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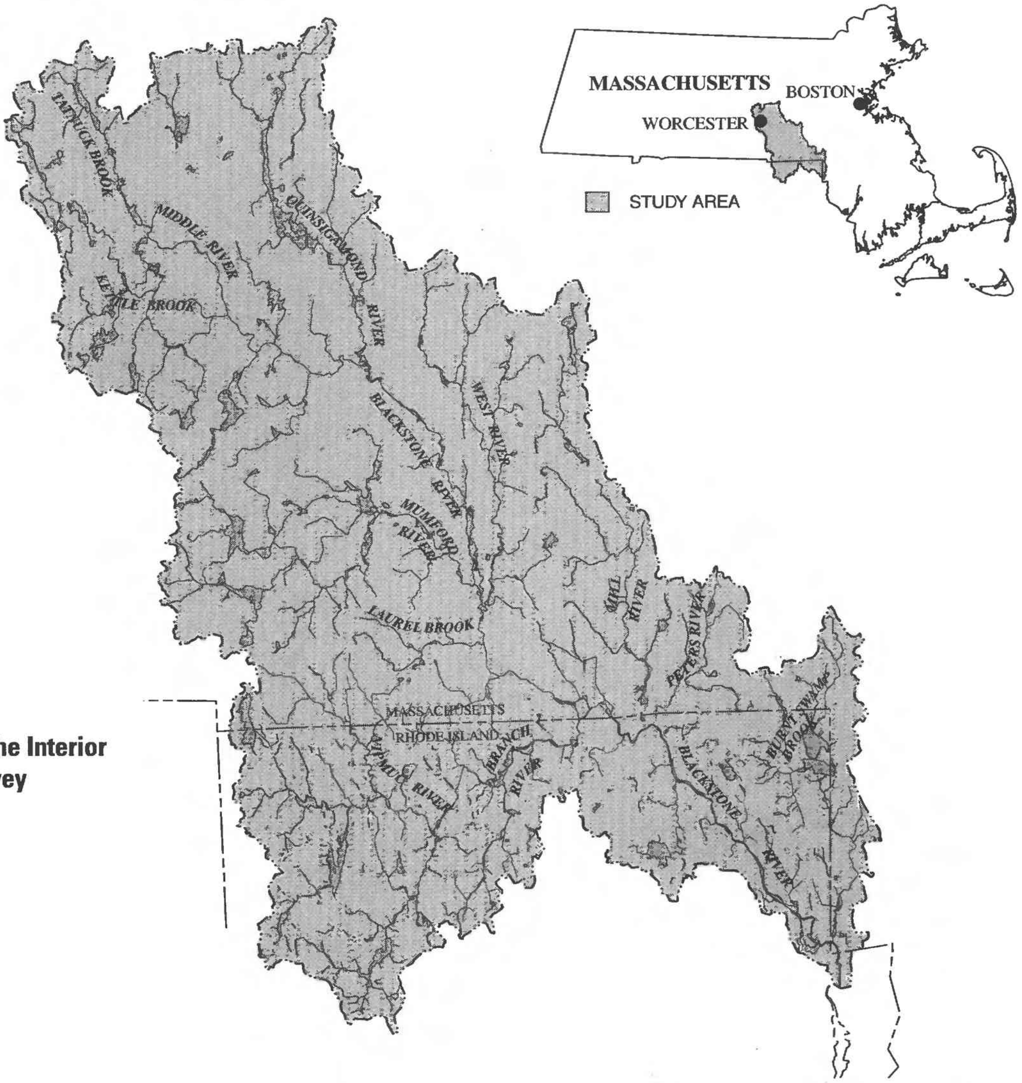
Water Resources of the Blackstone River Basin, Massachusetts

Water-Resources Investigations Report 93-4167



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Water Resources of the Blackstone River Basin, Massachusetts

By JOHN A. IZBICKI

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Northborough, Massachusetts
2000

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To Obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.0109	cubic meter per second 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
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°C = (0.556) (°F - 32)

VERTICAL DATUM

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

OTHER ABBREVIATIONS

mg/L	milligrams per liter
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius

WELL-IDENTIFICATION SYSTEM

Wells, borings, and test holes listed or discussed in this report are identified according to the town in which they are located. In each well number (for example MXW-3), the first two characters indicate the town (Millbury); the letter preceding the dash indicates if it is a well or well field (W), bridge or highway boring (B), or a test hole (X); and the numeral is a serial number for wells, borings, or test holes in that town. The 29 towns located entirely or partly in the study area and their respective character symbols are listed below.

Town	Identifier	Town	Identifier
Attleborough	AT	Millville	MZ
Auburn	AU	North Attleborough	NT
Bellingham	A6	Northbridge	NX
Blackstone	BD	Paxton	PB
Boylston	BK	Plainville	PV
Douglas	DU	Shrewsbury	SN
Franklin	FZ	Sutton	S7
Grafton	GH	Upton	UP
Holden	HR	Uxbridge	UX
Hopkinton	HW	Webster	WL
Hopedale	HV	West Boylston	WS
Leicester	LP	Westborough	WR
Mendon	MP	Worcester	XS
Milford	MW	Wrentham	XU
Millbury	MX		

Water Resources of the Blackstone River Basin, Massachusetts

By John A. Izbicki

Abstract

By 2020, demand for water in the Blackstone River Basin is expected to be 52 million gallons per day, one-third greater than the demand of 39 million gallons per day in 1980. Most of this increase is expected to be supplied by increased withdrawals of ground water from stratified-drift aquifers in the eastern and northern parts of the basin. Increased withdrawals from stratified-drift aquifers along the Blackstone River and in the western part of the basin also are expected.

The eastern and northern parts of the Blackstone River Basin contain numerous small, discontinuous aquifers which, as a group, comprise the largest ground-water resource of the study area. Fifteen aquifers, ranging in areal extent from 0.57 to 4.3 square miles, were identified. These aquifers have maximum saturated thicknesses ranging from less than 10 feet to 105 feet and maximum transmissivities ranging from less than 1,000 to more than 20,000 feet squared per day. Yields of nine study aquifers were estimated by use of digital ground-water-flow models. Yields depend on the hydraulic properties of the aquifer and the amount of streamflow available for depletion by wells. If streamflow is maintained at 98-percent duration, long-term yields from the aquifers that would be expected to be equaled or exceeded 50 percent of the time range from 0.22 to 11 million gallons per day, and long-term yields equaled or exceeded 95 percent of the time range from 0.06 to 1.0 million gallons per day. If streamflow is maintained at 99.5-percent duration, long-term yields equaled or exceeded 50 percent of the time range from 0.22 to 11 million gallons per day, long-term yields equaled or exceeded 95 percent of the time range from 0.04 to 1.4 million gallons per day, and long-term yields equaled or exceeded 98 percent of the time range from 0.02 to 0.39 million gallons per day. Maintaining streamflow at 98-percent duration is a more restrictive criterion than maintaining streamflow at 99.5-percent duration.

The upper Lake Quinsigamond, upper West River, and Stone Brook aquifers are capable of sustaining withdrawals of at least 1 million gallons per day more than their rates in the mid-1980s. The upper Mill River and Auburn aquifers are not capable of sustaining additional withdrawals of 0.25 million gallons per day. Ground-water quality in the Auburn aquifer has been degraded by activities and contaminants associated with urbanization.

A nearly continuous deposit of stratified drift almost 30 miles long and from 400 feet to more than 1 mile wide occupies lowland areas along the southeastern part of the Blackstone River. These deposits were divided into four aquifers ranging in areal extent from 1.8 to 3.5 square miles. These aquifers have maximum saturated thicknesses ranging from 54 to 170 feet and maximum transmissivities ranging from less than 1,500 to more than 20,000 feet squared per day. The Blackstone River receives substantial amounts of treated municipal wastewater. Infiltration of poor-quality surface water has significantly increased the specific conductance and the concentrations of all major ions, ammonia,

iron, and manganese in the water pumped from at least two wells near the river. These wells derive about 41 and 48 percent of their yield from infiltrated surface water. At both sites, aquifer heterogeneity controlled the movement of infiltrated water to the wells. At one of these sites, where the flow of infiltrated water was tracked (by use of a digital model) in three dimensions, infiltrated water moved to the well through gravel layers that did not constitute the entire thickness of the aquifer. Changes in stream discharge that resulted in changes in surface-water quality also affected the quality of ground water at that site.

The western part of the Blackstone River Basin contains the smallest aquifers evaluated in the study area. Six aquifers, ranging in areal extent from 0.05 to 1.3 square miles, were identified. The hydraulic properties of most of these aquifers have not been determined, but available data indicate that maximum saturated thicknesses range from 28 to 71 feet and maximum transmissivities range from 2,300 to 15,000 feet squared per day.

INTRODUCTION

By the year 2020, the average daily demand for water by communities in the Blackstone River Basin is expected to be 52 Mgal/d, one-third greater than the demand of 39 Mgal/d in 1980 (Massachusetts Department of Environmental Management, 1985). As early as 1990, 11 of 29 communities entirely or partly in the Blackstone River Basin are expected to experience water-supply shortages unless additional sources of supply are developed (Massachusetts Water Resources Commission, 1983). With the exception of Worcester, all communities in the Blackstone River Basin rely on ground water as their primary source of public supply; 13 of these communities depend entirely on ground water.

Most public-supply wells are completed in stratified-drift aquifers in the valleys of the Blackstone River and its major tributaries. These aquifers are discontinuous, are commonly less than 1 mi^2 in areal extent, and in most places are less than 60 ft thick. Surface water and ground water are hydraulically connected, and well yields depend on infiltration of surface water in addition to intercepted ground-water discharge and withdrawals from storage. Individually, these aquifers constitute relatively small ground-water resources capable of meeting the needs of nearby towns; collectively, they are the primary water resource on which future growth in the Blackstone River Basin may depend.

Concerns about quantity and quality of ground water available for future needs has increased because the quality of surface water in the Blackstone River has been degraded by municipal and industrial discharges of wastewater. Local water managers believe that wells along the Blackstone River that derive part of their yield from infiltration of surface water may not be suitable for use as a source of public supply. To address these concerns, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources (under Massachusetts Chapter 800 legislation), began a study of water resources in the Blackstone River Basin.

Purpose and Scope

This report presents the results of a 3-year study of the water resources of the Blackstone River Basin conducted from 1985 through 1988. The report includes descriptions of (1) the hydraulic properties and potential yields of the major stratified-drift aquifers, (2) surface-water and ground-water quality, and (3) the effect of infiltration of streamflow on the quality of water produced by wells. A conceptual model of the ground-water system is presented, and the development and application of a digital computer model of the system are described.

Acknowledgments

Agencies contributing unpublished data used in this report include the Massachusetts Department of Environmental Management, Office of Water Resources, Massachusetts Department of Environmental Protection, municipal water departments, and local water companies. The author thanks the Massachusetts–American Water Company, the Coz Chemical Company, and the many landowners who granted their permission for installation and measurement of wells on their property.

DESCRIPTION OF STUDY AREA

The Blackstone River Basin is in south-central Massachusetts and northern Rhode Island (fig. 1). The study area is the Massachusetts part of the Blackstone River Basin, an area of about 340 mi^2. The eastern and northern parts of the study area are characterized by gently rolling hills and long narrow valleys. The western part is characterized by gently rolling hills and valleys near the Rhode Island border that grade to increasingly rugged hills and steep valleys in the northwest. These two areas are separated by the valley of the Blackstone River. Land-surface altitudes range from about 150 ft above sea level where the Blackstone River enters Rhode Island to almost 1,400 ft above sea level in the northwest corner of the basin. Surface drainage is to the southeast, through the Blackstone River and its tributaries.

In Massachusetts, areas favorable for development of ground water in the Blackstone River Basin were mapped by Walker and Krejmas (1986); and in Rhode Island, areas favorable for development of ground water were mapped by Johnston and Dickerman (1974a and 1974b). Flow characteristics of streams in the Blackstone River Basin have been estimated by Wandle and Phipps (1984).

Climate

The climate of the study area is humid. Summers are warm and winters are mild and wet. Average annual precipitation (1943–84) at Worcester is about 47 in. In general, precipitation is evenly distributed throughout the study area and throughout the year, although the amount and distribution of precipitation in individual years may vary greatly.

Most of the data used in this study were collected in 1986. Data for Worcester indicate that precipitation in 1986 was about average. Hydrologic studies done during average or wetter-than-average conditions may not accurately represent the response of the system to extended dry periods unless data are related to long-term records that reflect natural variation in the hydrologic system. Annual-precipitation data for Worcester were used to identify a longer period of average precipitation. Such a period occurred during 1962–77 and was used as the base period for which most streamflow statistics presented in this report were calculated. A longer base period could not be used because many continuous-record streamflow-gaging stations operated during 1962–77 were not operated in later years.

Population

The study area includes all or part of 29 communities and, in 1980, had a population of about 320,000 people (Massachusetts Department of Environmental Management, 1985). At that time, more than 50 percent of the population lived in the city of Worcester. Population of the area is expected to decline slightly from 1980 through 1990 and then increase to more than 350,000 people by 2020. Changes in the population are expected to be accompanied by a shift in population away from Worcester to other communities. Communities expected to have the largest increase in population from 1980 through 2020 are Bellingham, Shrewsbury, Millbury, Northbridge, and Auburn (Massachusetts Department of Environmental Management, 1985). Most of these communities are in the eastern and northern parts of the Blackstone River Basin (fig. 1).

Land and Water Use

Land use is primarily urban, industrial, or commercial in Worcester; and industrial, commercial, or residential in Shrewsbury, Auburn, Millbury, and Grafton. Most of the remainder of the study area is rural, but includes small town centers and associated industrial, commercial, or residential land uses typical of New England. Rural land use is decreasing whereas industrial, commercial, and especially residential land uses are increasing as many towns—particularly in the eastern and northern parts of the study area—become part of the Boston metropolitan area.

Areas characterized by urban, industrial, or commercial land uses are not generally suitable for ground-water development for public supply, but these areas may contain wells installed when land use was different. Residential land use includes areas of low-density single-family homes, but it also may include small areas of open space. As a result, some locations in areas of residential land use may be suitable for ground-water development for public supply. Rural land use includes agricultural, conservation, forest, and wetland areas. These land uses are generally suitable for ground-water development for public supply.

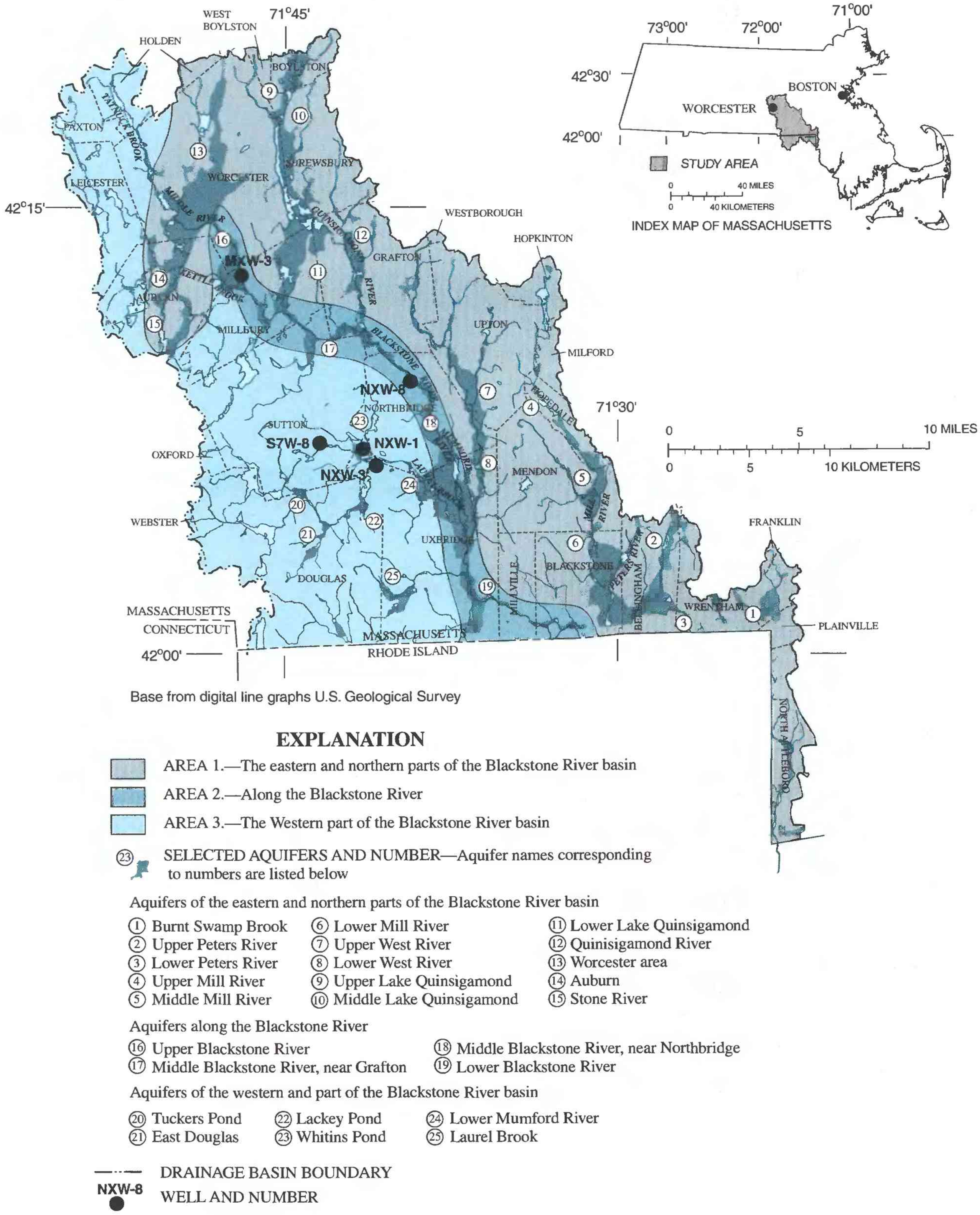


Figure 1. Location of study area and selected aquifers.

In 1980, the average daily demand for water in the Blackstone River Basin was about 39 Mgal/d and the maximum daily demand was about 59 Mgal/d. At that time, most water was used for residential purposes and, in general, water use was evenly distributed throughout the year. By 2020, the average daily demand is expected to increase to about 52 Mgal/d and the maximum daily demand to about 79 Mgal/d. Communities with the largest expected increase in water demand are Worcester, Shrewsbury, Bellingham, and Auburn (Massachusetts Department of Environmental Management, 1985).

The largest public water supplier in the area serves Worcester and parts of surrounding communities. In 1980, this supplier delivered about 26 Mgal/d, more than 60 percent of all public supply in the study area. To meet this demand, the city of Worcester imported 17.4 Mgal/d from sources outside the Blackstone River Basin. The city of Worcester has a long-term contract for an additional 10 Mgal/d of water from out-of-basin sources that it did not use in 1980. Demand for water in Worcester is expected to increase by about 4.5 Mgal/d between 1980 and the year 2020 (Massachusetts Department of Environmental Management, 1985). This increase in demand is expected to be met by new surface-water supplies outside the Blackstone River Basin.

Ground water from the Blackstone River Basin is the primary source of supply in parts of the study area that are outside of Worcester. In 1980, ground-water sources provided about 9 Mgal/d to 15 communities (Massachusetts Department of Environmental Management, 1985). Demand for water outside the Worcester metropolitan area is expected to increase by more than 8.5 Mgal/d by 2020. Most of this increased demand will be in the eastern and northern parts of the Blackstone River Basin (Massachusetts Department of Environmental Management, 1985) and is expected to be met by new ground-water supplies in the basin. In addition, communities outside the basin are considering ground water from the Blackstone River Basin as a potential source of new supply.

No water was exported for public supply from the Blackstone River Basin in 1980. Some water was discharged to wastewater-treatment plants outside the basin, and surface water from the Mill River is part of the public supply for Woonsocket, R.I.

Geohydrology

Bedrock underlying the Blackstone River Basin is predominantly gneiss, schist, and quartzite (Zen, 1983). The bedrock is relatively impermeable and only moderately weathered and fractured. Many wells in bedrock are used for domestic water supply. These wells typically yield less than 0.014 Mgal/d from fractures (Walker and Krejmas, 1986).

The bedrock surface is overlain by unconsolidated glacial deposits, of which till and stratified drift are the most common. Till is an unsorted mixture of sand, gravel, silt, clay, and rock fragments that overlies most of the study area. In general, till deposits are thicker in the eastern and northern parts of the study area and thinner in the western part. In some locations, till is discontinuous and bedrock crops out at land surface. Till generally has low permeability and is not an important aquifer, although some wells completed in till may yield enough water for an individual household (Walker and Krejmas, 1986). Stratified drift includes ice contact (kame), outwash (glacial-fluvial), and lake bottom (glacial-lacustrine) deposits. Stratified drift is typically composed of layers of sand and gravel interbedded with layers of silt and clay. If composed of sand and gravel or well-sorted medium sand, stratified-drift deposits may constitute aquifers capable of sustaining yields to public-supply wells. Because not all stratified-drift deposits are saturated they do not all constitute aquifers. For example, the western part of the Blackstone River Basin contains large areas of stratified drift (Byron Stone, U.S. Geological Survey, written commun., 1986) that are above the regional water table and, as a result, are not favorable for ground-water development.

Stratified-drift deposits favorable for ground-water development are shown on plate 1. Information on this plate was modified from a map of areas favorable for ground-water development prepared by Walker and Krejmas (1986) and reflects the results of test drilling and geophysical data collected as part of this study. Most of these deposits are located in the eastern and northern parts of the Blackstone River Basin or along the Blackstone River. These deposits constitute the largest aquifers in the study area.

These aquifers generally are long and narrow. The orientation of saturated stratified-drift deposits having major-axes greater than 0.6 mi long is shown in figure 2. Most deposits are aligned generally northwest

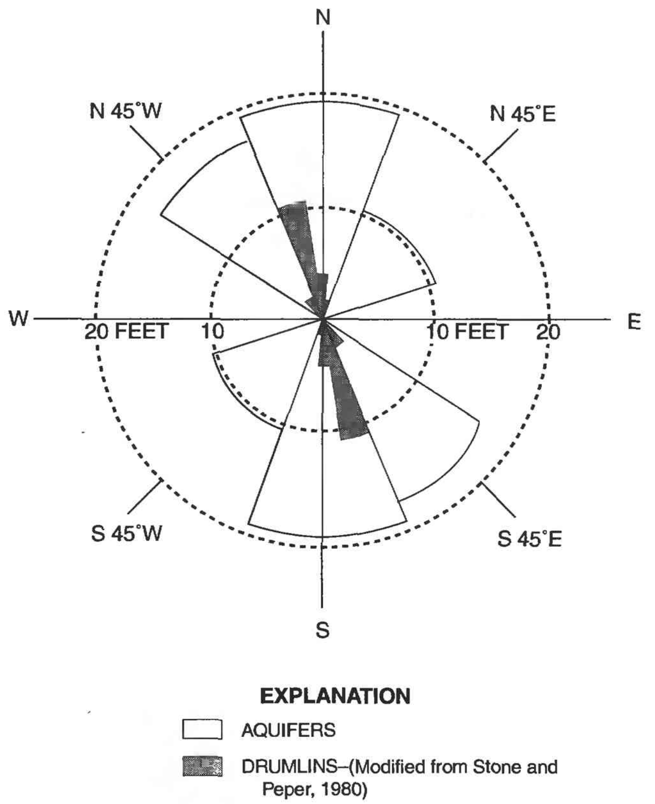


Figure 2. Orientation of the major axes of aquifers and drumlins in the Blackstone River Basin.

to southeast. This corresponds to the direction of glacial ice movement as indicated by the orientation of drumlins in the study area (Stone and Peper, 1980). Some aquifers are aligned generally northeast to southwest. These aquifers are primarily in the northern part of the study area and overlie a band of bedrock units that are oriented in a generally northeast to southwest direction (Zen, 1983). These bedrock units are more erodible than most other bedrock units in the area. Few aquifers are aligned east to west. These data show the placement of most aquifers was controlled by the direction of glacial ice movement and by preglacial drainages. Placement of some aquifers was controlled by the underlying geology.

In some places, stratified-drift deposits have been incised by streams and partly backfilled with alluvium. Alluvial deposits are typically composed of sand, gravel, silt, and clay. Where these deposits are coarse and well-sorted, they also may be capable of yielding enough water to sustain public-supply wells. Most alluvial deposits in the study area are along the Blackstone River (U.S. Soil Conservation Service, written commun., 1985).

In other places, stratified-drift deposits are covered by peat, which is composed of organic debris and mud. Peat, although commonly saturated, is not an important source of water to wells because it has low permeability; however, some wells yield water from stratified-drift or alluvial deposits beneath peat deposits. Stratified-drift deposits in the lower Mill River aquifer are overlain by as much as 20 ft of peat (Ground Water Associates, 1986). Many other aquifers, particularly the upper and lower Peters River and Auburn aquifers (fig. 1), also contain areally extensive, but thinner, deposits of peat.

The ground water in most aquifers is unconfined, and surface-water and ground-water systems are hydraulically connected. As a result, yields from some wells depend on infiltration of surface water in addition to intercepted ground-water discharge and withdrawals from storage. The quality of water yielded by these wells may be adversely affected by the infiltration of poor-quality surface water.

APPROACH

The Blackstone River Basin was divided into three areas on the basis of general physiography, geology, hydrology, and expected changes in land and water use (fig. 1). These areas represent three distinct environments in terms of water-resource development.

Area 1 includes the eastern and northern parts of the study area. Area 1 contains numerous aquifers which, as a group, compose the largest ground-water resource in the study area. Most of the population growth and subsequent demand for water is expected to be in area 1. Yields of selected aquifers were estimated from water budgets calculated by use of digital ground-water-flow models. Inputs to these models were determined from existing geologic and hydrologic data supplemented with streamflow, test-drilling, geophysical, and water-quality data collected during this study. It was not possible to collect enough ground-water-level data to calibrate the models, because there are numerous aquifers, and each aquifer represents only a small part of the ground-water resources of the study area. Instead, change models were used to reduce the amount of data required for modeling and to estimate short-term and long-term yields. This method is similar to the method used by Lapham (1988) for the Taunton River Basin.

Area 2 includes aquifers along the Blackstone River. Area 2 contains a nearly continuous aquifer system about 30 mi long but typically less than 1 mi wide. Population growth is expected to be less than in the eastern and northern parts of the study area, but the future demand for water is expected to exceed present supply. Some wells along the Blackstone River derive part of their yield from infiltration of surface water. The Blackstone River receives large amounts of treated municipal wastewater, and infiltration of this water may adversely affect the quality of water yielded by wells. To address this issue, the quantity and quality of surface water infiltrated by wells was studied at two locations near the Blackstone River.

Area 3 includes the western part of the study area. Area 3 contains few aquifers and has the smallest ground-water resources in the Blackstone River Basin. Population growth is expected to be less than in other parts of the study area; however, because the 1980 population was small, the relative increase in population and subsequent increase in demand for water may severely tax some municipal supplies. Geologic and hydrologic data originally presented by Walker and Krejmas (1986) were updated for aquifers in this part of the study area.

WATER RESOURCES OF THE EASTERN AND NORTHERN PARTS OF THE BLACKSTONE RIVER BASIN, AREA 1

This section describes the surface and ground-water resources of the eastern and northern parts of the Blackstone River Basin. The Middle River, Quinsigamond River, West River, Mill River, and the Peters River are the principal streams. The many small, discontinuous aquifers in the eastern and northern parts of the basin comprise the largest ground-water resource of the study area.

Surface Water

Surface drainage in the eastern and northern parts of the Blackstone River Basin is through the Middle River, the Quinsigamond River, the West River, the Mill River, the Peters River, and several smaller streams including Burnt Swamp Brook (fig. 3). Flows in Kettle and Tatnuck Brooks (tributaries to the Middle River) are regulated and diverted as part of the water supply for the city of Worcester. Floodflows in Kettle Brook are diverted through the Worcester aqueduct and floodflows in the West River are regulated by West Hill Dam. Flow in most other streams is unregulated, although natural streamflow in many streams has been altered by numerous millponds that were once managed for water power but are now managed primarily for recreation.

Continuous-record streamflow-gaging stations are, or have been, operated by the U.S. Geological Survey at sites on Kettle Brook, the Quinsigamond River, and the West River. October 1962 through September 1977 (a period of average precipitation) was selected on the basis of annual precipitation data at Worcester as the base period for calculation of streamflow statistics at these sites. Miscellaneous streamflow measurements were made at 72 sites as part of this study in Area 1. Additional streamflow measurements from earlier studies (Walker and Krejmas, 1986) also are available for some sites. Streamflow data were used to estimate the low-flow characteristics of streams that drain study aquifers, and subsequently to determine amount of streamflow available for depletion by wells. Locations of streamflow-gaging stations are shown in figure 3 and plate 2, and miscellaneous-measurement sites are shown on plate 2. Miscellaneous streamflow measurements are listed in appendix A.

Streamflow Characteristics

Analysis of data from streamflow-gaging stations in the eastern and northern parts of the Blackstone River Basin showed that, in general, streamflow is greatest in March and gradually declines to the lowest flows in September (Walker and Krejmas, 1986). Streamflow also varies from year to year in response to climatic factors. The variation in streamflow can be expressed by means of a flow-duration curve. Flow-duration curves show the percentage of time that streamflow of a given magnitude was equalled or exceeded in a given period of years (Searcy, 1959).

Flow-duration curves for streamflow-gaging stations were calculated from the cumulative distribution function of the ordered daily mean streamflows (Meeks, 1977) by use of the U.S. Geological Survey WATSTORE data-base program A969 (Hutchinson, 1975). Flow-duration curves for selected continuous-record streamflow-gaging stations are shown on plate 2.

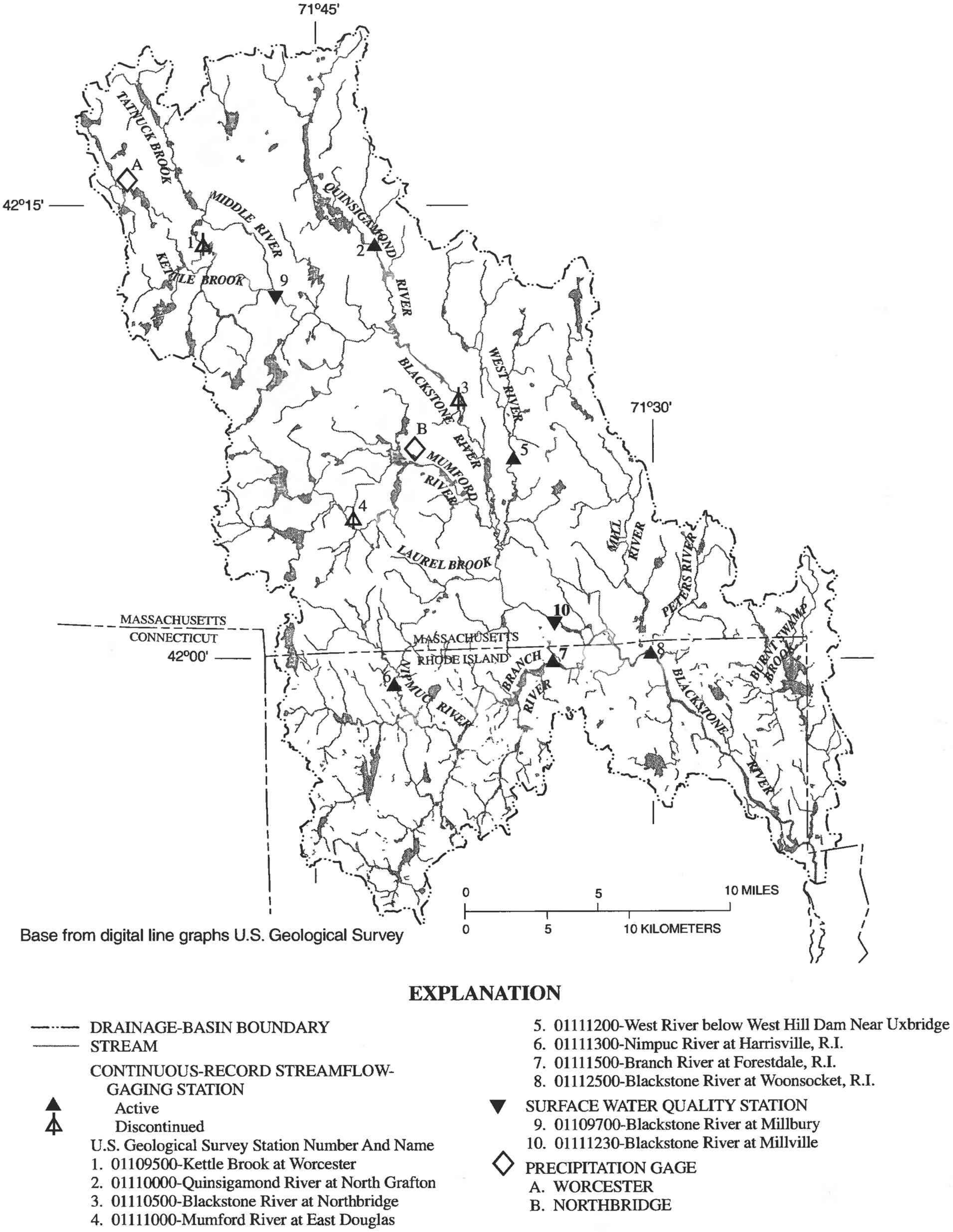


Figure 3. Surface-drainage network and location of streamflow-gaging stations, surface-water quality stations, and precipitation gages.

Flow duration curves at selected miscellaneous measurement sites were estimated graphically for streamflows between 50- and 90-percent duration by comparing measurements at the site to concurrent daily flows at the Nipmuc River streamflow-gaging station (station 01111300 in fig. 3) by use of a method explained by Riggs (1972). This station was used because (1) flow at this site is not affected by regulation or diversion; (2) part of the Nipmuc River Basin is in the study area; and, (3) although the Nipmuc River is in the western part of the Blackstone River Basin, its drainage area has topography and geology similar to that of most drainage basins in the eastern and northern part of the study area. The period of record October 1964 through September 1977 was used to calculate streamflow statistics because the Nipmuc River station was not operated before October 1964. Streamflow statistics from this station reflect a period when precipitation at Worcester was about 6 percent above average. Most of the data used to develop flow-duration curves at miscellaneous-measurement sites were collected from 1985 through 1987. During this time, precipitation was about average and streamflow ranged from flows equaled or exceeded less than 1 percent of the time to flows equaled or exceeded as much as 94 percent of the time. The lowest flows measured at miscellaneous-measurement sites were equaled or exceeded about 92 percent of the time.

It was not possible to estimate streamflow accurately for miscellaneous measurement sites at flow-durations greater than 90 percent by use of concurrent flow at the index station, because of the range of available data. As a result, streamflows equaled or exceeded more than 90 percent of the time were estimated from curves relating surficial geology to streamflow at ungaged sites (Thomas, 1966). The curves are intended for use in areas of gently rolling terrain and composed of relatively uniform deposits of stratified drift, with a climate similar to that of Connecticut. The curves have been used successfully in Massachusetts by de Lima (1991).

Flow-duration curves for selected miscellaneous measurement sites are shown on plate 2. These data were used to estimate the amount of water available for streamflow depletion by wells, a component of long-term yield discussed later in this report.

Surface-Water Quality

Specific conductance during low flow was used as an index of water quality of streams crossing study aquifers. Most of these streams have at least one set of conductance data collected during low flow, and specific conductance ranged from 63 to 973 µS/cm. Most water sampled had a specific conductance less than 220 µS/cm. Low specific conductances (less than 100 µS/cm) were measured in water from streams draining areas underlain primarily by till. Higher specific conductances (greater than 400 µS/cm) were measured in water from streams crossing the Auburn aquifer. These high specific conductances probably are related to urbanization and use of road salt for highway deicing. High specific conductances also were measured in water collected downstream from outfalls of wastewater-treatment plants that discharge to the West and Mill Rivers.

More frequent specific conductance data were collected from streams crossing the upper West River aquifer (pl. 2). These data show that decreases in streamflow can increase specific conductance of surface water, and increase the effect of wastewater discharges, both of which decrease the quality of water available for infiltration by wells. Similarly, data collected from streams crossing the lower Peters River aquifer show that increases in streamflow can result in decreases in the specific conductance of surface water and of the water available for infiltration by wells.

Specific conductance is an index of surface-water quality and of the quality of surface water available for infiltration by wells. Increases in specific conductance primarily reflect increases in several or all of the major ions dissolved in water. Organic compounds or trace elements, like iron or manganese, also may be present in water at objectionable concentrations (or in the case of iron and manganese also may be mobilized by reducing conditions that develop in the aquifer as a result of the infiltration of surface water) but may not be reflected in measurements of specific conductance.

Ground Water

Stratified-drift deposits that occupy lowland areas near streams or lakes are the major ground-water resource in this part of the study area. For the purposes of this report, these deposits have been subdivided into 15 aquifers ranging in areal extent from 0.39 to 4.3 mi^2. The location of study aquifers is shown in figure 1 and in greater detail on plate 1. Physical and hydraulic characteristics of each aquifer are summarized in table 1. Other stratified-drift deposits shown on plate 1, but not specifically delineated as aquifers, also may be capable of yielding water to public-supply wells; however, because of their small size, discontinuous areal extent, or thin nature, the ground-water resources of these areas have not been addressed specifically in this report.

Hydraulic Properties

Estimates of the saturated thickness, hydraulic conductivity, transmissivity, and specific yield of the aquifers and the hydraulic properties of streambeds were required as inputs to digital ground-water-flow models developed for calculations of ground-water yield.

Lithologic and hydraulic data from several hundred drillers logs of private wells, test holes, and borings and from geologic logs of wells drilled as part of this project were analyzed to determine hydraulic properties of each of the 15 study aquifers. Representative logs of aquifer materials are shown on plate 1. In addition, seismic-refraction surveys also were done along 11 lines having a total length of about 3 mi. Location of seismic-survey lines and sections interpreted from them are shown on plate 1.

Table 1. Physical and hydraulic characteristics of aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts

[**Maximum saturated thickness, Maximum transmissivity**, and **Maximum well yield:** Data from driller's information and U.S. Geological Survey files. Additional exploration may identify sites having greater saturated thickness, transmissivity, or well yields. **Yield of public-supply wells in 1980:** Data from Massachusetts Department of Water Resources, 1985. ft, foot; ft^2/d, foot squared per day; gal/min, gallon per minute; Mgal/d, million gallons per day; mi^2, square mile; >, actual value is greater than value shown; <, actual value is less than value shown; --, no data]

Aquifer	Location (town)	Area (mi^2)	Typical land use	Maximum saturated thickness (ft)	Maximum trans-missivity (ft^2/d)	Maximum well yield (gal/min)	Yield of public-supply wells in 1980 (Mgal/d)
Burnt Swamp Brook	Wrentham	0.73	Rural	<10	<1,000	--	0
Upper Peters River	Bellingham	1.1	Rural, residential	38	16,000	200	.35
Lower Peters River	Bellingham	1.6	Rural, residential	55	10,500	360	.62
Upper Mill River	Hopedale	.39	Industrial, residential	32	>4,000	350	.07
Middle Mill River	Hopedale, Mendon	1.1	Rural, residential	42	3,000	290	.40
Lower Mill River	Mendon	.57	Rural	105	4,500	--	0
Upper West River	Upton	2.1	Rural, residential	83	6,500	300	.69
Lower West River	Northbridge, Uxbridge	1.1	Rural	83	5,800	--	0
Upper Lake Quinsigamond	Boylston, Shrewsbury	1.7	Rural, residential	88	>20,000	1,200	4.8
Middle Lake Quinsigamond	Shrewsbury	1.3	Commercial, residential	46	>20,000	320	.84
Lower Lake Quinsigamond	Shrewsbury, Grafton, Worcester	1.5	Residential, industrial	36	5,400	450	.38
Quinsigamond River	Grafton	.97	Residential, commercial	63	19,000	700	2.2
Worcester area	Worcester	4.3	Urban, industrial, commercial	87	>20,000	500	0
Auburn	Auburn, Worcester	1.8	Commercial, residential	66	14,500	500	2.5
Stone Brook	Auburn	.65	Rural	53	12,000	--	0

Saturated Thickness

Saturated thicknesses of aquifers at each well, test hole, and boring were calculated by subtracting the altitude of the bottom of the aquifer from the altitude of the water table. In some places, saturated thickness was interpreted from seismic-refraction data. In areas where other data were not available, saturated thickness was calculated by comparing mapped altitudes of the bottom of the aquifer to water-table altitudes estimated from data at other locations. Saturated thickness of study aquifers ranged from zero near the edge of the aquifers to greater than 100 ft in the lower Mill River aquifer. Maximum saturated thicknesses for each study aquifer are listed in table 1.

Sections interpreted from seismic-refraction data show that many of the aquifers have relatively broad, flat bedrock bottoms and steep sides. This shape is typical of valleys modified by glacial action. Some aquifers contain buried bedrock valleys. Buried valleys in the Stone Brook and West River aquifers (pl. 1) increase the saturated thickness of the aquifer. Depressions in the bedrock surface also can increase the saturated thickness of overlying deposits. Saturated thicknesses greater than 100 ft in the lower Mill River aquifer are the result of a depression in the bedrock surface (Ground Water Associates, 1986). In contrast to buried valleys and depressions, subsurface features like buried bedrock hills can result in a decrease in the saturated thickness of the stratified drift. Bedrock hills have been inferred from seismic sections along parts of the upper West River aquifer.

Ice-contact deposits in many aquifers in this part of the Blackstone River Basin frequently are present as thin blankets of material overlying bedrock. These deposits are commonly less than 40 ft thick, with even thinner, sometimes nonexistent, saturated zones (pl. 1).

Hydraulic Conductivity and Transmissivity

Horizontal hydraulic conductivities of aquifer materials at each well, test hole, and boring were determined by comparing the predominant grain size of the material, as determined from lithologic logs, to laboratory-derived relations between grain size and hydraulic conductivity (Rosenshein and others, 1968). (All hydraulic conductivities discussed in this report are for the horizontal direction unless stated otherwise.) The hydraulic conductivities assigned by grain size and type of material are listed in table 2. Each aquifer contains a wide range of materials having a wide range of hydraulic conductivities.

Hydraulic-conductivity and saturated-thickness data were used to calculate aquifer transmissivity. Transmissivities were determined by multiplying the saturated thickness of each lithologic unit identified in the lithologic log by the estimated hydraulic conductivity of that unit. The values of transmissivity for each unit were then summed to determine the total transmissivity of the aquifer at that location. Maximum transmissivities of study aquifers ranged from less than 1,000 ft^2/d in fine-grained deposits with thin saturated thicknesses to greater than 20,000 ft^2/d in coarse deposits with large saturated thicknesses, such as the upper Lake Quinsigamond, middle Lake Quinsigamond, and Worcester area aquifers. Maximum transmissivity data for each aquifer are summarized in table 1. Some transmissivity data also were available from results of aquifer tests done by consulting firms. If these data were available, they were verified and used in preference to transmissivities calculated from lithologic logs.

Transmissivity data calculated for this study were used to update the map of favorable areas for ground-water development (Walker and Krejmas, 1986). With several minor exceptions, few changes were made in the earlier map. The Stone Brook and part of the upper West River aquifers are now considered more favorable for development of public-supply wells than indicated on the previous map; and the lower Peters River and some parts of the upper West River aquifers are now considered less favorable for development of public-supply wells (pl. 1). This study confirmed earlier conclusions about the favorability of most other aquifers for the development of public-supply wells.

