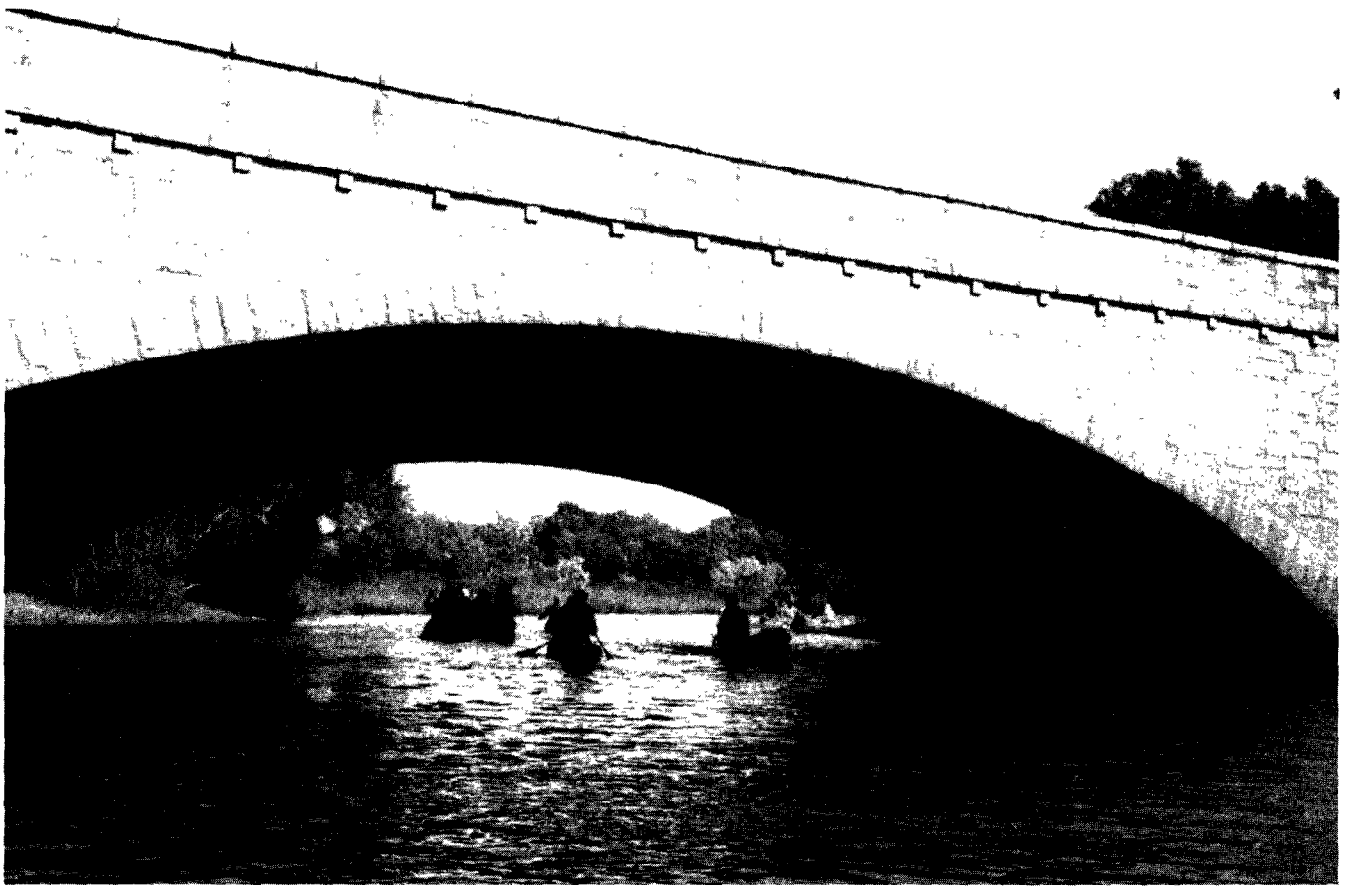
# ESTIMATED AVAILABILITY OF WATER FROM STRATIFIED-DRIFT AQUIFERS IN THE CONCORD RIVER BASIN, MASSACHUSETTS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4256



Prepared in cooperation with the
MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL MANAGEMENT,
OFFICE OF WATER RESOURCES

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**By Lisa Bratton and Gene W. Parker**

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Marlborough, Massachusetts
1995

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## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| cubic foot ($ft^3$) | 0.02832 | cubic meter |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| cubic foot per square mile ($ft^3/mi^2$) | 0.0109344 | cubic meter per square kilometer |
| foot (ft) | 0.3048 | meter |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day |
| inch (in.) | 25.4 | millimeter |
| inch per year (in/yr) | 25.4 | millimeter per year |
| mile (mi) | 1.609 | kilometer |
| million gallons (Mgal) | 0.003785 | million cubic meters |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |
| square mile ($mi^2$) | 2.590 | square kilometer |

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius by the following equation:

$$\text{Temp } °C = 5/9\ (°F) - 32.$$

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

# ESTIMATED AVAILABILITY OF WATER FROM STRATIFIED-DRIFT AQUIFERS IN THE CONCORD RIVER BASIN, MASSACHUSETTS

*By* Lisa Bratton *and* Gene W. Parker

## ABSTRACT

An understanding of water availability in the Concord River Basin for public and private supply requires an understanding of the interaction between surface-water and ground-water systems. This understanding is needed because excessive ground-water withdrawals may reduce streamflows to unacceptable levels. The U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources, studied the Concord River Basin to estimate the volume of water available from stratified-drift aquifers.

A combined hydrograph-separation and streamflow-duration-curve analysis indicates that 20.8 million cubic feet of water could be withdrawn from the stratified-drift aquifer above the South Acton streamflow-gaging station during a 102-day period of no recharge before streamflow would be reduced to a prescribed minimum level. This volume, which equals 2.85 million cubic feet per square mile of stratified drift, was used to estimate volume of available water in 17 aquifer areas in the Concord River Basin. The total volume of available water in the Concord River Basin is estimated to be 561 million cubic feet.

Finite-difference ground-water-flow models for the River Meadow Brook aquifer area and the Sudbury and Concord aquifer area quantified the current and potential water availability. The results of three withdrawal simulations for each aquifer area indicate that the 1989 ground-water withdrawal rates would not exceed the volume of water that would be available during a 102-day period of no recharge if water-table drawdowns were not considered. However, results do indicate that volumes of withdrawn water would exceed the available water in the two aquifer areas if maximum lowering of the water table as a percentage of total saturated thickness were 10 and 65 percent at existing and hypothetical wells.

## INTRODUCTION

Although Massachusetts is well endowed with water, withdrawals of water in urbanized eastern Massachusetts have approached and, in some areas, exceeded the capacity of local water resources. Primary local resources generally are narrow, thin, and discontinuous stratified-drift aquifers. When ground-water withdrawals exceed local capacity, surface water infiltrates the aquifer where the streambed is connected with the aquifer. Consequently, streamflow can decrease or cease as the result of ground-water withdrawal. Minimum low streamflows must be maintained to avoid degradation of wildlife habitat, to dilute wastewater discharges, and to preserve surface-water quality. Hence, ground-water supplies are limited to the extent that withdrawals must not reduce streamflow below some minimal level.

In an effort to improve the understanding of the local surface-water/ground-water interactions, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources (MDEM), began a 3-year study in 1989 in the Concord River Basin. USGS personnel investigated the degree of interconnection between the surface-water and ground-water systems, estimated the quantity of water involved in the interaction, and simulated the interaction with identifiable limits. This report describes the results of the study and presents—

1. estimates of available water during periods of no recharge based on a combined-hydrograph-separation and streamflow-duration-curve analysis, and
2. estimates of current and potential water available in two aquifer areas based on three withdrawal simulations with a finite-difference ground-water-flow model.

### Previous Investigations

This study expands on the results and findings in several reports previously published by the USGS on various aspects of the Concord River Basin. Pollock and others (1969) produced a hydrologic atlas describing the availability and quality of water in the Assabet River Basin. Brackley and Hansen (1985) published a hydrologic atlas describing the hydrology, water availability, and water quality for the entire Concord River Basin. Simcox (1992) reported on the general water resources in the Concord River Basin and Bratton (1991) reported on the water used by public supplies. The Massachusetts Department of Environmental Management, Office of Water Resources (1989), also has published a report on current and projected water use in the Concord River Basin.

### Acknowledgments

The authors appreciate the information on water withdrawals provided by Yvette DePeiza of the Massachusetts Department of Environmental Protection, Water Supply Division, and by water superintendents in the towns of Acton, Billerica, Chelmsford, East Chelmsford, Concord, Wayland, and Sudbury. William A. Brutsch of the Massachusetts Water Resource Authority (MWRA) provided invaluable information on withdrawals and transfers within the MWRA system. In addition, the authors wish to thank the people and agencies that provided data and gave permission for fieldwork on their property during this study.

## DESCRIPTION OF THE CONCORD RIVER BASIN

The Concord River drains 398 $mi^2$ in the northeastern part of central Massachusetts (fig. 1). The two major tributaries that form the Concord River are the Assabet River, which drains 177 $mi^2$, and the Sudbury River, which drains 162 $mi^2$. The climate of the basin is temperate and humid; average monthly temperatures range from 25°F in January to 73°F in July. Average annual precipitation in the basin is 53 in/yr (National Oceanic and Atmospheric Administration, 1989). Land-surface elevations in the basin range from 50 to about 480 ft above sea level. As a result of these characteristics, the streams in the basin generally are well supplied by precipitation but flow slowly.

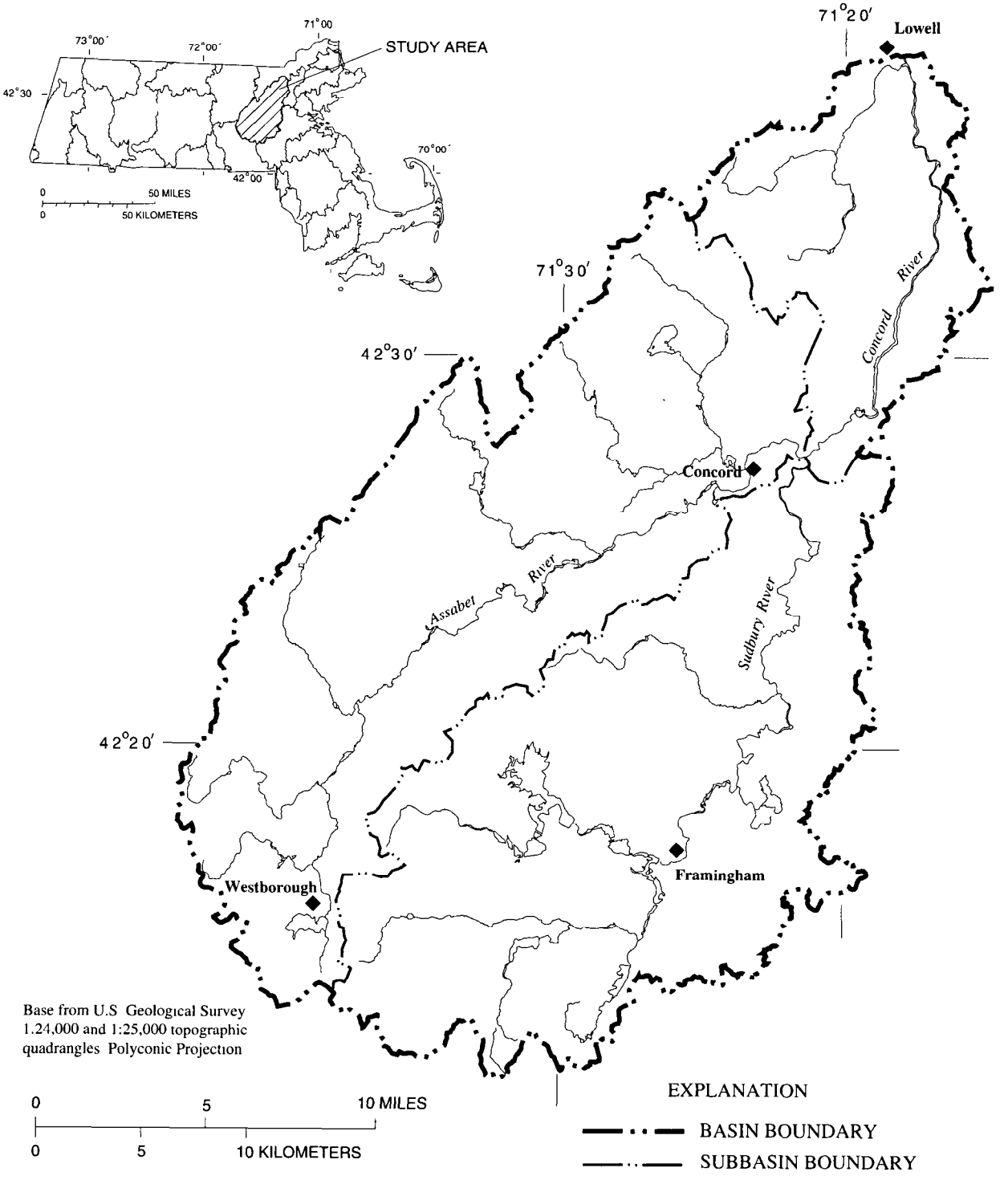


**Figure 1.** Location of the Concord River Basin, Massachusetts.

Glacial deposits overlie metamorphic bedrock in the Concord River Basin. Well-sorted and layered glacial deposits, called stratified drift, comprise the significant aquifers in the basin and cover about 10 percent of the basin area. Although the stratified-drift aquifers are long, thin, and mostly discontinuous, they provide most of the ground water for use because of their medium or high transmissivities. The 17 aquifer areas shown in figure 2 include stratified-drift aquifers with medium to high transmissivities and the surrounding areas that drain to them. Most of the surface-water and ground-water interaction occurs between these aquifers and the streams that flow over them.

