Delineation of Areas Contributing Water to the Dry Brook Public-Supply Well, South Hadley, Massachusetts

By Stephen P. Garabedian and Janet Radway Stone

In cooperation with the
Drinking Water Program, Massachusetts Department of Environmental Protection

Water-Resources Investigations Report 03-4320

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Cover photo: View of the Holyoke Range from Dry Brook Hill, South Hadley, Massachusetts. Photograph by Gene W. Parker, U.S. Geological Survey.

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CONVERSION FACTORS, VERTICAL DATUM, AND HORIZONTAL DATUM

Multiply	By	To obtain
inch (in.)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per minute (ft^3/min)	0.02832	cubic meter per minute (m^3/min)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	2.540	centimeter per year (cm/yr)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot squared per minute (ft^2/min)	0.09290	meter squared per minute (m^2/min)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Delineation of Areas Contributing Water to the Dry Brook Public-Supply Well, South Hadley, Massachusetts

By Stephen P. Garabedian and Janet Radway Stone

Abstract

Areas contributing water to the Dry Brook public-supply well in South Hadley, Massachusetts, were delineated with a numerical ground-water-flow model that is based on geologic and hydrologic information for the confined sand and gravel aquifer pumped by the supply well. The study area is along the Connecticut River in central Massachusetts, about 12 miles north of Springfield, Massachusetts. Geologic units in the study area consist of Mesozoic-aged sedimentary and igneous bedrock, late-Pleistocene glaciolacustrine sediments, and recent alluvial deposits of the Connecticut River flood plain. Dry Brook Hill, immediately south of the supply well, is a large subaqueous lacustrine fan and delta formed during the last glacial retreat by sediment deposition into glacial Lake Hitchcock from a meltwater tunnel that was likely near where the Connecticut River cuts through the Holyoke Range. The sediments that compose the aquifer grade from very coarse sand and gravel along the northern flank of the hill, to medium sands in the body of the hill, and to finer-grained sediments along the southern flank of the hill. The interbedded and overlapping fine-grained lacustrine sediments associated with Dry Brook Hill include varved silt and clay deposits. These fine-grained sediments form a confining bed above the coarse-grained aquifer at the supply well and partially extend under the Connecticut River adjacent to the supply well.

Ground-water flow in the aquifer supplying water to Dry Brook well was simulated with the U.S. Geological Survey ground-water-flow modeling code MODFLOW. The Dry Brook aquifer model was calibrated to drawdown data collected from 8 observation wells during an aquifer test conducted by pumping the supply well for 10 days at a rate of 122.2 cubic feet per minute (ft^3/min; 914 gallons per minute) and to water levels collected from observation wells across the study area. Generally, the largest hydraulic conductivity values used in the model were in the sand and gravel aquifer near the Dry Brook well, which is consistent with the geologic information. Results of aquifer-test simulation indicated that spatially variable aquifer hydraulic properties and boundary conditions affected heads and ground-water flow near the well. A comparison and analysis of water-level fluctuations in study area wells to fluctuations in the Connecticut River indicated a hydraulic connection of the aquifer with the river, which is also consistent with geologic information. Simulated ground-water levels indicated that most ground water in the study area flowed toward and discharged to the Connecticut River and the Dry Brook well. Small amounts of ground water also discharged to smaller streams (Dry Brook and Bachelor Brook) in the study area.

Areas contributing water to the well were delineated with the MODPATH particle-tracking routine. Results of the contributing-area analysis indicated that the greatest sources of water to the well were recharge in the Dry Brook Hill area and infiltration of Connecticut River water in an area beyond the extent of the confining bed where the aquifer is in hydraulic connection with the river. The amount of water entering the Dry Brook well from recharge dominated at a lower pumping rate (40.0 ft^3/min); about 90 percent of the pumped water originated from recharge and boundary flow, and infiltration from the Connecticut River supplied the remaining 10 percent. At a high pumping rate (122.2 ft^3/min), however, about half of the water pumped from the Dry Brook well originated from recharge and boundary flow (49 percent), and half originated from infiltration of water from the Connecticut River (51 percent).

Results of a sensitivity analysis of the extent of areas contributing water to the Dry Brook well when pumped at 122.2 ft^3/min indicated that the size of these areas did not substantially change when aquifer properties were varied. In contrast, however, the size of these areas changed most when the recharge rate was modified. When the recharge rate was decreased by 25 percent, the extent of the area increased by about 200 feet farther to the south and east across Dry Brook Hill. When recharge was increased by 25 percent, the extent of the area decreased by about 200 feet on the south and east sides of Dry Brook Hill. The flow contribution from the Connecticut River increased to 60 percent of the total pumpage when the recharge was decreased by 25 percent, as compared to 43 percent of the total pumpage when recharge was increased by 25 percent. These results indicated Dry Brook Hill is important to the protection of the water quality in the Dry Brook well

because this area contributes water under a number of simulated conditions, and is potentially vulnerable to contamination because of its permeable sandy soils and aquifer materials.

On the basis of this study, the important components needed in future studies to properly delineate areas contributing water to public-supply wells developed in confined aquifers include geologic information on the vertical and lateral extent of the confining beds and aquifer materials, and a conceptual model of ground-water flow in the aquifer based on hydrogeologic data that takes into consideration the movement of ground water from recharge to discharge areas. Other components include hydrologic data quantifying aquifer gains and losses of water from streams and ponds, and accurate estimates of recharge rates, which appear to be an important determinant of the extent of the areas contributing water to supply wells across Massachusetts, including those in confined ground-water-flow systems.

Introduction

An accurate delineation of the areas contributing water to public-supply wells is an important component of an overall strategy of protecting ground-water resources from contamination (U.S. Environmental Protection Agency, 1987). The Drinking Water Program of the Massachusetts Department of Environmental Protection (MDEP) regulates public-water supplies throughout the State and encourages land-use planning within areas that contribute water to public-supply wells to prevent contamination of those supplies (Massachusetts Department of Environmental Protection, 1996). Although MDEP uses a number of available methods to delineate areas contributing water to public-supply wells, particularly for unconfined aquifers composed of sand and gravel, the issue of areas contributing water for wells completed in confined aquifers had not been adequately addressed by these methods. Consequently, the U.S. Geological Survey began a study in 1999, in cooperation with MDEP, to investigate the factors needed to properly delineate areas contributing water to public-supply wells developed in confined aquifers in Massachusetts. The area contributing water to the Dry Brook well in the town of South Hadley, MA (fig.1), was delineated as an example of this approach. South Hadley Fire District No. 2, which provides water to the northern portion of the town, owns and operates the well. The delineated areas will be used as part of the process needed to protect the water quality of the well. The results of this study also point out the important factors needed to properly delineate areas contributing water to public-supply wells developed in confined aquifers, and techniques used as part of this delineation can be used in similar hydrogeologic settings in Massachusetts and the Northeast United States.

Purpose and Scope

This report describes geologic and hydrologic information, along with the analysis applied to that information, used to delineate areas contributing water to the Dry Brook public-supply well. The report presents geologic and hydrologic data, including the interpretations of geologic logs, ground-water levels, and streamflow measurements collected during the period of the study from October 1999 to November 2000. Data analysis included the preparation of geologic maps, geologic cross sections, a ground-water-flow model of the aquifer used for water supply in South Hadley, MA, and a particle-tracking analysis applied to the results of the flow model to delineate the areas contributing water to the supply well completed in the aquifer.

Description of Study Area

The study area is in the town of South Hadley in the Connecticut River Valley of central Massachusetts (fig. 1), but also includes portions of the towns of Hadley and Holyoke. The Dry Brook public-supply well (SUW-55) is about 200 ft from the Connecticut River, near the mouth of Dry Brook (fig. 2, table 1) in South Hadley, MA. Immediately north and west of the well are the Holyoke and Mt. Tom Ranges, bedrock ridges that divide the Connecticut River Valley. Immediately south of the well is Dry Brook Hill, a prominent deltaic sand and gravel deposit of late-Pleistocene age.

The climate of the area is moderately humid, with an average of 42 in. of precipitation per year. Precipitation is generally evenly distributed throughout the year, with slightly increased amounts during the fall and spring. Temperatures are moderate, with cold winters and temperate summers. Most evapotranspiration occurs during the warm-weather months from May through October, when vegetation actively removes water from the soil.

Acknowledgments

The authors thank Mr. William Selkirk of the South Hadley Fire District No. 2 for providing information about the operation of the Dry Brook public-supply well that was essential to the contributing-area analysis. Mr. Bruce Hansen, U.S. Geological Survey, collected hydrologic and geophysical data used as part of this study. Mr. Forest Lyford and Mr. Gene Parker, U.S. Geological Survey, provided field assistance for a number of activities during the project duration. Ms. Stacey Archfield, Ms. Elizabeth Farren, and Mr. Carl Carlson, U.S. Geological Survey, provided office support during the analysis of data used in this study.

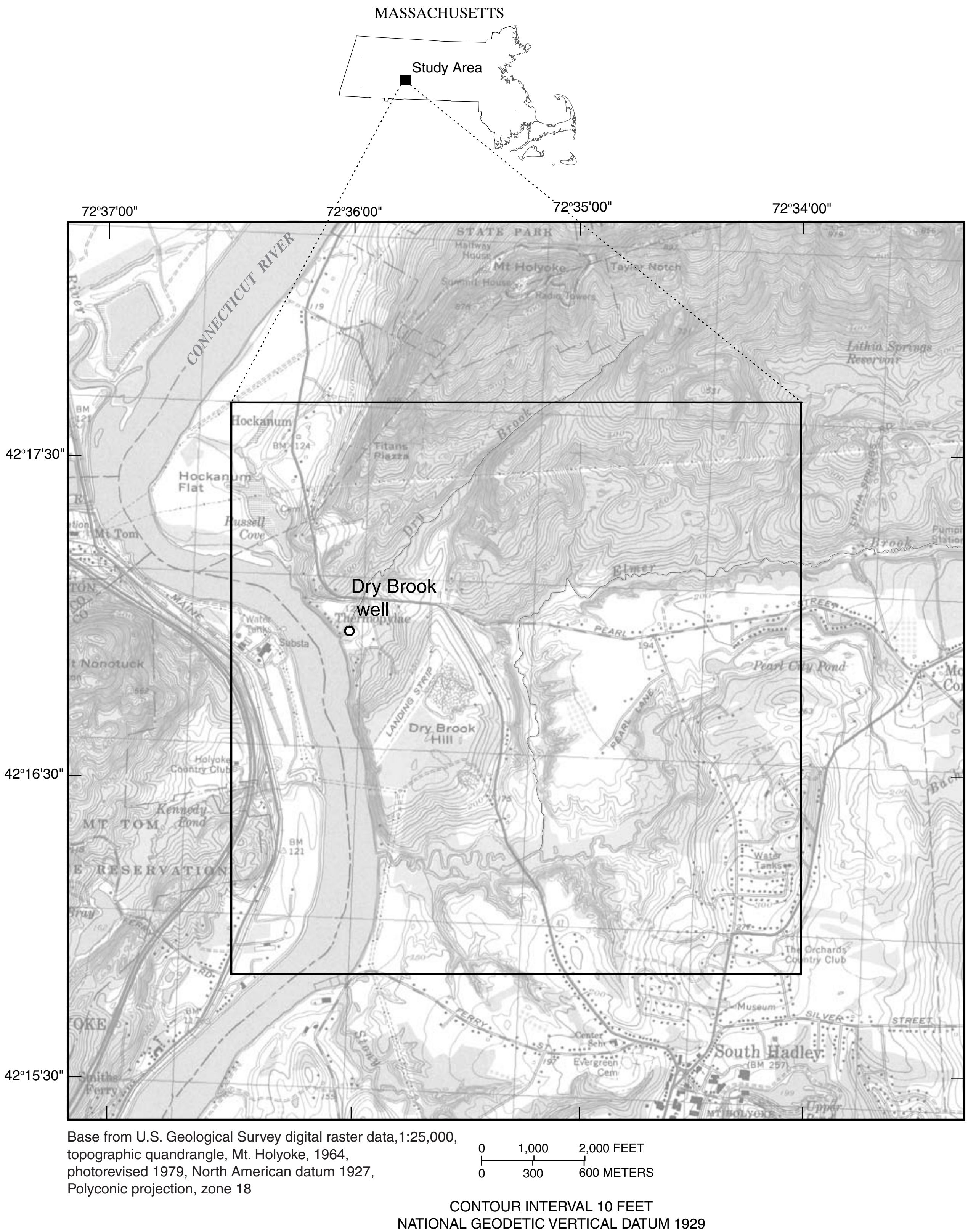
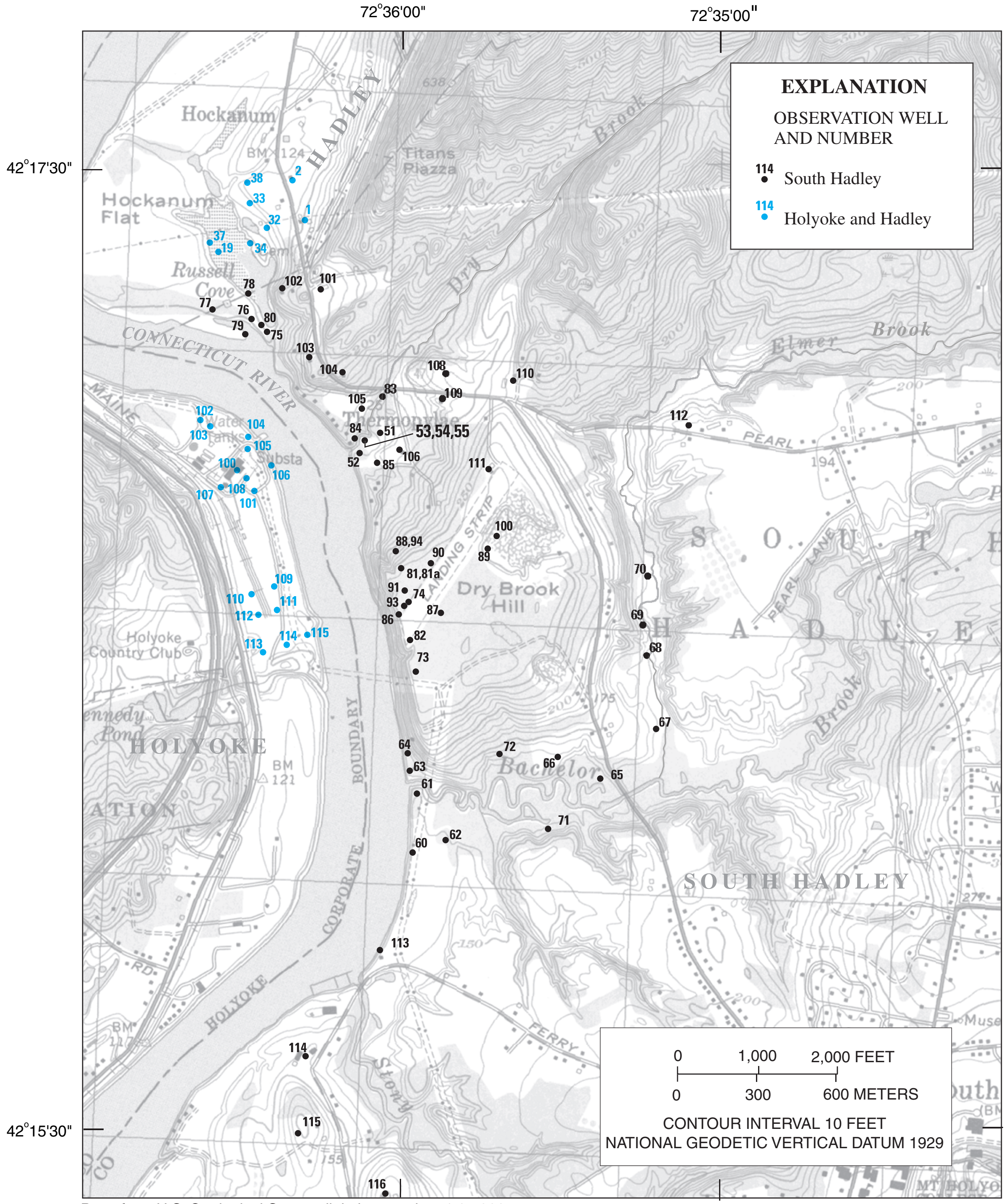


Figure 1. Location of the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.



Base from U.S. Geological Survey digital raster data,1:25,000, topographic quandrangle, Mt. Holyoke, 1964, photorevised 1979, North American datum 1927, Polyconic projection, zone 18

Figure 2. Wells used in the study of the Dry Brook area, Hadley, Holyoke, and South Hadley, Massachusetts.

Table 1. Records of selected wells and test borings in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

[Altitude relative to NGVD29. USGS, U.S. Geological Survey; ft, foot; gal/min, gallons per minute; <, actual value is less than value shown; --, unknown]

Local well number	USGS well number	Date drilled	Land-surface altitude (ft)	Measuring-point altitude (ft)	Borehole depth (ft)	Depth to bedrock or refusal (ft)	Altitude of bedrock surface (ft)	Screened interval(s) (ft)	Well yield (gal/min)	Remarks
Town of Hadley (HAW)										
--	1	12-01-50	145	--	210	126	19	--	--	Domestic bedrock well.
--	2	--	130	--	96	--	<34	90–96	--	Domestic well.
--	19	9-08-72	110	--	170	176	-66	163–170	745	Town of Hadley, test well.
--	32	3-06-63	108	--	133	133	-25	127–133	15	Town of Hadley, test well.
--	33	3-08-63	110	--	51	--	<59	43–51	--	Town of Hadley, test well.
--	34	3-34-63	100	--	150	152	-52	141–150	40	Town of Hadley, test well.
4-98	37	2-03-98	106.8	--	144.8	144.8	-38	134–144	13	Town of Hadley, test well.
7-98	38	6-05-98	130	--	79.9	--	<50	71–76	2	Town of Hadley, test well.
Town of Holyoke (HUW)										
HWPC 1	100	2-01-58	116	--	69	--	<44	--	425	Saines #16; Holyoke Power Company well.
HWPC 2	101	8-01-58	113	--	88	--	<25	73–88	610	Saines #17; Holyoke Power Company well.
B1	102	--	114.7	--	150	--	<-35	--	--	Holyoke Power Company test boring.
B2	103	--	115	--	124	119	-4	--	--	Holyoke Power Company test boring.
B3	104	--	110.1	--	102.5	--	<7	--	--	Holyoke Power Company test boring.
B4	105	--	113.3	--	110	105	8	--	--	Holyoke Power Company test boring.
B5	106	--	98.8	--	101	--	<-2	--	--	Holyoke Power Company test boring.
B6	107	--	121.8	--	12.1	7.1	115	--	--	Holyoke Power Company test boring.
B7	108	--	111.8	--	99.7	94.7	17	--	--	Holyoke Power Company test boring.
B8	109	--	113.8	--	100	--	<14	--	--	Holyoke Power Company test boring.
B9	110	--	117.4	--	101	101	16	--	--	Holyoke Power Company test boring.
B10	111	--	118.8	--	14.5	14.5	104	--	--	Holyoke Power Company test boring.
B11	112	--	113.7	--	39.5	39.5	74	--	--	Holyoke Power Company test boring.
B12	113	--	111.9	--	26.5	25.5	84	--	--	Holyoke Power Company test boring.
B13	114	--	117.5	--	51.5	51.5	66	--	--	Holyoke Power Company test boring.
B14	115	--	121.7	--	35	35	87	--	--	Holyoke Power Company test boring.

Table 1. Records of selected wells and test borings in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.—Continued

[Altitude relative to NGVD29. USGS, U.S. Geological Survey; ft, foot; gal/min, gallons per minute; <, actual value is less than value shown; --, unknown]

Local well number	USGS well number	Date drilled	Land-surface altitude (ft)	Measuring-point altitude (ft)	Borehole depth (ft)	Depth to bedrock or refusal (ft)	Altitude of bedrock surface (ft)	Screened interval(s) (ft)	Well yield (gal/min)	Remarks
Town of South Hadley (SUW)										
TW11-60	51	7-22-60	109	111.08	121	121	-12	95–112	--	
TW13-60	52	7-22-60	107	108.57	125	125	-18	118–125	50	
TW10-60	53	7-20-60	105	105.46	137	137	-22	98–106 114–125	60	Exploration-well for Fire District 2 well.
8-inch test well	54	11-22-60	105	--	114	--	<-9	100–112	300	8-inch test well.
Dry Brook supply well	55	--	105	--	114	--	<-9	101–113	1080	At location of 10-60; 10-day aquifer test available.
TW4-77	60	12-01-78	107	--	184	184	-77	--	--	Also called 4-78; screened interval not reported.
TW5-77	61	12-07-78	108	--	218	218	-110	176–181	--	Also called 5-78.
TW6-77	62	12-22-78	115	--	176	176	-61	--	--	Also called 6-78; screened interval not reported.
TW7-81	63	3-18-81	115	--	196	196	-81	124–134	30	
TW9-81	64	6-12-81	112	--	103	103	<9	70–75	50	
TW10-82	65	11-14-18	104	--	162	162	-58	123–133	60	Also called 10-81.
TW11-82	66	12-02-81	127	--	220	220	-93	110–120	20	Also called 11-81.
TW12-82	67	11-02-82	112	--	189	189	-77	122–127	43	Screened interval not clear on log.
TW13-82	68	11-15-82	112	--	177	177	-65	131–136	50	
TW14-82	69	11-22-82	114.3	115.05	241	241	-127	198–203	43	
TW15-82	70	11-23-82	114	116.39	207	207	-93	85–90	33	Well filled with silt below 105 ft.
TW1-94	71	12-13-94	120	--	191	191	-71	145–155	7	
TW2-94	72	12-28-94	125	--	234	234	-109	143–153	38	Well screened temporarily at 182-192 ft.
TW1-95	73	3-02-95	268.7	269.61	262	262	<7	--	--	Pipe driven to 235 ft; washed to 262 ft.
TW2-95	74	3-23-95	264.1	265.90	293	293	-29	283–293	185	
97-21	75	12-22-97	111	--	140	140	-29	128–138	32	
2-98	76	--	109.1	--	250	--	<-141	160–170	50	
3-98	77	--	111	--	152	--	<-41	136–146	60	
98-5	78	5-06-98	108.2	--	140	--	<-32	130–140	55	
98-6	79	6-02-98	110.1	--	140	--	<-30	130–140	45	
12-inch well	80	7-17-98	107.1	--	130	--	<-23	105–130	--	
TW3-95	81	--	262.7	264.03	233	--	<30	222–233	--	No refusal.
TW3-95B	81A	8-04-95	262	--	294	289	-27	286–289	120	Located 25 ft east of TW3-95.
TW4-95	82	10-31-95	264.3	265.92	293	293	-29	278–293	--	
TW9-97	83	1-29-97	115	117.77	52	52	63	39–49	--	Also called P-9.

Table 1. Records of selected wells and test borings in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.—Continued

[Altitude relative to NGVD29. USGS, U.S. Geological Survey; ft, foot; gal/min, gallons per minute; <, actual value is less than value shown; --, unknown]

Local well number	USGS well number	Date drilled	Land-surface altitude (ft)	Measuring-point altitude (ft)	Borehole depth (ft)	Depth to bedrock or refusal (ft)	Altitude of bedrock surface (ft)	Screened interval(s) (ft)	Well yield (gal/min)	Remarks
Town of South Hadley (SUW)—*Continued*										
TW7-97	84	2-03-97	115	116.39	136	136	-21	125–135	35	Also called P-7.
TW6-97	85	2-11-97	116.9	118.56	128	--	<-11	112–122	50	Also called P-6.
P-2	86	10-01-96	266.8	268.84	297	294	-27	--	--	
P-3	87	9-30-96	267.1	268.75	290	289	-22	--	--	
P-4A	88	4-03-97	215.9	218.49	247	--	<-31	237–247	--	Also called TW-4A.
P-4B	94	1-27-97	208.5	212.05	--	--	--	--	--	Also called TW-4B; 100 ft west of P-4A.
P-5	89	9-26-96	243.8	244.59	145	138	106	136–146	--	Partially screened in bedrock.
P-8	90	4-11-97	265.3	267.29	298	298	-33	288–298	--	
P-10	91	3-26-97	262	--	298	298	-36	288–298	--	
P-1	93	6-09-97	264.4	266.04	289	--	<-25	279–289	--	
T-1	100	--	250	--	142	139	111	--	--	Bedrock well.
2	101	3-01-46	200	--	202	34	166	--	8	Domestic bedrock well.
3	102	2-01-63	175	--	145	3.5	171	--	20	Domestic bedrock well.
6	103	--	190	--	52	6	184	--	5	Domestic bedrock well.
7	104	--	185	--	107	6	179	--	7	Domestic bedrock well.
10	105	--	122	--	55	--	<67	--	0.5	Domestic dug/augered well.
18	106	--	138	--	180	--	< -42	--	15	Domestic bedrock well.
21	108	--	190	--	455	208	-18	--	2.5	Domestic bedrock well.
23	109	--	183	--	170	98	85	--	8	Domestic bedrock well.
25	110	--	220	--	85	25	195	--	40–50	Domestic bedrock well.
26	111	--	230	--	180	80	150	--	15	Domestic bedrock well.
27	112	--	183	--	330	135	48	--	40	Domestic bedrock well.
31	113	--	111	--	22	--	<89	--	--	Well point.
34	114	--	143	--	80	3	140	--	40	Domestic bedrock well.
35	115	--	195	--	603	70	125	--	4	Domestic bedrock well.
37	116	--	200	--	174	80	120	--	10	Domestic bedrock well.
40	117	--	168	--	169	40	128	--	--	Domestic bedrock well (off figure 2).

