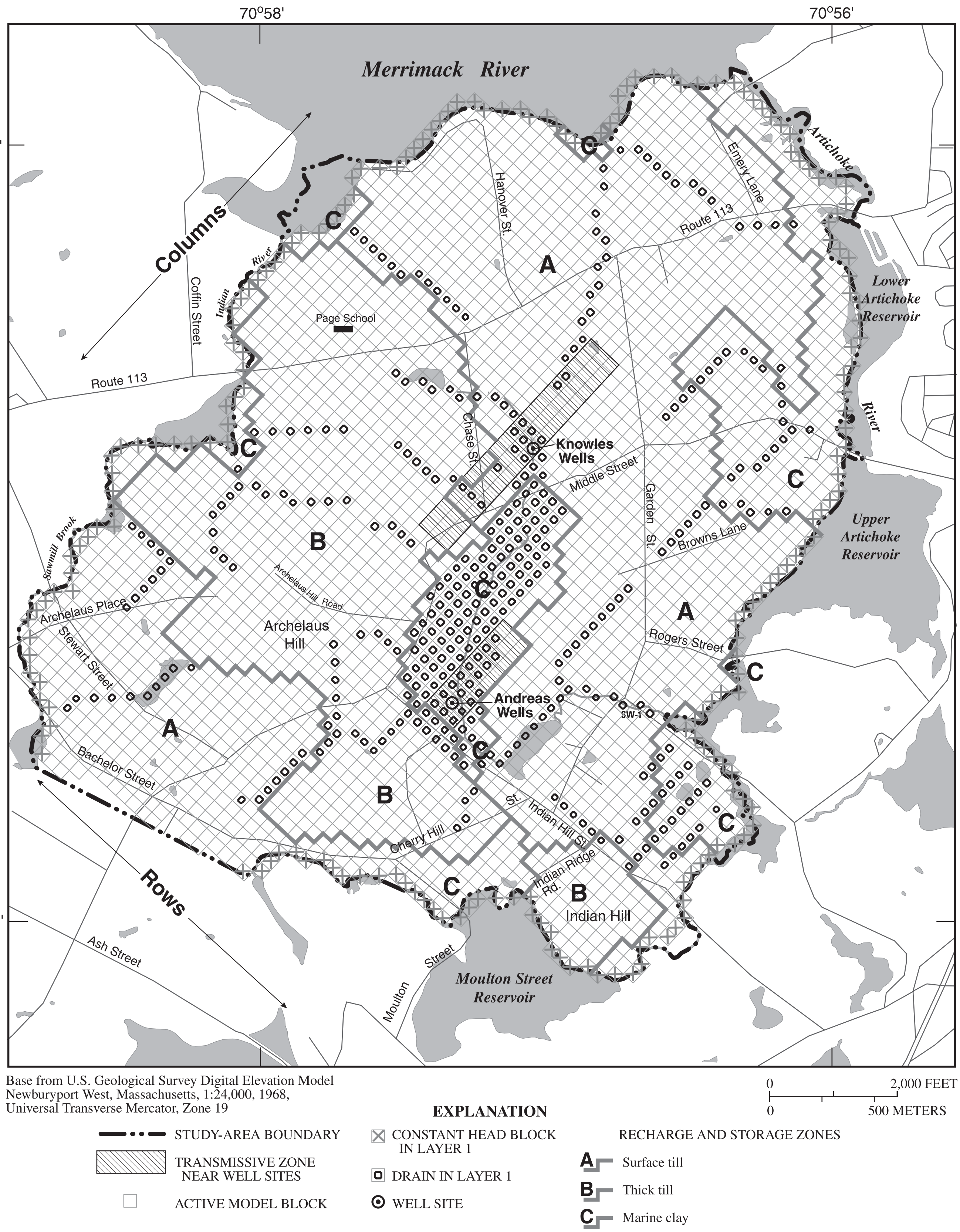



**Figure 17.** Model features and wells pumped during aquifer testing, West Newbury study area, Massachusetts.

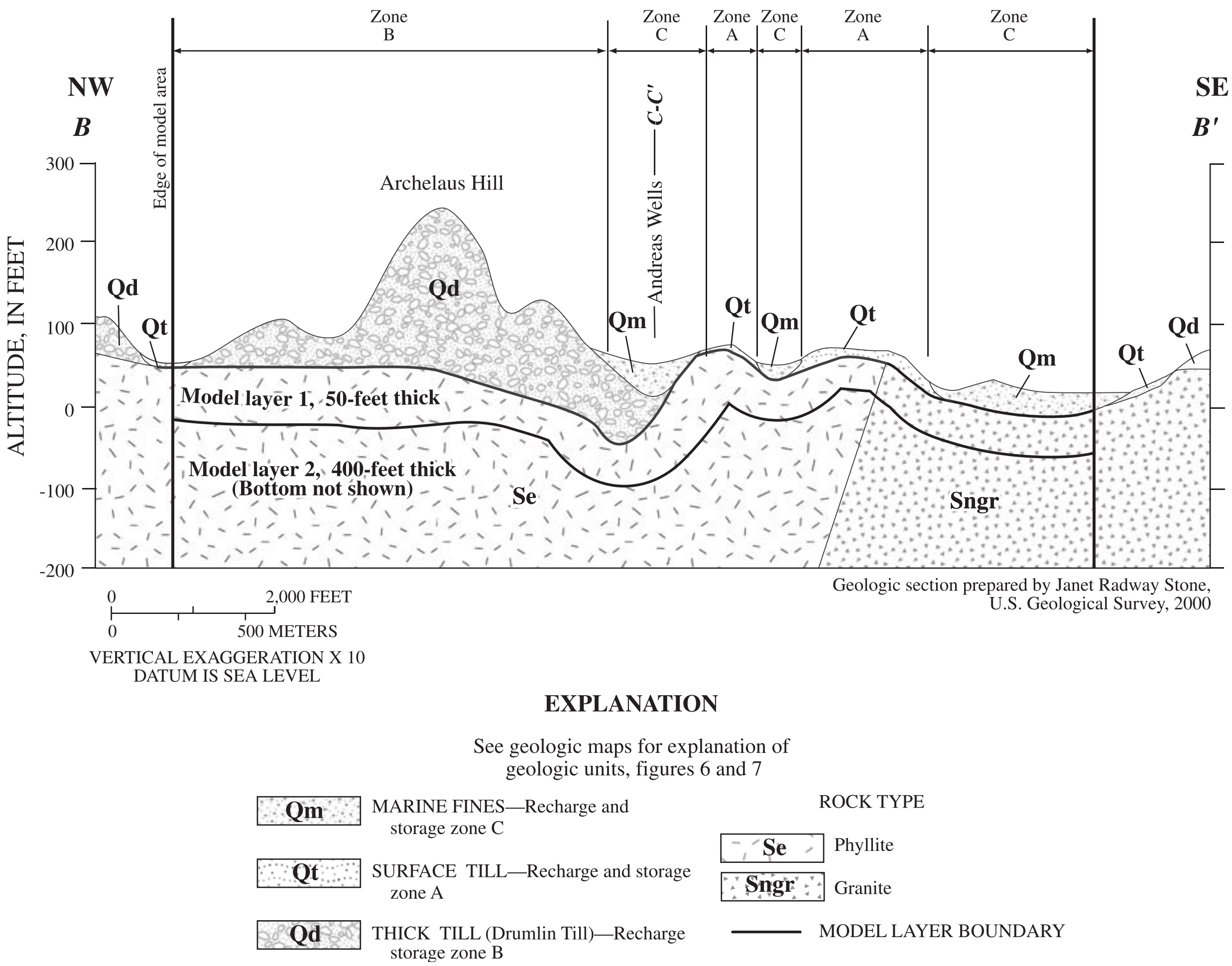



**Figure 18.** Geohydrologic cross section showing model layers and zones used for model recharge and storage properties, West Newbury study area, Massachusetts.

## Model Stresses

Drains were placed in likely ground-water-discharge areas along perennial and intermittent streams and in wetland areas. The altitudes of the drains are estimated from land-surface contours. A high-conductance value (defined as vertical hydraulic conductivity times the area of the stream divided by thickness of the streambed) of $1x10^4$ $ft^2$/d was selected to minimize resistance to flow from ground water to drains in thin till and thick till areas. A lower value of 1 $ft^2$/d was assigned to streams and wetlands in areas underlain by marine clays to simulate limited upward leakage in those areas. A drain conductance of 1 $ft^2$/d yields a vertical conductance over the area of a model cell (200 $ft^2$) in wetlands of $2.5x10^{-5}$ $day^{-1}$. This is consistent with a vertical hydraulic conductivity of $1x10^{-3}$ ft/d, the upper end of a range reported by Nielsen and others (1995), divided by an assumed average marine-clay thickness of 30 ft, which yields a vertical conductance of $3.3x10^{-5}$ $day^{-1}$. A drain conductance of $1x10^4$ $ft^2$/day was assigned in wetland areas at the contact between marine clays and thin till where the clays pinch out east and northeast of the Andreas site. Many drains placed in thick till areas were inactive in the model because simulated heads in bedrock were below the land surface in these areas.