## Water Use

Water use affects the interaction between surface water and ground water by superimposing manmade stresses on the natural hydrologic systems. Water-use activities, such as withdrawals and returns, can circumvent the local natural system and can stress the system through withdrawals of water in great volumes and rapid transport and return in a different location. Most of the withdrawals are from the aquifers in the River Meadow Brook, the Assabet River, the Wash Brook, and the Sudbury and Concord aquifer areas (fig. 3). These aquifers either underlie extensive areas where transmissivities are medium to high or are pumped at sites at or near a river. Wells or groups of wells and surface-water intakes associated with withdrawal sites in figure 3 are listed in table 1 along with 1989 withdrawal rates. Returns to the hydrologic system by wastewater discharge from treatment plants mostly contribute to flow in the main stems of the Assabet, Sudbury, and Concord Rivers (table 2), because large volumes of water are needed to dilute the wastewater. Wastewater-return sites in figure 3 are listed in table 2 along with 1989 wastewater returns.

## Land Use

Land use affects the interaction between ground water and surface water by altering the local hydrologic system. In parts of the Concord River Basin, such as the areas around Framingham and Lowell, industrial and urban development is extensive. In the Sudbury and Concord subbasins, land is relatively flat and historically was used for agriculture; much open space associated with agriculture is currently being redeveloped into residential areas. During the industrial revolution, a dam built in Billerica flooded meadows along the Sudbury River, forming wetlands that exist to this day. The Assabet River subbasin has narrower valleys and a steeper gradient than the other subbasins, making the Assabet River subbasin suitable for building mills. Other industry developed along the Assabet River, and this subbasin tends to have more industry and commercial land use than the Sudbury River subbasin has. These changes in land-use practices altered surface-water/ground-water interaction mostly by affecting levels of rivers, permeability to the aquifers, and evapotranspiration rate.

## Streamflow

Streamflow measurements were made at four gaged and seven ungaged sites (fig. 4). Streamflows in the Concord River Basin are recorded continuously at USGS streamflow-gaging stations on the Assabet River at Maynard (01097000), Nashoba Brook at South Acton (01097300), Sudbury River at Saxonville (01098530), and Concord River at Lowell (01099500) (fig. 4). A review of the entire period of streamflow records for the Maynard and Lowell stations indicates an increase in minimum daily streamflow after 1970. The minimum daily streamflow increased by 5 $ft^3/s$ at the Maynard station and 30 $ft^3/s$ at the Lowell station. These changes represent an approximate 20- to 30-percent increase in minimum streamflow from the period of record before 1970. These increased minimum daily streamflows coincide with the many wastewater-treatment facilities being built in the 1970's as a result of the Federal Clean Water Act, passed in 1972. The increase in minimum streamflow allows more water to be available for the interaction between the surface-water and ground-water systems. Streamflow was measured at medium and low flow during 1989 and 1990 at four ungaged sites on tributaries where streamflow is natural (fig. 4). Because of the change in low-flow characteristics observed for the period since 1970, these ungaged-site measurements are expected to characterize streamflow only for 1989 and 1990. Streamflow measurements at three ungaged sites on the Assabet River and Wash Brook verified that streamflows were regulated by wastewater returns.

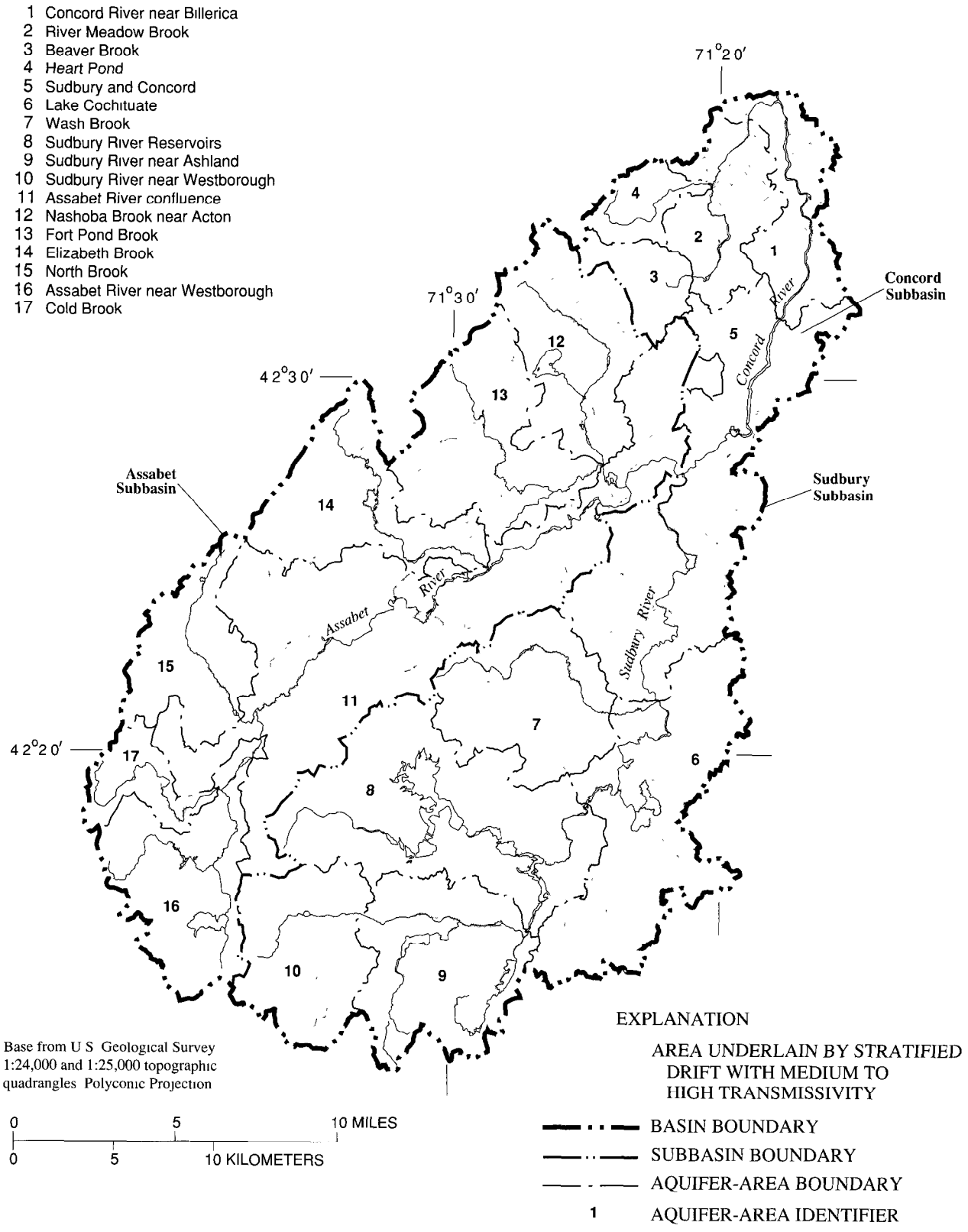


**Figure 2.** Location of aquifer areas in the Concord River Basin, Massachusetts.

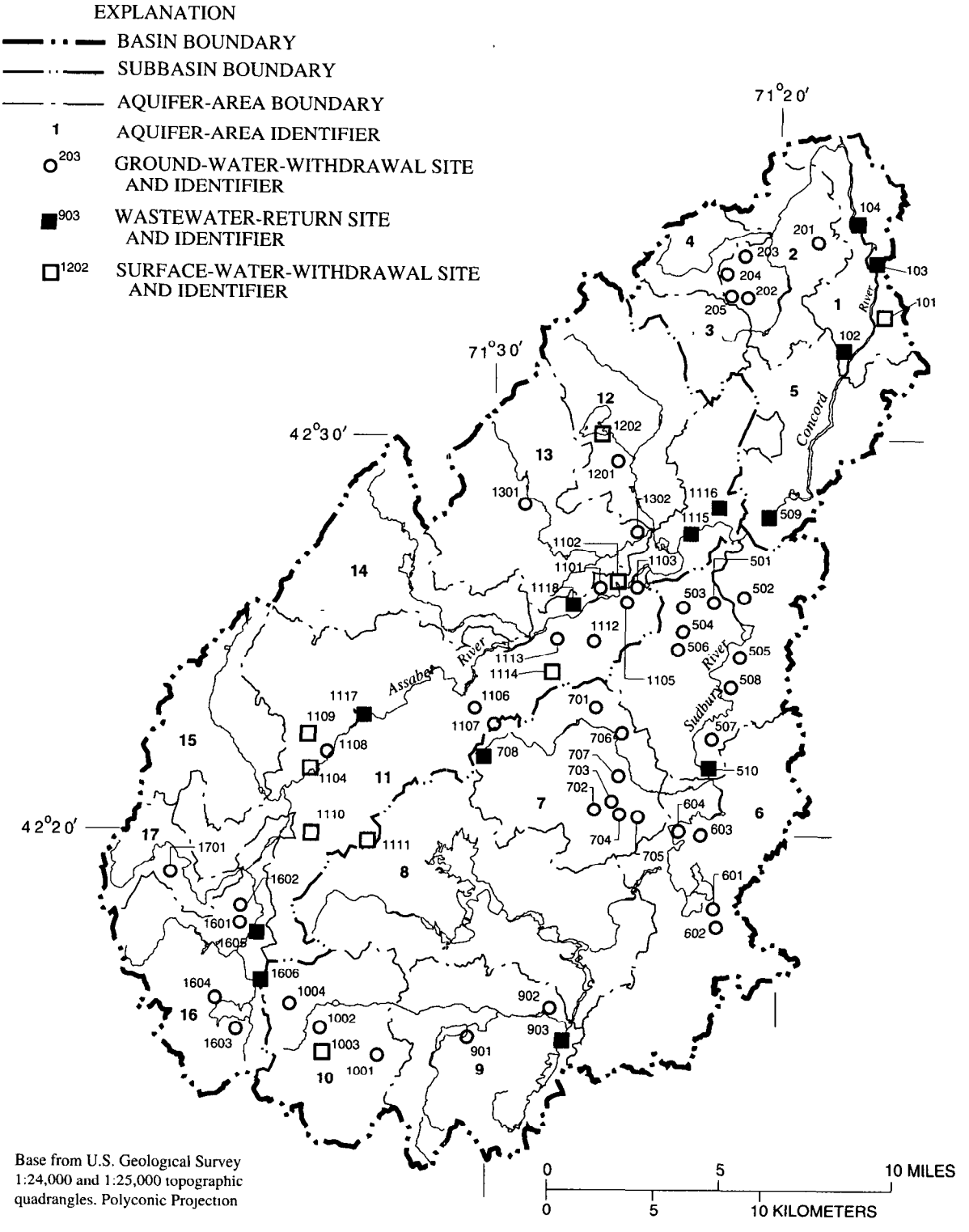


**Figure 3.** Location of water-withdrawal and wastewater-return sites in the Concord River Basin, Massachusetts.

**Table 1.** Water-withdrawal sites and withdrawal amounts in the Concord River Basin, Massachusetts, 1989

[Map identifier: The first one or two digits indicate the aquifer area and the last two digits identify the individual site. Type of site: GW, ground water; SW, surface water. Numbers in parentheses correspond to aquifer areas shown on figure 3. Mgal/d, million gallons per day]