Table 2. Hydraulic-conductivity values of saturated materials used to estimate aquifer transmissivity

[Modified from Rosenshein and others, 1968]

Material	Hydraulic conductivity (feet per day)
Sand and gravel	200
Coarse sand	80–135
Medium sand	70–105
Fine sand	35–55
Silt	4
Clay or till	0.1

Specific Yield

Areal variations in specific yield of aquifer materials were not possible to map because aquifer-test data were not well distributed throughout the study aquifers. Instead, a single value of specific yield of 0.2 was assigned to all aquifers. This specific yield value was used in similar regional studies of ground-water resources in eastern Massachusetts in the Taunton River Basin (Lapham, 1988) and Charles River Basin (Myette and Simcox, 1989). However, this value is lower than specific yields ranging from 0.28 to 0.32 used in modeling studies of aquifers in other parts of Massachusetts (Olimpio and de Lima, 1984; de Lima, 1991; and W.W. Lapham, U.S. Geological Survey, written commun., 1988). Use of a specific yield of 0.2 results in a more conservative estimate of ground-water yields than does use of a higher value.

Hydraulic Properties of Streambeds

Streambed width was determined from field measurements. Streambed hydraulic properties were determined from field investigation of streambed composition. At most sites, the stream appears to flow directly on top of the aquifer or reworked aquifer material, which typically consists of sand or mixed sand and gravel. Consequently, with few exceptions, vertical hydraulic conductivity of streambed material was assigned a value of 5 ft/d, which is considered to be a reasonable estimate of the vertical hydraulic conductivity of streambed material composed of sand and gravel in New England (Rosenshein and others, 1968; Gonthier and others, 1974). The primary exceptions are some parts of the streambeds of the Mill and Peters Rivers, and Kettle Brook that overlie the lower Mill River, the upper and lower Peters River, and the Auburn aquifers. In these areas, peat lowers the effective vertical hydraulic conductivity of the streambed to values of about 0.5 ft/d (Alan Klinger, U.S. Geological Survey, written commun., 1987).

Short-Term and Long-Term Yield for Public Supply

Short-term yield is the maximum rate of withdrawal that can be sustained by wells without causing an unacceptable decline in the hydraulic head of the aquifer. Short-term yield is analogous to aquifer yield as defined by Freeze and Cherry (1979). Long-term yield is the maximum rate of withdrawal that can be sustained by wells without causing unacceptable decline in the hydraulic head of the aquifer, or causing unacceptable changes to any other component of the hydrologic system, such as streamflow. Long-term yield is analogous to basin yield as defined by Freeze and Cherry (1979). Estimates of short-term and long-term yields were determined from water budgets calculated by use of digital ground-water-flow models. These models were designed to simulate changes in the ground-water system that would result from pumping. The models are subject to constraints and management criteria intended to duplicate typical ground-water-development and water-resource-management strategies for public supplies in this part of Massachusetts.

Short-term and long-term yield for public supply were not estimated for 6 of the 15 aquifers listed in table 1 because of unfavorable physical or hydraulic characteristics or a lack of data. Saturated thickness data from the Burnt Swamp Brook aquifer show that this aquifer is not capable of supporting yields to public-supply wells. Most of the lower West River aquifer is within the flood-storage pool of the West Hill Dam. It was not possible in the scope of this report to address changes in ground-water storage and surface-water availability resulting from inundation of the aquifer surface and regulation of streamflow; however, land-use, saturated-thickness, and transmissivity data indicate this aquifer has potential as a source for public supply. Parts of the upper West River aquifer also are within the flood-storage pool of West Hill Dam, and actual yields may differ from yields presented in this report because of inundation of parts of this aquifer. Urban, industrial, or commercial land uses on three aquifers—the middle Lake Quinsigamond, the lower Lake Quinsigamond area, and the Worcester area aquifers—are incompatible with further development for public supply; however, saturated-thickness, transmissivity, and well-yield data indicate these aquifers may be suitable sources for industrial, commercial, or agricultural supply. Short-term and long-term yields also were not estimated for the Quinsigamond River aquifer because of insufficient data; however, land use, saturated thickness, transmissivity, and existing ground-water withdrawals show that this aquifer is a significant source of public supply.

Conceptual Model of the Ground-Water System

The hydrologic characteristics of a typical stratified-drift aquifer and surrounding upland area are illustrated in figure 4. This simplified model shows the various components of ground-water recharge and discharge. These components change in response to pumping water from the aquifer.

Prepumping Conditions

Before pumping, water in the aquifer flows from recharge areas of the aquifer to discharge areas such as streams or other surface-water bodies. Ground-water-flow paths are typically short in small stratified-drift aquifers. Regional flow of ground water into, or out of, the aquifer through underlying bedrock probably is small.

Recharge to the stratified-drift aquifer is primarily from infiltration of precipitation and occurs mostly during the winter and spring when evapotranspiration rates are low. Estimates of average recharge to stratified-drift aquifers in Massachusetts range from 11.0 to 26.1 in/yr (Knott and Olimpio, 1986). These estimates include only water that actually reaches the water table. Precipitation that infiltrates the ground but does not reach the water table because it is transpired by plants is not included in estimates of recharge. The actual amount of recharge depends on soil type, antecedent soil-moisture conditions, vegetative cover, seasonal temperature, and the intensity, duration, and volume of precipitation. Because of these variables, recharge is not uniformly distributed areally or temporally throughout the study area. For example, in areas where the ground-water level is near land surface, precipitation that might otherwise infiltrate and recharge the aquifer cannot do so because no storage is available.

Additional water also can recharge the stratified-drift aquifer as leakage from adjacent till and bedrock and as ground-water flow from upgradient stratified drift. Mean annual leakage from till-covered and bedrock uplands to stratified drift is about 0.5 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2$ of the upland area (Daniel Morrissey, U.S. Geological Survey, written commun., 1983). Ground-water flow into the aquifer from upgradient stratified drift varies with head in the aquifer and the hydraulic properties and thickness of the aquifer at that location.

Discharge from the stratified-drift aquifer is primarily to streams, ponds, or other surface-water bodies. Discharge to surface water varies with head in the aquifer; stage in the stream, lake, or other surface-water body; and the hydraulic properties of the streambed (or lake bed).

Additional discharge also occurs as evapotranspiration of ground water in areas of wetland vegetation, and as ground-water flow out of the aquifer to downgradient stratified drift. In the study area, evapotranspiration of ground water, which generally is small in relation to other components of discharge, has been estimated to be 0.74 to 2.0 in. annually (Schicht and Walton, 1961). Discharge as ground-water flow from the aquifer to downgradient stratified drift varies with head in the aquifer and the hydraulic properties and thickness of the aquifer at that location.

Water-budget equations can be used to relate recharge and discharge components of ground-water systems. Before pumping (steady-state conditions), recharge to the aquifer is equal to discharge from the aquifer in the following equation:

$$\text{Recharge} = \text{Discharge}, \qquad (1)$$

or

$$Q_r + Q_l + Q_{gwin} + Q_i = Q_{et} + Q_{sd} + Q_{gwout}, \qquad (2)$$

where

Q_r is recharge from precipitation,

Q_l is recharge from ground-water flow from adjacent till and bedrock,

Q_{gwin} is recharge from ground-water flow from upgradient stratified drift,

Q_i is recharge from infiltration of surface water,

Q_{et} is discharge from evapotranspiration of ground water,

Q_{sd} is discharge to surface water, and

Q_{gwout} is discharge from ground-water flow to downgradient stratified drift.

In a humid environment like that in Massachusetts, most streams are naturally gaining throughout the year (aquifers discharge to the stream). As a result, infiltration of surface water is not an important component of the water budget before pumping, and $Q_i = 0$ in equation (2).

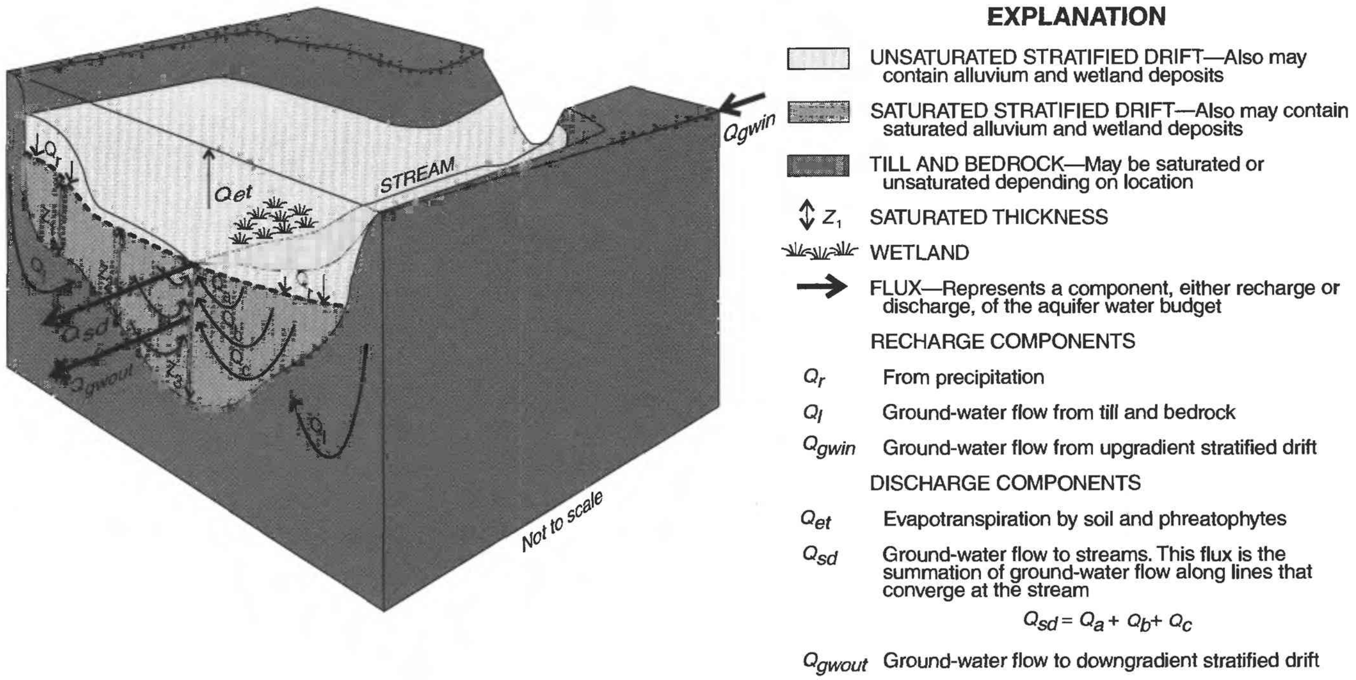


Figure 4. Hydrologic characteristics of a typical stratified-drift aquifer.

Pumping Conditions

During pumping, the flow of ground water and the relation between recharge and discharge are different from conditions before pumping. Water in the cone of depression around a pumped well moves toward the well, water that previously would have discharged from the aquifer is intercepted by the well, and, in some instances, water in streams or other surface-water bodies infiltrates into the aquifer and moves toward the well. Pumping (Q_p) becomes a new component of discharge from the aquifer that must be offset by increases in recharge, decreases in discharge, or changes in ground-water storage (ΔS) if the water-budget equation is to remain balanced. For the purposes of this report, ground-water withdrawals from pumping are assumed to be either completely consumed in the basin or entirely exported from the basin.

Increases in recharge as a result of pumping can occur as infiltration of streamflow and increased ground-water flow from stratified drift upgradient from the aquifer. These additional sources of water, especially infiltration of streamflow, can be important components of the water-budget equation. Increased infiltration of precipitation (capture of rejected recharge) and increased leakage from till-covered uplands also can occur in response to pumping, but these factors usually are a small component of the water budget. In some instances, additional recharge can occur as ground-water divides move in response to pumping. However, ground-water divides for most aquifers in the Blackstone River Basin coincide with topographic divides in the till-covered uplands. Because these divides are relatively far from pumping centers, their positions are not likely to change in response to pumping.

Discharge to streams, ponds, or other surface-water bodies can be greatly reduced or eliminated entirely as a consequence of pumping. Decreases in discharge from evapotranspiration of ground water (salvage from evapotranspiration) also may occur as a result of pumping, but because this is only a small element in the total hydrologic budget, the change is likely to be small. Decreases in discharge also may occur as decreased ground-water flow from the aquifer to downgradient stratified drift.

The water-budget equation during pumping is written

$$\text{Recharge} = \text{Discharge} + \Delta\text{Storage}, \qquad (3)$$

or

$$Q_r + Q_l + Q_{gwin} + Q_i$$
$$= (Q_{et} + Q_{sd} + Q_{gwout} + Q_p + \Delta S)\,. \qquad (4)$$

For the first small increment of pumping $Q_i = 0$; however, as pumping continues, Q_i may assume some value greater than zero but less than the amount of streamflow available for infiltration.

The discussion of conditions before and during pumping illustrates that, for aquifers typical of those in the Blackstone River Basin, the magnitudes of Q_r, Q_l, and Q_{et} do not change greatly in response to pumping. This discussion also shows that the magnitude of Q_{gwin} may increase in response to pumping, and that the magnitude of Q_i may increase greatly. In addition, Q_{gwout} may decrease in response to pumping, and the magnitude of Q_{sd} may decrease greatly. Changes in the water-budget equation resulting from pumping are the basis for the change model of the ground-water system.

Change Model of the Ground-Water System

In previous ground-water-availability studies of southeastern New England (Allen and others, 1966; Rosenshein and others, 1968; Johnston and Dickerman, 1974b; Gonthier and others, 1974; Toppin, 1987), yields of aquifers were estimated by use of analytical (image-well) models designed to determine rates of combined pumping of wells distributed throughout each aquifer for a specified maximum drawdown in each well. In more recent studies (Lapham, 1988; and de Lima, 1991), a finite-difference model (McDonald and Harbaugh, 1988) was used in place of an analytical model to aid in the calculation of short-term and long-term yield. A finite-difference model was used in this study. Finite-difference models have several advantages over analytical models because they can incorporate:

1. areal variation in saturated thickness and transmissivity of each aquifer,
2. actual locations of streams overlying each aquifer and differing hydraulic properties of each stream reach,
3. leakage from streams that do not fully penetrate the aquifer, and
4. actual locations of boundaries at the margins of each aquifer.

The ground-water models used in this study are called change models because they are used to calculate changes in head as a result of a change in stress. They do not calculate absolute head. The advantage of change models is that calculation of short-term and long-term yields is defined as changes in the system, and the effect of a known stress (pumping) can be evaluated when other stresses (recharge and discharge) and initial water levels are unknown. This approach reduces the amount of data required for short-term and long-term yield calculations. For linear systems, it can be shown that a change model produces valid results. In non-linear systems, however, the effects of stresses cannot be calculated independently (Reilly and others, 1987); that is, the effect of a stress depends on all the conditions occurring when the stress is applied. The flow systems being simulated in this study are non-linear because they include a water table and the transmissivity depends on the saturated thickness. Nevertheless, the change-model approach was used as an approximation. Bottom elevations were set so that initial saturated thickness approximated known values. Although predicted changes will not be exact, they can provide a reasonable basis for comparing potential yields of the simulated systems.

Under transient conditions, components of recharge (areal recharge from precipitation, Q_r, and leakage from adjacent till and bedrock, Q_l) and discharge (evapotranspiration of ground water in areas of wetland vegetation, Q_{et}) that are not likely to be affected by pumping (or the effect is so small in magnitude that it may be neglected) are set equal to zero, and subsequently removed from the water-budget equation. Components of recharge and discharge that are likely to be affected by pumping remain in the equation. These components include discharge to surface water (Q_{sd}), infiltration from surface water (Q_i), and flow of ground water into, or out of the aquifer through stratified drift (Q_{gwin} or Q_{gwout}). The water-budget equation for the change model is written

$$\Delta\text{Recharge} = \Delta\text{Discharge} + \Delta\text{Storage}, \quad (5)$$

or

$$\Delta Q_{gwin} + \Delta Q_i = \Delta Q_{sd} + \Delta Q_{gwout} + Q_p + \Delta S. \quad (6)$$

This equation can be solved for pumping (Q_p) and rewritten

$$Q_p = \Delta Q_{gwin} + \Delta Q_i - \Delta Q_{sd} - \Delta Q_{gwout} - \Delta S. \quad (7)$$

By definition (Jenkins, 1968) $\Delta Q_i - \Delta Q_{sd}$ = streamflow depletion (Q_{sfd}). This new term may be substituted into the water-budget equation to produce the form of the equation used in short-term and long-term yield calculations in this study—

$$Q_p = \Delta Q_{gwin} + Q_{sfd} - \Delta Q_{gwout} - \Delta S. \quad (8)$$

Short-term yield is actually a special case of this equation in which streamflow depletion (Q_{sfd}) is equal to 0 because the stream is dry and no water is available from that source. In this case, most of the yield to individual wells in an aquifer is derived from changes in storage, and smaller amounts are contributed by changes in the amount of ground water flowing into (ΔQ_{gwin}) or out of (ΔQ_{gwout}) the aquifer through adjacent stratified drift.

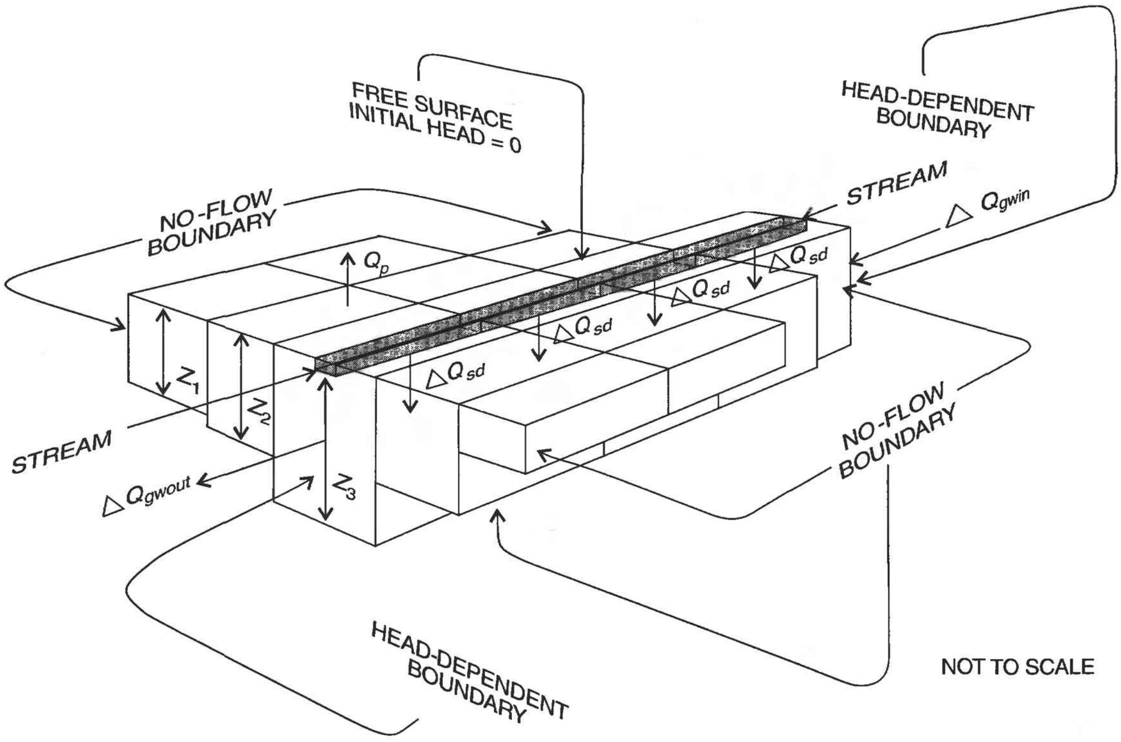
Long-term yield is the general case of this equation in which streamflow depletion is equal to the total amount of flow in the stream minus some minimum flow to be maintained in the stream. The minimum flow to be maintained in the stream is a management criterion that can differ from stream to stream and that depends on the uses and value of the stream resources.

Construction of the Change Model

The hydrologic characteristics of a typical stratified-drift aquifer as viewed in a change model are illustrated in figure 5. The aquifer is divided into blocks of material called cells. In each cell, initial water levels are set equal to zero and the bottom of the aquifer is set equal to zero minus the saturated thickness. Each cell is assigned a hydraulic conductivity on the basis of the average hydraulic properties of aquifer materials at that location.

All elements of the water-budget equation for the change model that have magnitudes of zero or near zero were simulated as no-flow boundaries. Streamflow depletion was simulated by use of the river package in the modular finite-difference model (McDonald and Harbaugh, 1988). Inputs to the river package were determined from the hydraulic properties of the streambed at that location. Stage in streams was set equal to zero. Changes in ground-water flow into or out of the aquifer through stratified drift were simulated by use of the general-head boundary package in the modular model (McDonald and Harbaugh, 1988). Inputs to the general-head boundary package were determined from the average hydraulic properties of the aquifer at that location. Water-level elevations at the head-dependent boundaries also were set equal to zero. The water table was simulated as a free surface (a type of no-flow boundary), and changes in ground-water storage were calculated in the modular model as the displacement of the free-surface boundary multiplied by the specific yield of the aquifer material.

Lakes and ponds were simulated as an additional model layer having a specific yield of 1 and thickness and areal extent approximating that of the lake or pond. The largest lake in the study area, Lake Quinsigamond, adjoins the upper Lake Quinsigamond aquifer. Because of the lake's large area and volume, it was not possible to simulate changes in lake storage resulting from pumping in the same manner as for smaller lakes and ponds. Instead, leakage from Lake Quinsigamond was simulated by use of a constant-head boundary, and the flux across this boundary was limited to the volume of water in the top 1 ft of the lake over the period of the model simulation. This volume was selected because 1 ft is the annual range in the water-surface level of the lake (George Johnson, Shrewsbury Water District, written commun., 1985). Some error is introduced by use of this approach because changes in the lake level are not simulated.



EXPLANATION

▭	MODEL CELL—Represents average hydraulic properties of saturated stratified drift, alluvium, and wetland deposits
▨	STREAM CELL—Represents average hydraulic properties of the streambed. Inactive for short-term aquifer-yield calculations. Head in the stream node is equal to zero for long-term basin-yield calculations
$\updownarrow Z_1$	SATURATED THICKNESS—Corresponds to saturated thickness illustrated on figure 4
⟶	FLUX—Represents a component, either inflow or outflow, of the model water budget
	INFLOW COMPONENTS
ΔQ_{sd}	From streamflow depletion. Includes ground-water discharge and infiltrated streamflow. Streamflow depletion occurs in short-term aquifer-yield calculations
ΔQ_{gwin}	Change in ground-water flow from upgradient stratified drift
	OUTFLOW COMPONENTS
ΔQ_{gwout}	Change in ground-water flow to downgradient stratified drift
Q_p	Ground-water pumpage

Figure 5. Change model of a typical stratified-drift aquifer.

Limitations of the Change Model

By design, the two-dimensional model developed for each aquifer is only a tool used to estimate short-term and long-term yields. These models have not been calibrated to extensive ground-water-level data, and the sensitivity of model output to variation in hydraulic properties of the aquifer has not been evaluated. Furthermore, because changes in the free-surface boundary that simulates the water table are nonlinear and therefore not additive (Reilly and others, 1987), these models cannot be used to predict specific changes in water-table configuration resulting from proposed plans for ground-water pumping—even if the initial water-table configuration is known. Results from these models are more similar to results obtained from analytical (image-well) models than results obtained from calibrated ground-water-flow models. Consequently, results should be interpreted in a relative sense, by comparing yields of one aquifer to another. Additional accuracy could be obtained by making a complete model of each system, but this would require extensive work beyond the scope of this study.

Short-term and long-term yields calculated by use of change models represent ground-water withdrawals that are either completely consumed within the basin or entirely exported from the basin. Ground water used by homes, business, and industry is exported to wastewater-treatment plants outside the Auburn, upper Lake Quinsigamond, and upper Mill River aquifers. Short-term and long-term yields calculated for these aquifers reflect total ground-water withdrawals that can be sustained by wells. If proposed ground-water-development plans for the Stone Brook (Daniel Morgan, Auburn Water Department, oral commun., 1986) and upper West River aquifers (Henry Papuga, Milford Water Company, oral commun., 1987) are implemented, ground water will also be exported from these aquifers.

In other aquifers (the middle Mill River and the upper West River—if proposed ground-water-development plans are not implemented), ground water used by homes, business, and industry is returned to the aquifer, or to streams crossing the aquifer, through septic systems, local wastewater-treatment plants, or industrial discharges. Consumptive use of the water is less than 100 percent, and returned water may be reused (if quality is not a problem) either directly as part of additional ground-water withdrawals or indirectly to maintain streamflow. Short-term and long-term yields presented in this report can be less than actual ground-water withdrawals in areas where substantial reuse of water occurs. The effects of in-basin return on the quantity and quality of streamflow are illustrated on plate 2 for streams crossing the middle Mill River and upper West River aquifers.

Use of water from most aquifers is a complex mixture of export, consumptive use, and in-basin return. Without detailed examination of water use—which was beyond the scope of this study—it is not possible to predict how much ground water pumped from these basins will be returned to augment streamflow or ground-water withdrawals. Readers should use caution when extrapolating short-term and long-term yields presented in this report to actual situations for which water-use data are not available.

Short-Term Yield

Short-term yield is the maximum rate of withdrawal that can be maintained without causing an unacceptable decline in the hydraulic head of the aquifer (Freeze and Cherry, 1979). For the purposes of this study, an unacceptable decline in the hydraulic head of the aquifer is represented by 50 percent desaturation of the aquifer material near the pumped well or drawdown in the pumped well to within 5 ft of the screened interval (10 ft total saturated thickness remaining in the well). These criteria were selected to be consistent with similar regional studies of short-term yield in the Charles River Basin (Myette and Simcox, 1989), Taunton River Basin (Lapham, 1988), and Nashua River Basin (de Lima, 1991) and to ensure that withdrawals are realistic given the hydraulics of individual wells. By these criteria, short-term yield is dependent on the number and location of wells and the rate and duration of pumping of individual wells in an aquifer. Calculations of short-term yield are based on the assumption that streamflow is zero; so that, ground water is withdrawn only from storage and from general-head boundaries. These calculations approximate the natural system only in extreme drought.

Constraints on Short-Term Yield

Existing public-supply wells and hypothetical wells were considered in calculations of short-term yield presented in this report. Location, construction, and pumping from existing wells were simulated as realistically as possible. Hypothetical wells represent sites that, on the basis of estimated physical and hydraulic characteristics of the aquifer, may be able to supply water to public-supply wells. Hypothetical wells were simulated to reflect reasonable ground-water development, given the properties of the aquifer and typical well-construction practices.

Existing wells were represented in the model as close as possible to their relative locations in the aquifer. Hypothetical wells were simulated only in cells representing aquifer material having a saturated thickness of at least 40 ft and a transmissivity of at least 3,600 ft^2/d. A minimum of 40 ft of saturated thickness was selected to allow for a 5-foot-long screen, a minimum of 25 ft of drawdown, a minimum of 5 ft of water above the well screen (to ensure compliance with state regulations), and 5 ft of water-level fluctuation. Hypothetical wells were located at least 800 ft from other existing or hypothetical wells to minimize interference. This well spacing is similar to that used by Lapham (1988) and de Lima (1991). Hypothetical wells were simulated only in cells representing areas of rural land uses and at least 2,500 ft from landfills to eliminate from consideration areas threatened by potential contamination.

Existing and hypothetical wells were simulated as individual wells located in the centers of model cells. At least 10 ft of saturated thickness was maintained in wells to ensure the screened interval would remain saturated during pumping. The Thiem equation (Thiem, 1906; as modified by Trescott and others, 1976) was used to extrapolate from the average hydraulic head in the pumped cell to the hydraulic head in a well having a radius of 1 ft located at the center of the cell. This approach differs from the approach used in studies of yield in the Taunton River Basin (Lapham, 1988) and Nashua River Basin (de Lima, 1991). In those studies yields were simulated as withdrawals from well fields consisting of many individual well points scattered throughout a model cell which was allowed to desaturate the cell by 50 percent.

Pumping of existing wells was simulated for rates up to but not exceeding the yield of the well as estimated by the Massachusetts Department of Environmental Management (1985). The yield of existing wells ranged from 50 to 1,166 gal/min (Walker and Krejmas, 1986). All wells but one have a yield greater than 200 gal/min, and the well having a yield of 50 gal/min is used only as a standby water supply. Most wells are pumped from 8 to 12 hours per day depending on water demand. Pumping of hypothetical wells was simulated at rates up to but not exceeding a maximum rate for each well estimated from the Thiem equation (1906; as modified by Trescott and others, 1976)—

$$Q_p = \frac{\pi K (H_n^2 - H_w^2)}{ln(r_e/r_w)}, \qquad (9)$$

where

Q_p is the maximum rate of pumping that can be sustained in a cell containing a hypothetical well when that cell has been desaturated 50 percent,

K is the hydraulic conductivity of the cell before pumping begins, in ft/d,

H_n is the saturated thickness of the cell at 50-percent desaturation, in ft,

H_w is the saturated thickness to be maintained in the hypothetical well (this value is a function of well construction; to maintain the necessary minimum saturated thickness at the well, H_w is set equal to 10 ft),

r_e is the effective radius of the pumped cell (for a square cell, r_e is related to the width of the cell (d_x) by the following approximation: $r_e = d_x/4.8$ (Prickett, 1967)), and

r_w is the radius of the hypothetical well (for the purposes of this study $r_w = 1$ ft).

This equation is used to calculate hydraulic head for a well with radius r_w in an unconfined aquifer. For the most restrictive condition evaluated in this study (an aquifer with a saturated thickness of 40 ft, a transmissivity of 3,600 ft^2/d, and an infinite areal extent) a well simulated in a cell 400 ft on a side could support a maximum pumpage of 100 gal/min with a drawdown of 30 ft. Hypothetical wells that could not yield at least 100 gal/min for a 180-day pumping period because of well interference or boundary effects were eliminated from aquifer-yield calculations. Locations of other hypothetical wells were then adjusted, and individual well yields were recalculated. This process was repeated by trial and error until a maximum number of wells, each capable of yielding at least 100 gal/min, were simulated for the aquifer.

Results of Short-Term Yield Calculations

Short-term yields for a 30-day pumping period range from 0.22 to 11 Mgal/d (table 3). Five of the nine aquifers studied are capable of yielding at least 1 Mgal/d over a 30-day pumping period.

Table 3. Short-term yield of selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts

Aquifer	Yield, in millions of gallons per day, for specified pumping period					Physical characteristics that limit yield (other than areal extent)
	30 days	60 days	90 days	180 days	365 days	
Upper Peters River	0.92	0.92	0.92	0.83	0.56	Saturated thickness
Lower Peters River	1.0	1.0	1.0	.90	.60	Saturated thickness, fine-grained deposits
Upper Mill River	.22	.22	.22	.22	.14	Land use, saturated thickness
Middle Mill River	.72	.72	.65	.56	.48	Fine-grained deposits, land use
Lower Mill River	.98	.97	.71	.58	.35	Fine-grained deposits
Upper West River	2.0	2.0	2.0	2.0	1.9	Fine-grained deposits
Upper Lake Quinsigamond	11	10	8.5	4.3	2.7	Flux from Lake Quinsigamond
Auburn	2.4	2.3	2.2	1.8	1.3	Land use
Stone Brook	1.6	1.6	1.3	1.0	.65	Saturated thickness

Short-term yields from all aquifers decrease, on a per day basis, as the duration of pumping increases; however, the total quantity of water withdrawn increases with increasing duration of pumpage. Short-term yields for a 180-day pumping period ranged from 0.22 to 4.3 Mgal/d (table 3). Four of the nine aquifers studied are capable of yielding at least 1 Mgal/d over a 180-day pumping period. The 180-day pumping period approximates the time between successive seasons during which ground water is recharged. The 180-day period represents a worst-case drought scenario that approximates the length of time streamflow might be unavailable for depletion by wells and ground water would be derived primarily from storage (Lapham, 1988).

For all pumping periods, short-term yields were not directly related to aquifer area (although larger aquifers tend to have larger yields) but rather were related to how the physical and hydraulic properties of each aquifer combined to limit the number of available well sites, the yields of existing wells, and the estimated yields of hypothetical wells. Short-term yield in the Auburn, middle Mill River, and upper Mill River aquifers was limited by land use and the number of suitable well sites. An abandoned landfill limited available well sites and, consequently, limited short-term yield from the middle Mill River aquifer. In contrast, an active landfill in the upper Peters River aquifer did not greatly affect short-term yield because the landfill is in an area where the saturated thickness is too thin for public-supply wells. Short-term yield in the middle Mill River, lower Mill River, and upper West River aquifers was limited by low transmissivity due to fine-grained deposits. These deposits limited the number of suitable well sites and yields of individual wells at those sites. Parts of the upper West River aquifer also are within the flood-storage pool of West Hill Dam, and actual yields may differ from yields presented in this report because of inundation of parts of this aquifer. Short-term yields from the upper Peters River and lower Peters River aquifers, and part of the upper Mill River aquifer also were limited by low transmissivity because of saturated thicknesses of less than 40 ft.

Long-Term Yield

Long-term yield is the maximum rate of withdrawal that can be maintained by the hydrologic system without causing unacceptable declines in the hydraulic head of the aquifer or causing unacceptable changes to any other component of the hydrologic system. For the purposes of this report, an unacceptable change to another component of the hydrologic system is a reduction of streamflow to less than the 98-percent flow duration. Long-term yields also were calculated for streamflows of 99.5-percent flow duration to evaluate how a less restrictive management criterion might affect yields. These criteria were selected for consistency with similar regional studies of long-term yield in the Charles River Basin (Myette and Simcox, 1989), Taunton River Basin (Lapham, 1988), and Nashua River Basin (de Lima, 1991).

Long-term yields in this report represent ground water withdrawn from storage, general head boundaries, and streamflow depletion on the 180th day of a 180-day pumping period. This pumping period was selected for consistency with a regional study of long-term yield in the Taunton River Basin (Lapham, 1988). Because conditions after 180 days of pumping approached steady state, withdrawals from storage and from general-head boundaries were small and most of the long-term yield is derived from streamflow depletion.

Constraints on Long-Term Yield Calculations

Long-term yield depends on the same constraints as short-term yield (number and location of wells, and rates and duration of pumping) and on the amount of water available to wells from streamflow depletion.

The amount of water available from streamflow depletion in each study aquifer is listed in table 4 for flow durations ranging from 50 to 99.5 percent. Water available for streamflow depletion at these sites includes streamflow that originated upstream from the study aquifer, from upland till and bedrock adjacent to the study aquifer, and from ground water discharged from the study aquifer to the stream. Streamflow that originated upstream from a study aquifer is available only if that water has not been withdrawn from upstream aquifers. With several exceptions, water available for streamflow depletion was estimated from flow-duration curves at miscellaneous-measurement sites near the downstream ends of study aquifers.

In the middle Mill River aquifer, a tributary stream (Muddy Brook, 01112190) enters the Mill River at the downstream end of the aquifer, and water from the stream is not available for streamflow depletion by wells in the aquifer. Therefore, water available for streamflow depletion was estimated as flow in the Mill River (01112200) immediately downstream from its confluence with Muddy Brook.

The upper Lake Quinsigamond aquifer is hydraulically connected to Lake Quinsigamond and is crossed by Seawall and Poor Farm Brooks which drain into Lake Quinsigamond. Surface flow from other areas also enters Lake Quinsigamond. Lake Quinsigamond is an additional source of water that is not present in most aquifers. The water available from Lake Quinsigamond was estimated from flow-duration data for the continuous-record streamflow gaging station located at the outlet of Lake Quinsigamond (Quinsigamond River, 01110000), minus the amount of water available from Seawall and Poor Farm Brooks.

Withdrawals from the Auburn, upper Lake Quinsigamond, and upper Mill River aquifers are exported to regional wastewater-treatment plants. Before estimating streamflow available from the Auburn and upper Lake Quinsigamond aquifers at flow durations less than 90 percent, streamflow data were corrected for existing ground-water withdrawals and interbasin transfer. In 1980, these transfers averaged 1.07 Mgal/d (1.7 ft^3/s) from the Auburn aquifer and 1.2 Mgal/d (1.9 ft^3/s) from the upper Lake

Table 4. Surface water available for streamflow depletion by wells in selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts

[No., number; mi^2, square mile]

Aquifer	Major stream	Station No.	Drainage area (mi^2)	Water available for streamflow depletion, in cubic feet per second, for specified percentage of time						
				50	70	80	90	95	98	99.5
Upper Peters River	Peters River	01112288	4.59	8.7	4.0	1.5	1.0	0.73	0.64	0.55
Lower Peters River	Peters River	01112380	11.8	14.5	6.6	3.4	3.0	2.7	1.9	1.4
Upper Mill River	Mill River	01112170	11.6	19.5	6.3	2.6	.93	.58	.37	.23
Middle Mill River	Mill River	01112200[1]	12.9	23.4	7.1	3.0	1.6	1.4	1.2	.88
Lower Mill River	Mill River	01112240	23.8	34.0	15.5	8.2	2.9	1.9	1.2	.90
Upper West River	West River	01111180	23.7	29.0	12.8	6.5	2.8	1.9	1.2	.88
Upper Lake Quinsigamond	Quinsigamond River	01110000[2]	25.5	32.8	17.8	14.4	6.6	4.0	2.6	2.3
Auburn	Kettle Brook	01109500[2]	31.6	28.7	17.7	14.1	5.6	3.8	2.2	1.6
Stone Brook	Stone Brook	01109456	1.89	2.4	1.1	.55	.23	.16	.13	.10

[1] Calculated as the difference in flow between the Mill River (01112200) and Muddy Brook (01112190).

[2] Corrected for water exported to wastewater treatment plants outside the drainage area.

Quinsigamond aquifer (Massachusetts Department of Environmental Management, 1985). No correction was made for flow durations greater than 90 percent because these flow durations were calculated from equations that produce estimates of natural streamflow. No correction was made for ground water withdrawn from the upper Mill River aquifer because withdrawals are intermittent and small (less than 0.07 Mgal/d or about 0.1 ft^3/s) in comparison to total streamflow. It was not necessary to correct for withdrawals from other aquifers where water is returned to the aquifer as septic-system discharge or returned to streams crossing the aquifer as treated wastewater; in these cases, consumptive use of water is assumed to be negligible.

Results of Long-Term-Yield Calculations

If streamflow is maintained at a flow duration of 98 percent, long-term aquifer yields equalled or exceeded 50 percent of the time range from 0.22 Mgal/d for the upper Mill River aquifer to 11 Mgal/d for the upper Lake Quinsigamond aquifer (table 5). Five of the nine aquifers can yield at least 1.0 Mgal/d 50 percent of the time. Long-term yields equalled or exceeded 95 percent of the time range from 0.02 Mgal/d for Stone Brook aquifer to 1.0 Mgal/d for the Auburn aquifer. Only one aquifer, the Auburn aquifer, can yield at least 1.0 Mgal/d 95 percent of the time. As a result of the management criterion, long-term yields for all aquifers are zero 2 percent of the time.

Results of long-term yield calculations are shown in figure 6. Each curve has 2 distinct parts: a flat, plateau-like maximum, and a steeply sloping curved section. The flat part of the curve represents that part of the time when long-term yield is limited by the physical and hydraulic properties of the aquifers. Long-term yields from the upper Mill River, lower Mill River, Auburn, upper West River, and middle Mill River aquifers are limited by the physical and hydraulic properties of the aquifers greater than 80 percent of the time. The steeply sloping part of each curve represents that part of the time when long-term yield is limited by the amount of water available for streamflow depletion. Long-term yield from the Stone Brook aquifer is the most limited by the amount of water available for streamflow depletion.

For that part of the time when long-term yield is limited by the amount of water available for streamflow depletion, reduction of the minimum streamflow requirement can increase long-term yield. For example, if streamflow is maintained at a flow duration of 99.5 percent, long-term yields equalled or exceeded 50 percent of the time range from 0.22 Mgal/d for the upper Mill River aquifer to 11 Mgal/d for the upper Lake Quinsigamond aquifer (table 6, fig. 7). Five of

Table 5. Long-term yield and percentage of yield developed for selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts, if streamflow is maintained at 98-percent duration

[**Yield of public-supply wells in 1980:** Data from Massachusetts Department of Environmental Management, Office of Water Resources, 1985. All yields are in million gallons per day; PYD, percentage of yield developed; --, undefined]

Aquifer	Yield of public-supply wells in 1980	Yield and percentage of yield developed for specified percentage of time											
		50		70		80		90		95		98	
		Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD
Upper Peters River	0.35	0.92	38	0.92	38	0.56	63	0.23	152	0.06	583	0	--
Lower Peters River	.62	1.0	62	1.0	62	.97	64	.71	87	.52	119	0	--
Upper Mill River	.07	.22	32	.22	32	.22	32	.22	32	.14	50	0	--
Middle Mill River	.42	.72	58	.72	58	.72	58	.72	58	.39	107	0	--
Lower Mill River	0	.58	0	.58	0	.58	0	.25	0	.13	0	0	--
Upper West River	.69	2.0	34	2.0	34	2.0	34	1.0	69	.45	153	0	--
Upper Lake Quinsigamond	4.8	11	44	9.9	48	7.7	62	2.6	185	.96	500	0	--
Auburn	2.4	2.4	100	2.4	100	2.4	100	2.2	109	1.0	208	0	--
Stone Brook	0	1.5	0	.63	0	.27	0	.06	0	.02	0	0	--

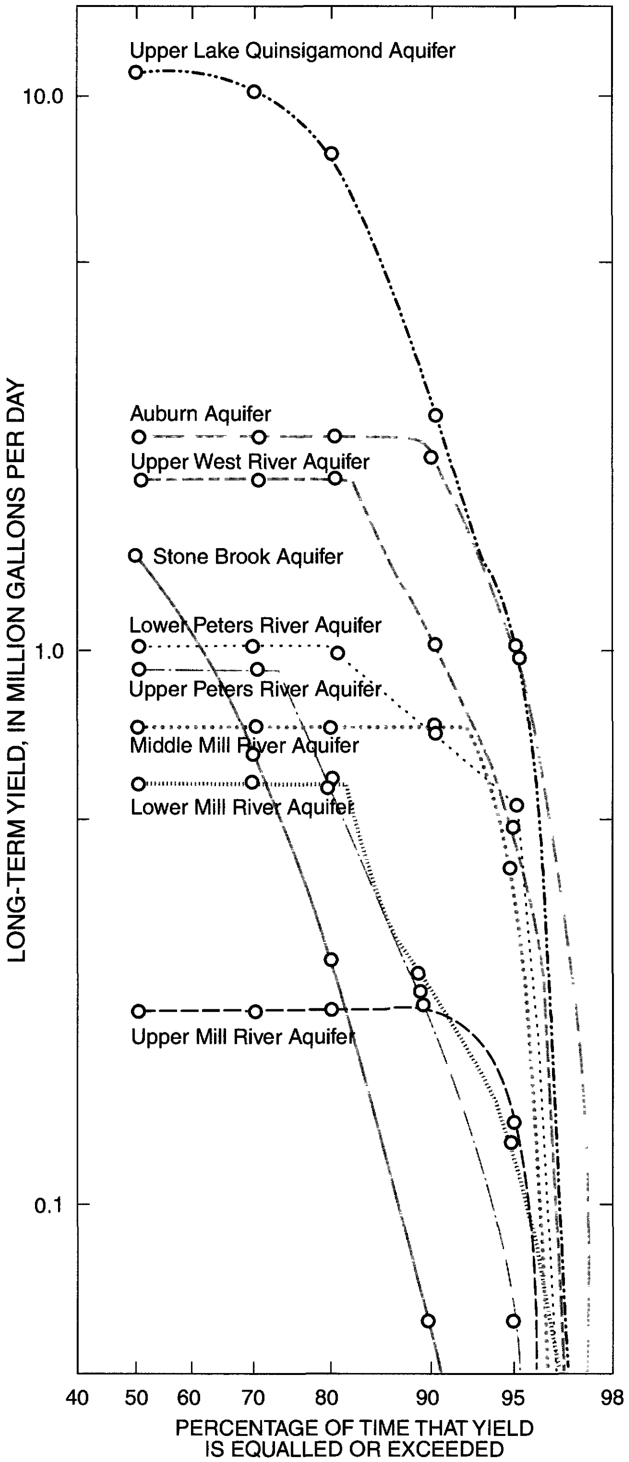


Figure 6. Long-term yield for selected aquifers in the eastern and northern parts of the Blackstone River Basin if streamflow is maintained at 98-percent duration.

the nine aquifers have long-term yields of at least 1.0 Mgal/d. Long-term yields equalled or exceeded 95 percent of the time range from 0.04 Mgal/d for the Stone Brook aquifer to 1.4 Mgal/d for the Auburn aquifer. Only two aquifers, the Auburn and upper Lake Quinsigamond aquifers, have long-term yields greater than 1.0 Mgal/d 95 percent of the time. Long-term yields equalled or exceeded 98 percent of the time range from 0.02 Mgal/d for the Stone Brook aquifer to 0.39 Mgal/d for the Auburn aquifer. This differs from results obtained by use of the previous management scenario (streamflow maintained at a flow duration of 98 percent) where long-term yields for all aquifers were zero 2 percent of the time. As a result of the management criterion, long-term yields for all aquifers are zero 0.5 percent of the time.