Recharge rates were varied for three types of surficial materials (fig. 17**,** table 1). A constant recharge rate of 0.0007 ft/d (3 in/yr) was assumed for areas of thick till. This value simulates an assumed leakage rate through the thick till to bedrock. Although the leakage rate may vary areally with the vertical hydraulic gradient and thickness, a uniform value was assumed. The area of thick till shown on the

**Table 1.** Summary of properties used for model Case A, West Newbury study area, Massachusetts

[$day^{-1}$, 1/day; ft, foot; ft/d, foot per day; $ft^3/d$, cubic feet per day; $ft^2/d$, square foot per day; gal/min, gallons per minute]

| Model property | Case A value |
|---|---|
| Thickness | |
| Layer 1 | 50 ft |
| Layer 2 | 400 ft |
| Hydraulic conductivity, layer 1 | |
| Area | 0.4 ft/d |
| Knowles site | 10 ft/d |
| Andreas site | 5 ft/d |
| Hydraulic conductivity, layer 2 | |
| Area | 0.2 ft/d |
| Knowles site | 5 ft/d |
| Andreas site | 2.5 ft/d |
| Vertical conductance | |
| Area | 0.002 $day^{-1}$ |
| Knowles site | 0.04 $day^{-1}$ |
| Andreas site | 0.02 $day^{-1}$ |
| Storage coefficient, layer 1 (primary and secondary) | |
| Thin till area | 0.002 |
| Thick till area | 0.00001 |
| Marine clay area | 0.005 |
| Storage coefficient, layer 2 | |
| Primary | 0.00001 |
| Secondary | 0.001 |
| Recharge | |
| Thin till area | 0.0034 ft/d |
| Thick till area | 0.0007 ft/d |
| Marine clay area | 0.00001 ft/d |
| Drain conductance | |
| Till areas | 10,000 $ft^2/d$ |
| Marine clay area | 1 $ft^2/d$ |
| Pumping rate | |
| Knowles site (2 wells) | 28,877 $ft^3/d$ (150 gal/min) |
| Andreas site (1 well) | 19,444 $ft^3/d$ (101 gal/min) |