Physiography and Geology

The physiography of the area surrounding the Dry Brook public-supply well (figs. 1 and 3) is a result of the lithology and structure of igneous and sedimentary bedrock, the distribution of unconsolidated glacial sediments, and postglacial erosional and depositional processes. High hills in the western (Mt. Tom Range) and northern part (Holyoke Range) of the study area consist of erosionally resistant igneous bedrock (basalt and tuff); the highest peaks in these hills are just above 900 ft in altitude. In most places, relatively thin deposits of glacial till laid down beneath the last (late Wisconsinan) ice sheet blanket the bedrock. Lower lying areas are underlain by softer sedimentary bedrock (sandstone, siltstone, and shale) and by relatively thick deposits of glacial meltwater sediment (gravel, sand, silt, and clay) laid down in glacial Lake Hitchcock during the retreat of the last ice sheet. The bedrock surface lies as much as 125 ft below NGVD29 in parts of the area; surfaces of glacial lake deposits are generally between 200 and 260 ft in altitude.

The Connecticut River, which developed on the drained glacial lake bed in postglacial time, flows through a steep-walled, narrow gap in the Holyoke and Mt. Tom Ranges, and has incised deeply into glacial Lake Hitchcock sediments along the reaches of its flood plain north and south of the gap. The flood plain lies generally between 110 to 120 ft in altitude along its course through the study area. Other postglacial streams, such as Elmer Brook, Bachelor Brook, and Stony Brook have also incised deeply into glacial lake sediments. The upper reaches of the Dry Brook valley consist of a narrow, steep-walled channel controlled by bedrock structure. From its headwaters, the stream descends 350 ft in altitude in less than a mile to a point at about 200 ft altitude where the valley widens as it enters the area underlain by glacial lake deposits. Downstream from this point, Dry Brook descends at a lesser, but still relatively steep gradient to about 100 ft altitude as it enters the Connecticut River. Maps and cross sections (figs. 3, 4, and 5) illustrate the distribution of surficial geologic units and the configuration of the underlying bedrock surface in the study area.

Bedrock Geology

The bedrock geology of the area is shown on a geologic map of the Mt. Holyoke quadrangle (Balk, 1957) and on the Bedrock Geologic Map of Massachusetts (Zen and others, 1983). A series of alternating units of early Jurassic-aged igneous and sedimentary bedrock underlie the study area. The area lies in the north-central part of a broad structural lowland in central Connecticut and Massachusetts known as the Hartford Rift Basin. In the vicinity of the South Hadley well field, the rock units strike northeast (parallel with the Mt. Holyoke ridge) and dip gently (15–20°) to the southeast. Northwest to southeast trending sections, *B-B′*, *C-C′*, and *D-D′* (fig. 4), are drawn nearly perpendicular to the strike direction and show the entire stratigraphic section of rock units in the study area. (Note the gentle southeasterly dip appears much steeper on these sections because of the 8X vertical exaggeration.).

The lowest (oldest) bedrock unit in the study area is the Holyoke Basalt, a fine-grained, massive, dark greenish-gray columnar basalt (called diabase by Balk, 1957), interpreted to have formed as one or more ponded lava flows; the Holyoke Basalt is 300 to 400 ft thick in the Mount Holyoke quadrangle. The basalt is highly fractured by cooling joints that form columns in the rock; the columnar jointing is perpendicular to the bottom and top of the flow, or flows, producing large concentrations of high-angle fractures. Low-angle fractures, parallel to the top and bottom of the flow are also well-developed, but spaced wider than the high-angle fractures. The East Berlin Formation stratigraphically overlies the Holyoke Basalt and consists of reddish-brown arkosic sandstone and siltstone, gray sandstone and mudstone, and local black shale units; it is interpreted to have formed as lake beds. Balk (1957, p. 494) described the unit as about 150 ft thick in the study area, although he referred to it as the basal unit of the Longmeadow Sandstone. Fracturing in these sedimentary rocks typically includes through-going, low-angle, bedding-parallel fractures and less extensive high-angle fractures that dip perpendicular to the bedding and have bedding-parallel strike; these high-angle fractures occur most frequently in the coarser grained beds.

Granby Basaltic Tuff and stratigraphically equivalent Hampden Basalt overlie the East Berlin Formation. The Granby Tuff–Hampden Basalt unit consists of chocolate brown, fine, medium, and coarse-grained, well stratified or massive tuff that locally incorporates sedimentary fragments and grades laterally into massive basalt. The unit is interpreted to have formed as lava flows, volcanic ash, and bedded volcanics. The Portland Formation (called Longmeadow Sandstone by Balk, 1957) is the youngest unit in the sequence, and in the study area consists of reddish-brown to pale-red arkose and siltstone, gray sandstone and siltstone, and black shale. The unit is interpreted to have formed as lake beds. Fracturing in these rocks is similar to that described for the East Berlin Formation.

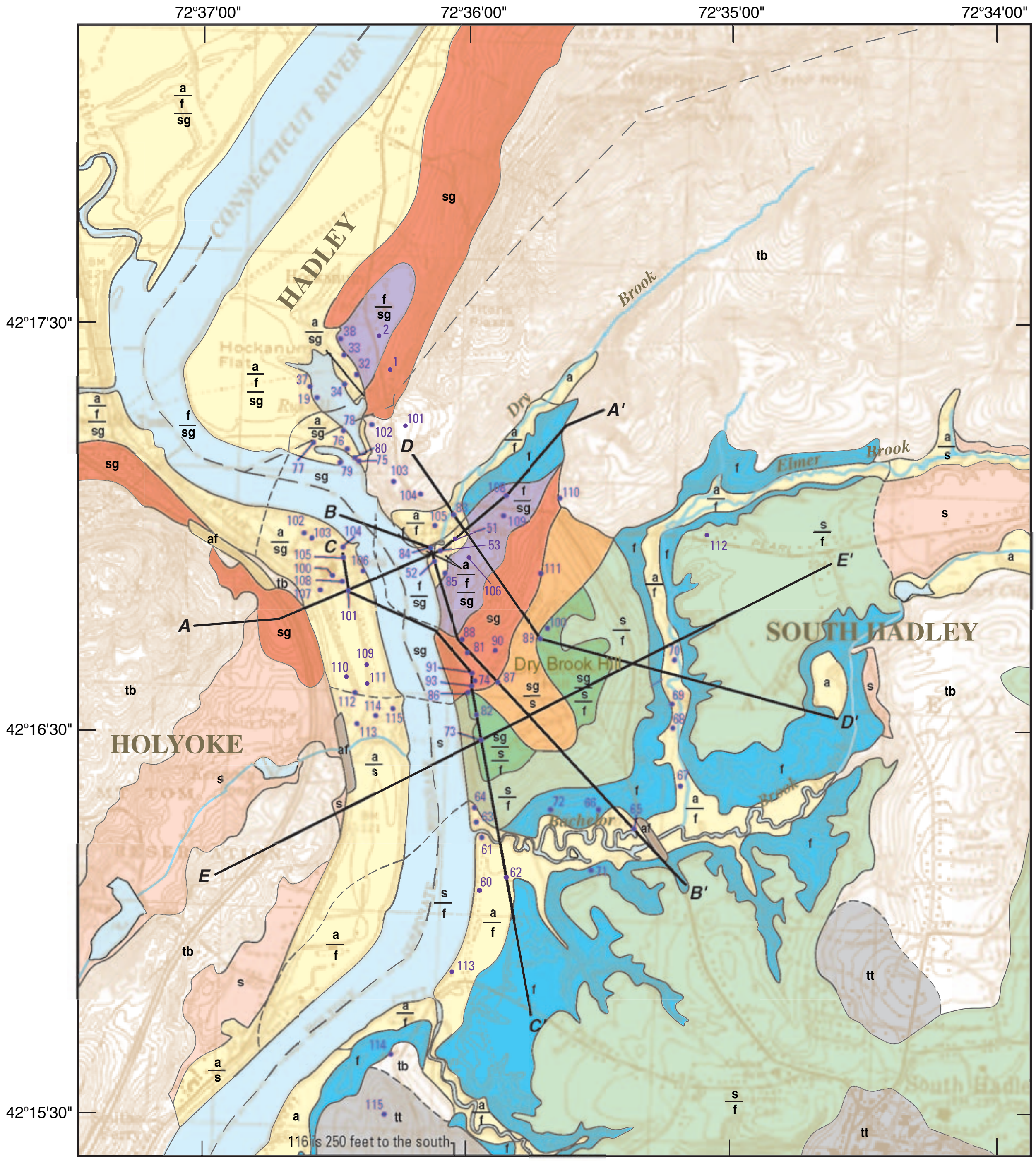
Areas where bedrock is at or near land surface are indicated by map unit tb (fig. 3), and the configuration of the bedrock surface beneath thick surficial materials (where the bedrock lies at or below 200 ft altitude in the study area) is shown on figure 5. Locations of bedrock outcrops (from Balk, 1957) and reported depths to bedrock in logs of wells and test holes were used to construct the bedrock-surface map (fig. 5). The bedrock surface beneath thick glacial deposits forms an irregularly shaped basin; the lithology and structure of the underlying bedrock control the basin shape. Millions of years of differential erosion, accentuated by glacial plucking during Pleistocene glacial advances, has produced the configuration of the bedrock surface. The processes of erosion and plucking by glacial ice produced lows in the bedrock surface where the rock is softer and more highly fractured. The northeast-southwest trending lows in the bedrock surface (north and south of Dry Brook Hill) are scoured along the trends of the East Berlin and Portland Formations, which are less resistant sedimentary units; the more resistant Granby Tuff forms a higher ridge between these two lows in the bedrock surface. The northwest-southeast trending low in the bedrock surface that forms the gap in the Holyoke Range, through which the Connecticut River flows, extends beneath the west side of Dry Brook Hill and is most likely a fault or fracture zone.

Surficial Geology

The surficial geology of the Mt. Holyoke quadrangle was mapped and reported by Balk (1957), and the distribution of coarse- and fine-grained surficial materials in the region was described by Stone and others (1979), and Langer (1979). Marine seismic-reflection data from tracklines along the Connecticut River through the study area were presented by Hansen (1986). Many other earlier publications describe the deposits, depositional environments, and history of glacial Lake Hitchcock in the Connecticut Valley of central Massachusetts (Antevs, 1922; Jahns and Willard, 1942; Hartshorn and Koteff, 1968; Gustavson and others, 1975; Ashley and others, 1982; Koteff and others, 1988; Ridge and Larsen, 1990), to name a few. Several theses done at the University of Massachusetts and Mt. Holyoke College have also addressed the geology and geohydrology of the South Hadley area (Saines, 1973; Jacobson, 1981; Donner, 1991; Delude, 1995; Rittenour, 1999).

Glacial deposits overlie the bedrock surface and range from a few feet to more than 250 ft thick in the study area. The surficial materials map (fig. 3) shows the distribution of surficial materials that lie between the land surface (below the pedogenic soil horizon) and the locally till-draped bedrock surface. Cross sections *A-A′*, *B-B′*, *C-C′*, *D-D′*, and *E-E′* (fig. 4) illustrate the characteristic vertical succession of glacial till, glacial meltwater deposits, and postglacial deposits. Most of these materials are deposits of the last two continental ice sheets that covered New England during the middle and late Pleistocene. Most of the glacial deposits were laid down during the advance and retreat of the last (late Wisconsinan) ice sheet, which reached its terminus on Long Island, NY, about 21,000 radiocarbon years ago, and retreated northward through the South Hadley area by about 14,000 radiocarbon years ago (Stone and Borns, 1986; Ridge and others, 1999; Stone, 1999). The glacial deposits are divided into two broad categories—glacial till and glacial stratified deposits. Glacier ice directly deposited the till, which is characterized as a nonsorted, nonlayered mixture of sand, silt, and clay with variable amounts of stones. During deglaciation, glacial stratified deposits were laid down by meltwater in lakes and streams in front of the retreating ice margin. These materials consist of well sorted to poorly sorted layers of gravel, sand, silt, and clay.

Postglacial sediments make up some of the surficial materials, and in the study area consist primarily of alluvial flood-plain deposits of the Connecticut River and its tributary streams–Bachelor Brook, Elmer Brook, Stony Brook, and Dry Brook. These sediments are inset into (and derived from) surrounding glacial deposits and in most places they are relatively fine grained, consisting of fine sand and silt. In the upper reaches of Dry Brook, alluvium is much coarser than most deposits and consists of cobble to boulder gravel and sand. For several hundred feet downstream from where Dry Brook exits its steep-walled bedrock canyon, the alluvium consists almost entirely of angular rock fragments.



Base from U.S. Geological Survey digital raster data,1:24,000, topographic quadrangle, Mt. Holyoke, 1964, photorevised 1979, North American datum 1927, Polyconic projection, zone 18

Surficial materials mapping by J.R. Stone, 2000-01; modified from Balk, 1957

0 1,000 2,000 FEET

0 300 600 METERS

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM 1929

Figure 3. Surficial materials map and locations of cross sections shown in figure 4, Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

EXPLANATION

DESCRIPTION OF MAP UNITS

POSTGLACIAL DEPOSITS

af Artificial Fill—Composed predominantly of earth materials emplaced along large road and railroad embankments

a/f/sg, a, a/sg Flood plain Alluvium—Composed of sand, silt, and local gravel, with varying amounts of organic material. Alluvium is beneath the modern flood plain surfaces along the Connecticut River, Dry Brook, Elmer Brook, Bachelor Brook, and Stony Brook. In the steep-gradient section of Dry Brook, alluvium is composed predominantly of boulder-cobble gravel. Along the smaller streams, alluvium is generally thin (<10 ft thick) and overlies thicker glacial stratified deposits indicated by letter symbol (see description below); along the Connecticut River, alluvium is as much as 50 ft in thick.

GLACIAL STRATIFIED DEPOSITS

Gravel, sand, silt, and clay particles (as defined in the adjacent particle-size diagram), that occur in layers and are classified into three textural units on the basis of grain-size distribution—sand and gravel deposits, sand deposits, and fine deposits. The texture of glacial stratified deposits is described throughout their entire vertical extent either as a single textural unit or two or more units in various orders or superposition, referred to as “stacked units.” Areas where sand and gravel deposits underlie sand or fines are shown by the orange-dotted pattern on the cross sections. Contacts between subsurface textural units are not mapped with as great an accuracy and detail as those at the surface. All units of glacial stratified deposits overlie glacial till and (or) bedrock, which are not included in the stacked unit.

Coarse Deposits

sg Sand and gravel—Composed of mixtures of gravel and sand particles within individual layers and as alternating layers; sand and gravel layers range from 25- to 50-percent gravel particles and from 50- to 75-percent sand particles. Layers are well to poorly sorted; bedding may be distorted by postdepositional collapse *(proximal deltaic and fluvial deposit and delta topset beds)*. Typical hydraulic conductivity is 100 to 500 feet per day.

s Sand—Composed mainly of very coarse to fine sand particles; coarser layers may contain up to 25-percent gravel particles, generally granules and pebbles; finer layers may contain some very fine sand, silt, and clay. Layers are commonly well sorted *(delta foreset beds, distal lacustrine fan deposits and distal fluvial deposits)*. Typical horizontal hydraulic conductivity is 25 to 250 feet per day.

Fine Deposits

f Fines (very fine sand, silt, and clay)—Composed of well sorted, thin layers of alternating silt and clay and (or) thicker layers of very fine sand and silt; locally may contain lenses of coarser material *(lake-bottom deposits)*. Typical horizontal hydraulic conductivity is less than 5 feet per day.

Stacked Map Units

sg/s Sand and gravel overlying sand—Sand and gravel is generally less than 20 feet thick, horizontally bedded and overlies thicker, inclined layers of sand *(deltaic deposits)*.

sg/s/f Sand and gravel overlying sand overlying fines—Sand and gravel is generally less than 20 feet thick, horizontally bedded and overlies thicker inclined beds of sand, which in turn overlie thinly bedded fines of variable thickness *(deltaic deposits overlying lake-bottom sediment)*.

s/f Sand overlying fines—Sand is of variable thickness, commonly in inclined foreset beds and overlies thinly bedded fines of variable thickness *(distal deltaic deposits overlying lake-bottom sediment)*.

f/sg Fines overlying sand and gravel—Fines of variable thickness overlies sand and gravel of variable thickness *(lake-bottom sediments overlying collapsed ice-marginal deltaic or lacustrine fan deposits)*.

GLACIAL DEPOSITS (NONSTRATIFIED)

tt tb Till—Nonsorted, nonstratified, generally compact mixture of grain sizes ranging from clay to large boulders; matrix is largely sand particles containing up to 25-percent silt and clay. Till blankets the bedrock surface in most places and underlies glacial stratified deposits but is not included in the stacked units. In most of the map area (unit tb), till is less than 10 feet-thick and bedrock is exposed at land surface in many places, particularly on steep hillsides. Shading indicates areas where till is greater than 10 feet thick (unit tt). Hydraulic conductivity is generally less than 1 foot per day.

MAP SYMBOLS

——— — — Contact between map units, dashed where inferred

A——A′ Line of geologic section shown in figure 4.

•111 OBSERVATION WELL AND NUMBER

Figure 3—Continued. Surficial materials map and locations of cross sections shown in figure 4, Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

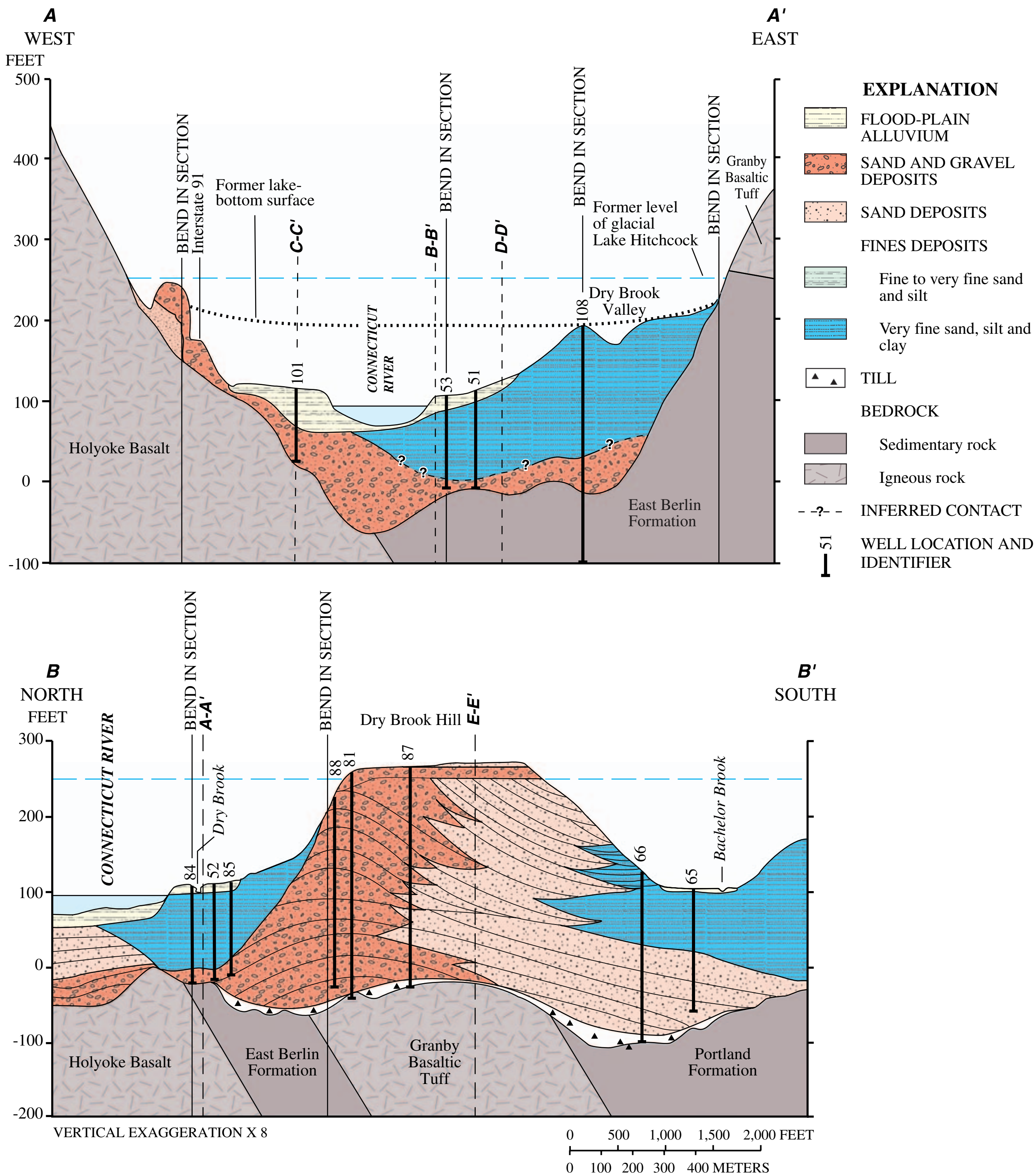


Figure 4. Geologic cross sections, Dry Brook study area, Holyoke and South Hadley, Massachusetts.

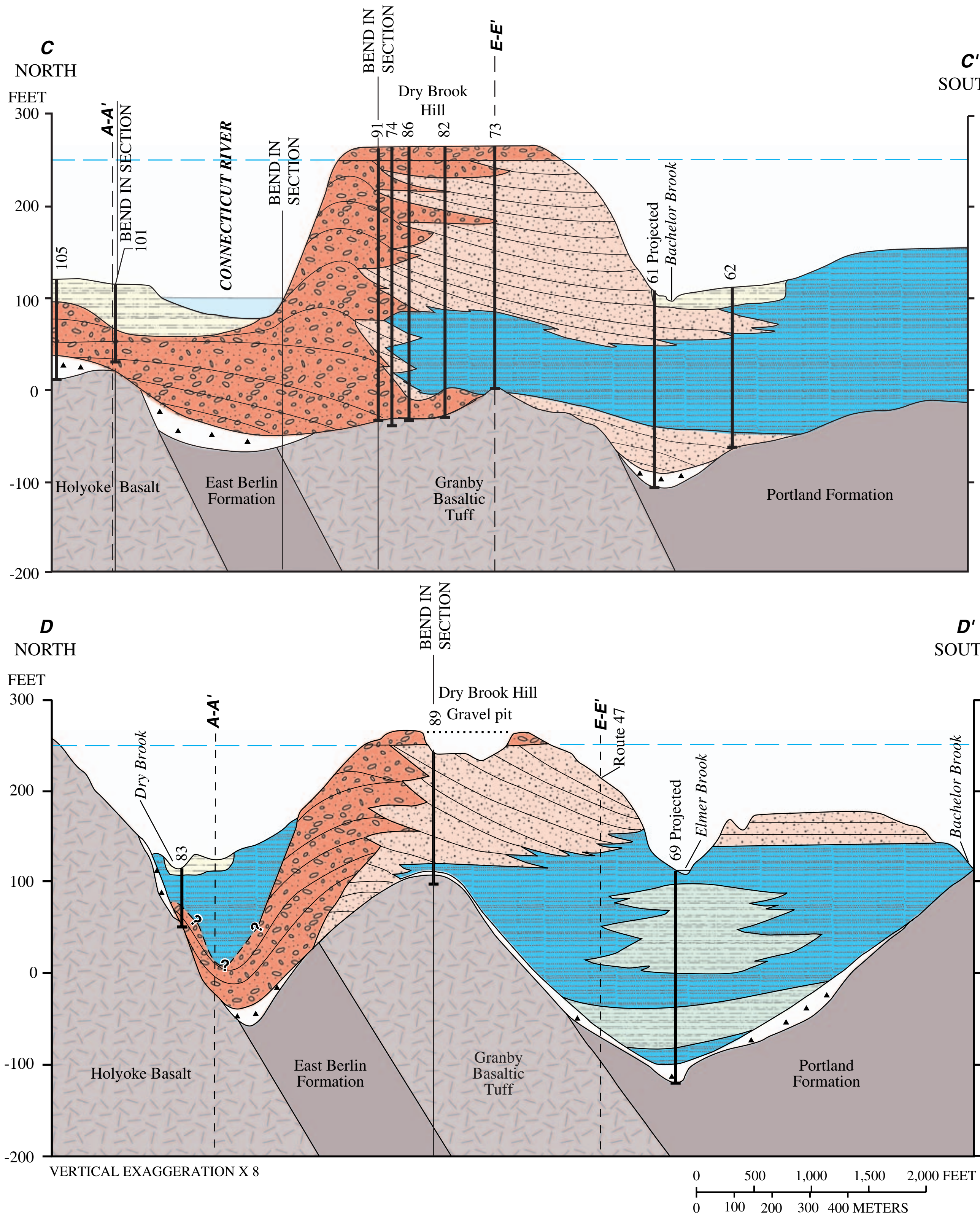


Figure 4—Continued. Geologic cross sections, Dry Brook study area, Holyoke and South Hadley, Massachusetts.