| Map identifier (fig. 3) | Town | Company | Site name | Type of site | Annual withdrawals (Mgal/d) |
|---|---|---|---|---|---|
| | | CONCORD RIVER NEAR BILLERICA (1) | | | |
| 101 | Billerica | Billerica Water Works | Concord River | SW | 4.749 |
| | | RIVER MEADOW BROOK (2) | | | |
| 201 | Chelmsford | Chelmsford Water District | Canal Street Well #1 | GW | 0 .034 |
| | | | Canal Street Well #2 | GW | .034 |
| | East Chelmsford | East Chelmsford Water District | Canal Street Well #1 | GW | .000 |
| | | | Canal Street Well #2 | GW | .000 |
| 202 | Chelmsford | Chelmsford Water District | Mill Road Well #1 | GW | .220 |
| | | | Mill Road Well #2 | GW | .220 |
| | | | Mill Road Well #3 | GW | .220 |
| 203 | Chelmsford | Chelmsford Water District | Riverneck Road #1 | GW | .000 |
| | | | Riverneck Road #2 | GW | .379 |
| 204 | Chelmsford | Chelmsford Water District | Turnpike Road Well | GW | .000 |
| 205 | Chelmsford | Chelmsford Water District | Warren Avenue Gravel Packed #1 | GW | .000 |
| | | | Warren Avenue Gravel Packed #2 | GW | .000 |
| | | | Warren Avenue Well Field | GW | .001 |
| | | SUDBURY AND CONCORD (5) | | | |
| 501 | Concord | Concord Water Department | Deaconess Well | GW | 0.489 |
| 502 | Concord | Concord Water Department | Hugh Cargill Well | GW | .002 |
| 503 | Concord | Concord Water Department | Jennie Dugan Well | GW | .252 |
| 504 | Concord | Concord Water Department | White Pond Well | GW | .123 |
| 505 | Lincoln | Lincoln Water Department | Farrar Pond Well #2 | GW | .000 |
| 506 | Sudbury | Sudbury Water Department | Route 117 Well #5 | GW | .000 |
| 507 | Wayland | Wayland Water Department | Baldwin Pond #1 | GW | .184 |
| | | | Baldwin Pond #2 | GW | .184 |
| | | | Baldwin Pond #3 | GW | .288 |
| 508 | Wayland | Wayland Water Department | Campbell Road Well | GW | .735 |
| | | LAKE COCHITUATE (6) | | | |
| 601 | Natick | Natick Water Department | Evergreen Well #1 | GW | 1.100 |
| | | | Evergreen Well #2 | GW | 1.041 |
| 602 | Natick | Natick Water Department | Springvale #1 & 2 | GW | .120 |
| | | | Springvale #3 | GW | 1.033 |
| | | | Springvale #4 | GW | .609 |
| | | | Springvale #5 | GW | .000 |
| 603 | Wayland | Wayland Water Department | Happy Hollow #1 | GW | .434 |
| | | | Happy Hollow #2 | GW | .588 |
| 604 | Wayland | Wayland Water Department | Meadowview Well | GW | .323 |

**Table 1.** Water-withdrawal sites and withdrawal amounts in the Concord River Basin, Massachusetts, 1989 —*Continued*

| Map identifier (fig. 3) | Town | Company | Site name | Type of site | Annual withdrawals (Mgal/d) |
|---|---|---|---|---|---|
| | | | WASH BROOK (7) | | |
| 701 | Sudbury | Sudbury Water Department | East Street Well #3 | GW | 0.298 |
| | | | East Street Well #8 | GW | .412 |
| 702 | Sudbury | Sudbury Water Department | Nobscot Road Well #7 | GW | .281 |
| 703 | Sudbury | Sudbury Water Department | Raymond Road #2 | GW | .212 |
| 704 | Sudbury | Sudbury Water Department | Raymond Road Well #6 | GW | .451 |
| 705 | Sudbury | Sudbury Water Department | Warran Road #4 | GW | .129 |
| 706 | Sudbury | Sudbury Water Department | Well #1 | GW | .000 |
| 707 | Sudbury | Sudbury Water Department | Well #9 | GW | .000 |
| | | | SUDBURY RIVER NEAR ASHLAND (9) | | |
| 901 | Ashland | Ashland Water Department | Howe Street Well #4 | GW | 0.000 |
| | | | Howe Street Well #5 | GW | .000 |
| 902 | Ashland | Industry | Well #1 | GW | .028 |
| | | | Well #2 | GW | .070 |
| | | | Well #2 | GW | .100 |
| | | | Well #3 | GW | .025 |
| | | | Well #3 | GW | .020 |
| | | | Well #4 | GW | .110 |
| | | | SUDBURY RIVER NEAR WESTBOROUGH (10) | | |
| 1001 | Hopkinton | Hopkinton Water Department | Fruit Street Well #1 | GW | 0.000 |
| | | | Fruit Street Well #2 | GW | .000 |
| | | | Fruit Street Well #3 | GW | .000 |
| 1002 | Westborough | Westborough Department of Public Works | Hopkinton Road Well | GW | .105 |
| | | | Morse Street Well | GW | .285 |
| 1003 | Westborough | Westborough Department of Public Works | Sandra Pond | SW | .572 |
| 1004 | Westborough | Industry | Well #2 | GW | .100 |
| | | | Well #3 | GW | .020 |
| | | | Well #4 | GW | .110 |
| | | | ASSABET RIVER CONFLUENCE (11) | | |
| 1101 | Acton | Acton Water District | Assabet Well #1 | GW | 0.200 |
| | | | Assabet Well #2 | GW | .200 |
| 1102 | Acton | Industry | Assabet River | SW | .170 |
| 1103 | Acton | Chemical company | Gravel Packed Well #1 | GW | .000 |
| | | | Gravel Packed Well #2 | GW | .000 |
| | | | Gravel Packed Well #3 | GW | .185 |
| 1104 | Berlin | Concrete company | Assabet River | SW | .220 |
| | | | Assabet River | SW | .005 |
| 1105 | Concord | Concord Water Department | Second Division Well | GW | .398 |
| 1106 | Hudson | Hudson Department of Public Works | Chestnut Well #1 | GW | .546 |
| | | | Chesnut Well #2 | GW | .123 |
| | | | Kane Well | GW | .229 |

**Table 1.** Water-wthdrawal sites and withdrawal amounts in the Concord River Basin, Massachusetts, 1989 —*Continued*

| Map identifier (fig. 3) | Town | Company | Site name | Type of site | Annual withdrawals (Mgal/d) |
|---|---|---|---|---|---|
| | | ASSABET RIVER CONFLUENCE (11) —*Continued* | | | |
| 1107 | Hudson | Hudson Department of Public Works | Cranberry Well | GW | 0.808 |
| 1108 | Hudson | Hudson Department of Public Works | Rimkus Well | GW | .000 |
| 1109 | Hudson | Hudson Department of Public Works | Gates Pond | SW | .482 |
| 1110 | Marlborough | Marlborough Department of Public Works | Lake Williams | SW | .000 |
| 1111 | Marlborough | Marlborough Department of Public Works | Millham Reservoir | SW | 1.300 |
| 1112 | Maynard | Maynard Public Works | Marlborough Road Well #1 | GW | .285 |
| | | | Marlborough Road Well #2 | GW | .292 |
| 1113 | Maynard | Maynard Public Works | Route 117 Well | GW | .000 |
| 1114 | Maynard | Maynard Public Works | White Pond Reservoir | SW | .367 |
| | | NASHOBA BROOK NEAR ACTON (12) | | | |
| 1201 | Acton | Acton Water District | Conant Well | GW | 0.172 |
| 1202 | Concord | Concord Water Department | Nagog Pond | SW | 1.071 |
| | | FORT POND BROOK (13) | | | |
| 1301 | Acton | Acton Water District | Clapp Well | GW | 0.157 |
| | | | Whitcomb Well | GW | .051 |
| 1302 | Acton | Acton Water District | Lawsbrook Wellfield | GW | .204 |
| | | | Marshall Well | GW | .065 |
| | | | School Street Well | GW | .204 |
| | | | Scribner Well | GW | .204 |
| | | ASSABET RIVER NEAR WESTBOROUGH (16) | | | |
| 1601 | Northborough | Northborough Water Department | Brigham Street Well | GW | 0.377 |
| 1602 | | | Lyman Street Well | GW | .000 |
| 1603 | Westborough | Westborough Department of Public Works | Andrews Well I | GW | .447 |
| | | | Andrews Well II | GW | .250 |
| | | | Wilkinson Well | GW | .149 |
| 1604 | Westborough | Westborough Department of Public Works | Otis Street Well | GW | .466 |
| | | COLD BROOK (17) | | | |
| 1701 | Northborough | Northborough Water Department | Crawford Street Well | GW | 0.029 |

Table 2. Wastewater-return sites and return amounts in the Concord River Basin, Massachusetts, 1989

[Map identifier: The first one or two digits indicate the aquifer area and the last two digits identify the individual site. Numbers in parentheses correspond to aquifer areas shown in figure 3. Mgal/d, million gallons per day]

| Map identifier (fig. 3) | Town | Company | Return location | Annual wastewater returns (Mgal/d) |
|---|---|---|---|---|
| | | CONCORD RIVER NEAR BILLERICA (1) | | |
| 102 | Billerica | Billerica Massachusetts Corrections Institute | Concord River | 0.104 |
| 103 | Billerica | Billerica Wastewater Treatment Plant | | 2.290 |
| 104 | Lowell | Industry | | .001 |
| | | SUDBURY AND CONCORD (5) | | |
| 509 | Concord | Concord Wastewater Treatment Plant | Concord River | 1.026 |
| 510 | Wayland | Laboratory | Sudbury River | .000 |
| | | WASH BROOK (7) | | |
| 708 | Marlborough | Marlborough East Wastewater Treatment Plant | Hagar Pond | 3.207 |
| | | SUDBURY RIVER NEAR ASHLAND (9) | | |
| 903 | Ashland | Concrete plant | Sudbury River | 0.050 |
| | | | Sudbury River | .050 |
| | | ASSABET RIVER CONFLUENCE (I1) | | |
| 1115 | Concord | Concord Massachusetts Corrections Institute | Assabet River | 0.259 |
| 1116 | Concord | Middlesex School | Spencer Brook | .017 |
| 1117 | Hudson | Hudson Wastewater Treatment Plant | Assabet River | 2.035 |
| 1118 | Maynard | Maynard Wastewater Treatment Plant | Assabet River | 1.167 |
| | | ASSABET RIVER NEAR WESTBOROUGH (16) | | |
| 1605 | Marlborough | Marlborough West Wastewater Treatment Plant | Assabet River | 1.599 |
| 1606 | Westborough | Westborough Wastewater Treatment Plant | Assabet River | 4.032 |