geologic map was extended to include well 97 because observed head at that location is about 10 ft higher than the head in nearby well 142, indicating a poor hydraulic connection vertically between surficial materials and bedrock. A recharge rate of 0.00001 ft/d (0.05 in/yr) was assumed for marine clay. A recharge rate of 0.0041 ft/d (18 in/yr) was initially assumed for areas of thin till on the basis of recharge rates presented by Bent (1995; 1999), but was lowered to 0.0034 ft/d (15 in/yr) during model calibration.

Pumping rates from residential wells were assumed to be negligible. Although numerous residences use water from private wells, much of the water pumped in thin-till areas is recycled to the aquifer through private septic systems, typically within a distance smaller than a model block (200 ft).

Pumping rates were adjusted several times during aquifer testing. A stress period was added in the model for each adjustment of pumping rate. Figure 19 summarizes observed variations in pumping rates and simulated stress periods.

Wells were placed at the Andreas and Knowles sites and pumped at MADEP-approved rates to simulate contributing areas to wells and effects of pumping on wetlands and streams. The approved rates are 101 gal/min for the Andreas site and 150 gal/min for the Knowles site (Joseph Cerutti, Massachusetts Department of Environmental Protection, verbal commun., 2000).

### Hydraulic Properties

The transmissivity distribution for bedrock is delineated in three zones shown in figure 17. These zones include a transmissivity representative of the regional aquifer system and much of the model area, a zone near the Andreas site with a transmissivity greater than the regional transmissivity, and another transmissive zone near the Knowles site (table 1). For much of the model area, the hydraulic conductivity of the upper layer was assumed to be 0.4 ft/d, twice the value of 0.2 ft/d for the lower layer. A similar conceptual model and approach for fractured bedrock was used by Starn (1997). The composite transmissivity in these two layers for fully saturated conditions is 100 $ft^2/d$, which is consistent with well yields of 10 to 20 gal/min. Higher transmissivity values were assumed for two linear zones that include the Knowles and Andreas sites (fig. 17). For initial model simulations, a hydraulic conductivity value of 10 ft/d for the upper layer and 5 ft/d for the lower layer were assumed for the Knowles site, and a value of 5 ft/d for the upper layer and 2.5 ft/d for the lower layer were assumed for the Andreas site. For a fully saturated condition, these

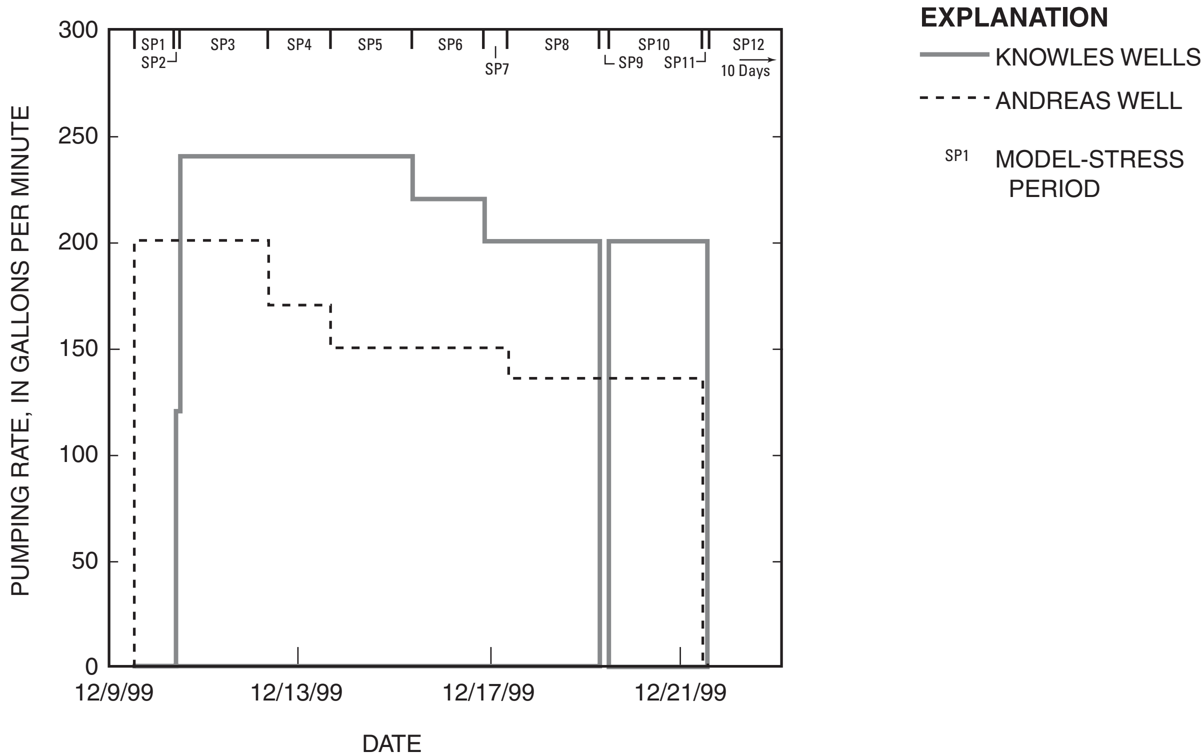



**Figure 19.** Pumping rates during aquifer testing and simulated stress periods, West Newbury study area, Massachusetts.

values yield composite transmissivities of about 2,500 $ft^2/d$ for the Knowles site and 1,250 $ft^2/d$ for the Andreas site.