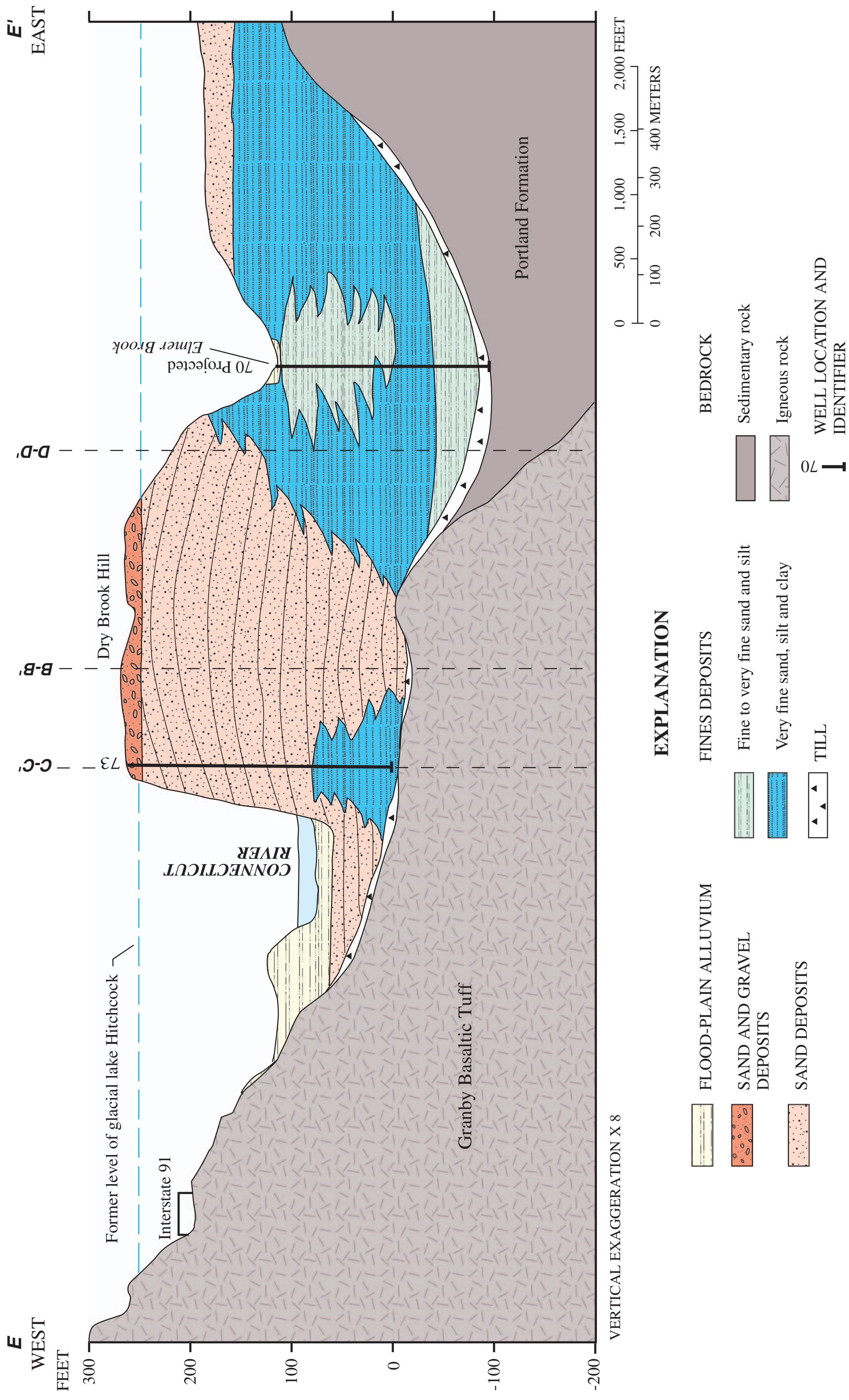
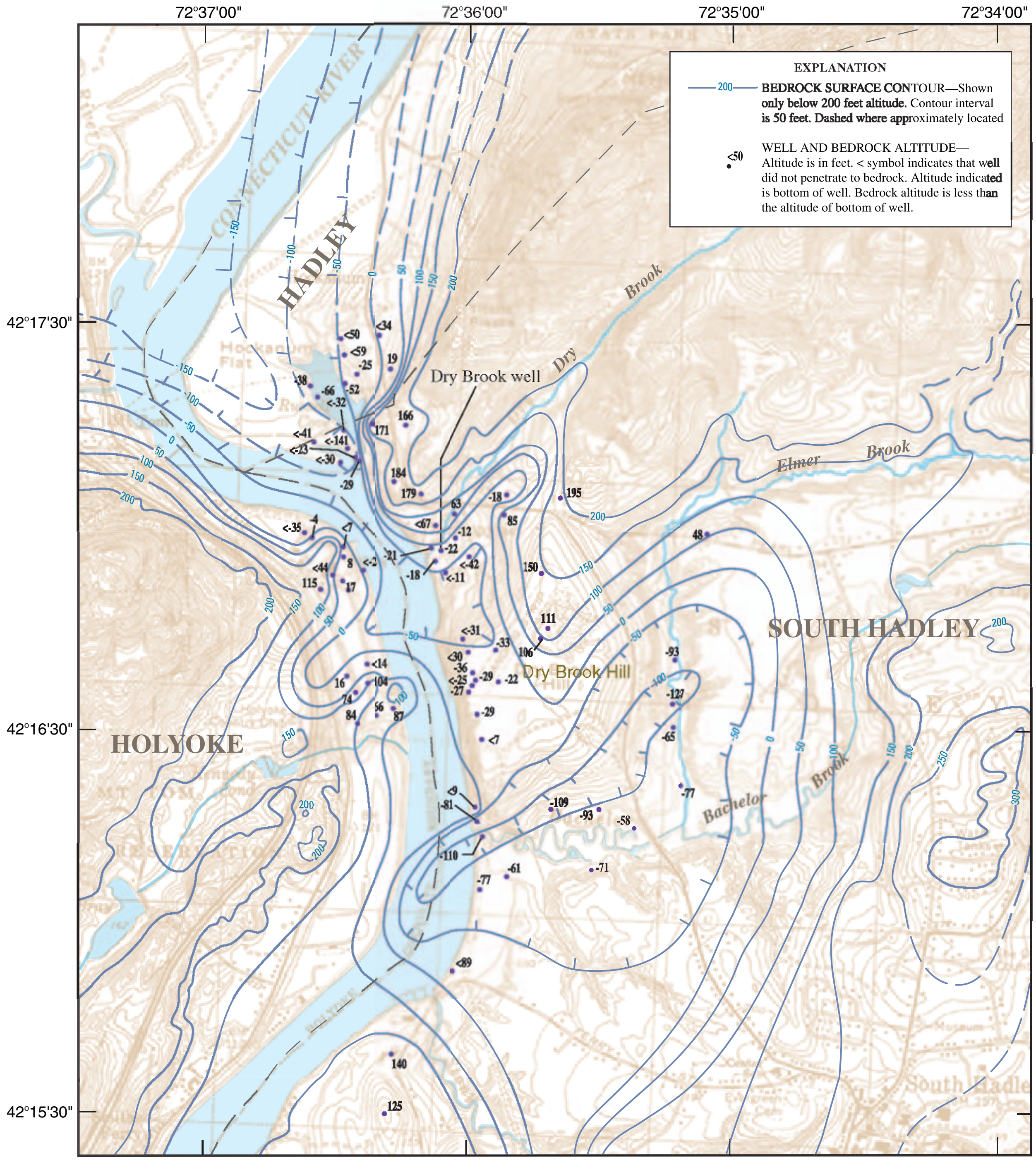


Figure 4—Continued. Geologic cross sections, Dry Brook study area, Holyoke and South Hadley, Massachusetts.



Base from U.S. Geological Survey digital raster data,1:24,000, topographic quadrangle, Mt. Holyoke, 1964, photorevised 1979, North American datum 1927, Polyconic projection, zone 18

0 1,000 2,000 FEET
0 300 600 METERS

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM 1929

Figure 5. Altitude of the bedrock surface in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

Glacial Till

In the study area, till was deposited predominantly as lodgment till beneath the ice sheet. The color and texture of the till vary locally and are related to the type of bedrock in northerly adjacent areas from which the till was derived. No exposures of till were available for examination in the Dry Brook area at the time of this study; however, till in the region is typically reddish-brown in areas of sedimentary bedrock and varies to grayish brown near basalt ridges. The material (fig. 6*D*) consists of a nonsorted, nonlayered mixture of grain sizes with a matrix of 50- to 60-percent sand, 30- to 40-percent silt, and 10- to 15-percent clay; larger rock fragments generally constitute 10 to 20 percent of the total volume of material and include angular blocks of sandstone, basalt, tuff, and erratic clasts of metamorphic rock (Melvin and others, 1992). Till is relatively thin (less than 20 ft thick) over most of the study area, and is absent where bedrock crops out at land surface in many places. Locally, however, till is thicker than 20 ft (unit *tt*, fig. 3). Several NNW–SSE trending hills in the area are drumlins composed entirely of glacial till; these include Prospect Hill just east of Mt. Holyoke College and two hills southeast of Stony Brook in South Hadley, MA.

Glacial Stratified Deposits

In the study area, stratified deposits were laid down by meltwater as lacustrine fans, deltas, and lake-bottom sediments in glacial Lake Hitchcock, an extensive proglacial lake that occupied the Connecticut Valley for several thousand years as the last ice sheet retreated from central Connecticut northward through Massachusetts to the vicinity of Burke, VT (Koteff and others, 1988; Koteff and Larsen, 1989; Stone and others, in press). These meltwater deposits overlie the glacially scoured and till-draped bedrock surface at altitudes below 260 ft, controlled by the level of Lake Hitchcock at the time the ice retreated through the South Hadley area. Sediments range from a few to more than 300 ft in thickness and include coarse-grained and fine-grained sedimentary facies (fig. 6). Various sedimentary facies that constitute glacial meltwater deposits in southern New England are described in detail by Stone and others (in press).

Coarse-Grained Deposits

Coarse-grained stratified deposits (fig. 6*A* and *B*) consist of gravel and sand with local diamict sediment in ice-proximal (northerly) parts, and grade to finer gravels and sand within short distances in distal (southerly) directions. The principal unit of coarse-grained glacial stratified deposits in the study area underlies Dry Brook Hill to the southeast of the Dry Brook supply well. Dry Brook Hill is an ice-marginal delta built into glacial Lake Hitchcock at a time when the ice margin stood along the north and northwest side of the Holyoke Range and a narrow tongue of ice protruded through the gap (fig. 1; Saines, 1973; Donner, 1991). Deposition of this feature began when sediment-laden meltwater discharged (under hydrostatic head) from a subglacial tunnel onto the floor of Lake Hitchcock and constructed a subaqueous lacustrine fan. Deposition continued after fan sediments had reached lake level and the final construction of the landform was accomplished by delta progradation southeasterly into the lake. The interpretation of well logs and test borings, and three-dimensional reconstruction of the distribution of sedimentary facies (fig. 4) within Dry Brook Hill, provide evidence that the deltaic landform has a core of lacustrine fan beds in the northwest and central parts, although these beds have not been exposed.

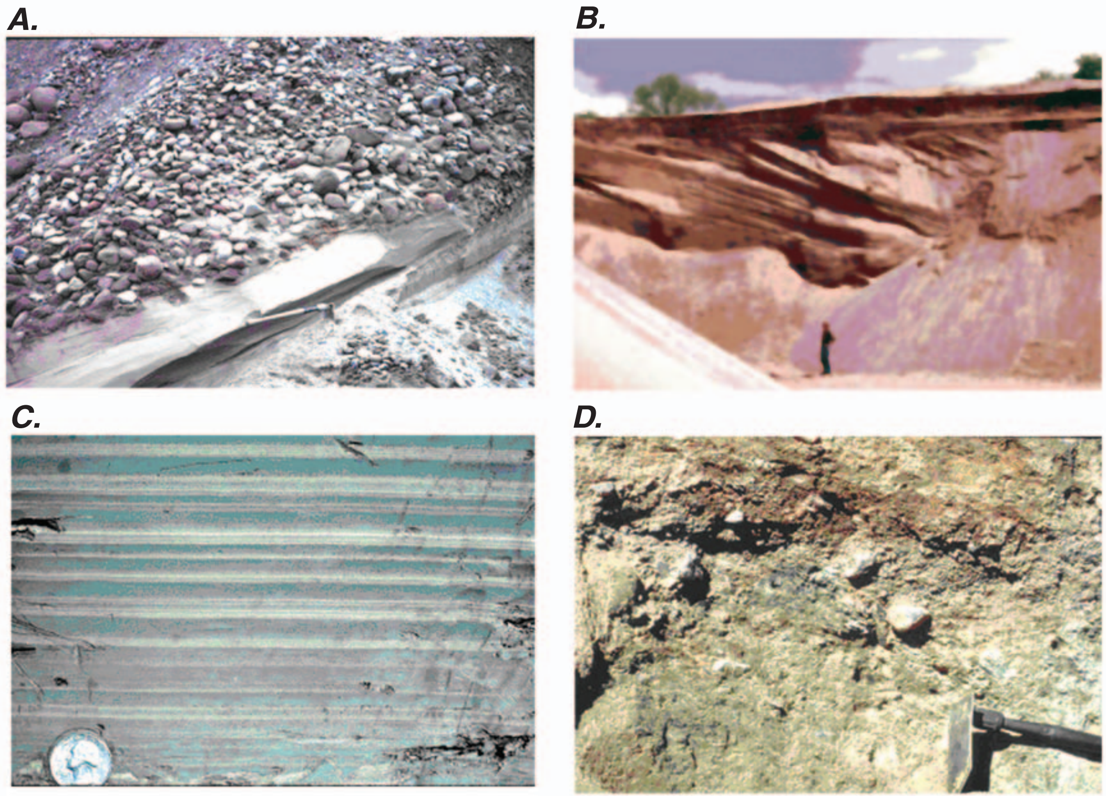


Figure 6. Examples of glacial deposits in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts: *A*, gravel and sand beds in an ice-marginal delta; *B*, flat-lying gravel topset beds overlying dipping sandy foreset beds in the Pearl City delta, South Hadley; *C*, glacial Lake Hitchcock varved silt (darker layers) and clay (lighter layers); and *D*, typical red till in the Hartford Basin.

The northwest side of Dry Brook Hill is underlain by coarse, poorly sorted gravel and sand that extends beneath subsequently deposited glacial lake clays in Dry Brook Valley at the northwest base of the hill. These gravels compose the highly productive aquifer tapped by the Dry Brook supply well (fig. 4, sections *B*-*B′* and *D*-*D′*). The eastern and southern sides of Dry Brook Hill, underlain by sands and clays, are the frontal foreset slopes of the delta.

The steep western slope of Dry Brook Hill is an erosional scarp, cut first by water spilling from Lake Hitchcock north of the Holyoke Range, after the southern basin of the lake had drained (Stone and Ashley, 1995; Stone, 1999), and later by the ancestral Connecticut River as it continued to incise the entirely drained lake bed. A small portion of the delta remains on the west side of the river as a 245-ft hill on west side of I-91 (figs. 3 and 4, section *A*-*A′*). The Dry Brook delta plain has a surface altitude of 265 to 270 ft; a sand and gravel excavation cut into the delta surface (fig. 3) exposes 10 to 12 ft of flat-lying layers of gravel and sand (topset beds) overlying about 30 ft of easterly dipping sandy layers (foreset beds). The contact between the topset and foreset beds marks the level (altitude) of the glacial lake at the time the delta was constructed. Figure 6*B* shows the topset-foreset contact in the Pearl City delta about 2 mi east of Dry Brook Hill. The altitude of the topset-foreset contact in the Dry Brook delta is 255 ft (Jacobson, 1981). In the southern and eastern parts of Dry Brook Hill, distal sandy beds interfinger with and overlie fine-grained glaciolacustrine sediments.

Fine-Grained Deposits

Fine-grained glaciolacustrine deposits in the study area consist of finely laminated silt, clay, and minor fine sand in couplets (varves) ranging from 0.4 to 1.6 in. thick, each couplet representing annual deposition into Lake Hitchcock (fig. 6*C*). These sediments are gray in upper parts of the lacustrine sections but locally are red, especially in lower parts of lacustrine sections; deposits range from a few feet to as much as 200 ft in thickness. These varved silt and clay sediments settled out in relatively still, deep water as the ice margin retreated farther to the north. Each silt-clay couplet (fig. 6*C*) represents deposition in the glacial lake during one year; the silt layer was deposited during the spring-summer melt season, and the clay slowly settled out of the water column during the winter when the lake was frozen.

Glaciolacustrine silt and clay deposits underlie and interfinger with sand beds of the Dry Brook delta in central and southern parts of Dry Brook Hill. In some places, lenses of coarser grained lacustrine sediment consisting of alternating layers of very fine to fine sand and silt lie beneath and within the varved silt and clay sections (fig. 4, sections *D-D′* and *E-E′*). North of the hill and at the site of the Dry Brook supply well, silt and clay deposits overlie collapsed, ice-marginal gravels and sands of the Dry Brook delta and lacustrine fan beds. Beneath lake-bottom surfaces (at 175–205 ft altitude) east and south of Dry Brook Hill, lacustrine varved silt and clay grade upward to a coarser, sandy material deposited in shallow water as the glacial lake filled with sediment and eventually drained. These sandy lake-bottom deposits consist of well-sorted fine to medium sand. This 5- to 20-ft thick facies gradationally overlies the finer-grained silt-clay facies.

Hydrology

The surface- and ground-water hydrology of the study area is dominated by topography, underlying geologic materials, and the Connecticut River. The source of all water in the area is precipitation, which averages about 42 in. per year. Generally, because of steep slopes and thin soil cover, much of the precipitation occurring on the Holyoke and Mt. Tom Ranges runs off quickly during and immediately after precipitation. On Dry Brook Hill, however, much of the precipitation infiltrates through the sandy soils on the higher elevations of the hill. Lacustrine silts and clays (varves) that impede infiltration occur along the flanks and lower elevations of the hill, creating surface runoff during precipitation. The Dry Brook supply well is completed in the sand and gravel aquifer that underlies the lacustrine sediments near the mouth of Dry Brook. This sand and gravel aquifer is physically contiguous with coarse sediments in Dry Brook Hill. Water in the study area (not pumped from wells) will generally flow to the Connecticut River under natural conditions.

Streamflow

Four streams flow in the vicinity of the Dry Brook supply well: Dry Brook, Elmer Brook, Bachelor Brook, and the Connecticut River. The smallest of the streams is Dry Brook (fig. 7), which drains 0.8 mi^2 at its confluence with the Connecticut River. Flow measurements of Dry Brook on September 8, 2000 (table 2, fig. 7), indicate rapid gains and losses in flow along the stream length. For example, Dry Brook gained flow in its upper reach, and then rapidly lost all flow after exiting from a bedrock gorge as it came in contact with rubble and cobble streambed materials (alluvium). Flow then gained downstream from the alluvial fan at the mouth of the gorge for a distance of about 3,000 ft, where it began to lose flow again into the sandy material in the streambed. On the date of these measurements, all flow was lost at the point where Dry Brook reached Massachusetts Route 47. The streamflows measured in Dry Brook on this date (0.01–0.07 ft^3/s) are small relative to the annual median flow estimated for a drainage basin of this size (0.7 ft^3/s), indicating that these flows are at the lowest range for this stream. The annual median flow was estimated for Dry Brook using the Streamstats Internet application developed to estimate streamflow duration statistics for Massachusetts streams (Ries and Friesz, 2000).

Although these observations of gains and losses along Dry Brook indicate a significant interaction between surface and ground water along Dry Brook, most of the lower reach of Dry Brook is underlain by varved lacustrine sediments, which are exposed in the streambed just north of Route 47 (figs. 3, 4, section *D-D′*). Most likely much of the water that infiltrates along the lower reach of Dry Brook flows laterally through the alluvial materials in the streambed as underflow to discharge to the Connecticut River at the confluence. It is also possible, however, that some water from Dry Brook infiltrates to and through the fractured bedrock and lacustrine sediments to recharge the sand and gravel aquifer at depth.

Elmer Brook flows along the eastern flank of Dry Brook Hill and drains 4.0 mi^2 at its confluence with Bachelor Brook (fig. 7). Streamflow measurements also were made on Elmer Brook on September 8, 2000 (table 2). These measurements indicate that Elmer Brook did not gain or lose much water under the hydrologic conditions on that date along the reach that runs from north to south along the east side of Dry Brook Hill (table 2, fig. 7). The measured flows (1.79–1.89 ft^3/s) are smaller than the estimated annual median flow (4.0 ft^3/s; Ries and Freeze, 2000), which is indicative of the low-flow conditions on this date. Elmer Brook will gain substantial amounts of water from surface runoff during rainfall because the lacustrine sediments (fig. 4, section *D-D′*) exposed in the streambed and in the hillside above the brook will limit infiltration. These sediments also likely cause the small change in streamflow because they transmit and discharge small amounts of ground water during periods between rainfall events, and much of that flow would be lost as evapotranspiration to the heavy vegetation on the slopes above the brook.

The largest streams in the study area are Bachelor Brook and the Connecticut River. Bachelor Brook flows along the southern flank of Dry Brook Hill (fig. 7) and is a tributary of the Connecticut River. Bachelor Brook drains about 32 mi^2 and has an estimated median flow of 32 ft^3/s (Ries and Freze, 2000). The Connecticut River is the largest stream in central New England and has an average flow of about 14,000 ft^3/s at the streamflow-gaging station at Montague City, MA, about 22 mi upstream from the study area. The river continues to gain flow from several large tributaries as it crosses central Massachusetts and averages about 17,000 ft^3/s at the streamflow-gaging station near the State line at Thompsonville, Connecticut, about 20 mi downstream of the study area. Streamflow in the Connecticut River is highly regulated by releases from several upstream dams, used primarily for hydroelectric power generation and flood control. These releases can cause large and rapid fluctuations in the Connecticut River stage and flow.

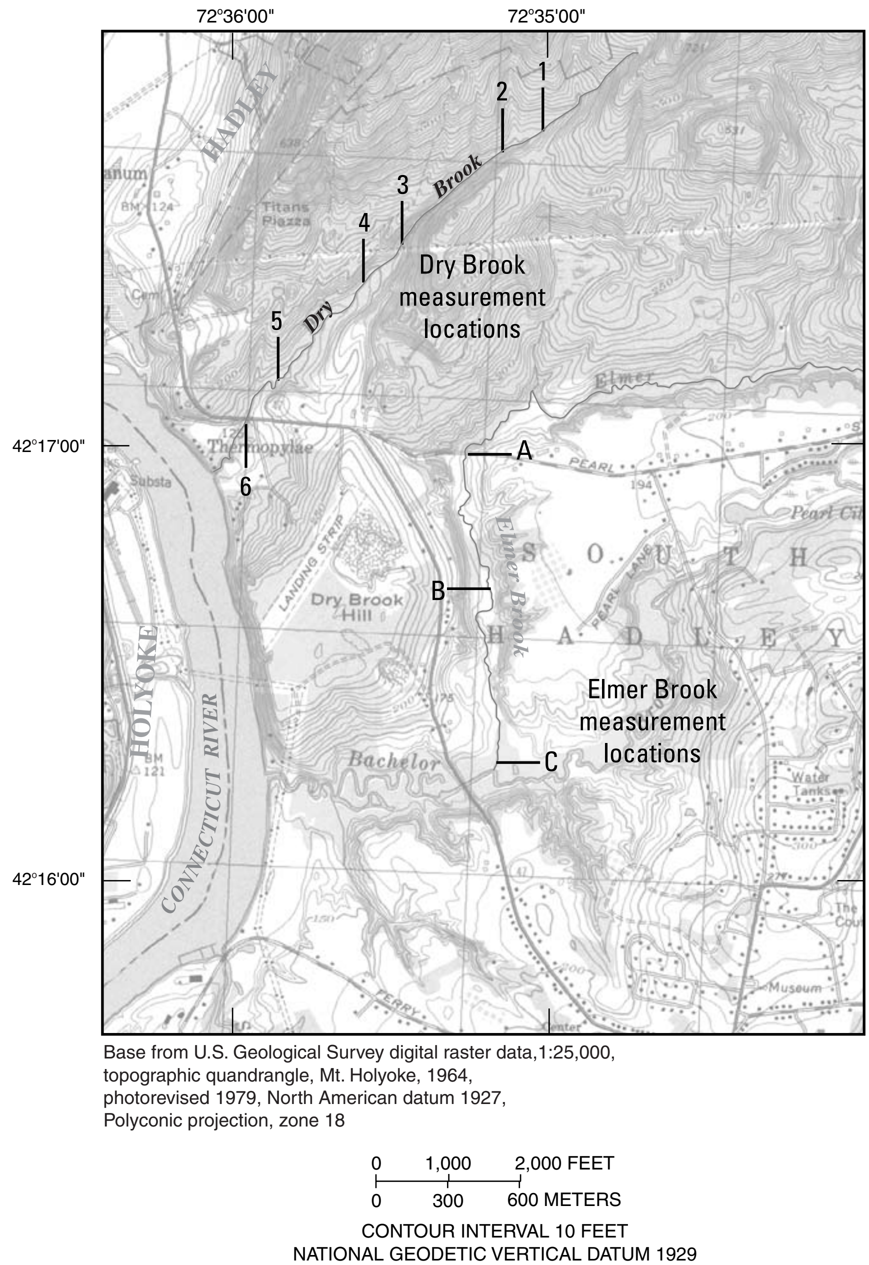


Figure 7. Locations of streamflow measurements for Elmer and Dry Brooks, Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

Ground-Water Levels and Flow

Ground-water levels measured as part of this study are shown in table 3, and water levels measured on November 16, 2000, are shown on figure 8. Wells in table 3 are listed with two names, one of which is assigned by the USGS (for example, SUW-85), and the other a local name assigned at the time of installation (for example, TW6-97). In the following discussion, the USGS names will be used for consistency.