From the standpoint of water supply, maintaining streamflow at a flow duration 98 percent is more restrictive than maintaining streamflow at 99.5-percent duration. In some instances, both streamflow-management criteria may be too restrictive. For example, streams draining areas covered primarily by stratified drift tend to have relatively flat flow-duration curves. As a result, differences in streamflow between flow durations of 80 and 99.5 percent are small, although the total amount of streamflow may be relatively large. Management of ground-water withdrawals to maintain streamflow can preclude use of much of the streamflow available from depletion and can eliminate entirely use of short-term yield. These management criteria have resulted in a small long-term yield for the Stone Brook aquifer, whereas the short-term yield for the aquifer is relatively large.

From the standpoint of protecting in-stream aesthetic and recreational resources, or to ensure enough streamflow to mitigate water-quality problems associated with municipal or industrial waste discharges during periods of low flow, both the 98- and 99.5-percent flow-duration criteria may be unacceptable. To achieve aesthetic and recreational objectives, other management criteria that call for maintaining even more streamflow may be necessary. It is likely that decisions about withdrawals from each aquifer and minimum streamflow requirements need to be made on a case-by-case basis and need to be based on different management criteria for each stream-aquifer system.

Table 6. Long-term yield and percentage of yield developed for selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts, if streamflow is maintained at 99.5-percent duration

[**Yield of public-supply wells in 1980:** Data from Massachusetts Department of Environmental Management, Office of Water Resources, 1985. All yields are in million gallons per day; PYD, percentage of yield developed; --, undefined]

Aquifer	Yield of public-supply wells in 1980	Yield and percentage of yield developed for specified percentage of time													
		50		70		80		90		95		98		99.5	
		Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD	Yield	PYD
Upper Peters River	0.35	0.92	38	0.92	38	0.61	57	0.45	78	0.18	194	0.09	388	0	--
Lower Peters River	.62	1.0	62	1.0	62	1.0	62	1.0	62	.84	74	.32	193	0	--
Upper Mill River	.07	.22	32	.22	32	.22	32	.22	32	.22	32	.09	78	0	--
Middle Mill River	.42	.72	58	.72	58	.72	58	.72	58	.55	76	.16	262	0	--
Lower Mill River	0	.58	0	.58	0	.58	0	.45	0	.32	0	.19	0	0	--
Upper West River	.69	2.0	34	2.0	34	2.0	34	1.2	58	.66	105	.21	328	0	--
Upper Lake Quinsigamond	4.8	11	44	10	48	7.8	62	2.8	171	1.1	436	.13	3,700	0	--
Auburn	2.4	2.4	100	2.4	100	2.4	100	2.4	100	1.4	171	.39	615	0	--
Stone Brook	0	1.5	0	.65	0	.29	0	.08	0	.04	0	.02	0	0	--

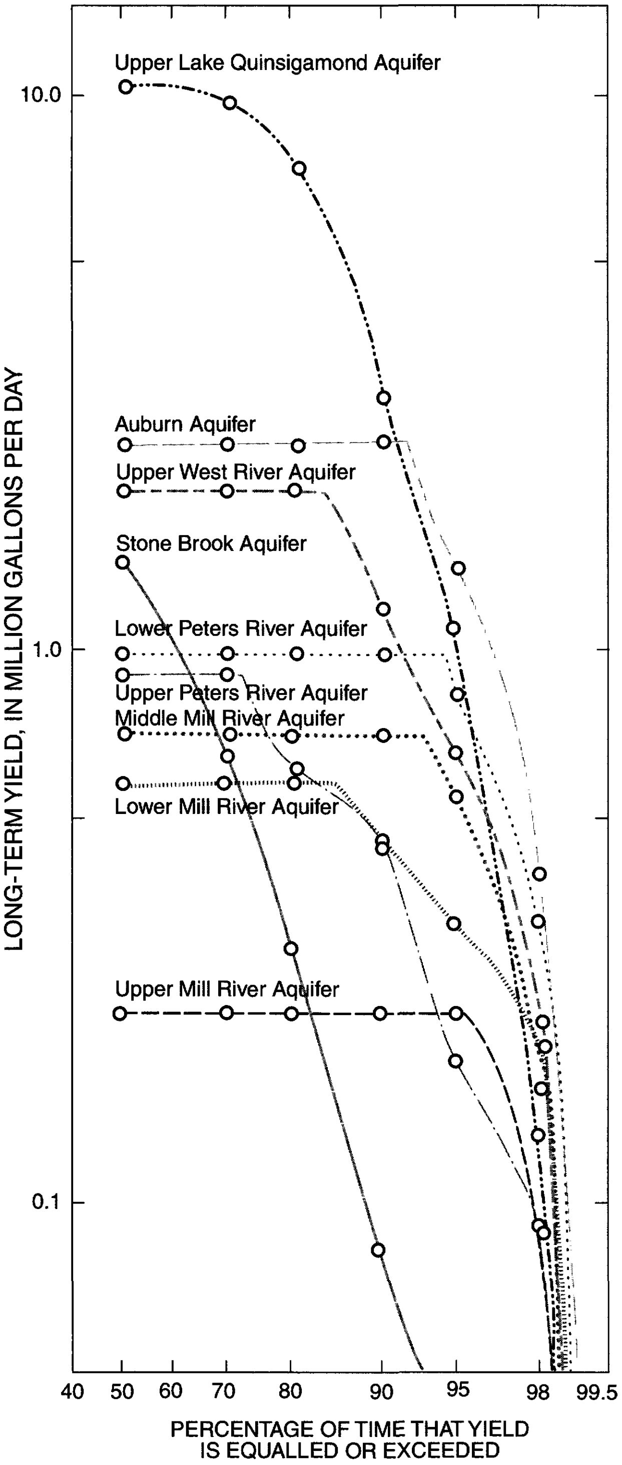


Figure 7. Long-term yield for selected aquifers in the eastern and northern parts of the Blackstone River Basin if streamflow is maintained at 99.5-percent duration.

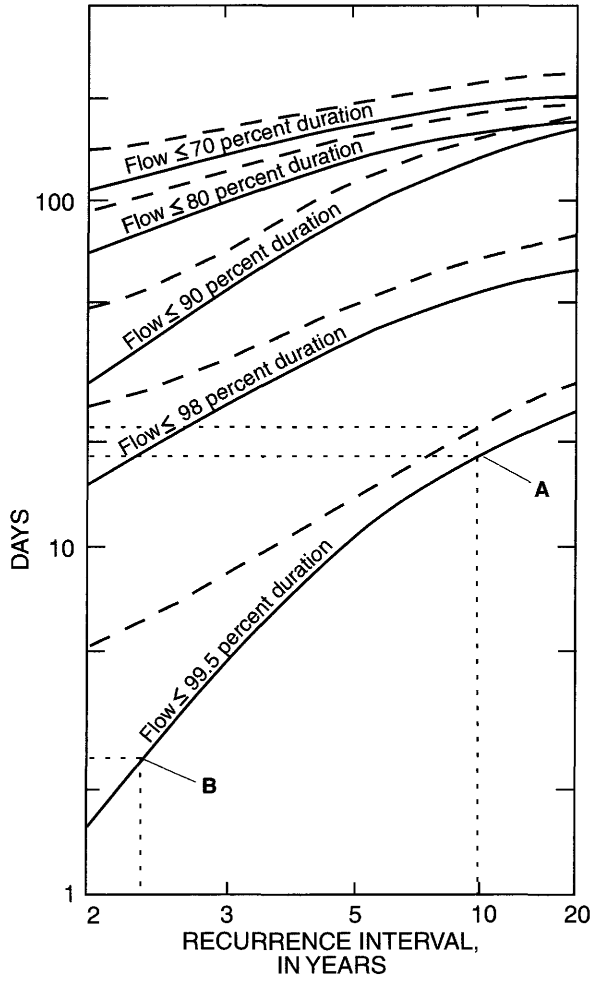
Effect of Drought on Long-Term Yield

Most years are either wetter or drier than average, and corresponding streamflows are greater or less than average. In wet years, streamflow may be plentiful and withdrawals may be unrestricted throughout the entire year. In drought years streamflow is reduced and the amount of time withdrawal may need to be curtailed or prohibited will be increased.

The calculations presented in this section are based on estimates of streamflow depletion derived from steady-state model runs. The results are intended to show how often demand for water (represented by pumping) exceeds surface water available for infiltration in drought conditions. A more complete analysis incorporating transient changes in pumping in response to drought conditions is beyond the scope of this report. It is worth noting that the results of more complete analyses may be unrealistic, because water-resource managers would have to reduce or stop pumping entirely, far in advance of the drought condition, in order to prevent induced infiltration during the drought.

The number of days that flow was less than the 98- and 99.5-percent duration at the Nipmuc River streamflow-gaging station (01111300, fig. 3, October 1964 through September 1977) was used as an index to the number of days that flow was less than the 98- and 99.5-percent durations in streams crossing study aquifers for (1) an average year and (2) the worst drought likely to occur in any given 10- and 20-year period. This site was used because streamflow is unregulated and not affected by diversions.

The number of days that flow was less than 98-percent duration in each year for the Nipmuc River (01111300) was determined from frequency analysis of observed daily mean flow obtained from program A969 (Hutchinson, 1975) in the U.S. Geological Survey WATSTORE data base. The number of days that flow is expected to be less than 98-percent duration was estimated over a range of recurrence intervals by plotting the set of annual number of days that flow was less than 98-percent duration to a log-Pearson Type III distribution by use of a method outlined by Viessman and others (1977). The distribution obtained (along with other durations) is shown in figure 8. Viessman and others (1977) estimate that the average year in a log-Pearson Type III distribution has a recurrence interval of about 2.33 years. The number of days no



EXPLANATION

—— LOG-PEARSON CURVE

— — UPPER 95-PERCENT CONFIDENCE LIMIT ABOUT LOG-PEARSON CURVE

≤ LESS THAN OR EQUAL TO

Example **A.**—A flow of ≤ 99.5-percent duration can be expected to occur for 19 days during a drought having a recurrence interval of 10 years.

For planning purposes, the upper limit of the 95-percent confidence interval about the 19-day estimate can be expected to occur for 21 days during a drought having a recurrence interval of 10 years.

Example **B.**— A flow of ≤ 99.5-percent duration can be expected to occur for 2.5 days in an average year (recurrence interval 2.33 years).

Figure 8. Curves used to estimate the number of days streamflow (at various percent duration levels and recurrence intervals) in the Nipmuc River (above station 01111300) is unavailable for depletion by wells in average and drought years.

water can be withdrawn from study aquifers in an average year if streamflow is maintained at 98-percent duration, using the Nipmuc River flows as an index, is listed in table 7. The number of days no water can be withdrawn from an aquifer in an average year if streamflow is maintained at 99.5-percent duration was estimated in a similar manner and is also shown in table 7.

Chow (1964) recommends that engineering and water-supply structures built for extreme events be designed at the upper 95-percent confidence limit about the log-Pearson curve. The upper 95-percent confidence limit was estimated by use of a method developed by Beard (1962) and in this report is used to represent droughts referred to as the 1-in-10 and 1-in-20 design years. These estimates, presented in table 7, are the number of days no water can be withdrawn from study aquifers if streamflow is to be maintained at 98- or 99.5-percent duration in drought years. The 1-in-10, and 1-in-20 design-year droughts are the worst droughts likely to occur in any given 10- or 20-year period with a confidence criterion of 5 percent. The design-year droughts are more severe than a drought with a 1-in-10, or 1-in-20 year recurrence interval, because they include the chance that a drought with a 1-in-25, 1-in-50, or even 1-in-100 year recurrence interval also may occur in any given 10- or 20-year period. These estimates are very conservative but have been presented in this report to illustrate worst-case drought scenarios.

Even in years of average streamflow, withdrawals from some aquifers may need to be reduced if minimum streamflow is to be maintained. The number of days a given quantity of water can be withdrawn from study aquifers if streamflow is maintained at 98- or 99.5-percent duration (table 7) was estimated from a set of log-Pearson Type III distributions fit to the sets of the annual number of days of flow less than 70-, 80-, 90-, and 98- and 99.5-percent duration at the Nipmuc River streamgaging station (01111300, fig. 8). For example, in the upper Peters River aquifer, long-term yield is about 0.5 Mgal/d 90 percent of the time if streamflow is to be maintained at 99.5-percent duration (table 6). From the curves in figure 8 and from table 7 this amount would be unavailable for withdrawal for 54 days in an average year. During the 1-in-10 and 1-in-20 design years this amount would be unavailable for 161 and 183 days, respectively (table 7).

Table 7. Number of days during average years and drought years that water cannot be withdrawn from selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts, if streamflow is to be maintained at 98- or 99.5-percent duration

[**Withdrawal:** Assumes either 100-percent consumptive use of water or export of all water from the aquifer. Mgal/d, million gallons per day]

Aquifer	Withdrawal (Mgal/d)	Number of days that withdrawal cannot be sustained if streamflow is maintained at 98-percent duration			Number of days that withdrawal cannot be sustained if streamflow is maintained at 99.5-percent duration		
		Average year	1-in-10 design year	1-in-20 design year	Average year	1-in-10 design year	1-in-20 design year
Upper Peters River	0.92	120	200	214	102	173	188
	.50	61	157	184	54	161	183
	.25	34	141	166	34	129	162
	0	19	63	75	2.5	21	29
Lower Peters River	1.0	69	163	183	39	132	168
	.50	29	124	155	33	93	110
	.25	22	88	100	24	68	79
	0	19	63	75	2.5	21	29
Upper Mill River	.22	37	144	172	20	74	87
	0	19	63	75	2.5	21	29
Middle Mill River	.72	48	171	194	27	95	114
	.50	42	155	182	21	79	93
	.25	31	122	142	15	47	61
	0	19	63	75	2.5	21	29
Lower Mill River	.58	29	122	144	19	63	75
	.50	27	115	137	18	62	73
	.25	21	88	102	16	57	69
	0	19	63	75	2.5	21	29
Upper West River	2.0	61	158	188	61	157	180
	1.0	41	148	174	38	144	172
	.5	28	111	130	31	90	104
	0	19	63	75	2.5	21	29
Upper Lake Quinsigamond	5.0	56	158	184	54	162	184
	2.0	32	135	163	33	124	160
	1.0	22	92	106	30	88	102
	.5	20	79	85	27	73	85
	0	19	63	75	2.5	21	29
Auburn	2.4	36	143	171	34	94	108
	2.0	33	110	134	29	84	97
	1.0	24	77	95	18	62	72
	.5	21	69	84	10	48	58
	0	19	63	75	2.5	21	29
Stone Brook	.5	111	184	202	110	184	204
	.25	80	168	184	78	167	187
	0	19	63	75	2.5	21	29

Data in table 7 provide an estimate of the number of days alternative sources of supply or water conservation will be required in an average year and in the worst-case drought in the next 10 or 20 years. Aquifers where long-term yields are most affected by drought are those crossed by streams having small drainage areas, such as the Stone Brook aquifer. In other aquifers, particularly those that are crossed by streams having relatively large drainage areas—such as the lower Mill River, upper West River, upper Lake Quinsigamond, and Auburn aquifers—long-term yields are more dependable, and withdrawals would need to be reduced or ceased entirely for fewer days each year. For example, if streamflow is to be maintained at 99.5-percent duration, a withdrawal of 0.25 Mgal/d from the Stone Brook aquifer would exceed available supply for 78 days in an average year. This same withdrawal can be sustained for all but 16 days in an average year from the lower Mill River aquifer (table 7), even though the physical and hydraulic properties of the Stone Brook aquifer are more suited for the development of public supplies than those of the lower Mill River aquifer. In all aquifers, large withdrawals cannot be sustained for as many days each year as can small withdrawals. This effect is more pronounced in drought years than in average or wetter-than-average years.

Additional Sources of Public Supply

Long-term yield calculations illustrate how much water can be withdrawn from an aquifer if streamflow is to be maintained at 98- or 99.5-percent durations. They also can be used to determine where additional ground-water supplies can be developed without interfering with existing sources of supply.

Subtraction of 1980 ground-water development (Massachusetts Department of Environmental Management, 1985) from long-term yields in table 6 produces an estimate of the ground water available for future development in each aquifer if streamflow is to be maintained at 99.5-percent duration. For future development, long-term yields equaled or exceeded 50 percent of the time range from zero Mgal/d for the Auburn aquifer to 6.2 Mgal/d for the Upper Lake Quinsigamond aquifer (table 8). The Auburn aquifer is completely developed and has no remaining sources of additional supply. The upper Lake Quinsigamond is the next most completely developed aquifer. Reaches of some streams crossing the upper Lake Quinsigamond aquifer go dry part of the year as a result of present ground-water withdrawals. Three of nine aquifers studied have at least 1.0 Mgal/d 50 percent of the time available for future development. Of these three aquifers, the upper West River is the most favorable for development of a supply of 1.0 Mgal/d, followed by the upper Lake Quinsigamond and Stone Brook aquifers (fig. 9). The Stone Brook aquifer is capable of yielding 1.0 Mgal/d only 50 percent of the time. The aquifers capable of sustaining a small additional supply of 0.25 Mgal/d are, in order of productivity, the lower Mill River, lower Peters River, middle Mill River, the upper West River, upper Lake Quinsigamond, Stone

Table 8. Long-term yield available for future development in selected aquifers in the eastern and northern parts of the Blackstone River Basin, Massachusetts, if streamflow is maintained at 99.5-percent duration

Aquifer	Yield, in million gallons per day, available for future development for specified percentage of time						
	50	70	80	90	95	98	99.5
Upper Peters River	0.57	0.57	0.26	0.10	0	0	0
Lower Peters River	.38	.38	.38	.38	.22	0	0
Upper Mill River	.15	.15	.15	.15	.15	.02	0
Middle Mill River	.30	.30	.30	.30	.13	0	0
Lower Mill River	.58	.58	.58	.45	.32	.19	0
Upper West River	1.3	1.3	1.3	.51	0	0	0
Upper Lake Quinsigamond	6.2	5.2	3.0	0	0	0	0
Auburn	0	0	0	0	0	0	0
Stone Brook	1.5	.65	.29	.08	.04	.02	0

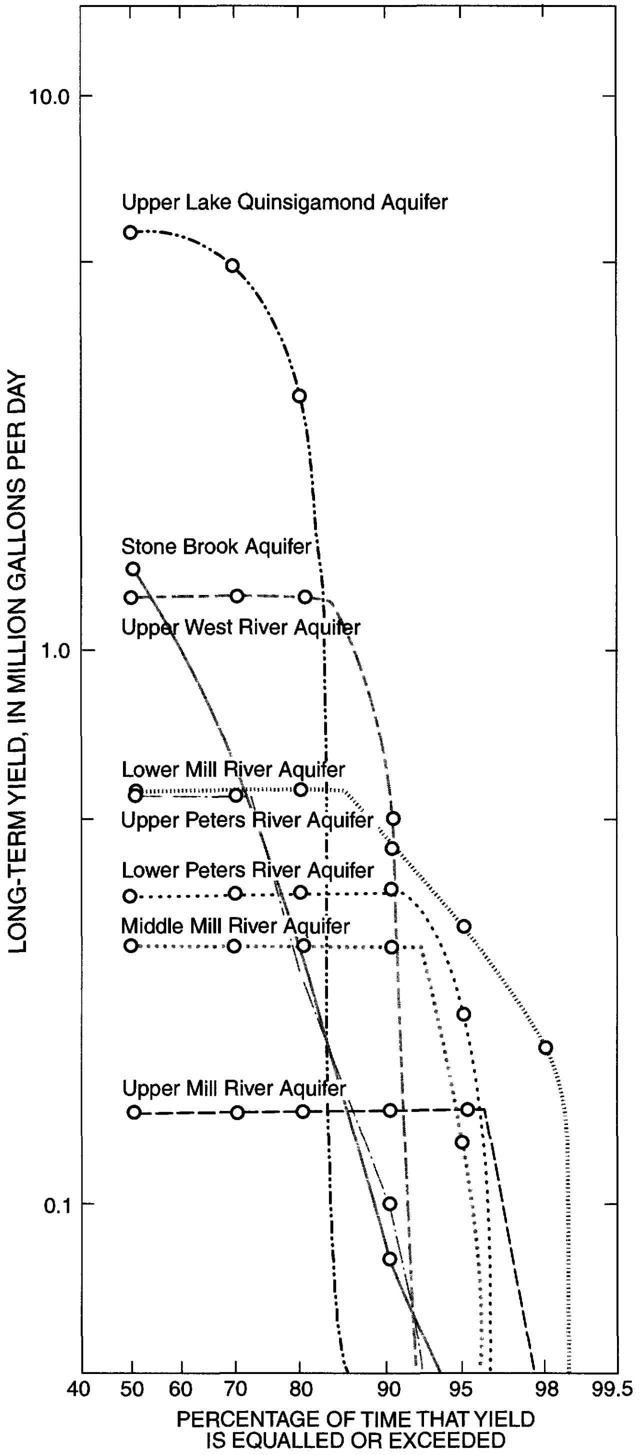


Figure 9. Additional long-term yield for selected aquifers in the eastern and northern parts of the Blackstone River Basin if streamflow is maintained at 99.5-percent duration.

Brook, and upper Peters River aquifers (fig. 9). The upper Mill River and Auburn aquifers are not capable of supporting an additional supply of 0.25 Mgal/d.

Streamflow regulation can affect the amount of streamflow and can represent an important management tool for increasing the amount of water available from streamflow depletion. The effect of streamflow regulation is discussed on plate 2.

Ground-Water Quality

On the basis of samples collected from public-supply wells and analyzed by the Massachusetts Office of Environmental Quality Engineering in 1984, water from wells in the eastern and northern parts of the Blackstone River Basin, exclusive of the Auburn aquifer, is slightly acidic, poorly to moderately buffered, and soft to moderately hard (table 9). In most samples, no single anion or cation predominated. Water from all wells sampled was suitable for public supply; however, some wells yielded water with iron and manganese concentrations that exceeded U.S. Environmental Protection Agency (1986) secondary maximum contamination levels (SMCL's) (300 µg/L and 50 µg/L, respectively). The pH of water from some wells was adjusted with potassium hydroxide to reduce the corrosiveness of the water and enhance treatment processes. This water was easily identified by potassium concentrations ranging from 20 to 115 mg/L, neutral to slightly alkaline pH, and alkalinities greater than 90 mg $CaCO_3$/L. These samples were eliminated from the data base and are not included in table 9.

Water collected from wells in the Auburn aquifer was different from water collected from all other wells in the eastern and northern parts of the Blackstone River Basin (table 9). Water from wells in the Auburn aquifer was slightly acidic, moderately to well buffered, and moderately hard to hard. In most samples, no single cation was dominant but chloride was the dominant anion. All wells sampled yielded water that exceeded the former U.S. Environmental Protection Agency (1976) drinking-water regulation for sodium of 20 mg/L. This standard was developed to protect individuals on sodium-restricted diets and is no longer enforced by the U.S. Environmental Protection Agency; however, the State of Massachusetts still requires utilities to notify consumers if sodium concentrations in drinking water exceed 20 mg/L.

Table 9. Summary of water-quality data for wells in the eastern and northern parts of the Blackstone River Basin, Massachusetts

[**All wells sampled:** Includes three wells sampled in the Auburn aquifer. All properties and constituents are given in milligram per liter of filtered samples unless otherwise noted. µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, actual value is less than value shown; --, no data]

Properties and constituents	Data from Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection) January through June 1984								Data from U.S. Geological Survey July through August 1985			
	Wells in the Auburn aquifer				All other wells sampled				All wells sampled			
	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum
Specific conductance (µS/cm)	5	297	[1]376	687	12	87	104	343	13	101	179	[2]920
pH	5	6.3	6.4	6.5	12	5.9	6.3	6.6	13	5.8	6.2	6.8
Hardness	5	87	[1]91	169	12	17	24	95	13	--	--	--
Calcium	5	29	[1]30	60	12	4.7	7.4	29	13	6.5	12	[2]52
Magnesium	5	3.5	[1]3.9	4.6	12	1.1	1.5	5.3	13	1.3	2.3	[2]4.9
Sodium	5	24	[1]32	100	12	5.3	9.4	23	13	6.0	15	[2]99
Potassium	5	3.4	[1]4.6	5.8	12	.6	1.1	2.8	13	1.2	2.0	[2]7.5
Alkalinity (as $CaCO_3$)	5	49	[1]56	65	12	11	16	50	13	11	19	[2]64
Sulfate	5	18	[1]23	33	12	8	12	39	13	8.3	12	60
Chloride	5	49	[1]85	175	12	7	14	52	13	12	25	[2]200
Fluoride	0	--	--	--	0	--	--	--	13	<.1	<.1	[2].1
Silica	0	--	--	--	0	--	--	--	13	8.0	11	[2]17
Dissolved solids	0	--	--	--	0	--	--	--	13	58	98	[2]551
Nitrogen, nitrite plus nitrate	5	.50	.50	1.7	12	.2	.75	2.9	13	.33	.66	[2]3.3
Nitrogen, ammonia	5	.01	.03	.06	12	<.01	<.01	.05	13	<.01	.02	[2].09
Phosphorus, ortho	0	--	--	--	0	--	--	--	13	<.01	<.01	[2].38
Boron (µg/L)	0	--	--	--	0	--	--	--	13	<20	<20	[2]50
Iron (µg/L)	5	30	60	340	12	<10	<10	450	13	<10	10	[2]800
Manganese (µg/L)	5	<10	150	360	12	<10	40	430	13	<10	60	330

[1] Median concentration significantly greater than for all other wells sampled by the Massachusetts Department of Environmental Quality Engineering on the basis of the median test (Neter and Wasserman, 1974) with a confidence criterion of 5 percent.

[2] Two of the three greatest values are from the Auburn aquifer.

Water from most wells exceeded the U.S. Environmental Protection Agency (1986) SMCL for manganese of 50 µg/L. The median specific conductance, hardness, and concentrations of all major ions in water collected from wells in the Auburn aquifer were determined to be significantly greater than the median values and concentrations in water from all other wells sampled in this part of the Blackstone River Basin on the basis of the median test (Neter and Wasserman, 1974), at a confidence criterion 10 percent (table 9). Large concentrations of these constituents, particularly sodium, were the reason for closing at least one public-supply well in the Auburn aquifer (Pollock, 1971) and probably are the result of urbanization and the application of road-deicing salts (Frimpter, 1974). Similar changes in ground-water quality resulting from urbanization were found in stratified-drift aquifers in Connecticut by Grady and Weaver (1988 and 1989). Differences between water collected from wells in the Auburn aquifer and wells in other parts of the basin were not statistically significant for other water-quality properties: median pH values, concentrations of selected nutrients, and trace elements (table 9).

No data were collected from wells in the Worcester area aquifer in 1984 because no public-supply wells tap this aquifer; however, a review of data collected between 1945 and 1965 and on file at the U.S. Geological Survey Office in Massachusetts showed that water from wells in this aquifer has greater specific conductances, hardness, and concentrations of most dissolved constituents than water from the Auburn aquifer. In general, water from wells in the Worcester area aquifer probably is not suitable for public supply, but may be suitable for industrial or commercial water uses. Elevated concentrations of dissolved constituents probably are the result of urban development.

Water samples analyzed by the Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection) were collected by representatives of local water districts over a 6-month period in 1984 and were subject to variable and uncontrolled hydrologic conditions. These data and results were verified with water samples collected as part of this study in the summer of 1985 (table 9). Fewer data were available from the 1985 sampling because not all wells sampled in 1984 were operating when samples were collected in 1985. Analytical results are similar for the two sampling periods and the median concentrations of all properties and constituents are not statistically different based on the median test (Neter and Wasserman, 1974) at a confidence criterion of 5 percent.

WATER RESOURCES ALONG THE BLACKSTONE RIVER, AREA 2

This section describes the surface- and ground-water resources of the Blackstone River Valley. The Blackstone River is the main stream in the study area. A nearly continuous deposit of stratified drift about 30 mi long occupies lowland areas along the Blackstone River. Results of detailed study on the effect of infiltration of surface water on ground-water quality at two locations along the Blackstone River are presented.

Surface Water

The Blackstone River begins in the southern part of Worcester and flows southeastward into Rhode Island near the city of Woonsocket. It is the largest stream in the study area. Major tributaries to the Blackstone River from the eastern and northern parts of the basin are the Middle, Quinsigamond, West, Mill, and Peters Rivers; major tributaries from the western part of the basin are the Mumford and the Branch Rivers (fig. 3). In the past, flow in the Blackstone River was extensively regulated. At one time, almost 90 percent of the total head along the river had been developed for water power, and the Blackstone was one of the most completely developed rivers in the world (New England Regional Planning Commission, 1936). Flow in the Blackstone is still regulated for water power; however, use of water power by local industries has declined, and many mill ponds along the Blackstone River are now used primarily for recreation. Flow in the Blackstone River is also affected by regulation, diversion, and interbasin transfer for water supply.

Continuous-record streamflow-gaging stations on the Blackstone River are or have been operated by the U.S. Geological Survey at Northbridge (01110500) and Woonsocket (01112500). Miscellaneous measurements of streamflow were made at seven sites along the Blackstone River during this project. Additional measurements of streamflow from previous studies (Walker and Krejmas, 1986) also are available for some sites. Locations of streamflow-gaging stations are shown in figure 3. Miscellaneous-measurement sites are shown on plate 2, and miscellaneous measurements are listed in appendix A.

Streamflow Characteristics

Analysis of data from the streamflow-gaging station at Northbridge (Walker and Krejmas, 1986) showed that, in general, streamflow in the Blackstone River is highest in March and gradually declines to the lowest flows in July. This contrasts with streamflow data from the eastern and northern parts of the Blackstone River Basin where the lowest flows occur in September. This difference may result, in part, from interbasin transfer of water from the Nashua River Basin. This water, 17.4 Mgal/d (26.9 ft^3/s), is part of the public supply for Worcester. The remainder of Worcester's public supply, about 9 Mgal/d (14 ft^3/s), is obtained from surface-water sources near the headwaters of the Blackstone River. After the water has been used, it enters the Blackstone River at the outfall of the regional wastewater-treatment plant serving the Worcester metropolitan area, where it affects the quantity of streamflow in the river through all ranges of flow. In 1980, total discharge from this outfall averaged 26 Mgal/d (40 ft^3/s).

The flow-duration curve for the Blackstone River at Millbury, about one mile downstream from the outfall of the regional wastewater-treatment plant, is shown in figure 10. This figure also shows the estimated flow-duration curve if water from interbasin transfer were not present, and the total wastewater discharge to the Blackstone River at Millbury. At a flow duration of 50 percent, almost 50 percent of the flow in the river is treated municipal wastewater; at a flow duration of 80 percent, almost 70 percent of the flow in the river is treated municipal wastewater. The percentage of wastewater at any given flow duration in the Blackstone River at Northbridge and Woonsocket, R.I. is less than that at Millbury because of surface-water inflows and ground-water discharge to the river.

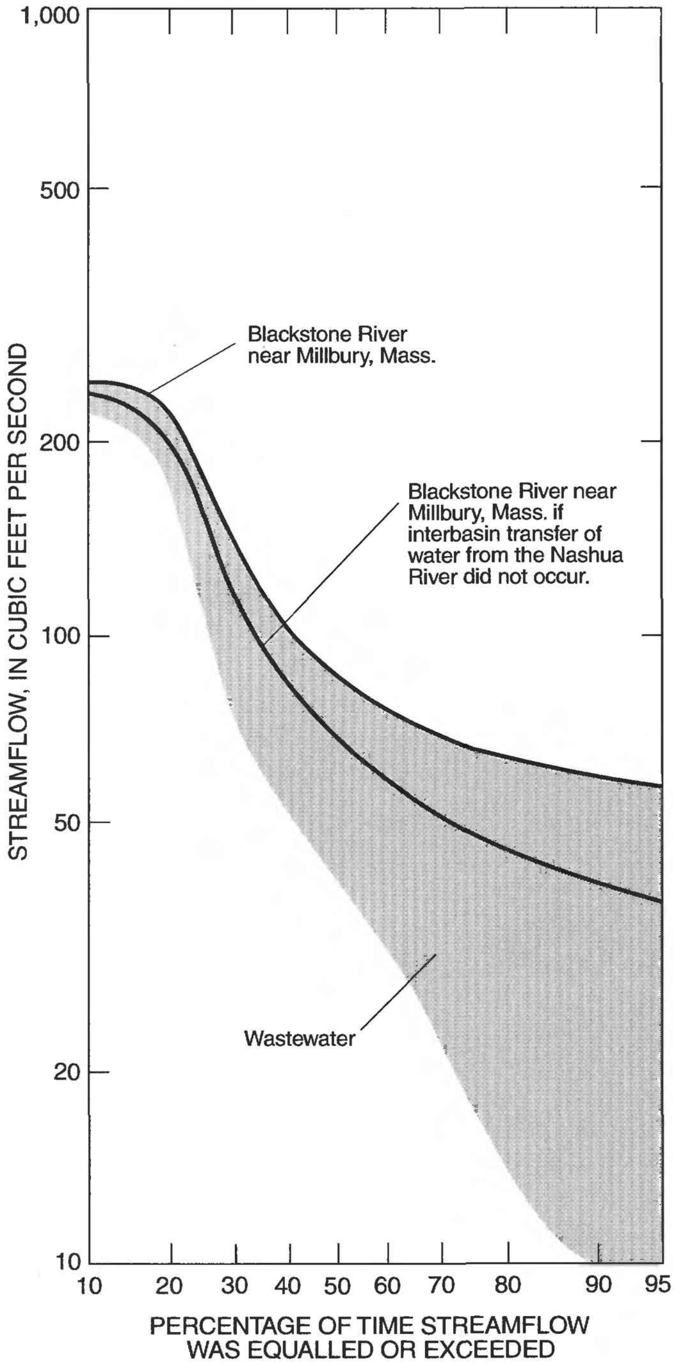


Figure 10. Flow-duration curve for the Blackstone River near Millbury (01109700).

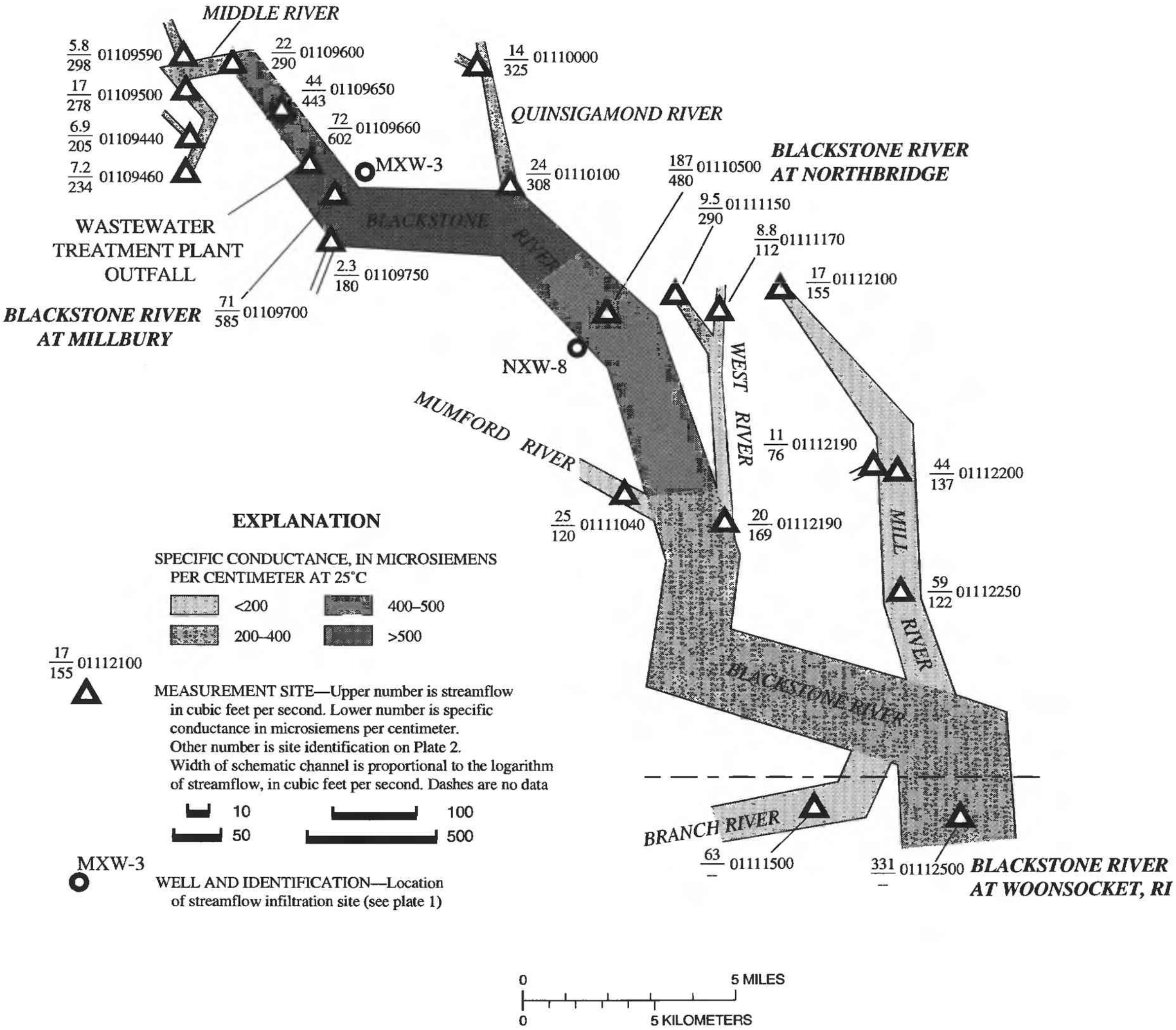
Surface-Water Quality

Water quality in the Blackstone River is affected by the large amounts of treated wastewater the river receives. Surface-water quality in the Blackstone River, in turn, determines the quality of water available for infiltration by wells along the river and, ultimately, the quality of water yielded by these wells.

Specific conductance was used as an index to evaluate variations in water quality along the Blackstone River and changes in water quality with streamflow. Specific conductance was selected as an index because it is easily measured, data from previous studies were available, and the specific conductance of treated wastewater discharged to the Blackstone River is greatly different than that of most other surface water (or ground water) in the Blackstone River Basin. Because specific conductance is only an index of the chemical quality of water, other properties and constituents also were measured at selected sites.

Specific Conductance

Measurements of streamflow and specific conductance were made at selected sites on the Blackstone River and its tributaries from March 30 through April 8, 1985. These data were collected following an extended period of little or no precipitation and represent surface-water quantity and quality at a flow duration of about 50 percent. Data are presented on the diagram in figure 11. Approximate specific conductances for the Branch River (01111500), and the Blackstone River at Woonsocket, R.I. (01112500) were estimated from earlier specific-conductance measurements at those sites. Also shown in figure 11 is the location of the outfall of the regional wastewater-treatment plant serving the Worcester metropolitan area. At the time these data were collected, treated wastewater from this outfall composed almost half of the flow in the Blackstone River immediately downstream, and the specific conductance in the river was greatest immediately downstream from the outfall. Discharge gradually increased and specific conductance gradually decreased with increasing distance downstream from the outfall.



EXPLANATION

SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25°C

░ <200	▒ 400–500
▒ 200–400	▓ >500

17/155 01112100 △ MEASUREMENT SITE—Upper number is streamflow in cubic feet per second. Lower number is specific conductance in microsiemens per centimeter. Other number is site identification on Plate 2. Width of schematic channel is proportional to the logarithm of streamflow, in cubic feet per second. Dashes are no data

10	100
50	500

MXW-3 ○ WELL AND IDENTIFICATION—Location of streamflow infiltration site (see plate 1)

Figure 11. Streamflow and specific conductance of water from the Blackstone River, April 30 through May 8, 1985.

On the basis of these data, two sites, the Blackstone River at Millbury (01109700) and the Blackstone River at Northbridge (01110500) (fig. 3), were selected for detailed data collection to evaluate changes in specific conductance with changes in streamflow. The detailed data were used to evaluate the effect of infiltration of surface water on ground-water quality, which is discussed later in this report. Additional data collected from the Blackstone River at Millville (01111230, pl. 2) as part of the U.S. Geological Survey's National Stream Quality Accounting Network (NASQAN) and miscellaneous data collected from the Blackstone River at Northbridge also were used in this analysis (table 10). The data from Millville and Northbridge have longer periods of record than data collected during the course of this study; however, no problems should result from combining data sets having slightly different periods of record because there was no statistically significant trend in specific conductance or flow-adjusted specific conductance in water from the Blackstone River at Millville from 1979 through 1983 (Briggs and Feiffer, 1986).

Specific conductance of water in the Blackstone River increases with decreasing streamflow and decreases with increasing streamflow. The relations between specific conductance and streamflow are shown in figure 12. These relations were developed from the polynomial function

$$Y = \beta_0 + \beta_1 Q + \beta_2 Q^2, \qquad (10)$$

where

Y is the dependent variable (specific conductance, in µS/cm);

Q is the independent variable (streamflow, in ft^3/s); and

β_0, β_1, and β_2 are statistical estimators of intercept, slope, and curvature (Neter and Wasserman, 1974).

The functions were fit by use of the method of least squares to obtain estimates of intercept, slope, and curvature. The F-test (Neter and Wasserman, 1974), at a confidence criterion of 5 percent, was used to establish that β_0, β_1, and β_2 were significantly different from zero and should remain in the model.

Estimates of intercept, slope, and curvature developed from data collected at Millville were statistically different from estimates obtained at the other sites. This is based on analysis of covariance, with sample-site location as the concomitant variable (Neter and Wasserman, 1974), at a confidence criterion of 5 percent. Estimates of intercept, slope, and curvature developed from data collected at Northbridge and Millbury were not statistically different from each other based on a similar analysis of covariance. As a result, data from Northbridge and Millbury were combined. The functions were refit and the following statistical models and associated R^2 were obtained:
At Millville

$$Y = 298 - 0.13Q + 0.000027Q^2 \qquad (11)$$
$$(R^2 = 0.46);$$

at Northbridge and Millbury

$$Y = 559 - 0.99Q + 0.00056Q^2 \qquad (12)$$
$$(R^2 = 0.79).$$

These polynomial functions yield a minimum (or maximum if β_2 is negative) value of Y at $Q_{min} = -\beta_1/2\beta_2$. Because of the behavior of the polynomial function at values of Q greater than Q_{min}, these relations are not valid at values of Q greater than Q_{min} (Izbicki, 1985). At Millville this threshold streamflow is 2,407 ft^3/s. At Northbridge and Millbury this threshold streamflow is 884 ft^3/s.