The vertical hydraulic connection, referred to as VCONT (vertical conductance defined as vertical hydraulic conductivity divided by thickness) between bedrock layers, was assumed to be 0.002 $day^{-1}$ for most of the model area, a factor of 10 higher for the Andreas site (0.02 $day^{-1}$), and a factor of 20 higher for the Knowles site (0.04 $day^{-1}$). For comparison, Tiedeman and Hsieh (2001) report a VCONT of $1.6x10^{-4}$ $day^{-1}$ for a crystalline bedrock aquifer in New Hampshire. Barton and others (1999) assumed the same vertical as horizontal hydraulic conductivity for a crystalline bedrock aquifer in Pennsylvania. A value of VCONT of 0.002 $day^{-1}$ for most of the area reflects a vertical hydraulic conductivity that is about the same as the horizontal hydraulic conductivity.

Storage coefficients were needed for transient simulation of aquifer tests. The storage properties of the upper layer were assigned to reflect the combined storage properties of the bedrock and surficial materials. A value of $1x10^{-5}$, representative of a confined aquifer, was assigned to areas overlain by thick till, assuming that storage properties were similar for the bedrock and surficial materials. Values of 0.002 for the area overlain by surface till, and 0.005 for the area overlain by marine clay, were determined during calibration for aquifer-test conditions. The value of 0.005 for the area overlain by marine clay is interpreted to reflect release from storage by clay compaction (transient leakage). The value of 0.002 for thin till is less than specific yields reported in the literature, but it may be reasonable where gravity drainage of water from till is not instantaneous or where the till is unsaturated and drainage is from less porous fractured rock. Storage properties for layer 1 were not altered when simulated head was below the top of the aquifer. For comparison, the value of 0.002 for areas of thin surface till is within the range reported by Gburek and others (1999) for moderately and highly fractured rock. Conceptually, the storage coefficient might be lower where water is derived solely from storage in bedrock and not from till. Further refinement of storage properties, however, was considered unnecessary for the intended use of the model.

A uniform primary (confined) storage coefficient of $1x10^{-5}$, considered representative of fractured rock, and a secondary storage coefficient of 0.001 (unconfined) was assigned to layer 2. Heads at observation points were found to be insensitive to the storage coefficient of layer 2 during calibration.

### Alternative Models for Uncertainty Analysis

A set of aquifer properties derived through model calibration produced a numerical model (Case A, described in table 1) that approximately simulated observed heads. Other combinations of properties, however, could yield a suitable solution. Case A was used for comparison to other plausible models. Table 2 summarizes the variations used for these uncertainty analyses, the rationale for those variations, a comparison of modeled heads to observed heads before and during aquifer testing, and effects on the contributing areas to wells. In the process of sensitivity testing, lower transmissivity values near the Andreas site than those used for Case A yielded a closer match of observed to simulated heads. Model Case K represents the closest match of observed to simulated heads and was used for analysis of contributing area and effects of pumping on wetlands and streams.

### Model-Simulated Heads

Model-simulated heads for the aquifer test using Case K properties are shown for selected wells in figure 20. Generally, simulated water-level trends follow observed trends for the drawdown and recovery periods. The initial modeled heads at wells 146 and 141 are higher than measured heads, indicating transmissivities are too low or recharge rates are too high. The simulated starting head at well 149 was somewhat lower than the observed head indicating a transmissivity that is too high or a recharge rate that is too low in this area.

No reasonable set of hydraulic properties was found that would simulate drawdowns at the model node that contained the pumped wells at the Knowles site (wells 151 and 152). Differences between modeled and observed drawdowns might be attributed to well-entry losses, local fracture characteristics, and an effective well radius that is less than the size of the model block. Simulated water levels at the pumped well at the Andreas site (well PW3), however, reasonably matched observed water levels. The effective radius of this well, because of the presence of highly transmissive subhorizontal fractures, may be as large or larger than the size of the model block. Most variations in hydraulic properties and recharge from case K conditions caused drawdowns that fit poorly with observed drawdowns.

Cases D and F were unreasonable because of excessive drawdowns for either the simulation of the aquifer test or simulation of the approved steady pumping rate. A reduction of VCONT by 0.01 throughout the model area (Case D) caused starting heads that were too high and drawdowns to fall below the base of layer 1 near the Andreas site while pumping at the approved rates. For Case E, a reduction of recharge from 15 in/yr to 9 in/yr in thin till areas caused greater drawdowns and slower recovery rates for simulation of the aquifer test than those caused with Case A conditions. These results indicate that aquifer testing during extended dry periods in areas such as the Knowles site, where drawdown extends over a relatively large area, could generate lower estimates of potential yield than during periods of higher recharge. Simulation of anisotropy (Case F) by assigning a uniform hydraulic conductivity representative of the low-transmissivity rocks for the study area but 10 times greater along rows (in the northeast-southwest direction), caused the pumping well at the Andreas site to go dry during simulation of the aquifer test. By increasing the hydraulic conductivity and recharge for another test of anisotropy (Case G), heads were not lowered below the base of the layer 1 for simulation of the aquifer test and steady pumping, but heads at observation wells were poorly simulated. These tests support the concept of a laterally extensive transmissivity zone, such as along subhorizontal fractures, rather than an anisotropic aquifer where flow is along high-angle fractures of a preferred orientation.