Ground-water measurements made in the study area (table 3, fig. 8) indicate that ground-water levels were generally higher than 100 ft above NGVD29 under Dry Brook Hill, and less than that immediately around the Dry Brook supply well (SUW-55, fig. 2), because of drawdown caused by pumping at the supply well. The water levels measured at well SUW-89 near the center of Dry Brook Hill are higher than those closer to the Connecticut River (table 3, fig. 8). The altitude of the Connecticut River in the vicinity of Dry Brook Hill is about

Table 2. Streamflow measurements for Elmer and Dry Brooks, South Hadley, Massachusetts, September 8, 2000.

[See figure 7 for locations of measurements. ft^3/s, cubic foot per second]

Location	Flow rate (ft^3/s)	Comments
Dry Brook		
1 (upstream)	0.01	Stream begins at seep
2	.03	
3	.04	
4	0	Lost all flow at alluvial fan
5	.07	
6 (downstream)	0	Lost all flow at Massachusetts Highway Route 47
Elmer Brook		
A	1.79	
B	1.84	
C	1.89	

100 ft. These water-level data indicate that, in general, ground water in this area flows towards the Connecticut River. In addition, because the water levels measured in wells near the Dry Brook supply well were below the stage of the Connecticut River, water may also flow from the river to the supply well when the well is pumped.

Ground-water levels vary seasonally, with highest levels in the late spring and lowest levels in early fall. This pattern of ground-water levels is caused by increased recharge rates during the period from late fall through spring when evapotranspiration rates are lowest. The seasonal variation in ground-water level can be seen in data from a nearby USGS observation well completed in a glacial outwash aquifer in Granby, MA (fig. 9; Socolow and others, 2002). Water levels measured during the study period (October 1999 through November 2000) were typical of the normal range of water levels expected for surficial aquifers in central Massachusetts (fig. 9).

The stage of the Connecticut River also affects ground-water levels in the study area. The continuous measurement of water levels in well SUW-81 (fig. 2) near the river, and the variations in stage of the Connecticut River at the Montague (Massachusetts) station about 22 mi upstream of the Dry Brook area, are shown in figure 10. There are no dams that impound the river between this station and the study area. In addition, there are no major tributaries that enter the river in this reach. The stage of the Connecticut River adjacent to Dry Brook Hill would be expected to follow the rise and fall in river stage at the Montague station with a 1- to 2-day time lag in stage response. Although upstream reservoirs heavily regulate the Connecticut River on a daily basis, the flows in the river are highest in the spring after the snow melts (fig. 10). The good correlation between these two hydrographs indicates a hydraulic connection between the ground-water system under Dry Brook Hill and the river.

Ground-Water Recharge and Discharge

The rate of ground-water recharge in the study area was assumed to vary with the topography (slope), texture (grain size) of the soil, and the type of underlying rock or sediments. Recharge was assumed to be greatest, about 24 in/yr, on the northern part of Dry Brook Hill and other locations where the sediments are the coarsest in the study area. This recharge amount represents about half of the available precipitation. Recharge was assumed to be about 12 in/yr in areas along the flanks of the Holyoke Range, where steep slopes and bedrock at or near the surface increase surface runoff of precipitation. In areas underlain by lacustrine silts and clays (varves), particularly where these sediments are thick in the area immediately around the Dry Brook well, recharge was assumed to be 6 in/yr. Recharge rates of 22 in/yr for stratified deposits and 8 in/yr for till were used in a similar study in Connecticut for an area underlain by Mesozoic-aged bedrock and glacial sediments (Starn and others, 2000). As noted previously, most ground water in the study area discharges to streams or is pumped from wells. A small amount of ground-water discharge is lost by evapotranspiration, primarily in low-lying areas where seeps and springs feed streams, creating wet soils and wetlands.

Aquifer Responses to Pumping

An aquifer test was conducted for 10 days (September 25, 1998–October 5, 1998) by pumping the Dry Brook well (SUW-55, fig. 2) at an average rate of 914 gal/min (Tighe and Bond, 1999). The Dry Brook supply well is completed in the sand and gravel aquifer below about 100 ft of lacustrine silts and clays; these overlying fine-grained sediments locally confine the aquifer tapped by the supply well (fig. 4, sections *A-A′* and *B-B′*). The extent of the confined portion of the sand and gravel aquifer is shown on figure 11; however, the sand and gravel aquifer extends beyond the area shown in figure 11 and is either unconfined or overlain by the Connecticut River beyond the confining bed (figs. 3 and 4).

Ground-water levels measured during the aquifer test in wells near the Dry Brook well and open to the aquifer (fig. 11) are shown in figure 12. A small amount of precipitation (0.25 in.) fell on the third day of the test (September 27, 1998), but did not appear to affect the confined aquifer responses. The responses are shown as drawdowns, which are the water-level declines observed in the wells from the beginning of the aquifer test. The drawdowns observed in these wells indicated a variety of responses to the stress caused by the pumping at the Dry Brook well. The largest drawdowns generally were in wells closest to the pumped well, the closest of which is SUW-53, only 2 ft away from the pumped well within the pump house.

Table 3. Manual ground-water-level measurements in Dry Brook study area, South Hadley, Massachusetts.

[**DTW and Altitude:** Relative to NGVD29. DTW, depth to water; USGS, U.S. Geological Survey; --, no measurement]

Local well name	USGS number (SUW)	Measuring-point altitude	Date of measurement									
			10-22-1999		11-19-1999		1-06-2000		2-24-2000		4-06-2000	
			DTW	Altitude	DTW	Altitude	DTW	Altitude	DTW	Altitude	DTW	Altitude
TW11-60	51	111.08	13.84	97.24	--	--	--	--	--	--	--	--
TW13-60	52	108.57	13.51	95.06	--	--	--	--	--	--	--	--
TW14-82	69	115.05	11.84	103.21	--	--	--	--	--	--	--	--
TW15-82	70	116.39	11.26	105.13	11.30	105.09	11.37	105.02	--	--	10.54	105.85
TW1-95	73	269.61	168.36	101.25	--	--	--	--	--	--	165.38	104.23
TW2-95	74	265.90	164.06	101.84	--	--	--	--	--	--	160.27	105.63
TW3-95	81	264.03	164.55	99.48	164.78	99.25	161.95	102.08	164.42	99.61	156.96	107.07
TW9-97 (P9)	83	117.77	19.66	98.11	19.83	97.94	13.23	104.54	--	--	13.16	104.61
TW6-97 (P6)	85	118.56	20.64	97.92	20.79	97.77	17.46	101.10	--	--	12.71	105.85
P-2	86	268.84	166.53	102.31	166.56	102.28	166.38	102.46	--	--	163	105.84
P-3	87	268.75	166.16	102.59	166.25	102.50	165.85	102.90	166.36	102.39	163.89	104.86
P-4A	88	218.49	119.49	99.00	--	--	--	--	--	--	111.47	107.02
P-5	89	244.59	136.79	107.80	137.02	107.57	137.08	107.51	--	--	136.53	108.06
P-8	90	267.29	165.3	101.99	165.41	101.88	164.54	102.75	165.42	101.87	162.11	105.18
P-1	93	266.04	164.36	101.68	164.54	101.50	--	--	--	--	160.34	105.70
P-4B	94	212.05	113.95	98.10	114.19	97.86	--	--	--	--	105.65	106.40

Local well name	USGS number (SUW)	Measuring-point altitude	Date of measurement							
			6-08-2000		8-10-2000		9-21-2000		11-16-2000	
			DTW	Altitude	DTW	Altitude	DTW	Altitude	DTW	Altitude
TW11-60	51	111.08	--	--	--	--	--	--	--	--
TW13-60	52	108.57	--	--	--	--	--	--	--	--
TW14-82	69	115.05	9.8	105.25	--	--	--	--	11.18	103.87
TW15-82	70	116.39	9.2	107.19	9.86	106.53	10.25	106.14	10.79	105.60
TW1-95	73	269.61	166.55	103.06	167.58	102.03	167.94	101.67	167.78	101.83
TW2-95	74	265.90	164.3	101.60	163.04	102.86	163.19	102.71	163	102.90
TW3-95	81	264.03	160.53	103.50	163.68	100.35	163.58	100.45	162.73	101.30
TW9-97 (P9)	83	117.77	15.91	101.86	17.52	100.25	19.69	98.08	17.96	99.81
TW6-97 (P6)	85	118.56	16.4	102.16	18.34	100.22	20.03	98.53	17.9	100.66
P-2	86	268.84	164.3	104.54	165.69	103.15	165.98	102.86	166.2	102.64
P-3	87	268.75	163.92	104.83	165.04	103.71	165.34	103.41	165.37	103.38
P-4A	88	218.49	--	--	--	--	--	--	--	--
P-5	89	244.59	135.88	108.71	136.28	108.31	136.26	108.33	136.42	108.17
P-8	90	267.29	162.74	104.55	164.2	103.09	164.4	102.89	164.32	102.97
P-1	93	266.04	--	--	--	--	--	--	--	--
P-4B	94	212.05	109.53	102.52	--	--	112.87	99.18	111.91	100.14

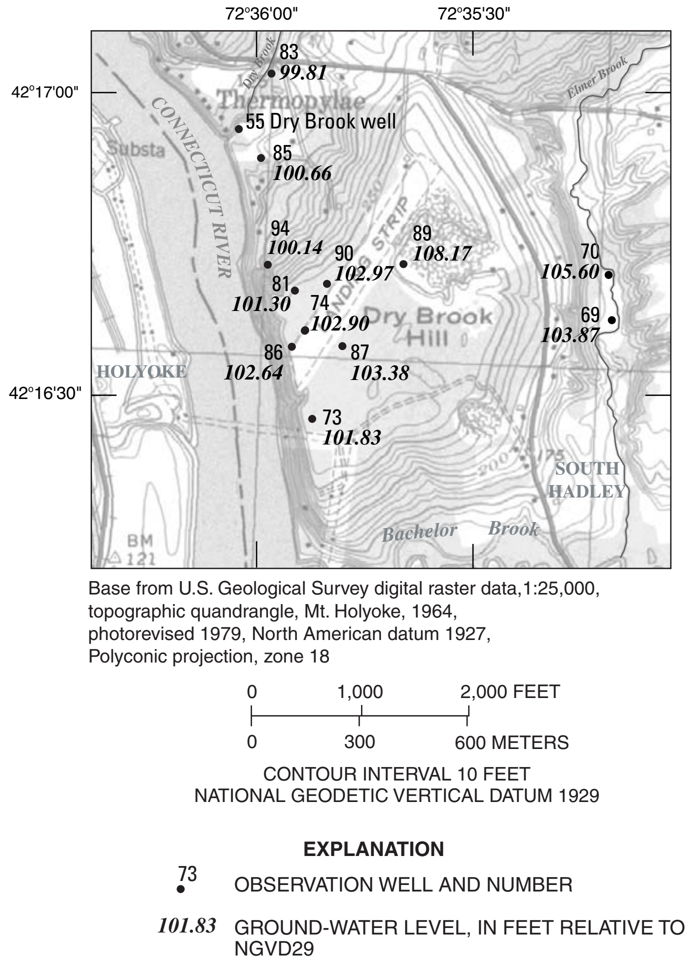


Figure 8. Ground-water levels measured in the Dry Brook study area on November 16, 2000, Hadley, Holyoke, and South Hadley, Massachusetts.

There were, however, some exceptions. For example, drawdown after 10 days for well SUW-84, 150 ft from the pumped well, was significantly greater than drawdown in well SUW-52, which is also 150 ft from the pumped well. The same was true for well SUW-83, which is 600 ft away from the pumped well, but had drawdown after 10 days that was greater than drawdown in well SUW-85, which is about 300 ft from the supply well (fig. 11). Data in figure 11 indicate that the drawdown cone was likely elongated in a northern direction towards well SUW-83. Deviations from radially concentric drawdown conditions would likely be caused by variations in aquifer properties and (or) type of aquifer boundary.

In addition to these likely deviations from ideal conditions, variations in the drawdown responses over time differ at the observation wells. Although the thick overlying varved clays should confine the aquifer yielding water to the well (fig. 11), most of the drawdowns observed in the observation wells indicated some type of stabilization of the confined-storage drawdown response a few minutes to a few tens of minutes after the beginning of the test (fig. 12). To separate the effect of distance from the pumped well from other effects, the drawdown responses were plotted against time divided by the square of radial distance (fig. 13). In the ideal case (Theis-type, or confined- aquifer conditions with uniform hydraulic properties), drawdown responses observed in wells with different radial distances from the pumped well should be identical when plotted in this fashion.

Drawdown reponses over time vary significantly between the observation wells, even after distance is considered (fig. 13). For example, the early confined response is substantially different at each of the observation wells, with SUW-83 responding most rapidly, and SUW-53 responding the slowest.

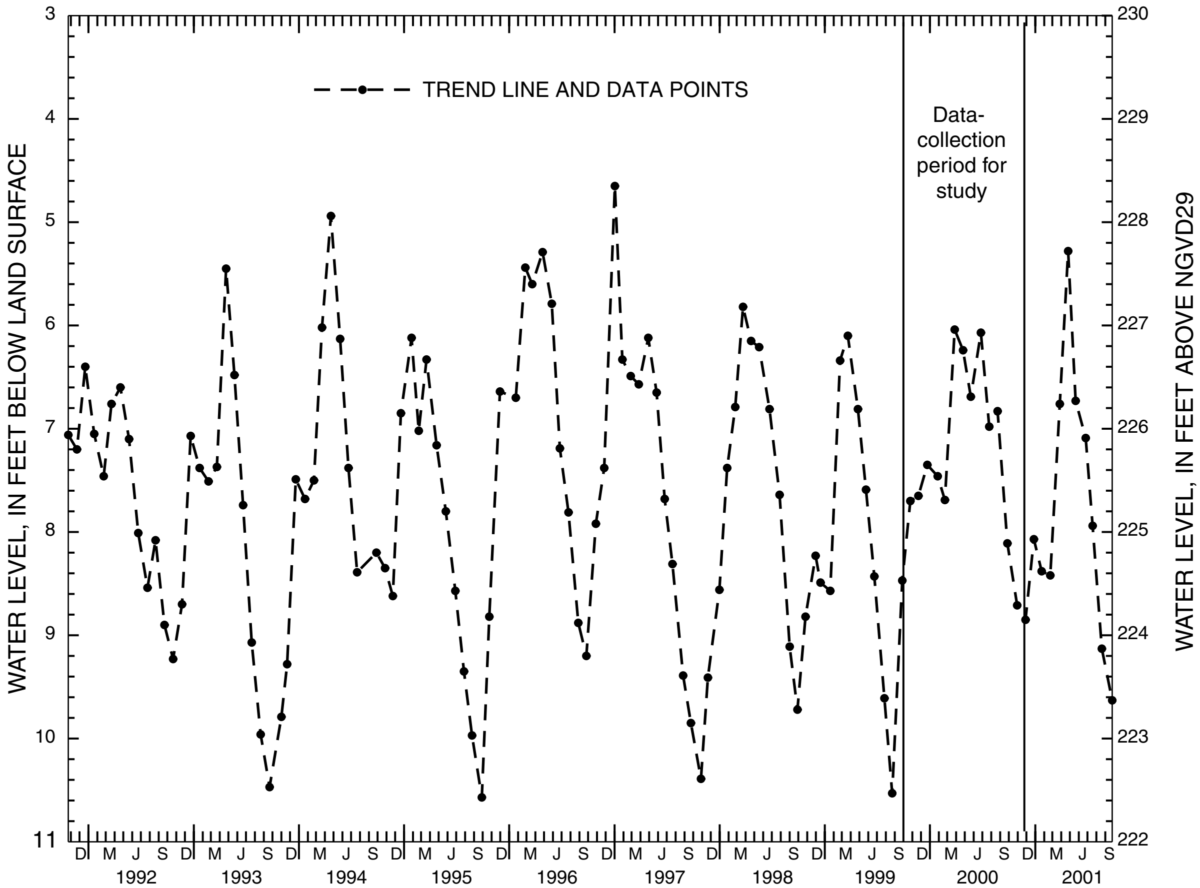


Figure 9. Ground-water levels measured in well GKW-68 in Granby, Massachusetts.

The sluggish relative early response in SUW-53 may be at least partially attributed to borehole storage effects, in which the early drawdown in the pumped well deviates from the ideal response because a real (but finite) amount of water in the well reduces the water-levels declines in, and immediately around, the pumped well. Also, Tighe and Bond (1999, p. 3–6) reported that data from observation wells SUW-51, -52, and -53 may be limited in their use because of the age (approximately 40 years) and suspected deterioration of well screens in these wells. The potential deterioration of the well screens in SUW-51, -52, and -53 is likely the cause of their poor early response, in which they clearly lag behind responses in the newer wells. Early drawdown responses generally extend most rapidly to the north towards SUW-83 and northwest to SUW-84, relative to the response in well SUW-85 (fig. 13).

There appears to be an intermediate time stabilization of the drawdown that is likely caused by vertical drainage from either leaky confining beds above the pumped well, or from the unconfined part of the aquifer southeast of the pumped well (fig. 4, section *B-B′*). Later drawdown responses vary in the observation wells, but generally increase steadily over time (figs. 12, 13). The type of aquifer boundary closest to the well likely affects these later responses (fig. 11). For example, the later increase in drawdown (fig. 13) at SUW-83 is nearly double that in other observation wells. This greater slope in the drawdown curve at later time is likely caused by the truncation of the aquifer near SUW-83 (fig. 4, section *D-D′*), effectively creating a no-flow boundary. In contrast, the slope of the later drawdown curves for SUW-84 and SUW-52 are less than those for either SUW-51 or SUW-85. These decreased drawdown slopes are because of the closer proximity of these wells to the Connecticut River. A close examination of cross sections *A-A′* and *B-B′* (fig. 4, sections *A-A′* and *B-B′*) indicates that the aquifer is hydraulically connected to the Connecticut River west of the Dry Brook supply well either directly (southwest) or through overlying alluvium (west and northwest). The stage of the Connecticut River should not change in response to leakage through the sediments to the supply well because of the large amount of flow in the river relative to the rate of pumping by the well.

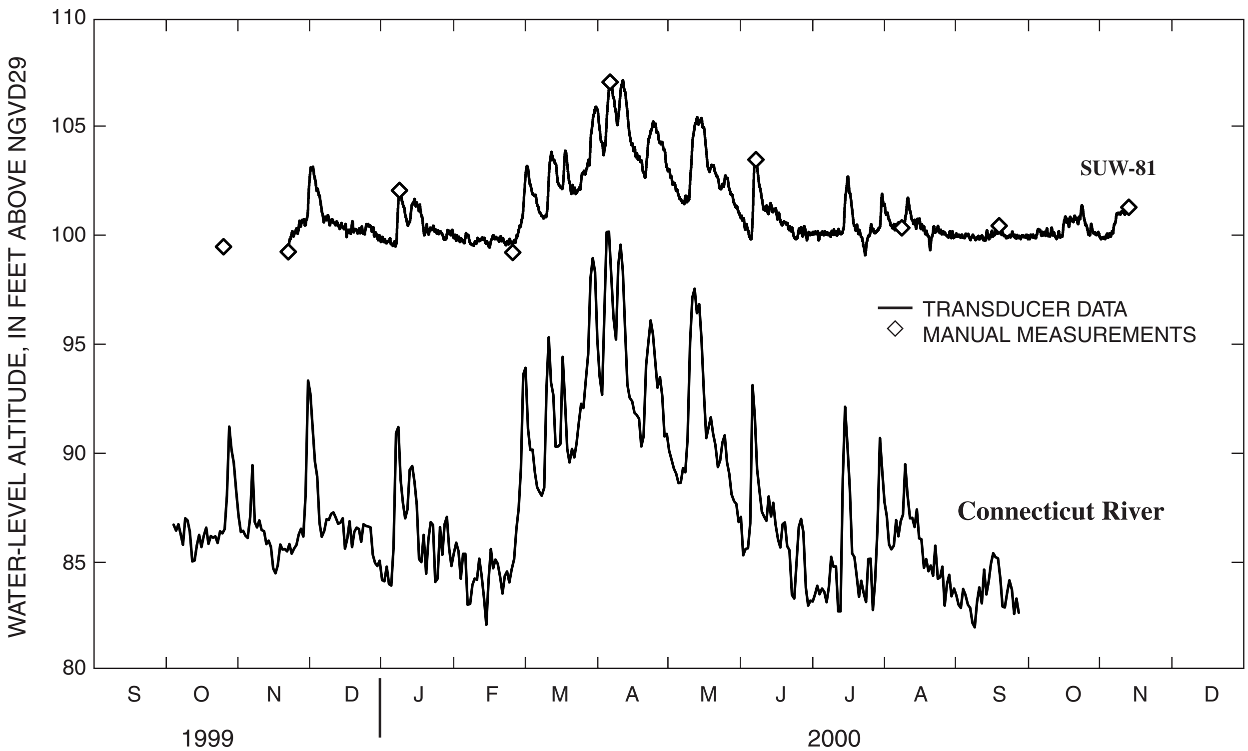


Figure 10. Ground-water levels measured in well SUW-81 compared to the stage of the Connecticut River at Montague, Massachusetts. Connecticut River stage 75 feet above arbitrary datum.

Examination of the drawdown response in well SUW-53 (fig. 13) shows four segments of the curve, each with a different slope. Although the typical unconfined response will involve three segments, early confined, intermediate (vertical) drainage stabilization, and later unconfined (Neuman, 1972), the fourth (last) segment of the drawdown curve for SUW-53 would appear to be due to an aquifer boundary. In this case, because the fourth response segment shows a stabilization of drawdown, a positive (recharge) boundary is indicated. As noted previously, the aquifer is likely hydraulically connected to the Connecticut River, and river water infiltrates the aquifer near the Dry Brook well when it is pumped. River leakage, therefore, stablizes ground-water levels in that part of the aquifer when the well is pumped.

Ground-water levels also responded to Connecticut River stage fluctuations during the aquifer test, similar to that noted for SUW-81 (fig. 10). On a daily basis, upstream hydroelectric dams release water for power generation, creating fluctuations in river stage. These rises in river stage cause a subsequent rise in ground-water levels in the aquifer near the river. For example, the water level in well SUW-84 (fig. 11) rose about 0.2 ft in response to a 1-ft rise in the Connecticut River stage (Tighe and Bond, 1999), about 5,700 minutes after the start of the test (fig. 14). The stage of the Connecticut River was measured near the Dry Brook well during the 10-day aquifer test. In comparison, a muted water-level response of about 0.02 ft to this rise in river stage was recorded in well SUW-51, and the peak response in this well occurred after that in well SUW-84 (fig. 14) because it is further from the river (fig. 11).

