Simulation of the Effects of Water Withdrawals, Wastewater-Return Flows, and Land-Use Change on Streamflow in the Blackstone River Basin, Massachusetts and Rhode Island

By Jeffrey R. Barbaro

Prepared in cooperation with the Rhode Island Water Resources Board

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per day (gal/d)	3.785	liter per day (L/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in./yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Flow rate in Mgal/d can be converted to ft^3/s as follows:
Mgal/d=1.547 ft^3/s

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms and Abbreviations

CSO	Combined sewer overflow
DEEPFR	HSPF model parameter for fraction of ground water that enters a deep flow system
DSN	Data Set Number associated with the Watershed Data Management database
ET	Evapotranspiration
FTABLE	Function table that defines the relation between depth, storage and discharge of water in a reach
HRU	Hydrologic response unit
HSPF	Hydrologic Simulation Program—FORTRAN
IMPLND	HSPF impervious-area land element
KORH	Climatological station at Worcester Regional Airport, Worcester, MA
KPVD	Climatological station at T.F. Green Regional Airport, Warwick, RI
LULC	Land Use Land Cover
PERLND	HSPF pervious-area land element
PET	Potential Evapotranspiration
RCHRES	HSPF steam or reservoir reach
RIWRB	Rhode Island Water Resources Board
STRMDEPL	Analytical program to compute streamflow depletion from a pumped well
TAC	Technical advisory committee
UBWPAD	Upper Blackstone Water Pollution Abatement District
UBWWTF	Upper Blackstone wastewater-treatment facility
UCI	HSPF user control input file
USGS	U.S. Geological Survey
WDM	Watershed Data Management database
WWTP	Wastewater-treatment plant

Simulation of the Effects of Water Withdrawals, Wastewater-Return Flows, and Land-Use Change on Streamflow in the Blackstone River Basin, Massachusetts and Rhode Island

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Abstract

Streamflow in many parts of the Blackstone River Basin in south-central Massachusetts and northern Rhode Island is altered by water-supply withdrawals, wastewater-return flows, and land-use change associated with a growing population. Simulations from a previously developed and calibrated Hydrological Simulation Program—FORTRAN (HSPF) precipitation-runoff model for the basin were used to evaluate the effects of water withdrawals, wastewater-return flows, and land-use change on streamflow. Most of the simulations were done for recent (1996–2001) conditions and potential buildout conditions in the future when all available land is developed to provide a long-range assessment of the effects of possible future human activities on water resources in the basin.

The effects of land-use change were evaluated by comparing the results of long-term (1960–2004) simulations with (1) undeveloped land use, (2) 1995–1999 land use, and (3) potential buildout land use at selected sites across the basin. Flow-duration curves for these land-use scenarios were similar, indicating that land-use change, as represented in the HSPF model, had little effect on flow in the major tributary streams and rivers in the basin. However, land-use change—particularly increased effective impervious area—could potentially have greater effects on the hydrology, water quality, and aquatic habitat of the smaller streams in the basin.

The effects of water withdrawals and wastewater-return flows were evaluated by comparing the results of long-term simulations with (1) no withdrawals and return flows, (2) actual (measured) 1996–2001withdrawals and wastewater-return flows, and (3) potential withdrawals and wastewater-return flows at buildout. Overall, the results indicated that water use had a much larger effect on streamflow than did land use, and that the location and magnitude of wastewater-return flows were important for lessening the effects of withdrawals on streamflow in the Blackstone River Basin. Ratios of long-term (1960–2004) simulated flows with 1996–2001 water use (representing the net effect of withdrawals and wastewater-return flows) to long-term simulated flows with no water use indicated that, for many reaches, 1996–2001 water use did not deplete flows at the 90-percent flow duration substantially compared to flows unaffected by water use. Flows generally were more severely depleted in the reaches that include surface-water supplies for the larger cities in the basin (Kettle and Tatnuck Brooks, Worcester, Mass. water supply; Quinsigamond River, Shrewsbury, Mass. water supply; Crookfall Brook, Woonsocket, R.I. water supply; and Abbott Run, Pawtucket, R.I. water supply). These reaches did not have substantial wastewater-return flows that could offset the effects of the withdrawals. In contrast, wastewater-return flows from the Upper Blackstone Wastewater Treatment Facility in Millbury, Mass. increased flows at the 90-percent flow duration in the main stem of the Blackstone River compared to no-water-use conditions. Under the assumptions used to develop the buildout scenario, nearly all of the new water withdrawals were returned to the Blackstone River Basin at municipal wastewater-treatment plants or on-site septic systems. Consequently, buildout generally had small effects on simulated low flows in the Blackstone River and most of the major tributary streams compared to flows with 1996–2001 water use.

To evaluate the effects of water use on flows in the rivers and major tributary streams in the Rhode Island part of the basin in greater detail, the magnitudes of water withdrawals and wastewater-return flows in relation to simulated streamflow were calculated as unique ratios for individual HSPF subbasins, total contributing areas to HSPF subbasins, and total contributing areas to the major tributary streams. For recent conditions (1996–2001 withdrawals and 1995–1999 land use), ratios of average summer (June through September) withdrawals

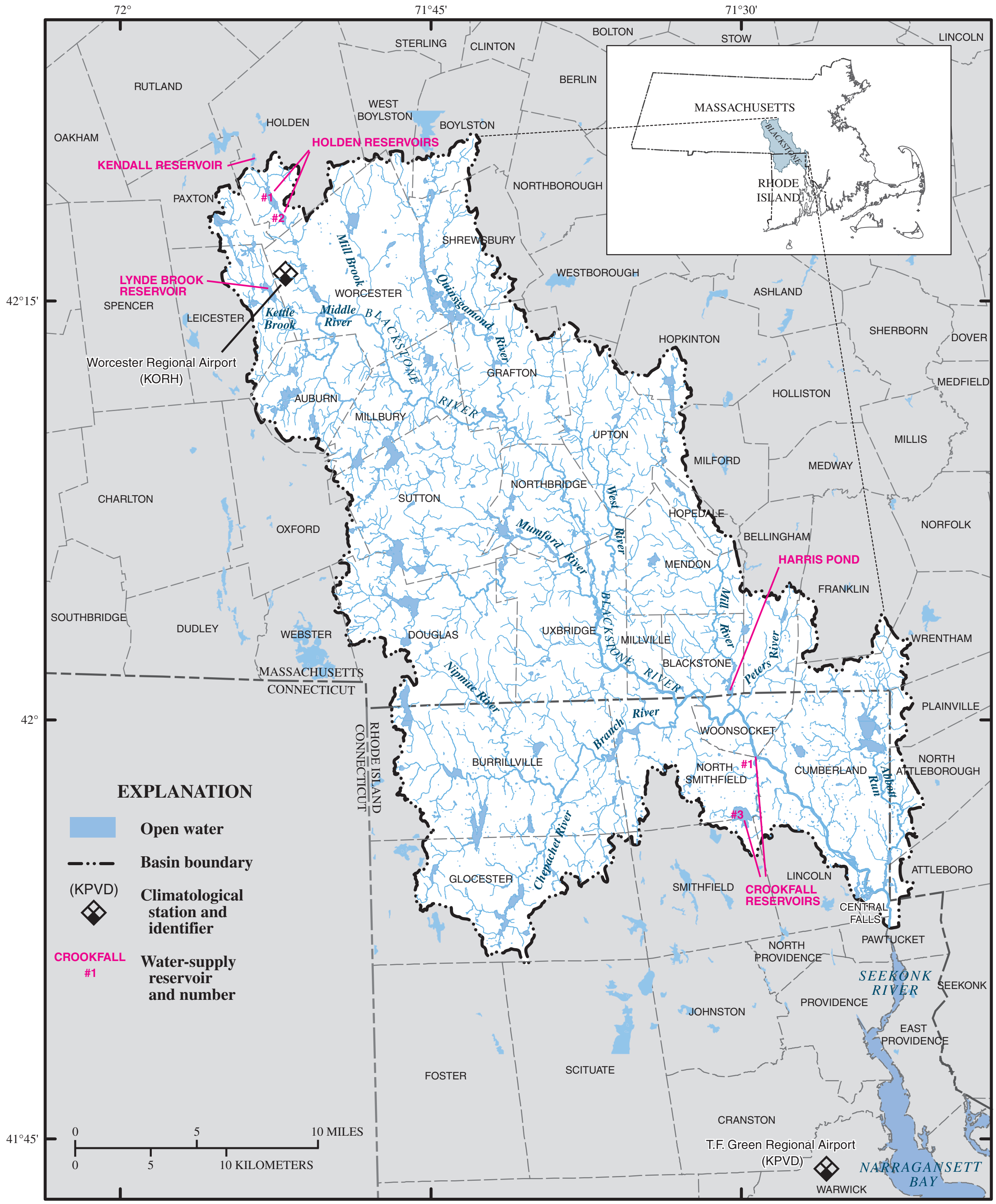
to the long-term (1960–2004) medians of average summer streamflow simulated in the absence of water use ranged from 0.039 to 2.5 with a median value of 0.11 for total contributing areas to HSPF subbasins. The largest ratios of withdrawal rates to streamflow were for Crookfall Brook and Abbott Run, the subbasins with major withdrawals for municipal water supply. The smallest ratios were for the rural subbasins in the Branch River drainage area in the southwestern part of the basin. For recent conditions, ratios of average summer wastewater-return flows to average summer streamflows ranged from 0.0 to 0.20 with a median value of 0.029 for total contributing areas to HSPF subbasins. The largest ratios of wastewater-return flows to streamflows were for the subbasins that contained return flows from municipal wastewater-treatment plants and the subbasins along the Blackstone River because of high wastewater-return-flow rates from upstream facilities. Under the assumptions used to develop the buildout analysis, withdrawal and return-flow ratios were estimated to increase for most of the HSPF subbasins in the Rhode Island part of the basin. Ratios more than doubled for some subbasins, but the large increases mainly were for subbasins that had low ratios in 1996–2001.

The HSPF model also was used to estimate the effects of water-conservation measures on low flows in rivers and major tributary streams in the Rhode Island part of the basin, the contribution of wastewater-return flows to streamflow in the Blackstone River, and the effects of changes to two local water supplies in Rhode Island. Water-conservation measures were evaluated by reducing 1996–2001 withdrawals by 20 percent. Simulations with 20-percent reductions in withdrawal rates indicated that conservation measures would result in appreciable increases in low flows in the subbasins with the highest withdrawal rates in the Rhode Island part of the Blackstone River Basin, whereas the effects on streamflow would be much less pronounced in subbasins with lower withdrawal rates. The contribution of wastewater-return flows to streamflow in the Blackstone River was evaluated by comparing simulated flows with and without municipal wastewater-return flows. Under typical summer low-flow conditions, treated wastewater was a major component of streamflow (35 to 50 percent) in the Blackstone River, and the percentage of treated wastewater was larger during the driest periods. The simulations conducted to evaluate changes to local water supplies (effects of potential withdrawals from an inactive well adjacent to Slatersville Reservoir in North Smithfield on flows in the Branch River, and the effects of connecting the town of North Smithfield to the water-supply system for the city of Woonsocket, Rhode Island) indicated that each of these activities would alter low flows only slightly in the associated stream reaches.

Introduction

The Blackstone River Basin encompasses an area of 474.5 square miles (mi^2) in south-central Massachusetts and northern Rhode Island (fig. 1). The basin is densely populated and has a long history of streamflow alteration for industrial development, flood control, and water supply. Although most of the industrial activity that relied upon hydropower has ceased, current (2006) water-supply withdrawals and wastewater-return flows associated with a growing population continue to alter streamflow in many parts of the basin. Withdrawals deplete streamflow and potentially have an adverse effect on aquatic habitat, water quality, and the scenic and recreational value of the streams and rivers in the basin. Wastewater-return flows lessen the effects of withdrawals on streamflow depletion, but may degrade water quality by adding nutrients and other detrimental constituents. Managing the water resources of the basin to provide sustainable water supplies while maintaining flows adequate for aquatic habitat and other uses is of increasing concern to government agencies, environmental organizations, and citizens groups. The need for water-resources management has been intensified by rapid population growth and land-use change in the basin. The population in 36 of the 39 towns in the basin increased between 1990 and 2000, and the population in four towns in the Massachusetts part of the basin grew more than 30 percent (U.S. Census Bureau, 2005). The average population growth for all of the towns in the basin was 7.7 percent over this period.

To address the need for water-resources management in the basin, the U.S. Geological Survey (USGS), in cooperation with the Rhode Island Water Resources Board (RIWRB), developed a Hydrological Simulation Program–FORTRAN (HSPF) precipitation-runoff model (Bicknell and others, 2000) for the Blackstone River Basin. The RIWRB is the principal agency in the state of Rhode Island concerned with the management of water supplies and the fair and equitable allocation of state water resources. The development and calibration of the model is described in detail in Barbaro and Zarriello (2006). This report presents the results of simulations done with the calibrated model to estimate the effects of withdrawals, wastewater-return flows, and land-use change on streamflow and to evaluate selected water-resources-management issues in the Rhode Island part of the basin. Most of the simulations were based on recent (1996–2001) and potential future buildout conditions (Blackstone River Valley National Heritage Corridor Commission, 2001) to provide a long-range assessment of the effects of possible future human activities on water resources in the basin.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 1. The Blackstone River Basin, towns and climatological stations used to simulate streamflow, Massachusetts and Rhode Island. From Barbaro and Zarriello (2006).