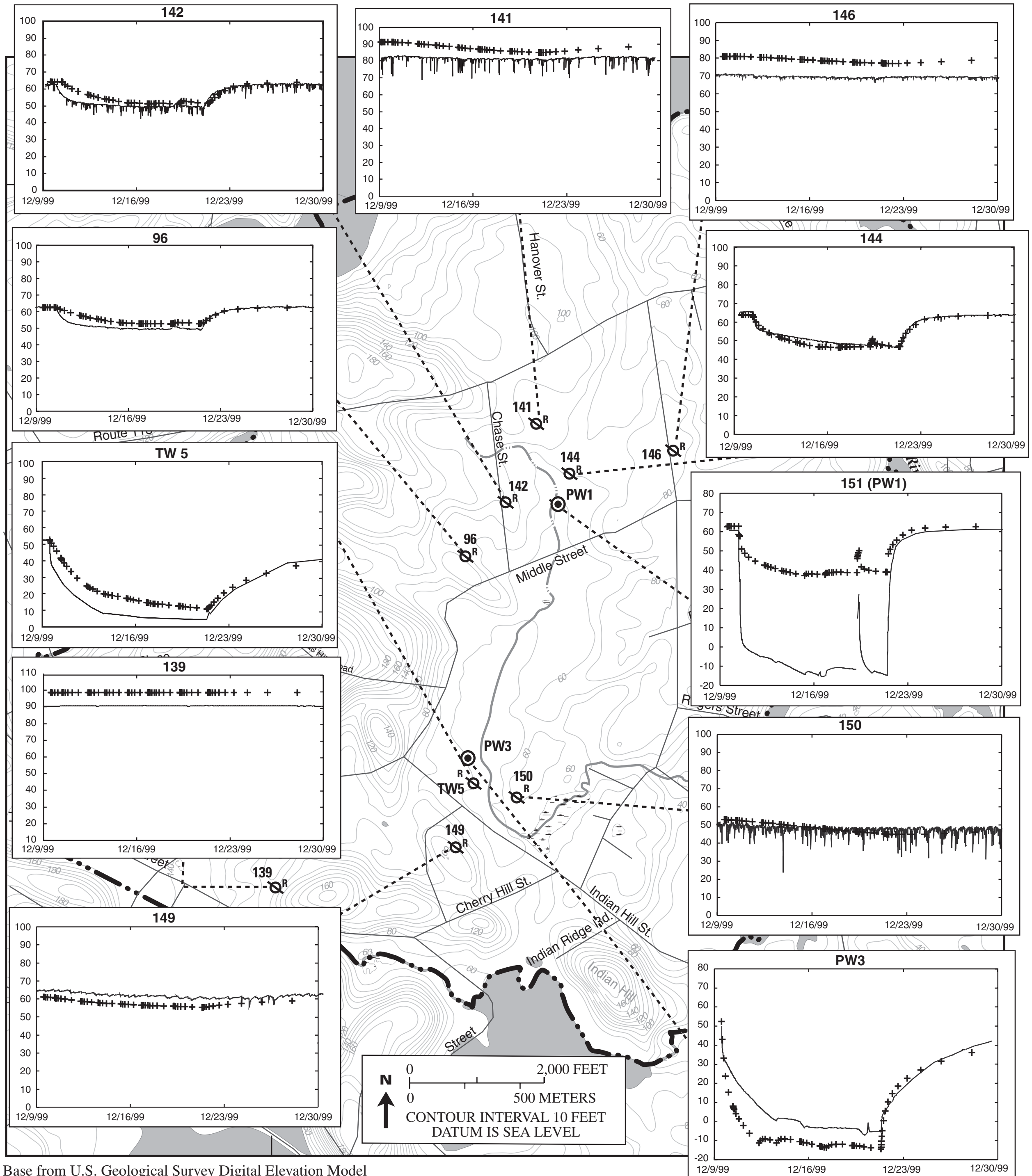
**Table 2.** Variations of model characteristics for alternative numerical models, rationale, and assessment, West Newbury study area, Massachusetts

[**Variation from Case A:** VCONT, vertical conductance or hydraulic conductivity divided by thickness; ft/d, foot per day; in/yr, inches per year]