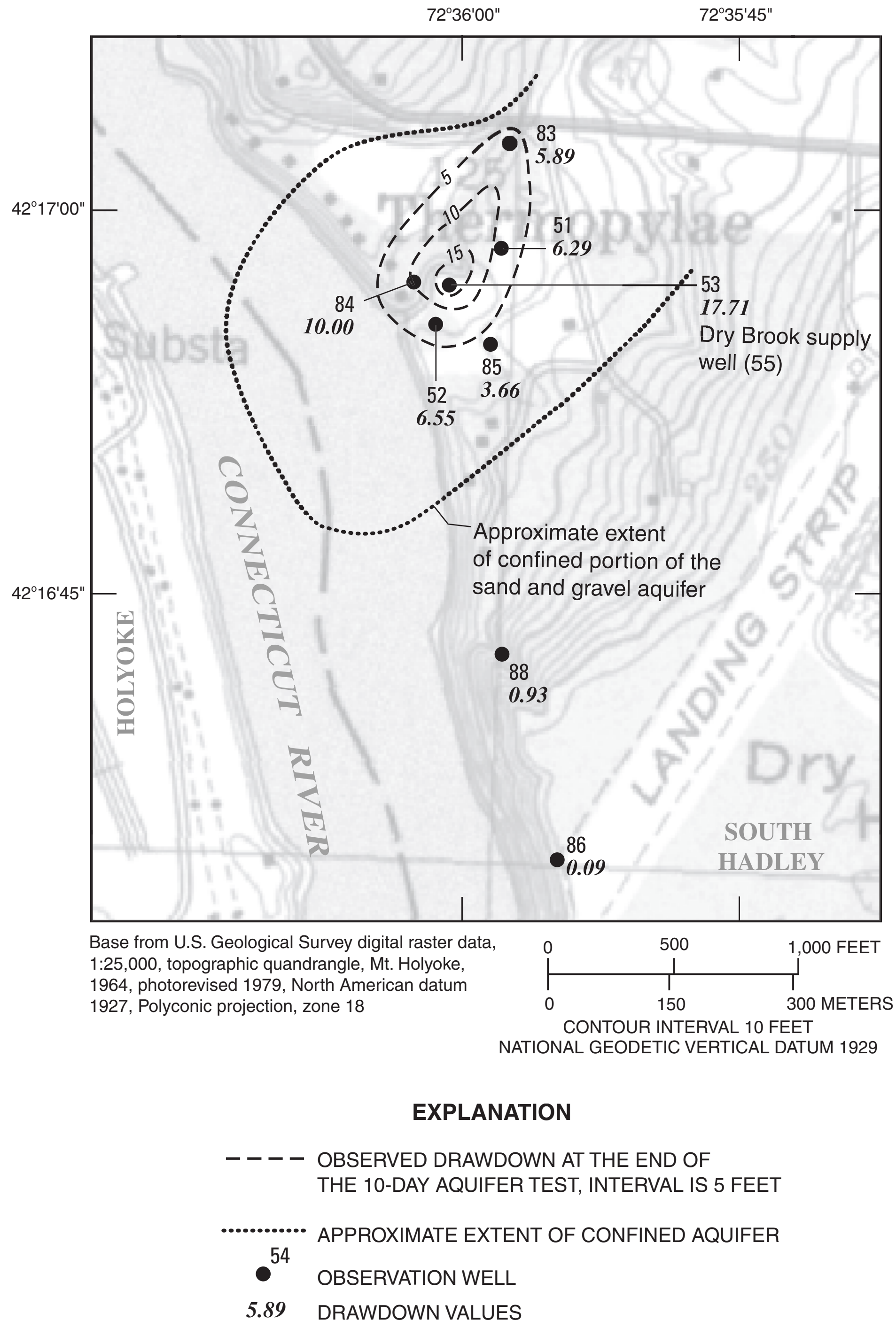


Figure 11. Observation-well network for a 10-day aquifer test of Dry Brook well (September 25, 1998–October 5, 1998), South Hadley, Massachusetts (Tighe and Bond, 1999).

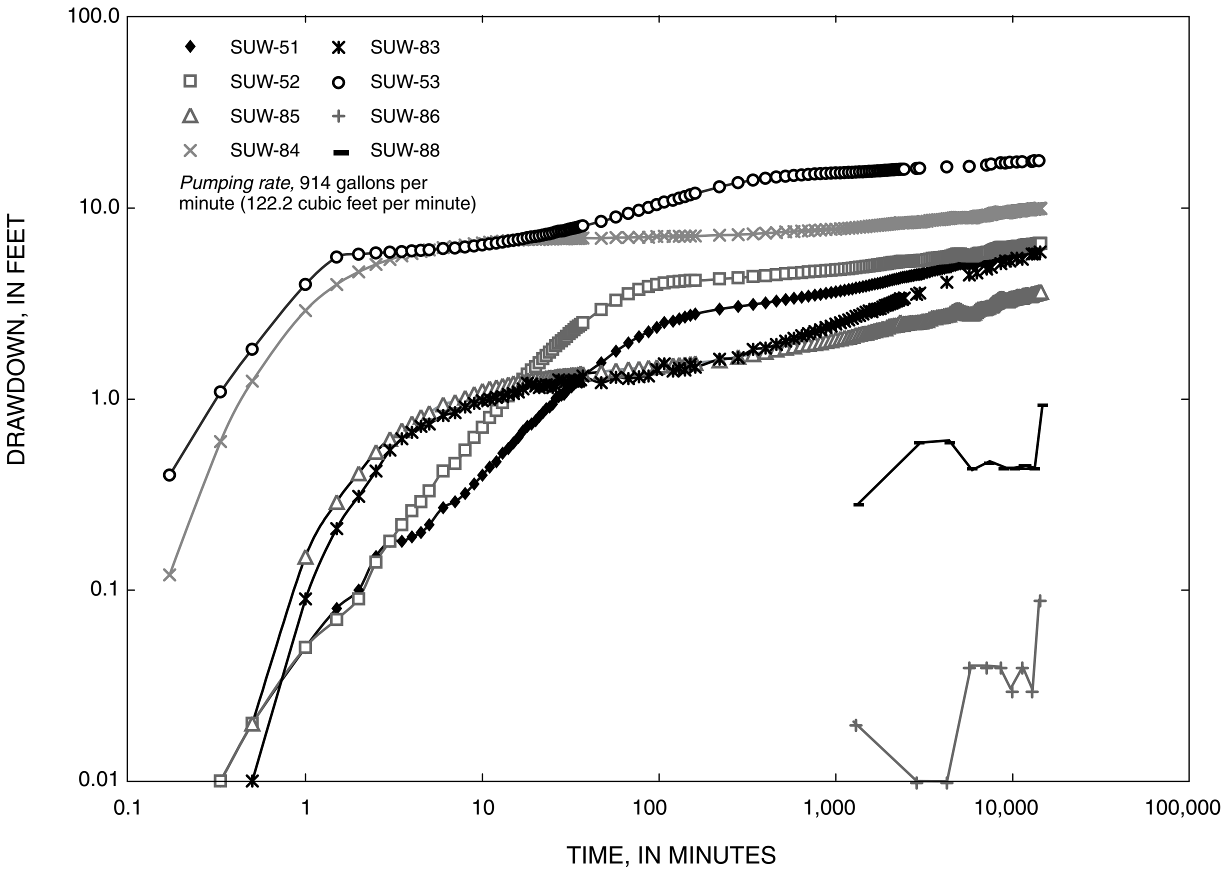


Figure 12. Drawdowns in observation wells during the Dry Brook well 10-day aquifer test (September 25, 1998–October 5, 1998), South Hadley, Massachusetts (Tighe and Bond, 1999).

The difference in time to the peak response at these two wells can be used to estimate the distance to the point where the aquifer is exposed to the river bottom, by applying an equation developed for the analysis of tidal effects on coastal aquifers (Todd, 1980; p. 243–245, eq. 6.17):

$$t_L = x(t_0 S / 4\pi T)^{1/2}, \quad (1)$$

where

t_L is the time lag between a change in river stage and the aquifer response;
x is the distance from river to observation well;
t_0 is the tidal period, the time from peak to peak;
S is the aquifer storage coefficient; and
T is the aquifer transmissivity.

Taking the ratio of lag time for two observation wells creates the following relation:

$$t_{L1} / t_{L2} = x_1 / x_2, \quad (2)$$

in which the numbered subscripts refer to the two different wells. The use of this relation eliminates the need for estimates of aquifer properties or of the tidal period. This approach is based on the assumption, however, that the aquifer properties are constant in the area between the river and the two wells. The time at the peak stage of the Connecticut River was 5,700 minutes, and peak responses at wells SUW-84 and -51 occurred at 5,920 and 6,040 minutes from the beginning of the aquifer test (fig. 14), respectively; therefore, response times were 220 minutes for SUW-84 and 340 minutes for SUW-51.

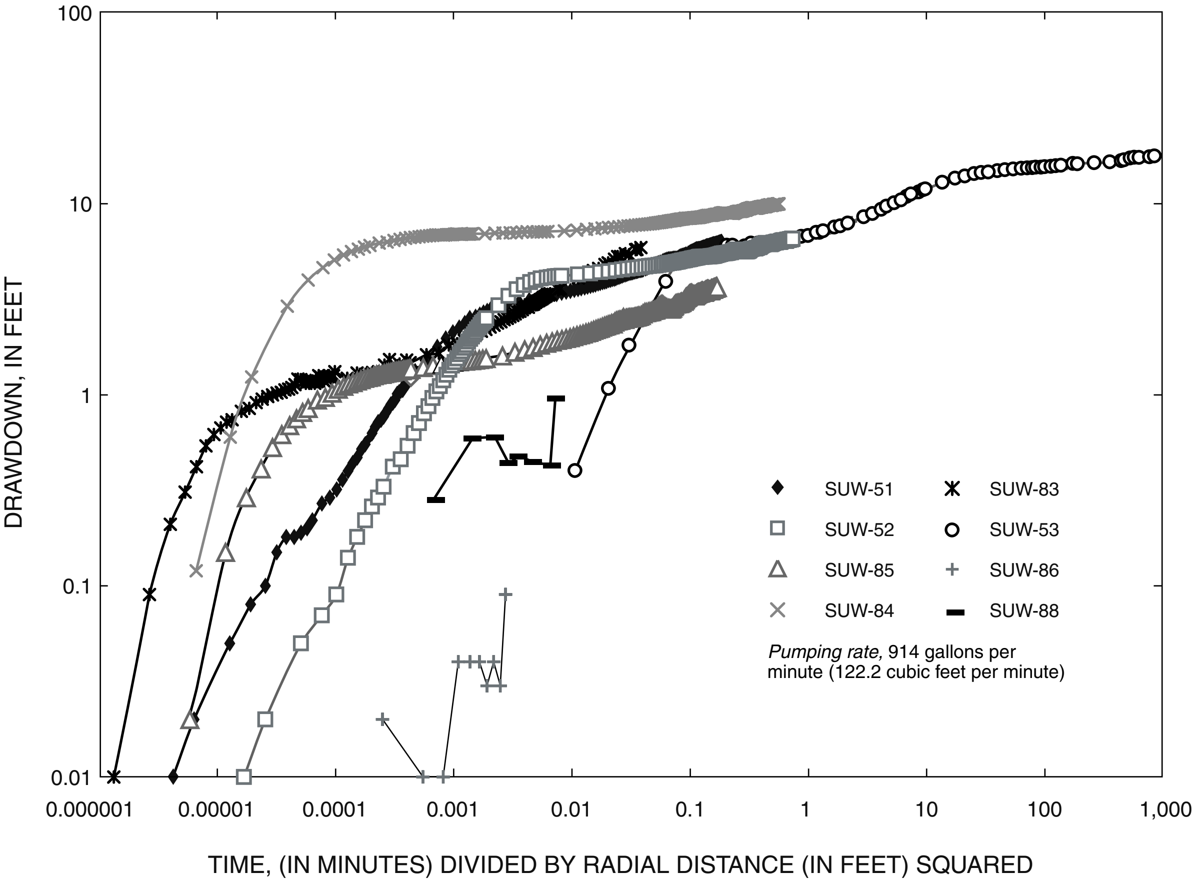


Figure 13. Drawdowns in observation wells during the Dry Brook well 10-day aquifer test (September 25, 1998–October 5, 1998) using relative time scale, South Hadley, Massachusetts.

The distance from the river bank to SUW-51 is 440 ft, and is 80 ft for SUW-84 (fig. 11). The ratio of distances from the river to the wells for SUW-51 to SUW-84 (5.50) is significantly different than the ratio of the lag times (1.55); however, it is likely that this difference is because the aquifer is not exposed to the river at the bank, and there is some distance from the river's edge to where the aquifer is hydraulically connected to the river. This distance (*d*) can be calculated from the ratio of lag times as follows:

$$x_1/x_2 = (440 + d)/(80 + d) = t_{L1}/t_{L2} = 1.55\,, \qquad (3)$$

which, after algebraic manipulation, gives the result that *d* is 575 ft, about two thirds the distance across the Connecticut River at this location. This indicates a hydraulic connection between the Connecticut River and the aquifer that is consistent with the interpretation that the confining bed in the immediate area around Dry Brook well pinches out underneath the river as shown in geologic cross sections *A-A′* and *B-B′* (fig. 4, sections *A-A′* and *B-B′*and fig. 11).

The Dry Brook well aquifer test was conducted at the same time as another aquifer test which used a well on Hockanum Flat in the northernmost part of South Hadley near Russell Cove, north and west of the Dry Brook well (fig. 1). No interference effects were noted at either well during the coincident 10-day aquifer tests. An earlier set of 48-hour aquifer tests conducted separately on Dry Brook and Hockanum Flat wells also indicated no drawdown (interference response) between the well fields, indicating a hydraulic separation between the two areas (Tighe and Bond, 1999). These results indicate either a pinch-out of the aquifer pumped by the Dry Brook well to the northwest because of the bedrock structure or limits of the surficial materials (figs. 3 and 4, section *B-B′*), and (or) a hydraulic connection to the Connecticut River of the aquifer areas with well fields such that declines in water levels in the aquifer(s) are localized around the pumped wells.

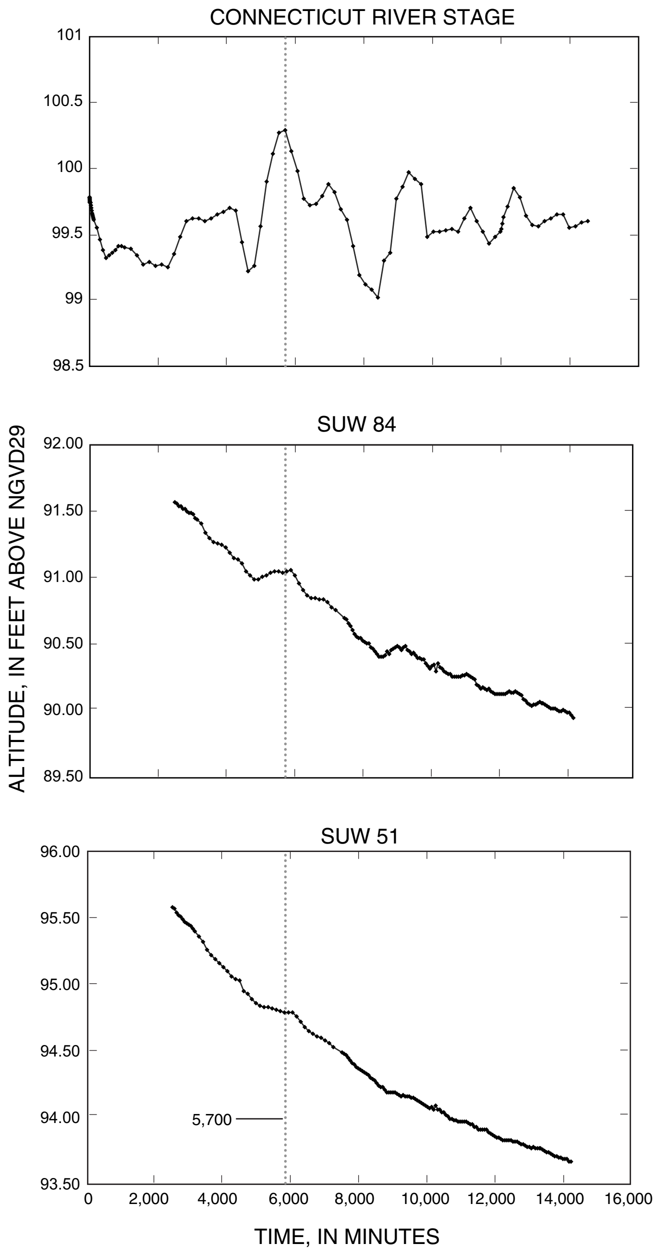


Figure 14. Connecticut River stage compared to water levels measured in observation wells SUW-84 and SUW-51 during the Dry Brook well 10-day aquifer test, South Hadley, Massachusetts.

Simulation of Ground-Water Flow

Ground-water flow in the surficial and bedrock aquifers supplying water to the Dry Brook well was simulated with numerical methods of analysis. Numerical methods have advantages over analytical methods in that boundary and initial conditions, along with aquifer properties, can be varied across the area of interest, increasing the degree to which the models represent the conditions in aquifer systems. The numerical method used in these analyses is the MODFLOW model, a three-dimensional finite-difference simulator documented by McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996).

The approach to analysis included several steps. First, a long-term average flow condition was simulated in the aquifer at the Dry Brook site as a steady-state condition. The result from the steady-state simulation then provided a stable initial condition for the second step, simulation of the Dry Brook aquifer test. These steps were then repeated as calibration of the aquifer properties proceeded, with the goal of improving the degree of representativeness for each set of changes in aquifer conditions made during model calibration. Aquifer properties were changed during model calibration to produce simulated hydrologic conditions similar to those observed in the aquifer under average conditions (steady-state simulations), and to conditions observed during the Dry Brook aquifer test (transient simulations). After steady-state and transient calibration steps were completed, a steady-state version of the model was used to simulate the area contributing water to the Dry Brook supply well.

Model Design and Boundary Conditions

The model grid covers a 7,000-ft-by-7,000-ft area centered on the northwestern edge of Dry Brook Hill (fig. 15). The model area was subdivided into 20-ft (square) cells (or blocks), creating a mesh of 350 blocks on each (horizontal) side; figure 15 shows every fifth block division, or groups of 5×5 blocks. The model has four layers, which for most of the modeled area are composed of surficial sediments in the upper three layers and a bottom layer that represents the Mesozoic-aged bedrock (fig. 16). The upper three layers were simulated as water-table layers, or as convertible layers, which allow a cell in an underlying layer to become a water-table layer if the cell above becomes dewatered (dry). The bottom layer (four), representing fractured Mesozoic-aged bedrock, was assumed to have a fixed transmissivity. Ground water in the Mesozoic-aged bedrock likely flows primarily through fractures, and these fractures were assumed to be continuous enough that an equivalent porous-media approach would provide a good representation and simulation of flow in the bedrock aquifer. For those portions of the simulated area that are underlain solely by bedrock (along Mt. Tom and the Holyoke Range, see figs. 3 and 15), all four model layers are used to represent ground-water flow in the bedrock. The top altitude of each layer was set equal to the bottom altitude of the layer above, and the top of layer 1 was generally set to land surface. These top and bottom surfaces were allowed to vary spatially across the modeled area (fig. 16*A, B*). For example, the upper two layers in the area immediately around the Dry Brook well were used to represent the confining bed composed of varved lacustrine sediments, the third layer was used to represent the sand and gravel aquifer pumped by the Dry Brook supply well, and layer 4 was used to represent the Mesozoic-aged bedrock beneath the aquifer (fig. 16*A*).

Boundary conditions for the model included no-flow boundaries at the bottom of layer 4 and specified ground-water-flow conditions along the perimeter, particularly along the flank of the Holyoke Range north of the Dry Brook well and Mt. Tom Range west of the Connecticut River. Specified flows on the lateral boundary of the model were incorporated into the recharge rate. These flows enter the aquifer at that point of the uppermost active node on the model boundary. Specified ground-water-flow rates were 7.5 ft^3/min along the northern boundary of the model and 9.9 ft^3/min on the western boundary (fig. 15). The flows on the northern boundary of the model were distributed in three zones that include areas west of Dry Brook (3.1 ft^3/min), Dry Brook alluvium (2.6 ft^3/min), and east of Dry Brook (1.8 ft^3/min). These specified ground-water boundary flows are small in comparison to the estimates of median flow for the Dry Brook drainage basin (24 ft^3/min at the model boundary), but are reasonable when the steep mountain slopes and thin soils that limit the infiltration of precipitation are considered. Other model boundaries included specified-head conditions that represent the Connecticut River in layer 1, and river nodes that act as drains (but as not sources of water) along Dry Brook, Elmer Brook, Bachelor Brook, and in a steep gully ascending the northeastern flank of Dry Brook Hill (fig. 15).

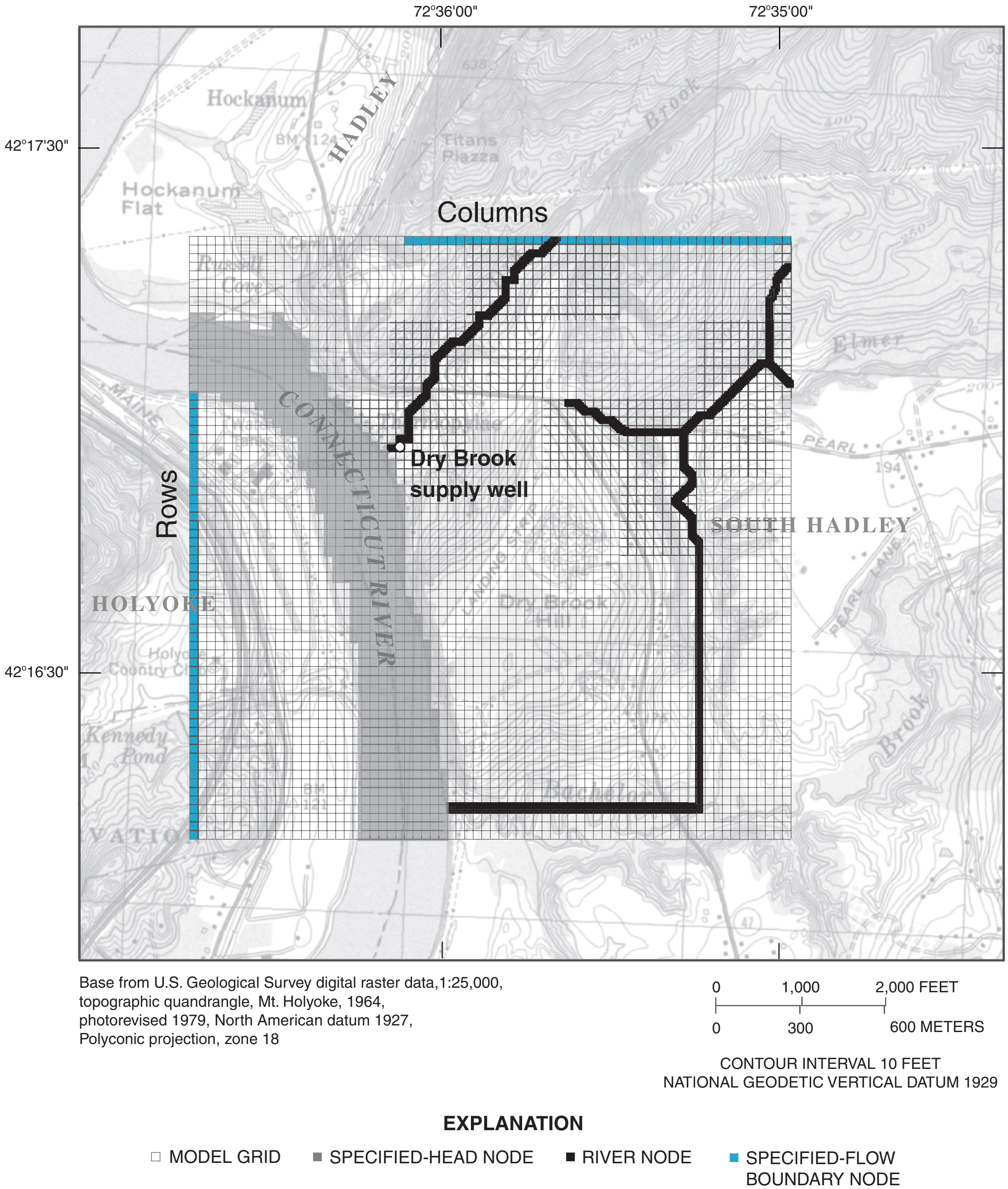


Figure 15. The lateral extent of and boundary conditions for the MODFLOW model grid in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

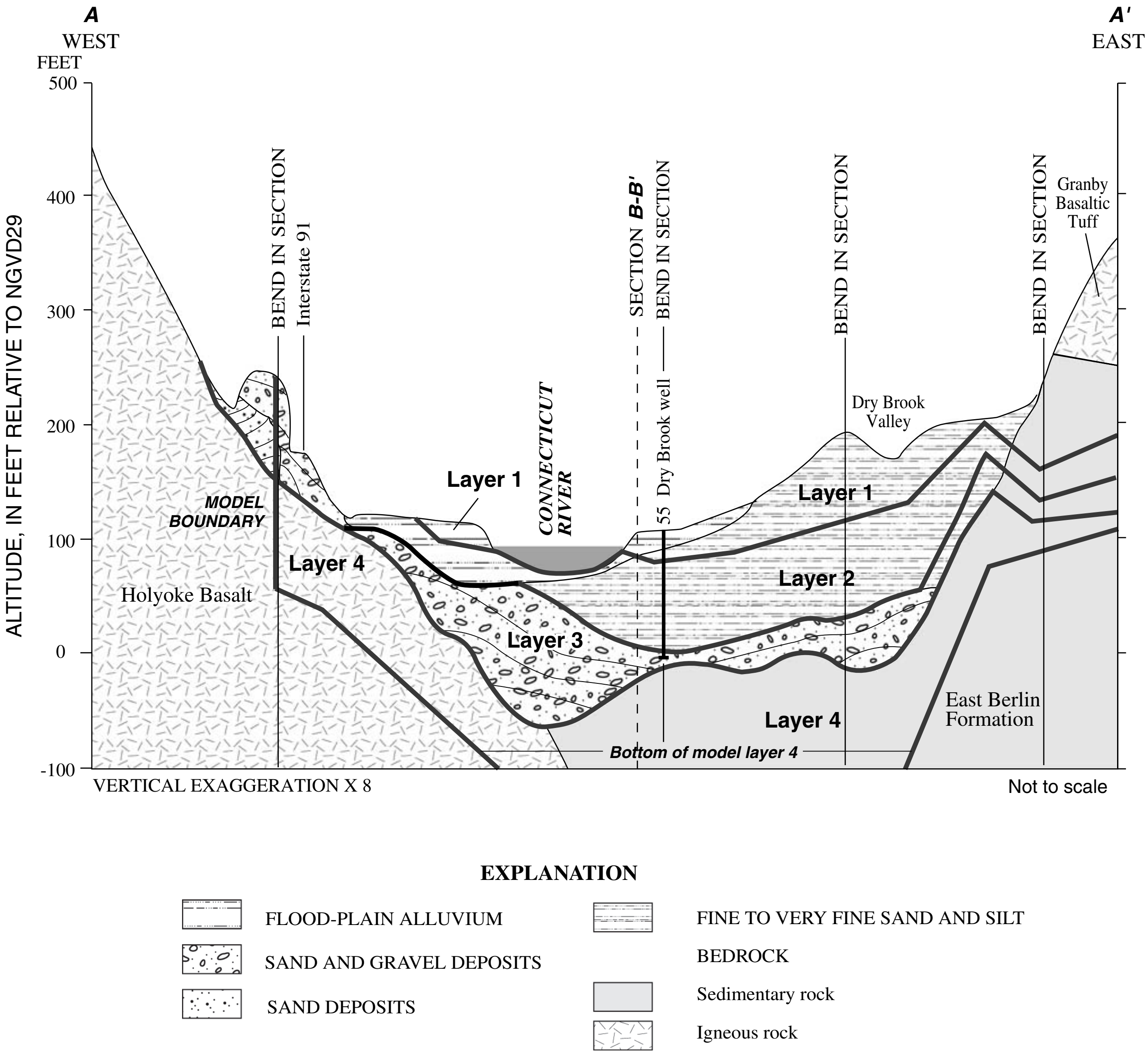


Figure 16. Geologic cross sections showing the vertical distribution of MODFLOW model layers in the Dry Brook study area, Holyoke and South Hadley, Massachusetts.