Purpose and Scope

This report describes the results of simulations done with the Blackstone River Basin HSPF model to evaluate the effects of water withdrawals, wastewater-return flows, and land-use change on streamflow in the entire basin. A second part of the report describes simulation results used to evaluate selected water-resources management issues in the Rhode Island part of the basin. The water-resources-management issues were identified by the USGS in consultation with a Technical Advisory Committee (TAC) formed for the project, and include (1) identification of the areas of the basin where withdrawals and wastewater-return flows have the greatest effect on streamflow, (2) assessment of the effects of water-conservation measures (reductions in water withdrawals) on streamflow, (3) evaluation of the contribution of wastewater-return flows to streamflow in the Blackstone River, and (4) assessment of the effects of new water-supply withdrawals on streamflow in the Branch River. A buildout analysis conducted by the Massachusetts Executive Office of Environmental Affairs, the Rhode Island Department of Environmental Management, and the Blackstone River Valley National Heritage Corridor Commission (Massachusetts Executive Office of Environmental Affairs, 2006) also was incorporated into the HSPF model to evaluate the effects of potential development on streamflow across the basin and is described in the report. This buildout assessment was done by comparing the results of simulations for recent conditions (1996–2001 water use and 1995–1999 land use) with the results of simulations incorporating potential water use and land use at buildout.

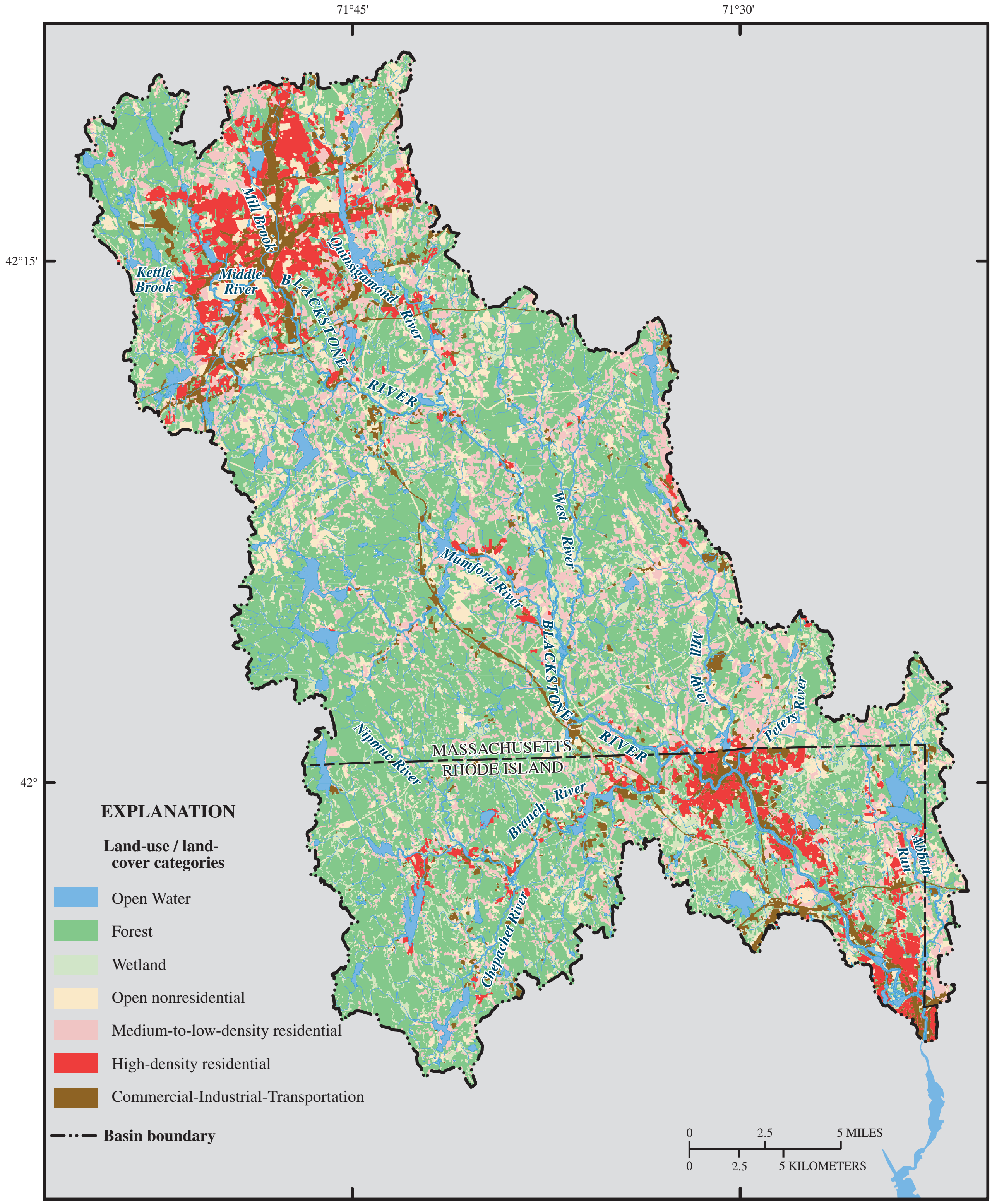
Description of the Basin

Approximately 71 percent (337 mi^2) of the Blackstone River Basin is in south-central Massachusetts and 29 percent (138 mi^2) is in northern Rhode Island (fig. 1). The major tributaries to the Blackstone River are the Quinsigamond River, Mumford River, and West River in the Massachusetts part of the basin, and the Branch River, Mill River, Peters River, and Abbott Run mainly in the Rhode Island part of the basin. For 1960–2004, precipitation averaged 46.4 inches per year (in/yr) in the northern part of the basin (data from the Worcester Regional Airport, Worcester, Mass., station KORH on fig. 1) and 44.7 in/yr in the southern part of the basin (data from T.F. Green Airport, Warwick, R.I., station KPVD on fig. 1). The average annual air temperature for 1960–2004 ranged from 47.0 ^{o}F in the northern part of the basin to 50.8 ^{o}F in the southern part of the basin. The regional slope of the basin is to the southeast, with altitudes ranging from about 1,390 ft above sea level in the hilly region north and west of Worcester to sea level where the Blackstone River enters Narragansett Bay at Pawtucket. The topography of the northern and western parts of the basin is rolling with steep, rocky hills. The southern part of the basin has less relief with large areas of flatter ground.

On the basis of 1995–1999 land-use and land-cover (LULC) data layers published by the States of Massachusetts and Rhode Island (Massachusetts Geographic Information System, 2003; Rhode Island Geographic Information System, 2003), the basin is predominantly forested (50.7 percent) (fig. 2). The next largest LULC category is residential (21.3 percent), of which 14.7 percent is medium- to low-density residential and 6.6 percent is high-density residential, followed by open, nonresidential (10.7 percent), forested and non-forested wetlands (7.7 percent), and commercial-industrial-transportation (5.8 percent). The remaining 3.8 percent of the basin is classified as open water. The northern and southeastern parts of the Blackstone River Basin have substantial urban development, and the eastern side of the basin, near the Route 495 corridor, is more developed and populated than the western side. The western part of the basin south of Worcester is relatively undeveloped, with about 70 percent of the land classified as forest.

Till and sand and gravel (glacial outwash) deposits cover most of the basin (Barbaro and Zarriello, 2006). Till, which covers about 71 percent of the basin, is present mainly in upland areas (fig. 3). Stream valleys are typically underlain by stratified, well-sorted sand and gravel deposits. These stratified glacial-outwash deposits, which cover the remaining 29 percent of the basin, form the major aquifers in the basin, with transmissivities up to 40,000 feet squared per day (ft^2/d) (Johnston and Dickerman, 1974a,b).

In 2000, approximately 467,000 residents lived in the Blackstone River Basin (U.S. Census Bureau, 2004a,b). Both surface water and ground water are used for water supply. Woonsocket, R.I. and Worcester, Mass. use surface water as the sole source, whereas Cumberland, R.I. and Pawtucket, R.I. use a combination of surface water and ground water. Worcester also imports water from the Nashua River Basin to supplement its water supply. Other communities rely primarily on ground water obtained from municipal wells completed in sand and gravel aquifers. Residents in areas not served by public water systems obtain water from private wells completed in either the bedrock or sand and gravel aquifers. Wastewater disposal in the Blackstone River Basin takes place at 11 municipal wastewater treatment plants (WWTPs), permitted wastewater outfalls, and private septic systems (refer to the “Water Use” section of the report for more detailed information on water use in the basin). The public water and sewer lines that were in the basin around the year 2000 are shown on figure 3.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Land-use data from Massachusetts GIS, 1999; RIGIS, 1995

Figure 2. 1995–1999 land use in the Blackstone River Basin, Massachusetts and Rhode Island. From Barbaro and Zarriello (2006).

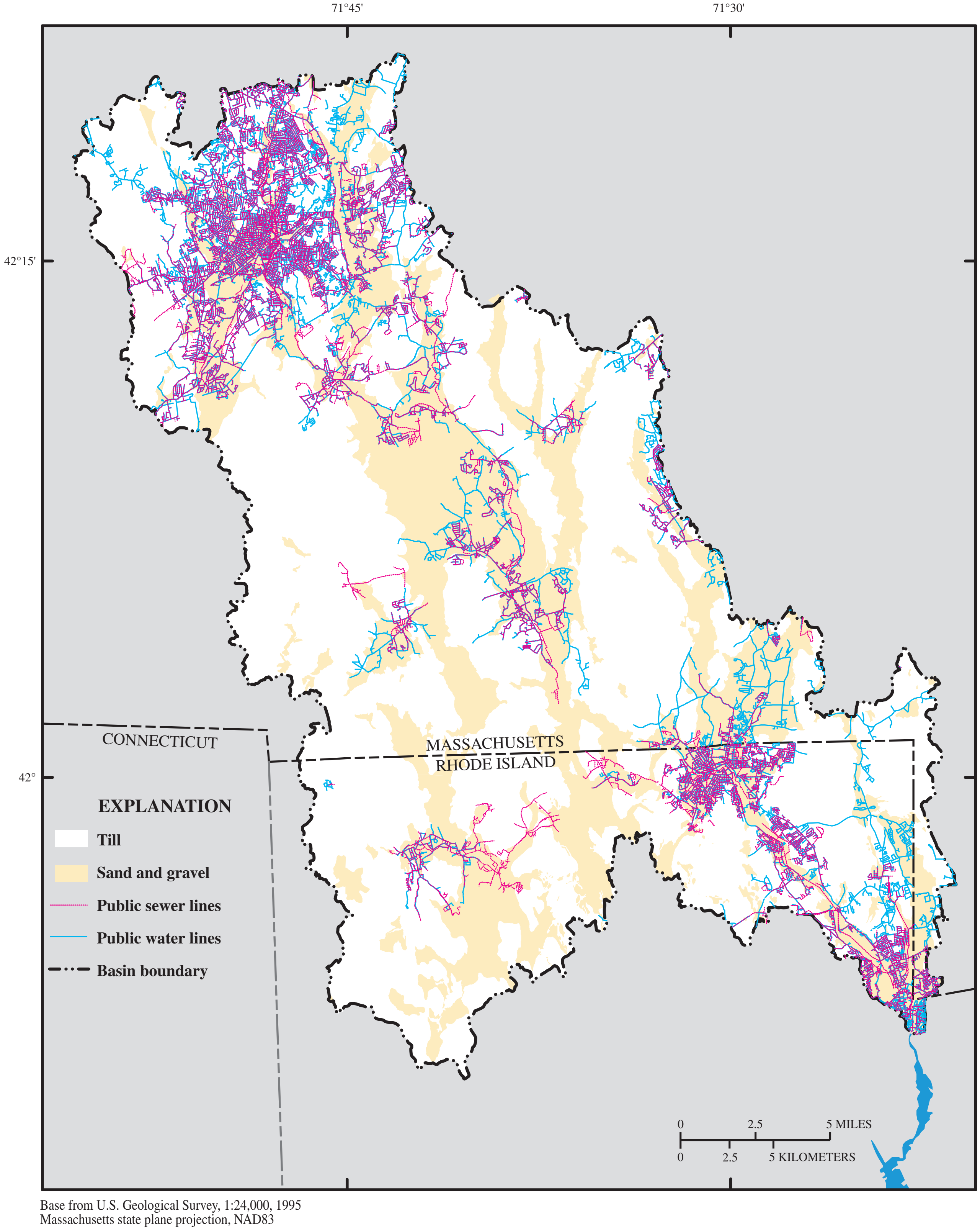


Figure 3. Public water and sewer lines in the basin around the year 2000 and surficial geology in the Blackstone River Basin, Massachusetts and Rhode Island.

Streamflow-Gaging Stations

During 1997–2001, the calibration period for the HSPF model, the USGS operated eight continuous-record streamflow-gaging stations in the basin as part of the ongoing cooperative streamgaging network (fig. 4; table 1 at back of report). Seven additional streamflow-gaging stations (also referred to as project stations) were installed between October 2003 and January 2004 for this study (fig. 4). These seven stations were operated for about 2 years and were removed on September 30, 2005. Flows in the urbanized and densely populated headwaters of the basin were measured at stations on Kettle Brook at Auburn, Mass. (station no. 01109439), the Quinsigamond River at North Grafton, Mass. (station no. 01110000), and the Blackstone River at Millbury, Mass. (station no. 01109730).