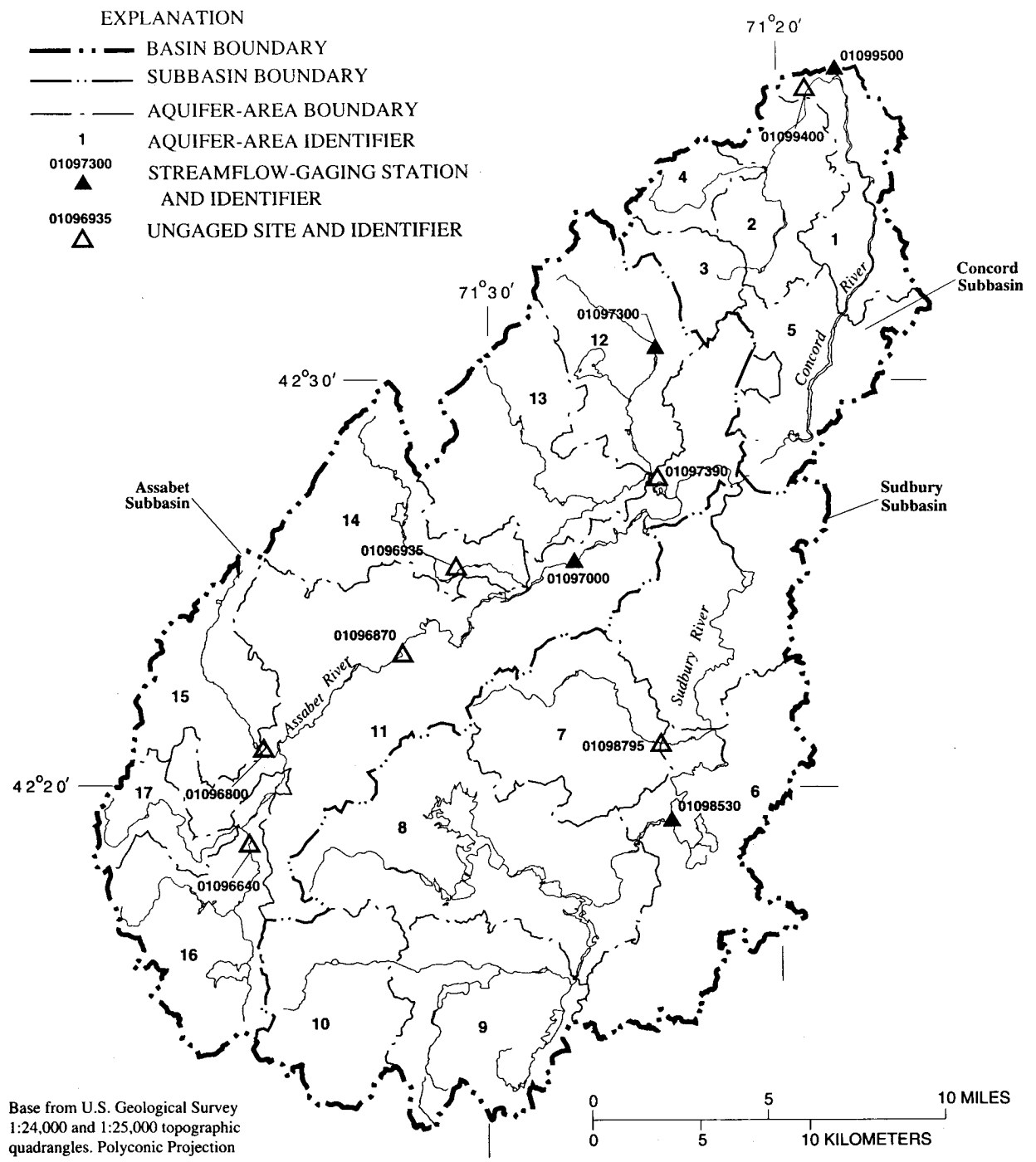


**Figure 4.** Location of U.S. Geological Survey streamflow-gaging stations and ungaged measurement sites in the Concord River Basin, Massachusetts.

## ESTIMATED AVAILABILITY OF WATER

Potential ground water available from aquifer areas was determined using streamflow-duration curves and a finite-difference ground-water-flow model. The available ground water, based on the combined hydrograph-separation and streamflow-duration curve analysis, depends strictly on the areas of the stratified-drift deposits and was estimated for all 17 aquifer areas. The ground-water-flow model involved more detailed hydrologic information.

### Water Availability During Periods of No Recharge, Based on Hydrograph-Separation and Streamflow-Duration Curves

As a result of the close hydraulic connection between surface water and ground water, streamflow data from a gaging station can be used to estimate availability of water from an aquifer area during periods of no recharge (Yager, 1991). The amount of water available during a period of no recharge for each aquifer area in the Concord River Basin was estimated by means of a combined hydrograph-separation and streamflow-duration-curve analysis of data from the South Acton station.

Streamflow on a hydrograph is combined (1) direct surface-water runoff, (2) ground-water discharge to the stream, (3) interflow discharge to the stream, and (4) direct precipitation on the channel (Viessman and others, 1977). After several days of no precipitation and during periods of no recharge to the aquifer, the major or only component that is represented by the streamflow is the ground-water discharge. This condition is common during the late spring and summer.

Streamflow-duration curves show the percentage of time during which streamflows are equaled or exceeded at a specific site for the period of record analyzed. If conditions such as land use and climate in the basin remain constant, the streamflow-duration curve also can be considered a probability curve, which can be used to estimate the percentage of time that a given streamflow will be equaled or exceeded in the future (U.S. Geological Survey, 1977).

For this investigation, limits had to be defined and assumptions had to be made about the streamflow-gaging stations and the aquifer areas to use the combined hydrograph-separation and streamflow-duration-curve analysis for estimates of water availability in the aquifer areas:

1. The gaging station is downgradient from a stratified-drift area that is hydraulically connected to the stream.
2. The gaging station is in a bedrock or till area with no ground-water underflow.
3. Streamflow is not regulated or diverted in the basin upstream from the gaging station.
4. The thickness of the aquifer areas is assumed to be negligible as compared to areal extent.
5. The hydrologic properties within each aquifer area are uniform.

Streamflow record for the gaging station on Nashoba Brook at South Acton (01097300) is the only long-term record of unregulated streamflow in the Concord River Basin. The South Acton station, which has been in operation since 1963, is in the middle of the Nashoba Brook aquifer area (fig. 4). The drainage area for the South Acton station is 11.7 $mi^2$, compared to 21.1 $mi^2$ for the Nashoba Brook aquifer area. The area of the stratified drift upgradient from the South Acton station is 7.3 $mi^2$. The total area of stratified drift in the Nashoba Brook aquifer area is 9.6 $mi^2$.

A hydrograph of the average of daily mean streamflow for the 1970-92 period of record for the South Acton station was plotted for separation (fig. 5). A straight line was drawn through the lowest points of the general recession that occurs after the spring peak. A second straight line was drawn through the lowest points of the late spring and summer streamflow period. In such analyses, the second line is usually not as steep as the first line because it represents the slow drainage from the upgradient aquifer when the other components for the total streamflow have been mostly or entirely taken up by evapotranspiration (ET), thus eliminating recharge. The second line is not a recession line because the plot is for a composite of years. The point where the

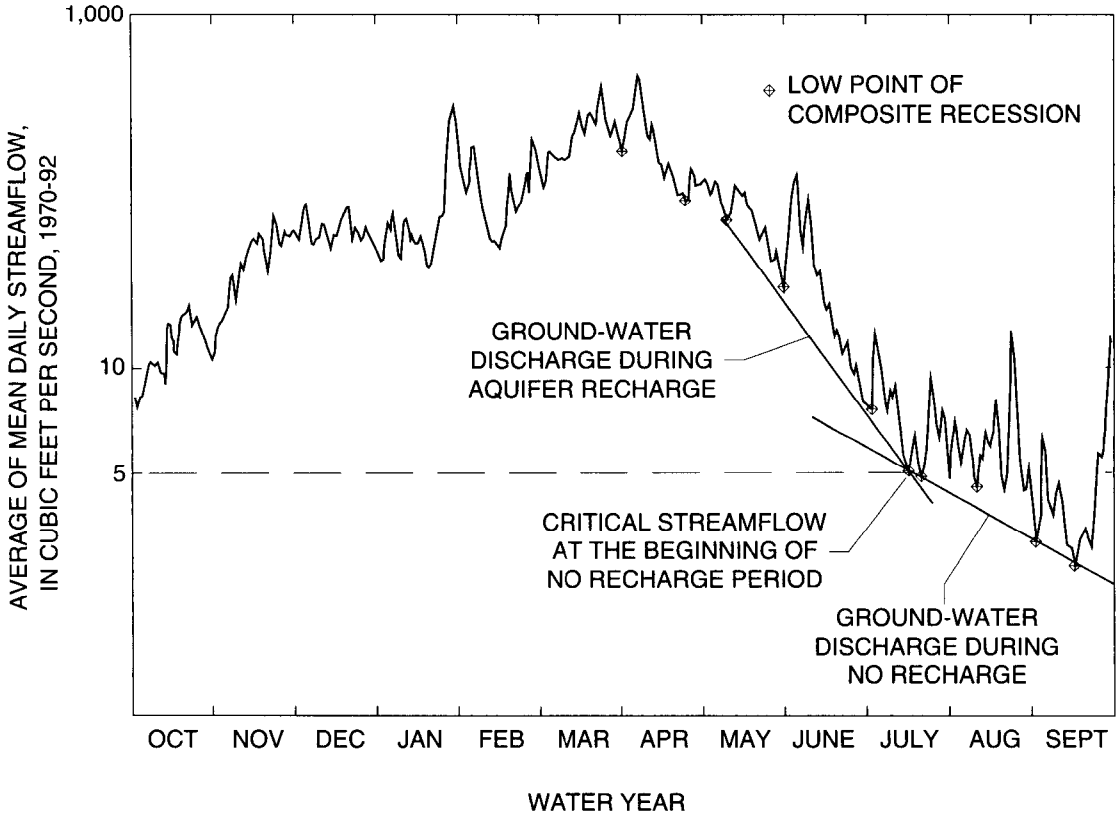


**Figure 5.** Average of daily mean streamflow for Nashoba Brook at South Acton, Massachusetts (station 01097300), 1970-92.

lines cross is the highest streamflow on average that could be identified for the period of no recharge. The highest average of daily mean streamflow of no recharge from October 1, 1970, through September 30, 1992, is about 5 $ft^3/s$ (fig. 5).

The volume of water potentially available from the aquifer area upgradient from the South Acton station during a period of no recharge is represented by the area under the streamflow-duration curve defined by the maximum streamflow of no recharge and a minimum streamflow desired to be maintained in the stream. The highest daily mean streamflow during a period of no recharge, 5 $ft^3/s$, corresponds to the 70-percent duration on the streamflow-duration curve for the South Acton station (fig. 6). The minimum daily mean streamflow is that which is equaled or exceeded 98 percent of the time, as defined in previous studies (Lapham, 1988). The average time required for the daily mean streamflow to decrease from 70- to 98-percent duration during a period of no recharge is about one-third of a year or about 102 days. The streamflow-duration curve is integrated between 70- and 98-percent duration to calculate a volume of available water. The volume of available water for the area upgradient from the South Acton station is $20.8 \times 10^6$ $ft^3$ for a 102-day period of no recharge or $2.85 \times 10^6$ $ft^3/mi^2$ of stratified drift. This volume per area of stratified drift closely agrees with ratios determined for similar aquifer areas in the Taunton River Basin (Lapham, 1988) for the same 102-day interval of the duration curve.