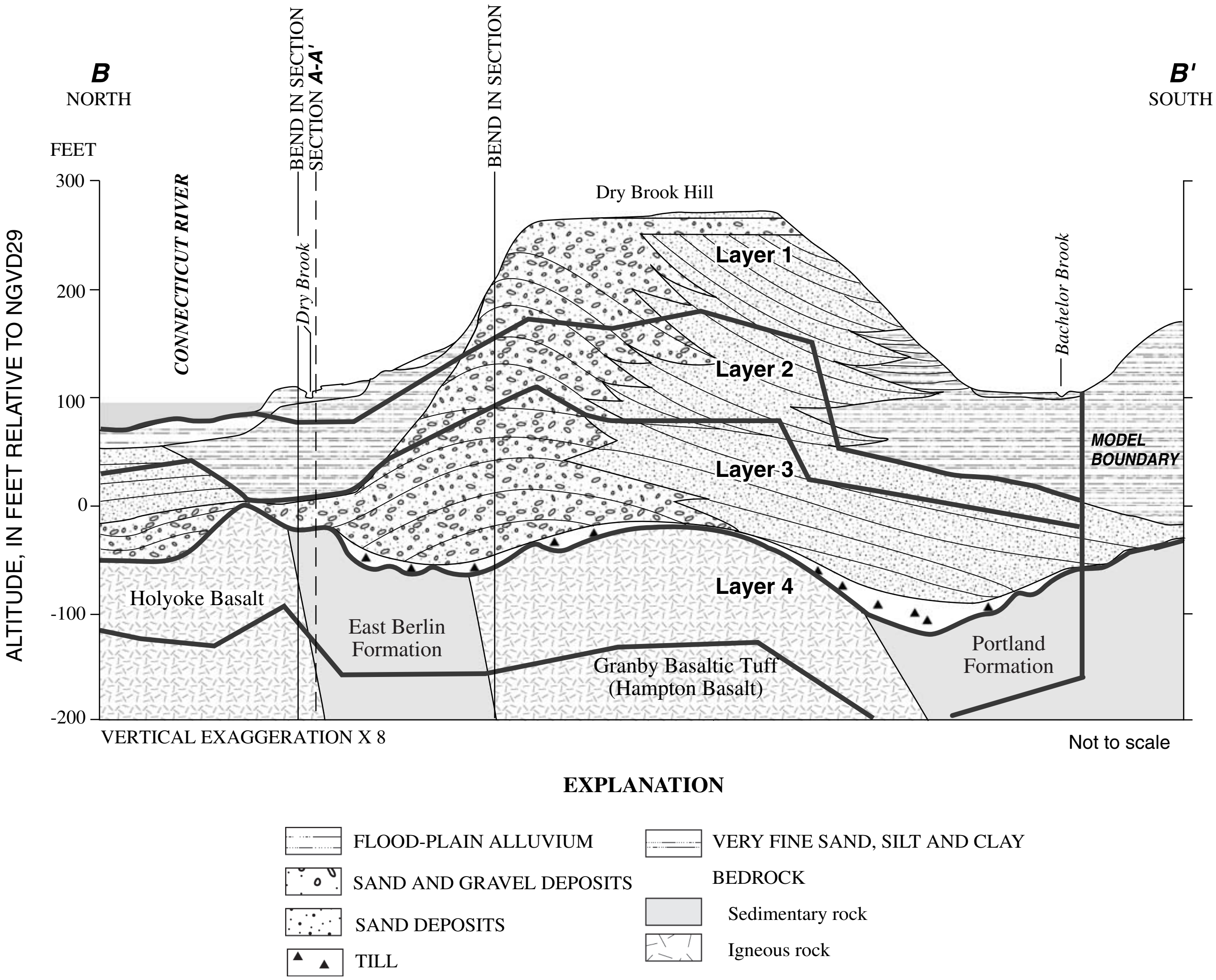


Figure 16. Geologic cross-sections showing the vertical distribution of MODFLOW model layers in the Dry Brook study area, Holyoke and South Hadley, Massachusetts.—Continued

Hydraulic Properties and Recharge Rates

The hydraulic properties of the model were varied horizontally and vertically to represent the surficial sediments and bedrock in the study area (table 4, fig. 3). In general, the largest horizontal hydraulic conductivities (along model layers) were for the sand and gravel aquifer around the Dry Brook well (0.5 ft/min, 720 ft/d). Most of the sand and gravel aquifer was assigned a horizontal hydraulic conductivity of 0.12 ft/min (173 ft/d) to 0.08 ft/min (115 ft/d). The values of horizontal hydraulic conductivity in the aquifer decreased as the sediments became finer to the southeast across Dry Brook Hill (fig. 3) and to the northeast up Dry Brook. The smallest hydraulic conductivity values were for the varved lacustrine silts and clays (1.0×10^{-3} ft/min, 1.4 ft/d), followed by Mesozoic-aged bedrock in the upper three layers (3.0×10^{-3} ft/min, 4.3 ft/d), and by fine sands (2.5×10^{-2} ft/min, 36 ft/d). These rates are similar to those used in a study in Connecticut for an area underlain by Mesozoic-aged bedrock and glacial sediments (Starn and others, 2000). The transmissivity value used for layer 4 varied as the thickness changed across the modeled area (fig. 16), but was relatively uniform under the surficial sediments (0.3 ft^2/min, 432 ft^2/d) because the thickness of the active-flow zone in the Mesozoic-aged bedrock aquifer was assumed to be 100 ft. The largest transmissivities were in layer 3 (the pumped zone); these values were about 18 ft^2/min (26,000 ft^2/d) immediately around the Dry Brook well, but typically ranged from less than 1 to greater than 9 ft^2/min (1,000–13,000 ft^2/d) in the area a few hundred feet around the well. Variations in aquifer thickness and hydraulic conductivity cause the variability of layer 3 transmissivity, which agrees well with previously determined values for this aquifer (Saines, 1973; Delude, 1995).

Table 4. Aquifer properties and recharge rates for the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

[Sediment or rock type: See figure 3. ft, foot; ft/min, foot per minute, in/yr, inch per year]

Sediment or rock type	Horizontal hydraulic conductivity (ft/min)	Vertical hydraulic conductivity (ft/min)	Ratio of vertical to horizontal hydraulic conductivity	Recharge rate (in/yr)
Mesozoic bedrock	3.0×10^{-3}	3.0×10^{-4}	0.1	12
Alluvium	8.0×10^{-2}	2.0×10^{-2}	0.25	[2]12, 24
Sand and gravel[1]	0.5, 1.2×10^{-1}	3.0×10^{-2}	0.25	24
Sand	8.0×10^{-2}	2.0×10^{-2}	0.25	24
Fines (fine sand to silt) [3]	2.0×10^{-2}, 2.5×10^{-2}	1.0×10^{-3}, 2.5×10^{-3}	0.05, 0.1	12
Varves (very fine sand to clay)	1.0×10^{-3}	1.0×10^{-5}	0.01	6

[1]The horizontal hydraulic conductivity for 30 ft around Dry Brook well was set to 0.5 ft/min.; for all other sand and gravel sediment, the horizontal hydraulic conductivity was set to 1.2×10^{-1} ft/min.

[2]The recharge rate for alluvium along Elmer and Dry Brooks was set to 12 in/yr; the rate for all other alluvium was set to 24 in/yr.

[3]The horizontal hydraulic conductivity in an area of fine sediment north of Dry Brook well was set to $2.0\text{x}10^{-2}$ ft/min, the vertical hydraulic conductivity in this area was set to 1.0×10^{-3} ft/min, so that the ratio of vertical to horizontal hydraulic conductivity was 0.05. The horizontal hydraulic conductivity of all other areas of fine sediment was set to 2.5×10^{-2} ft/min, the vertical hydraulic conductivity was set to 2.5×10^{-3} ft/min, and the ratio of vertical to horizontal hydraulic conductivity was 0.01.

The largest value of vertical hydraulic conductivity used in the model was for the sand and gravel at 3.0×10^{-2} ft/min (table 4). This value produced an average vertical to horizontal hydraulic conductivity anisotropy ratio of 0.25 for this sediment type. The smallest values of vertical hydraulic conductivity used in the model were those for vertical flow through the varved lacustrine sediments (1.0×10^{-5} ft/min); intermediate values were used for vertical flow in the Mesozoic-aged bedrock (3.0×10^{-4} ft/min) and for vertical flow in the fine sand and silty sediments (2.5×10^{-3} ft/min). The vertical to horizontal hydraulic conductivity anisotropy ratios ranged from 0.01 to 0.25 for these sediments and rock types (table 4). Vertical conductances for flow between model layers were calculated (external from the model) by using the vertical hydraulic conductivities for the two adjacent layers decribed previously, half the adjacent layer thicknesses, and the equation for the harmonic mean (McDonald and Harbaugh, 1988, section 5). Streambed leakances were set to a uniform value of 10 ft/min/ft for Dry Brook, Elmer Brook (and tributaries), and Bachelor Brook. Storage coefficients were varied across the study area from 0.25 in areas of unconfined conditions to 1.0×10^{-4} for confined conditions in the upper two layers. The storage coefficients used for the sand and gravel aquifer and the fine-grained sediments in layer 3 were 3.0×10^{-4} and 3.0×10^{-5}, respectively. The storage coefficient used for the bedrock aquifer in layer 4 was set to 1.0×10^{-5}.

A spatially varying recharge rate was applied across the modeled area: 24 in/yr (3.8×10^{-6} ft/min) in areas underlain by sand, 12 in/yr (1.9×10^{-6} ft/min) in areas underlain by Mesozoic-aged bedrock and fine-grained sediments (fine sand and silt), and 6 in/yr (9.5×10^{-7} ft/min) in areas underlain by lacustrine (varved) silts and clays (fig. 3, table 4). These recharge rates are similar to those used in a study in Connecticut for an area underlain by Mesozoic-aged bedrock and glacial sediments (Starn and others, 2000). The option of recharge entering the highest active cell at any given location was used to ensure that recharge continued to enter the simulated aquifer even if overlying model cells became dry and inactive.

Pumping Stresses

Pumping in the simulations was limited to the Dry Brook well, in layer 3 of the model. Pumping rates for the Dry Brook well were specified as either zero, 40.0 ft^3/min (299 gal/min), or 122.2 ft^3/min (914 gal/min). These rates correspond to a pre-aquifer test condition (zero), the average pumping rate for water supply during the year 2000 (Mr. William Selkirk, South Hadley Fire District No. 2, written commun., 2002), and an average pumping rate during the aquifer test. Although there are several rural water-supply wells for homes in the study area, the amount of pumpage by these wells would be expected to be small (less than 1 gal/min on a sustained 24-hour basis), and most of the water would be returned to the ground through on-lot septic systems. For these reasons, the pumpage by these wells was not included as part of the aquifer simulation.

Model Calibration

The Dry Brook aquifer model was calibrated with information from the 10-day aquifer test (Tighe and Bond, 1999) by adjusting model parameters (hydraulic conductivity and storage coefficients) until a reasonable match to the aquifer-test results was achieved (fig. 17). The aquifer test was simulated by using two stress periods, an initial period of 10 days in which the Dry Brook well was not pumped, and a second period of 10 days in which the well was pumped at a constant rate of 122.2 ft^3/min (914 gal/min). Simulated and observed drawdown at the end of the 10-day aquifer test were compared (table 5). The differences between simulated and observed drawdowns at the end of the aquifer test were 1 ft or less for all but one of the wells shown in figure 17. Some of these differences were positive and others were negative. The average difference is 0.21 ft, and the average of the absolute values of these differences is 0.67 ft. As was noted, observed early drawdowns were likely less than simulated drawdowns for the older wells, SUW-51, -52, and -53 (fig. 17), because corroded well screens prevented these wells from rapidly responding to changing head conditions in the aquifer.

A comparison of observed and simulated drawdowns at the end of the 10-day aquifer test for the Dry Brook well (table 5), when plotted in relation to radial distance, is shown in figure 18. The relative sequence of observed drawdowns (from largest to smallest–SUW-53, SUW-84, SUW-52, SUW-51, SUW-83, SUW-85, SUW-88, SUW-86) is similar to the sequence of simulated drawdowns (SUW-53, SUW-84, SUW-52, SUW-51, SUW-85, SUW-83, SUW-88, SUW-86). For the ideal case of uniform aquifer hydraulic properties, along with boundary and confining conditions, drawdowns are expected to decrease with increased radial distance. As stated previously, however, the magnitudes of the observed drawdowns do not uniformly decrease with radial distance from the pumped well. Drawdown at wells SUW-84 and SUW-52 are significantly different, even though these wells are at the same radial distance from the pumped well; the same is true for wells SUW-51 and SUW-85, (fig. 18). The transmissivity value calculated by using the trend line in figure 18 and the distance-drawdown method of analysis (Fetter, 2001) is 6.4 ft^2/min, which is similar to the values used in this and previous studies. The storage coefficient calculated by using this method is 0.04, a value that is low for an unconfined system and high for a confined system, indicative of the partially confined condition of the sand and gravel aquifer pumped by the Dry Brook well.

The largest difference between simulated and observed drawdowns is for observation well SUW-83, located 600 ft from the pumped well and farthest from the river of all observation wells. In addition, wells north and west of the pumped well (SUW-83 and SUW-84) had observed drawdowns that plot above the trend line, whereas the wells south and east of the pumped well (SUW-52, SUW-85) had drawdowns that plot below this trend line (fig. 18). The calibrated model reasonably simulates the drawdown variations, as shown in figure 18, and simulated drawdowns generally cluster near the observed drawdowns but are closer to the overall trend line than the observed drawdowns. The conclusion that can be drawn, therefore, is that these deviations in drawdowns from the ideal case are most likely caused by spatially varying boundary conditions, hydraulic properties, and confining conditions for the aquifer.

In addition to simulating the aquifer test, steady-state model simulations were conducted by using the average pumping rate for the Dry Brook well during the year 2000, 40.0 ft^3/min (299 gal/min) and the results were compared to ground-water levels obtained over the period of data collection. Ground-water-level contours from steady-state model simulations are shown in figure 19, and a comparison of observed and simulated water levels is shown in table 6. These results are based on a steady-state simulation that has a different constant-stage condition for the Connecticut River than that used for the 10-day aquifer test. The Connecticut River stage near the Dry Brook well during the 10-day aquifer test was about 99.5 ft above NGVD29 (fig. 14), whereas it was estimated that the average Connecticut River stage was 101.25 ft above NGVD29 during the data-collection period. This latter value was used as the constant head for the Connecticut River during steady-state simulations for comparison to ground-water-level values collected during the study, and was assumed to be close to the average boundary condition for the Dry Brook aquifer.

A comparison of ground-water levels indicates that the simulated steady-state water levels were, on average, within half a foot of the observed water levels, and that the majority of the simulated water levels at the observation wells were within the range of the water levels observed in these wells (table 6). The average difference between the observed ground-water levels and simulated ground-water levels is 0.36 ft, and the average of the absolute values of these differences is 1.22 ft. The ground-water levels measured on November 16, 2000, were compared to the simulated ground-water levels because the observed ground-water levels were collected at a time when the water-level conditions observed in SUW-81 were closest to their average for the study period (fig. 10). Ground-water levels in SUW-81 ranged over 7 ft during the study period because of seasonal changes in recharge and and the effect of stage changes in the Connecticut River.

The ground-water-level contours for model layers 3 and 4 are shown in figure 19; however, in some locations layer 3 was dry (for example, in the northeast portion of Dry Brook Hill) and layer 4 was the only active layer. These contours show that ground water generally moves from topographically higher areas to discharge at the Connecticut River, and the contours also show the effect of ground-water pumping at the Dry Brook well on the overall flow pattern and local head distribution. The effect of the plunging ridges of bedrock (figs. 3 and 4) can also be observed in the higher ground-water levels north and east of Dry Brook. The ground-water gradients become much less steep southwest of the Dry Brook well across Dry Brook Hill as the sediments become thicker and more permeable.

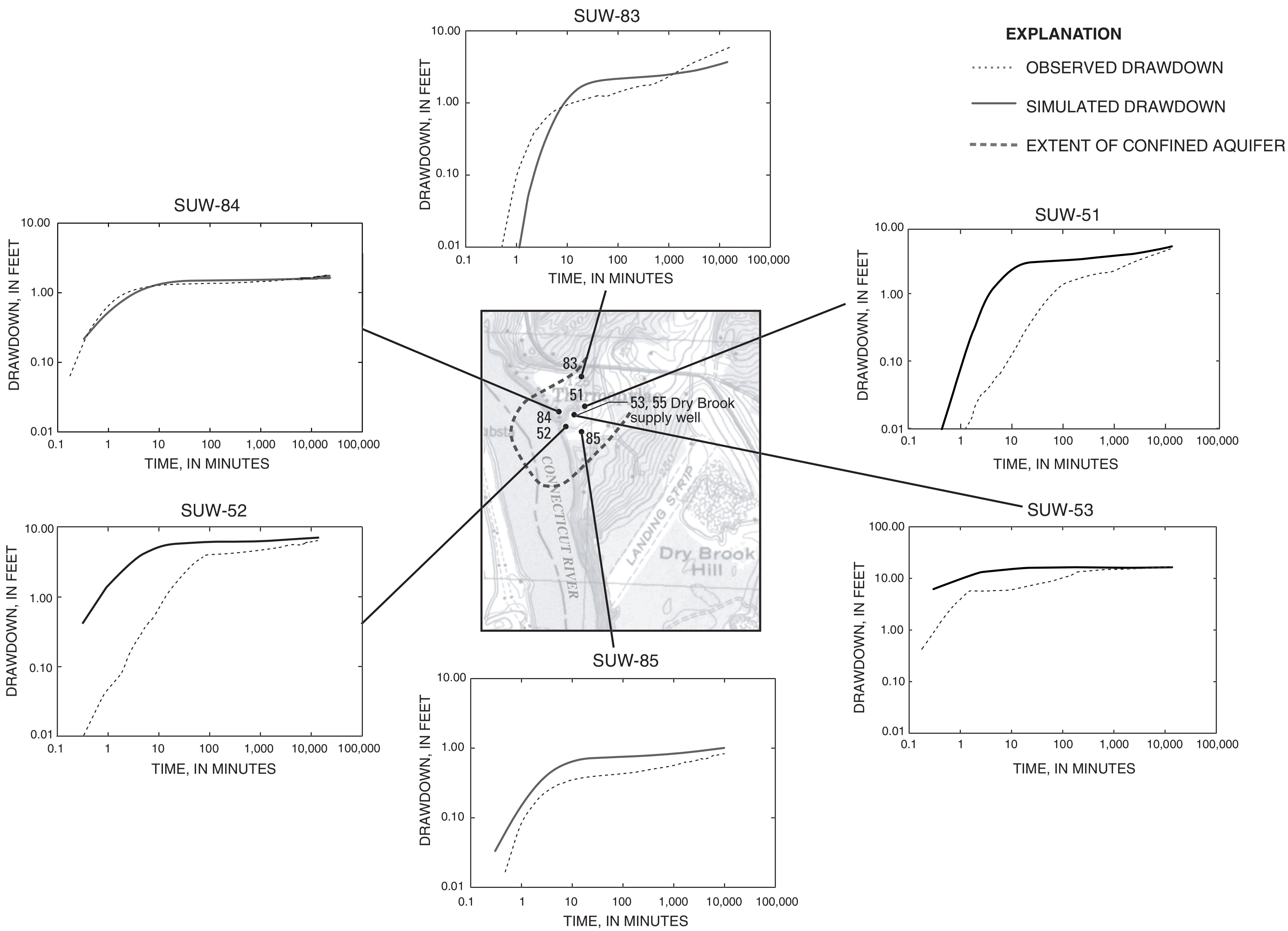


Figure 17. Model-calibration results comparing observed and simulated drawdown at observation wells during the Dry Brook well 10-Day aquifer test, South Hadley, Massachusetts.

Table 5. Comparison of observed to simulated drawdowns at the end of the 10-day Dry Brook well aquifer test (September 25, 1998–October 5, 1998), South Hadley, Massachusetts.

[**Radial distance:** Distance in feet from the Dry Brook Well, as reported by Tighe and Bond, 1999. USGS, U.S. Geological Survey; ft, foot]

Local well number	USGS well number (SUW)	Radial distance (ft)	Observed drawdown (ft)	Simulated drawdown (ft)	Difference between observed and simulated (ft)
TW11-60	51	300	6.29	6.17	0.12
TW13-60	52	150	6.55	7.17	-.62
2 inch (TW10-60)	53	2	17.71	17.87	-.16
TW9-97 (P9)	83	600	5.89	3.70	2.19
TW7-97 (P7)	84	150	10.00	9.05	.95
TW6-97 (P6)	85	300	3.66	4.71	-1.05
P-2	86	2,300	.09	.08	.01
P-4A (TW-4A)	88	1,400	.93	.70	.23
		Average			0.21
		Average of absolute values			0.67

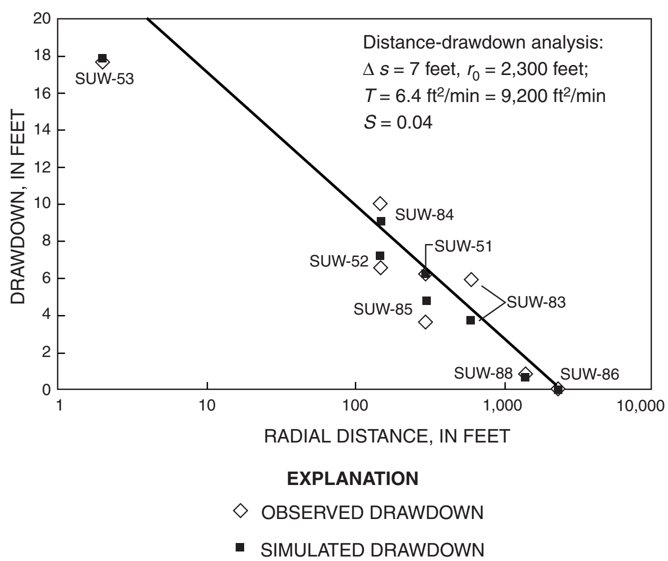


Figure 18. Observed and simulated drawdowns at the end of the Dry Brook well 10-day aquifer test in relation to radial distance from the well, South Hadley, Massachusetts. Δs is the change in drawdown over one logarithmic interval of radial distance; r_0 is the intercept of radial distance, at zero drawdown; T is the aquifer transmissivity; and S is the aquifer storage coefficient.