Flows in the major tributaries in the central part of the basin were measured at streamflow-gaging stations on the Mumford River at Uxbridge, Mass. (station no. 01111050), the Branch River at Forestdale, R.I. (station no. 01111500), the West River at Uxbridge, Mass. (station no. 01111200), the Peters River at Woonsocket, R.I. (station no. 01112382), and the Mill River at Woonsocket, R.I. (station no. 01112268) (fig. 4). The drainage area to the station on the Blackstone River at Woonsocket, R.I. (station no. 01112500), south of these major tributaries, is 416 mi^2 or approximately 88 percent of the basin area. Flows in the drainage area between the Woonsocket station and the mouth of the basin are measured at the stations on Abbott Run at Valley Falls, R.I. (station no. 01113760) and the Blackstone River at Pawtucket, R.I. (station no. 01113895). Similar to the Worcester area, this part of the basin is urban, with a higher population density, more impervious area, and the percentage of the drainage area served by public water and sewers greater than in other parts of the basin. The average annual discharges at these stations for the various periods of record are shown in table 1.

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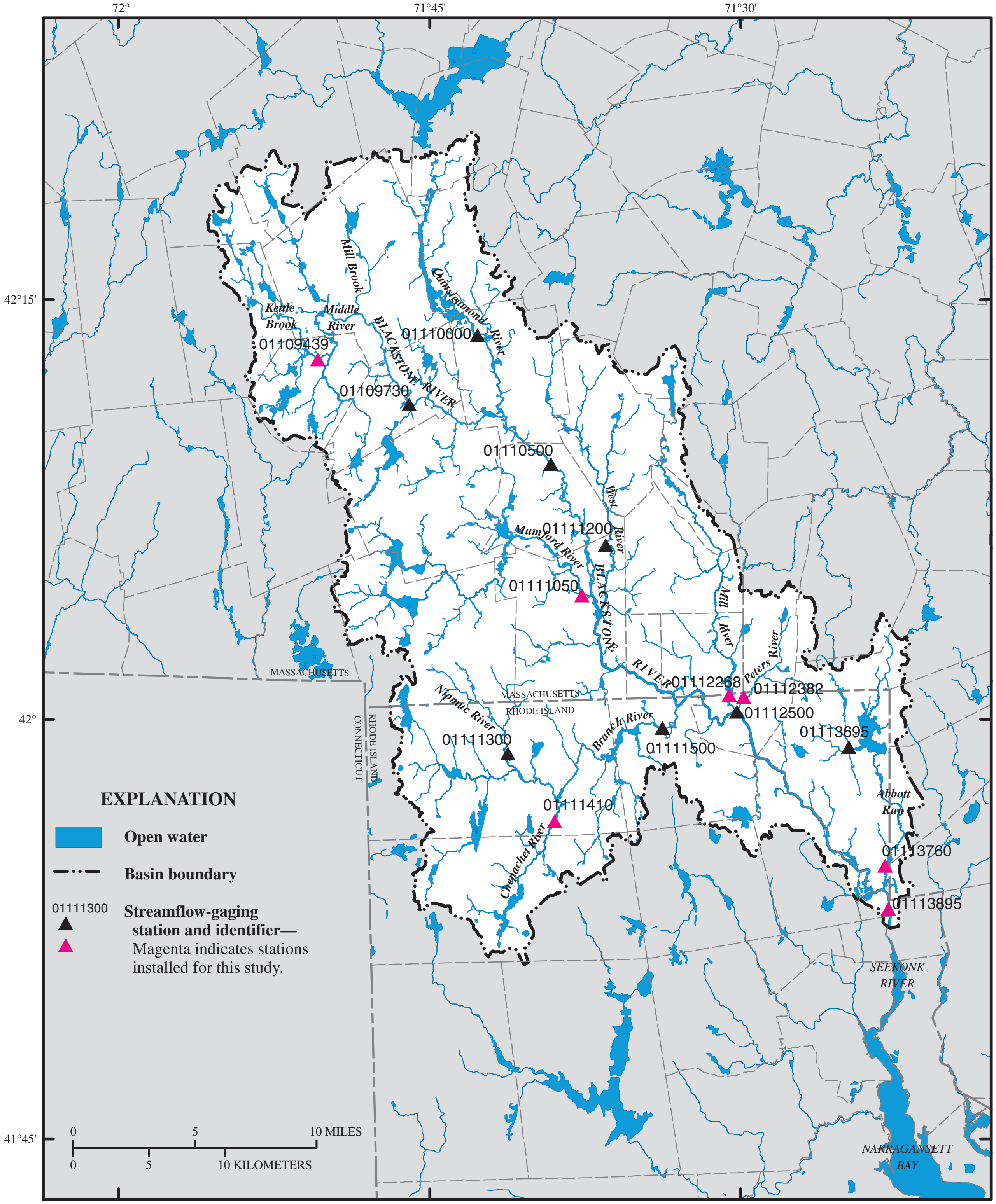
[1] The USGS water year begins on October 1 and ends on September 30 of the following year. For example, water year 2005 began on October 1, 2004 and ended on September 30, 2005.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 4. Streamflow-gaging stations in the Blackstone River Basin, Massachusetts and Rhode Island. From Barbaro and Zarriello (2006).

Overview of the Precipitation-Runoff Model

A detailed description of the structure and use of the Hydrological Simulation Program–FORTRAN (HSPF) model is provided by Bicknell and others (2000) and Donigian and others (1984). In brief, the physical and spatial representation of the basin is defined by the combination of hydrologic response units (HRUs), their contributing areas to a reach (also referred to as subbasins), and the linkage of one stream reach to another (Bicknell and others, 2000). A baseline HSPF model for the Blackstone River Basin (reflecting 1995–1999 land use, 1996–2001 water use, and the parameter values used to calibrate the model to 1997–2001streamflow conditions in the basin) was developed by Barbaro and Zarriello (2006). The baseline model-construction and calibration information is summarized in this section and described in detail in Barbaro and Zarriello (2006). Changes made to the baseline model to simulate water-management scenarios are described in other sections of this report.

Hydrologic Response Units (HRUs)

Hydrologic response units are hydrologically similar land areas that drain into a network of reaches (RCHRES) consisting of streams, lakes, or reservoirs. Each HRU represents areas of similar land use, surficial geology, and other factors deemed important to produce a similar hydrologic response to precipitation and potential evapotranspiration. Data layers representing surficial geology, 1995–1999 land use, and the areal distributions of public-water supply and public-sewer systems in the basin around the year 2000 were used to define the HRUs and calibrate the HSPF model (Barbaro and Zarriello, 2006). Intersecting these data layers yielded 19 HRUs: 17 pervious land elements (PERLNDs) and 2 impervious land elements (IMPLNDs). The definitions, areas, and spatial distributions of the HRUs for the baseline model are shown in table 2 (at back of report) and figure 5. Pervious surfaces that allow infiltration and impervious areas that drain to pervious areas are represented in HSPF as PERLNDs.

Impervious areas that drain directly to streams (hydrologically effective impervious areas) are simulated in HSPF as IMPLNDs. Urban land-use categories (table 10 in Barbaro and Zarriello, 2006) and the percentages of these areas considered to be effective impervious are shown on figure 6. In 1995–1999, about 31 percent of the basin was developed, but the effective impervious area was estimated to be about 5 percent of the basin. The estimated total effective impervious area as a percentage of subbasin area ranged from about 0.1 to 2 percent in undeveloped areas to about 10 to 40 percent in developed areas. IMPLNDs were created by removing area from the developed land-use categories (PERLNDs). For example, 64 percent of the total area classified as commercial-industrial-transportation (PERLND 1) was estimated to be effective impervious, and therefore, was removed from the PERLND area and added to the IMPLND area (table 10 in Barbaro and Zarriello, 2006). The two IMPLNDs created for the HSPF model (table 2) are similar hydrologically, but they were given unique HRU identifiers for possible future water-quality simulations.

Pervious areas in the basin are represented by eight PERLNDs overlying till, eight PERLNDs overlying sand and gravel, and one PERLND overlying both surficial-geology types (table 2). Two HRUs represent open, nonresidential land (PERLND 2 overlying till and PERLND 10 overlying sand and gravel), two HRUs represent forested areas (PERLND 3 overlying till; PERLND 11 overlying sand and gravel), six HRUs represent medium- to low-density development with different water-supply and wastewater-disposal combinations (PERLNDs 4, 5, and 6 overlying till and PERLNDs 12, 13, and 14 overlying sand and gravel), and six HRUs that represent high-density development with the same water-supply and wastewater-disposal combinations as for medium- to low-density development (PERLNDs 7, 8, and 9 overlying till; PERLNDs 15, 16, and 17 overlying sand and gravel). Lot sizes, housing densities, and population densities for the consolidated residential areas in the baseline model are listed in table 3 (at back of report). Areas classified as commercial-industrial-transportation overlying both till and sand and gravel were combined to form a single HRU (PERLND 1).

Residential areas of similar density were divided into three HRUs for each type of surficial geology to account for differences in the water and sewer infrastructure serving these areas (table 2; fig. 5). Residential areas on public water and on-site septic systems were considered to produce a net inflow (or import) of water to the area - PERLNDs 6 (till) and 14 (sand and gravel) represent medium- to low-density residential areas, and PERLNDs 9 (till) and 17 (sand and gravel) represent high-density residential areas. Residential areas on private wells and public sewer systems were considered to produce a net outflow (or export) of water from the area - PERLNDs 5 (till) and 13 (sand and gravel) represent medium- to low-density residential areas, and PERLNDs 8 (till) and 16 (sand and gravel) represent high-density residential areas (table 2). The water imported to or exported from these residential areas was not linked to any specific source or treatment facility; the location of the public water-supply sources or treatment facilities was inconsequential to these transfers.

Residential areas with the other two water-supply and disposal combinations, private wells and septic systems and public water and public sewer systems, were considered to produce no net transfer of water from the area. In areas where water is self-supplied and wastewater is self-disposed, water is cycled (withdrawn and returned) locally. In areas where residences and businesses are connected to both public water and public sewer systems, there is no net import or export of water for human use from the area. Because of the lack of import and export, the model was simplified by combining the residential areas with these water-sewer infrastructure combinations (private wells and septic systems and public water and public sewer systems) to form PERLNDs 4, 7,