These equations show that surface-water quality in the Blackstone River, as indicated by specific conductance, varies with flow and distance downstream from the outfall of the regional wastewater-treatment plant at Worcester. The river can be divided into two reaches on the basis of specific-conductance data. Reach 1 is described by data collected at Millbury and Northbridge and is that part of the river downstream from the outfall to the Mumford River. Reach 2 is described by data collected at Millville and is that part of the river downstream from the Mumford River to the Rhode Island State line. Specific conductance is lower in the downstream part of reach 1 near Northbridge than in the upstream part near Millbury primarily because streamflow is greater at Northbridge. The increases in streamflow dilute the treated municipal wastewater. Specific conductance is lowest in reach 2 near Millville not only because streamflow is greater and the wastewater has been diluted, but also because of changes associated with improving water quality farther downstream.

Table 10. Summary of water-quality data for the Blackstone River, Massachusetts

[All properties and constituents given in milligram per liter of filtered samples unless otherwise noted. ft^3/s, cubic foot per second; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, actual value is less than value shown; --, no data]

Properties and constituents	Blackstone River at Millbury (01109700), October 1985 through September 1986				Blackstone River at Northbridge (01110500), October 1976 through September 1986				Blackstone River at Millville (01111230), October 1976 through September 1986			
	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum
Instantaneous discharge[1] (ft^3/s)	11	66	116	1,130	29	96	238	1,170	97	83	352	2,830
Specific conductance (µS/cm)	11	197	438	545	29	134	350	545	97	134	247	369
pH	10	6.2	7.0	7.2	10	6.7	7.0	7.4	85	5.6	6.5	7.3
Hardness	9	29	57	66	10	30	49	60	33	25	35	54
Calcium	9	9.3	18	21	10	1.6	2.6	3.1	36	1.3	1.9	2.5
Magnesium	9	1.4	2.8	3.3	10	1.6	2.6	3.1	36	1.3	1.9	2.5
Sodium	9	33	46	78	10	29	40	65	36	16	24	39
Potassium	9	2.6	5.4	9.3	10	2.6	4.7	6.9	36	1.5	2.7	5.2
Alkalinity (as $CaCO_3$)	10	19	56	82	10	18	38	63	0	--	--	--
Sulfate	9	13	29	42	10	13	22	31	36	10	17	35
Chloride	9	55	69	110	10	42	62	110	38	24	36	61
Fluoride	9	<.1	.4	.5	10	.1	.3	.92	32	.1	.15	.4
Silica	9	4.8	7.2	8.9	9	4.8	6.4	7.3	32	3.7	5.6	8.7
Dissolved solids	9	129	224	292	9	129	197	260	15	87	129	199
Nitrogen, nitrite plus nitrate	9	.25	.57	4.8	9	.19	.81	4.4	32	.12	.88	2.7
Nitrogen, ammonia	9	.51	2.8	6.4	9	.19	1.4	5.5	33	.02	.51	3.3
Phosphorus, ortho	7	.27	.61	1.1	9	.06	.24	.83	0	--	--	--
Boron (µg/L)	9	<10	130	300	10	<10	90	180	0	--	--	--
Iron (µg/L)	10	110	260	860	10	96	190	490	5	130	280	370
Manganese (µg/L)	9	110	150	250	9	36	140	200	5	30	110	160

[1] Descriptive of conditions at the time water-quality samples were collected. Minimum, median, and maximum discharge measurements should not be used as streamflow statistics.

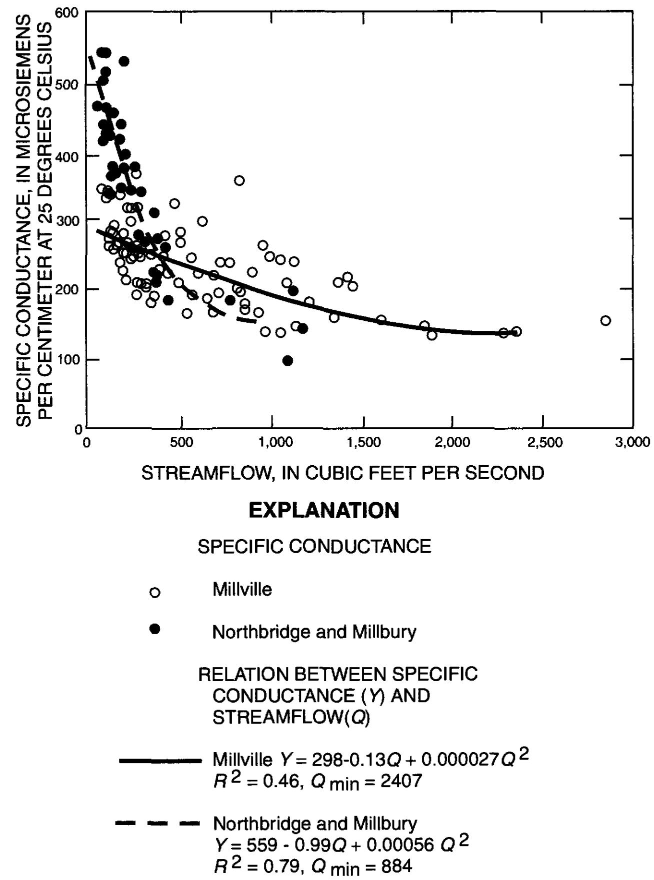


Figure 12. The relation between specific conductance and streamflow in the Blackstone River at Millville (01111230), and at Northbridge (01110500), and at Millbury (01109700).

Other Properties and Constituents

Physical properties and concentrations of major ions, nutrients, and selected trace elements in water from the Blackstone River at Millbury, Northbridge, and Millville are summarized in table 10. Individual analyses are listed in appendix B. Water in the Blackstone River ranges from near neutral to slightly acidic, from moderately well to poorly buffered, and from moderately hard to soft. Most dissolved constituents are inversely correlated with streamflow (Kendall's Tau β correlation coefficient at a confidence criterion of 10 percent), which indicates that water in the Blackstone River contains fewer dissolved constituents at higher flows than at lower flows. This conclusion is also supported by decreases in specific conductance with increases in flow in the Blackstone River. pH and concentrations of alkalinity, nitrite plus nitrate nitrogen, ammonia, iron, and manganese are not significantly correlated, either positively or negatively, with streamflow (Kendall's Tau β correlation coefficient at a confidence criterion of 10 percent).

In general, pH, alkalinity, hardness, and the concentrations of most other dissolved constituents decrease downstream from Millbury. This decrease probably is related to increased streamflow and subsequent dilution downstream from Millbury. In contrast, the concentration of nitrite plus nitrate nitrogen increases downstream from Millbury. Increases in nitrite plus nitrate nitrogen may be related to biological transformation of ammonia, which originates from treated wastewater, to nitrate. In general, ammonia is the predominant nitrogen species in water from the Blackstone River in reach 1 near Millbury and Northbridge, and nitrate nitrogen is the predominant nitrogen species in reach 2 near Millville. These data agree with specific-conductance data indicating that water quality improves with increasing downstream distance from the outfall of the regional wastewater-treatment plant in Worcester.

Ground Water

A nearly continuous deposit of stratified drift almost 30 mi long and from 400 ft to greater than 1 mi wide occupies lowland areas along the Blackstone River (fig. 1). These deposits constitute important aquifers in the study area. For the purposes of this study, these deposits have been divided into four aquifers: upper Blackstone River, middle Blackstone River near Grafton, middle Blackstone River near Northbridge, and lower Blackstone River. Locations of these aquifers are shown in figure 1 and in greater detail on plate 1.

Hydraulic Properties

Saturated thickness, hydraulic conductivity, and transmissivity of aquifer materials were estimated. Lithologic and hydrologic data from drillers' and geologic logs were analyzed in the same manner as similar data from the northern and eastern parts of the Blackstone River Basin. In addition to these data, seismic-reflection profiles were done along the Blackstone River. Location of seismic profiles, sections interpreted from the seismic data, and a brief explanation of the seismic-reflection technique are shown on plate 1. Because of numerous fallen trees in the river channel, it was not possible to collect seismic-reflection data in the lower Blackstone River area. As a result, seismic-refraction data along lines having a total length of 0.7 mi were collected. Location of seismic-refraction lines and sections interpreted from seismic-refraction data are shown on plate 1.

Saturated Thickness

Saturated thickness of aquifers along the Blackstone River ranged from zero near the edges of the aquifers to almost 170 ft in the middle Blackstone River aquifer near Northbridge. The estimate of 170 ft from seismic-reflection data is almost 70 ft greater than any saturated thickness previously recorded in the Blackstone River Basin. The V-shaped bedrock valley shown on the seismic-reflection profiles of this area (pl. 1) indicates that the bedrock topography has not been greatly modified by glacial action and that preglacial drainage is the controlling factor in aquifer orientation in this part of the Blackstone River Basin. The other three aquifers along the Blackstone River have a maximum saturated thickness ranging from 54 to 140 ft. Each of these aquifers has a broad flat bedrock bottom more typical of valleys modified by glacial action. Saturated thickness data are summarized in table 11.

Table 11. Physical and hydraulic characteristics of aquifers along the Blackstone River, Massachusetts

[**Maximum saturated thickness, Maximum transmissivity, and Maximum well yield:** Data from driller's information and U.S. Geological Survey files. **Yield of public-supply wells in 1980:** Data from Massachusetts Department of Environmental Management, Office of Water Resources, 1985. Additional exploration may identify sites having greater saturated thickness, transmissivity, or well yields. ft, foot; ft^2/d, foot squared per day; gal/min, gallon per minute; Mgal/d, million gallons per day; mi^2, square mile; >, actual value is greater than value shown; <, actual value is less than value shown; --, no data

Aquifer	Location (town)	Area (mi^2)	Typical land use	Maximum saturated thickness (ft)	Maximum transmissivity (ft^2/d)	Maximum well yield (gal/min)	Yield of public-supply wells in 1980 (Mgal/d)	Quality of surface water available for infiltration by wells near the Blackstone River
Upper Blackstone River	Worcester, Millbury	2.0	Urban, industrial, residential	54	10,300	750	1.3	Primarily treated municipal wastewater. Elevated specific conductance and concentrations of most dissolved constituents as compared to native ground water. Nitrogen species dominated by ammonia.
Middle Blackstone River, near Grafton	Millbury, Sutton, Grafton, Northbridge	3.0	Rural, residential	73	>20,000	1,350	1.1	Elevated specific conductance and concentrations of most dissolved constituents as compared to native ground water. Nitrogen species dominated by ammonia.
Middle Blackstone River, near Northbridge	Northbridge	1.8	Rural	170	<1,500	--	--	Elevated specific conductance and concentrations of most dissolved constituents as compared to native ground water. Nitrogen species dominated by ammonia.
Lower Blackstone River	Uxbridge	3.5	Rural, residential, commercial	140	19,000	770	2.1	Elevated specific conductance and concentrations of most dissolved constituents as compared to native ground water. Nitrogen species dominated by ammonia.

Hydraulic Conductivity and Transmissivity

Aquifers along the Blackstone River contain a variety of materials having a wide range of hydraulic conductivities and transmissivities (table 11). The finest grained deposits are found in the middle Blackstone River aquifer near Northbridge. In this area, aquifer materials consist primarily of silt and clay. Despite saturated thicknesses up to 170 ft aquifer transmissivities are generally less than 1,500 ft^2/d. Seismic-reflection data (pl. 1) collected along this part of the Blackstone River indicate coarser material may be found at depth near terrace deposits along the edge of the valley. Amory Engineers (1986) recommended this area to the community of Northbridge for ground-water exploration.

In other areas, especially along the lower Blackstone River, transmissivities are more favorable for the development of public supplies. Maximum transmissivities are summarized in table 11.

Short-Term and Long-Term Yield for Public Supply

Short-term yields were not estimated because the Blackstone River is such a large stream and receives so much additional flow (26.9 ft^3/s) as interbasin transfer from the Nashua River Basin, that it is unreasonable to expect streamflow to approach zero during even the most extreme drought. Long-term yields were not estimated because it is likely that enough water is available at all times to support foreseeable ground-water development and subsequent streamflow depletion by wells. Because the lowest flows in the Blackstone River typically occur in July (as opposed to September in most other streams in the study area) water may be available for streamflow depletion by wells along the Blackstone River when it is not available in other parts of the basin. The difference in timing of low flow may be beneficial for regional ground-water-resource management; however, surface-water quality in the Blackstone River has been affected by wastewater discharges, and infiltration of water from the Blackstone River can adversely affect the quality of water yielded by wells.

Ground-Water Quality

Based on samples collected from public-supply wells and analyzed by the Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection) in 1984, water from most wells in aquifers along the Blackstone River is slightly acidic, poorly buffered, and soft. Sodium and chloride are the predominant ions. Water from most wells is suitable for public supply, but one well yielded water with manganese concentrations that exceeded the U.S. Environmental Protection Agency (1986) SMCL of 50 mg/L. The median specific conductance, pH, hardness, and concentrations of all major ions, nutrients, and trace elements listed in table 12 were not significantly different from the median values and concentrations in water from most wells sampled from the eastern and northern parts of the Blackstone River Basin (table 9), on the basis of the median test (Neter and Wasserman, 1974) at a confidence criterion of 5 percent.

Two wells (MXW-3 and NXW-8, fig. 1) yielded water significantly different in chemical quality from all other wells sampled from aquifers along the Blackstone River. The median specific conductance, and concentrations of all major ions, ammonia, iron, and manganese in water from wells MXW-3 and NXW-8 was significantly greater than the median values and concentrations of water from other wells, on the basis of the median test (Neter and Wasserman, 1974) with a confidence criterion of 5 percent (table 12). The median hardness of water from well MXW-3 was also significantly greater than the median hardness of water from other wells sampled; however, the median hardness of water from well NXW-8 was not. These wells are less than 100 ft from the Blackstone River. Concentrations of sodium and manganese in all water sampled from both wells exceeded the U.S. Environmental Protection Agency (1976, 1986) recommended limits. Differences in major-ion concentrations are the result of infiltration of water from the Blackstone River in the vicinity of MXW-3 and NXW-8. Differences in iron and manganese concentrations probably are the result of reducing conditions in the aquifer created by infiltration of poor-quality surface water and subsequent dissolution of iron and manganese from aquifer materials.

Because of the proximity of wells MXW-3 and NXW-8 to the Blackstone River and the differences in their water quality from other wells near the river, these wells were selected for more detailed study of infiltration of surface water.

Table 12. Summary of water-quality data for wells in aquifers along the Blackstone River, Massachusetts

[All properties and constituents given in milligram per liter of filtered samples unless otherwise noted. µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, actual value is less than value shown; --, no data]

Properties and constituents	Data from U.S. Geological Survey October 1985 through September 1986								Data from Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection) January through June 1984			
	Well MXW-3				Well NXW-8				All other wells sampled			
	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum	Number of observations	Minimum	Median	Maximum
Specific conductance (µS/cm)	10	380	[1]408	474	8	215	[1]230	244	6	69	123	149
pH	8	6.3	6.5	6.7	8	5.8	6.3	6.7	6	6.1	6.2	6.4
Hardness	10	44	[1]50	57	8	29	32	44	6	17	22	30
Calcium	10	14	[1]16	18	8	9.0	[1]10	14	6	5.7	6.4	8.4
Magnesium	10	2.3	[1]2.4	3.6	8	1.6	1.7	2.2	6	.78	1.5	2.2
Sodium	10	45	[1]49	58	8	25	[1]28	30	6	4.5	14	15
Potassium	8	4.9	[1]6.1	6.6	8	2.5	[1]2.7	3.9	6	1.2	1.5	2.3
Alkalinity (as $CaCO_3$)	8	42	[1]50	52	8	13	16	19	6	9.0	14	17
Sulfate	10	17	[1]20	28	8	14	[1]16	20	6	8.0	13	14
Chloride	10	66	[1]74	97	8	40	[1]45	51	6	7.0	20	24
Fluoride	10	.2	.2	.2	8	.1	.1	.3	0	--	--	--
Silica	10	9.6	10	11	8	6.7	9.6	11	0	--	--	--
Dissolved solids	10	168	212	320	8	114	128	150	0	--	--	--
Nitrogen, nitrite plus nitrate	9	.53	1.3	1.9	8	.91	1.1	1.3	6	.5	1.4	1.8
Nitrogen, ammonia	8	2.7	[1]3.0	3.5	8	.12	[1].18	.24	6	<.01	.02	.03
Phosphorous, ortho	9	.02	.04	.17	8	<.01	<.01	.02	0	--	--	--
Boron (µg/L)	8	110	140	200	8	<10	60	130	0	--	--	--
Iron (µg/L)	8	10	[1]40	120	8	20	[1]30	50	6	<10	20	40
Manganese (µg/L)	9	410	[1]550	630	7	81	[1]110	140	6	<10	20	40

[1] Median concentration significantly greater than that for all other wells sampled in aquifers along the Blackstone River on the basis of the median test (Neter and Wasserman, 1974) with a confidence criterion of 5 percent.

Infiltration of Surface Water Near Well MXW-3

This site contains two public-supply wells that have a combined yield of 1.3 Mgal/d (Massachusetts Department of Environmental Management, 1985). Locations of the public-supply wells and observation wells are shown in figure 13. These wells provide one of the largest sources of public supply in the Blackstone River Basin. Most of the water withdrawn from this site is withdrawn from well MXW-3. Well MXW-4, to the northwest, is used primarily to augment supply during periods of peak demand.

This site was selected for study because it is on one of the most degraded reaches of the Blackstone River. The site is less than 1 mi downstream from the outfall of the regional wastewater-treatment plant serving the Worcester metropolitan area. In addition, both wells are less than 100 ft from the river. Water-quality data indicate that these wells derive part of their yield from the infiltration of surface water (Izbicki, 1987a).

Hydrologic Setting

The wells are in the upper Blackstone River aquifer. Physical and hydraulic properties of that aquifer are summarized in table 11. Near well MXW-3 the aquifer is between 500 and 600 ft wide, has a saturated thickness typically less than 50 ft, and extends for several miles along the Blackstone River. Test drilling done near the closest approach of the Blackstone River to well MXW-3 along geologic section *A–A′* (fig. 14) showed that well MXW-3 is separated from the Blackstone River by a deposit of fine sand and silt that grades to clay with increasing depth. Test drilling also showed that well MXW-3 is completed in a buried gravel deposit that extends along the main axis of the valley.

The areal extent of the silt and clay deposits and the location of the buried gravel deposits were mapped by use of the very-low-frequency radio-wave electromagnetic technique (VLF) (Izbicki, 1987b). The results of this work are shown in figure 15. To verify VLF data, additional test drilling was done along geologic section *B–B′* (fig. 16). Lithologic data show that deposits of fine sand, silt, and clay along section *A–A′* thin or pinch out entirely and are replaced by coarser deposits of sand and gravel. Buried gravel deposits were found at wells MXW-60, 66, and 73 from 20 to 30 ft below land surface.

Surface-Water/Ground-Water Relations

The heterogeneity of the deposits near well MXW-3 affects ground-water flow to the well and, in part, determines the hydraulic connection of the well to the Blackstone River. For the purposes of this study, the hydraulic connection of the well to the river was evaluated as streamflow depletion, for a typical pumping cycle of 0.6 days at 700 gal/min (1.56 ft^3/s), along geologic sections *A–A′* (predominantly fine material) and *B–B′* (predominantly coarse material). The curves in figure 17 show that the effect of pumping along geologic section *B–B′* is more rapid and greater in magnitude than near section *A–A′*, even though the distance along *B–B′* is nearly three times greater than the distance along section *A–A′*.

The curves shown in figure 17 were calculated according to a method developed by Jenkins (1968). This method incorporates several limiting assumptions (most importantly a fully-penetrating stream that behaves as a line source of recharge) that are not strictly met at this site; thus, figure 17 should be interpreted as an indication of the relative amounts and timing of streamflow depletion rather than an estimate of the actual quantity of streamflow depletion along each geologic section.

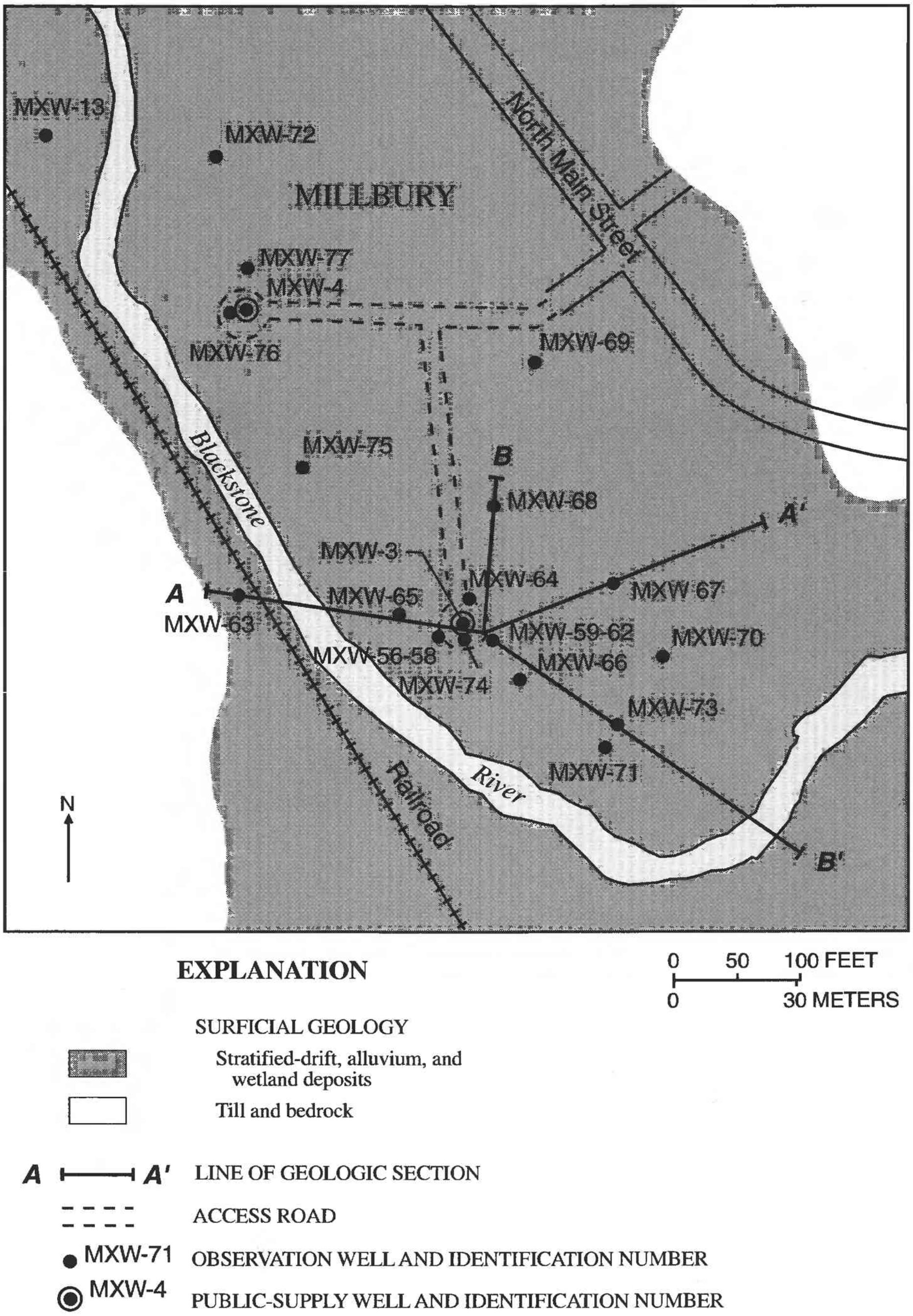


Figure 13. Location of well MXW-3 and nearby observation wells.

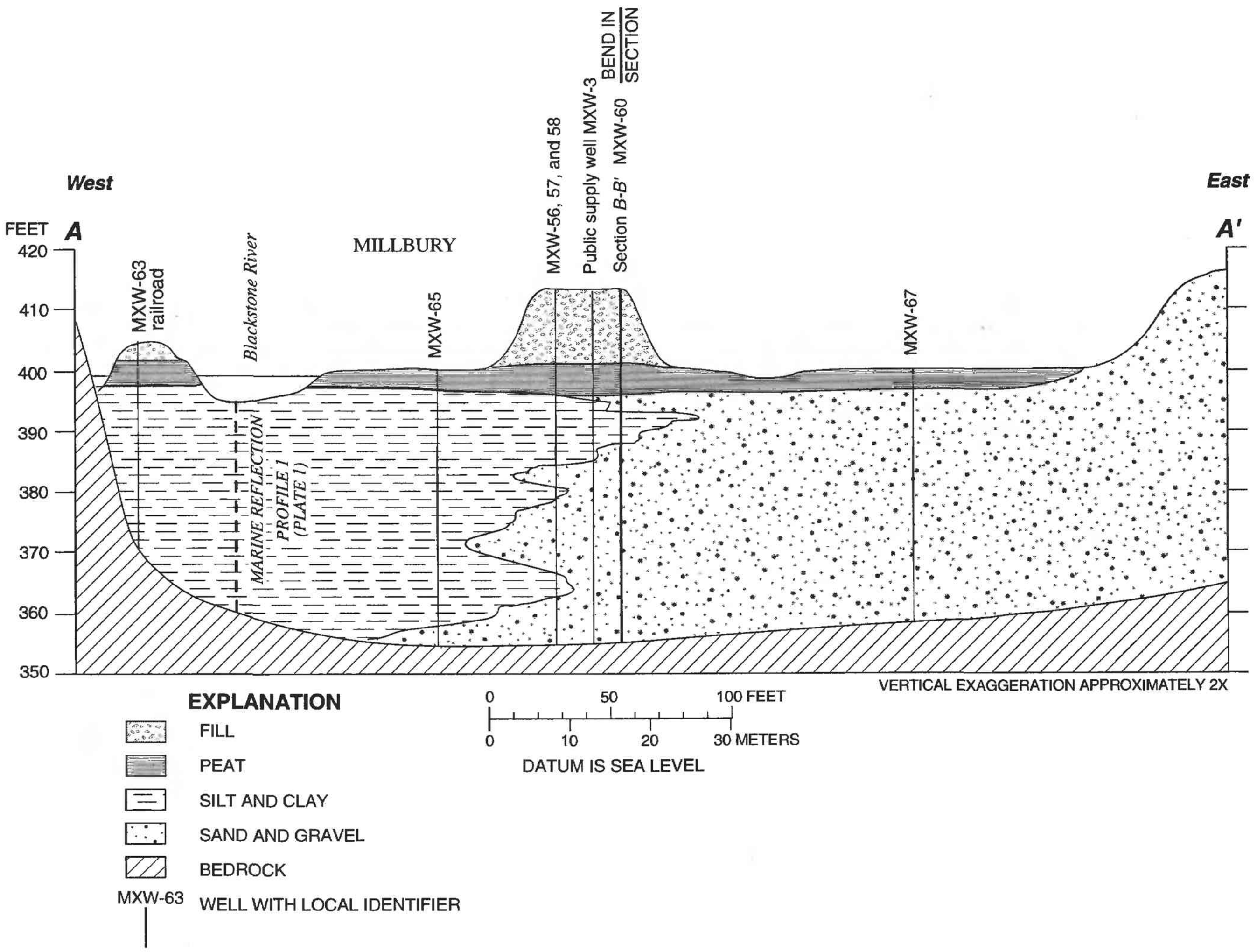


Figure 14. Geologic section *A–A'*, Blackstone River, Millbury, (trace of section shown in figure 13).

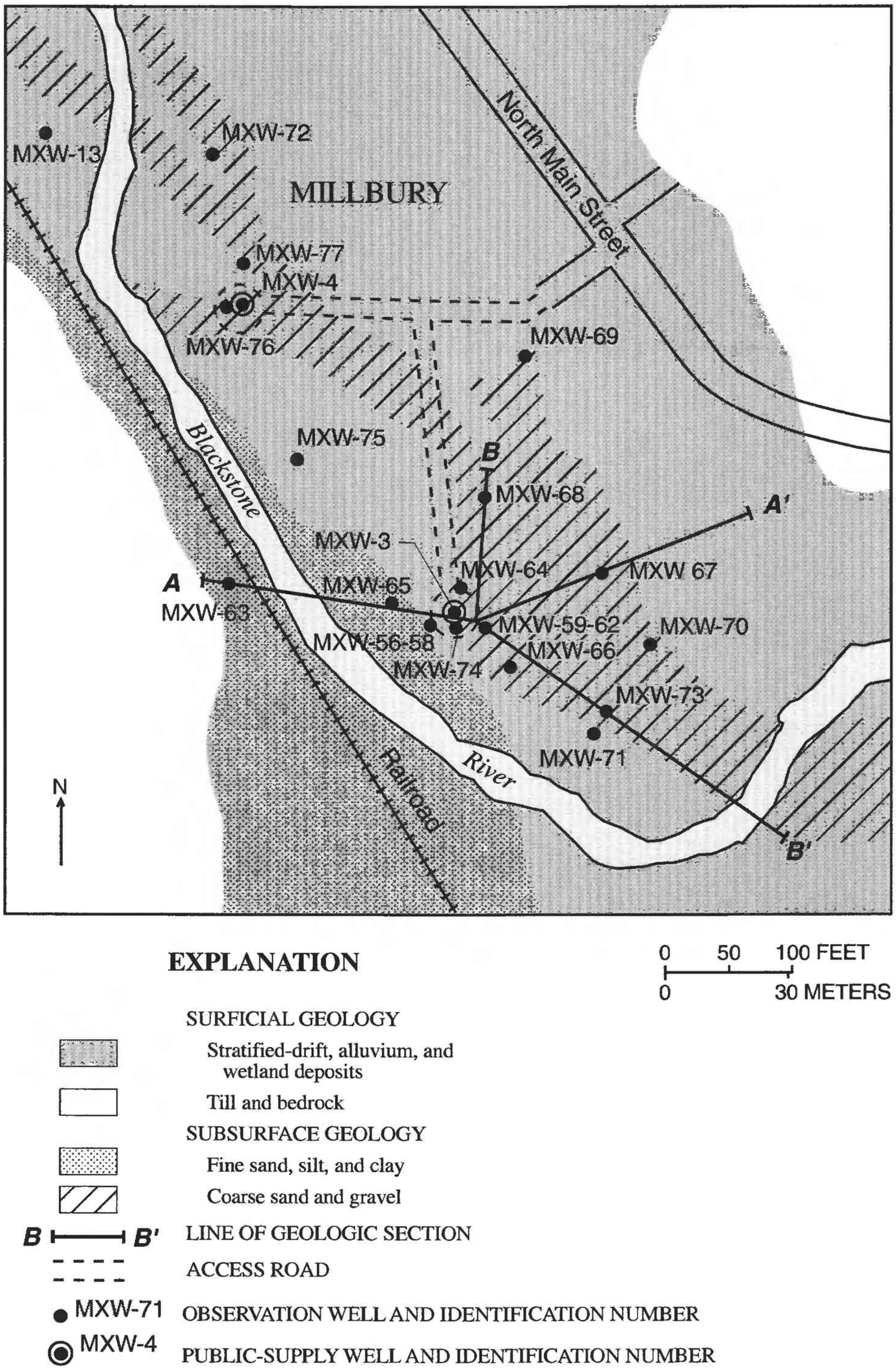


Figure 15. Location of buried gravel deposits and extent of fine-grained deposits near well MXW-3.

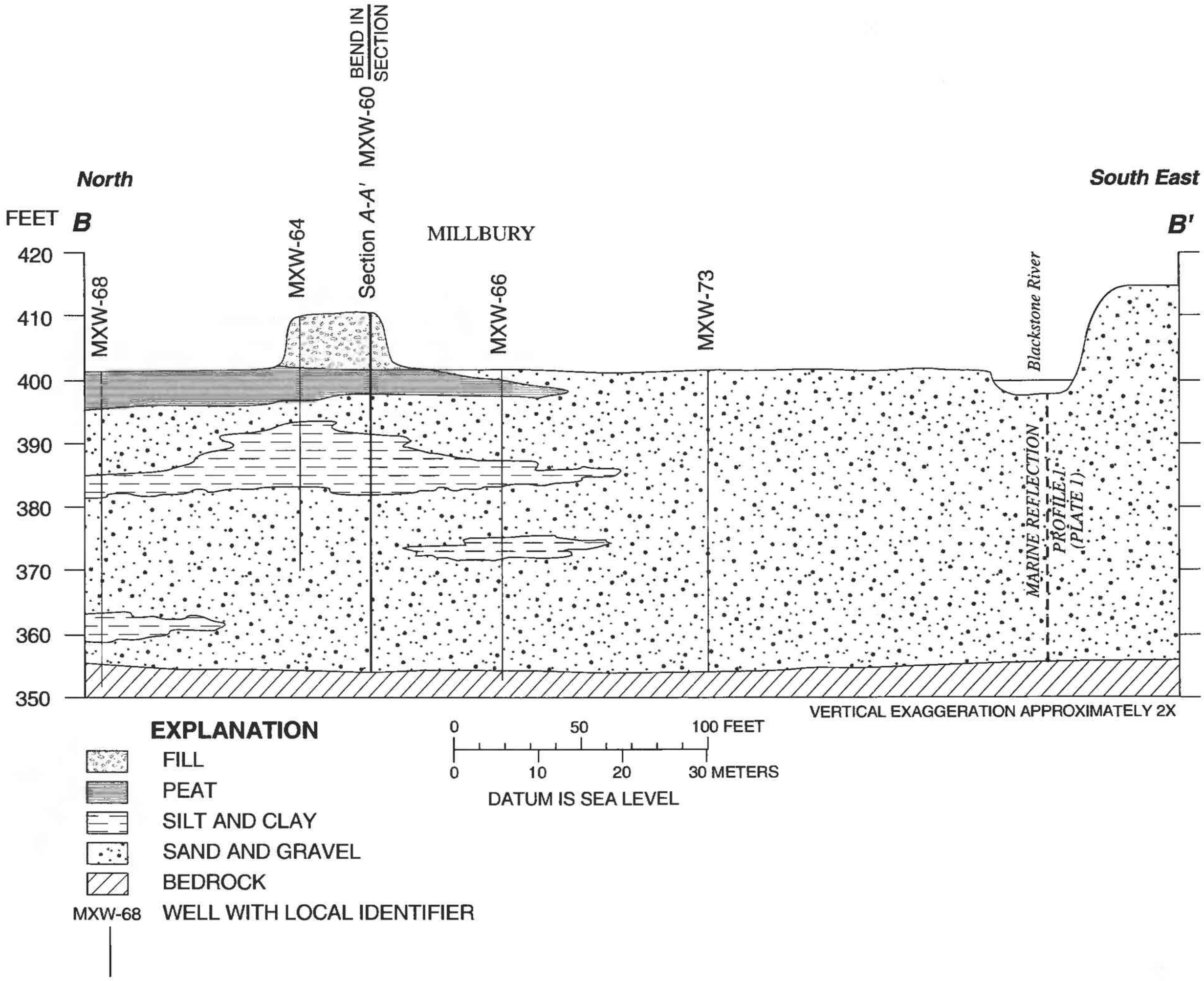


Figure 16. Geologic section *B–B'*, Blackstone River, Millbury (trace of section in figure 15).

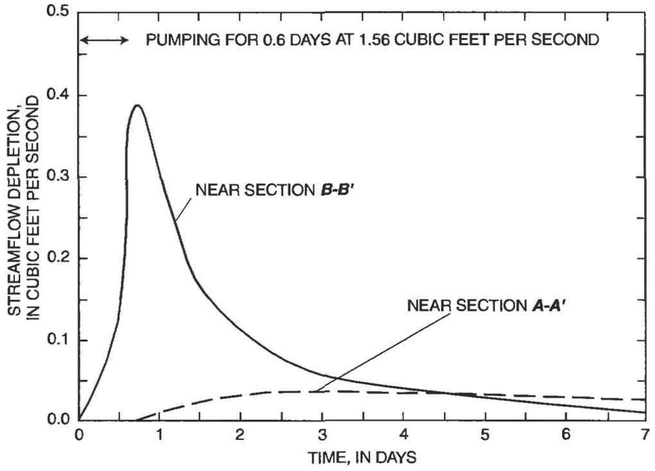


Figure 17. Streamflow depletion along geologic sections *A–A′* and *B–B′* for a typical pumping cycle at well MXW-3.

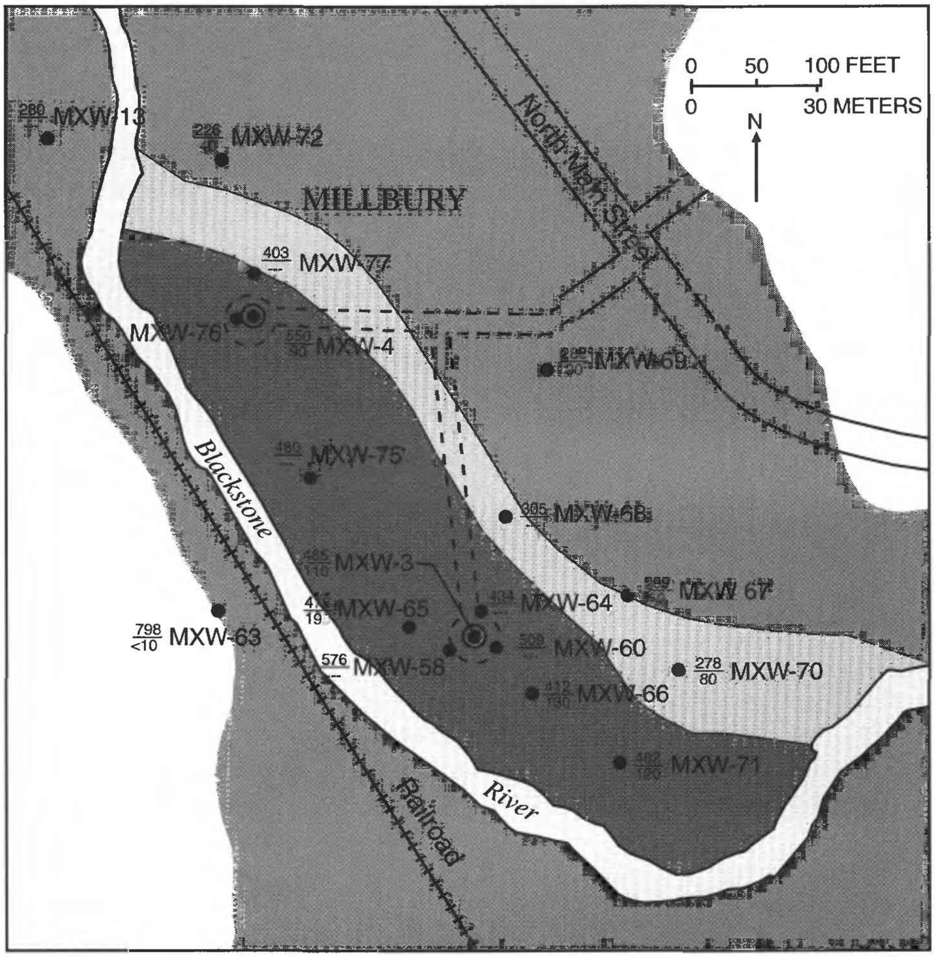
Ground-Water Quality Near Well MXW-3

Specific conductance and concentrations of boron in water from wells near well MXW-3 between April 18 and 25, 1986 are shown in figure 18. At that time, specific conductance ranged from 226 to 798 µS/cm, and boron concentration ranged from <10 to 190 µg/L.

Specific conductance and boron are indicators of surface water infiltrated from the Blackstone River. During low flows most of the water in the Blackstone River is treated municipal wastewater (fig. 10). This water has high specific conductance compared to most other surface and ground waters in the Blackstone River Basin (fig. 11). Boron, a component of many laundry detergents (LeBlanc, 1984), is also present at high concentrations in the Blackstone River as a result of the discharge of treated municipal wastewater. Boron, which is not present naturally at concentrations greater than 50 µg/L in most water from wells sampled in the Blackstone River Basin (table 9) is conservative in geochemical environments such as that of the aquifer near well MXW-3 (LeBlanc, 1984; Kimmel and Braids, 1980; Koerner and Haws, 1979; Bouwer, 1973).

Water that is primarily infiltrated surface water has a specific conductance greater than 400 µS/cm and a boron concentration greater than 50 µg/L. This water defines an area affected by the infiltration of surface water along a 900-foot reach of the Blackstone River. Water in this area is reducing and is characterized by the presence of dissolved hydrogen sulfide gas. As a result of the reducing conditions, iron and manganese concentrations are as high as 3,500 µg/L and 1,300 µg/L (appendix C).

Water from wells that is primarily native ground water has a specific conductance less than 300 µS/cm and a boron concentration less than or equal to 50 µg/L. Because water from most other wells sampled in the Blackstone River Basin has a boron concentration less than 20 µg/L (table 9), water from some wells in this area may have been at least partly mixed with surface water infiltrated from the Blackstone River. The water from one well, MXW-63, has a specific conductance of 798 µS/cm but has a boron concentration of <10 µg/L. This well is completed in silt and clay deposits (fig. 14) and, on the basis of boron concentrations, specific conductance values of water from this well probably are related to geologic conditions rather than infiltration of surface water.



EXPLANATION

WATER-QUALITY GROUPS

▨ Primarily infiltrated surface water.
Water from wells has a specific conductance of more than 400 µS/cm and a boron concentration more than 50 µg/L

▨ Primarily native ground water.
Water from wells has specific conductance of less than 300 µS/cm and a boron concentration less than 50 µg/L

▨ Primarily a mixture of native ground water and infiltrated surface water.
Water from wells in this group has some of the chemical characteristics of infiltrated surface water and native ground water

——— – – – CONTACT—Dashed where uncertain

● 278/80 MXW-71 OBSERVATION WELL AND NUMBER—
Upper number is specific conductance in µS/cm at 25°C. For multilevel samplers MXW-58, 60, and 68, upper numbers is the median of the specific conductance collected from each port. Lower number is boron concentration in µg/L

◉ 550/90 MXW-4 PUBLIC SUPPLY WELL AND NUMBER—
Upper number is specific conductance in µS/cm at 25°C. Lower number is boron concentration in µg/L

Figure 18. Specific conductance and boron concentrations of ground water near well MXW-3, April 22 through 25, 1986.

An area of intermediate ground-water quality where water has partly mixed with surface water infiltrated from the Blackstone River is shown in figure 18. Water from wells in this area has some of the chemical characteristics of native ground water and some characteristics of infiltrated surface water.

Mass-balance calculations were made to determine the percentage of water yielded by well MXW-3 that originated as infiltration from the Blackstone River. An estimate of the percent of water derived from the infiltration of surface water was obtained on July 25, 1986, after a period of sustained low flow. At that time, water in the Blackstone River had a boron concentration of 300 µg/L, and water from well MXW-3 had a boron concentration of 130 µg/L. If 40 µg/L is assumed to be the boron concentration of native ground water, well MXW-3 derives about 35 percent of its water as infiltrated surface water. Because water from wells thought to be primarily native ground water may have already partly mixed with infiltrated surface water, the mass-balance calculation was repeated with 10 µg/L as the boron concentration of native ground water. This calculation indicates that about 41 percent of the water yielded by well MXW-3 is derived as infiltration from the Blackstone River.