The volume of available water in the 17 aquifer areas in the Concord River Basin can be estimated from the volume determined for the area upgradient from the South Acton station by the equation

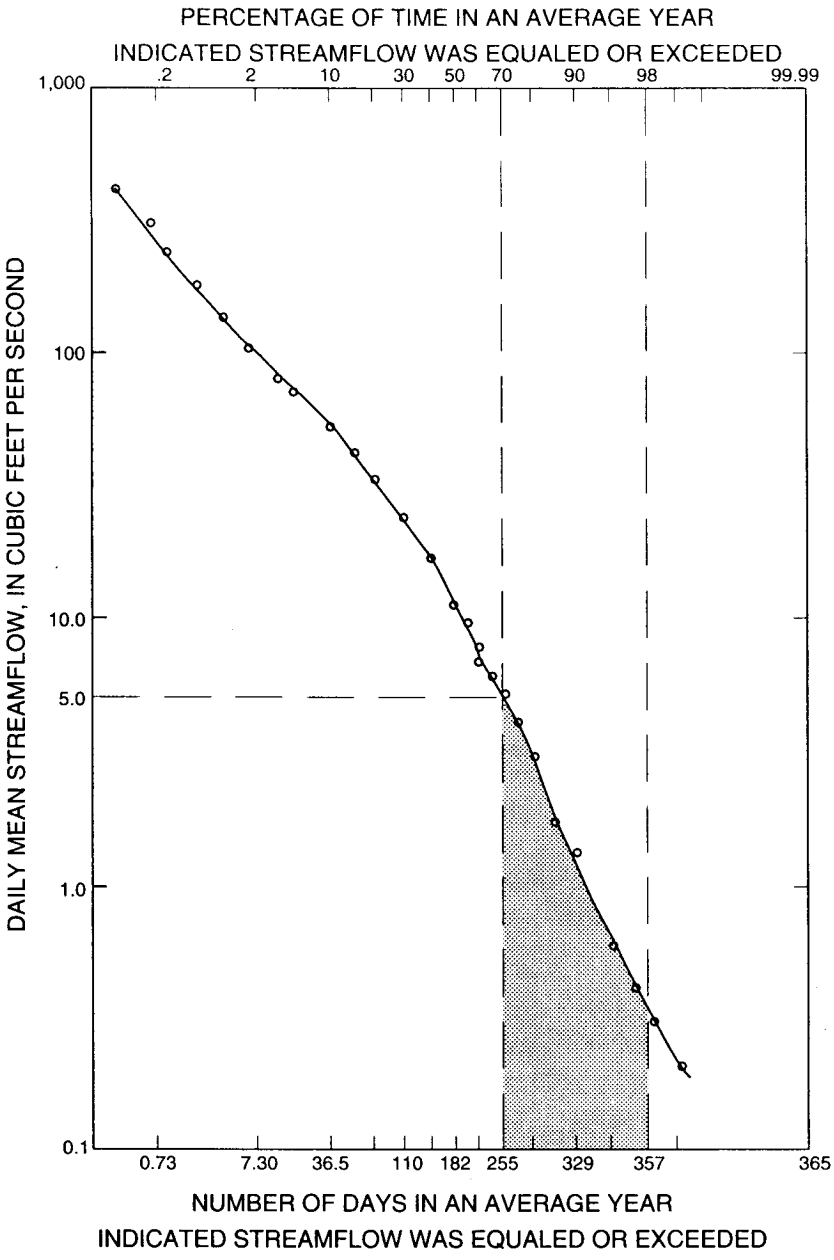


**Figure 6.** Streamflow-duration curve for Nashoba Brook at South Acton, Massachusetts (station 01097300), 1970-92.

$$V_{aquifer} = (V_{SA} / SD_{SA}) * SD_{aquifer}, \quad (1)$$

where

$V_{aquifer}$ is the volume of available water in any aquifer area in the Concord River Basin, in million cubic feet, for the selected period of no recharge;

$V_{SA}$ is the volume of available water upgradient from the South Acton station, in million cubic feet;

$SD_{SA}$ is the area of stratified drift upgradient from the South Acton gage, in square miles; and

$SD_{aquifer}$ is the area of stratified drift in the aquifer area, in square miles.

The volume of available water for each of the 17 aquifer areas in the Concord River Basin was estimated from equation 1 and is listed in table 3. The volumes in table 3 are estimates of the available water that would naturally drain from the individual aquifer areas over a 102-day period of no recharge while maintaining the specified minimum streamflow. The total volume of available water for the entire Concord River Basin is estimated to be $561 \times 10^6$ $ft^3$ (4,190 Mgal) for the 102-day period of no recharge. This volume reflects only what would drain from the system naturally while maintaining a streamflow at the 98-percent duration.

## Current and Potential Water Availability for Three Withdrawal Scenarios

Ground-water-flow models have successfully demonstrated the interaction between surface-water and ground-water systems in the past. Collins (1972) showed that, as water continues to be withdrawn from a well, especially during periods of no recharge, ground-water flow to a river may gradually decline to the point when flow direction reverses (that is, flow is from the river to ground water). For this study, the finite-difference ground-water-flow model of McDonald and Harbaugh (1988) was used to simulate three withdrawal scenarios during a period of no recharge in parts of the River Meadow Brook aquifer area and the Sudbury and Concord aquifer area (fig. 7). The model simulations were done on these aquifer areas because of the depth and areal continuity of the aquifers within the areas.

Table 3. Volumes of available water from aquifer areas in the Concord River Basin, based on hydrograph-separation and streamflow-duration curve analysis for Nashoba Brook at South Acton, Massachusetts

[$ft^3$, cubic foot., $mi^1$, square mile]

| Map identifier (fig. 2) | Aquifer areas | Area of stratified drift ($mi^1$) | Volume of available water ($10^6$ $ft^3$) |
|---|---|---|---|
| 1 | Concord River near Billerica | 9.68 | 27.6 |
| 2 | River Meadow Brook | 8.79 | [1]25.0 |
| 3 | Beaver Brook | 3.00 | 8.50 |
| 4 | Heart Pond | 3.60 | 10.4 |
| 5 | Sudbury and Concord | 31.6 | [1]89.9 |
| 6 | Lake Cochituate | 18.4 | 52.5 |
| 7 | Wash Brook | 19.7 | 56.1 |
| 8 | Sudbury River Reservoirs | 14.1 | 40.7 |
| 9 | Sudbury River near Ashland | 7.06 | 20.1 |
| 10 | Sudbury River near Westborough | 8.20 | 23.3 |
| 11 | Assabet River confluence | 34.2 | 97.7 |
| 12 | Nashoba Brook near Acton | 9.60 | 27.3 |
| 13 | Fort Pond Brook | 8.10 | 23.1 |
| 14 | Elizabeth Brook | 5.80 | 16.6 |
| 15 | North Brook | 3.60 | 10.2 |
| 16 | Assabet River near Westborough | 8.40 | 24.0 |
| 17 | Cold Brook | 2.80 | 7.86 |
| | Total[2] | 197 | 561 |

[1]Used as available-water limit for the results from the ground-water-flow model simulations for the River Meadow Brook and the Sudbury and Concord aquifer areas.

[2]Totals rounded to nearest whole number.

River Meadow Brook Model Area.-The River Meadow Brook model area covers most of the River Meadow Brook aquifer area, including River Meadow Brook and its tributaries (fig. A1, at back of report). The aquifers in the model area, which have saturated thicknesses of 0 to 80 ft and hydraulic conductivities of 0 to 100 ft/d, are primarily in Chelmsford and parts of Lowell, Billerica, and Carlisle (figs. A2 and A3, at back of report). The model area is highly developed and densely populated, and it is crossed by several Interstate highways.

Sudbury and Concord Model Area.-The Sudbury and Concord model area covers all significant aquifers in the Sudbury and Concord aquifer area (fig. A4, at back of report). The model grid extends from Wash Brook to about 2 mi downstream from the confluence of the Sudbury River with the Assabet River. The aquifers in the model area have saturated thicknesses of 0 to 140 ft and hydraulic conductivities of 0 to 150 ft/d (figs. A5 and A6, at back of report). Land use in the model area is primarily agricultural, single-family residences, forests, and open space with pockets of industrial and commercial land use. Wetlands are extensive along the Sudbury River.

## Description of Model

Model grids were developed for the River Meadow Brook and the Sudbury and Concord model areas. The grid cell dimensions are 1,000 by 1,000 ft. The grid for the River Meadow Brook model area covers about 22 $mi^2$, and the grid for the Sudbury and Concord model area covers about 66 $mi^1$. The model-grid data for the two model areas include stream, well, and wetland cells along with saturated thickness and hydraulic conductivity.

The well cells correspond to existing and hypothetical wells. Because of the size of the cells, well cells behave like well fields, and some well cells may contain more than one existing well. Hypothetical well-cells were placed in undeveloped areas with the transmissivity greater than 4,000 $ft^2/d$ and the saturated thickness greater than 30 ft. The River Meadow Brook model area contains nine existing wells in eight well cells (fig. A 1) and an additional six hypothetical wells in six well cells. The Sudbury and Concord Rivers model area contains 8 existing wells in 6 well cells (fig. A4) and an additional 18 hypothetical wells in 18 well cells.

Transmissivities and saturated thicknesses were determined from maps created from lithologic logs collected during the early 1970's (B.P Hansen, U.S. Geological Survey, written commun., 1972). The saturated thickness used for the models was modified slightly based on seismic-refraction and marine-reflection surveys done during this study. Transmissivities for the existing-well cells were derived from results of pumped-well tests (B.P. Hansen, U.S. Geological Survey, written commun., 1972).

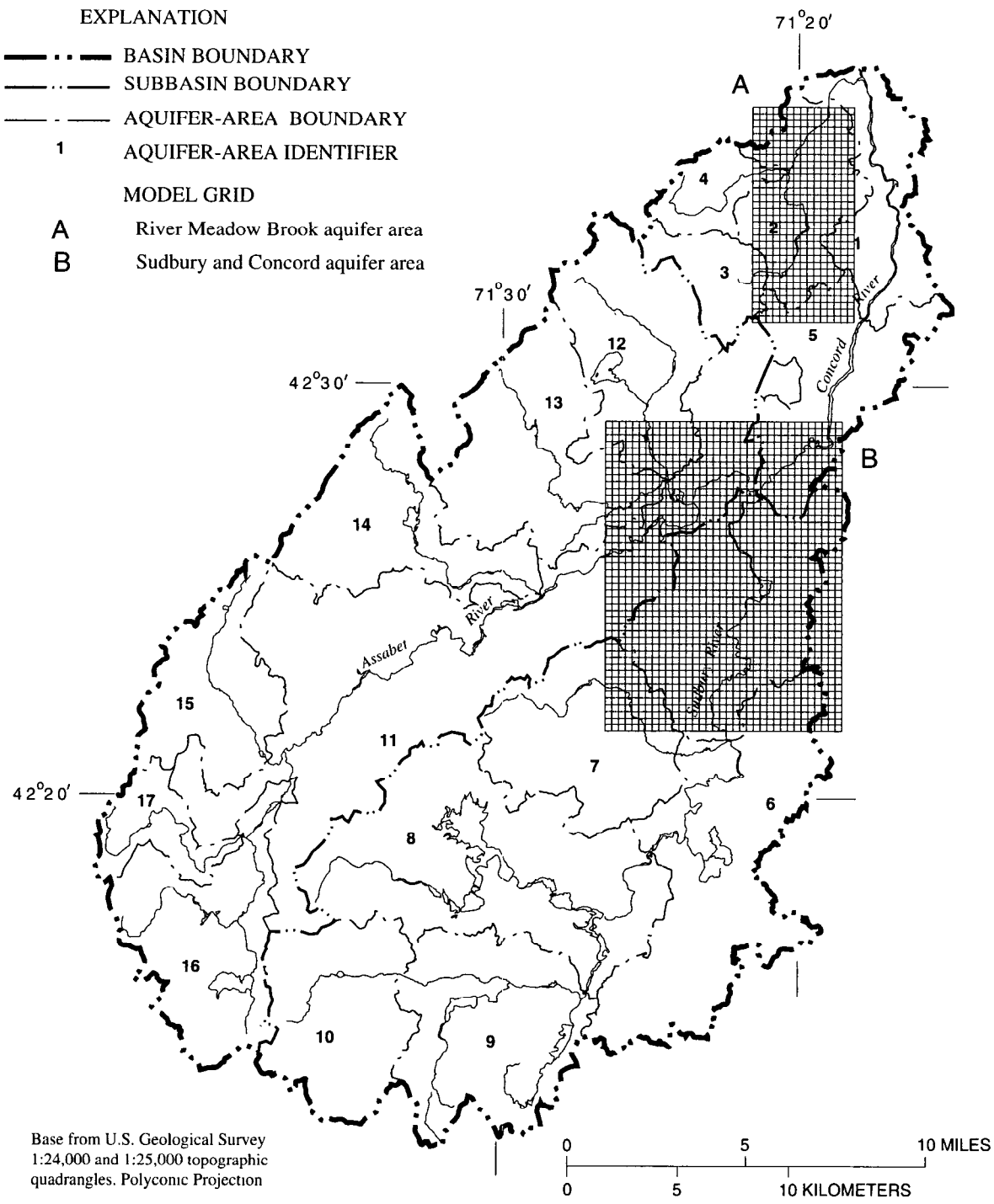


**Figure 7.** Location of ground-water-flow-model areas in the Concord River Basin, Massachusetts.

Hydraulic conductivity ($K$) for each cell was calculated from transmissivity ($T$) and saturated thickness ($b$) by use of the equation

$$K = T/b, \qquad (2)$$

where

$K$ is the hydraulic conductivity, in feet per day;
$T$ is transmissivity, in feet squared per day; and
$b$ is saturated thickness, in feet (Freeze and Cherry, 1979).

### Assumptions and Limitations

For this investigation, the ground-water-flow model is theoretical and is based on generalized hydrogeologic information; it is not meant to be used to simulate actual ground-water and surface-water levels in the two model areas. The model is intended only be used to simulate the interaction between ground water and surface water. The user must define all the limits to the model to evaluate the model results.