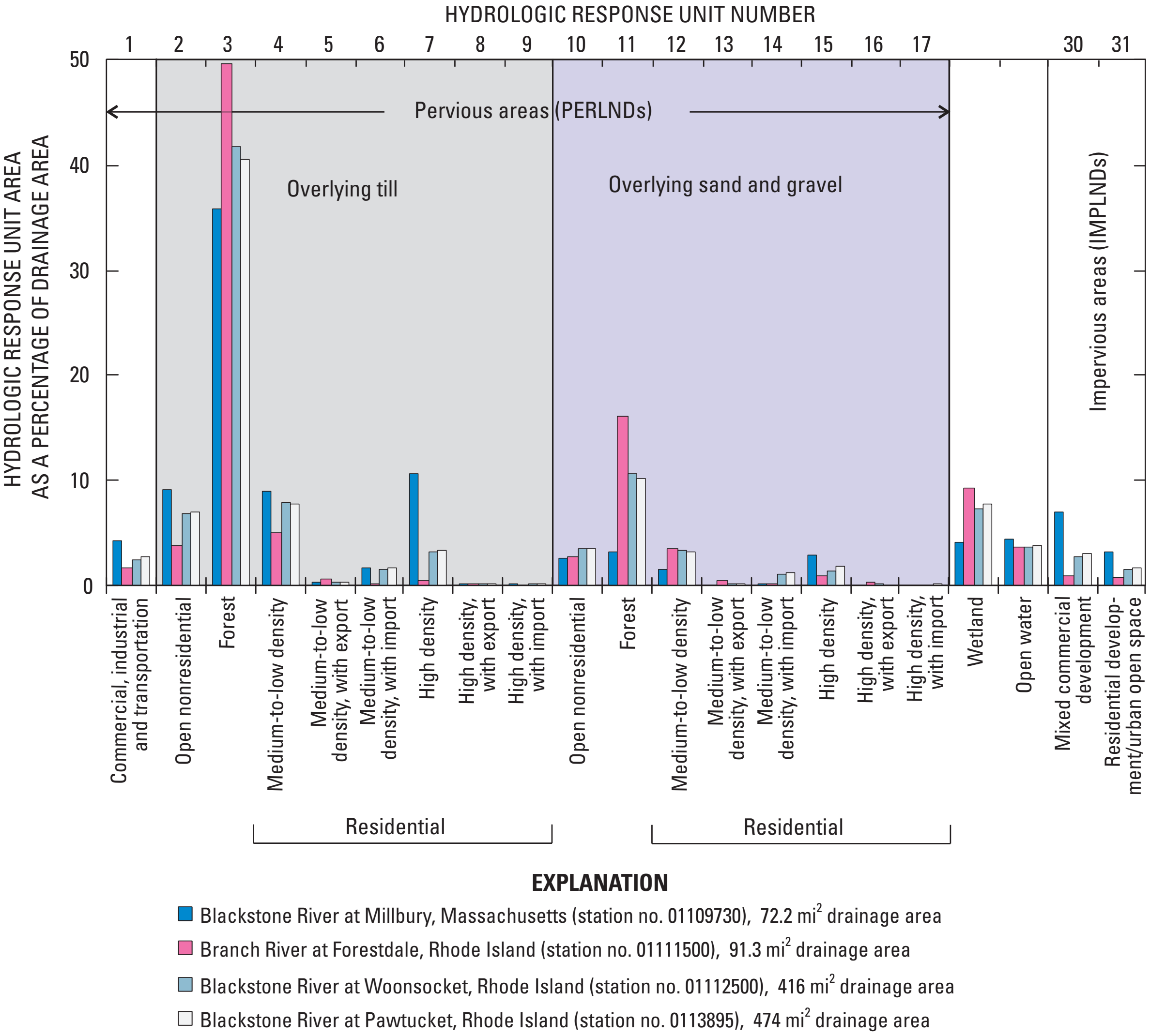
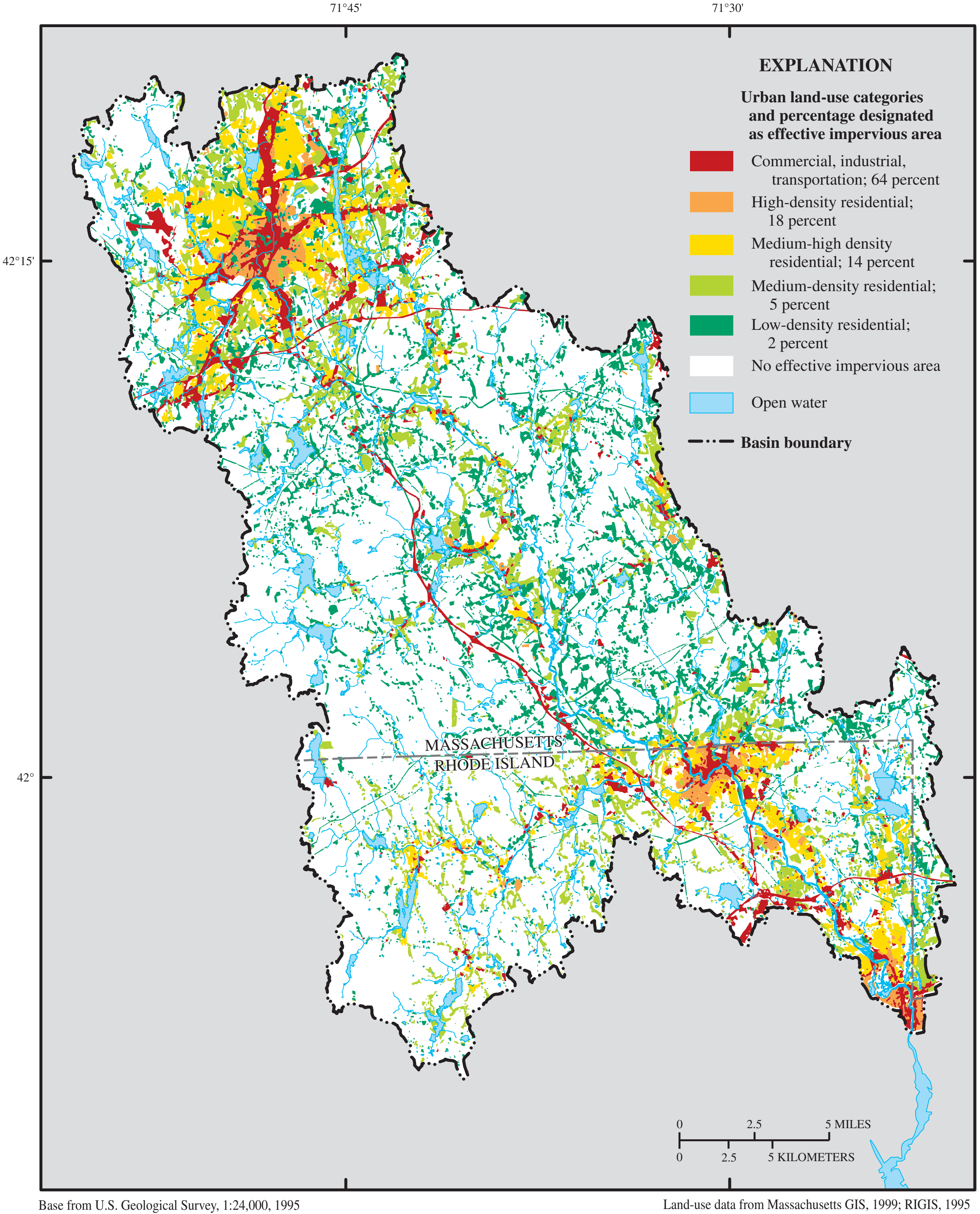


Figure 5. Areas of hydrologic response units (HRUs), wetlands, and open water as a percentage of drainage area for the baseline Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Land-use data from Massachusetts GIS, 1999; RIGIS, 1995

Figure 6. Urban land-use areas and percentages of the areas considered to be effective impervious in the baseline Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.

12, and 15 (table 2). PERLNDs 4 (till) and 12 (sand and gravel) represent medium- to low-density residential areas, and PERLNDs 7 (till) and 15 (sand and gravel) represent high-density residential areas. One consequence of this simplification was that private withdrawals and return flows were not explicitly represented in the baseline model.

Stream Reaches

The Blackstone River Basin was segmented into 50 reaches to represent junctions at tributaries, major lakes and reservoirs, and contributing areas to streamflow-gaging stations (fig. 7 and table 4 at back of report). Segmentation was based on hydrologic characteristics, the availability of streamflow data, and to a lesser extent, the size of the drainage area and water- and land-use characteristics. Drainage areas to the reaches are referred to as subbasins. Fourteen reaches were established along the main stem of the Blackstone River, and 36 reaches were established on the major tributaries. Stage-storage-discharge characteristics (FTABLEs) were developed for the outflow gate used to route water from each of the 50 reaches into the downstream reach. These characteristics were usually defined by the hydraulic properties at the downstream end of the reach, but the discharge-volume relation was a function of the properties of the entire reach. FTABLEs were developed to represent lake or reservoir depth-storage-discharge relations in the 14 reaches dominated by large surface-water bodies; FTABLEs representing stream reaches were developed for the remaining 36 reaches (Barbaro and Zarriello, 2006).

Wetlands and open water, which account for 11.5 percent of the basin area, represent an important storage component of the watershed (table 2). To account for this storage, wetlands were combined with open water and simulated as a “virtual” stream reach that receives runoff from surrounding pervious and impervious areas. Water from the virtual reach was routed into the stream reach along with any water from upstream stream reaches. This approach was used to achieve greater flexibility in calibrating evapotranspiration (ET) losses from wetlands during the growing season.

Water Use

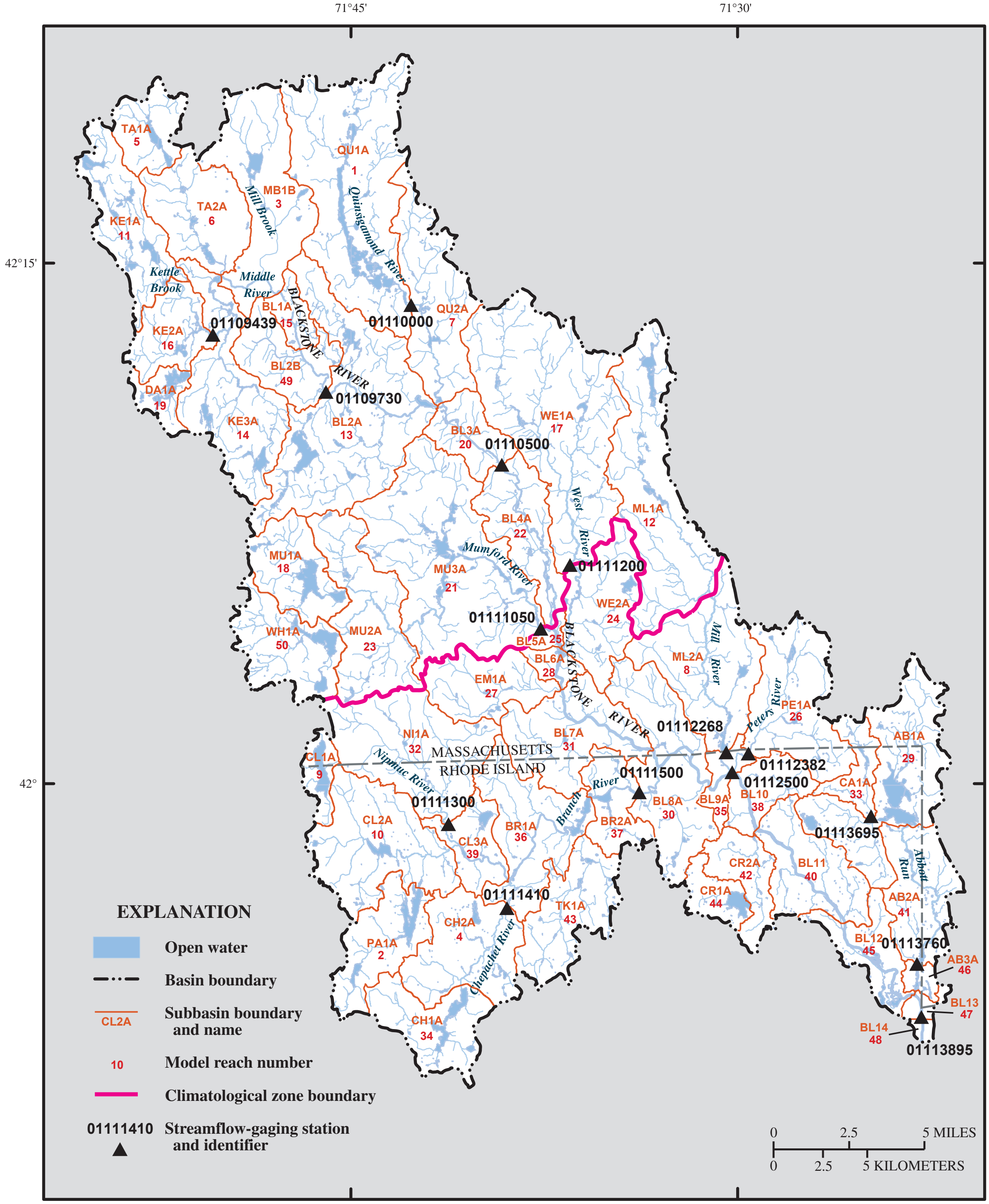
The approach used to incorporate water use into the HSPF model is described in detail by Barbaro and Zarriello (2006) and summarized below.

Water Withdrawals

The water withdrawals simulated in the baseline model include (1) the major ground-water and surface-water withdrawals for municipal water supply and commercial/industrial uses, (2) ground-water and surface-water withdrawals for golf-course irrigation, and (3) ground-water withdrawals from private wells in residential areas with public sewer systems. Infiltration of water into the public sewer systems in the basin also was simulated as a withdrawal by use of the DEEPFR parameter (Barbaro and Zarriello, 2006). Withdrawal records for municipal, commercial/industrial, and golf-course withdrawals were obtained for 1996–2001. Streamflow depletion was computed for all time-varying ground-water withdrawals by use of the program STRMDEPL prior to simulation (Barlow, 2000). The 129 municipal, commercial/industrial, and golf-course withdrawals included in the model are shown in figure 8 and table 5 (at back of report). Of these withdrawals, 17 were from surface water and the remaining 112 were from ground water. Of the ground-water withdrawals, 96 were from the sand and gravel aquifer and 16 were from the bedrock aquifer. For the baseline model, 36 of the subbasins in the model had municipal, commercial/industrial, and golf-course withdrawals. If a subbasin had multiple withdrawals, they were added to obtain a total withdrawal rate from the reach.