A two-dimensional picture of ground-water quality near well MXW-3 provides some information about infiltration of surface water at this site. However, because ground water moves in three dimensions, additional information is needed to characterize ground-water quality and the flow of infiltrated surface water to wells (Gay and Frimpter, 1985). Three multilevel ground-water-quality samplers (MXW-58, 60, and 68), each with 15 sampling ports, were installed at selected locations along sections *A–A′* and *B–B′* (fig. 13) to address this concern. These samplers are similar to those used in a tracer study on Cape Cod (LeBlanc and others, 1987; LeBlanc and Quadri, 1987). Eight sets of samples were collected from sampling devices MXW-58 and 60 during the course of this study, but only five sets of samples were collected from MXW-68 because sample ports froze during the winter.

The range of specific conductance in water obtained from each sampling port at sampler MXW-60 is shown in figure 19. This sampler was intended to show variations in ground-water quality along section *B–B′*. Section *B–B′* is hydraulically well connected to the Blackstone River through buried gravel deposits. Location of the sampling ports and the aquifer lithology at this site are shown along the right margin of the diagram. The relation of aquifer lithology at this site to other parts of section *B–B′* is shown in figure 16. Specific conductance ranged from 308 to 713 µS/cm. The greatest range in specific conductance was in that part of aquifer above the silt and clay layer, where the specific conductance of ground water increased in the winter and decreased in the summer. Below the clay layer, sampling ports are in the buried gravel deposits mapped by use of the VLF technique (fig. 15). These deposits are hydraulically connected to the Blackstone River (fig. 17), and specific conductance of water from these deposits varies with antecedent flow in the Blackstone River. When flow in the Blackstone River was high before sampling, the specific conductance of water in the river was low; subsequently, the specific conductance of ground water decreased. When flow in the Blackstone River was low before sampling, the specific conductance of water in the river was high; subsequently, the specific conductance of ground water increased.

To establish the relation between streamflow and ground-water quality, the specific conductance of water from sampling ports was ranked and the ranks were correlated with ranked streamflow data from 0 to 10 days before sampling. Streamflow data from the continuous-record streamflow-gaging station at Northbridge were used in this analysis. For the purposes of this analysis, specific conductance was treated as a conservative species, and individual solutes that contribute to specific conductance were assumed

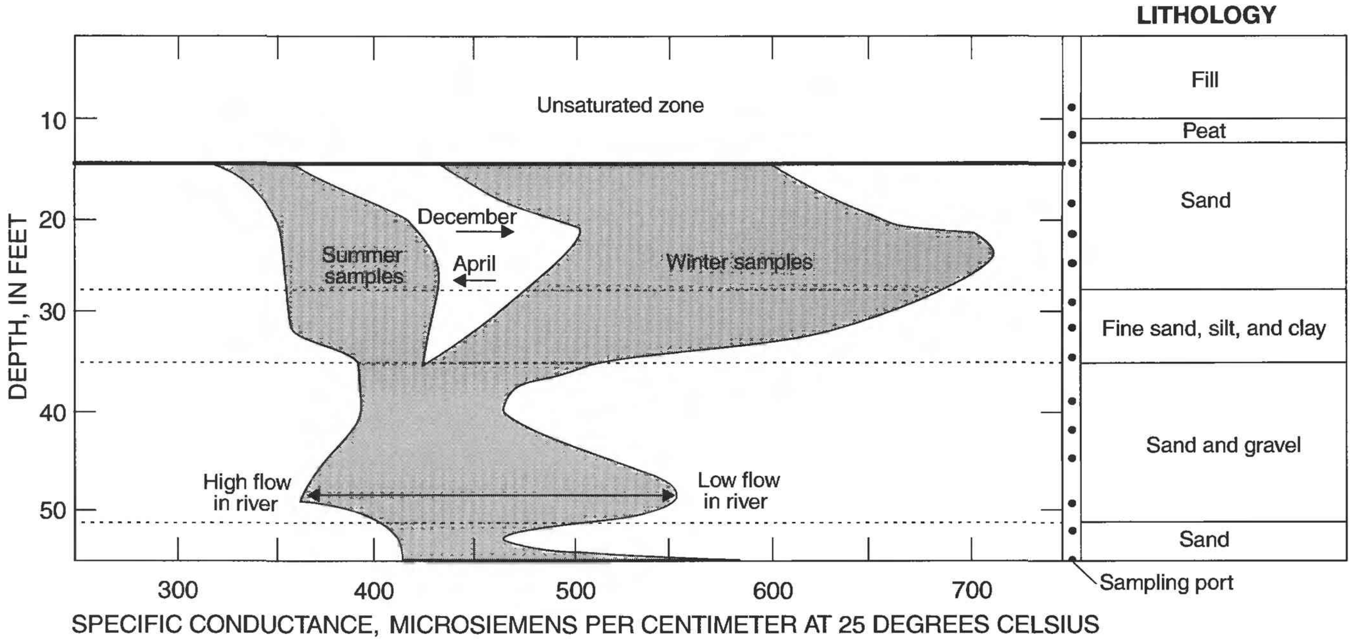


Figure 19. Range of specific conductance of water collected from multilevel ground-water sampler MXW-60 (October 1985 through July 1987).

to not react greatly with aquifer materials. Although this assumption is not valid for some trace constituents such as iron and manganese, it is reasonable for the major ions that contribute most to specific conductance, given the geochemical environment in the aquifer and the short travel times from the river to the well. The strongest correlation was found for flows that occurred 2 days prior to sampling (fig. 20). This correlation indicates an average time of 2 days for water to travel from the Blackstone River through the buried gravel deposits to well MXW-3. The correlation is negative because streamflow and specific conductance are inversely correlated. Calculations based on estimates of the hydraulic properties of the aquifer from aquifer-test data and assuming a porosity of 0.35 for the buried gravels (Freeze and Cherry, 1979) verify that the time of travel for water from the Blackstone River to the sample site should be about 2.1 days.

Statistically significant correlations between streamflow and ground-water quality also were found for 1 and 3 days before sampling for three reasons. First, not all of the water and solutes follow the same flow path—some follow shorter flow paths and arrive earlier, whereas some follow longer flow paths and arrive later. Second, solutes are affected by dispersion and retardation. These processes cause some solutes to travel more rapidly (arrive earlier), and other solutes to travel more slowly (arrive later) than most solutes traveling at the average linear velocity of the ground water, even though they followed the same flow path. Third, there is a strong autocorrelation between streamflow in the Blackstone River on a given day and streamflow on the previous day, or the next day.

Statistically significant correlations were not found between streamflows that occurred 4 or more days before sampling and ground-water quality data for water in the gravel layer. In addition, no statistically significant correlations were found between streamflows that occurred from 0 to 10 days before sampling and ground-water-quality data for water above or below the gravel layer. These data suggest that the gravel layer acts as a conduit that facilitates the flow of infiltrated surface water from the Blackstone River to well MXW-3.

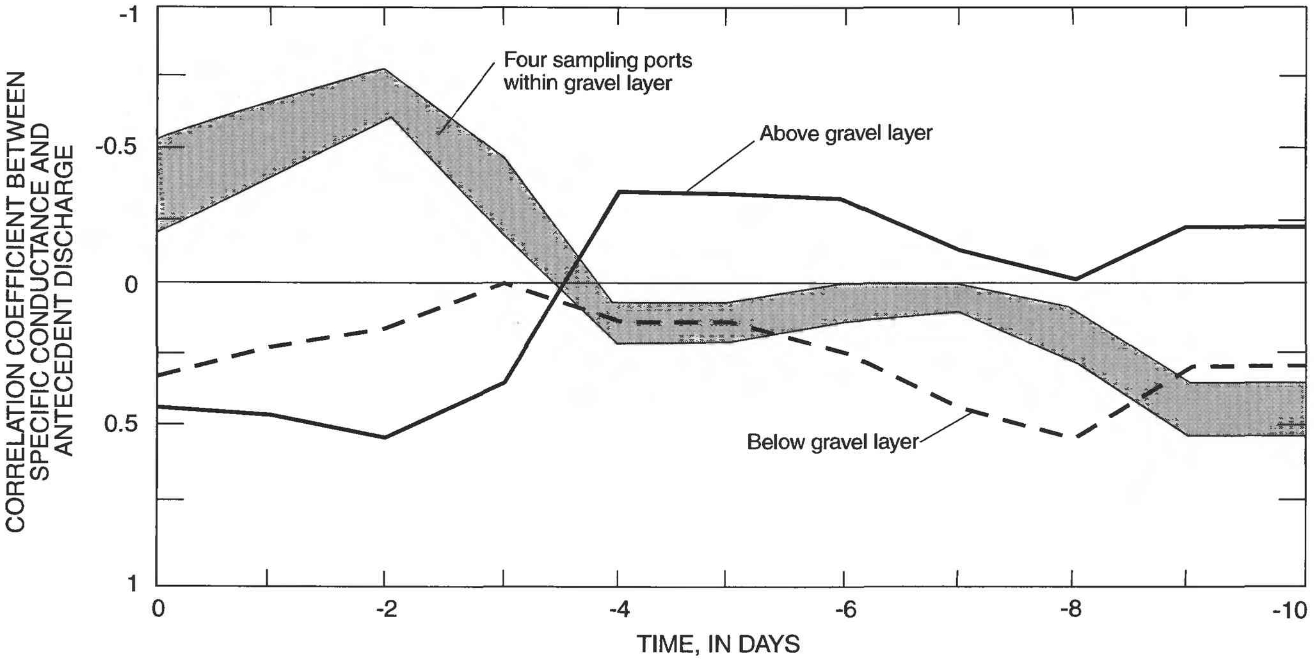


Figure 20. Correlation between specific conductance of water collected from multilevel ground-water sampler MXW-60 and antecedent streamflow in the Blackstone River.

The range of specific conductance of water obtained from each sampling port of sampler MXW-58 is shown in figure 21. This sampler was intended to show variations in ground-water quality along section *A–A′*. Section *A–A′* is poorly connected to the Blackstone River because of fine-grained deposits between the well and the river. Locations of the sampling ports and the aquifer lithology at the site are shown along the right margin of the diagram. The relation of lithology at this site to other parts of section *A–A′* is shown in figure 14. Specific conductance ranged from 355 to 773 µS/cm. The greatest range in specific conductance was near the top of the saturated zone. At all sampling ports, differences between the specific conductance of ground water collected in summer and in winter were large. These results are similar to those for water from sample ports above the sand and gravel layer in sampler MXW-60 (fig. 19). There were no statistically significant correlations between antecedent streamflow and specific conductance of ground water collected from any sample ports in well MXW-58.

The lack of a correlation between the specific conductance of ground water and surface water is not entirely unexpected in view of the poor hydraulic connection between the river and the well along section *A–A′* (fig. 17). Calculations based on estimates of the hydraulic properties of the aquifer from lithologic data and an assumed porosity of 0.35 (Freeze and Cherry, 1979) show that the time of travel along section *A–A′* is almost 6 months. Seasonal changes in ground-water quality in this part of the aquifer may be related to seasonal changes in the quality of water available for infiltration from the Blackstone River. The lower flows typically occur during the summer. Specific conductances are highest during these low flows (fig. 12), but because of the longer traveltime along section *A–A′*, this water is not sampled until winter, almost 6 months later.

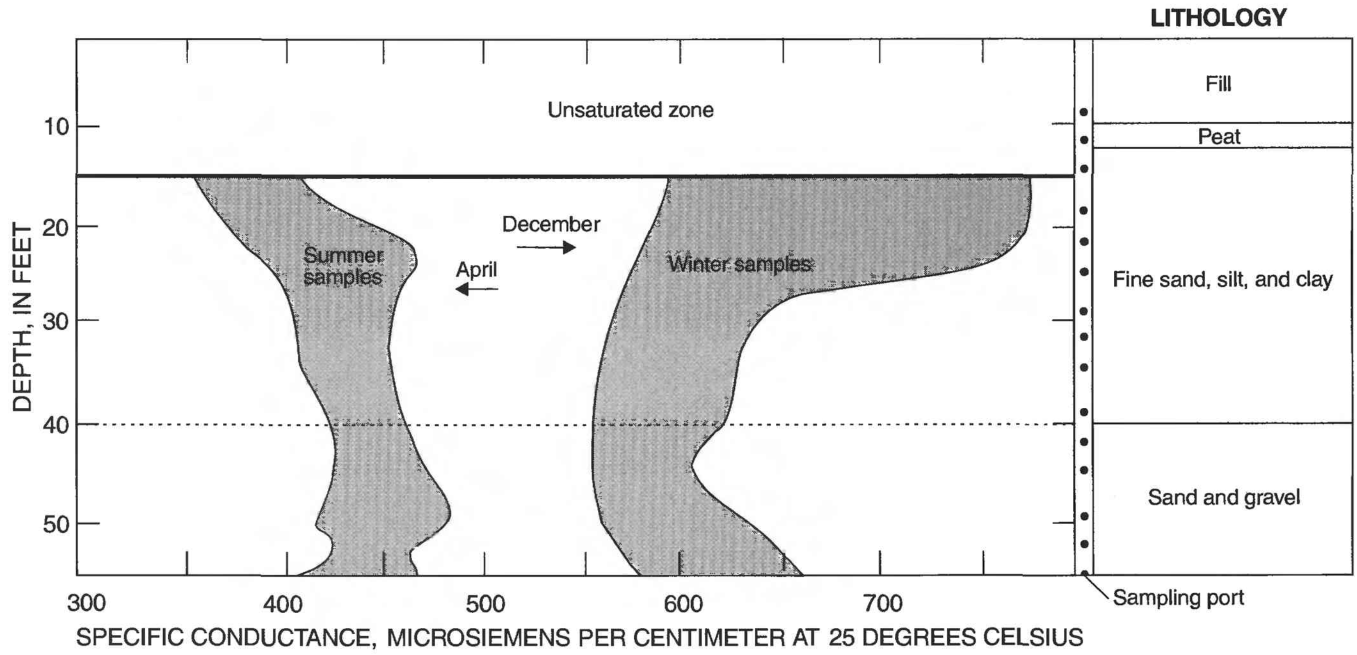


Figure 21. Range of specific conductance of water collected from multilevel ground-water sampler MXW-58 (October 1985 through July 1987).

The range of specific conductance obtained from each port in sampler MXW-68 is shown in figure 22. This sampler was intended to provide information on the quality of native ground water, but water-quality data in figure 18 show that MXW-68 is actually in an area of mixed ground-water quality. Location of the sampling ports and aquifer lithology at this location are shown along the right margin of the diagram. The specific conductance of at least some samples collected from ports from 15 to 30 ft deep exceeds 400 µS/cm, which indicates that at least some of the water is infiltrated river water. One sample collected from a port located at a depth of 27 ft on December 9, 1986, had a boron concentration of 120 µg/L and iron and manganese concentrations of 1,900 and 270 µg/L. This water was primarily infiltrated river water. The low specific conductance, 300 µS/cm, probably is related to high flow in the Blackstone River before sampling and mixing with native ground water. Another sample collected at the same time from a sample port at a depth of 44 ft had a boron concentration of 50 µg/L and iron and manganese concentrations of 100 and 30 µg/L (appendix C). This water was primarily native ground water and had a specific conductance of 232 µS/cm.

Data collected at wells and multilevel samplers near well MXW-3 show that (1) ground-water quality is affected by infiltration of surface water, and (2) changes in streamflow that result in changes in surface-water quality can affect the quality of ground water near wells. In addition, the data are consistent with generalizations about flow of infiltrated surface water to wells (Gay and Frimpter, 1985) and the movement of ground-water solutes at the Cape Cod tracer test site (Garabedian and LeBlanc, 1987; LeBlanc and others, 1987; Garabedian and others, 1987):

1. Ground-water solutes move in three dimensions, frequently through thin zones that do not occupy the entire thickness of the aquifer, and
2. the movement of these solutes is controlled by local heterogeneities in the aquifer.

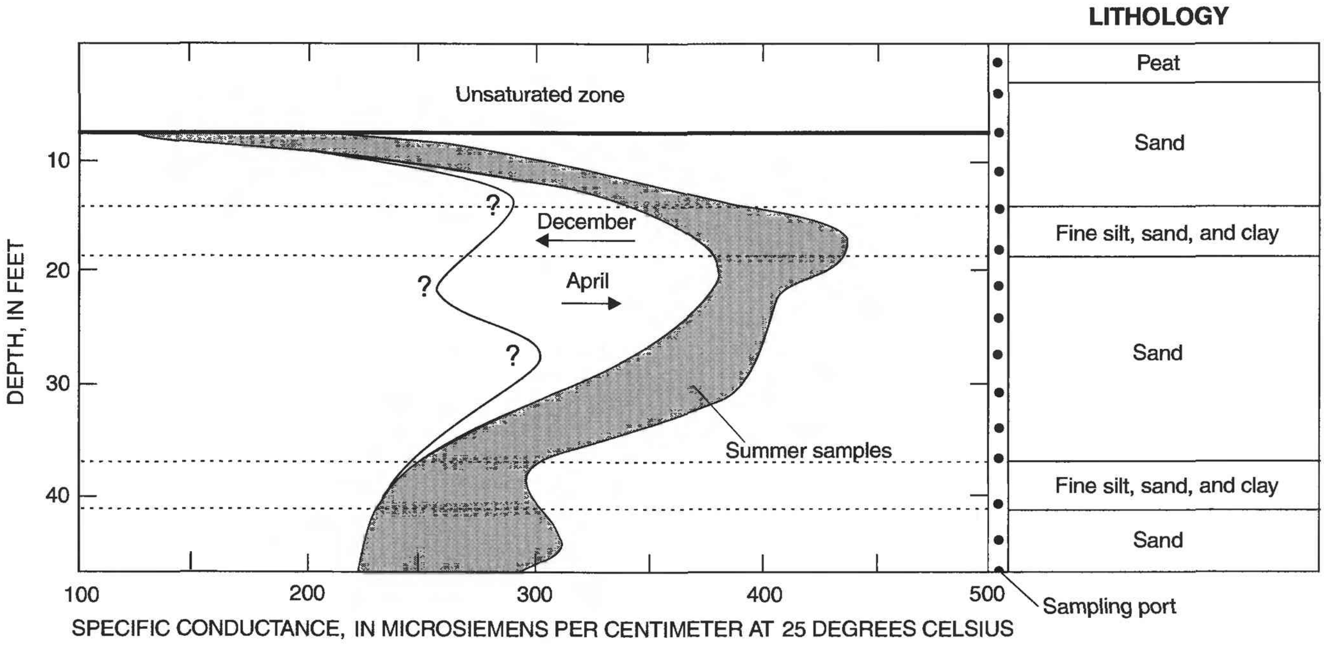


Figure 22. Range of specific conductance of water collected from multilevel ground-water sampler MXW-68 (October 1985 through July 1987).

Infiltration of Surface Water Near Well NXW-8

This site contains an industrial well field that has an installed capacity of about 1.9 Mgal/d. The well field consists of 57 individual well points from which water is withdrawn by suction by use of a centrifugal pump. Some of these well points are located less than 10 ft from the Blackstone River. Another industrial well field, NXW-7, is about 1,000 ft southwest of well NXW-8. This well is several hundred feet away from the Blackstone River and is used to augment supply during periods of peak demand.

Well NXW-8 was selected for study, in part, because it is located along one of the more degraded reaches of the Blackstone River; however, the Blackstone River at this site is not as degraded as the Blackstone River near Millbury, primarily because flow at this site is greater and treated municipal wastewater is more diluted. The location of the individual well points and observation wells are shown in figure 23.

Hydrologic Setting

The well field is in the middle Blackstone River aquifer in Northbridge (location shown on pl. 1). The physical and hydraulic properties of this aquifer are summarized in table 11. The aquifer in this area is between 500 and 1,200 ft wide, has a saturated thickness typically less than 60 ft, and extends for several miles along the Blackstone River. An unnamed tributary stream crosses the well field along its western edge. Test drilling in the well field showed that the saturated thickness is about 30 ft along the northern edge of the well field and gradually increases to between 45 and 60 ft along the southern edge. Test drilling and seismic-reflection data showed that aquifer materials consist of fine to medium sand and interbedded layers of coarse sand and gravel. Deposits are coarser along the eastern edge of the well field near the Blackstone River and are finer along the western and southern edges of the well field.

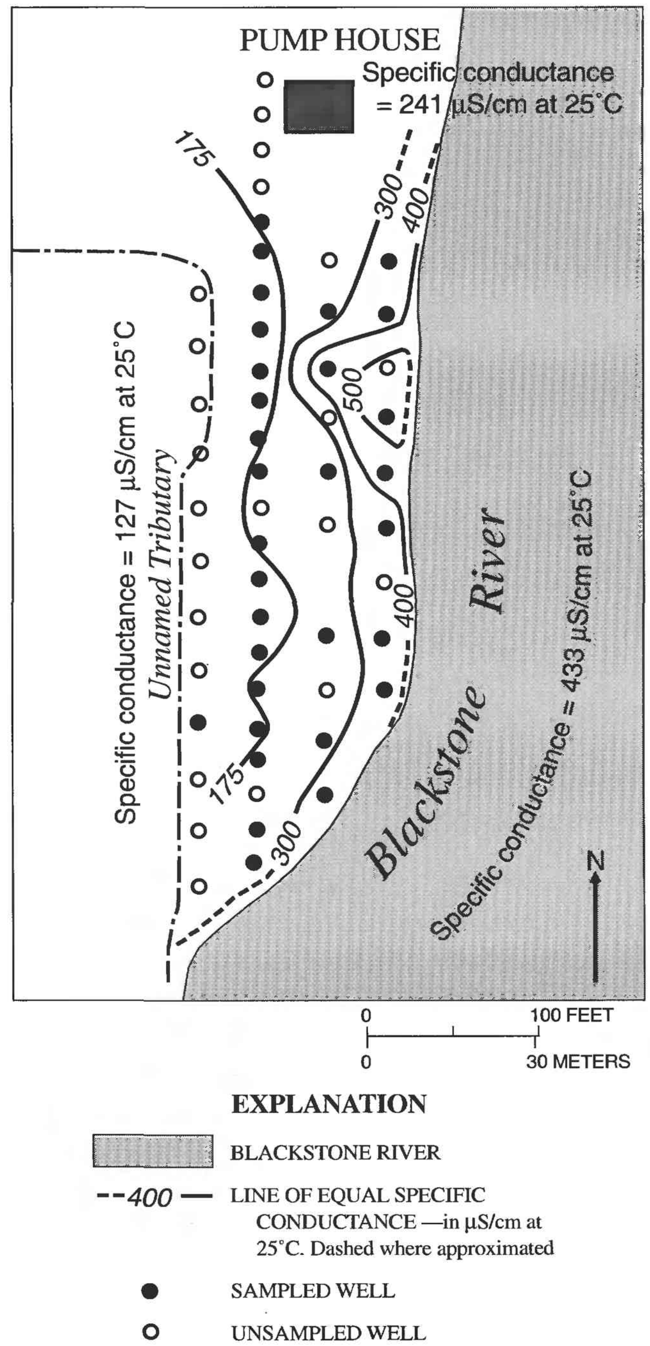


Figure 23. Map showing specific conductance of ground water at well NXW-8.

Ground-Water Quality Near Well NXW-8

Specific conductance and temperature of water from individual well points was measured during October 23–25, 1985, and February 26–27, 1986, to determine if surface water was infiltrating from the Blackstone River and being withdrawn by well NXW-8.

The distribution of specific conductance in the well field between February 26–27, 1986 is shown in figure 23. At that time, specific conductance ranged from 136 to 593 µS/cm and the well field yielded a mixture of water with a specific conductance of 241 µS/cm. For comparison, well NXW-7 yielded water with a specific conductance of 102 µS/cm. The highest specific conductances were measured near the northeast corner of the well field in an area where test-drilling data show the coarsest deposits are located. These data indicate that coarse sand and gravel in this part of the well field acts as a conduit for water from the Blackstone River. The lowest specific conductances were measured near the western edge of the well field near the tributary stream. It was not possible to measure the specific conductance of water from well points along the stream in February 1986 because ice had formed in the valve openings; however, data collected in October 1985 show that well points in this part of the well field yield water with specific conductances similar to those of the water in the tributary stream.

Discharge measurements show that the tributary stream is a losing stream near the well field and typically loses about 0.5 ft^3/s as it flows across the well field. When flow in the stream is less than 0.5 ft^3/s, all the water infiltrates and no flow reaches the Blackstone River. Leakage from the tributary stream was 0.08 ft^3/s (3 percent of the total yield) in October and 0.5 ft^3/s (17 percent of the total yield) in February. From these data, mass balance calculations were made to determine the percentage of water yielded by well NXW-8 that originated from the Blackstone River. These calculations are based on assumptions that specific conductance is conservative and that 100 µS/cm is the specific conductance of the native ground water. The value of

100 µS/cm was determined from samples of water from nearby observation wells. On the basis of these calculations, well NXW-8 derived from 41 to 48 percent of its yield from infiltration from the Blackstone River and from 42 to 49 percent as intercepted ground-water discharge. At this site, infiltration from the Blackstone River is inversely related to the amount of surface water in the tributary stream available for infiltration.

WATER RESOURCES OF THE WESTERN PART OF THE BLACKSTONE RIVER BASIN

This section describes the surface- and ground-water resources of the western part of the Blackstone River Basin. The Mumford and Branch Rivers are the principal streams. Aquifers are of smaller areal extent and generally have less saturated thickness than aquifers in other parts of the study area.

Surface Water

Surface drainage in the western part of the Blackstone River Basin is through the Mumford and Branch Rivers and several smaller streams, including the Nipmuc River, and Kettle, Tatnuck, and Laurel Brooks (fig. 3). Streamflow in Kettle and Tatnuck Brooks is regulated and diverted as part of the water supply for Worcester, and streamflow in the Mumford River is regulated as part of the water supply for Northbridge. Streamflow in the Nipmuc River and Laurel Brook is unregulated.

A continuous-record streamflow-gaging station was operated by the U.S. Geological Survey on the Mumford River (01111000) from October 1939 through September 1951. Location of this station is shown in figure 3. Streamflow data available for this site do not overlap the base period used to calculate streamflow statistics in other parts of the study area; however, precipitation data at Northbridge show that streamflow data were collected during a period of about average precipitation so that flow-duration data calculated for this site probably are comparable to most of the other streamflow data in this report. Streamflow at this site is distributed seasonally in the same manner as streamflow in the eastern and northern parts of the Blackstone River Basin—greatest in March and gradually declining to the lowest flows in September.

Miscellaneous measurements of streamflow were not made at any sites in the western part of the Blackstone River as part of this project; however, miscellaneous streamflow data are available from earlier studies (Walker and Krejmas, 1986). In spite of limited data, some general characteristics can be inferred about streamflow on the basis of geologic conditions. Most streams in this part of the study area drain watersheds in which deposits of stratified drift cover less than 10 percent of the total drainage area. These streams can be expected to have more steeply sloped flow-duration curves, to be more flashy, and to go dry more frequently than streams that drain areas of similar size with larger deposits of stratified drift in the eastern and northern parts of the Blackstone River Basin.

Ground Water

Stratified-drift deposits in this part of the study area have been subdivided into six aquifers ranging in areal extent from 0.05 to 1.3 mi^2. The locations of study aquifers are shown in figure 1 and in greater detail on plate 1. Other deposits of stratified drift shown on plate 1, but not specifically designated as aquifers, also may represent ground-water resources capable of yielding water to public-supply wells. Because these deposits are small, discontinuous, or thin, the ground-water resources of these areas have not been addressed in this report.

With the exception of the Lackey Pond aquifer, the hydraulic properties of most aquifers have not been well defined. Data summarized in table 13 show two of the aquifers have maximum saturated thicknesses of less than 40 ft. The two thickest aquifers, the Lackey Pond and lower Mumford River aquifers, have not been developed for public supply; although available transmissivity and well yield data indicate that these aquifers may be able to yield large quantities of water to wells. No test-drilling data are available for assessment of the hydraulic properties of the Laurel Brook aquifer. Short-term and long-term yields have not been estimated in this part of the study area because of the limited amount of hydrologic data available.

Table 13. Physical and hydraulic characteristics of aquifers in the western part of the Blackstone River Basin, Massachusetts

[**Maximum saturated thickness, Maximum transmissivity, and Maximum well yield**: Data from driller's information and U.S. Geological Survey files. Yield of public-supply wells in 1980: Data from Massachusetts Department of Environmental Management, Office of Water Resources, 1985. Additional exploration may identify sites having greater saturated thickness, transmissivity, or well yields. ft, foot; ft^2/d, foot squared per day; gal/min, gallon per minute; Mgal/d, million gallons per day; mi^2, square mile; >, actual value is greater than value shown; <, actual value is less than value shown; --, no data]

Aquifer	Location (town)	Area (mi^2)	Typical land use	Maximum saturated thickness (ft)	Maximum trans-missivity (ft^2/d)	Maximum well yield (gal/min)	Yield of public-supply wells in 1980 (Mgal/d)
Tuckers Pond	Sutton	0.05	Rural	28	4,300	250	0.45
East Douglas	Douglas	.18	Rural, residential, industrial	44	2,300	375	.5
Lackey Pond	Douglas, Uxbridge	.36	Rural, industrial	73	8,800	550	--
Whitins Pond	Sutton, Northbridge	.19	Rural, residential	34	15,000	1,100	1.73
Lower Mumford River...	Northbridge, Uxbridge	1.3	Residential, industrial	71	8,000	--	--
Laurel Brook	Uxbridge	.76	Rural	--	--	--	--

Surface-Water/Ground-Water Relations

In contrast to other parts of the study area, aquifers in the western part of the Blackstone River Basin are more limited in areal extent, and generally have less saturated thickness. As a result, some communities rely on the conjunctive use of ground-water and surface-water resources and on specially constructed wells to meet their water needs.

For example, part of the water supply for the community of Northbridge is from wells in the Whitins Pond aquifer (NXW-1 and 3). According to Walker and Krejmas (1986), a large part of the yield of these wells results from management of the pond. Whitins Pond was formed by a milldam built in 1847. The dam raised the surface-water level by 13 ft. The higher surface-water level brought about a corresponding rise in the ground-water level at the shore of the pond and increased the saturated thickness of the aquifer to as much as 34 ft (table 13). In addition, sand-and-gravel deposits along the shore of the pond near well NXW-1 were leveled and back filled into the pond to increase the area available for well points. During the course of this study, Whitins Pond was managed, in part, to maintain ground-water levels in the municipal wells along its shores (Delwyn Barnes, Whitinsville Water Company, oral commun., 1985).

Well S7W-7 is another example of the conjunctive use of ground and surface water resources. This well consists of about seventy 2 1/2-inch wells driven into the sand and gravel beneath three manmade lagoons. Flow in a nearby stream is regulated and diverted into the lagoons to recharge the underlying sand and gravel (Walker and Krejmas, 1986; Delwyn Barnes, Whitinsville Water Company, oral commun., 1985). Well yields in these areas rely so heavily on the infiltration of surface water that the sand and gravel deposits are used more for their ability to filter water than for their ability to store and transmit water.

Ground-Water Quality

On the basis of samples collected from public-supply wells and analyzed by the Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection), water from wells in the western part of the Blackstone River Basin is slightly acidic, poorly buffered, and soft. In most samples, no single cation predominated, but chloride was the dominant anion. Water from all wells sampled was suitable for public supply; however, concentrations of sodium from some wells exceeded the former U.S. EPA SMCL of 20 mg/L for sodium, and concentrations exceeded the SMCL of 50 mg/L for manganese (U.S. Environmental Protection Agency, 1986). Median specific conductance, pH, hardness, and concentrations of all major ions, nutrients, and selected trace elements (table 14) were not significantly different from those in the eastern and northern parts of the Blackstone

Table 14. Summary of water-quality data for wells in aquifers in the western part of the Blackstone River Basin, Massachusetts, January through June 1984

[Data from Massachusetts Department of Environmental Quality Engineering (now the Massachusetts Department of Environmental Protection). All properties and constituents are given in milligrams per liter of filtered samples unless otherwise noted; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, actual value is less than value shown]

Properties and constituents	Number of observations	Minimum	Median	Maximum
Specific conductance (µS/cm)	7	32	105	214
pH	7	5.8	6.2	6.3
Hardness	7	7.0	20	32
Calcium	7	2.0	6.0	10.
Magnesium	7	.41	1.1	1.8
Sodium	7	2.9	7.5	28
Potassium	7	.3	1.2	1.6
Alkalinity (as $CaCO_3$)	7	4.0	12	20.
Sulfate	7	2.0	7	13
Chloride	7	3.0	15	51
Nitrogen, nitrite plus nitrate	7	<.01	<.01	.70
Nitrogen, ammonia	7	<.01	<.01	.02
Iron (µg/L)	7	<10	20	110
Manganese (µg/L)	7	10	10	160

River Basin (table 9), and along the Blackstone River (table 12) on the basis of the median test (Neter and Wasserman, 1974) at a confidence criterion of 5 percent.

SUMMARY

By year 2020, demand for water in the Blackstone River Basin is expected to be 52 Mgal/d, one-third greater than the demand of 39 Mgal/d in 1980. Most of this increase is expected to be supplied by increased ground-water withdrawals from aquifers in the eastern and northern parts of the basin. Increased withdrawals from aquifers along the Blackstone River and in the western part of the basin also are expected.

The eastern and northern parts of the Blackstone River Basin contain many small, discontinuous aquifers which, as a group, compose the largest ground-water resource of the study area. Fifteen aquifers, ranging in areal extent from 0.39 to 4.3 mi^2, were studied. These aquifers have maximum saturated thicknesses ranging from less than 10 to 105 ft and maximum transmissivities ranging from less than 1,000 to greater than 20,000 ft^2/d. Short-term and long-term yields were calculated for nine aquifers from water-budget equations solved by use of digital ground-water-flow models.

Short-term yield is the maximum rate of withdrawal that can be sustained by wells without causing an unacceptable decline in the hydraulic head of the aquifer. For the purposes of this study, an unacceptable decline in hydraulic head was 50-percent desaturation of the aquifer material near the pumped well, or a saturated thickness of less than 10 ft remaining at the well itself. In calculations of short-term yield, most ground water is derived from changes in ground-water storage, and smaller amounts are contributed by changes in the amount of water flowing into or out of the aquifer through adjacent stratified drift. Short-term yield is a function of the duration of pumping. For a 30-day pumping period, short-term yields range from 0.22 to 11 Mgal/d; for a 180-day pumping period, short-term yields range from 0.22 to 4.3 Mgal/d. Short-term yield is also a function of how the physical and hydraulic properties of each aquifer combine to limit the number of suitable well sites and the yield of individual wells. Land use limited the number of suitable well sites, and consequently reduced short-term yields, in the Auburn and upper Mill River aquifers and, to a lesser extent, in the middle Mill River aquifer. Low aquifer transmissivity resulting from fine-grained deposits limited the number of suitable well sites and reduced the yield of individual wells—consequently reducing short-term yield—in the middle Mill River, lower Mill River, and upper West River aquifers. Similarly, low transmissivity resulting from thin saturated thicknesses limited short-term yields from the upper Peters River and lower Peters River aquifers.

Long-term yield is the maximum rate of withdrawal that can be sustained by the hydrologic system without causing unacceptable declines in the hydraulic head of the aquifer or causing unacceptable changes to any other component of the hydrologic system (such as streamflow). In calculations of long-term yield, most ground water is derived from streamflow depletion, and smaller amounts are derived from changes in storage and changes in the amount of ground water flowing into or out of the aquifer through adjacent stratified drift. Long-term yield, like short-term yield, is a function of how the physical and hydraulic properties of each aquifer combine to limit the number of suitable well sites and the yield of individual wells; however, long-term yield is also a function of the amount of streamflow available for depletion by wells and the minimum flow to be maintained in streams crossing study aquifers. If streamflow is to be maintained at 98-percent duration, long-term yields equaled or exceeded 50 percent of the time range from 0.22 to 11 Mgal/d; long-term yields equaled or exceeded 95 percent of the time range from 0.02 to 1.0 Mgal/d. If streamflow is to be maintained at 99.5-percent duration, long-term yields equaled or exceeded 50 percent of the time range from 0.22 to 11 Mgal/d; long-term yields equaled or exceeded 95 percent of the time range from 0.04 to 1.4 Mgal/d; and long-term yields equalled or exceeded 98 percent of the time range from 0.02 to 0.39 Mgal/d. From the standpoint of water supply, maintaining streamflow at 98-percent duration is a more restrictive criterion than maintaining streamflow at 99.5-percent duration. If streamflow is to be maintained at 99.5-percent duration, the aquifers capable of sustaining an additional supply of 0.25 Mgal/d above their mid-1980 rates are, in order of productivity, the lower Mill River, lower Peters River, middle Mill River, upper West River, upper Lake Quinsigamond, Stone Brook, and upper Peters River aquifers. The aquifers capable of sustaining an additional supply of 1.0 Mgal/d above their mid-1980 rates are, in order of productivity, the upper West River, the upper Lake Quinsigamond and Stone Brook aquifers. The Stone Brook aquifer can support a long-term yield of 1.0 Mgal/d less than 50 percent of the time. The Auburn aquifer is completely developed and cannot support any additional withdrawals. The upper Lake Quinsigamond is the next most completely developed aquifer. Reaches of some streams crossing the upper Lake Quinsigamond aquifer go dry part of the year as a result of ground-water withdrawal. Long-term yields are greatly reduced during drought, especially in those aquifers crossed by streams with small drainage areas, such as the Stone Brook aquifer.

Water from most wells in the eastern and northern parts of the Blackstone River Basin is slightly acidic, and ranges from poorly to moderately well buffered, and from soft to moderately hard. Water from all wells sampled was suitable for public supply; however, some wells yielded water that exceeded U.S. Environmental Protection Agency recommended limits for iron and manganese. Water from wells in the Auburn aquifer had the highest specific conductance and the highest concentrations of hardness, and of all major ions in this part of the study area. Elevated concentrations of these constituents, particularly sodium, were the reason for closing at least one public-supply well in the Auburn aquifer. These elevated concentrations probably are the result of the application of road-deicing salts. A similar trend was observed in historical analysis of water from wells in the Worcester area aquifers.

A nearly continuous deposit of stratified drift almost 30 mi long and ranging in width from 400 ft to greater than 1 mi occupies lowland areas along the Blackstone River. These deposits were divided into four aquifers ranging in areal extent from 1.8 to 3.5 mi^2. These aquifers have maximum saturated thicknesses ranging from 54 to 170 ft and maximum transmissivities ranging from less than 1,500 to greater than 20,000 ft^2/d. Short-term yield was not calculated for these aquifers because the Blackstone River is such a large stream, and receives so much additional flow (26.9 ft^3/s) as interbasin transfer from the Nashua River Basin that it is unreasonable to expect streamflow to approach zero under even the most extreme drought. Long-term yield was not calculated because it is likely that enough water is available at all times to support foreseeable ground-water development and subsequent streamflow depletion by wells. Because the lowest flows in the Blackstone River typically occur in July (as opposed to September in most other streams in the study area) water may be available for streamflow depletion by wells along the Blackstone River when it is not available in other parts of the basin.

The quality of water from most wells along the Blackstone River was not significantly different from that in most other wells in the Blackstone River Basin and was generally suitable for public supply. However, because the Blackstone River receives substantial amounts of treated municipal wastewater, infiltration of surface water has significantly increased the specific conductance, and the concentrations of all major ions, ammonia, iron, and manganese in water yielded by at least two wells near the river. The quality of surface water available for depletion by wells was poorest in the reach of the Blackstone River immediately downstream from the outfall of the regional wastewater-treatment plant serving the Worcester metropolitan area and gradually improved downstream. The quality of surface water was also worse at low flow than at higher flows.

Infiltration of water from the Blackstone River to wells was studied at two sites. At both sites, wells derived a large part of their yields (between 41 and 48 percent) from infiltrated surface water. At both sites, aquifer heterogeneity controlled the movement of infiltrated water to wells. At one site in Millbury, most infiltrated water moved through buried gravel deposits and reached the pumped well in about 2 days; in contrast, in another part of the aquifer almost six months was required for water to flow from the river to the well because of fine-grained deposits. Changes in stream discharge that resulted in changes in surface-water quality also affected ground-water quality.

The western part of the Blackstone River Basin contains the smallest aquifers evaluated in the study area. Six aquifers, ranging in areal size from 0.05 to 1.3 mi^2, were identified. The hydraulic properties of most of these aquifers have not been well defined, but available data indicate that the maximum saturated thicknesses range from 28 to 73 ft and the maximum transmissivities range from 2,300 to 15,000 ft^2/d. Short-term and long-term yields were not estimated for these aquifers because of the small amount of test-drilling and streamflow data available.

The quality of water from wells in the western part of the Blackstone River Basin was not significantly different from the quality of water from most other wells in the basin. Water from all wells sampled was suitable for public supply, although one well yielded water that exceeded the former U.S. Environmental Protection Agency secondary maximum contamination level for sodium.