The following conditions were assumed for the model:

1. The aquifer material is homogeneous and isotropic within individual grid cells.

2. Ground-water flow is horizontal.

3. No ground water flows into or from the till and bedrock. The contact between aquifer materials and till and bedrock form the model boundary; otherwise the river subbasin forms the model boundary.

4. The specific yield is constant throughout the aquifer and is set at 0.2, which is an average for stratified-drift aquifers in New England (Lapham, 1988).

5. Two periods of no recharge are used for the simulations. One period of 180 days was selected because it approximates an extended drought in New England. A second period of 102 days was selected, on the basis of results from the South Acton streamflow-record analysis, which identified this as a period of no recharge in an average year for October 1, 1970, through October 1, 1992.

6. All ground-water and surface-water levels initially were set at the top of the aquifer.

7. For the river cells in the model, the streambed thickness was assumed to be 1 ft and the vertical hydraulic conductivity of the streambed material was assumed to be 5 ft/d on the basis of similar studies by (Lapham, 1988). The rivers are assumed to be in direct hydraulic connection with the aquifers.

8. A limit is set for availability of surface water. The river interaction subroutine in the model continues to show surface-water contributions to the ground-water system although ground-water levels drop below the depth of the riverbed and the aquifer loses hydraulic connection with the river. The limit for each model was calculated by use of equation 1 and is listed in table 3. This limit, which is $25\times10^6$ ft$^3$ for the River Meadow Brook model and $89.9\times10^6$ ft$^3$ for the Sudbury and Concord Rivers model, is called the available water limit throughout the rest of this report.

9. The source of water in model simulations can be either (a) interception of water that would otherwise have flowed to a river or (b) ground-water storage. Because this theoretical model cannot differentiate between the two ground-water sources, it is assumed that all water is flowing toward a river.

10. Wetland cells are assigned an initial average potential evapotranspiration ($ET$) rate of 0.01 ft/d or 44 in/yr, as calculated by use of the Thornthwaite equation (Chow, 1964). Evapotranspiration ceases in the wetland cells once ground-water levels reach a predetermined critical depth of 3 ft in the model.

## Simulated Withdrawal Rates and Volumes

Three withdrawal scenarios were simulated to assess current and potential interaction between surface water and ground water. A simulation of current interaction was based on existing wells and 1989 annual withdrawals for these wells. Simulations of potential interaction were estimated by setting initial water levels in existing- or hypothetical-well cells as drawdowns of 10 or 65 percent of the saturated thickness. The 10-percent drawdown results simulate processes at rates greater than the 1989 withdrawals but not at maximum withdrawal rates. The 65-percent drawdown results simulate maximum potential withdrawals based on well performance (Driscoll, 1986).

The simulated withdrawal rate and volume of water withdrawn from the well cells for the 1989 withdrawal rates, 10-percent drawdown, and 65-percent drawdown in River Meadow Brook model area and the Sudbury and Concord Rivers model area are shown in figures 8 through 13. The volume of withdrawn water is calculated by multiplying the withdrawal rate by the number of days in the simulation when a withdrawal is recorded.

Withdrawal rates and volumes of withdrawn water for the River Meadow Brook model area based on existing public-supply wells and 1989 withdrawals are shown in figure 8. The total withdrawal rate is about $0.15\times10^6$ $ft^3/d$. The surface-water contribution to the total withdrawal rate exceeds the ground-water contribution after 5 days have transpired (fig. 8*A*). The total volume of water withdrawn is largely surface water (fig. 8*B*). These two results indicate that the existing wells are close to the river and that most of the water withdrawn is supplied indirectly by the river. The total volume of withdrawn water reaches the available water limit at 180 days (fig. 8*B*).

Withdrawal rates and total volumes of withdrawn water for the River Meadow Brook model area based on existing and hypothetical wells and drawdowns set initially at 10 percent of saturated thickness are shown in figure 9. The surface-water contribution to the withdrawal rate exceeds ground-water contribution after about 40 days have transpired. In this simulation, the ground-water withdrawal rate (fig. 9*A*) constitutes a greater part of the total withdrawal rate because the hypothetical-well cells are farther from the river. This change in proportions of surface water and ground water is reflected in a larger volume of ground water withdrawn (fig. 9*B*). The total volume of water withdrawn reaches the available water limit at about 50 days. In reality, the line representing the total volume of water withdrawn would tend to flatten out as less water was available from the river.

Withdrawal rates and volumes of withdrawn water for the River Meadow Brook model area based on existing and hypothetical wells and drawdowns set initially at 65 percent of saturated thickness are shown in figure 10. Again, the ground-water withdrawal rates are initially much greater than surface-water withdrawal rates (fig. 10*A*). The ground-water withdrawal rates decrease by almost one-half within the first 50 days of simulated withdrawals, whereas the surface-water withdrawal rates are relatively constant. The surface-water contribution to the withdrawal rate surpasses the ground-water contribution at about 80 days. The total water volume withdrawn exceeds the available water limit at 10 days (fig. 10*B*), and in reality, the line would begin to flatten out at that point.

Simulated withdrawal rates and volumes of water withdrawn for the Sudbury and Concord model area based on existing wells and 1989 withdrawals are shown in figure 11. The 1989 withdrawal rate is constant at about $0.5\times10^6$ $ft^3/d$. The ground-water contribution to the withdrawal rate decreases during the simulation period until the contributions from ground water and surface water are approximately equal at 180 days (fig. 11*A*). The areal extent and depth associated with the Sudbury and Concord aquifer area are greater than those for the River Meadow Brook aquifer area. Therefore, well cells are farther from the rivers, and the importance of surface-water contribution to the withdrawal rate is reduced. The increased volume of ground water withdrawn at the well cells supports this observation (fig. 11*B*). The total volume of water withdrawn does not reach the available water limit of $89.9\times10^6$ $ft^3$ before the simulation is terminated at 180 days.

Withdrawal rates and the volume of water withdrawn for the Sudbury and Concord model area based on existing and hypothetical wells and drawdowns set initially at 10 percent of saturated thickness are shown in figure 12. The surface-water contribution to the withdrawal rate exceeds the ground-water contribution at roughly 50 days (fig. 12*A*). Total volume withdrawn reaches the available water limit in 50 days (fig. 12*B*) and would be expected to flatten out.

Withdrawal rates and volume of water withdrawn for the Concord and Sudbury model area based on existing and hypothetical wells and drawdowns set initially at 65 percent of saturated thickness are shown in figure 13. The surface-water contribution to the withdrawal rate does not exceed the ground-water contribution until approximately 125 days (fig. 13*A*), and this result is reflected in a consistently larger volume of ground water than surface water withdrawn (fig. 13*B*). The total volume of water withdrawn reaches the available water limit at about 10 days, and the line would be expected to flatten out.

In New England, wetlands have a strong hydraulic connection with surficial aquifers, cover a large part of the top of these aquifers, and can have a significant effect on a hydrologic system (O'Brien, 1988). Because the Sudbury River is flanked by a large area of wetlands, the role of the wetlands was investigated in the Sudbury and Concord model simulations. The wetland cells were identified by use of topographic maps, and a potential *ET* was assigned to each cell. A depth to water of 3 ft was selected within a wetland cell to determine when *ET* would cease. The total potential *ET* by wetlands is shown in figure 13*A*. The line on the plot indicates negative streamflow corresponding to loss of water from the ground-water system. With time, the line trends toward zero or a constant *ET* rate. As the ground-water levels decrease, less water is available to plants and the result is less *ET*. The overall withdrawal rate from the hydrologic system is at a lower rate than if *ET* is not present (fig. 13*A*).

For this report, the total volume of water withdrawn by the well cells in each simulation is assumed to be the water available during a period of no recharge. The River Meadow Brook aquifer area and the Sudbury and Concord aquifer area simulations are summarized in table 4 for the three withdrawal scenarios. The estimated volume of available water from the Sudbury and Concord aquifer area is roughly four times the volume available from the River Meadow Brook aquifer area when the water levels in the well cells are initially set at 65 percent of the saturated thickness. The Sudbury and Concord Rivers aquifer area is four times as large as the River Meadow Brook aquifer area; therefore, more water is available. The Sudbury and Concord Rivers aquifer area includes the wetlands along the Sudbury River, which can provide additional surface water to the ground-water system. The slope of the Sudbury River is low and, combined with the storage capacity of the wetlands, the residence time of water is longer and the surface-water system functions more as a lake than as a river.

**Table 4.** Volumes of available water from River Meadow Brook and Sudbury and Concord aquifer areas, Massachusetts, during 102-day period on the basis of ground-water-flow simulations

[$ft^3$, cubic feet]

| Aquifer areas (fig. 2) | Estimated total volume of available water ($10^6$ $ft^3$) | Available water-volume limit ($10^6$ $ft^3$) |
|---|---|---|
| River Meadow Brook (2) | | |
| 1989 withdrawals | 14.0 | 25.0 |
| 10-percent drawdown | 49.0 | |
| 65-percent drawdown | 175.0 | |
| Sudbury and Concord (5) | | |
| 1989 withdrawals | 34.0 | 89.9 |
| 10-percent drawdown | 151 | |
| 65-percent drawdown | 500 | |

Given the assumption that the ground water involved in the interaction would have eventually discharged to the stream, several important observations can be made. First, the River Meadow Brook aquifer area produces only about one-half the total volume of available water, $25 \times 10^6$ $ft^3$ (table 3), when the 1989 withdrawal rates are simulated. Second, the volumes of water withdrawn when the 10- and 65-percent drawdowns were simulated exceed the total available volume for the River Meadow Brook aquifer area. Third, the volume of water withdrawn from the Sudbury and Concord Rivers aquifer area is a bit more than one-third the total available water, $89.9 \times 10^6$ $ft^3$ (table 3), when the 1989 withdrawals are simulated. Fourth, the volumes of water withdrawn when the 10- and 65-percent drawdowns were simulated significantly exceed the total available volume for the Sudbury and Concord aquifer area.

# SUMMARY

An understanding of water availability requires an understanding of the interaction between surface-water and ground-water systems so that future resource management decisions can have a sound basis. The U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Management, studied the Concord River Basin by use of two techniques to determine the volume of water available in the surface-water and ground-water systems and to identify the interaction between these water systems. The interaction between surface water and ground water in the basin was defined by the investigators using a hydrograph-separation/streamflow-duration-curve analysis and a theoretical finite-difference ground-water-flow model.

Hydrograph separation combined with streamflow-duration-curve analysis was used to estimate the volume of available water in stratified-drift aquifers as a result of interaction with surface-water systems. Use of this method requires unregulated streamflow data from a gaging station downstream from the area overlying a stratified-drift aquifer and at a location of minimal ground-water underflow. Such a location would allow an estimate of ground-water flow during periods of low streamflow when all the streamflow is derived from ground water. A hydrograph separation was done on a composite hydrograph constructed from data collected from October 1, 1970, through September 30, 1992, for the Nashoba Brook station at South Acton. The highest average of daily mean streamflow during a period of no recharge was defined as 5 $ft^3/s$. This represents a daily mean streamflow that is exceeded or equaled 70 percent of the time on a streamflow-duration curve for the South Acton station. A minimum streamflow was selected where the streamflow at the station is exceeded or equaled 98 percent of the time. The average time between 70- and 98-percent duration on a streamflow-duration curve is available one-third of an average year, or 102 days. The streamflow-duration curve was integrated between 70- and 98-percent duration to calculate a volume of water, $20.8 \times 10^6$ ft'. This equates to $2.85 \times 10^6$ $ft^3/mi^1$ of water for the area of stratified drift above the South Acton station. This coefficient agrees with comparable coefficients for aquifers in the Taunton River Basin and was used to estimate the total available volume of water for 17 aquifer areas in the Concord River Basin at $561 \times 10^6$ $ft^3$.

A finite-difference ground-water-flow model was used to quantify the current and potential water availability for three withdrawal scenarios. The River Meadow Brook aquifer area and the Sudbury and Concord aquifer area were selected for the model simulations. Historical and newly acquired hydrologic and geologic data were used. Model grids were 1,000 by 1,000 ft. Simulations were run on three data sets: (1) actual 1989 well withdrawal rates and existing-well locations, (2) existing and hypothetical wells at which drawdowns were set initially at 10 percent of saturated thickness, and (3) existing and hypothetical wells at which drawdowns were set initially at 65 percent of saturated thickness.