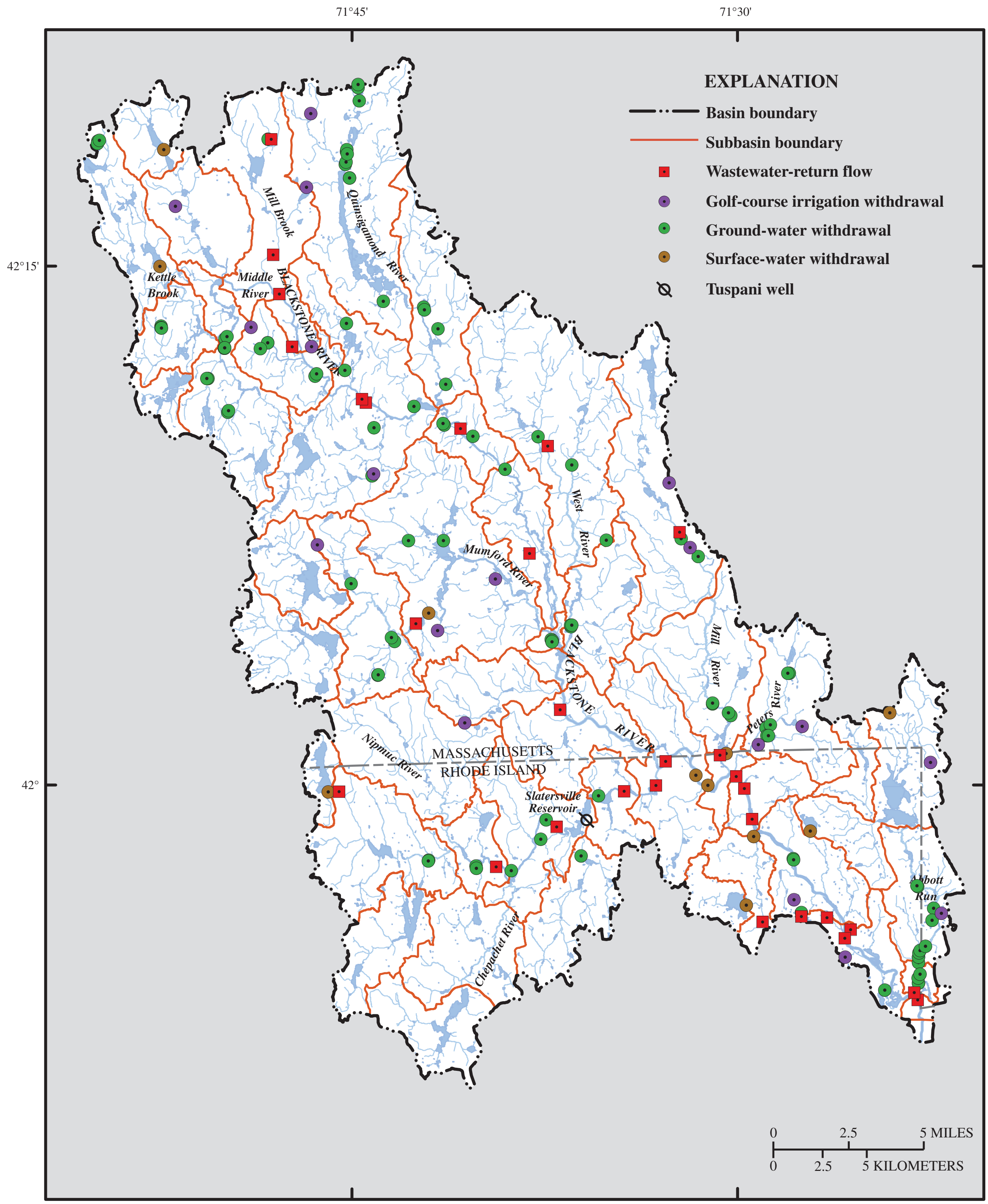
Residential withdrawals were estimated from population-density and water-use data. Ground-water withdrawals from private wells in residential areas with public sewer systems (exports) were calculated by multiplying the population density (table 3) by an average rate of water use of 71 gallons per day (gal/d) per person for privately supplied water (Korzendorfer and Horn, 1995); these calculations resulted in export rates of 1,015 gal/d per acre for high-density residential areas, and 263 gal/d per acre for medium- to low-density residential areas. These export rates were then multiplied by the total area of the appropriate residential density in each subbasin and added together to obtain a total rate of export from the subbasin. Exports were simulated as withdrawals from the model reach. Because the exports represent wastewater flows to municipal WWTPs from residential areas with private wells, they are returned to the basin in municipal wastewater-return flows (discussed below). Thirty-five reaches in the baseline model had withdrawals from residential areas with private wells and public sewer systems.

Consumptive use is defined in this study as withdrawn water that is used by humans and not returned to the basin. Examples are irrigation, car washing, and other activities that result in water being transferred to the atmosphere. Consumptive losses associated with most of the municipal withdrawals were implicitly represented in the baseline model as the difference between reported withdrawal rates and municipal wastewater-return flow rates. Because private withdrawals returned locally to on-site septic systems were not represented by an individual HRU, consumptive losses associated with these residential withdrawals were not included in the baseline model. Consumptive losses associated with municipal withdrawals returned to on-site septic systems (imports) also were not represented in the baseline model. These omitted losses, which totaled about 1.8 Mgal/d under the assumption that consumptive losses were 20 percent of the total withdrawals of about 9.0 Mgal/d returned to septic systems, were small in comparison to the total basin wide withdrawals of about 65 Mgal/d for the baseline-model calibration period (1997–2001).



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 7. Hydrological Simulation Program—FORTRAN (HSPF) model subbasins, reach numbers, and the boundary between climatological zones, Blackstone River Basin, Massachusetts and Rhode Island.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 8. Water withdrawals and transfers and wastewater-return flows in the Blackstone River Basin, Massachusetts and Rhode Island.

Wastewater-Return Flows

The wastewater-return flows simulated in the baseline model include (1) municipal wastewater return flows from the 11 municipal wastewater-treatment plants in the basin (these return flows include the exported water from residential areas with private wells, discussed above), (2) commercial and industrial return flows from permitted facilities, (3) filter-backwash return flows from municipal water-treatment plants, and (4) return flows of on-site septic effluent in residential areas on public-water supplies. The 29 municipal and commercial/industrial wastewater-return flows included in the model are shown in figure 8 and table 6 (at back of report). Records for the municipal and commercial/industrial return flows were obtained for the period 1996–2001. Municipal and commercial wastewater was returned as an inflow time series to the reach in which the outfall was located. When a subbasin had multiple return flows, they were added to obtain a total return-flow rate for that reach. Twenty reaches in the baseline model had municipal and commercial/industrial wastewater return flows.

Return flows of septic effluent in residential areas with public water systems (imports) were calculated by multiplying the population density by the average rate of water use of 67 gal/d per person for publicly supplied water (Korzendorfer and Horn, 1995); these calculations resulted in import rates of 959 gal/d per acre for high-density residential areas and 251 gal/d per acre for medium- to low-density residential areas. These return flows were added to the applicable HRUs as inflow to lower-zone storage in the HSPF model.

Model Calibration

The model was calibrated for January 1, 1997 to December 31, 2001 with data from climatological stations at Worcester Regional Airport, Worcester, Mass. (KORH) and T.F. Green Airport in Warwick, R.I. (KPVD) (fig. 1). Because a NW-SE trend in climatological data was observed, data from Worcester Regional Airport were used for the northern part of the basin, and data from T.F. Green Airport were used for the southern part of the basin. The boundary between these two climatological zones is shown on figure 7. Streamflow data from the 15 streamflow-gaging stations in the basin (fig. 4) provided the model-calibration points. Record-extension techniques were used to compute streamflow for 1997–2001 at the seven project streamflow gaging stations that were installed in 2003-2004 (Barbaro and Zarriello, 2006). The model was calibrated in accordance with guidelines by Donigian and others (1984) and Lumb and others (1994). Calibration entailed first adjusting the parameter values to fit the model output to total and seasonal water budgets, and then adjusting values to improve the model fit for daily flows while maintaining the total and seasonal water budgets. The model fit at low flows was given the most consideration because the primary purpose of the model was to simulate the effects of possible land-use and water-use changes on low flows in the basin.

The quality of the model fit was evaluated by using mathematical summary statistics and visual inspection of the hydrographs, flow-duration curves, and scatter plots of simulated and observed streamflows at varying time scales. Overall, the model-fit statistics and visual inspection of simulated and observed streamflow indicate that the model performs well over a wide range of hydrologic conditions. Love and Donigian (2002) indicate that HSPF model fits for streamflow are considered very good when errors between simulated and observed flows are less than 10 percent, good when errors are between 10 and 15 percent, and fair when errors are between 15 and 25 percent. The errors in mean monthly and daily flows for the calibration period (1997–2001) were less than 10 percent at 12 stations, 10 to 15 percent at 2 stations, and 15 to 25 percent at 1 station (Barbaro and Zarriello, 2006). Agreement between simulated and observed flows generally was poorest at the stations where observed flows were estimated by record-extension techniques.

The simulated mean annual discharge to streams for the entire basin for 1997–2001 was 23.1 in., of which about 44 percent (10.1 in.) was from forested areas overlying till, and about 11 percent (2.5 in.) was from forest overlying sand and gravel (Barbaro and Zarriello, 2006). Overall, PERLNDs overlying till accounted for 67 percent of the discharge to streams, PERLNDs overlying sand and gravel accounted for 21 percent, IMPLNDs accounted for 9 percent, and the PERLND representing commercial-industrial-transportation areas accounted for the remaining 3 percent. Forested areas accounted for about 63 percent (12.2 in.) of the mean annual ET losses (19.5 in.) from the basin during this period. Thus, because of the large amount of forested acreage in the basin and associated large fluxes of water, the hydrologic response of forested areas overlying till strongly affects the basin water budget.

Numerical watershed models necessarily simplify the complex processes and physical characteristics of a basin. Consequently, there are limitations to the types of questions that can be addressed by the model. The assumptions, uncertainties, estimation procedures, information used to develop and calibrate the model, spatial resolution of the model, and the possible applicability of alternative model structures and parameters should be considered when evaluating the model and using its results for water-resources management decisions. Specific limitations and uncertainties of the Blackstone River Basin HSPF model are described in Barbaro and Zarriello (2006).

Use of Buildout Analysis to Simulate Effects of Potential Development on Streamflow

The Massachusetts Executive Office of Environmental Affairs, Rhode Island Department of Environmental Management, and John H. Chafee Blackstone River Valley National Heritage Corridor Commission collaborated on a buildout analysis for the towns in the Blackstone River Basin (Blackstone River Valley National Heritage Corridor Commission, 2001). Information on the methodology of the buildout analysis was provided by the Massachusetts Executive Office of Environmental Affairs (2006). Updated buildout information for the Rhode Island towns of Burrillville, Central Falls, Cumberland, Lincoln, North Smithfield, Pawtucket, and Woonsocket was provided by Mapping and Planning Services of Jamestown, R.I. The buildout analysis for a community consists of maps that show future development patterns based upon current zoning and projections of the growth of population, households, services, and residential and commercial water use (Massachusetts Executive Office of Environmental Affairs, 2006). The analysis shows how a community might develop if all remaining developable areas were fully built out in accordance with current local zoning regulations. Information from the buildout analysis was incorporated into the HSPF model to simulate the effects of potential future development on streamflow.

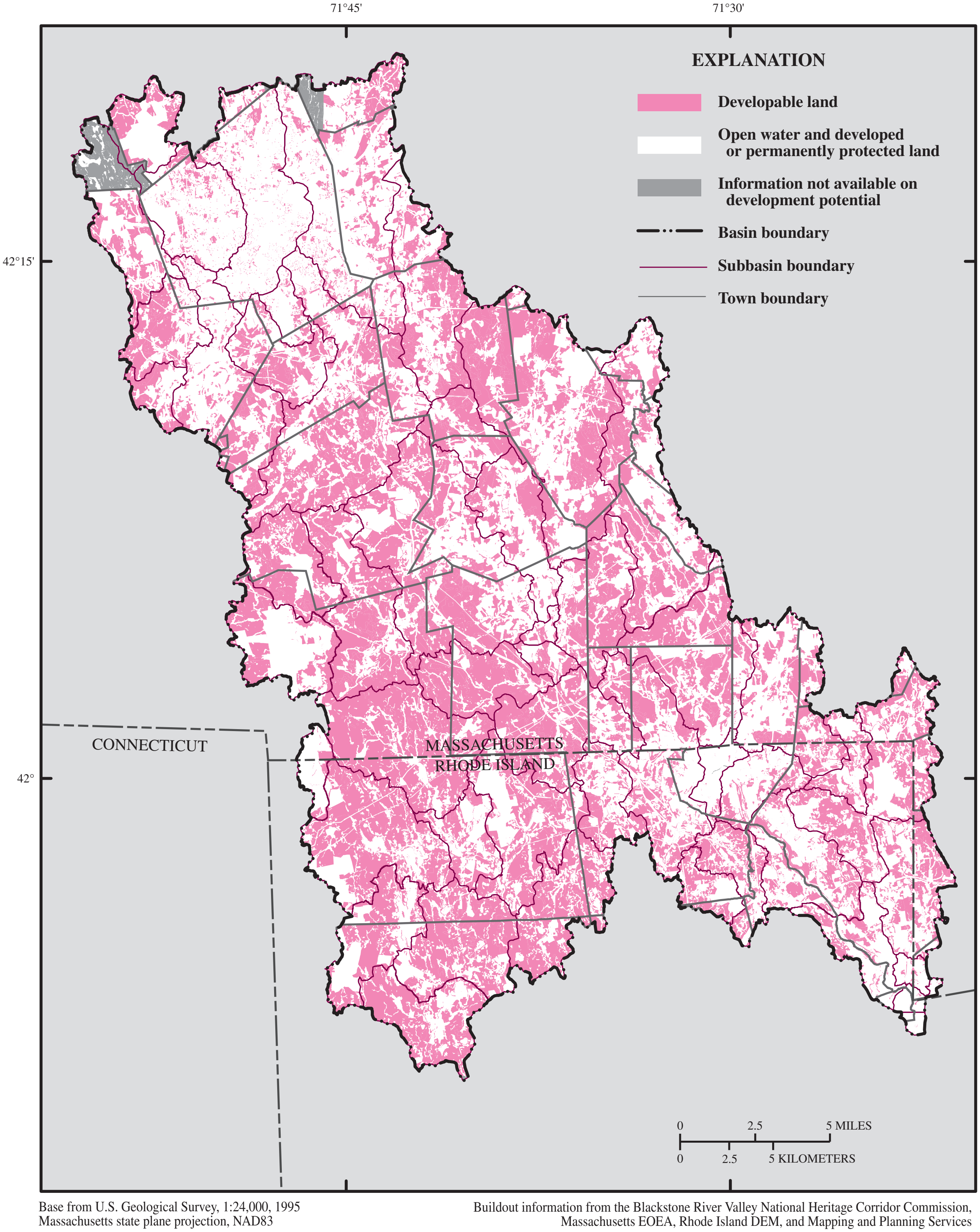
Land Use at Buildout

A data layer of potential future land use at buildout was created by combining buildout information with the LULC information used to develop the baseline model. Buildout information for each town in the basin included a data layer showing areas that were already developed or had absolute constraints on development (for example, permanently protected open space, vegetated buffers, wetlands, and flood plains), and areas that were developable. Developable land in the basin is shown in figure 9. The developable areas were represented in the buildout analysis by a regionalized zoning code that was created from individual town zoning codes to provide consistent zoning across the basin. To estimate land use at buildout, it was assumed that development would occur (1) only on land that was not currently developed or was permanently protected, and (2) in accordance with the zoning codes that were in place at the time of the analysis (1990s).