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APPENDIX A

Appendix A. Streamflow data

[Locations shown on plate 2. **Station Name:** BK, brook; DS, downstream; NR, near; RR, railroad; SE, southeast; ST, street; TR, tributary; US, upstream. See Gadoury and others (1993) for complete description of station names. ft, foot; ft^3/s, cubic foot per second; mi^2, square mile; µS/cm, microsiemen per centimeter at 25 degrees Celsius; °C, degrees Celsius. --, no data]

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	Water temperature (°C)	Air temperature (°C)
01109440	Kettle BK at Stoneville, Mass.	4-30-85	1030	18.3	6.9	305	15.5	--
		8-15-86	1300	18.3	2.6	306	23.0	--
01109445	Dark BK Water ST at Auburn, Mass.	8-15-86	1100	1.00	.5	334	20.5	--
01109446	Dark BK TR at Auburn, Mass.	8-15-86	1150	.62	.17	973	18.5	23.0
01109448	Dark BK at Auburn, Mass.	8-15-86	0900	2.04	.5	529	17.5	23.0
01109450	Dark BK 100 ft US of South Bridge ST at Auburn, Mass.	8-15-86	1020	2.32	.6	561	18.0	24.5
01109452	Stone BK NR Auburn, Mass.	6-18-86	1600	.37	.91	63	16.5	20.0
		7-08-86	1200	.37	.25	71	20.0	20.0
		7-23-86	1500	.37	.09	79	19.5	29.5
		8-14-86	1410	.37	.15	72	18.0	23.5
		9-02-86	1500	.37	.06	83	12.5	22.5
		7-23-87	1140	.37	.002	95	19.0	23.0
01109453	Stone BK 50 ft DS RR Bridge NR Auburn, Mass.	7-08-86	1315	.68	.44	109	20.0	24.5
		9-09-86	1430	.68	.12	133	13.5	17.5
01109454	Stone BK TR NR Auburn, Mass.	7-08-86	1345	.2	.14	91	19.0	23.5
		9-09-86	1400	.2	.02	109	11.5	17.5
01109455	Stone BK TR at Auburn, Mass.	7-08-86	1400	.15	.0	--	--	24.5
		9-09-86	1500	.15	.0	--	--	17.5
01109456	Stone BK at Auburn, Mass.	6-18-86	1525	1.89	3.9	99	20.5	22.0
		7-08-86	1130	1.89	1.3	102	24.5	28.0
		7-23-86	1230	1.89	.66	103	25.0	28.0
		8-14-86	1400	1.89	.5	95	24.0	23.5
		9-09-86	1530	1.89	.35	104	20.5	23.0
		7-23-87	1130	1.89	.13	100	27.5	27.0
01109458	Ramshorn BK at Auburn, Mass.	8-15-86	1310	7.45	6.0	90	23.5	29.0
01109460	Dark BK at Auburn, Mass.	4-30-85	0940	11.1	7.2	234	9.0	--
		7-08-86	1600	11.1	6.6	270	24.5	26.5
		7-23-86	1615	11.1	7.1	178	25.5	27.0
		8-14-86	1530	11.1	7.0	169	24.0	28.0
		8-15-86	1630	11.1	7.4	180	23.5	23.0
		9-11-86	0900	11.1	7.2	176	21.0	17.0
01109485	Kettle BK NR Stoneville, Mass.	8-15-86	1530	30.4	8.8	240	22.5	24.0
01109495	Kettle BK TR NR Stoneville, Mass.	8-15-86	1430	.31	.07	354	24.5	27.5
01109500	Kettle BK at Worcester, Mass.	4-30-85	1140	31.6	17	278	16.0	--
		8-15-86	1400	31.6	9.7	219	23.0	24.5
01109590	Beaver BK at Worcester, Mass.	4-30-85	1240	16.4	5.8	298	16.5	--
01109600	Middle River at Worcester, Mass.	4-30-85	1415	50.2	22	290	19.0	--
01109650	Blackstone River Rt. 146 at Worcester, Mass.	4-30-85	1730	63.8	44	443	17.0	--
01109660	Blackstone River near Millbury, Mass.	5-01-85	0930	65.5	71	585	15.5	25.5
01109670	Worcester Aqueduct NR Millbury, Mass.	5-01-85	1030	--	3.0	393	16.5	18.0

Appendix A. Streamflow data—*Continued*

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	Water temperature (°C)	Air temperature (°C)
01109700	Blackstone River at Millbury, Mass.	10-18-85	1130	--	96	418	15.5	19.5
		11-19-85	1100	--	238	343	9.5	18.5
		1-06-86	1030	--	148	458	7.5	8.5
		1-15-86	1500	--	110	517	5.0	-9.0
		1-27-86	1500	--	1,130	197	3.5	4.0
		2-13-86	1030	--	112	545	4.0	-2.0
		3-06-86	1030	--	148	458	7.5	8.5
		4-18-86	0945	--	94	545	11.0	11.5
		6-17-86	0945	--	211	398	19.0	20.0
		7-25-86	1030	--	66	468	24.0	29.5
		8-20-86	0945	--	116	340	22.0	23.0
01109750	Singletary BK at Millbury, Mass.	5-01-85	1415	5.60	2.3	180	19.5	23.0
01109920	Sewall BK at Morningdale, Mass.	9-09-86	1015	3.47	1.4	124	15.0	17.0
		10-17-86	0945	3.47	1.0	162	10.5	11.0
01109922	Newton Pond TR NR Shrewsbury, Mass.	9-09-86	1030	.24	.03	276	12.0	17.5
01109925	Sewall BK 0.6 mi SE Morningdale, Mass.	9-09-86	1115	4.33	1.9	136	19.0	18.5
01109930	Sewall BK 0.9 mi SE Morningdale, Mass.	9-09-86	1150	4.48	1.4	151	16.5	19.5
01109934	Poor Farm BK at Morningdale, Mass.	9-09-86	1220	3.57	.38	327	17.0	20.5
01109936	Poor Farm BK NR Morningdale, Mass.	9-09-86	1300	3.72	.0	--	--	20.5
01109950	West BK NR Shrewsbury, Mass.	9-09-86	0910	2.08	.27	219	10.0	16.0
		10-17-86	1230	2.08	.31	220	8.0	10.5
01110000	Quinsigamond River at North Grafton, Mass.	1-16-85	0800	25.6	13	310	1.0	--
		2-26-85	1030	25.6	28	255	3.5	--
		4-29-85	1315	25.6	1.3	320	15.0	--
		5-02-85	0910	25.6	12	325	13.0	--
		6-11-85	0950	25.6	11	273	21.5	--
		7-25-85	1530	25.6	2.7	325	25.0	28.0
		9-12-85	1455	25.6	30	--	19.0	--
		10-31-85	1405	25.6	11	290	9.0	--
		11-26-85	1425	25.6	46	270	3.0	--
		1-22-86	1255	25.6	40	250	2.5	--
		2-26-86	1505	25.6	55	260	--	--
		4-09-86	1600	25.6	45	300	10.0	--
		5-21-86	1015	25.6	15	330	22.5	--
		7-09-86	2000	25.6	28	290	27.0	--
		8-29-86	1205	25.6	12	270	18.5	14.0
		10-08-86	1333	25.6	9.7	310	14.0	--
		12-01-86	1208	25.6	49	280	4.0	--
		1-07-87	1425	25.6	53	300	1.0	--
		2-24-87	1056	25.6	22	351	1.0	--
		4-21-87	1158	25.6	125	280	13.0	--
		5-26-87	1303	25.6	42	310	17.0	--
		7-13-87	1530	25.6	13	290	27.0	--
		8-18-87	1422	25.6	7.3	322	29.0	--
		10-09-87	1400	25.6	34	262	--	--

Appendix A. Streamflow data—*Continued*

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	Water temperature (°C)	Air temperature (°C)
		11-20-87	1057	25.6	25	303	6.0	--
01110100	Quinsigamond River NR Grafton, Mass.	5-02-85	1015	37.1	24	308	16.0	12.5
		10-17-86	1430	37.1	8.4	282	9.5	12.0
01110500	Blackstone River at Northbridge, Mass.	10-21-85	1230	141	139	367	13.0	17.5
		11-20-85	1130	141	429	263	10.0	22.0
		1-17-86	1230	141	195	442	1.5	1.0
		1-28-86	1300	141	1,170	145	1.5	-6.0
		2-13-86	1500	141	209	533	3.0	-.5
		3-06-86	1400	141	270	380	5.0	5.5
		4-17-86	1330	141	209	378	13.5	17.5
		6-18-86	1200	141	370	312	18.5	22.5
		7-25-86	1300	141	159	371	26.0	30.5
		8-19-86	1230	141	238	263	21.5	20.0
01111040	Mumford River NR Uxbridge, Mass.	5-02-85	1400	55.0	25	120	17.5	16.0
01111148	West River NR Northbridge, Mass.	9-04-86	1330	13.2	2.0	143	16.5	19.0
		10-16-86	1450	13.2	1.8	157	11.0	11.5
01111150	West River at West Upton, Mass.	5-02-85	1600	14.7	9.5	290	16.0	17.5
		9-04-86	1445	14.7	2.2	371	17.0	19.0
		10-16-86	1400	14.7	2.0	412	11.5	15.5
01111155	West River NR West Upton, Mass.	9-04-86	1530	15.1	3.0	334	16.5	17.0
		10-16-86	1300	15.1	2.7	399	10.5	14.0
01111170	Center BK Mendon ST at Upton, Mass.	5-08-85	1520	6.03	8.8	112	15.5	16.5
		9-04-86	1140	6.03	1.5	148	15.5	18.5
		10-16-86	1135	6.03	1.1	167	8.5	14.5
01111172	Center BK TR at West Upton, Mass.	9-04-86	1300	0.4	0.1	160	15.0	18.5
		10-16-86	1200	.4	.08	181	8.0	13.0
01111180	West River NR Upton, Mass.	6-23-86	1500	23.7	29	150	17.5	26.0
		7-09-86	1530	23.7	14	162	23.5	26.0
		7-24-86	0930	23.7	9.2	187	19.5	25.0
		9-04-86	0950	23.7	6.1	211	14.5	18.5
		9-11-86	1630	23.7	4.4	204	17.5	21.5
		10-16-86	1010	23.7	5.6	248	9.0	11.0
01111184	Taft Pond Bk 100 ft DS Taft Pond NR Upton, Mass.	9-09-86	1045	.95	.08	60	15.0	18.5
		10-16-86	1045	.95	.05	63	10.5	13.0
01111186	Taft Pond BK NR Upton, Mass.	9-09-86	1015	1.49	.16	68	15.0	18.5
		10-16-86	1030	1.49	.14	73	6.0	11.0
01112100	Mill River NR Milford, Mass.	5-08-85	1430	6.63	17	155	14.5	14.0
		6-24-86	1515	6.63	8.8	173	20.5	21.0
		7-09-86	1630	6.63	5.7	181	26.0	27.0
		8-06-86	1200	6.63	3.0	173	24.0	27.0
		9-05-86	0830	6.63	1.1	176	17.0	16.5
		10-16-86	1800	6.63	1.6	223	12.0	10.0
01112105	Mill River TR NR Upton, Mass.	6-24-86	1600	1.50	1.1	125	15.0	22.5
		9-05-86	0845	1.50	.08	74	14.0	16.5
		10-17-86	1600	1.50	.04	190	9.5	10.0

Appendix A. Streamflow data—*Continued*

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	Water temperature (°C)	Air temperature (°C)
01112160	Mill River at Route 16 at Spindleville, Mass.	9-05-86	1000	10.8	1.3	196	18.0	19.0
01112170	Mill River at Spindleville, Mass.	6-24-86	1350	11.6	16	191	21.0	23.0
		9-02-86	0730	11.6	2.4	130	18.0	20.0
		9-05-86	1100	11.6	2.4	268	17.5	19.5
		10-16-86	1030	11.6	2.6	264	13.5	15.0
01112180	Mill River NR Spindleville, Mass.	9-05-86	1200	12.6	3.3	243	16.5	20.0
		7-24-87	1200	12.6	2.6	336	26.0	26.5
01112190	Muddy BK at South Milford, Mass.	5-08-85	1320	6.23	11	76	12.5	20.5
		8-06-86	1300	6.23	1.2	121	18.0	20.5
		9-05-86	1330	6.23	1.1	168	14.5	21.5
		7-24-87	1100	6.23	.62	121	19.5	22.0
01112200	Mill River at South Milford, Mass.	5-08-85	1320	19.1	44	170	13.5	13.0
		8-06-86	1330	19.1	7.2	182	21.5	22.5
		9-05-86	1410	19.1	4.5	196	16.5	21.0
01112205	Mill River TR 2 at South Milford, Mass.	9-05-86	1230	.2	.12	185	15.0	20.0
01112210	Mill River TR 2 at South Milford, Mass.	8-07-86	1400	.65	.33	131	19.0	25.0
		9-05-86	1300	.65	.41	132	16.0	21.5
01112220	Mill River TR 3 Thayer RD NR South Milford, Mass.	9-05-86	1600	.48	.0	--	--	21.5
01112230	Round Meadow BK NR Mendon, Mass.	9-05-86	1540	1.06	.2	42	17.0	21.5
01112235	Mill River TR 4 Providence ST NR Mendon, Mass.	8-07-86	1215	0.3	0.07	43	23.5	26.5
		9-05-86	1520	.3	.12	39	23.0	26.5
01112240	Mill River NR Mendon, Mass.	6-24-86	1245	23.8	28	138	18.0	20.5
		7-10-86	1230	23.8	15	157	22.5	27.0
		7-24-86	1445	23.8	7.7	178	24.5	35.0
		8-06-86	1215	23.8	10	190	20.5	26.5
		9-05-86	1500	23.8	6.2	156	17.0	21.5
		9-11-86	1530	23.8	10	181	20.5	25.0
		7-24-87	1030	23.8	3.5	265	23.0	22.5
01112250	Mill River NR Blackstone, Mass.	5-08-85	1145	25.3	59	122	13.0	10.0
		9-11-86	1500	25.3	12	181	18.5	26.5
		10-16-86	1430	25.3	7.8	146	11.5	14.5
01112270	Silver Lake TR at Bellingham, Mass.	9-02-86	1430	.07	.0	127	--	--
		10-17-86	1330	.07	.0	--	--	11.0
01112272	Silver Lake TR NR Bellingham, Mass.	10-17-86	1400	.4	.25	386	10.5	11.0
01112274	Silver Lake TR 2 NR Bellingham, Mass.	9-02-86	1330	.88	.29	220	--	--
		10-17-86	1130	.88	.31	200	9.0	11.5
01112275	Peters River NR Bellingham, Mass.	9-02-86	1300	1.71	.71	171	--	--
		10-17-86	1050	1.71	5.4	174	12.0	13.0
01112278	Peters River TR Maple ST NR Bellingham, Mass.	9-02-86	1230	1.27	.62	86	--	--
		10-17-86	1215	1.27	.68	81	8.5	11.0
01112280	Peters River TR Lake ST NR Bellingham, Mass.	9-02-86	1200	1.48	.6	102	--	--
		10-17-86	0930	1.48	.74	83	8.0	12.5
01112282	Peters River TR 2 NR Bellingham, Mass.	9-02-86	1130	.25	.07	49	--	--
		10-17-86	1230	.25	.08	52	10.5	11.5

Appendix A. Streamflow data—*Continued*

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	Water temperature (°C)	Air temperature (°C)
01112284	Peters River TR 2 Cross ST NR Bellingham, Mass.	9-02-86	1100	0.43	0.11	113	--	--
		10-17-86	1000	.43	.13	96	7.5	12.5
01112286	Peters River TR 3 NR Bellingham, Mass.	9-02-86	1030	.06	.0	243	--	--
		10-17-86	0915	.06	.0	229	7.0	12.5
01112288	Peters River Park ST NR Bellingham, Mass.	5-01-86	1315	4.59	5.6	138	17.0	22.5
		7-10-86	1345	4.59	2.6	138	22.0	27.0
		7-23-86	1400	4.59	2.0	203	23.5	31.5
		9-02-86	1000	4.59	.89	147	--	--
		9-10-86	1345	4.59	.9	147	15.5	19.0
		10-17-86	0900	4.59	7.5	164	8.5	13.5
		7-23-87	1445	4.59	.40	249	26.0	31.5
01112289	Peters River TR 4 NR Crooks Corner, Mass.	5-02-86	1200	.07	1.3	165	15.0	18.0
		9-10-86	1630	.07	.03	220	17.0	21.5
01112290	Peters River NR Crooks Corner, Mass.	5-02-86	1100	5.32	5.8	151	14.5	21.0
		9-10-86	1500	5.32	1.9	164	14.0	21.0
01112292	Jenks Reservoir Outlet at Crooks Corner, Mass.	5-02-86	1130	.83	.7	121	16.0	18.0
		9-10-86	1515	.83	.11	113	21.0	20.0
01112300	Bungay BK NR Sheldonville, Mass.	5-02-86	0900	2.62	1.8	121	13.5	15.0
		9-10-86	1215	2.62	.53	133	17.0	26.5
		7-23-87	1404	2.62	.11	138	27.0	27.5
01112320	Bungay BK NR Crooks Corner, Mass.	5-02-86	1000	2.88	2.4	122	13.5	17.0
		9-10-86	1130	2.88	.74	140	15.0	23.0
01112350	Bungay BK at Crooks Corner, Mass.	5-01-86	1545	3.84	3.5	132	18.0	19.5
		9-10-86	1045	3.84	.83	156	15.5	22.5
01112365	Arnolds BK at Crooks Corner, Mass.	5-01-86	1400	1.40	.95	217	17.5	21.0
		9-10-86	1600	1.40	.25	257	15.0	20.5
01112380	Peters River at Crooks Corner, Mass.	5-01-86	1445	11.8	10	148	17.5	21.5
		7-10-86	1445	11.8	5.9	171	21.5	24.5
		7-23-86	1400	11.8	2.9	182	22.0	31.5
		9-10-86	1010	11.8	3.1	166	13.0	20.5
		10-16-86	1200	11.8	7.1	145	10.0	17.0
		7-23-87	1540	11.8	1.4	225	24.0	29.0
01113655	Burnt Swamp BK Rt 121 at Sheldonville, Mass.	6-19-86	1430	1.26	1.6	222	17.0	18.5
		9-11-86	1345	1.26	.06	274	16.5	23.0
01113658	Burnt Swamp BK TR at Sheldonville, Mass.	6-19-86	1500	.16	.4	80	17.0	19.5
		9-11-86	1130	.16	.0	--	--	20.5
01113660	Burnt Swamp BK Hancock ST Sheldonville, Mass.	6-19-86	1145	1.80	2.5	191	13.5	19.0
		7-10-86	1615	1.80	.5	200	18.5	22.5
		7-23-86	1145	1.80	.2	191	19.5	31.5
		8-14-86	0745	1.80	1.0	173	14.5	19.0
		9-11-86	1115	1.80	.17	188	15.0	21.5
		7-23-87	1345	1.80	.004	101	23.0	27.0
01113662	Burnt Swamp BK at Sheldonville, Mass.	9-11-86	1245	2.30	.19	148	17.5	23.5
01113664	Burnt Swamp BK TR 2 at Sheldonville, Mass.	6-19-86	1500	.45	.68	106	17.0	19.5
		9-11-86	1045	.45	.02	128	16.5	20.5

Appendix A. Streamflow data—*Continued*

Station No.	Station name	Date	Time	Drainage area (mi^2)	Streamflow, instantaneous (ft^3/s)	Specific conductance (μS/cm)	Water temperature (°C)	Air temperature (°C)
01113666	Burnt Swamp BK TR 3 at Sheldonville, Mass.	6-19-86	1330	1.03	0.16	58	22.5	19.5
		9-11-86	1230	1.03	.01	62	18.0	23.0
01113669	Burnt Swamp BK TR 4 NR Grants Mills, R.I.	9-11-86	1230	.02	.01	201	17.5	21.5
01113670	Burnt Swamp BK NR Grants Mills, R.I.	6-19-86	1400	4.62	5.7	157	16.0	19.0
		7-10-86	1545	4.62	1.5	175	23.5	24.0
		7-23-86	1400	4.62	.72	186	23.5	31.5
		8-14-86	0900	4.62	4.1	153	16.0	20.0
		9-11-86	1215	4.62	.76	207	18.0	21.5
		7-23-87	1330	4.62	.19	192	25.5	25.5

APPENDIX B

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts

[Locations shown on plate 2. See Gadoury and others (1993) for complete description of station name. ft^3/s, cubic foot per second; mg/L, milligram per liter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; µg/L, microgram per liter; °C, degrees Celsius; <, actual value is less than value shown; --, no data]

Date	Time	Streamflow, instan-taneous (ft^3/s)	Specific conduc-tance (µS/cm)	pH (standard units)	Water temper-ature (°C)	Air temper-ature (°C)	Hardness, total (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCo_3$)	Calcium, dissolved (mg/L)
Station No.: 01109700 Blackstone River at Millbury, Mass.									
10-18-85	1130	96	418	7.2	15.5	19.5	56	--	18
11-19-85	1100	238	343	7.0	9.5	18.5	55	18	18
1-06-86	1030	148	458	7.0	7.5	8.5	57	--	18
1-15-86	1500	110	517	7.0	5.0	-9.0	--	--	--
1-27-86	1500	1,130	197	6.2	3.5	4.0	29	10	9.3
2-13-86	1030	112	545	7.0	4.0	-2.0	64	--	20
3-06-86	1030	148	458	7.0	7.5	8.5	--	--	--
4-18-86	0945	94	545	7.0	11.0	11.5	65	--	21
6-17-86	0945	211	398	6.8	19.0	20.0	59	3	19
7-25-86	1030	66	468	6.7	24.0	29.5	66	20	21
8-20-86	0945	116	340	6.9	22.0	23.0	50	21	16
Station No.: 01110500 Blackstone River at Northbridge, Mass.									
10-19-76	1515	76	--	--	11.5	--	--	--	--
11-24-76	1445	96	505	--	5.0	--	--	--	--
1-05-77	1645	99	441	--	1.0	--	--	--	--
2-09-77	1000	112	465	--	.0	--	--	--	--
2-16-77	1600	112	436	--	1.5	--	--	--	--
4-07-77	1315	774	186	--	5.5	--	--	--	--
6-24-77	1700	126	420	--	22.5	--	--	--	--
7-13-77	1745	138	380	--	23.5	--	--	--	--
11-24-81	1000	318	270	--	--	--	--	--	--
1-16-82	1100	1,090	99	--	--	--	--	--	--
3-29-82	1445	389	275	--	7.5	--	--	--	--
7-09-82	1030	190	350	--	24.5	--	--	--	--
8-23-82	1030	132	430	--	18.5	--	--	--	--
11-16-82	1300	282	280	--	7.5	--	--	--	--
12-28-82	1230	186	420	--	7.5	--	--	--	--
3-15-83	1610	886	--	--	4.5	--	--	--	--
10-21-85	1230	139	367	7.0	13.0	17.5	48	9	15
11-20-85	1130	429	263	6.9	10.0	22.0	44	16	14
1-17-86	1230	195	442	7.2	1.5	1.0	--	--	--
1-17-86	1230	195	442	7.2	1.5	1.0	60	0	19
1-28-86	1300	1,170	145	7.0	1.5	-6.0	30	12	9.5
2-13-86	1500	209	533	6.7	3.0	-.5	54	0	17
3-06-86	1400	270	380	7.0	5.0	5.5	48	3	15
4-17-86	1330	209	378	7.1	13.5	17.5	51	0	16
6-18-86	1200	370	312	6.8	18.5	22.5	50	13	16
7-25-86	1300	159	371	7.0	26.0	30.5	60	28	19
8-19-86	1230	238	263	7.4	21.5	20.0	44	18	14
Station No.: 01111230 Blackstone River at Millville, Mass.									
11-06-78	1400	280	252	6.2	11.0	21.5	37	25	12
12-13-78	0845	431	280	6.3	1.5	.0	35	16	11
1-03-79	0930	1,370	210	6.2	4.5	-3.5	--	--	--
3-07-79	0915	2,830	153	6.3	4.5	9.0	21	7	6.5
4-04-79	1315	720	197	6.7	7.0	10.0	--	--	--
4-24-79	0800	405	230	6.5	12.5	15.0	36	17	11
5-02-79	0900	860	173	6.8	14.5	9.0	--	--	--
5-15-79	1215	--	215	6.2	17.5	18.0	35	24	11
6-07-79	1230	572	195	6.8	19.5	25.5	34	24	11
6-18-79	1200	246	255	6.5	24.5	25.0	44	36	14

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium adsorption ratio	Sodium, percent	Potassium, dissolved (mg/L)	Alkalinity, field (mg/L as $CaCO_3$)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)
Station No.: 01109700 Blackstone River at Millbury, Mass.—*Continued*										
10-18-85	2.8	46	3	61	6.1	66	66	36	0.20	7.1
11-19-85	2.4	38	2	58	4.4	37	59	23	.20	7.5
1-06-86	2.9	54	3	65	5.4	63	82	29	.40	7.3
1-15-86	--	--	--	--	--	70	--	--	--	--
1-27-86	1.4	33	3	69	2.6	19	56	13	<.10	4.8
2-13-86	3.3	78	4	71	5.7	71	110	29	.40	8.9
3-06-86	--	--	--	--	--	63	--	--	--	--
4-18-86	3.1	58	3	63	6.3	82	91	32	.50	6.6
6-17-86	2.8	46	3	61	4.4	56	69	27	.20	7.2
7-25-86	3.2	64	4	64	9.3	46	77	42	.50	7.4
8-20-86	2.4	41	3	61	5.1	29	55	22	.41	5.9
Station No.: 01110500 Blackstone River at Northbridge, Mass.—*Continued*										
10-19-76	--	--	--	--	--	--	--	--	--	--
11-24-76	--	--	--	--	--	--	--	--	--	--
1-05-77	--	--	--	--	--	--	--	--	--	--
2-09-77	--	--	--	--	--	--	--	--	--	--
2-16-77	--	--	--	--	--	--	--	--	--	--
4-07-77	--	--	--	--	--	--	--	--	--	--
6-24-77	--	--	--	--	--	--	--	--	--	--
7-13-77	--	--	--	--	--	--	--	--	--	--
11-24-81	--	--	--	--	--	--	--	--	--	--
1-16-82	--	--	--	--	--	--	--	--	--	--
3-29-82	--	--	--	--	--	--	--	--	--	--
7-09-82	--	--	--	--	--	--	--	--	--	--
8-23-82	--	--	--	--	--	--	--	--	--	--
11-16-82	--	--	--	--	--	--	--	--	--	--
12-28-82	--	--	--	--	--	--	--	--	--	--
3-15-83	--	--	--	--	--	--	--	--	--	--
10-21-85	2.6	35	2	58	5.1	39	56	22	0.20	6.6
11-20-85	2.2	30	2	57	3.9	28	46	20	.20	6.7
1-17-86	--	--	--	--	--	63	--	--	--	--
1-17-86	3.1	51	3	62	5.6	63	75	26	.30	7.8
1-28-86	1.6	29	2	65	2.6	18	45	13	.10	4.8
2-13-86	2.8	65	4	70	4.8	57	110	29	.30	7.3
3-06-86	2.6	44	3	64	4.6	45	69	19	.30	6.3
4-17-86	2.6	42	3	62	4.7	57	69	26	.30	4.9
6-18-86	2.4	37	2	60	3.5	37	57	23	.10	5.7
7-25-86	3.0	48	3	60	6.9	32	67	31	.40	6.3
8-19-86	2.1	31	2	58	4.5	26	42	19	.92	5.3
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*										
11-06-78	1.8	26	2	58	3.3	12	40	26	--	--
12-13-78	1.9	32	2	64	2.8	19	52	20	--	--
1-03-79	--	--	--	--	--	--	--	--	--	--
3-07-79	1.1	20	2	65	1.9	14	30	11	--	--
4-04-79	--	--	--	--	--	--	--	--	--	--
4-24-79	2.0	26	2	59	2.6	19	43	17	0.10	4.8
5-02-79	--	--	--	--	--	--	--	--	--	--
5-15-79	1.8	24	2	57	3.0	11	39	16	.10	5.3
6-07-79	1.7	20	2	54	2.3	11	35	16	--	--
6-18-79	2.2	30	2	58	3.0	8	47	18	.20	5.8

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Solids, residue at 180°C (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)
Station No.: 01109700 Blackstone River at Millbury, Mass.—*Continued*									
10-18-85	--	222	--	--	--	--	180	700	130
11-19-85	183	184	1.20	2.60	0.30	2.9	110	340	--
1-06-86	224	237	--	--	--	--	0	400	210
1-15-86	254	--	.580	6.40	2.7	9.1	--	860	250
1-27-86	129	135	.540	.520	.58	1.1	30	170	150
2-13-86	292	308	.570	4.90	1.4	6.3	200	620	250
3-06-86	--	--	.570	3.70	2.0	5.7	--	--	--
4-18-86	263	276	.250	5.30	2.7	8.0	200	190	240
6-17-86	199	210	.480	2.80	.60	3.4	130	180	110
7-25-86	264	275	4.80	.740	.86	1.6	300	110	120
8-20-86	150	179	2.80	.510	.79	1.3	<10	170	110
Station No.: 01110500 Blackstone River at Northbridge, Mass.—*Continued*									
10-19-76	--	--	--	--	--	--	--	--	--
11-24-76	--	--	--	--	--	--	--	--	--
1-05-77	--	--	--	--	--	--	--	--	--
2-09-77	--	--	--	--	--	--	--	--	--
2-16-77	--	--	--	--	--	--	--	--	--
4-07-77	--	--	--	--	--	--	--	--	--
6-24-77	--	--	--	--	--	--	--	--	--
7-13-77	--	--	--	--	--	--	--	--	--
11-24-81	--	--	--	--	--	--	--	--	--
1-16-82	--	--	--	--	--	--	--	--	--
3-29-82	--	--	--	--	--	--	--	--	--
7-09-82	--	--	--	--	--	--	--	--	--
8-23-82	--	--	--	--	--	--	--	--	--
11-16-82	--	--	--	--	--	--	--	--	--
12-28-82	--	--	--	--	--	--	--	--	--
3-15-83	--	--	--	--	--	--	--	--	--
10-21-85	--	167	--	--	--	--	100	490	90
11-20-85	150	145	0.810	1.20	0.40	1.6	60	390	--
1-17-86	--	--	.820	5.50	1.8	7.3	--	--	--
1-17-86	190	226	--	--	--	--	180	120	200
1-28-86	129	120	.540	.560	.44	1.0	40	350	140
2-13-86	260	279	.740	3.50	.70	4.2	150	240	190
3-06-86	197	194	.710	2.30	1.0	3.3	80	310	180
4-17-86	197	207	.730	3.00	.50	3.5	120	120	150
6-18-86	157	167	1.00	1.40	.40	1.8	90	110	130
7-25-86	225	221	4.40	.190	.91	1.1	160	96	36
8-19-86	146	144	2.00	.340	.56	.90	<10	140	110
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*									
11-06-78	--	116	--	--	--	--	--	--	--
12-13-78	--	131	--	--	--	--	--	--	--
1-03-79	--	--	--	--	--	--	--	--	--
3-07-79	--	79	--	--	--	--	--	--	--
4-04-79	--	--	--	--	--	--	--	--	--
4-24-79	134	118	--	--	--	1.0	--	--	--
5-02-79	--	--	--	--	--	--	--	--	--
5-15-79	122	107	--	--	--	1.3	--	--	--
6-07-79	--	93	--	--	--	--	--	--	--
6-18-79	164	126	--	--	--	.76	--	330	140

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Time	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	pH (standard units)	Water temperature (°C)	Air temperature (°C)	Hardness, total (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCo_3$)	Calcium, dissolved (mg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*									
7-10-79	0915	285	320	6.6	21.5	24.5	--	--	--
7-25-79	1400	200	270	6.8	26.5	29.5	49	21	16
8-09-79	0900	240	300	6.4	22.0	22.5	--	--	--
8-22-79	0700	570	247	6.3	20.0	14.5	43	25	14
9-18-79	0815	280	248	6.3	18.5	16.5	41	24	13
10-16-79	0800	822	204	6.1	9.0	3.0	35	18	11
11-13-79	0800	1,050	139	6.9	9.5	5.0	25	17	8.0
11-27-79	1430	1,450	205	6.2	12.0	13.5	34	8	11
12-11-79	0800	500	212	6.3	2.5	6.5	38	16	12
1-09-80	0830	296	260	6.3	.5	-3.5	44	30	14
2-05-80	0830	480	325	6.3	1.0	-4.5	50	18	16
3-05-80	1000	214	355	6.6	1.5	1.0	54	37	18
4-15-80	0915	1,600	156	6.1	11.0	14.5	30	19	9.3
5-06-80	0900	930	168	6.1	14.5	11.0	32	15	10
6-18-80	1330	296	210	5.8	21.0	23.0	37	23	12
7-08-80	0845	230	253	6.2	21.5	20.0	41	21	13
8-13-80	0900	275	212	5.8	23.0	21.0	40	23	13
9-09-80	0745	200	283	6.0	18.5	4.0	52	32	17
10-15-80	0945	180	240	6.0	9.5	.0	--	--	--
11-18-80	0845	250	320	6.5	2.5	1.5	47	16	15
12-18-80	1000	230	320	7.1	.5	-1.0	44	25	14
1-20-81	0900	840	360	6.9	1.0	1.0	53	14	17
2-17-81	1020	955	265	6.8	4.5	15.0	--	--	--
3-10-81	0900	835	198	6.4	4.5	4.0	35	15	11
4-07-81	0945	540	168	6.8	9.0	12.0	--	--	--
5-12-81	0900	195	254	6.1	16.5	14.0	38	13	12
6-10-81	0945	512	270	6.8	20.0	22.0	49	24	16
7-07-81	0930	1,420	217	6.2	24.0	31.0	31	14	9.8
8-18-81	0930	130	340	6.5	20.0	19.5	--	--	--
9-01-81	1000	275	369	5.6	20.5	23.0	55	39	18
10-14-81	1030	150	295	6.6	8.0	15.5	--	--	--
11-03-81	0930	696	221	6.2	9.5	10.5	38	16	12
12-15-81	1435	1,090	210	6.4	.5	3.0	--	--	--
1-19-82	1015	610	225	7.0	.5	-6.0	--	--	--
2-09-82	1045	1,350	160	5.8	.5	.0	--	--	--
3-09-82	1000	778	240	7.3	1.0	-4.0	30	18	9.3
4-13-82	1015	1,060	243	6.4	6.0	11.0	--	--	--
5-11-82	0900	418	250	6.0	15.0	12.0	32	15	10
6-10-82	0930	2,280	137	6.9	16.0	19.0	--	--	--
6-15-82	1330	1,880	134	5.9	16.0	29.0	25	13	7.8
7-13-82	0845	238	258	6.6	23.0	37.0	45	26	14
8-11-82	0845	370	192	6.8	--	19.0	--	--	--
8-31-82	1015	83	348	7.1	17.5	26.0	59	38	19
10-14-82	0930	238	245	6.7	12.0	14.0	--	--	--
11-17-82	1030	322	205	6.4	3.5	10.0	32	19	10
12-14-82	1000	135	340	6.9	.5	.0	--	--	--
1-05-83	1140	224	265	7.1	2.0	4.0	--	--	--
2-09-83	1130	900	225	6.5	.5	.0	--	--	--

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium adsorption ratio	Sodium, percent	Potassium, dissolved (mg/L)	Alkalinity, field (mg/L as $CaCO_3$)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*										
7-10-79	--	--	--	--	--	--	--	--	--	--
7-25-79	2.3	32	2	56	3.5	29	50	19	0.10	6.3
8-09-79	--	--	--	--	--	--	--	--	--	--
8-22-79	2.0	21	1	49	3.2	18	43	19	.10	6.5
9-18-79	2.1	29	2	58	3.4	17	43	17	.20	4.6
10-16-79	1.9	24	2	57	2.8	17	35	15	.10	7.2
11-13-79	1.3	17	2	57	2.0	8	24	12	.10	6.5
11-27-79	1.7	23	2	57	2.7	27	34	15	.10	7.1
12-11-79	1.9	24	2	56	2.7	22	36	17	.10	7.4
1-09-80	2.3	26	2	54	3.4	15	42	21	.20	7.3
2-05-80	2.4	34	2	57	4.2	32	54	35	.40	7.5
3-05-80	2.2	32	2	54	4.4	17	61	28	.20	6.5
4-15-80	1.6	16	1	52	2.0	11	27	15	.10	5.2
5-06-80	1.7	20	2	56	2.1	17	29	16	.10	4.9
6-18-80	1.7	23	2	55	3.0	14	35	17	.20	4.7
7-08-80	2.0	27	2	57	3.1	20	43	18	.20	4.8
8-13-80	1.9	21	2	51	3.3	17	35	16	.20	5.3
9-09-80	2.4	30	2	53	4.5	20	44	29	.30	4.8
10-15-80	--	--	--	--	--	--	--	--	--	--
11-18-80	2.3	34	2	58	5.1	--	51	26	.30	6.7
12-18-80	2.2	34	2	60	3.8	--	49	26	--	--
1-20-81	2.5	39	2	59	5.2	--	61	30	.40	8.7
2-17-81	--	--	--	--	--	--	--	--	--	--
3-10-81	1.9	22	2	56	2.3	--	36	16	.10	6.6
4-07-81	--	--	--	--	--	--	--	--	--	--
5-12-81	1.9	26	2	58	2.9	--	41	19	.20	3.8
6-10-81	2.3	34	2	58	3.6	--	46	18	--	--
7-07-81	1.5	19	2	55	2.6	--	31	12	.10	4.3
8-18-81	--	--	--	--	--	--	--	--	--	--
9-01-81	2.5	37	2	57	4.6	--	58	33	.40	5.1
10-14-81	--	--	--	--	--	--	--	--	--	--
11-03-81	2.0	20	1	51	2.3	--	35	17	.20	6.3
12-15-81	--	--	--	--	--	--	--	--	--	--
1-19-82	--	--	--	--	--	--	--	--	--	--
2-09-82	--	--	--	--	--	--	--	--	--	--
3-09-82	1.6	29	2	66	2.0	--	45	17	.10	6.0
4-13-82	--	--	--	--	--	--	--	--	--	--
5-11-82	1.7	23	2	59	2.7	--	28	10	.10	3.7
6-10-82	--	--	--	--	--	--	--	--	--	--
6-15-82	1.4	17	2	58	1.5	--	25	13	<.10	5.4
7-13-82	2.5	33	2	60	2.7	--	44	19	.20	5.5
8-11-82	--	--	--	--	--	--	--	--	--	--
8-31-82	2.8	39	2	57	4.9	--	60	31	.40	6.3
10-14-82	--	--	--	--	--	--	--	--	--	--
11-17-82	1.8	22	2	57	2.7	--	30	19	.10	6.2
12-14-82	--	--	--	--	--	--	--	--	--	--
1-05-83	--	--	--	--	--	--	--	--	--	--
2-09-83	--	--	--	--	--	--	--	--	--	--

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Solids, residue at 180°C (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*									
7-10-79	--	--	--	--	--	--	--	--	--
7-25-79	158	147	--	--	--	0.83	--	--	--
8-09-79	--	--	--	--	--	--	--	--	--
8-22-79	148	120	--	--	--	.20	--	--	--
9-18-79	158	130	1.60	--	--	.55	--	180	50
10-16-79	120	108	.120	0.090	0.88	.97	--	--	--
11-13-79	94	78	.570	.120	.52	.64	--	--	--
11-27-79	124	118	1.30	.640	.46	1.1	--	280	80
12-11-79	129	120	1.00	1.00	.20	1.2	--	--	--
1-09-80	145	132	.960	2.10	.50	2.6	--	--	--
2-05-80	178	180	.920	2.20	1.5	3.7	--	120	190
3-05-80	190	169	.800	2.20	2.3	4.5	--	--	--
4-15-80	102	86	.570	.530	.35	.88	--	--	--
5-06-80	100	98	.760	.270	.41	.68	--	230	90
6-18-80	131	114	2.10	.180	.41	.59	--	--	--
7-08-80	158	133	2.20	.070	.62	.69	--	--	--
8-13-80	138	115	2.10	.140	.59	.73	--	--	--
9-09-80	157	156	2.70	.020	.59	.61	--	210	30
10-15-80	--	--	--	--	--	--	--	--	--
11-18-80	185	170	1.50	3.30	.20	3.5	--	130	160
12-18-80	--	140	--	--	--	--	--	--	--
1-20-81	199	192	.680	1.50	2.2	3.7	--	--	--
2-17-81	--	--	--	--	--	--	--	--	--
3-10-81	117	112	.650	.780	.0	.57	--	260	110
4-07-81	--	--	--	--	--	--	--	--	--
5-12-81	137	129	1.50	.510	.32	.83	--	--	--
6-10-81	--	135	--	--	--	--	--	--	--
7-07-81	111	95	.950	.080	.54	.62	--	360	80
8-18-81	--	--	--	--	--	--	--	--	--
9-01-81	198	179	2.30	.020	.36	.38	--	110	40
10-14-81	--	--	--	--	--	--	--	--	--
11-03-81	118	116	1.60	.300	--	--	.28	200	71
12-15-81	--	--	--	--	--	--	--	--	--
1-19-82	--	--	.750	.980	--	--	.18	--	--
2-09-82	--	--	--	--	--	--	--	--	--
3-09-82	135	122	.680	.640	--	--	.18	200	110
4-13-82	--	--	--	--	--	--	--	--	--
5-11-82	87	96	1.10	.940	--	--	.31	--	--
6-10-82	--	--	--	--	--	--	--	--	--
6-15-82	99	79	--	--	--	--	--	290	71
7-13-82	173	143	2.20	.080	--	--	.61	--	--
8-11-82	--	--	--	--	--	--	--	--	--
8-31-82	206	192	3.40	.050	--	--	.58	58	21
10-14-82	--	--	--	--	--	--	--	--	--
11-17-82	133	105	.780	.850	--	--	.37	230	120
12-14-82	--	--	--	--	--	--	--	--	--
1-05-83	--	--	--	--	--	--	--	--	--
2-09-83	--	--	--	--	--	--	--	--	--

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Time	Streamflow, instantaneous (ft^3/s)	Specific conductance (µS/cm)	pH (standard units)	Water temperature (˚C)	Air temperature (˚C)	Hardness, total (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCo_3$)	Calcium, dissolved (mg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*									
3-08-83	1000	1,210	182	7.3	3.0	2.0	31	20	9.5
4-05-83	1245	1,140	148	6.8	8.0	10.0	--	--	--
5-10-83	1045	685	170	6.8	13.0	14.0	35	19	11
6-15-83	1200	365	192	6.0	24.5	28.0	--	--	--
7-13-83	1030	141	285	6.5	23.0	30.5	--	--	--
8-03-83	1000	114	345	6.8	25.0	33.0	54	36	17
9-07-83	0945	129	286	6.5	24.5	30.0	51	31	16
9-11-83	1015	--	--	--	--	--	--	--	--
10-04-83	1135	215	215	6.0	18.0	25.0	--	--	--
11-09-83	1015	174	270	6.7	8.5	13.0	45	25	14
12-14-83	1115	2,350	140	5.6	4.5	7.5	--	--	--
1-10-84	0950	441	225	5.9	2.0	4.5	--	--	--
2-08-84	1115	729	240	6.0	1.0	-4.5	--	--	--
3-07-84	0915	1,130	240	6.5	4.0	--	30	18	9.5
4-10-84	1210	1,840	147	7.0	8.0	21.0	--	--	--
5-09-84	0945	860	181	6.7	14.0	16.5	31	21	9.5
6-12-84	1200	964	141	6.4	22.5	27.0	--	--	--
7-18-84	1100	327	210	6.4	23.0	24.0	--	--	--
8-15-84	1030	163	265	6.9	23.5	35.5	42	22	13
9-12-84	1220	117	275	6.9	21.0	20.5	42	21	13
10-10-84	1055	118	265	6.4	14.0	--	--	--	--
11-07-84	1000	193	228	6.8	9.0	14.0	--	--	--
12-05-84	1110	273	194	7.2	3.0	3.5	--	--	--
1-09-85	0910	225	265	6.7	1.0	-10.0	--	--	--
2-06-85	0945	180	340	7.1	.5	-6.5	--	--	--
3-13-85	1000	1,000	248	7.0	5.0	6.0	29	14	9.1
4-17-85	0835	293	248	6.0	12.5	10.5	38	23	12
5-15-85	1000	255	250	6.7	16.0	--	--	--	--
6-04-85	1100	--	264	6.9	20.5	--	38	21	12
6-05-85	1020	225	270	6.4	19.5	--	--	--	--
7-10-85	0930	112	335	6.6	23.0	--	--	--	--
8-14-85	1045	141	260	6.8	23.5	27.5	42	24	13
9-11-85	0815	350	182	6.0	18.0	--	30	18	9.5
10-09-85	1055	352	250	6.1	14.0	19.0	--	--	--
11-13-85	1100	653	188	5.9	9.0	16.0	--	--	--
12-04-85	0930	808	255	5.6	2.0	1.5	32	21	9.8
1-08-86	0940	192	310	5.6	1.0	-7.0	--	--	--
2-05-86	1145	635	300	6.3	2.0	4.0	--	--	--
3-05-86	1035	516	285	6.5	5.0	9.0	39	16	12
4-02-86	1025	505	235	7.2	13.0	21.0	--	--	--
5-07-86	1050	322	300	6.6	15.0	12.0	--	--	--
6-10-86	1025	2,500	163	6.5	18.0	26.0	28	11	8.6
7-09-86	1110	274	265	6.1	24.0	27.0	--	--	--
8-13-86	1200	269	240	6.3	22.0	24.0	--	--	--
9-03-86	0940	115	345	6.4	18.0	15.0	43	19	14