| Model alternative | Variation from Case A (see table 1 for Case A properties) | Rationale | Assessment |
|---|---|---|---|
| Case B | Reduce recharge to 9 in/yr in thin till area and hydraulic conductivity by 1/2 in low-transmissivity areas. | The size of the contributing area was strongly controlled by recharge rates, and recharge rates were poorly constrained by available data. A reduction of hydraulic conductivity and recharge by these amounts yielded similar model heads. | Improved simulation of aquifer test near the Andreas site, but drawdowns were too large near the Knowles site. For simulation of contributing areas, layer 1 was dry near the Knowles site. |
| Case C | Reduce the hydraulic conductivity by 1/2 in low-transmissivity areas. | Hydraulic conductivity alone was reduced to evaluate the importance of this property on the size and shape of the contributing area. | Simulation of aquifer test similar to Case B. Contributing area was nearly identical to Case A. |
| Case D | Reduce VCONT to 0.01 of Case A value. | This property was poorly constrained by the available data. A reduction may affect the shape of the contributing area. | Starting heads generally too high and drawdowns too large near Knowles site. Layer 1 was dry for steady-state pumping near the Andreas site, so wells went dry and the contributing area was not delineated. |
| Case E | Reduce recharge to 9 in/yr in thin till area. | The lower recharge rate was reasonable and will increase the size of the contributing area to a maximum likely size. | Simulation of aquifer test was similar to Case A near the Andreas site, but drawdowns were larger and the rate of recovery after aquifer testing was less rapid near the Knowles site. The contributing area was similar to Case B. |
| Case F | Simulate anisotropy rather than transmissivity zones. Hydraulic conductivity the same as low-transmissivity area but 10 times greater in the direction of anisotropy. | An alternative conceptual model attributed an anisotropic response to pumping to fracture patterns rather than to transmissivity zones. The effects of this alternative conceptual model on the shape of the contributing area is not known. | Andreas site well went dry during simulation of aquifer test. Drawdowns were much too large near Knowles site except in wells perpendicular to the anisotropy where simulated drawdowns were too low. The simulated contributing area was similar to Case A, but narrower on the northwest and southeast sides. |

**Table 2.** Variations of model characteristics for alternative numerical models, rationale, and assessment, West Newbury study area, Massachusetts—*Continued*

| | | | |
|---|---|---|---|
| Case G | Simulate anisotropy but increase the hydraulic conductivity of 2 layers by 2 times and increase recharge by 1.5 times. | The transmissivity for Case F conditions was too low based on simulation of the aquifer test. | Starting heads were generally too high and drawdowns were too low near the Knowles site. Simulated drawdowns in pumped wells at both sites were closer to observed drawdowns than for other simulations. Contributing area was similar in length to Cases A and F, but narrower in the direction of least hydraulic conductivity. |
| Case H | No recharge in thick-till areas. | This was considered an extreme but possible condition in areas of thick till. The effect would be to enlarge the contributing area in thin-till areas. | Simulation of aquifer test was not substantially affected. The contributing areas were nearly identical to Case A because most recharge for Case A was in the thin-till area and flow lines passed under the thick-till areas. |
| Case I | Recharge set at 24 in/yr (0.0055 ft/d) in drawdown area near Knowles site. | Lowering of the water table in wetland areas by pumping may result in additional recharge to an upper limit of 24 in/yr. | Simulated drawdowns for the aquifer test were generally too low near the Knowles site but were not affected near the Andreas site. The contributing area was reduced somewhat near the Knowles site. |
| Case J | Reduce length dimension of high-transmissivity zone near Knowles site by 1/2. | The dimensions of the high-transmissivity zone were not well constrained, but the model may not be sensitive to this property. | Simulated drawdowns for the aquifer test were generally greater than observed drawdowns near the Knowles site. The contributing area near the Knowles site was shifted on the northwest and northeast sites by several hundred feet. |
| Case K | Reduce the hydraulic conductivity of layers 1 and 2 in the southwestern half of the model area by 1/2. | Lower transmissivity values in this part of the model area might improve the match between simulated and measured heads. | Simulated drawdowns for aquifer test more closely simulated observed drawdowns near the Andreas site. The contributing area was slightly smaller in the southeast corner than for Case A; otherwise, the contributing area was identical to Case A. |




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

**EXPLANATION**

VERTICAL SCALE OF GRAPHS IS WATER-LEVEL ALTITUDE, IN FEET ABOVE SEA LEVEL

STUDY-AREA BOUNDARY

MEASURED HEAD

\+ MODEL-SIMULATED HEAD

150 R WELL OR PIEZOMETER EQUIPPED WITH TRANSDUCER DURING AQUIFER TEST, AND IDENTIFIER

PW3 WELL PUMPED DURING AQUIFER TEST, AND IDENTIFIER

**Figure 20.** Simulated heads for model case K and measured heads in wells for aquifer tests, West Newbury study area, Massachusetts.

## Simulated Contributing Areas to Wells

Average recharge conditions and permitted pumping rates of 150 gal/min from two wells at the Knowles site and 101 gal/min for one well at the Andreas site were used as stresses in the calibrated model to determine contributing areas to wells (table 1). Source areas were determined by forward tracking particles placed on the upper surface of layer 1 to the wells. The contributing area, which includes areas of underflow, was determined by delineating path lines for backtracked particles and projecting all pathlines to land surface. As stated previously, model Case K yielded the best match of initial heads and drawdowns during aquifer testing and is considered a reasonable representation of the ground-water system.

The contributing area to the Andreas and Knowles wells for model Case K (about 1.3 $mi^2$) encompasses much of the drainage area for the unnamed tributary to the Artichoke River (fig. 21) and extends northeastward across a gentle topographic divide about 1,500 ft into a tributary basin of the Merrimack River. The position of the simulated ground-water divide (not shown) was nearly the same for pumping and nonpumping conditions, indicating that pumping at permitted rates was intercepting water that would have otherwise discharged near the wells. A tributary stream on the southwest side of the model area is the main sink for shallow ground water, but is an area of underflow to wells. Areas of underflow near the contributing area boundary reflect flow paths that are not direct to the wells. The contributing area for Case K was nearly identical to Case A, indicating that the contributing area is not particularly sensitive to transmissivity for the ranges considered.