To construct the data layer of potential land use at buildout, the data layer of developed and developable land (fig. 9) was combined with the 21-category 1995–1999 LULC data layer that was used to compute the PERLNDs and IMPLNDs for the baseline HSPF model (Barbaro and Zarriello, 2006). Land in developable areas then was converted to developed land by use of the regionalized zoning code (table 7 at back of report). The resulting 21-category LULC data layer representing buildout shows land use when all developable areas are fully developed in accordance with recent (1990s) zoning codes. Land use in the developed areas was not changed from the 1995–1999 LULC data layer unless the regionalized zoning code allowed higher density development. Thus, the analysis ensured that none of the developed areas (commercial-industrial-transportation areas and residential development of different densities) in the 1995–1999 data layer was modified unless the regionalized zoning code allowed an area to be converted to a higher density use.

All wetlands and open water in the 1995–1999 data layer also were retained regardless of their location in the basin. Developable areas zoned for very low-density residential development (R1) and residential/agricultural (RA), parcels with lot sizes greater than about 2 acres (table 7), were assumed to remain predominantly forest covered and function hydrologically as forested areas; consequently, they were recoded as forest rather than as medium- to low-density residential or as open, undeveloped areas. Other aspects of the buildout analysis, such as partial constraints on development in developable areas because of slope, soil type, or odd lot sizes, were not considered; however, these factors were considered in the computations by individual municipalities of the new residential and commercial water demands associated with buildout. Overall, the recoding and other assumptions used to change land use in the developable areas resulted in a worst-case scenario with respect to the area that could become developed on the basis of recent (1990s) zoning codes.

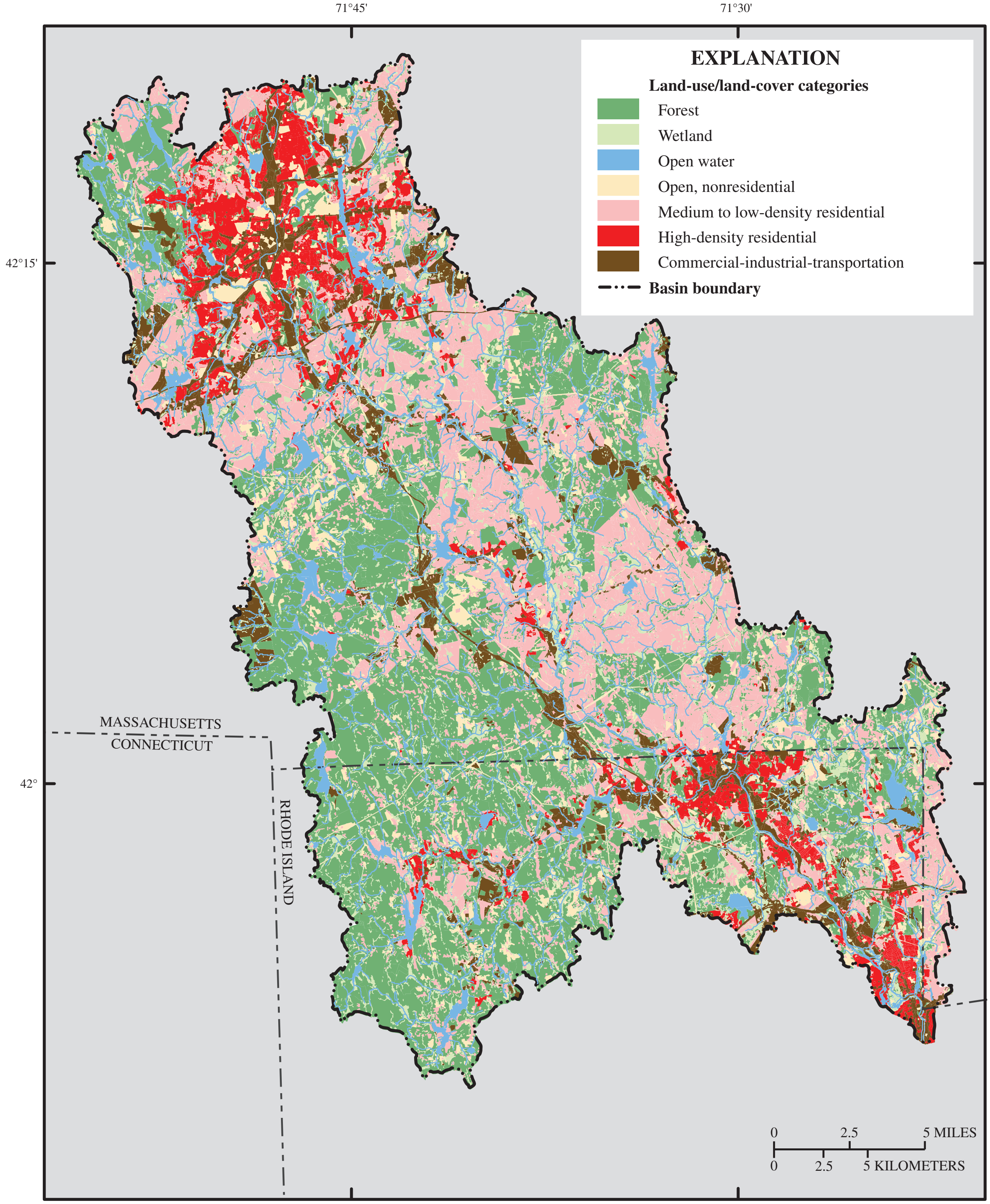
The 21-category LULC data layer representing buildout conditions then was aggregated into 7 categories: (1) commercial-industrial-transportation, (2) high-density residential, (3) medium- to low-density residential, (4) open nonresidential, (5) forest, (6) forested and non-forested wetlands, and (7) open water (fig. 10). These categories are the same as those used to calibrate the parameters in the baseline HSPF model. The aggregated LULC data layer representing buildout conditions indicates that 36.0 percent of the basin would be forested, 27.7 percent would be medium- to low-density residential, 9.3 percent would be commercial-industrial-transportation, 8.0 percent would be high-density residential, 7.5 percent would be open, non-residential, 7.7 percent would be wetlands, and 3.8 percent would be open water. Abrupt changes in land use along town boundaries reflect different zoning of rural areas (fig. 10); for example, rural areas zoned R2 were converted to the medium- to low-density residential land-use category, whereas rural areas zoned R1 or RA were converted to the forest category. The buildout information indicated that the major change in land use potentially will be the conversion of forested areas to medium- to low-density residential development; forests decreased from 50.7 percent to 36.0 percent of the basin area, whereas medium- to low-density residential areas increased from 14.7 percent to 27.7 percent of the



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Buildout information from the Blackstone River Valley National Heritage Corridor Commission, Massachusetts EOEA, Rhode Island DEM, and Mapping and Planning Services

Figure 9. Developable land identified by a buildout analysis done in 2001, Blackstone River Basin, Massachusetts and Rhode Island.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Buildout information from the Blackstone River Valley National Heritage Corridor Commission,
Massachusetts EOEA, Rhode Island DEM, and Mapping and Planning Services

Figure 10. Potential land use at buildout in the Blackstone River Basin, Massachusetts and Rhode Island.

basin area. Developed areas such as high-density residential and commercial-industrial-transportation potentially will be larger at buildout, whereas non-developed areas represented by the open, non-residential category potentially will be smaller at buildout. Areas of open water and wetlands will remain unchanged.

HRUs at buildout were then developed by following the same procedures that were used for the baseline model. Briefly, these procedures included creating effective impervious area from urban land-use categories; intersecting the data layers of potential land use at buildout, surficial geology, and areas served by public sewer and public water systems; and grouping the resulting areas to reduce the number of HRUs to the same 17 PERLNDs and 2 IMPLNDs defined for the baseline model (Barbaro and Zarriello, 2006) with revised areas and geographical distributions reflecting the changes in land use. For example, the amount of effective impervious area in the HSPF model increased from 4.7 percent of the basin area in 1995–1999 to 7.9 percent at buildout.

Potential Water Withdrawals and Wastewater-Return Flows at Buildout

Land-use changes based on the recent (1990s) zoning were used to determine the spatial distribution of new water demands in the basin. New demands were computed on the basis of conditions in the basin during the period 1990-2000; this period reflects the dates of the population, land-use, and water-use data used in the buildout analysis and the baseline HSPF model. To simulate potential new withdrawals and wastewater-return flows at buildout, water-use information compiled by the towns in the basin as part of the buildout analysis was distributed among the HSPF subbasins. As described in greater detail in the following sections, three major assumptions were used to incorporate the potential new withdrawals and return flows into the HSPF model:

1. New demands in the subbasins—generated by changes in land use—will be met by new withdrawals from the subbasins. The exceptions were the major surface-water supplies for the cities of Worcester, Mass., Woonsocket, R.I., and Pawtucket, R.I. that had extensive distribution systems; the potential new demands in the subbasins that had water lines for these systems were assumed to be met by increased withdrawals from the subbasins that had the existing water-supply reservoirs;
2. New municipal wastewater-return flows will be to existing WWTPs in the basin. Potential new demands in subbasins that contained sewers to these facilities were used to estimate new return flows; and
3. The public water and public sewer systems in the basin will not expand appreciably compared to the sizes of the systems in 2000. The public water and public sewer system data layer used to develop the baseline model was used in the buildout analysis because information on future expansion of the public water and public sewer systems was generally not available for the towns in the basin. It should be noted that the commercial and residential areas served by public water and public sewer systems were larger at buildout than for the baseline model because undeveloped lots along the existing public-utility lines were converted to developed land uses in accordance with zoning codes. Nonetheless, most of the potential new low-density residential development in rural areas is likely to be constructed with private wells and on-site septic systems.

These assumptions and the limitations of the HSPF model should be considered when evaluating the results of the buildout-model scenarios.

An outcome of assumptions 1 and 2 is that nearly all potential new withdrawals and return flows at buildout originated from and were discharged to the basin; therefore, they were nearly in balance at the basin scale. At the reach scale, however, withdrawals may effectively be consumptive losses if the extracted water is exported from the drainage area. A worst-case, basin-scale scenario based on the assumption that a large-scale export of new withdrawals to WWTPs outside the basin would occur was considered to be less plausible and was not evaluated in the current study. This study also does not address the availability of new sources of water (for example, new private or municipal wells) to meet the potential new demands; the capacities of existing WWTPs to treat the new wastewater-return flows; the effects of increases in rates of withdrawal from existing individual supplies in the basin (other than the major surface-water supplies mentioned above); the relation between increased withdrawal rates and permitted withdrawal rates, if applicable, from existing individual supplies and their ability to provide the needed water; or the effects of the possible expansion of the existing public water and public sewer systems in the basin. Additional basin- and subbasin-scale scenarios could be developed to address some of these issues.

Water Withdrawals

Potential water withdrawals at buildout were estimated from water-use information compiled by each town as part of the buildout analysis. The zoning of developable areas was used to compute the potential number of new dwelling units and square footage of new commercial space at buildout (table 8 at back of report). Buildout data indicated the potential for about 86,000 new dwelling units and 152 million ft^2 of new commercial floor area at buildout basin wide compared to conditions in the 1990s (table 8). Under the assumption that each dwelling unit houses 2.5 persons (to be consistent with the baseline model), the population in the basin would increase by 215,000, from 436,000 persons in 1990 (U.S. Census) to about 651,000 persons at buildout. Based on recent rates of issuance of building permits, buildout could be complete by the middle of the 21st century (Blackstone River Valley National Heritage Corridor Commission, 2001).