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium adsorption ratio	Sodium, percent	Potassium, dissolved (mg/L)	Alkalinity, field (mg/L as $CaCO_3$)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*									
3-08-83	1.7	21	2	58	1.9	--	35	16	0.10
4-05-83	--	--	--	--	--	--	--	--	--
5-10-83	1.9	20	2	53	2.4	--	32	17	.10
6-15-83	--	--	--	--	--	--	--	--	--
7-13-83	--	--	--	--	--	--	--	--	--
8-03-83	2.7	41	3	60	5.0	--	57	28	.40
9-07-83	2.6	33	2	56	4.2	--	46	23	--
9-11-83	--	--	--	--	--	--	--	--	--
10-04-83	--	--	--	--	--	--	--	--	--
11-09-83	2.3	29	2	56	4.2	--	41	23	.30
12-14-83	--	--	--	--	--	--	29	--	--
1-10-84	--	--	--	--	--	--	--	--	--
2-08-84	--	--	--	--	--	--	--	--	--
3-07-84	1.6	31	3	67	1.9	--	51	15	.10
4-10-84	--	--	--	--	--	--	--	--	--
5-09-84	1.7	20	2	56	2.2	--	31	25	.20
6-12-84	--	--	--	--	--	--	39	--	--
7-18-84	--	--	--	--	--	--	--	--	--
8-15-84	2.2	29	2	58	3.9	--	46	23	.30
9-12-84	2.3	31	2	59	4.6	--	48	22	--
10-10-84	--	--	--	--	--	--	--	--	--
11-07-84	--	--	--	--	--	12	--	--	--
12-05-84	--	--	--	--	--	--	--	--	--
1-09-85	--	--	--	--	--	--	--	--	--
2-06-85	--	--	--	--	--	--	--	--	--
3-13-85	1.5	33	3	69	2.1	16	54	16	.10
4-17-85	2.0	27	2	58	3.3	--	47	17	--
5-15-85	--	--	--	--	--	--	--	--	--
6-04-85	2.0	28	2	59	2.8	18	44	18	.20
6-05-85	--	--	--	--	--	--	--	--	--
7-10-85	--	--	--	--	--	--	--	--	--
8-14-85	2.2	30	2	59	3.6	19	47	17	.20
9-11-85	1.5	20	2	56	3.4	12	30	16	--
10-09-85	--	--	--	--	--	--	--	--	--
11-13-85	--	--	--	--	--	--	--	--	--
12-04-85	1.7	28	2	64	2.6	--	48	14	.20
1-08-86	--	--	--	--	--	--	--	--	--
2-05-86	--	--	--	--	--	--	--	--	--
3-05-86	2.1	32	2	62	3.2	--	52	16	.20
4-02-86	--	--	--	--	--	21	--	--	--
5-07-86	--	--	--	--	--	25	--	--	--
6-10-86	1.5	19	2	58	2.0	--	29	21	.10
7-09-86	--	--	--	--	--	23	--	--	--
8-13-86	--	--	--	--	--	--	--	--	--
9-03-86	2.0	40	3	64	5.0	23	50	28	.30

Appendix B. Surface-water-quality data at three sites on the Blackstone River, Massachusetts—*Continued*

Date	Silica, dissolved (mg/L)	Solids, residue at 180˚C (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Phosphate, ortho, dissolved (mg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)
Station No.: 01111230 Blackstone River at Millville, Mass.—*Continued*								
3-08-83	6.5	99	102	0.620	0.540	0.0	150	75
4-05-83	--	--	--	--	--	--	--	--
5-10-83	5.1	115	104	.830	.400	.0	370	110
6-15-83	--	--	--	--	--	--	--	--
7-13-83	--	--	--	--	--	--	--	--
8-03-83	5.2	211	188	4.50	.00	1.1	78	15
9-07-83	--	--	137	--	--	--	--	--
9-11-83	--	--	--	--	--	--	--	--
10-04-83	--	--	--	--	--	--	--	--
11-09-83	5.8	148	145	2.40	1.30	1.0	100	100
12-14-83	--	--	--	--	--	--	--	--
1-10-84	--	--	--	--	--	--	--	--
2-08-84	--	--	--	--	--	--	--	--
3-07-84	5.9	135	127	.520	.550	.12	170	79
4-10-84	--	--	--	--	--	--	--	--
5-09-84	5.0	121	105	.670	.710	.18	370	110
6-12-84	--	--	--	--	--	--	--	--
7-18-84	--	--	--	--	--	--	--	--
8-15-84	5.8	159	149	2.90	.060	.80	150	19
9-12-84	--	--	133	--	--	--	--	--
10-10-84	--	--	--	--	--	--	--	--
11-07-84	--	--	--	--	--	--	--	--
12-05-84	--	--	--	--	--	--	--	--
1-09-85	--	--	--	--	--	--	--	--
2-06-85	--	--	--	--	--	--	--	--
3-13-85	5.0	139	130	--	--	--	130	110
4-17-85	--	--	117	--	--	--	--	--
5-15-85	--	--	--	--	--	--	--	--
6-04-85	5.0	150	131	1.60	.170	.46	180	81
6-05-85	--	--	--	--	--	--	--	--
7-10-85	--	--	--	--	--	--	--	--
8-14-85	5.7	160	140	2.10	.050	.40	230	27
9-11-85	--	--	88	--	--	--	--	--
10-09-85	--	--	--	--	--	--	--	--
11-13-85	--	--	--	--	--	--	--	--
12-04-85	7.3	129	122	.590	.660	.21	140	69
1-08-86	--	--	--	--	--	--	--	--
2-05-86	--	--	--	--	--	--	--	--
3-05-86	6.5	143	144	.680	1.70	.49	250	130
4-02-86	--	--	--	--	--	--	--	--
5-07-86	--	--	--	--	--	--	--	--
6-10-86	5.7	96	100	.550	.280	.15	350	60
7-09-86	--	--	--	--	--	--	--	--
8-13-86	--	--	--	--	--	--	--	--
9-03-86	5.1	200	174	3.20	.040	1.1	--	--

APPENDIX C

Appendix C. Ground-water-quality data

[Locations shown on plate 1 and figures 13 and 14. No., number; mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter at 25° Celsius; <, actual value is less than value shown; --, no data]

Station No.	Well identification	Date	Time	Specific conductance (µS/cm)	pH (standard units)	Water temperature (°C)	Air temperature (°C)
420142071284601	A6W-4	7-26-85	0830	101	6.2	8.5	--
420203071301601	BDW-30	8-06-85	1305	112	6.0	10.5	--
420316071275801	A6W-1	7-26-85	1030	114	6.2	9.5	--
420439071362801	UXW-19	8-06-85	1000	162	5.8	10.5	--
420703071411301	NXW-2	7-24-85	1230	131	6.1	18.0	--
420912071391201	NXW-8	11-12-85	0125	215	6.1	13.5	22.5
		11-20-85	1255	215	6.1	13.5	22.5
		1-16-86	1315	221	6.4	10.5	.5
		2-13-86	1550	239	5.8	8.5	.0
		3-06-86	1450	240	6.7	7.5	5.5
		4-17-86	1430	222	6.4	9.5	17.0
		6-18-86	1300	221	6.2	14.0	22.5
		7-25-86	1400	244	6.0	16.0	30.5
		8-19-86	1555	244	--	17.0	25.5
420918071363104	UPW-9	8-08-85	1000	104	6.1	9.5	--
421007071374301	UPW-2	8-08-85	0845	116	6.0	11.5	--
421145071461401	MXW-70	4-24-86	1530	462	6.9	7.5	13.0
421146071503501	AUW-16	7-23-85	0930	920	6.2	10.5	--
421147071461201	MXW-71	4-25-86	1230	278	6.6	7.5	19.0
421147071461202	MXW-73-10	12-11-86	1430	450	6.6	14.0	.5
421147071461203	MXW-73-26	12-11-86	1300	203	7.1	14.0	.5
421147071461204	MXW-73-40	12-11-86	1515	128	6.1	12.5	.5
421149071461901	MXW-66	4-22-86	1200	412	6.6	12.0	22.0
421150071461806	MXW-60-39	12-10-86	1100	393	6.7	14.5	9.0
421150071461807	MXW-60-50	12-10-86	1000	247	6.5	15.0	9.0
421150071461901	MXW-3	7-23-85	1430	380	7.3	12.0	--
		10-18-85	1300	391	6.5	14.0	19.5
		11-19-85	1225	474	7.2	14.0	15.0
		1-16-86	1100	424	6.4	13.0	-4.0
		2-13-86	1145	441	6.4	12.0	-1.5
		3-07-86	0900	448	6.5	11.0	-2.0
		4-18-86	1040	465	6.7	8.5	16.5
		6-18-86	0840	392	6.6	9.5	20.0
		7-25-86	0900	333	6.5	13.0	28.0
		8-20-86	1330	386	6.3	14.0	20.5
		11-19-86	1225	474	7.2	14.0	15.0
421150071462002	MXW-65	4-22-86	1330	475	7.0	11.0	22.0
421150071462004	MXW-56-22	12-10-86	1400	633	7.2	14.0	7.5
421152071461702	MXW-68-11	12-09-86	1420	267	5.6	10.5	.0
421152071461703	MXW-68-27	12-09-86	1300	300	5.9	10.0	.0
421152071461704	MXW-68-44	12-09-86	1200	232	6.3	10.0	-3.0
421154071461701	MXW-69	4-24-86	1230	288	6.6	7.5	13.0
421154071462401	MXW-4	1-16-86	0940	416	6.2	12.5	-6.0
		4-22-86	1430	550	6.8	9.0	22.0
421158071462401	MXW-72	4-28-86	1330	226	6.5	7.5	24.0
421257071495301	AUW-20	7-23-85	1100	380	6.8	10.5	--
421321071451501	MXW-2	7-24-85	0845	640	5.8	12.0	--
421556071435301	SNW-5	8-08-85	1400	179	6.0	11.0	--
421734071451001	SNW-6	8-07-85	1100	257	6.2	10.5	--
421759071451601	SNW-10	8-07-85	0930	425	6.4	10.0	--
421817071451001	SNW-8	8-07-85	1508	300	6.2	12.0	--

Appendix C. Ground-water-quality data—*Continued*

Station No.	Date	Hardness, total (mg/L as $CaCO_3$	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sodium adsorption ratio	Sodium, percent	Potassium, dissolved (mg/L)
420142071284601	7-26-85	30	9.2	1.6	6.0	0.5	30	1.2
420203071301601	8-06-85	25	7.7	1.4	10	.9	45	1.2
420316071275801	7-26-85	32	10	1.7	8.3	.7	35	1.7
420439071362801	8-06-85	29	8.6	1.8	15	1	51	2.0
420703071411301	7-24-85	26	7.8	1.5	11	1	46	2.0
420912071391201	11-12-85	--	--	--	--	--		--
	11-20-85	--	--	--	--	--		--
	1-16-86	32	10	1.8	27	2	62	2.7
	2-13-86	31	9.7	1.6	25	2	62	2.5
	3-06-86	35	11	1.8	30	2	63	2.7
	4-17-86	29	9.0	1.6	27	2	65	2.5
	6-18-86	30	9.2	1.6	27	2	64	2.7
	7-25-86	32	10	1.7	31	2	65	2.9
	8-19-86	32	10	1.7	31	2	65	3.1
420918071363104	8-08-85	22	6.5	1.3	9.1	.9	46	1.4
421007071374301	8-08-85	24	7.5	1.4	9.7	.9	44	1.6
421145071461401	4-24-86	--	--	--	--	--	--	--
421146071503501	7-23-85	150	52	4.9	99	4	57	7.5
421147071461201	4-25-86	--	--	--	--	--	--	--
421147071461202	12-11-86	61	19	3.4	50	3	62	4.8
421147071461203	12-11-86	48	15	2.5	16	1	40	3.7
421147071461204	12-11-86	--	--	--	--	--	--	--
421149071461901	4-22-86	53	16	3.1	49	3	65	4.3
421150071461806	12-10-86	55	17	3.0	49	3	64	4.8
421150071461807	12-10-86	48	15	2.6	49	3	67	3.9
421150071461901	7-23-85	57	18	2.9	58	3	53	44
	10-18-85	--	--	--	--	--	--	--
	11-19-85	47	15	2.3	46	3	50	43
	1-16-86	51	16	2.6	49	3	65	5.6
	2-13-86	57	18	2.9	53	3	64	5.6
	3-07-86	57	18	3.0	54	3	64	6.6
	4-18-86	57	18	2.9	51	3	63	6.4
	6-18-86	50	16	2.5	50	3	66	5.3
	7-25-86	47	15	2.4	49	3	67	4.9
	8-20-86	50	16	2.4	49	3	65	5.8
	11-19-86	--	--	--	--	--	--	--
421150071462002	4-22-86	59	19	2.9	57	3	65	4.8
421150071462004	12-10-86	54	17	2.7	54	3	65	7.1
421152071461702	12-09-86	28	9.1	1.4	37	3	71	3.3
421152071461703	12-09-86	30	9.7	1.5	43	4	72	4.4
421152071461704	12-09-86	48	15	2.5	23	2	49	3.2
421154071461701	4-24-86	--	--	--	--	--	--	--
421154071462401	1-16-86	60	19	3.1	53	3	64	4.5
	4-22-86	--	19	3.2	58	3	61	17
421158071462401	4-28-86	--	--	--	--	--	--	--
421257071495301	7-23-85	100	34	4.5	23	1	31	5.3
421321071451501	7-24-85	67	21	3.5	89	5	73	4.4
421556071435301	8-08-85	39	12	2.3	15	1	44	2.0
421734071451001	8-07-85	47	15	2.4	24	2	51	2.6
421759071451601	8-07-85	110	33	5.5	28	1	36	3.1
421817071451001	8-07-85	87	28	4.2	15	.7	27	2.2

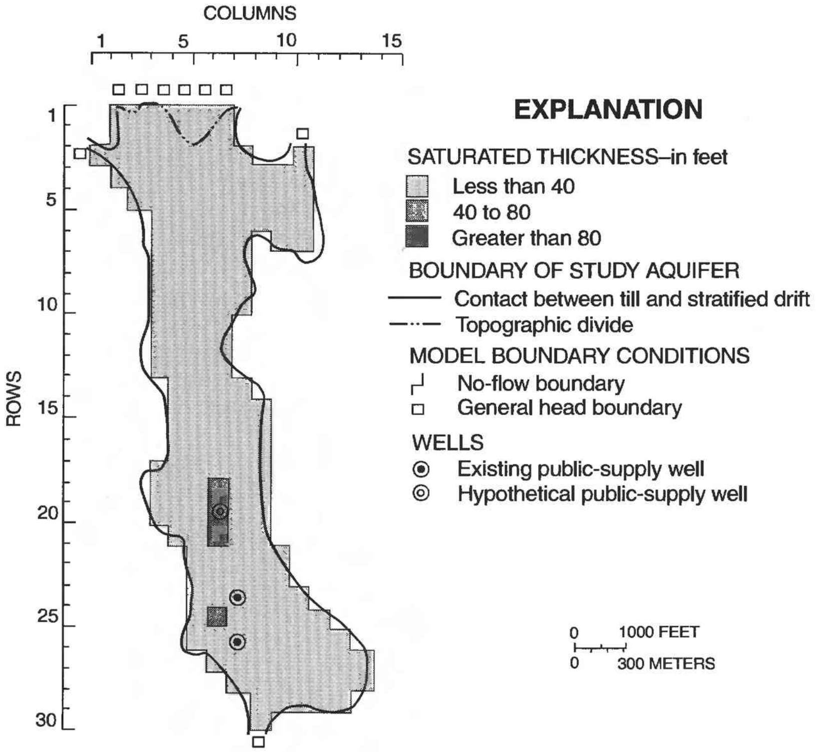
Appendix C. Ground-water-quality data—*Continued*

Station No.	Date	Alkalinity, field (mg/L as $CaCO_3$)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Solids, residue at 180°C (mg/L)	Solids, sum of constituents, dissolved (mg/L)
420142071284601	7-26-85	17	12	8.5	<0.10	10	68	65
420203071301601	8-06-85	17	14	9.0	<.10	9.3	65	65
420316071275801	7-26-85	21	13	11	<.10	12	73	73
420439071362801	8-06-85	12	25	10	<.10	10	88	148
420703071411301	7-24-85	18	20	6.9	<.10	6.7	71	69
420912071391201	11-12-85	15	--	--	--	--	--	--
	11-20-85	15	--	--	--	--	--	--
	1-16-86	15	42	14	.10	9.9	114	123
	2-13-86	18	45	14	.10	9.4	127	124
	3-06-86	14	51	16	.10	9.5	129	137
	4-17-86	16	44	14	.10	9.1	121	122
	6-18-86	19	40	17	.10	9.8	118	123
	7-25-86	19	48	16	.10	9.9	140	136
	8-19-86	--	45	16	.29	11	64	132
420918071363104	8-08-85	11	15	8.3	<.10	12	58	63
421007071374301	8-08-85	11	14	12	<.10	12	61	68
421145071461401	4-24-86	69	--	--	--	--	--	--
421146071503501	7-23-85	57	200	27	<.10	11	551	445
421147071461201	4-25-86	40	--	--	--	--	--	--
421147071461202	12-11-86	53	82	33	.20	9.6	243	238
421147071461203	12-11-86	54	14	14	.20	17	106	123
421147071461204	12-11-86	28	--	--	--	--	--	--
421149071461901	4-22-86	60	78	17	.10	10	208	220
421150071461806	12-10-86	50	69	34	.20	9.9	211	228
421150071461807	12-10-86	46	71	33	.10	10	186	217
421150071461901	7-23-85	92	91	20	.20	9.8	320	308
	10-18-85	47	--	--	--	--	--	--
	11-19-85	90	66	21	.20	10	260	230
	1-16-86	45	76	17	.20	9.6	198	204
	2-13-86	52	86	17	.20	11	222	237
	3-07-86	51	94	17	.20	10	233	246
	4-18-86	50	97	17	.20	10	236	245
	6-18-86	51	72	26	.20	10	203	223
	7-25-86	50	71	23	.20	10	203	215
	8-20-86	42	66	28	.31	11	168	213
	11-19-86	90	--	--	--	--	--	--
421150071462002	4-22-86	84	83	30	.30	7.6	246	263
421150071462004	12-10-86	70	70	26	.30	7.1	232	232
421152071461702	12-09-86	10	56	24	<.10	12	162	159
421152071461703	12-09-86	15	64	25	<.10	12	176	174
421152071461704	12-09-86	22	39	19	<.10	14	138	141
421154071461701	4-24-86	15	--	--	--	--	--	--
421154071462401	1-16-86	63	81	17	.10	11	204	235
	4-22-86	64	110	20	.20	10	283	286
421158071462401	4-28-86	16	--	--	--	--	--	--
421257071495301	7-23-85	64	54	17	<.10	17	205	196
421321071451501	7-24-85	20	150	21	.10	10	366	327
421556071435301	8-08-85	19	27	12	<.10	11	98	94
421734071451001	8-07-85	36	38	20	<.10	9.9	137	141
421759071451601	8-07-85	53	64	25	<.10	12	242	205
421817071451001	8-07-85	21	25	60	.50	15	173	165

Appendix C. Ground-water-quality data—*Continued*

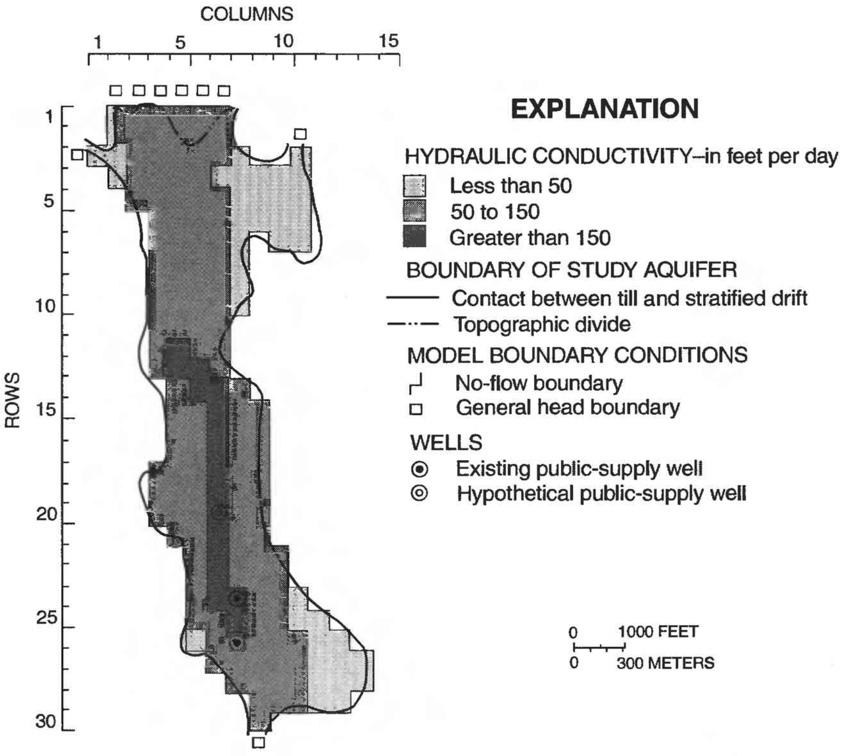
Station No.	Date	Nitrogen, nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)
420142071284601	7-26-85	--	<0.010	0.03	0.17	0.20	<20	<10	60
420203071301601	8-06-85	--	<.010	.03	.37	.40	<20	20	230
420316071275801	7-26-85	.610	.020	<.010	--	.30	<20	<10	<10
420439071362801	8-06-85	--	<.010	.020	.28	.30	<20	60	280
420703071411301	7-24-85	--	<.010	.040	.16	.20	<20	400	170
420912071391201	11-12-85	--	--	--	--	--	--	20	--
	11-20-85	--	<.010	.240	.36	60	--	--	--
	1-16-86	1.29	.010	.200	.50	.70	130	30	140
	2-13-86	--	<.010	.180	.12	.30	80	40	140
	3-06-86	--	<.010	.150	.25	.40	0	30	110
	4-17-86	--	<.010	.130	.27	.40	50	36	81
	6-18-86	--	<.010	.120	.18	.30	50	50	100
	7-25-86	--	<.010	.190	.21	.40	60	--	--
	8-19-86	--	<.010	.170	.23	.40	<10	32	120
420918071363104	8-08-85	--	<.010	<.010	--	.20	<20	<10	10
421007071374301	8-08-85	--	<.010	<.010	--	.10	<20	32	120
421145071461401	4-24-86	--	--	--	--	--	120	350	230
421146071503501	7-23-85	1.98	.020	.030	.17	.20	50	<10	20
421147071461201	4-25-86	--	--	--	--	--	80	120	420
421147071461202	12-11-86	.190	.020	2.50	.60	3.1	210	10	20
421147071461203	12-11-86	1.30	.100	1.00	.40	1.4	80	80	1100
421147071461204	12-11-86	--	--	--	--	--	--	--	--
421149071461901	4-22-86	--	<.010	3.30	.0	3.2	130	50	670
421150071461806	12-10-86	.500	.010	3.40	.0	3.2	190	3,500	850
421150071461807	12-10-86	--	<.010	3.50	.10	3.6	160	10	20
421150071461901	7-23-85	--	<.010	2.60	.50	3.1	180	<10	620
	10-18-85	--	--	--	--	--	--	120	550
	11-19-85	.480	.050	2.10	.60	2.7	140	10	--
	1-16-86	--	--	--	--	--	200	80	590
	2-13-86	--	<.010	2.70	.20	2.9	140	50	540
	3-07-86	--	<.010	2.60	.10	2.7	0	50	630
	4-18-86	--	<.010	2.40	.0	2.3	110	27	580
	6-18-86	--	<.010	2.20	.0	2.2	120	30	410
	7-25-86	--	<.010	2.30	2.0	2.50	130	30	420
	8-20-86	--	<.010	2.30	.0	2.2	<10	11	460
	11-19-86	--	--	--	--	--	--	--	--
421150071462002	4-22-86	--	<.010	4.20	.10	4.3	190	1,900	440
421150071462004	12-10-86	--	<.010	3.00	.20	3.2	150	310	1300
421152071461702	12-09-86	--	<.010	<.010	--	.30	70	2,300	350
421152071461703	12-09-86	--	<.010	<.010	--	.30	120	1,900	270
421152071461704	12-09-86	--	<.010	<.010	--	.60	50	100	30
421154071461701	4-24-86	--	--	--	--	--	30	120	20
421154071462401	1-16-86	1.09	.010	2.20	.20	2.4	230	60	550
	4-22-86	--	<.010	2.40	.10	2.5	90	20	920
421158071462401	4-28-86	--	--	--	--	--	40	50	330
421257071495301	7-23-85	.310	.020	.090	.21	.30	30	800	320
421321071451501	7-24-85	2.87	.430	.050	.25	.30	50	10	130
421556071435301	8-08-85	--	<.010	<.010	--	.30	<20	40	70
421734071451001	8-07-85	--	<.010	<.010	--	.50	<20	10	10
421759071451601	8-07-85	--	<.010	.010	.29	.30	20	<10	330
421817071451001	8-07-85	--	<.010	<.010	--	.30	20	530	--

APPENDIX D



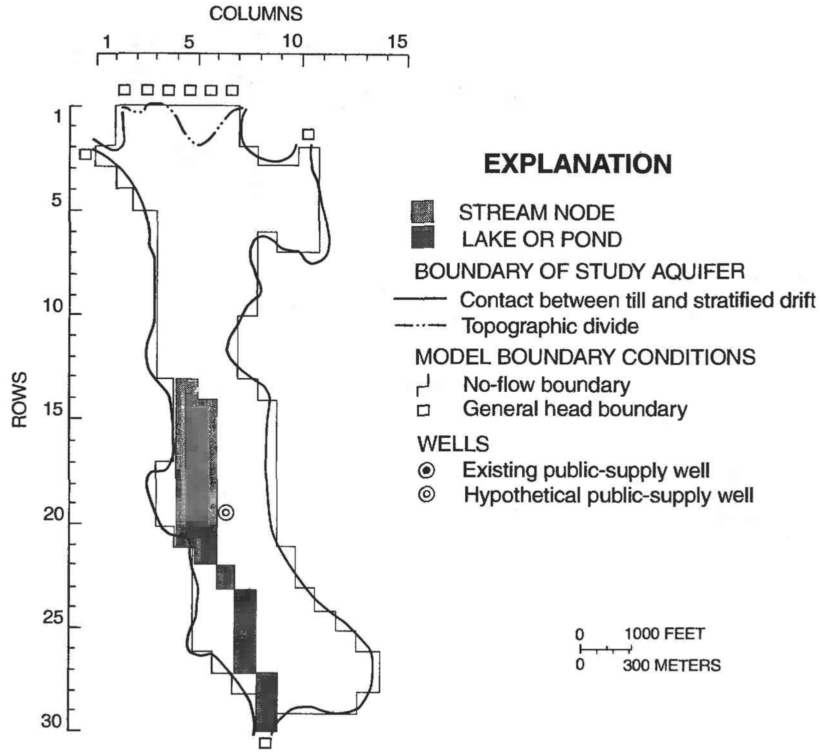
SATURATED THICKNESS FOR MODEL OF THE UPPER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.



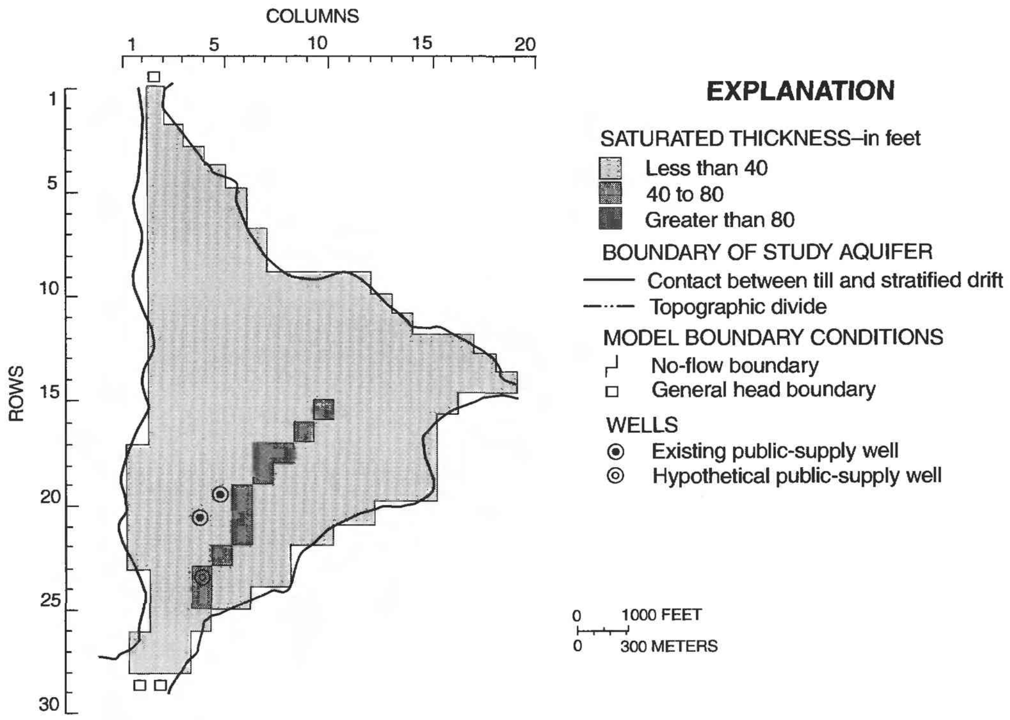
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE UPPER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



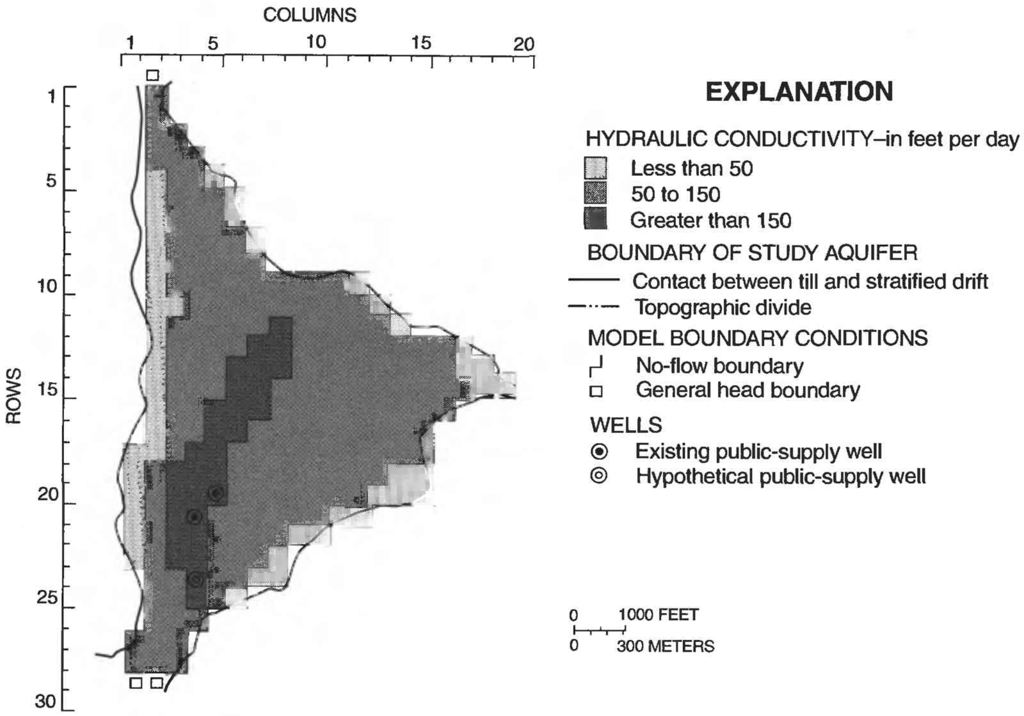
STREAM NODES FOR MODEL OF THE UPPER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



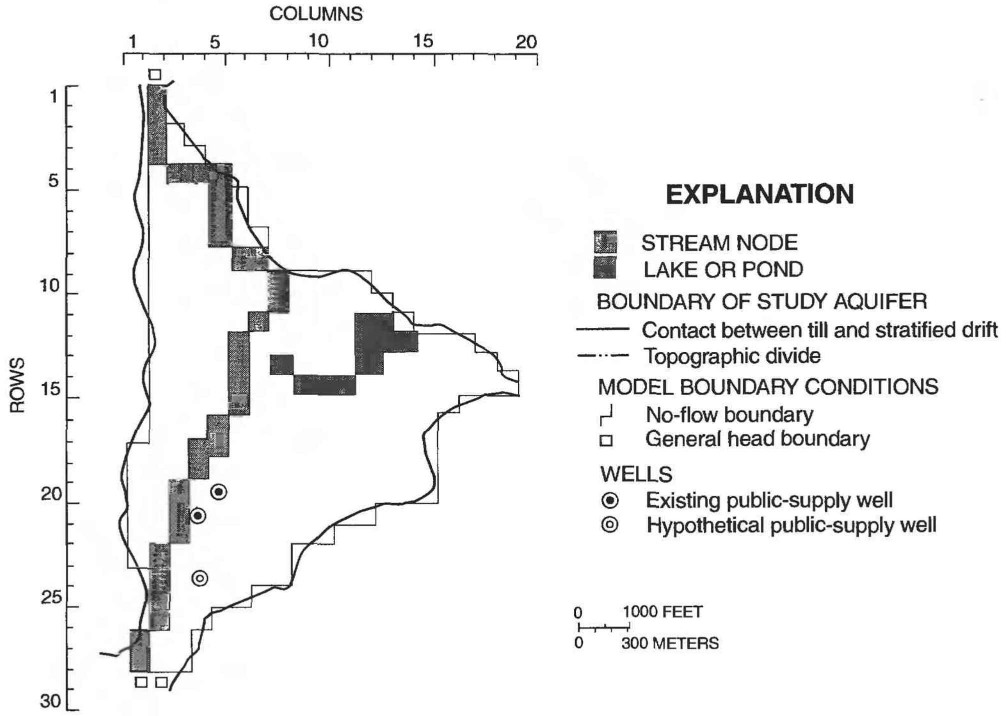
SATURATED THICKNESS FOR MODEL OF THE LOWER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



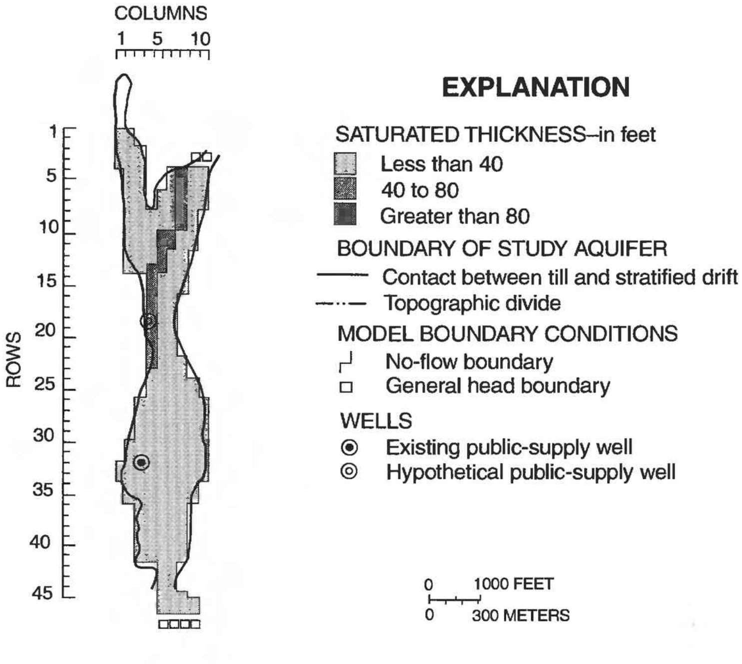
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE LOWER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



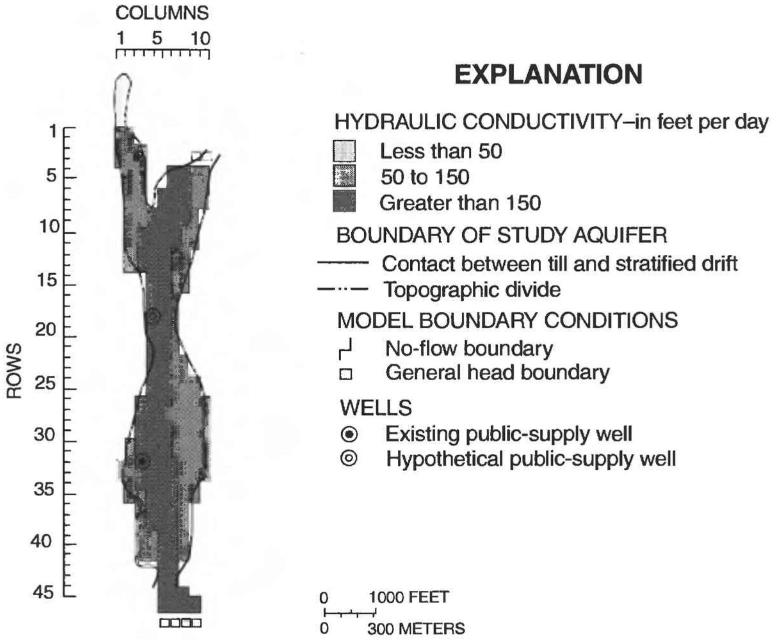
STREAM NODES FOR MODEL OF THE LOWER PETERS RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



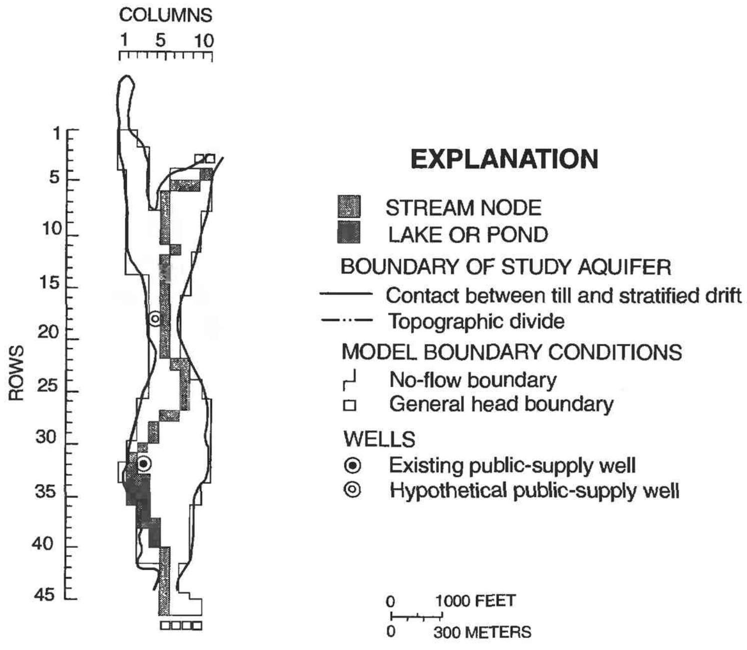
SATURATED THICKNESS FOR MODEL OF THE UPPER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



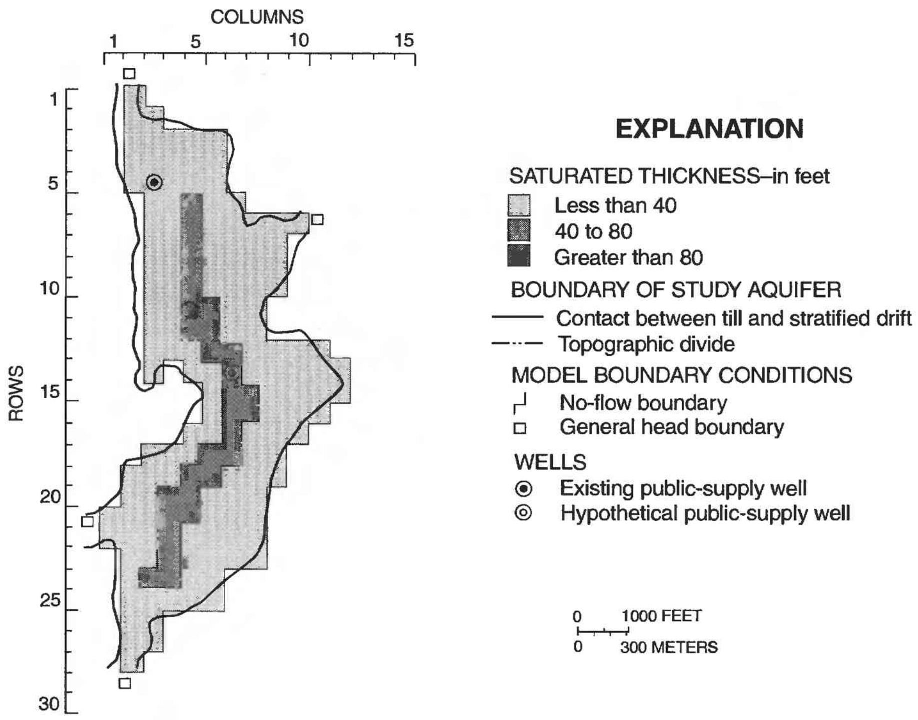
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE UPPER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



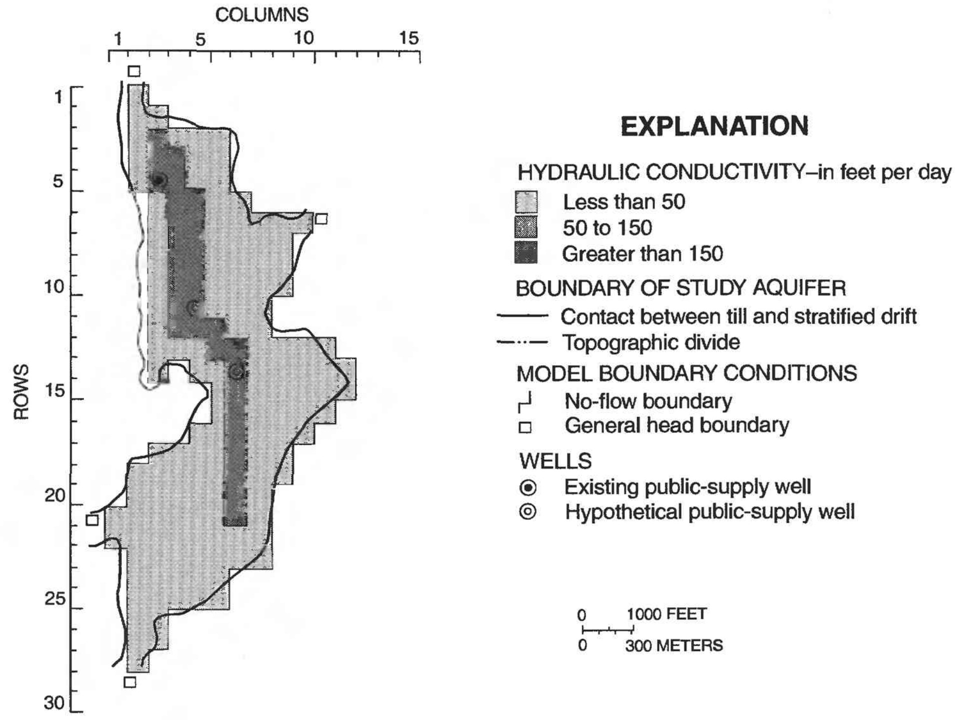
STREAM NODES FOR MODEL OF THE UPPER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



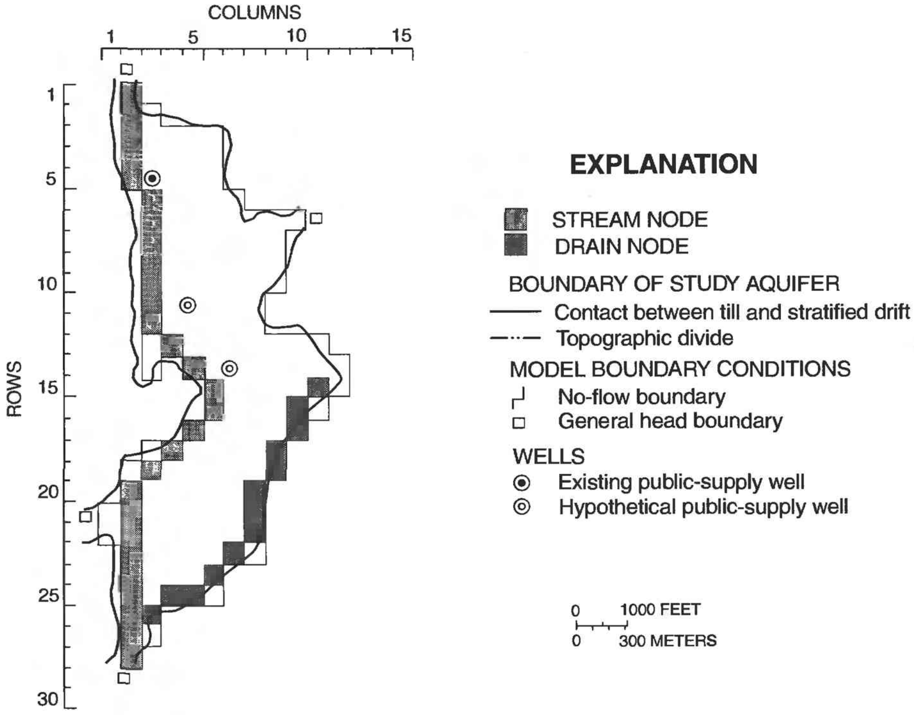
SATURATED THICKNESS FOR MODEL OF THE MIDDLE MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