Interpretation of the model results was based on the limit of available water during a period of no recharge, as determined by the combined hydrograph separation and streamflow-duration-curve analysis. At 1989 withdrawal rates, the amount of water produced from the River Meadow Brook aquifer area is a bit more than one-half the limit of $25 \times 10^6$ $ft^3$ of available water. In the Sudbury and Concord aquifer area, the amount produced is a bit more than one-third the limit of $90 \times 10^6$ $ft^3$ for the 1989 withdrawals. In both aquifer areas, production exceeds the available volume in the 10- and 65-percent-drawdown withdrawal simulations.

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# APPENDIX A

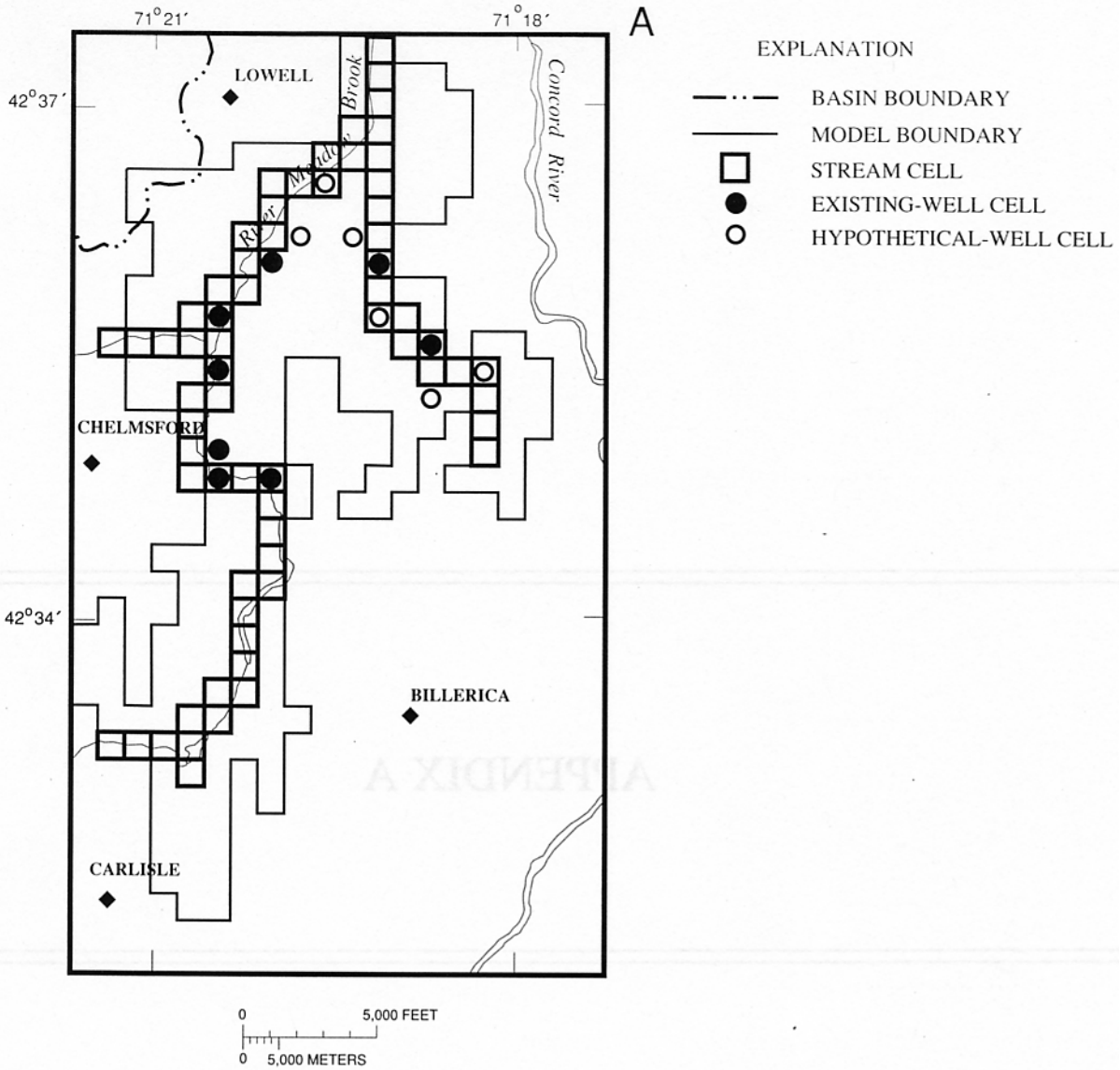


**Figure A1.** Grid for the model of the River Meadow Brook aquifer area, Massachusetts.

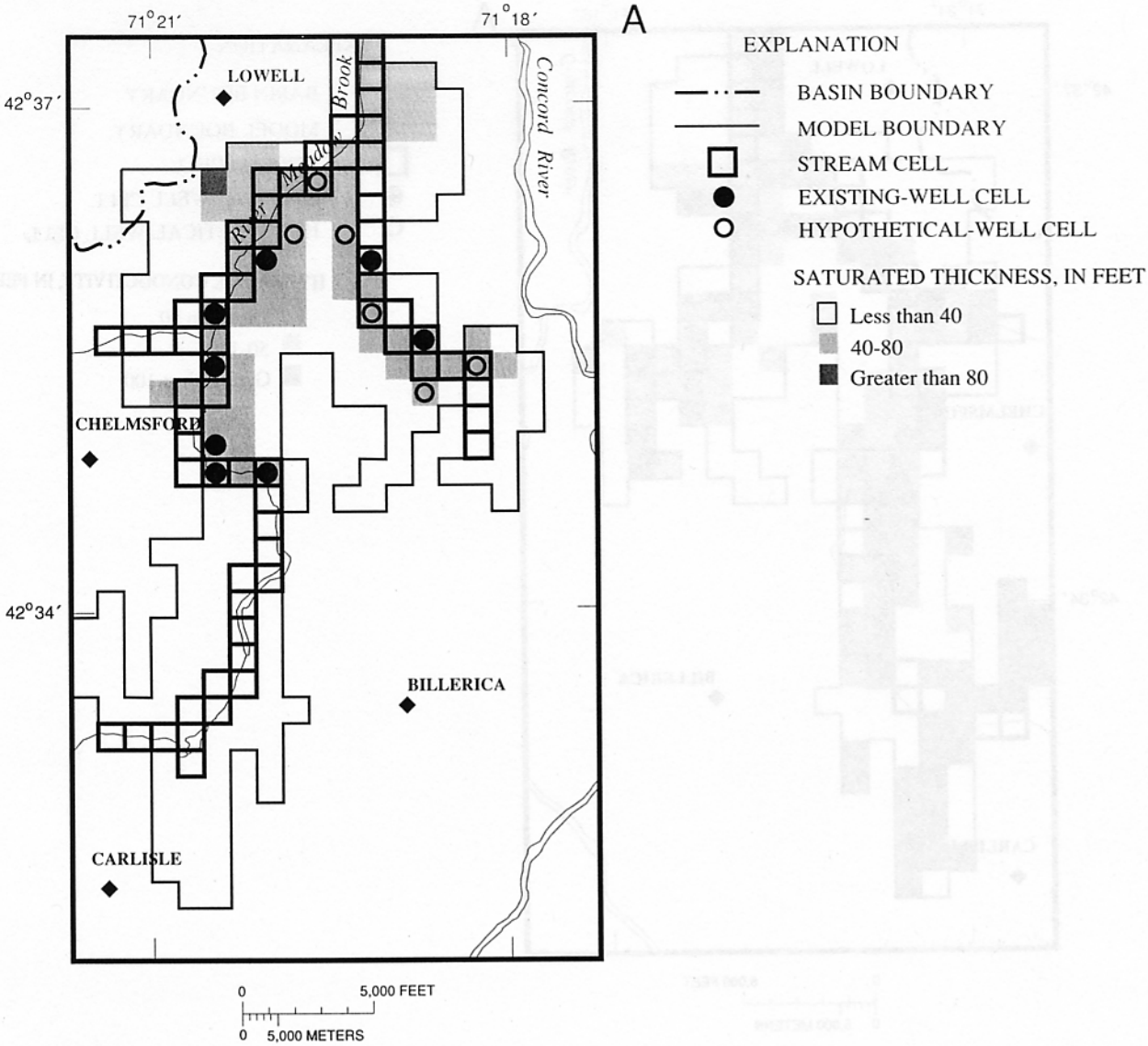


**Figure A2.** Ranges of saturated thickness used for the model of the River Meadow Brook aquifer area, Massachusetts.

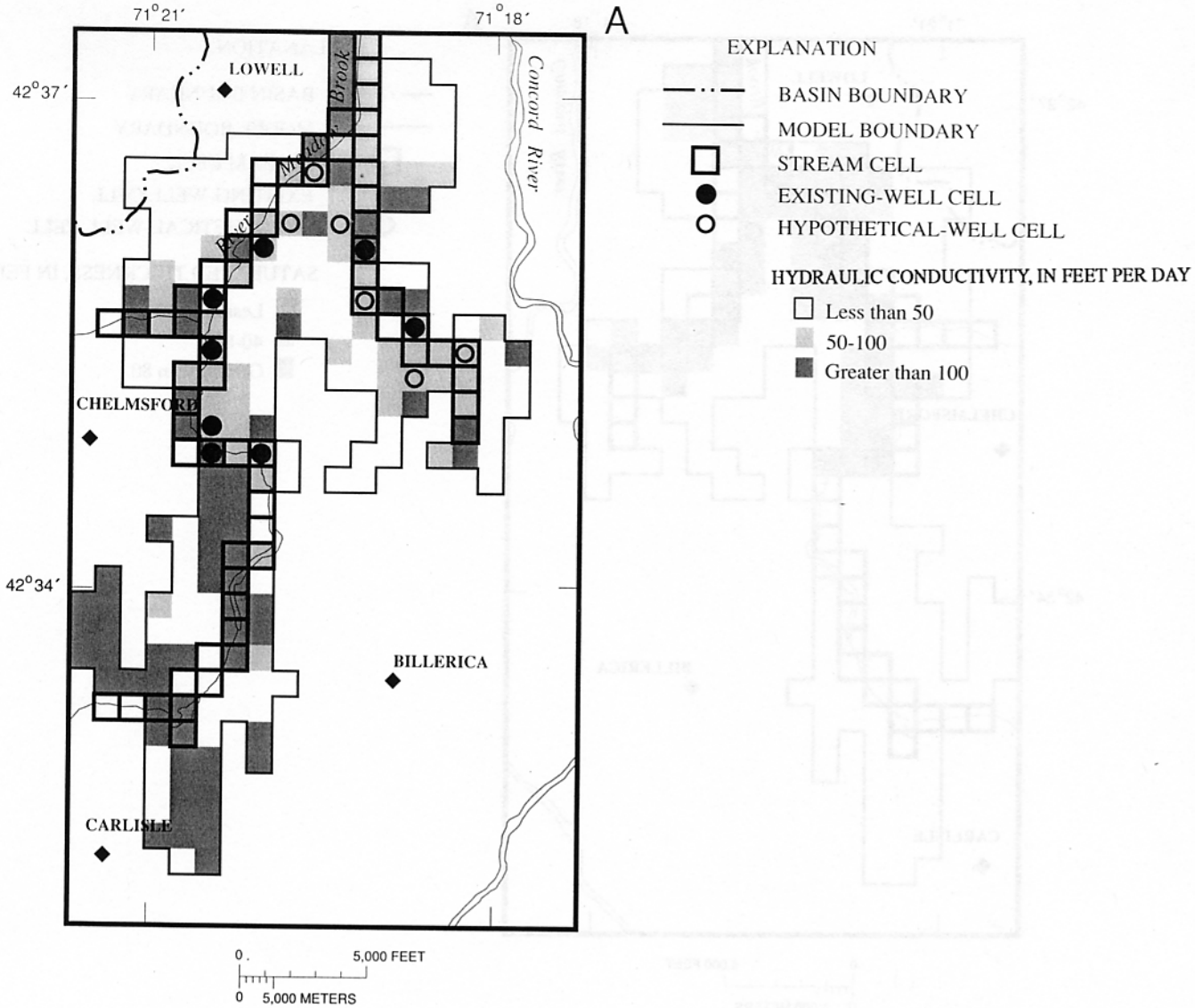


**Figure A3.** Ranges of hydraulic conductivity used for the model of the River Meadow Brook aquifer area, Massachusetts.