To estimate demands associated with the new development, the number of new dwelling units was multiplied by a residential density of 2.5 persons per dwelling unit and the privately supplied water-use rate of 71 gal/d per person; the area of new commercial space was multiplied by 71 gal/d per 1,000 square feet. New demands in the towns straddling the boundary of the basin were apportioned by multiplying the total increase in demand for the town by the fraction of the town area in the basin. These calculations indicate that the total new demand potentially will be 26.0 Mgal/d, of which 15.2 Mgal/d will be from residential development and 10.8 Mgal/d will be from commercial development (table 8). The largest new residential demand at buildout potentially will be in Worcester, Mass. (1.9 Mgal/d), followed by Burrillville, R.I. (1.3 Mgal/d), North Smithfield, R.I. (1.1 Mgal/d), and Sutton, Mass. (1.1 Mgal/d). The largest new commercial demand also will be in Worcester, Mass. (1.5 Mgal/d), followed by Shrewsbury, Mass. (1.3 Mgal/d), and Cumberland, R.I. (0.92 Mgal/d). As a percentage of average 1996–2001 withdrawals, potential new demands in the larger cities, which were already densely developed, were smaller in comparison to most of the smaller towns, which had open space available for residential and commercial development.

To incorporate the new demands into the HSPF model, the town-based demands (table 8) were distributed among the HSPF subbasins. The first step in distributing the town-based data to the subbasins was to determine the basin-wide increases in demand for four residential land-use categories and the commercial-industrial-transportation land-use category (table 9 at back of report). The four residential land-use categories include (1) areas with private water (on-site wells) and private sewers (on-site septic systems), (2) areas with private wells and public sewer systems, (3) areas with public water systems and on-site septic systems, and (4) areas with public water and public sewer systems. These areas were based on the public water and public sewer system data layer used to develop the baseline model. The total new residential water demand of 15.2 Mgal/d was first apportioned among the four residential land-use categories (table 9). For example, 71 percent of the total increase in residential area potentially will be in areas with private wells and on-site septic systems (that is, no public water or public sewer systems around the year 2000), and these areas will account for 10.8 Mgal/d of the 15.2 Mgal/d total new residential water demand. Second, the amount of new residential and commercial development in the 50 HSPF subbasins was determined (table 10 at back of report). This was done for each subbasin by subtracting the areas in 1995–1999 from the areas at buildout. For each land-use category, new demands were distributed among the subbasins by computing the percentage of the total basin-wide increase in area for each subbasin (table 10) and then multiplying the percentage for each subbasin by the total new demand (table 11 at back of report). The total new demand for each subbasin (table 11; column L) was obtained by adding the new demands from each residential and commercial land-use category.

The following assumptions about consumptive losses from human activity were made to estimate total new withdrawals from HSPF subbasins at buildout. Consumptive use was assumed to be 20 percent of demand. Thus, in residential areas with private wells and on-site septic systems, where water from wells is returned to the local ground-water flow system through on-site septic systems, 20 percent of the total demand was simulated as withdrawn to represent consumptive use (table 11; column D). Thus, 2.16 Mgal/d of the total new demand of 10.8 Mgal/d from this type of development was simulated as a new withdrawal from the basin. For new commercial-industrial-transportation development, it was assumed that new development would occur in urban areas served by public water and public sewer systems; therefore, if public sewers were present in a subbasin around the year 2000, 100 percent of the new commercial demand was withdrawn from the basin and returned to one (typically the nearest) of the municipal WWTPs in the basin. For the nine subbasins with no public sewer systems around the year 2000 (shaded rows in table 11), however, it was assumed that water would be obtained from private wells and returned to on-site septic systems; consequently, 20 percent of the commercial demand in these subbasins was simulated as withdrawn to represent consumptive use (table 11; column I). Overall, the difference between the total new demand of 26.0 Mgal/d estimated from the town-based buildout data (table 8) and the actual total withdrawal of 16.3 Mgal/d (table 11, sum at bottom of column L) was the 9.7 Mgal/d that would be returned locally in residential and commercial areas with private wells and on-site septic systems, and was not explicitly simulated in the model.

Because constant, year-round consumptive losses of 20 percent exceed actual consumptive losses from human activity, which occur mainly during summer months, this approach provides a worst-case estimate of potential consumptive losses at buildout. As discussed in the “Water Use” section of the report, consumptive losses associated with residential withdrawals from private wells and municipal withdrawals returned locally to on-site septic systems were not represented in the baseline model. Differences between the two models in the representation of consumptive losses did not, however, hinder the assessment of the effects of potential increased withdrawals at buildout because buildout simulations were evaluated relative to the calibrated baseline-model simulation.

Potential new withdrawals from HSPF subbasins were simulated by increasing the total 1996–2001 withdrawal rates from the reaches. The ratios of the total new withdrawal rates (table 11, column L) to the average 1996–2001 withdrawal rates were computed for each reach. The ratios then were used as multiplication factors in the HSPF user-control input (UCI) file to increase total withdrawal rates from the reaches. By multiplying the hourly values in the withdrawal time series by a constant, the seasonal variability in the measured 1996–2001 withdrawals was preserved. If there were no withdrawals from a subbasin in the baseline model, a new time series was developed for buildout simulations; exceptions were made for reaches 19 and 28, where new withdrawals were simulated by increasing withdrawal rates from adjacent subbasins (table 11). The withdrawals from residential areas with private wells and public sewer systems (table 11, column E) were simulated by computing new export rates from each subbasin with this type of development, and then including these withdrawals in the External Sources Block of the UCI file (Barbaro and Zarriello, 2006).

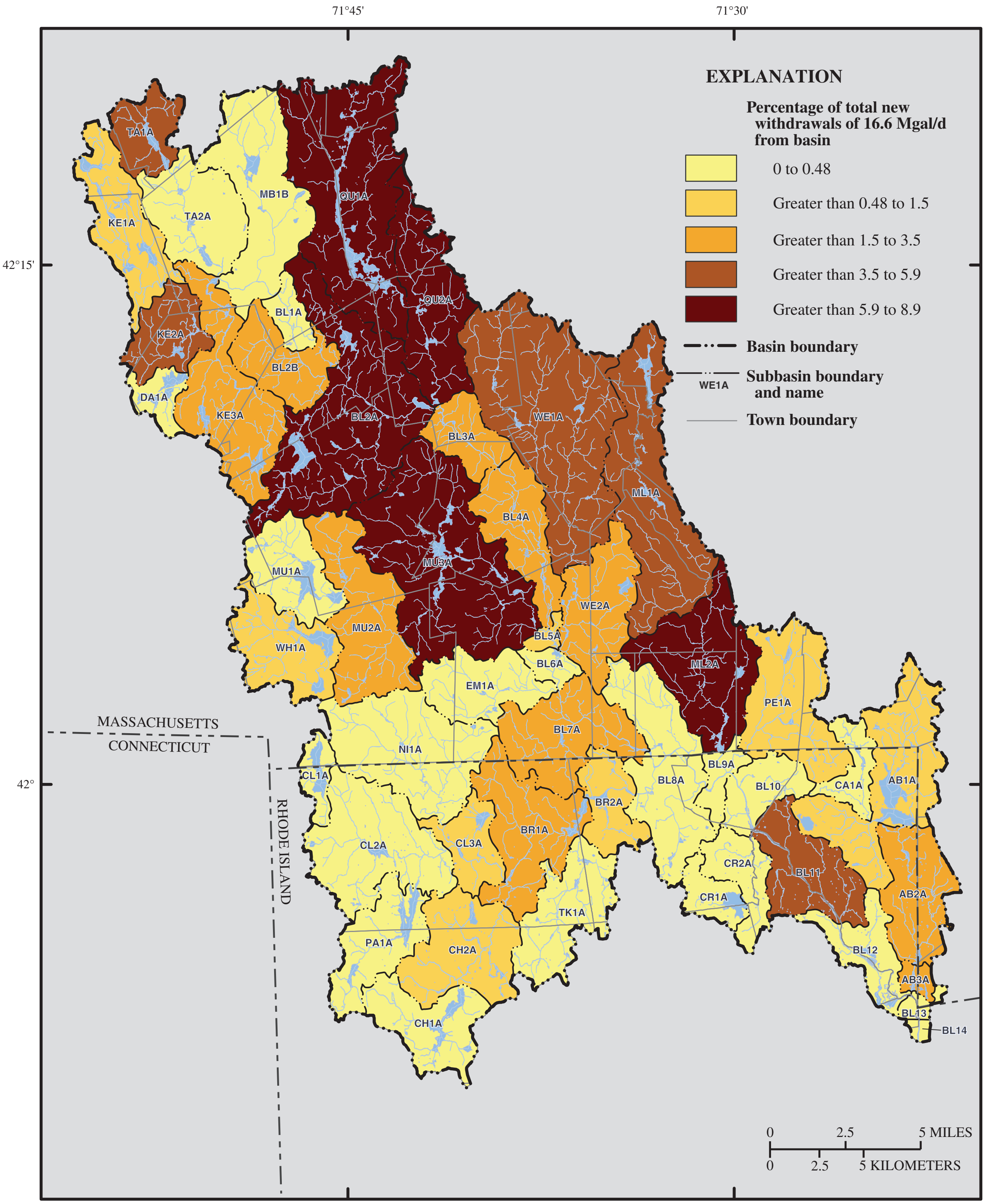
The new demands in the subbasins that receive municipal water from the larger water-supply systems were satisfied by withdrawing additional water from the reach containing the water supply itself (table 11). For example, the new demands in subbasins BL12 and BL13 (reaches 45 and 47) were added to the new demands in subbasin AB3A (reach 46, which contains the intake to the Pawtucket Water Supply filtration plant). An additional 0.25 Mgal/d was withdrawn from reach 46 to satisfy new demands from the city of Pawtucket (table 8), which is mainly outside the basin. This approach is equivalent to assuming that new water supplies will not be developed within these urban areas that contain extensive public water-supply systems; rather the existing surface-water supplies would be utilized to accommodate growth and therefore new demands would be satisfied by increased withdrawals from the existing supplies, in this case the reservoirs and wells in the Abbott Run subbasin. Similarly, for the Woonsocket water-supply system, it was assumed that all new demands in subbasins BL8A, BL9A, BL10, CR2A, and CR1A (reaches 30, 35, 38, 42, and 44) would be satisfied by water from Harris Pond in subbasin ML2A (reach 8), rather than from the Crookfall Brook reservoirs (reaches 42 and 44) because these reservoirs have little capacity to meet new demands (Barlow, 2003). Thus, at buildout, transfers from Harris Pond were increased to satisfy new demands in ML2A as well as from the service area of the Woonsocket water-supply system, and withdrawals from the Crookfall Brook subbasins remained at 1996–2001 rates. A new long-term time series with year-round flows (currently water is transferred from Harris Pond intermittently during the summer) was developed to transfer water from Harris Pond to the Crookfall Brook subbasins.

For the Worcester water-supply system, new demands in subbasins MB1B, TA2A, and BL1A (reaches 3, 6, and 15) were satisfied by increasing the withdrawals from reach 5 (subbasin TA1A, which contains the intake from Holden Reservoir No. 1 to the filtration plant). Holden Reservoir No. 1 receives transfers of water from Lynde Brook Reservoir and Kendall Reservoir in the Nashua River Basin. It was assumed that transfers from Lynde Brook Reservoir in subbasin KE1A (reach 11) would remain at 1996–2001 rates because of the reservoir's limited capacity to meet new demands, and thus all new demands (0.67 Mgal/d) were satisfied by increased rates of transfer from Kendall Reservoir. The water-supply systems for the cities of Worcester, Mass., Woonsocket, R.I., and Pawtucket, R.I. are described in detail in Barbaro and Zarriello (2006).

The spatial distribution of potential new water withdrawals at buildout is shown in figure 11. Potential new withdrawals for each subbasin are shown as percentages of the total basin-wide withdrawal rate of 16.3 Mgal/d. This figure shows only the withdrawals explicitly simulated in the model; the withdrawals in residential and commercial areas with private wells and on-site septic systems that are returned locally to ground water (80 percent or 9.7 Mgal/d) were excluded. These withdrawals were uniformly distributed across the basin, however, and would not greatly affect the spatial distribution shown in figure 11.

Wastewater-Return Flows

Wastewater-return flows to (1) municipal WWTPs and (2) septic systems in residential areas with public water and on-site septic systems were simulated explicitly in the HSPF model. Potential new return flows at buildout were estimated from the distribution of new withdrawals (table 11). The total new demands from residential and commercial-industrial-transportation areas with public water systems are shown in column K of table 11, and the total new demands from residential and commercial-industrial-transportation areas with public sewer systems (water that would be returned to WWTPs) are shown in column J of table 11. The difference between total demands in areas with public water systems (13.5 Mgal/d, sum at bottom of column K) and total return flows to WWTPs (12.1 Mgal/d, sum at bottom of column J) is accounted for by the difference between the return flows in residential areas with public water and on-site septic systems (1.78 Mgal/d, sum at bottom of column F) and the return flows in residential areas with private wells and public sewer systems (0.427 Mgal/d, sum at bottom of column E). Return flows in residential areas with public water and on-site septic systems (imports) were simulated in the External Sources Block of the UCI file (Barbaro and Zarriello, 2006).



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 11. Percentages of total new water withdrawals at buildout for each Hydrological Simulation Program—FORTRAN (HSPF) subbasin in the Blackstone River Basin, Massachusetts and Rhode Island.