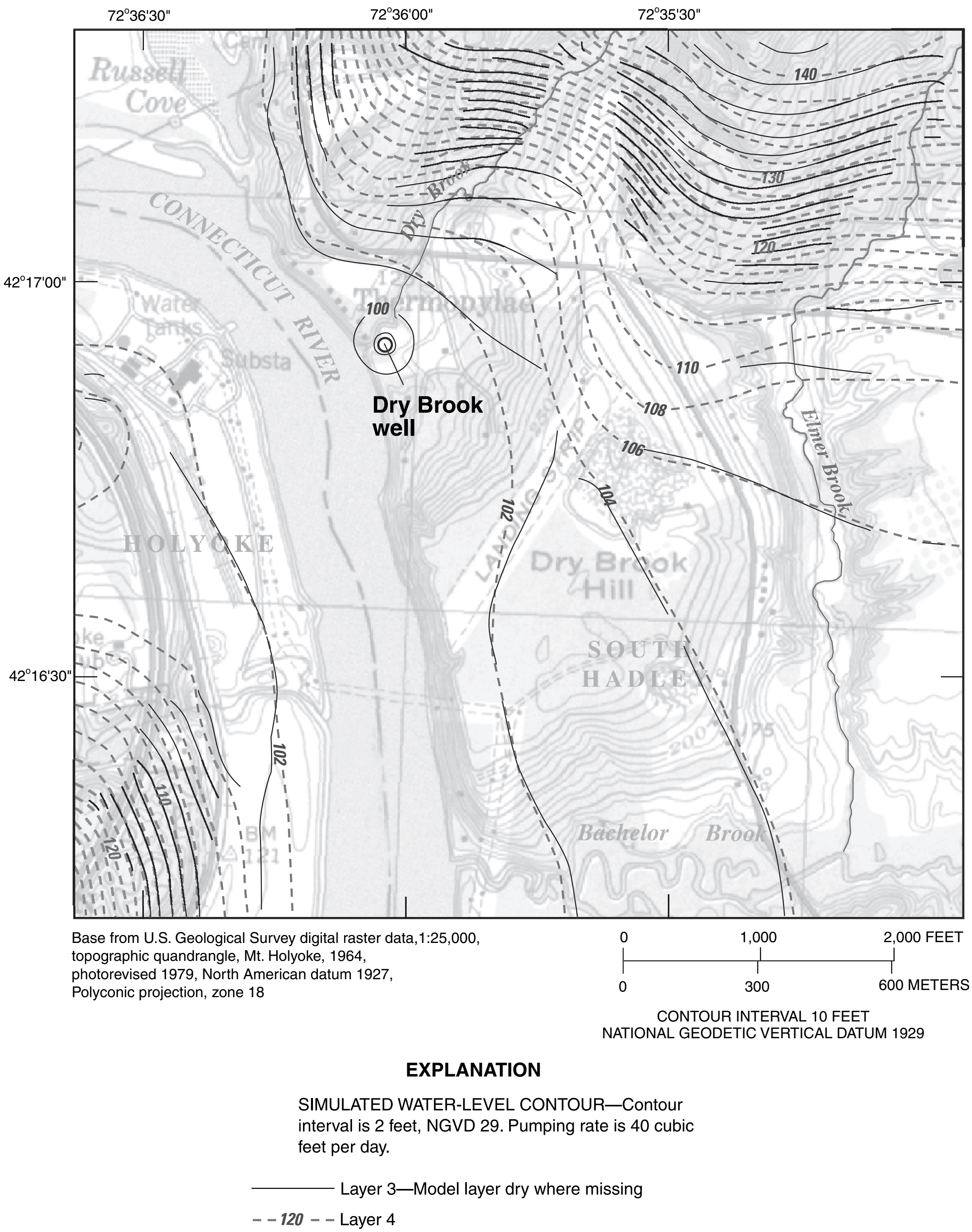


Figure 19. Steady-state simulated water-level contours for layers 3 and 4 at a pumping rate of 40.0 cubic feet per minute in the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts.

Table 6. Comparison of observed to steady-state simulated ground-water levels under an average pumping rate of 40.0 cubic feet per minute, Dry Brook study area, South Hadley, Massachusetts.

[**Range of observed water levels:** Measured water levels shown in table 3. USGS, U.S. Geological Survey; ft, foot; --, not measured]

Local well number	USGS well number (SUW)	Range of observed water levels	Observed water levels on 11-16-2000 (ft)	Steady-state simulated water levels (ft)	Difference between observed and simulated water levels (ft)
TW11-60	51	97.24	--	100.38	--
TW13-60	52	95.06	--	99.48	--
TW14-82	69	103.21–105.25	103.87	[1]105.18	-1.31
TW15-82	70	105.02–107.19	105.60	[1]105.64	-.04
TW1-95	73	101.25–104.23	101.83	[1]101.77	.06
TW2-95	74	101.60–105.63	102.90	[1]101.71	1.19
TW3-95	81	99.25–107.07	101.30	[1]101.61	-.31
TW9-97 (P9)	83	97.94–104.61	99.81	[1]101.89	-2.08
TW6-97 (P6)	85	97.77–105.85	100.66	[1]100.48	.18
P-2	86	102.28–105.84	102.64	[1]101.53	1.11
P-3	87	102.39–104.86	103.38	102.25	1.13
P-5	89	107.51–108.71	108.17	103.47	4.70
P-8	90	101.87–105.18	102.97	[1]101.87	1.10
P-1	93	101.50–105.70	--	[1]101.70	--
P-4B	94	97.86–106.40	100.14	[1]101.53	-1.39
		Average			0.36
		Average of absolute values			1.22

[1]Within range of observed water levels.

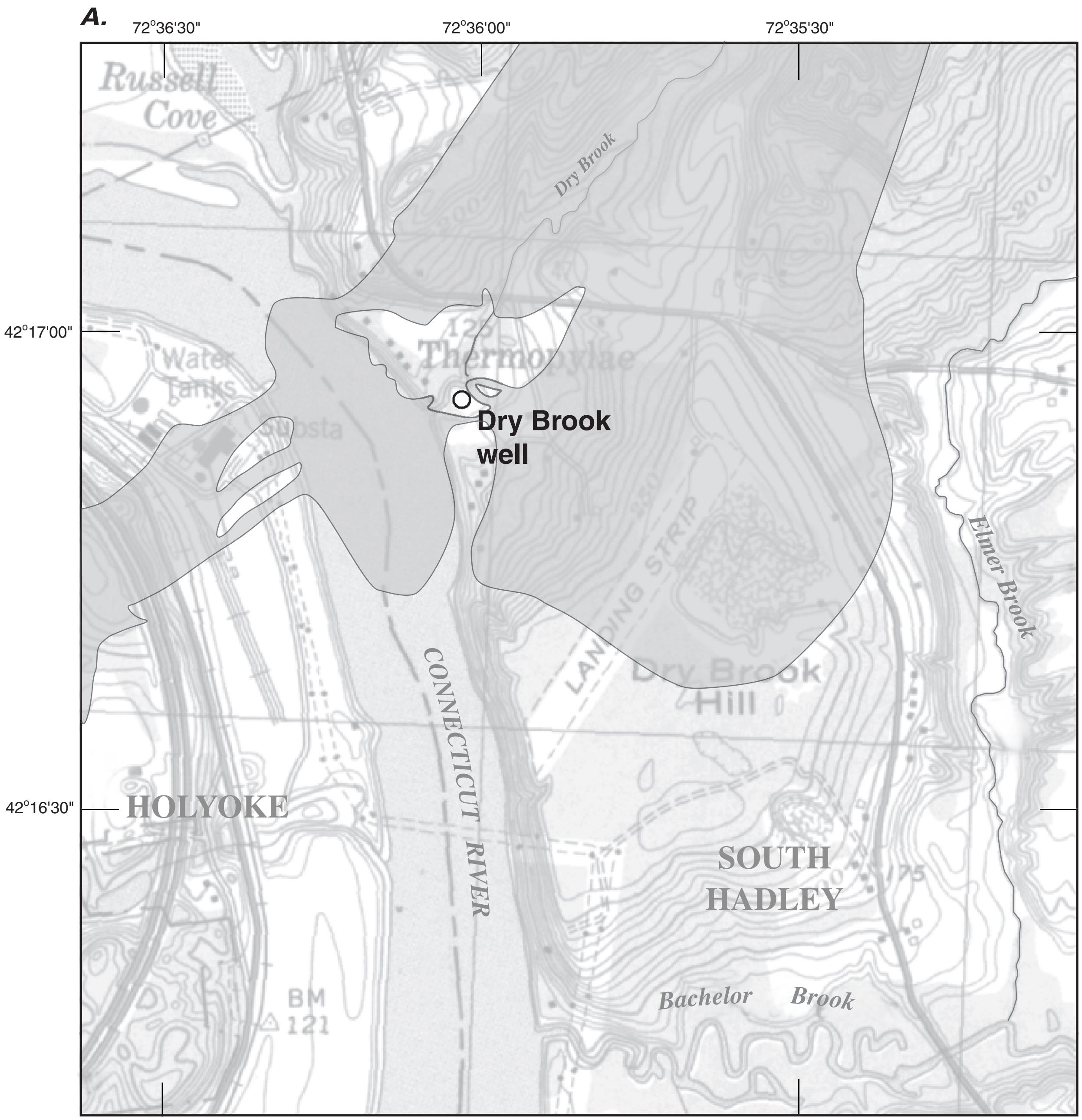
The ground-water-level contours indicate vertical head differences between layers 3 and 4 immediately around the Dry Brook well caused by sustained pumping at the well (fig. 19). Other locations with vertical head differences are east and southeast of the Dry Brook well, where 2- to 4-ft differences indicate upward flow from layer 4 to layer 3, the layer that was pumped (fig. 19). Simulated ground-water levels above stream stage indicate that ground water discharges to the lower ends of Dry Brook and Bachelor Brook, and to the Connecticut River. The close agreement of observed to simulated heads, along with the flow directions that are hydrologically reasonable, support the conclusion that the model as calibrated is a reasonable representation of the ground-water-flow system in the Dry Brook study area.

Delineation of Areas Contributing Water to Dry Brook Well

Areas contributing water to the Dry Brook public-supply well were delineated by using the calibrated steady-state ground-water-flow model with the MODPATH particle-tracking routine and the MODPLOT graphical routine available for the MODFLOW model (Pollock, 1994). For this application, the area contributing water to the Dry Brook well is defined as the surface area where water that eventually flows to the well enters the ground-water system (Reilly and Pollock, 1993; Franke and others, 1998; U.S. Geological Survey, 2003, Office of Ground Water Technical Memorandum No. 2003.02). Areas contributing water to the Dry Brook well were delineated by using the average rate of pumping in 2000 (40.0 ft^3/min, 299 gal/min) and the MDEP-approved yield (122.2 ft^3/min, 914 gal/min; Joseph Cerutti, Massachusetts Department of Environmental Protection, written commun., 2000) (fig. 20). The MDEP-approved yield is about three times greater than the average rate of pumping in 2000. The maps (fig. 20*A*, *B*) show the distribution of starting positions for model-simulated particles entering the ground-water system as recharge or boundary flow that were forward-tracked through the aquifer, and that leave the system through pumping from the Dry Brook well. These particles are simulated points that travel along flow paths in the ground-water system as determined by the three-dimensional MODFLOW model of the ground-water system in the area of the Dry Brook well.

A comparison of the water budgets for these two simulations is shown in table 7. The two sources of water flow to the supply well include water originating as either recharge and boundary flow, or infiltration from the Connecticut River.

A.



Base from U.S. Geological Survey digital raster data,1:25,000, topographic quandrangle, Mt. Holyoke, 1964, photorevised 1979, North American datum 1927, Polyconic projection, zone 18

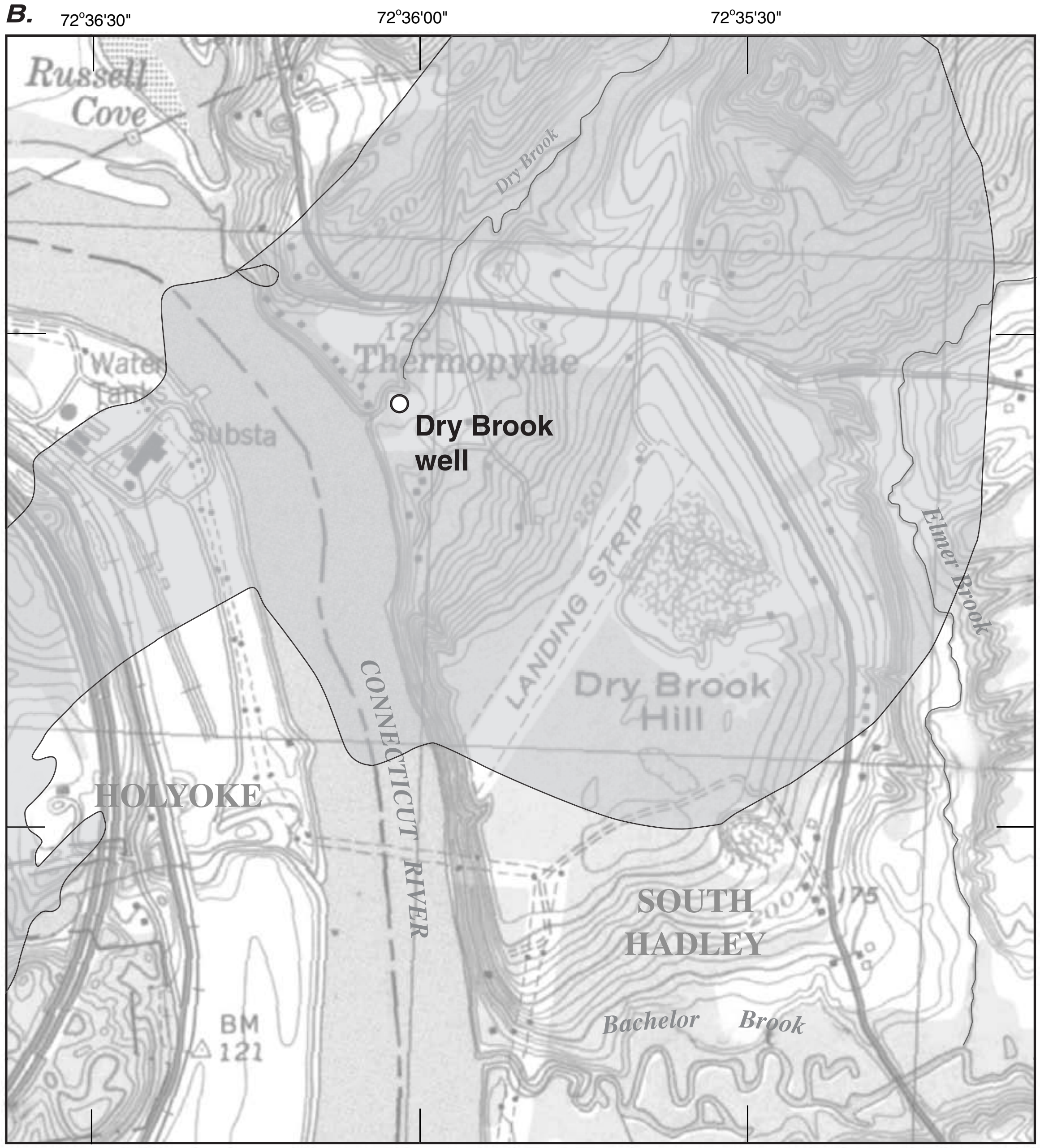
0 1,000 2,000 FEET
0 300 600 METERS

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM 1929

EXPLANATION

SIMULATED AREA CONTRIBUTING WATER TO DRY BROOK WELL AT PUMPING RATE OF 40.0 CUBIC FEET PER MINUTE (299 GALLONS PER MINUTE)

Figure 20. Extent of the simulated area contributing water to the Dry Brook well at pumping rates of *A*, 40.0; and *B*, 122.2 cubic feet per minute, Hadley, Holyoke, and South Hadley, Massachusetts.



Base from U.S. Geological Survey digital raster data,1:25,000,
topographic quandrangle, Mt. Holyoke, 1964,
photorevised 1979, North American datum 1927,
Polyconic projection, zone 18

0 1,000 2,000 FEET
0 300 600 METERS

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM 1929

EXPLANATION

SIMULATED AREA CONTRIBUTING WATER TO DRY BROOK WELL AT PUMPING RATE OF 122.2 CUBIC FEET PER MINUTE (914 GALLONS PER MINUTE)

Figure 20. Extent of the simulated area contributing water to the Dry Brook well at pumping rates of *A*, 40.0; and *B*, 122.2 cubic feet per minute, Hadley, Holyoke, and South Hadley, Massachusetts.—Continued

Table 7. Comparison of steady-state model-simulated water budgets under average and the Massachusetts Department of Environmental Protection's approved-yield pumping rates, and various model-parameter test simulations for the Dry Brook study area, Hadley, Holyoke, and South Hadley, Massachusetts

[In cubic feet per minute (not all totals equal the sum of items due to round-off error). A, MDEP-Approved Yield, "base case"; B, "base case" recharge × 1.25; C, "base case" recharge × 0.75; D, "base case" hydraulic conductivity × 1.2; E, "base case" hydraulic conductivity × 0.8; F, "base case" vertical hydraulic conductivity × 4.0; G, "base case" vertical hydraulic conductivity × 2.0; H, "base case" vertical hydraulic conductivity × 0.5. MDEP, Massachusetts Department of Environmental Protection]

Model budget component	Average pumping	A	B	C	D	E	F	G	H
IN (inflow to the modeled area)									
Constant heads (Connecticut River)	4.19	61.82	53.03	72.73	60.48	63.67	70.91	66.51	57.53
Recharge	103.40	103.40	129.25	77.55	103.40	103.40	103.40	103.40	103.40
Boundary flow	17.41	17.41	21.76	13.06	17.41	17.41	17.41	17.41	17.41
Total IN	125.00	182.63	204.05	163.34	181.29	184.48	191.72	187.32	178.34
OUT (outflow from modeled area)									
Constant heads (Connecticut River)	68.96	46.60	61.65	32.43	46.30	46.78	55.38	51.11	42.49
Wells	40.00	122.20	122.20	122.20	122.20	122.20	122.20	122.20	122.20
River leakage (small streams)	16.08	13.83	20.23	8.77	12.92	15.50	14.21	14.02	13.65
Total OUT	125.04	182.63	204.09	163.40	181.42	184.48	191.79	187.33	178.35
Total IN – Total OUT	-.04	.00	-.04	-.06	-.13	.00	-.07	-.01	-.01
Percent discrepancy	-.03	.00	-.02	-.04	-.07	.00	-.04	.00	.00

Water entering the Dry Brook well from recharge and boundary flow dominates at a lower pumping rate (40.0 ft^3/min); about 90 percent of the pumped water originates from this source, and infiltration from the Connecticut River supplies the remaining 10 percent. At a higher pumping rate (122.2 ft^3/min), in contrast, about half of the water pumped from the Dry Brook well originates from recharge and boundary flow (49 percent), and half originates from the infiltration of water from the Connecticut River (51 percent). Tripling the pumping rate from 40.0 to 122.2 ft^3/min, therefore, increases the amount of water entering the aquifer from the Connecticut River by nearly 15 times the amount entering at the lower pumping rate, a difference of 57.6 ft^3/min. The assumption that the water entering the model from the constant-head cells that represent the Connecticut River is pumped from the Dry Brook well was tested by reducing the pumping rate at the well to zero. Under this tested condition, no water entered the aquifer from the constant-head cells, because the Connecticut River stage is the lowest water level in the study area when the well is not pumped. Generally, as the pumping rate at the Dry Brook well increases, more Connecticut River water infiltrates into the aquifer and is a source of water for the Dry Brook supply well.

A comparison of the two areas contributing water to the Dry Brook well indicates that, although the area contributing water increased in size as the pumping rate was increased from 40.0 to 122.2 ft^3/min, the overall increase in area was not as proportionally large as the increase in flow from the Connecticut River (fig. 20, table 7). The amount of water pumped by the Dry Brook well originating from recharge and boundary flow under average pumping conditions (40.0 ft^3/min) is 35.8 ft^3/min, whereas under MDEP-approved yield conditions (122.2 ft^3/min), that amount increases to 60.4 ft^3/min, about 70 percent greater than the amount under average conditions. Most of this increased recharge will enter the aquifer from the area of Dry Brook Hill, because this is where the soils are most permeable. In addition, the large gap in the area contributing water immediately around the Dry Brook well at the lower pumping rate is absent at the higher pumping rate. This gap is caused by the lacustrine sediment (varves) confining layer, which inhibits vertical flow, forcing recharge in this area to discharge to the lower end of Dry Brook and the Connecticut River. Water will flow vertically at the larger pumping rate, however, and some portion of the recharge in the area around the well will discharge from the well. At the larger pumping rate, the size of the area under the Connecticut River from which water will flow to the well increases, and the size of the area contributing water to the well from west of the river also increases (fig. 20).

Sensitivity and Uncertainty Analysis

The model sensitivity to recharge, boundary flows, and horizontal and vertical hydraulic conductivity was tested by increasing and decreasing these values to determine how these changes affect the simulated ground-water levels and flows.

These results were also used to provide an estimate of uncertainty that can be expected within a reasonable range of accuracy of the model parameter values. Uncertainties associated with the contributing-area analysis were also evaluated by varying the model parameters within reasonable limits to simulate new areas contributing water to the well for comparison to the contributing area from the calibrated model.

Results of sensitivity tests that included increasing and decreasing the recharge and boundary flow rates by 25 percent when pumping the Dry Brook well at the higher rate (122.2 ft^3/min) are shown on figure 21*A* (cases B and C, respectively). These results indicated that the area contributing water to Dry Brook well is robust, with relatively small changes under conditions of varied recharge. Under these conditions, the overall area increased or decreased by about 200 ft from the base condition further to the south and east across Dry Brook Hill, and the contribution from the Connecticut River increased to 60 percent of the pumpage when the recharge was decreased, as compared to 43 percent of the pumpage under higher recharge conditions (table 7). Although the amount of ground water discharged to Dry Brook and Bachelor Brook in the study area was small, it was sensitive to changes in the recharge rates, with discharge to these streams at the higher recharge value more than double that at the lower recharge value (table 7).

Other sensitivity tests of the model were conducted by increasing or decreasing the horizontal hydraulic conductivity by 20 percent uniformly across the area and all layers (cases D and E, respectively, fig. 21*B*). These simulation results indicated a small overall change in the size of the area contributing water, particularly in the eastern portion along Elmer Brook, where the size of the contributing area increased or decreased by 100 ft or less. The overall size of the area contributing water generally increased as the hydraulic conductivity was increased, and the area decreased slightly as the hydraulic conductivity was decreased. This effect is caused by expansion of the cone of depression created by pumping at the Dry Brook well. The cone of depression expands outward as the hydraulic conductivity increases (see fig. 8.6 in Freeze and Cherry, 1979). As with reduced recharge, the contribution of flow to the well from the Connecticut River increased slightly when hydraulic conductivity was decreased, from 51 percent in the base case to 52 percent. The larger hydraulic gradient that develops around the Dry Brook well as the hydraulic conductivity is decreased, and drawdowns are increased, causes this small effect. The contribution of flow to the well from the Connecticut River decreased as hydraulic conductivity was increased, to 50 percent of the total pumpage (table 7).

Additional sensitivity tests were simulated in which the vertical hydraulic conductivity of the model was increased by factors of 4 and 2, and decreased by 50 percent (cases F, G, and H, respectively, fig. 21*B*). The first two simulations greatly increase vertical ground-water flow in the model. The size of the area contributing water on Dry Brook Hill changed very little under these three simulations, but the size of the area across the Connecticut River, west of the Dry Brook well, was significantly affected (fig. 21*B*). The amount of water contributed by the river to the Dry Brook well decreased to 47 percent when the vertical conductance was decreased by 50 percent, and the amount increased to 52 and 54 percent when this parameter was increased by factors of 2 and 4, respectively (table 7). The effect of pumping ground water on the west side of the Connecticut River was also tested. When a simulated well in the flood plain directly across the Connecticut River from the Dry Brook well was pumped at a steady rate of 40.0 ft^3/min (299 gal/min), the steady-state modeling results indicated that the size of the area that had contributed water from the west side of the river to Dry Brook well was substantially reduced. This result indicates that the additional pumping from this well captures most of the water that, under the simulated conditions shown in figure 20, would have traveled to the Dry Brook well from the west side of the Connecticut River.

Transient Analysis and Contributing Watersheds

The MDEP wellhead-protection guidelines state that the contributing area to a well should be determined at 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 was determined by using a transient analysis of ground-water flow in the study area. For this analysis, the steady-state ground-water levels for average recharge conditions while pumping at the MDEP-approved yield were used as starting water levels for a transient 180-day period of no recharge while continuing to pump at the MDEP-approved yield. The storage properties used to simulate the 10-day aquifer test were also used to simulate the 180-day period of no recharge. The resulting ground-water levels after the simulated 180-day period of no recharge are shown in figure 22, and were used to identify the zone in which ground water flowed toward the Dry Brook well during this period. This approach is commonly used to define wellhead-protection zones for public-supply wells in Massachusetts (Joseph Cerutti, Massachusetts Department of Environmental Protection, oral commun., 2003). Declines in simulated aquifer heads under these conditions were generally less than 5 ft in layer 3, and were only 0.55 ft for the Dry Brook well.