Case B was selected to illustrate a plausible variation of the contributing area (fig. 21). For Case B, recharge was reduced from 15 in/yr to 9 in/yr in thin-till areas, and the hydraulic conductivity of the low-transmissivity area was reduced by one half from Case A conditions. The size of the contributing area (about 1.8 $mi^2$) is larger than for Case K (fig. 21), mainly because of the lower recharge rate. The Case B contributing area encompasses contributing areas for all other test cases (not shown) and is considered a maximum likely contributing area for the Andreas and Knowles wells.

Simulation of contributing areas with the 2-layer model does not account for possible lateral flow through surficial materials into the contributing area shown on figure 21. Because the contributing area extends to topographic divides, this is not a concern for most of the study area. An exception is the drumlin along route 113 near Page School where shallow ground-water flow could follow the slope of the land surface before leaking downward to recharge the bedrock aquifer within the mapped contributing area. In this area, the contributing area to wells could extend approximately to the drainage-basin boundary (fig. 22).

## Simulated Effects of Pumping on Streamflow and Wetlands

Pumping the two wells will reduce ground-water discharge and area-wide streamflow by about the amount pumped. Conceivably, some water that would be lost to evapotranspiration may be captured by lowering heads in wetland areas. The quantity captured, however, would be negligible and small relative to total diversions by pumping. Pumping will rapidly affect streamflow as demonstrated by streamflow records at the Knowles site during aquifer testing and by modeled responses to pumping. Induced infiltration from streams near pumping wells during periods of storm runoff may increase recharge rates and thereby reduce the effect of pumping on streamflow during subsequent low-flow periods. Induced infiltration, however, is likely to be a small percentage of the water that would be pumped at both sites, because of low vertical hydraulic conductivity and limited areal extent of the stream channels.

The numerical model was used to determine possible effects of pumping on streamflow for subbasins within the model area by examining simulated flow reductions to drains caused by pumping (fig. 22). Table 3 summarizes simulated flows to drains by subbasin and changes caused by pumping. Also included in table 3 are volumetric budgets for the entire model for nonpumping and pumping conditions. Of the 251 gal/min pumped from the two wells, 214 gal/min are diverted from subbasins A, B, and C within the drainage basin of the unnamed tributary to the Artichoke River upstream from the Garden Street stream gage (SW1). Most (22 gal/min) of the remaining 37 gal/min is diverted from subbasin E on the Merrimack River. About 5 gal/min are diverted from constant head nodes on the model boundary.