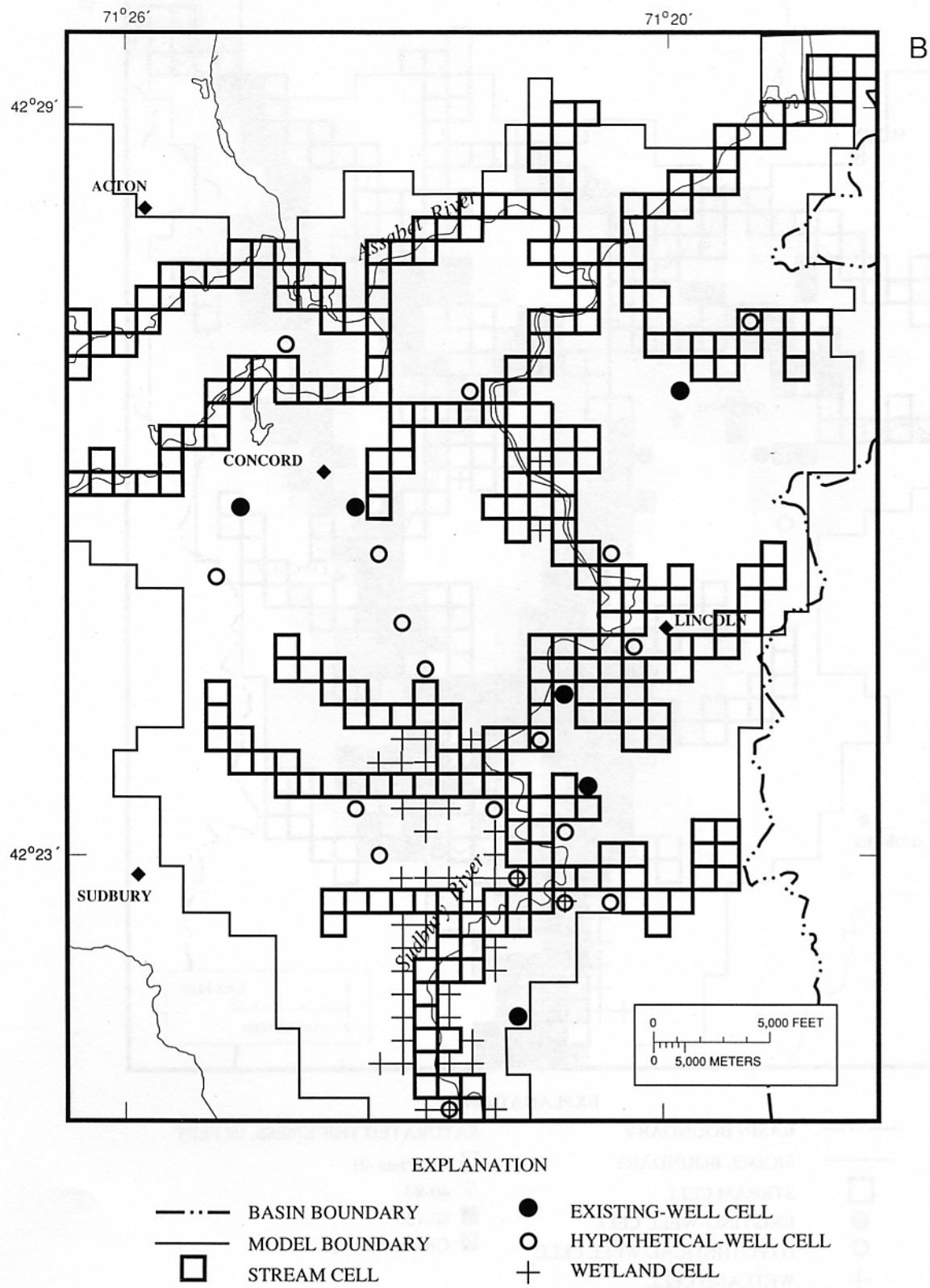


**Figure A4.** Grid for the model of the Sudbury and Concord aquifer area, Massachusetts.

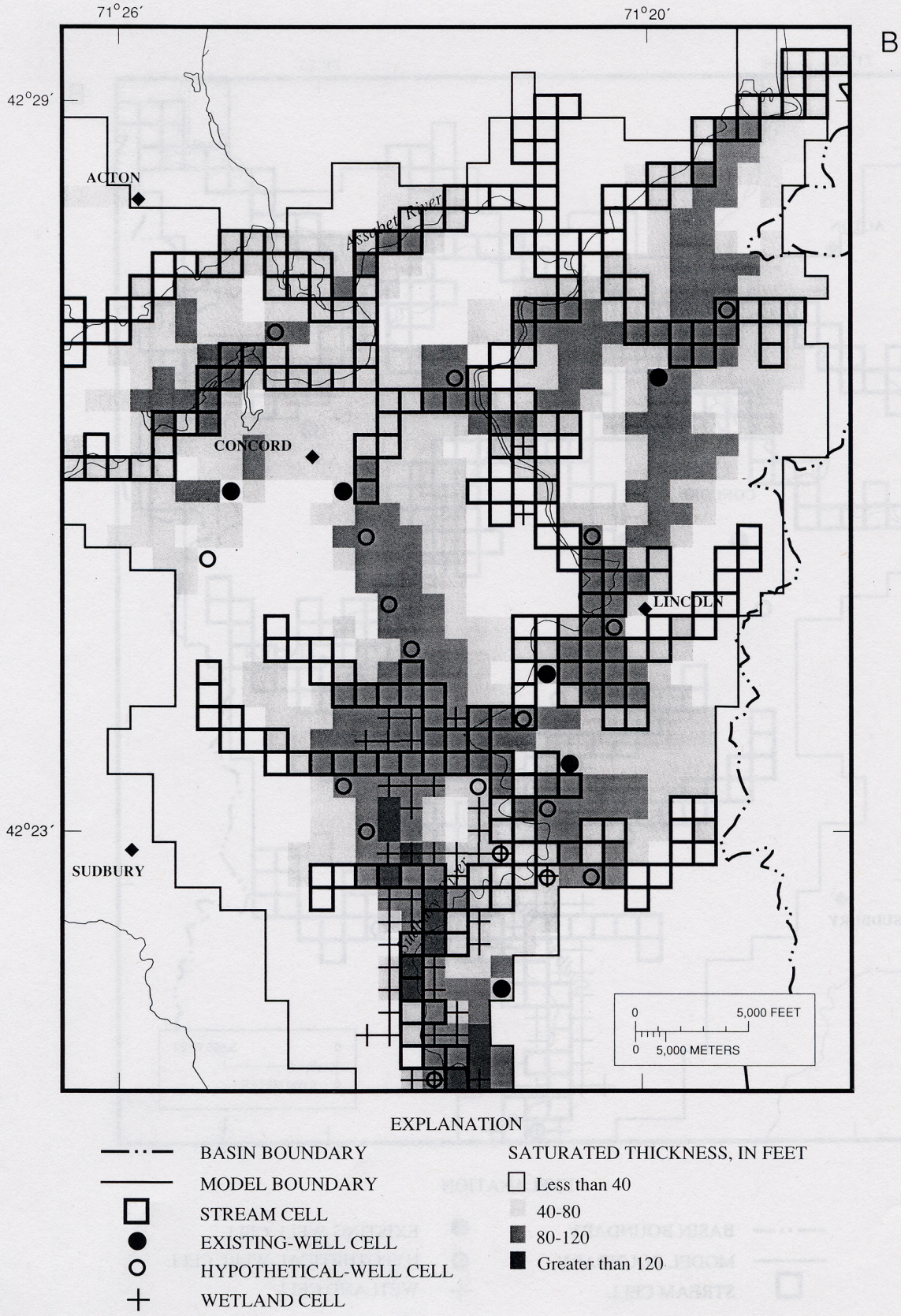


**Figure A5.** Ranges of saturated thickness used for the model of the Sudbury and Concord aquifer area, Massachusetts.

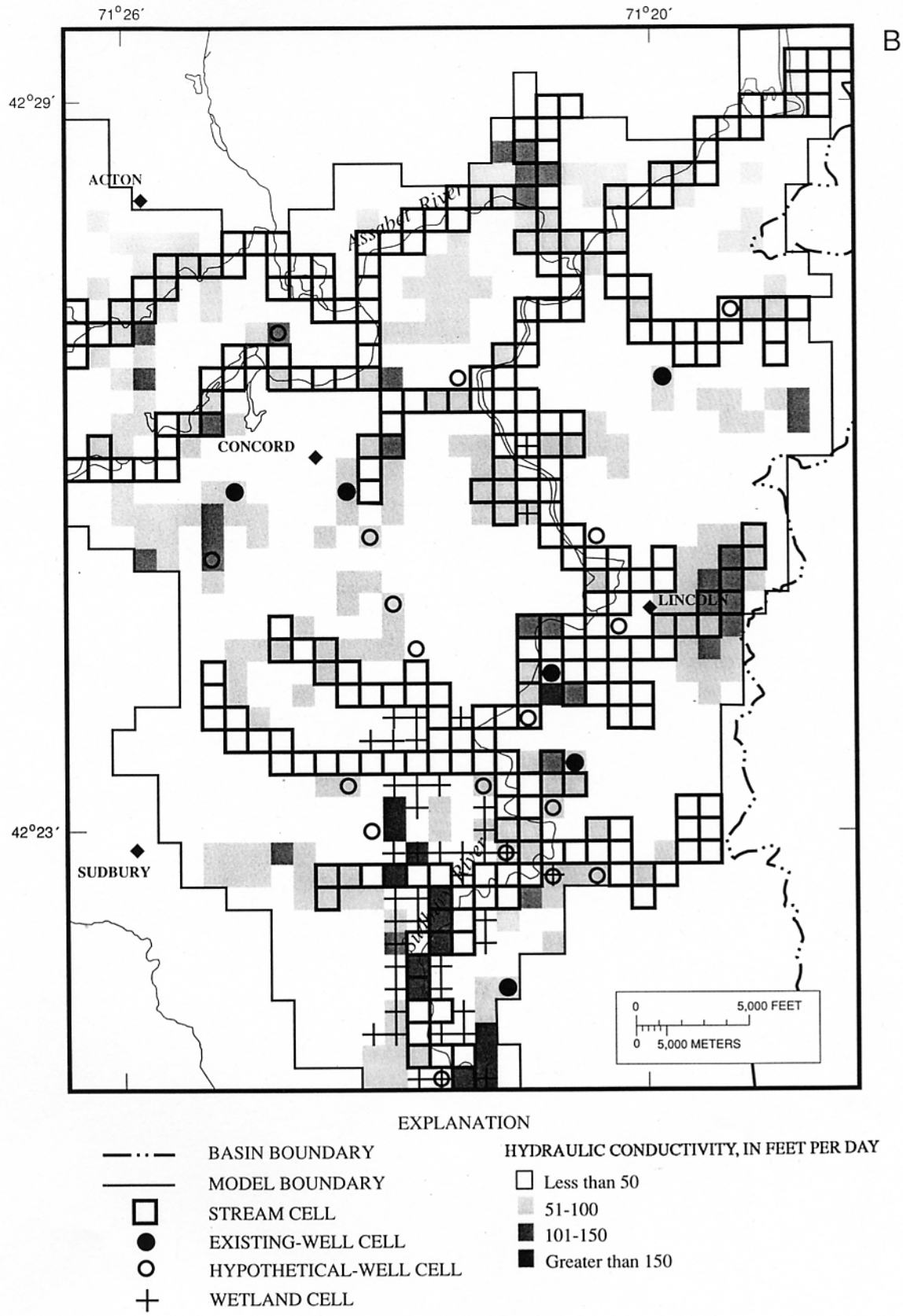


**Figure A6.** Ranges of hydraulic conductivity used for the model of the Sudbury and Concord aquifer area, Massachusetts.

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Bratton and Parker—ESTIMATED AVAILABILITY OF WATER FROM STRATIFIED-DRIFT AQUIFERS IN THE CONCORD RIVER BASIN, MASSACHUSETTS—WRIR 94-4256