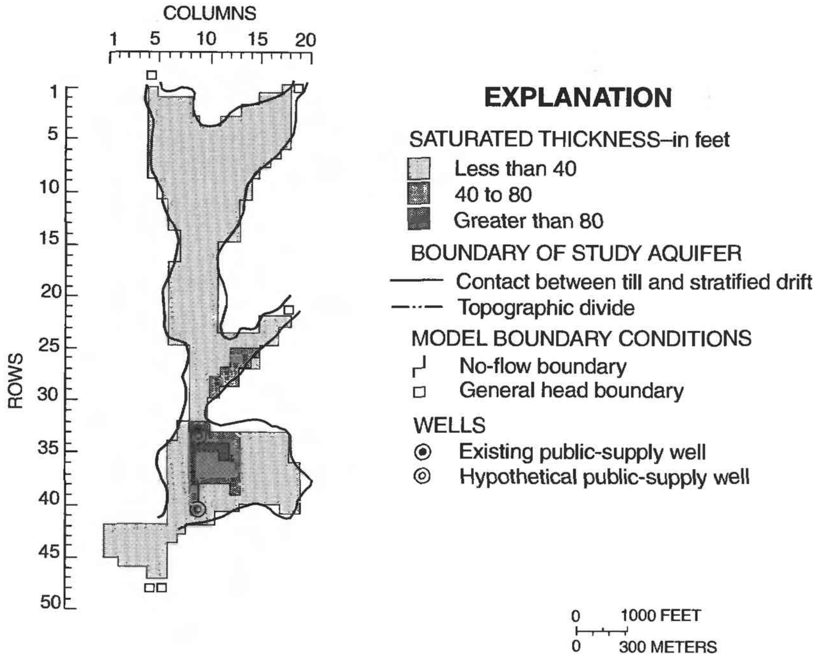
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE MIDDLE MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



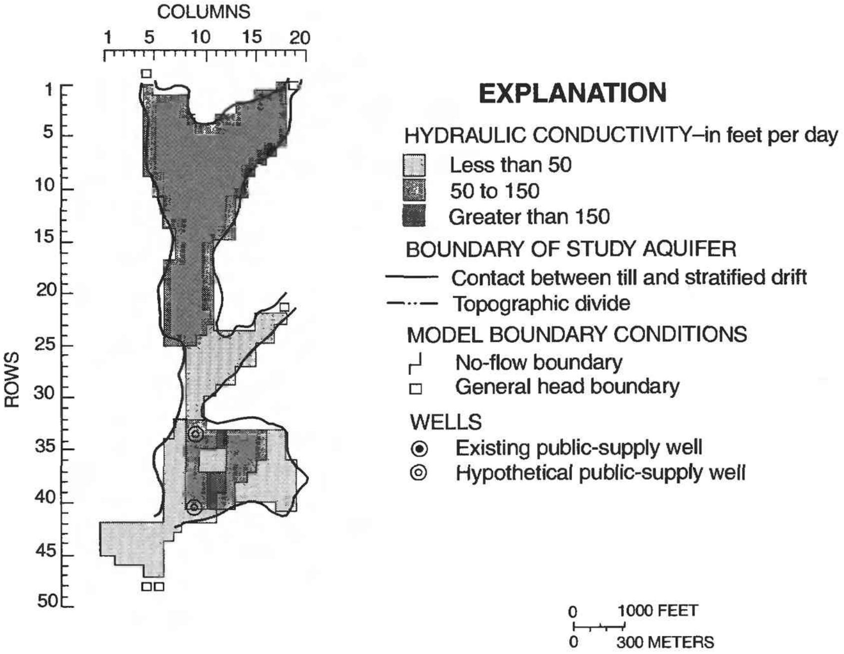
STREAM NODES FOR MODEL OF THE MIDDLE MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



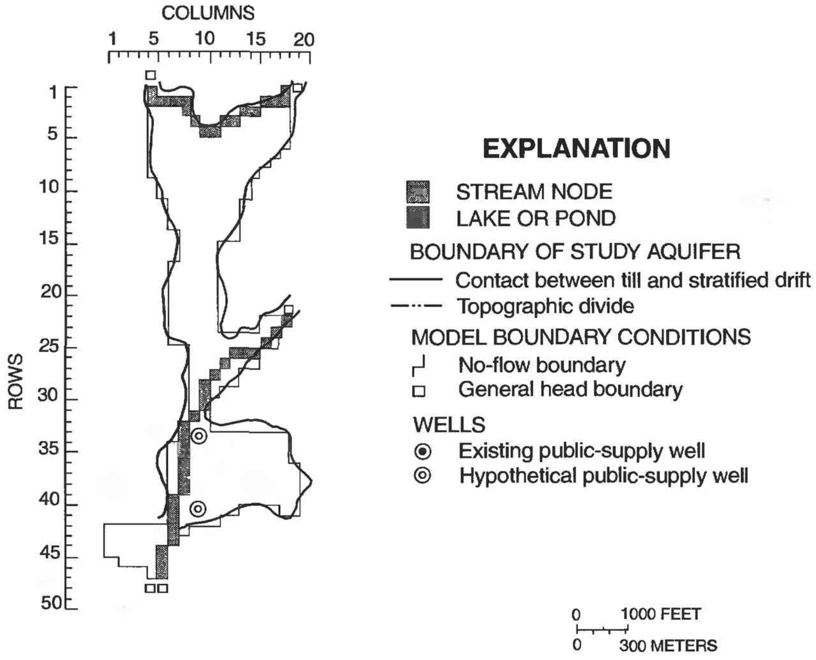
SATURATED THICKNESS FOR MODEL OF THE LOWER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



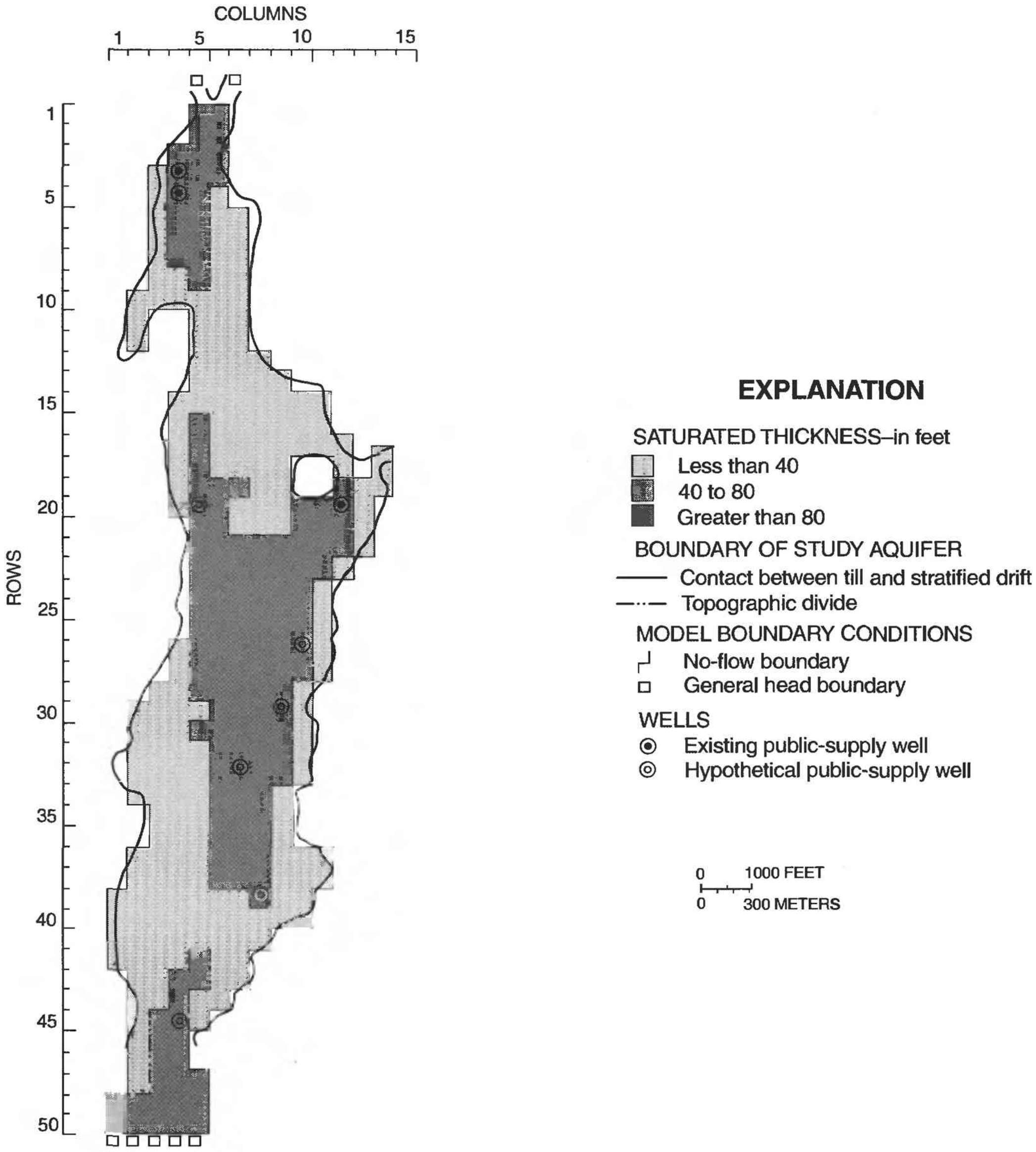
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE LOWER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



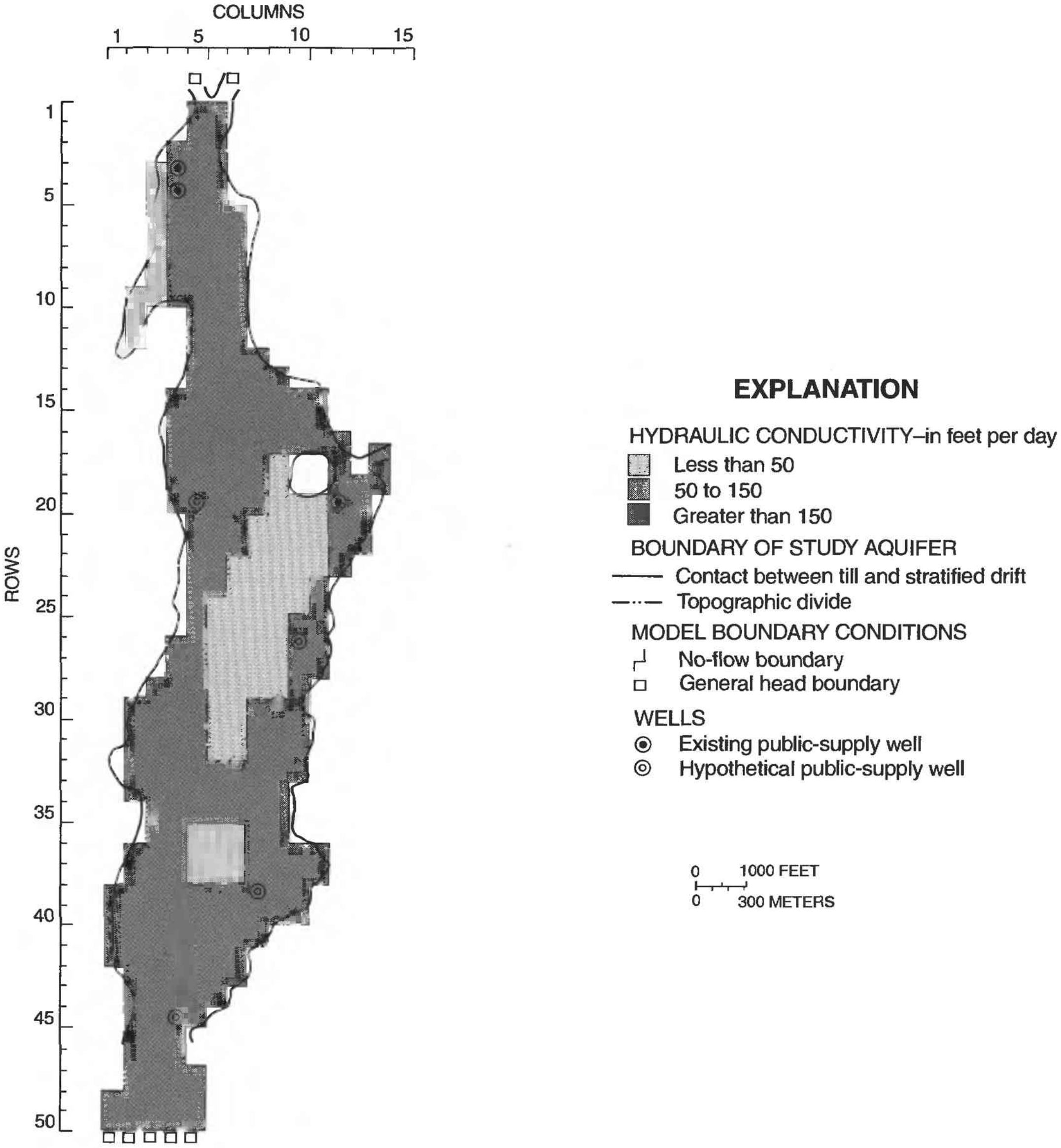
STREAM NODES FOR MODEL OF THE LOWER MILL RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



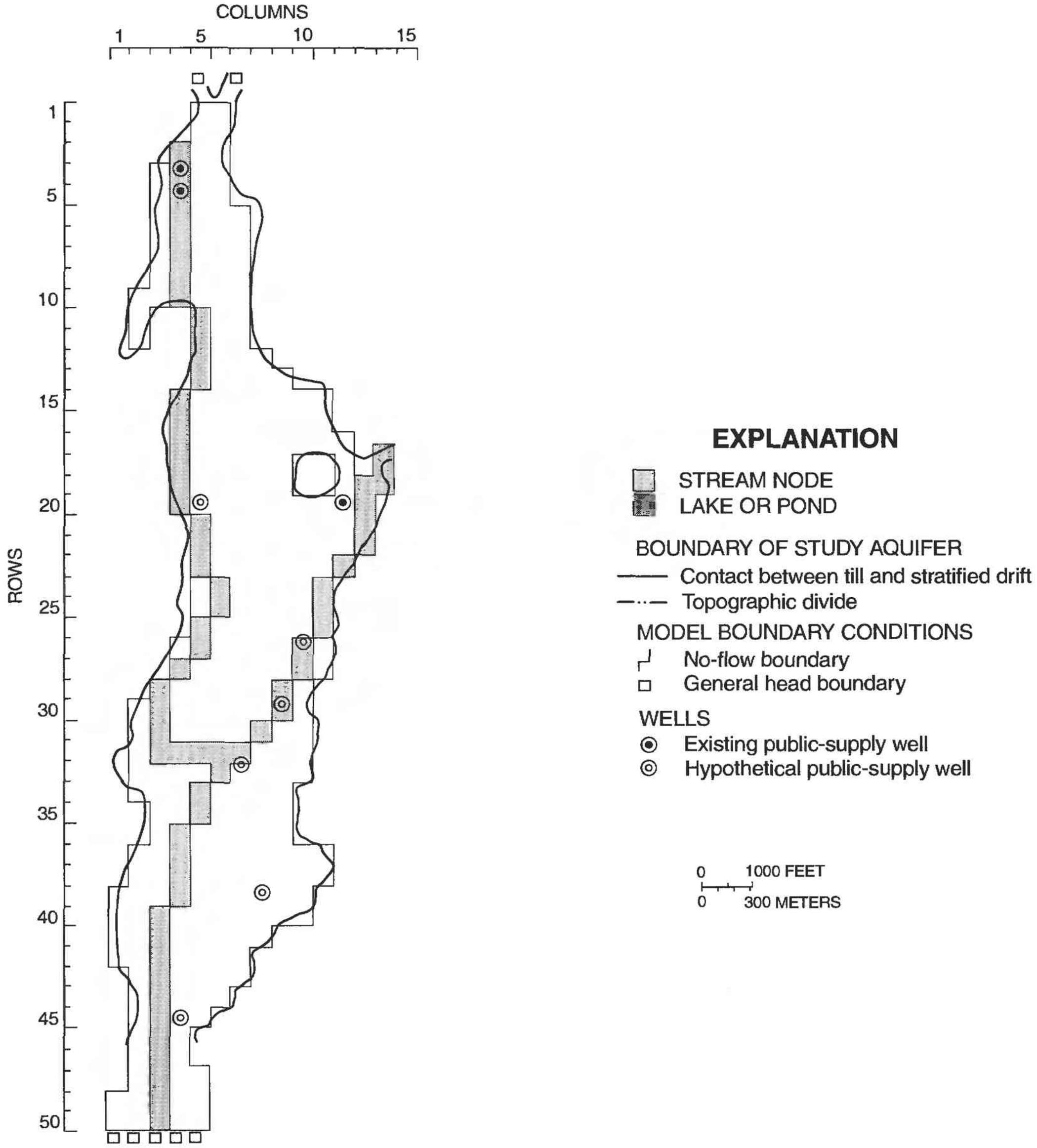
SATURATED THICKNESS FOR MODEL OF THE UPPER WEST RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



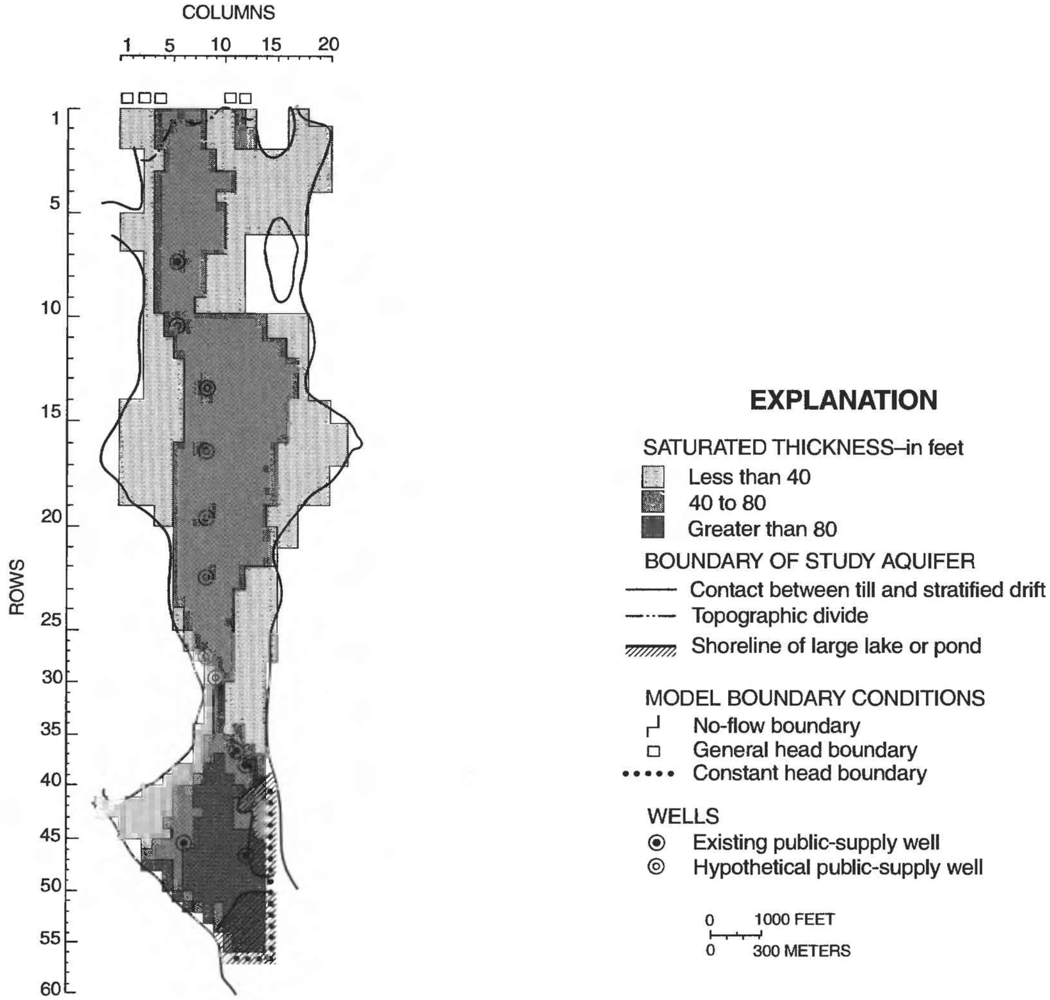
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE UPPER WEST RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



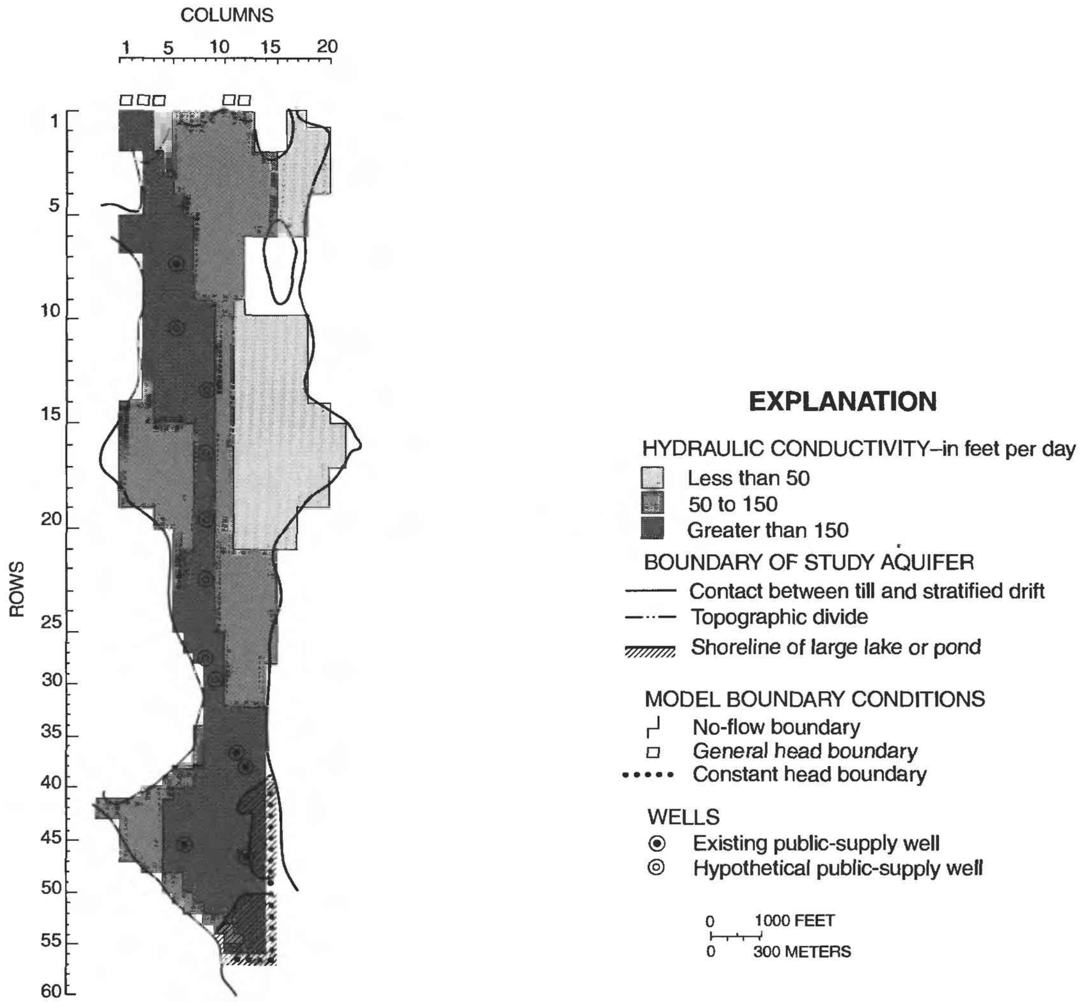
STREAM NODES FOR MODEL OF THE UPPER WEST RIVER AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



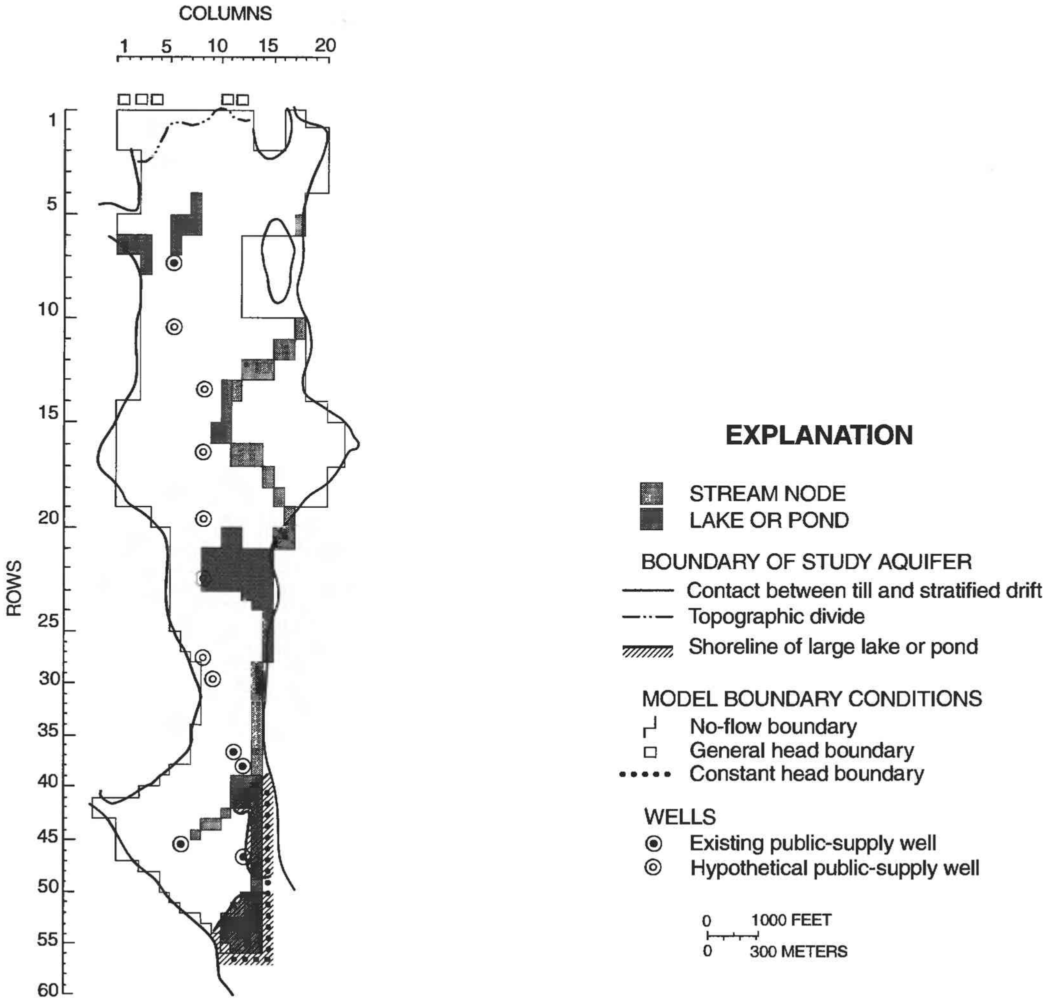
SATURATED THICKNESS FOR MODEL OF THE UPPER LAKE QUINSIGAMOND AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



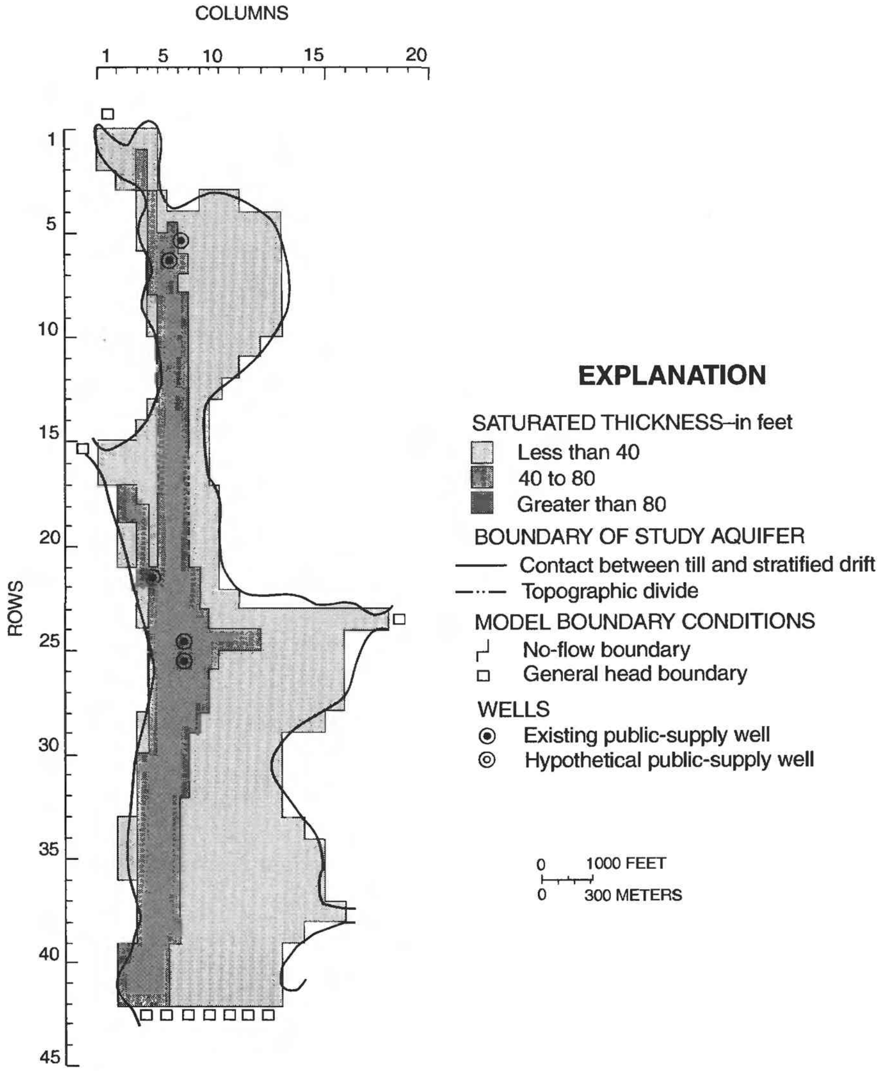
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE UPPER LAKE QUINSIGAMOND AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



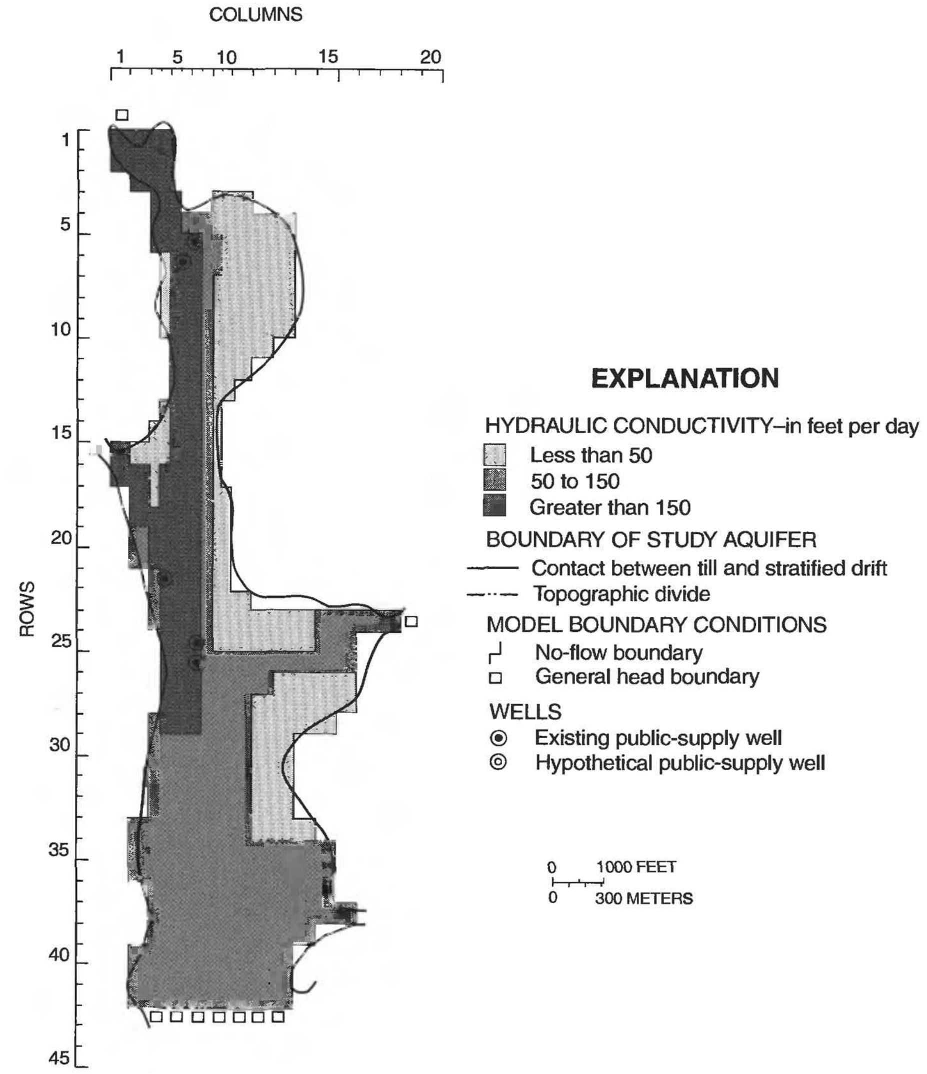
STREAM NODES FOR MODEL OF THE UPPER LAKE QUINSIGAMOND AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



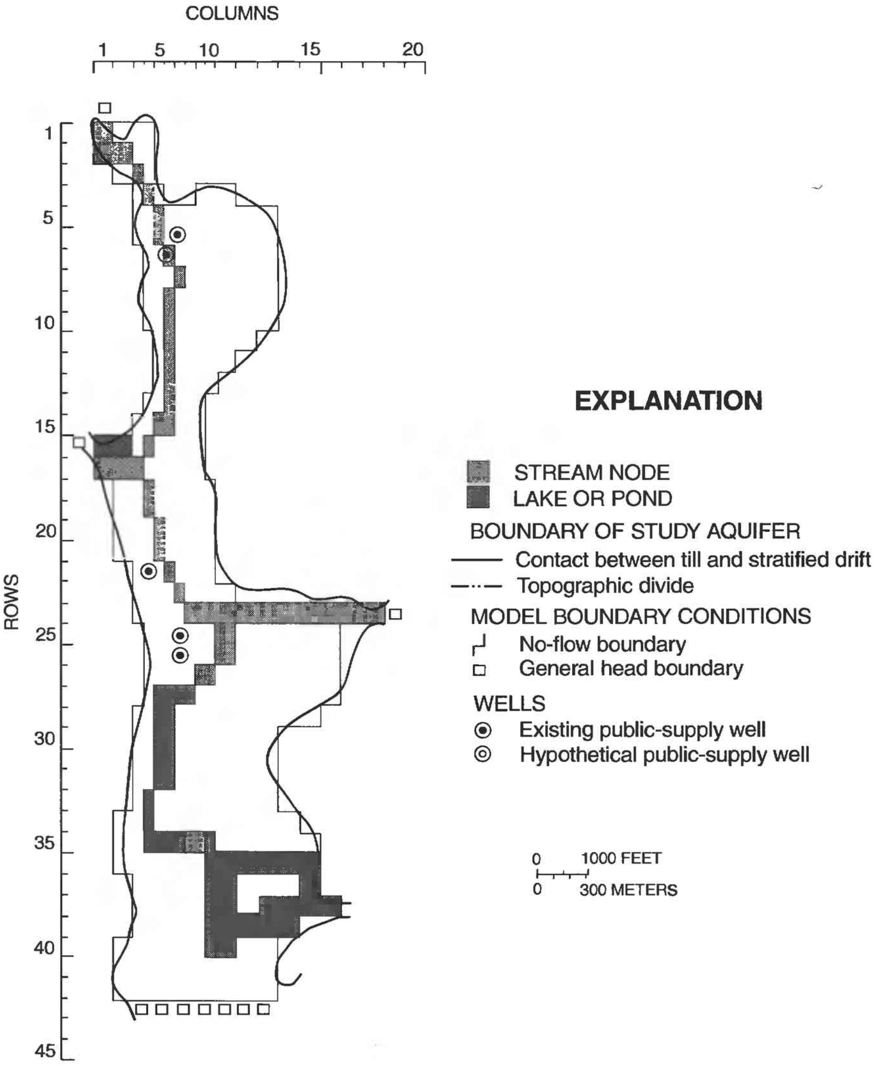
SATURATED THICKNESS FOR MODEL OF THE AUBURN AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



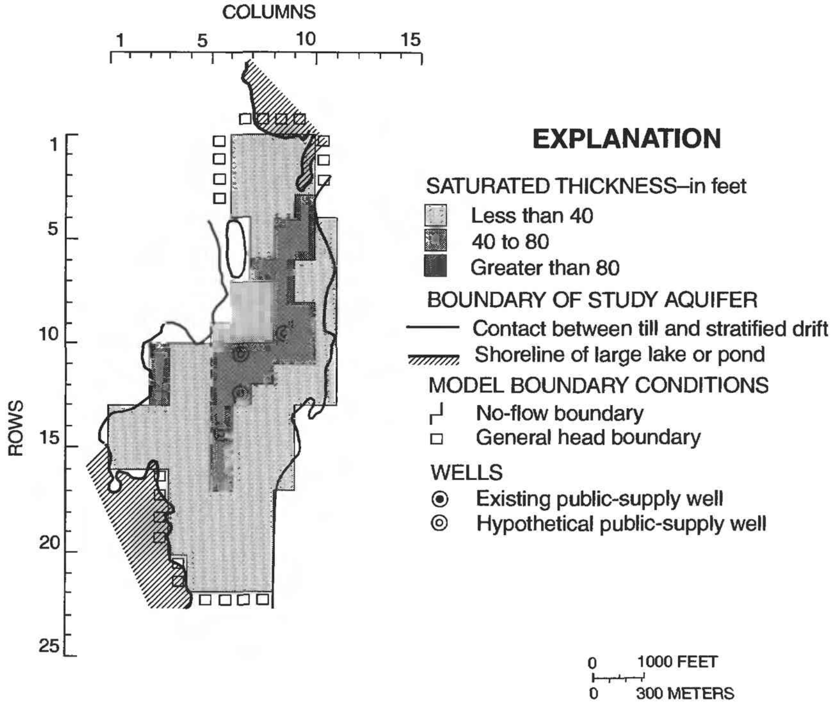
HYDRAULIC CONDUCTIVITY FOR MODEL OF THE AUBURN AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



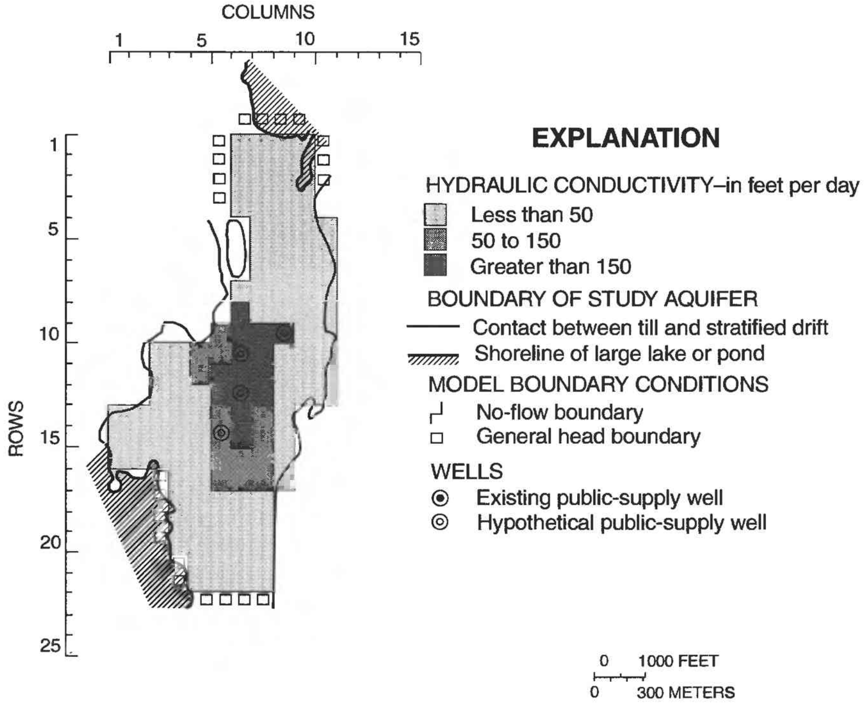
STREAM NODES FOR MODEL OF THE AUBURN AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



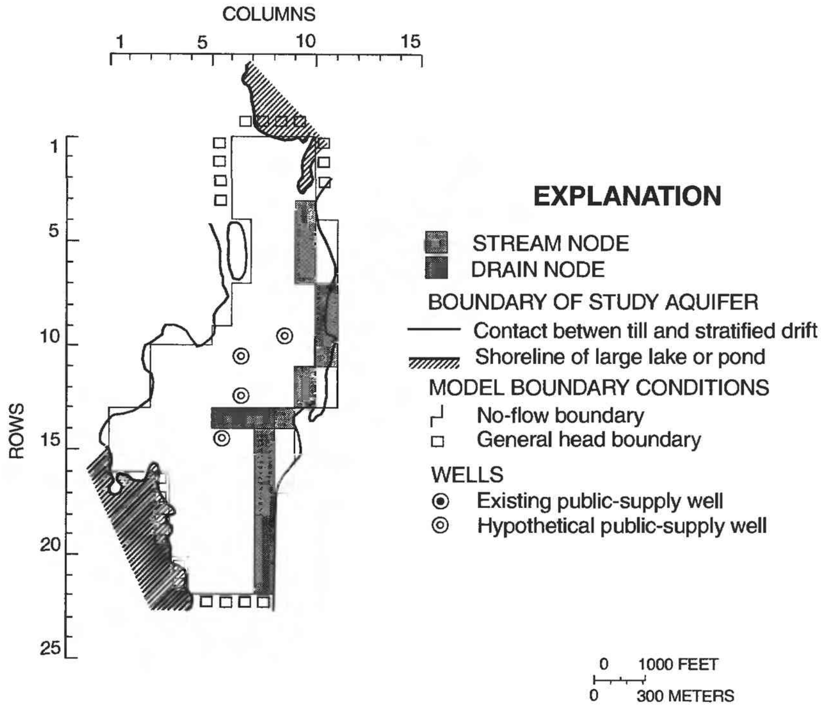
SATURATED THICKNESS FOR MODEL OF THE STONE BROOK AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



HYDRAULIC CONDUCTIVITY FOR MODEL OF THE STONE BROOK AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*



STREAM NODES FOR MODEL OF THE STONE BROOK AQUIFER

Appendix D. Saturated thickness, hydraulic conductivity, and stream nodes for nine study aquifers, Blackstone River, Mass.—*Continued.*

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