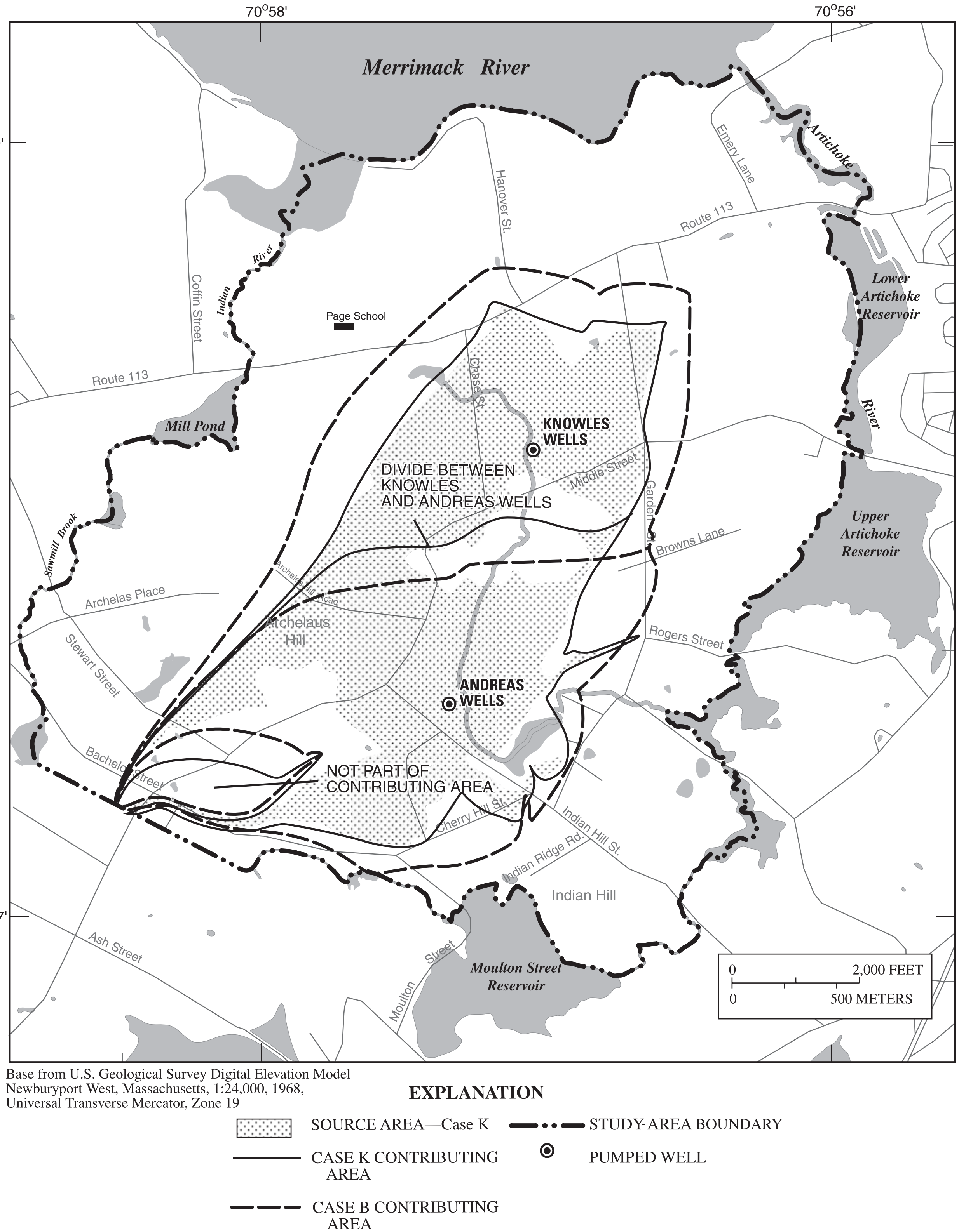
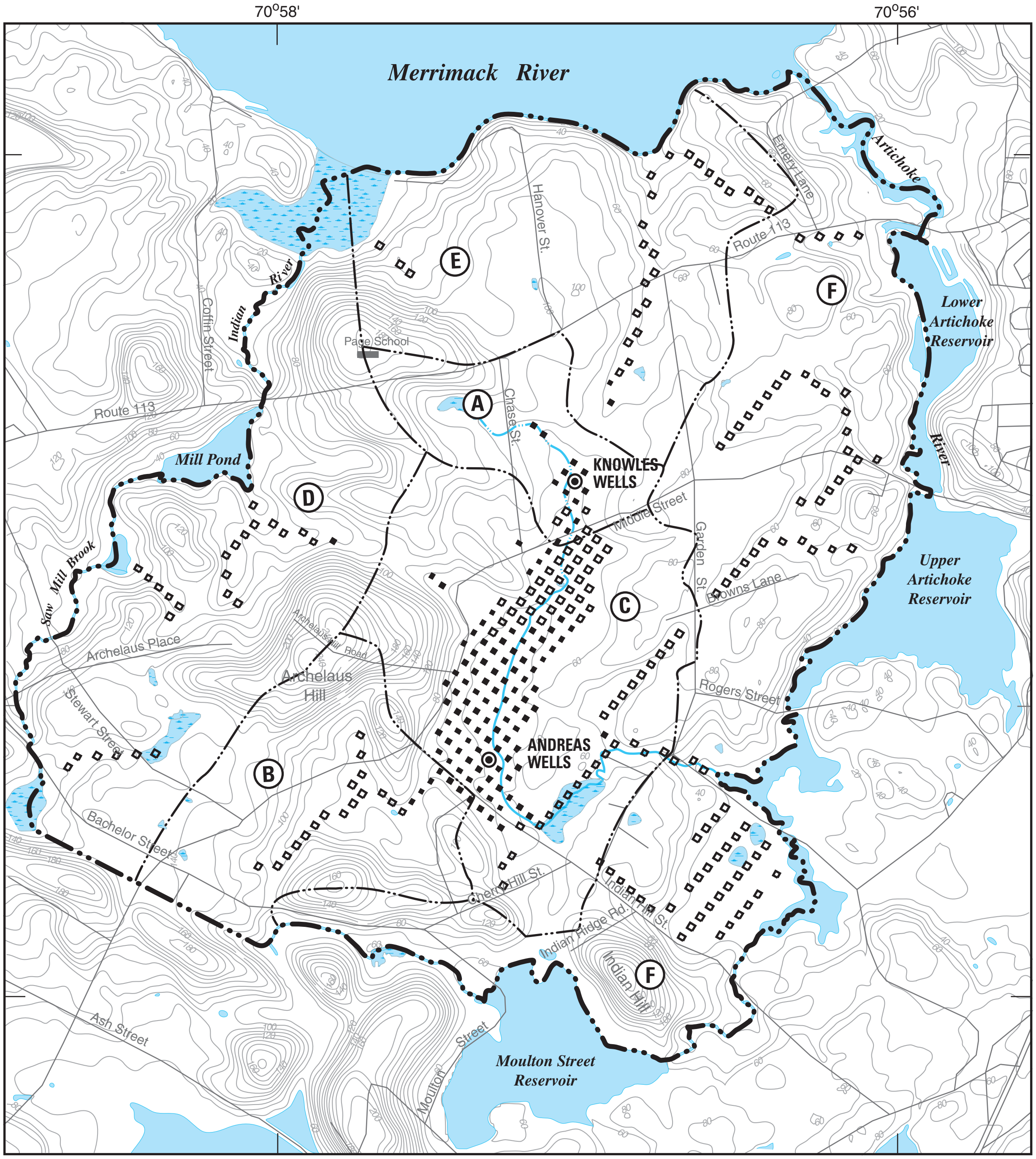



**Figure 21.** Simulated contributing areas to wells for model case K and case B conditions, West Newbury study area, Massachusetts.




Base from U.S. Geological Survey Digital Elevation Model
Newburyport West, Massachusetts, 1:24,000, 1968,
Universal Transverse Mercator, Zone 19

0 2,000 FEET
0 500 METERS

CONTOUR INTERVAL 10 FEET
DATUM IS SEA LEVEL

**EXPLANATION**

STUDY-AREA BOUNDARY

SUBBASIN BOUNDARY AND IDENTIFIER

DRAIN CELL
- Active while pumping
- Inactive while pumping

PUMPED WELL

**Figure 22.** Drain cells inactivated by pumping for model case K and subbasin boundaries, West Newbury study area, Massachusetts.