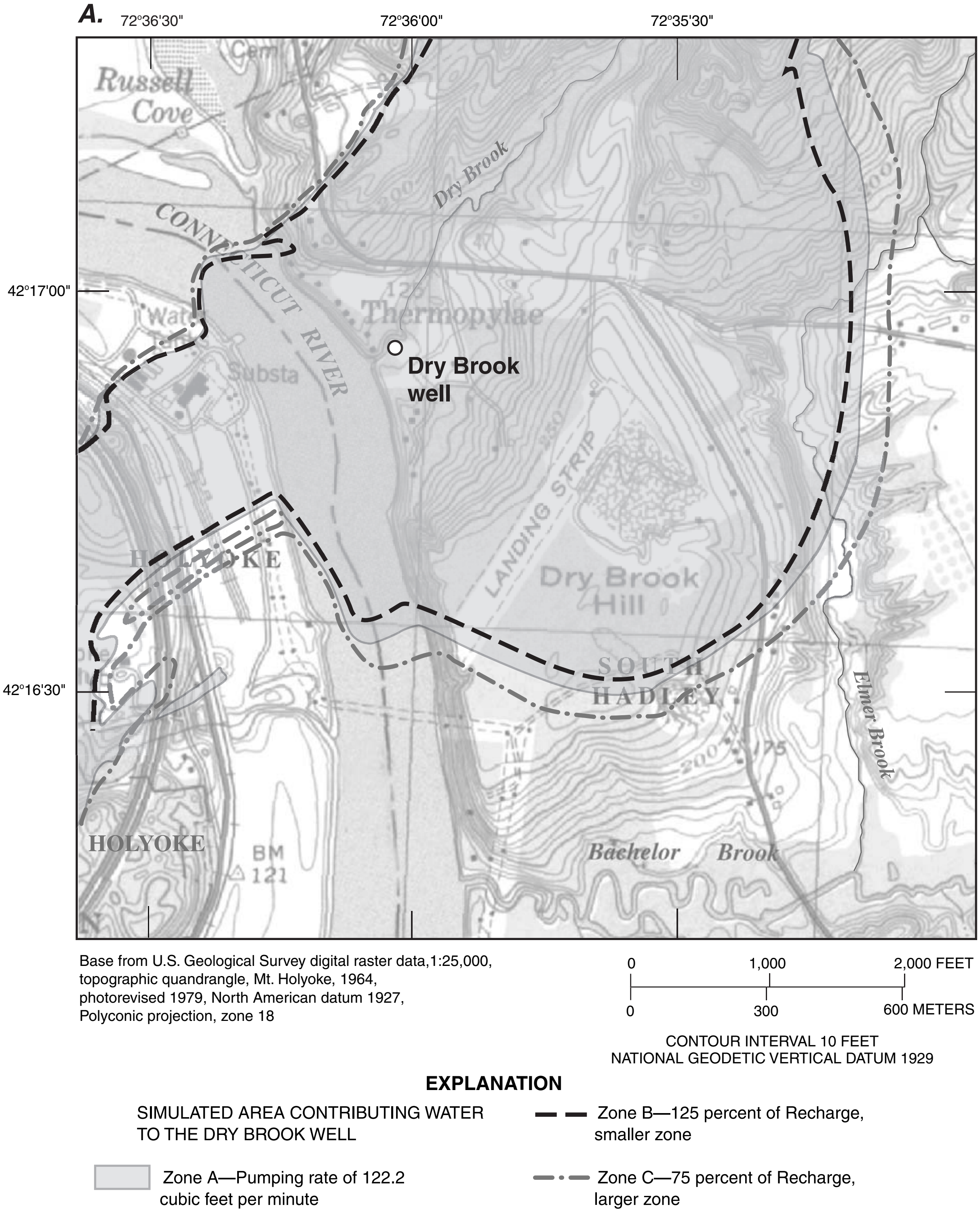


Figure 21. Sensitivity to various parameters of the simulated area contributing water to the Dry Brook well at a pumping rate of 122.2 cubic feet per minute for *A*, cases B and C; and *B*, cases D–H, Hadley, Holyoke, and South Hadley, Massachusetts.

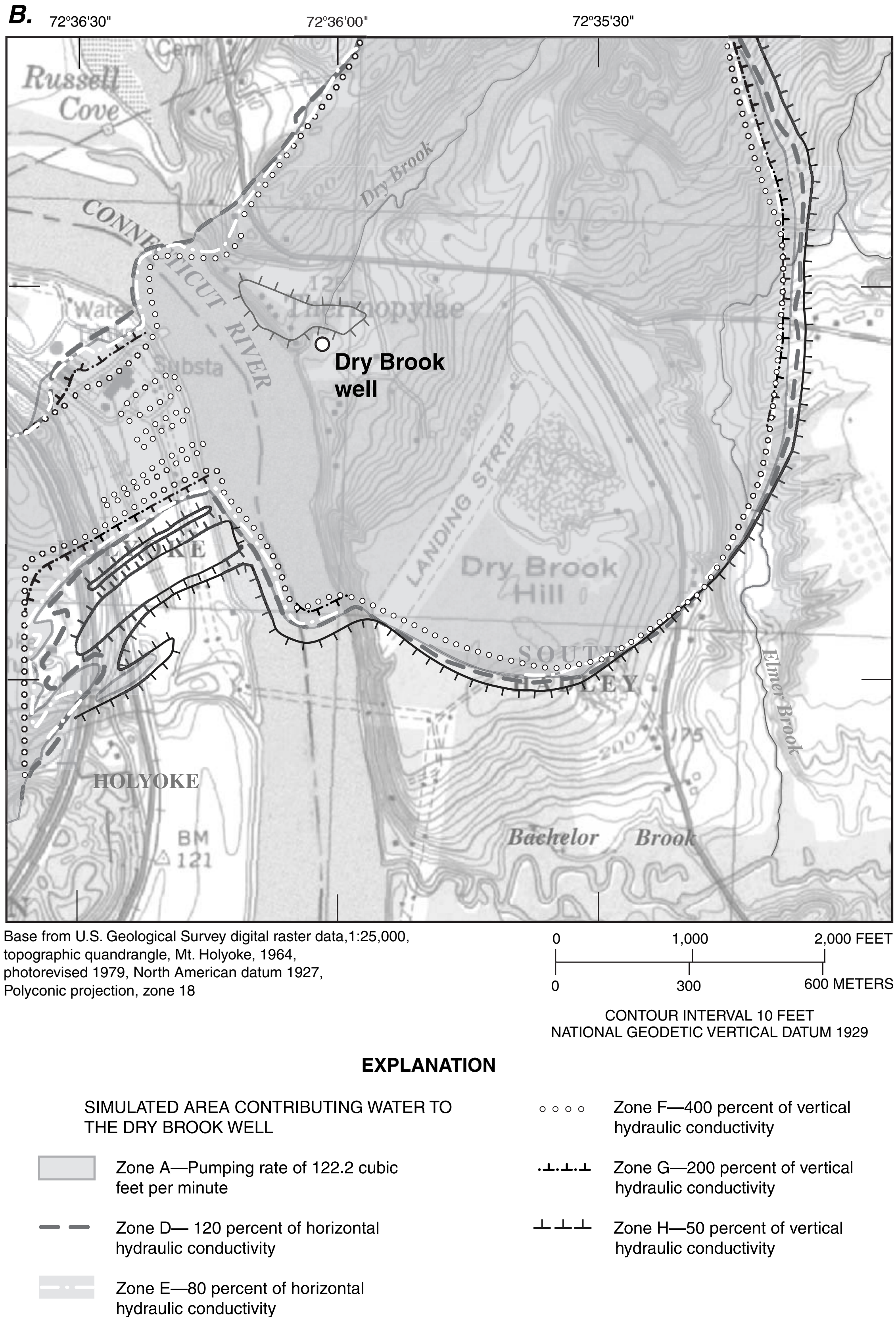
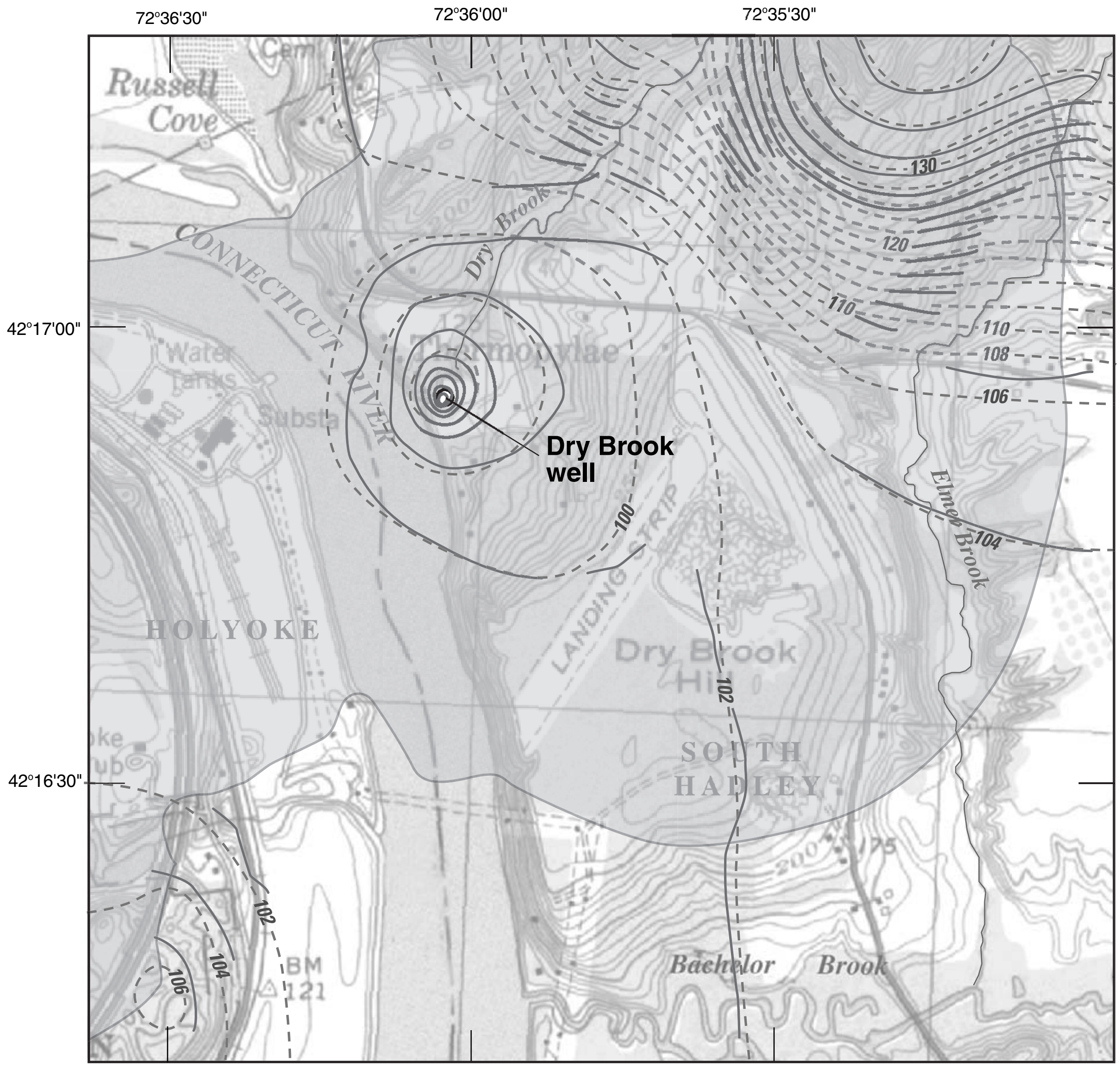


Figure 21—Continued. Sensitivity to various parameters of the simulated area contributing water to the Dry Brook well at a pumping rate of 122.2 cubic feet per minute for *A*, cases B and C; and *B*. cases D–H, Hadley, Holyoke, and South Hadley, Massachusetts.



Base from U.S. Geological Survey digital raster data,1:25,000, topographic quandrangle, Mt. Holyoke, 1964, photorevised 1979, North American datum 1927, Polyconic projection, zone 18

0 1,000 2,000 FEET
0 300 600 METERS

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM 1929

EXPLANATION

SIMULATED WATER-LEVEL CONTOURS—Contour interval is 2 feet above NGVD 29 at a pumping rate of 122.2 cubic feet per minute.

Zone of ground-water flow to Dry Brook well

Layer 3—Model layer dry where missing

– –*102*– – Layer 4

Figure 22. Simulated ground-water-level contours for layers 3 and 4 at a pumping rate of 122.2 cubic feet per minute after a transient, 180-day period of no recharge and associated zone of ground-water flow towards the Dry Brook well, Hadley, Holyoke, and South Hadley, Massachusetts.

The simulated potentiometric surface for layer 3 at the end of the transient 180-day period of no recharge indicated the size of the area in which water flows toward Dry Brook well expanded about 500 ft (fig. 22) as compared to the area delineated under steady-state conditions (fig. 20*B*), but had a shape similar to the steady-state area. Although the size of the simulated area in which ground water flows towards Dry Brook well expanded during the 180-day period, and flow was reversed near the previously determined ground-water 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 ground-water divides would shift closer to the pumped well and flow would again reverse near the divides away from the well. The net effect would be little or no change from average conditions in the area contributing water. Reilly and Pollock (1995) demonstrated that half-year cyclic changes in recharge generally caused minor differences from average conditions in areas contributing water and in ground-water flow paths. This analysis, however, does delineate an expanded area around the supply well that could provide additional water-quality protection.

The steady-state zone of contribution for the Dry Brook well at the MDEP-approved yield (122.2 ft^3/min) incorporates the area contributing water to the Dry Brook well within the model boundaries (fig. 20*B*), the associated watersheds draining to this area, and the area through which this water flows to the well (fig. 23). The primary area contributing water for the Dry Brook well is shown on figure 23, and the associated watersheds that contribute water to the well primarily by overland flow and a minor amount as subsurface flow are also shown on this figure. The slopes in the watershed areas are generally steep, and much of the precipitation in these areas may not infiltrate, but instead flow directly to Dry Brook or the Connecticut River. As discussed, simulation of water sources to the Dry Brook well at the MDEP-approved-yield conditions shown in figure 23 indicates that about half of the water pumped from the Dry Brook well entered the ground-water system from the Connecticut River, and half entered the ground-water system as recharge and boundary flow, most of which entered from Dry Brook Hill. Dry Brook Hill is important to the protection of the water quality in the Dry Brook well because this area contributes water under both higher and lower pumping scenarios, and is potentially vulnerable to contamination because of its permeable sandy soils and aquifer materials.

The aquifer pumped by the Dry Brook well is partially confined by very fine-grained (varved) lacustrine sediments, which overlie the area around the well. Although relatively little water passes through the confining bed (about 1 ft^3/min under the MDEP-approved yield), the confining bed overlying the Dry Brook well is included in the zone of contribution because water passes underneath this area as it travels from where it enters the aquifer to the well. An estimate of the time that it would take for water to travel vertically from the land surface to the Dry Brook well can be made by using simulation results with pumping at the MDEP-approved yield and the following equation:

$$\text{Time of travel} = z/v = nz^2/(K_v dh)\,, \qquad (4)$$

where

z is the vertical distance (100 ft),
v is the velocity of ground water,
n is the porosity (0.5),
K_v is the vertical hydraulic conductivity (10^{-5} ft/min), and
dh is the vertical head difference (17.8 ft).

The resulting travel time is about 50 years, indicating that although the confining bed likely protects the water quality of the aquifer from immediate degradation by surface contamination, long-term migration of persistent contaminants from the surface is possible if those contaminants are present. This calculation of time of travel assumes conservative (nonreactive) transport at the point of greatest head difference in the vertical; and because the head differences would be less at greater distances from the Dry Brook well, the time required for water to travel through the confining bed is likely to be greater than 50 years.

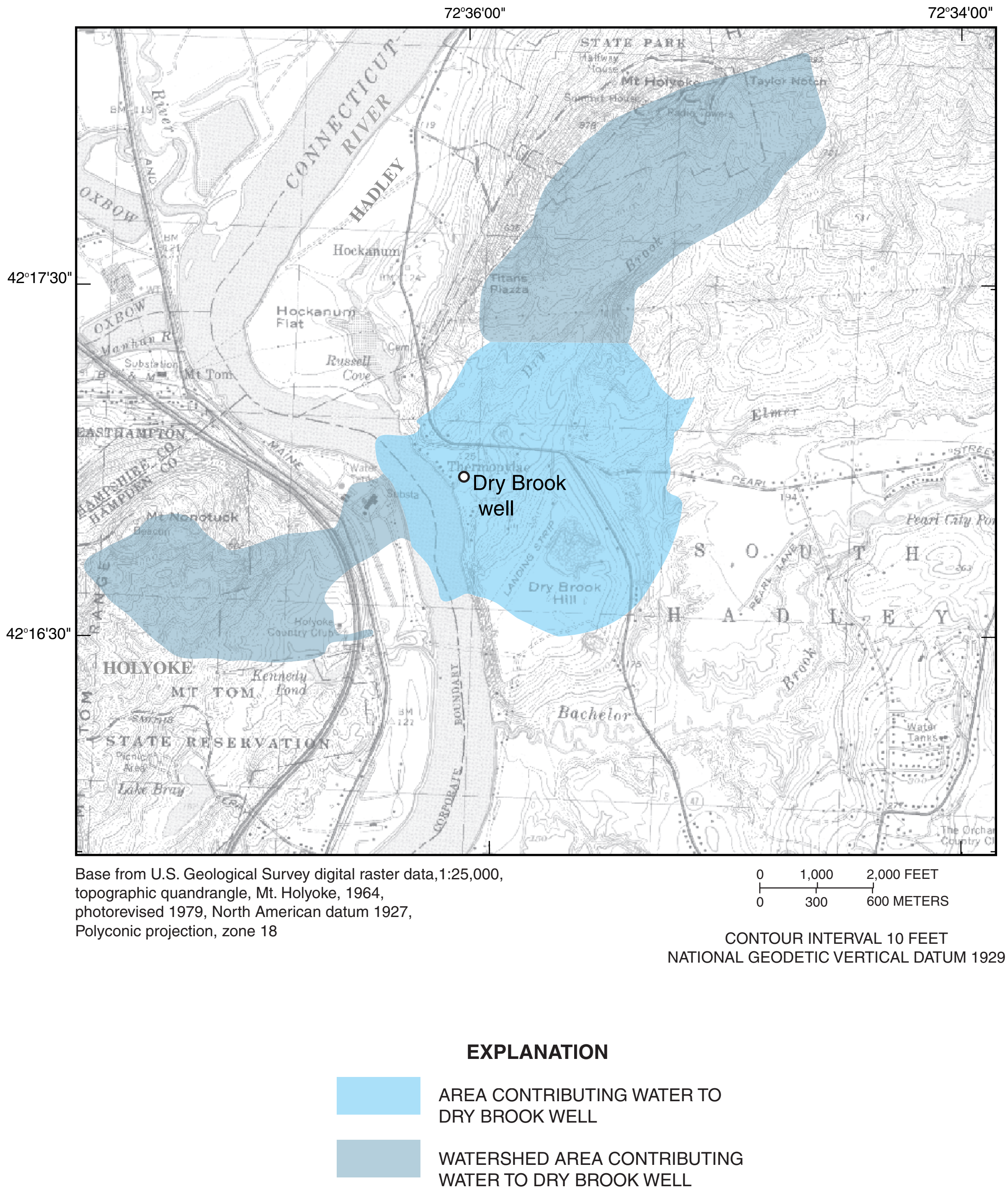


Figure 23. Zone of contribution and associated watershed areas contributing water to the Dry Brook well at a pumping rate of 122.2 cubic feet per minute, Hadley, Holyoke, and South Hadley, Massachusetts.

Suggestions for Future Study

The simulation results discussed above demonstrate the potential importance of drawdown observations from wells across the Connecticut River from the Dry Brook well for any additional aquifer tests conducted at the Dry Brook well. Water-level observations in this area would increase understanding of the degree to which the Connecticut River affects head conditions in the aquifer and ground-water flows under the river to the well. For example, if it can be shown that drawdown from pumping the Dry Brook well at a relatively high rate does not propagate under the river, as was the case for the Hockanum Flat test well located about 2,000 ft north of the Dry Brook well (Tighe and Bond, 1999), then this would be important information for any subsequent interpretation of the hydrogeologic conditions in this part of the aquifer. Future investigations of ground-water flow in the study area would benefit from additional water-level measurements in the Dry Brook Hill area, along with obtaining additional information on the hydraulic characteristics of the Mesozoic-aged bedrock underlying the hill.

On the basis of this study, the important components needed in future studies to properly delineate areas contributing water to public-supply wells developed in confined aquifers include geologic information on the vertical and lateral extent of the confining beds and aquifer materials, and a conceptual model of ground-water flow in the aquifer based on hydrogeologic data that takes into consideration the movement of ground water from recharge to discharge areas. Other components include hydrologic data quantifying aquifer gains and losses of water from streams and ponds, and accurate estimates of recharge rates, which appear to be an important determinant of the extent of the areas contributing water to supply wells across Massachusetts (Lyford and others, 2003), including those in confined ground-water-flow systems.

Summary and Conclusions

Areas contributing water to the Dry Brook public-supply well in South Hadley, MA, were delineated by using a numerical ground-water-flow model that was based on exisiting and newly developed geologic and hydrologic information for the confined sand and gravel aquifer tapped by the supply well. This study was undertaken in 1999 by the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection, to investigate the factors needed to properly delineate areas contributing water to public-supply wells developed in confined aquifers in Massachusetts. The study area is along the Connecticut River in central Massachusetts, about 12 mi north of Springfield, MA. Geologic units in the study area consist of Mesozoic-aged sedimentary and igneous bedrock, late-Pleistocene glaciolacustrine sediments, and recent alluvial deposits of the Connecticut River flood plain. Dry Brook Hill, immediately south of the supply well, is a large subaqueous lacustrine fan and delta formed during the last glacial retreat by sediment deposition into glacial Lake Hitchcock from a meltwater tunnel that was likely near where the Connecticut River cuts through the Holyoke Range. The sediments that compose the aquifer grade from very coarse sand and gravel along the northern flank of the hill to medium sands in the body of the hill, to finer-grained sediments along the southern flank of the hill. The interbedded and overlapping fine-grained lacustrine sediments associated with Dry Brook Hill include varved silt and clay deposits. These fine-grained sediments form a confining bed above the coarse-grained aquifer at the supply well and partially extend under the Connecticut River adjacent to the supply well.

Ground-water flow in the aquifer supplying water to the Dry Brook well was simulated with the USGS ground-water-flow modeling code MODFLOW. The Dry Brook aquifer model was calibrated by using drawdown data collected in 8 observation wells during an aquifer test conducted by pumping the supply well for 10 days at a rate of 122.2 ft^3/min. (914 gal/min) and by using water levels collected in observation wells across the study area. Generally, the largest hydraulic conductivities were in the sand and gravel aquifer in the immediate vicinity of the well, which is consistent with the geologic information. Results of aquifer-test simulation indicated heads and ground-water flow near the Dry Brook well are affected by spatially variable aquifer hydraulic properties and boundary conditions. A comparison and analysis of ground-water-level fluctuations in study-area wells to fluctuations in the Connecticut River indicated a hydraulic connection of the aquifer with the river, which is also consistent with geologic information. Simulated ground-water levels indicated that most ground water in the study area flows towards and discharges to the Connecticut River and the Dry Brook well. Small amounts of ground water also discharge to smaller streams in the study area (Bachelor Brook and Dry Brook).

Delineation of areas contributing water to the well was completed by using the MODPATH particle-tracking routine. Results of the contributing-area analysis indicated that the greatest sources of water to the well were recharge in the Dry Brook Hill area and infiltration of Connecticut River water in an area beyond the extent of the confining bed where the aquifer is hydraulically connected to the river. Water entering the Dry Brook well from recharge and boundary flow dominates at a lower pumping rate (40.0 ft^3/min); about 90 percent of the pumped water originates from this source, and infiltration from the Connecticut River supplies the remaining 10 percent. At a higher pumping rate (122.2 ft^3/min), in contrast, about half of the water pumped from the Dry Brook well originates from recharge and boundary flow, and half originates from the infiltration of water from the Connecticut River. Tripling the pumping rate from 40.0 to 122.2 ft^3/min increases the amount of water entering the aquifer from the Connecticut River by nearly 15 times the amount entering at the lower pumping rate.

Results of the sensitivity analysis of the extent of areas contributing water to the Dry Brook well indicated that the size of these areas did not substatially change when aquifer properties were varied; however, the size of these areas changed the most when the recharge rate was changed. When the recharge rate was decreased by 25 percent, the extent of the area increased by about 200 feet farther to the south and east across Dry Brook Hill. When recharge was increased by 25 percent, the extent of the area decreased by about 200 ft on the south and east sides of Dry Brook Hill. The contribution from the Connecticut River increased to 60 percent of the total pumpage when the recharge was decreased as compared to 43 percent of the total pumpage under higher recharge conditions. These results indicated Dry Brook Hill is important to the protection of the water-quality in the Dry Brook well because this area contributes water under a number of simulated conditions, and is potentially vulnerable to contamination because of its permeable sandy soils and aquifer materials.

On the basis of this study, the important components needed in future studies to properly delineate areas contributing water to public-supply wells developed in confined aquifers include geologic information on the vertical and lateral extent of the confining beds and aquifer materials, and a conceptual model of ground-water flow in the aquifer based on hydrogeologic data that takes into consideration the movement of ground water from recharge to discharge areas. Other components include hydrologic data quantifying aquifer gains and losses of water from streams and ponds, and accurate estimates of recharge rates, which appear to be an important determinant of the extent of the areas contributing water to supply wells across Massachusetts, including those in confined ground-water-flow systems.

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