These return flows were reduced by 20 percent to about 1.4 Mgal/d to account for consumptive losses associated with human activity. Septic return flows of this type were estimated to occur in 40 of 50 subbasins at buildout and, as indicated above, represented about 15 percent of the total return-flow rate to WWTPs. As indicated in the previous section, water use in residential and commercial areas with private wells and on-site septic systems was simulated by withdrawing 20 percent of the total demand from the model reaches to represent consumptive use; septic return-flow rates in these areas were not explicitly represented in the model.

The potential new wastewater-return flows to the WWTPs in the basin are shown in table 12 (at back of report). Flows to each WWTP were computed by estimating the areal extent of the sewer system (also referred to as the service area) and then adding all of the new municipal residential and commercial return flows (table 11, column J) for the subbasins that contained sewers connected to the WWTP (table 12). Public sewer lines are shown on figure 3. In some cases, subbasins contained sewers connected to more than one WWTP, and it was necessary to assign return flows from the entire subbasin to the WWTP that appeared to receive wastewater from the largest percentage of the sewered area[2]. The total new return flow to WWTPs (table 12, 10.8 Mgal/d) was less than the total of the new withdrawals in areas with public sewers (table 11, column J, 12.1 Mgal/d) because (1) there was a return flow of 1.3 Mgal/d that was conveyed through public sewers in the lower part of the basin (figure 7, model reaches 29, 40, 41, 42, 45, 46, 47, and 48) and out of the basin to the Narragansett Bay Commission Bucklin Point WWTP, and (2) return flows were reduced by an additional 20 percent to account for consumptive losses associated with human activity (table 12).

Potential new return flows to the subbasins with WWTPs were simulated by increasing the total 1996–2001 return-flow rates to the corresponding HSPF reaches. This was done by computing the ratio of the total new return-flow rate to the average 1996–2001 return-flow rate. The ratios then were used as multiplication factors in the UCI file to increase total return-flow rates to the reaches. As for the withdrawal rates, the hourly values in the withdrawal time series were multiplied by a constant to preserve the seasonal variability in the measured 1996–2001 return flows.

The spatial distribution of potential new water wastewater-return flows among subbasins is shown in figure 12. New return flows for each subbasin are shown as percentages of the total basin-wide return flow rate of 10.1 Mgal/d. This figure shows only the wastewater-return flows explicitly simulated in the model (WWTP return flows minus the 1.3 Mgal/d that was exported to the Narragansett Bay Commission Bucklin Point facility and septic-system return flows in areas with public water and on-site septic systems). Total new wastewater-return flows at buildout are not represented because the septic-system return flows in residential and commercial areas with private wells and on-site septic systems that are returned locally to ground water (80 percent or 9.7 Mgal/d) were excluded; however, these return flows were distributed uniformly across the basin and thus would not greatly affect the spatial distribution shown in figure 12. New wastewater return flows are not as evenly distributed as new withdrawals (fig. 11) because there are large-magnitude return flows in the subbasins with WWTP outfalls. Thus, wastewater movement through public sewer systems to WWTPs that treat large volumes of water is a means of diverting water from the areas where the water is withdrawn. In the Blackstone River Basin, these diversions may contribute to local streamflow depletion in reaches affected by water withdrawals.

Return flows to WWTPs in areas with the potential for substantial residential development may increase by over 100 percent compared to 1996–2001 return flows (for example, Hopedale, Mass. WWTP in subbasin ML1A), whereas return flows to the larger WWTPs in the more developed larger cities (for example, Worcester, Mass. and Woonsocket, R.I.) would likely increase much less as a percentage of 1996–2001 return flows. If public water and public sewer systems were to expand substantially into rural areas and thus decrease the area developed with private wells and septic systems, withdrawals from public supplies would increase, and return flows to existing and potentially new WWTPs also would be substantially larger. Because it was assumed for the buildout model that the public water and sewer systems would not expand to a large extent, the estimated municipal return-flow rates shown in table 12 likely reflect the lower range of probable return-flow rate increases at buildout.

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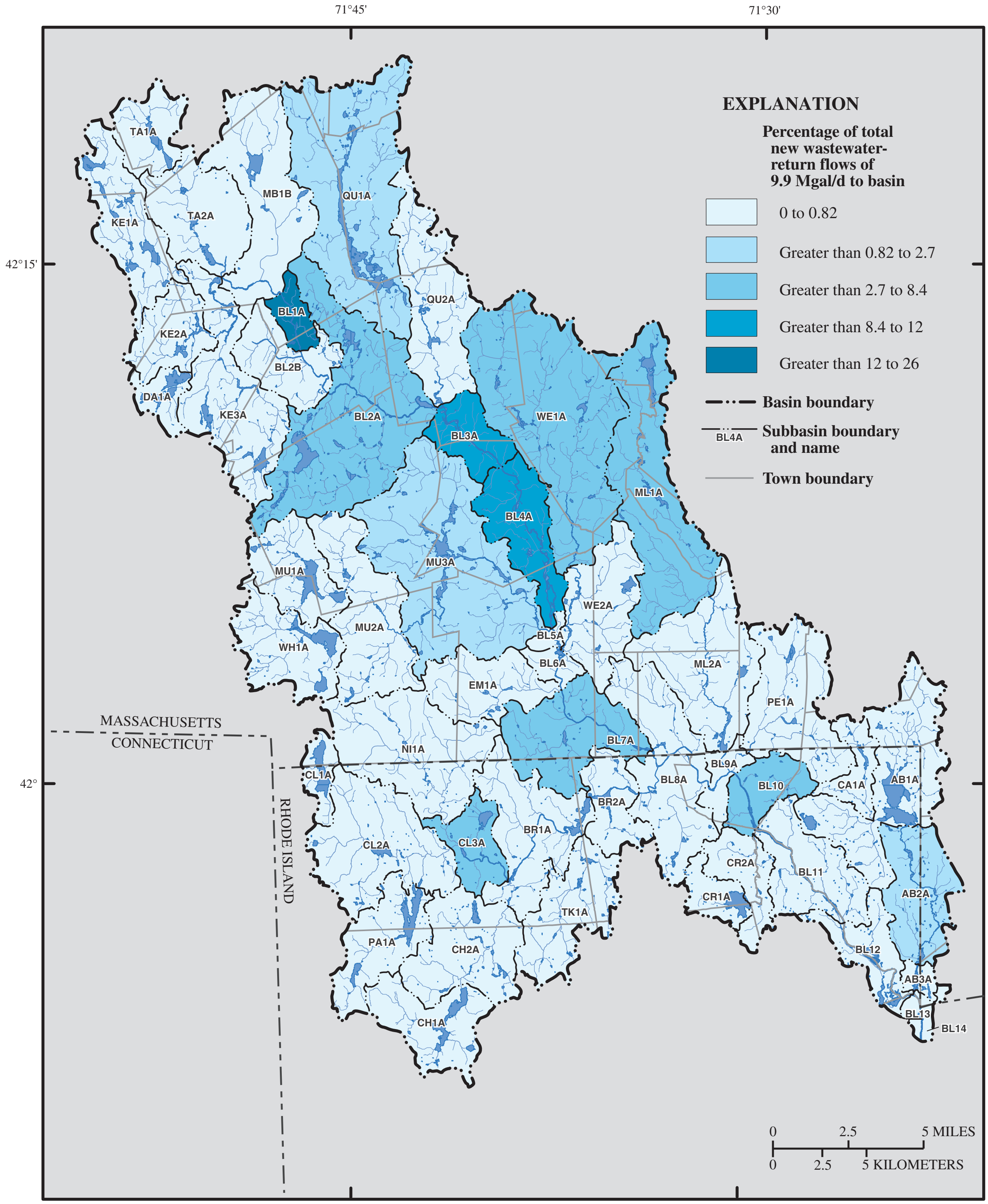
[2] Wastewater in the sewered areas in Shrewsbury, Mass., on the east side of Lake Quinsigamond in subbasin QU1A (fig. 4), was (2006) exported out of the basin to the Westborough WWTP in the Assabet River Basin. New wastewater-return flows by public sewer in subbasin QU1A, including areas in Shrewsbury, were assumed to be conveyed to the Upper Blackstone Wastewater Treatment Facility (UBWWTF) for treatment at buildout (table 1 at back of report). Similarly, wastewater in small sewered areas near the boundary of the basin in the towns of North Attleboro, Mass., Attleboro, Mass., Hopkinton, Mass., and Milford, Mass. (fig. 4) also was exported out of the basin for disposal, but new return flows were assumed to be to the Blackstone River Basin.



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 12. Percentages of total new wastewater-return flows at buildout for each Hydrological Simulation Program—FORTRAN (HSPF) subbasin in the Blackstone River Basin, Massachusetts and Rhode Island.

Simulation of the Effects of Water Withdrawals, Wastewater-Return Flows, and Land-Use Change on Streamflow

The HSPF model was developed to investigate the hydrologic effects of development and water use on streamflow in the Blackstone River Basin. The model was used to simulate the effects of potential changes in water use (defined here as all water withdrawals, transfers, and wastewater-return flows for a specified period of time or condition) and land use on streamflow over long-term climatological conditions (1960–2004). Model scenarios were developed and evaluated for the entire basin and for the Rhode Island part of the basin. Comparisons of relative changes in flows among simulation results, rather than absolute changes, were used to assess the effects of the changes in land use and water use.

Long-Term Basin-Scale Scenarios

Seven long-term (1960–2004) simulations were run to estimate the effects of potential changes in water use and land use on streamflow in the basin (table 13 at back of report). Scenario 7.0 provides the baseline condition for comparison with other simulations and reflects 1996–2001 water use and 1995–1999 land use (referred to as recent conditions), as developed for calibration of the baseline model. Scenarios 8.0 through 13.0 (table 13) represent the land-use and water-use scenarios described in the following sections.

Each simulation required a new UCI file with altered withdrawal and return-flow data in the External Sources Block and altered land-use data in the schematic block, as necessary. Each UCI file was uniquely identified by name and the scenario number (IDSCEN) attribute in the WDM file (table 13). Simulated streamflow generated for each scenario was assigned to a unique dataset in the WDM file to enable comparisons among the scenarios. Scenario 9.0 approximated the natural flow of the rivers in the basin by eliminating withdrawals and return flows and converting land use to undeveloped conditions. To develop this scenario, all developed HRUs (PERLND 1, PERLNDs 4 through 9, and PERLNDs 12 through 17) were converted to forested HRUs (PERLNDs 3 and 11) with similar surficial geology by changing the parameter values for the developed HRUs to the values for the forested HRUs in the PERLND block of the UCI file. Open nonresidential areas (PERLNDs 2 and 10) were retained to represent nonforested undeveloped land.

Long-term climatological data for the period 1960–2004 were obtained from the National Weather Service stations at the Worcester Regional Airport, Worcester, Mass., and T.F. Green Airport, Warwick, R.I. Long-term withdrawal and return-flow data were generally unavailable, except for the period 1996–2001. To estimate total withdrawals, transfers, or return flows for years with no data, an annual record of average daily flows was developed from the 1996–2001 data. These calculations were done for total withdrawal and return-flow rates from subbasins, rather than for individual sources within subbasins. The annual record of average daily flows was then used for 1960-1995 and 2002-2004 to develop the long-term time series. It should be noted that the long-term simulations represent average 1996–2001 or potential buildout water use and not the actual water use during 1960–2004, and that in the subbasins with recreational, water-supply, or flood-control reservoirs, specific management activities were not simulated (Barbaro and Zarriello, 2006). Similarly, these simulations represent undeveloped, 1995–1999, or potential buildout land use and not actual land use during 1960–2004. Thus, these long-term scenarios simulate streamflows for constant water-use conditions (average 1996–2001 or potential buildout water use) and constant land-use conditions (undeveloped, 1995–1999, or potential buildout land use) for long term (1960–2004) climatological conditions.

Effects of Land-Use Change on Streamflow

The effects of land-use change on streamflow in the Blackstone River Basin were evaluated by comparing flow-duration curves for simulations of scenario 8.0 (1995–1999 land use), scenario 9.0 (undeveloped land use), and scenario 11.0 (potential land use at buildout) at the six streamflow-gaging stations that were used to evaluate the baseline model calibration (Quinsigamond River at North Grafton, Mass., Blackstone River at Millbury, Mass., Nipmuc River near Harrisville, R.I., Branch River at Forestdale, R.I., Blackstone River at Woonsocket, R.I., and Blackstone River at Pawtucket, R.I.; fig. 13) and at four additional locations near the mouths of the major tributaries to the Blackstone River in the Rhode Island part of the basin (Mill River at Woonsocket, R.I., Peters River at Woonsocket, R.I., Abbott Run at Pawtucket, R.I., and Crookfall Brook at Woonsocket, R.I.; fig. 13). Scenarios with no water use were compared to isolate the effects of changing land use. In general, urbanization tended to increase peak flows and decrease low flows (Rose and Peters, 2001; Seaburn, 1969). These changes reflect increased direct runoff from storms and corresponding decreased infiltration and base flow, largely in response to an increase in the effective impervious area in the watershed. The increase in base flow for the undeveloped land-use scenario would likely be even larger, but gains from increased infiltration are offset by more ET losses in forested areas (Barbaro and Zarriello, 2006; Rose and Peters, 2001; Zarriello and Ries, 2000).

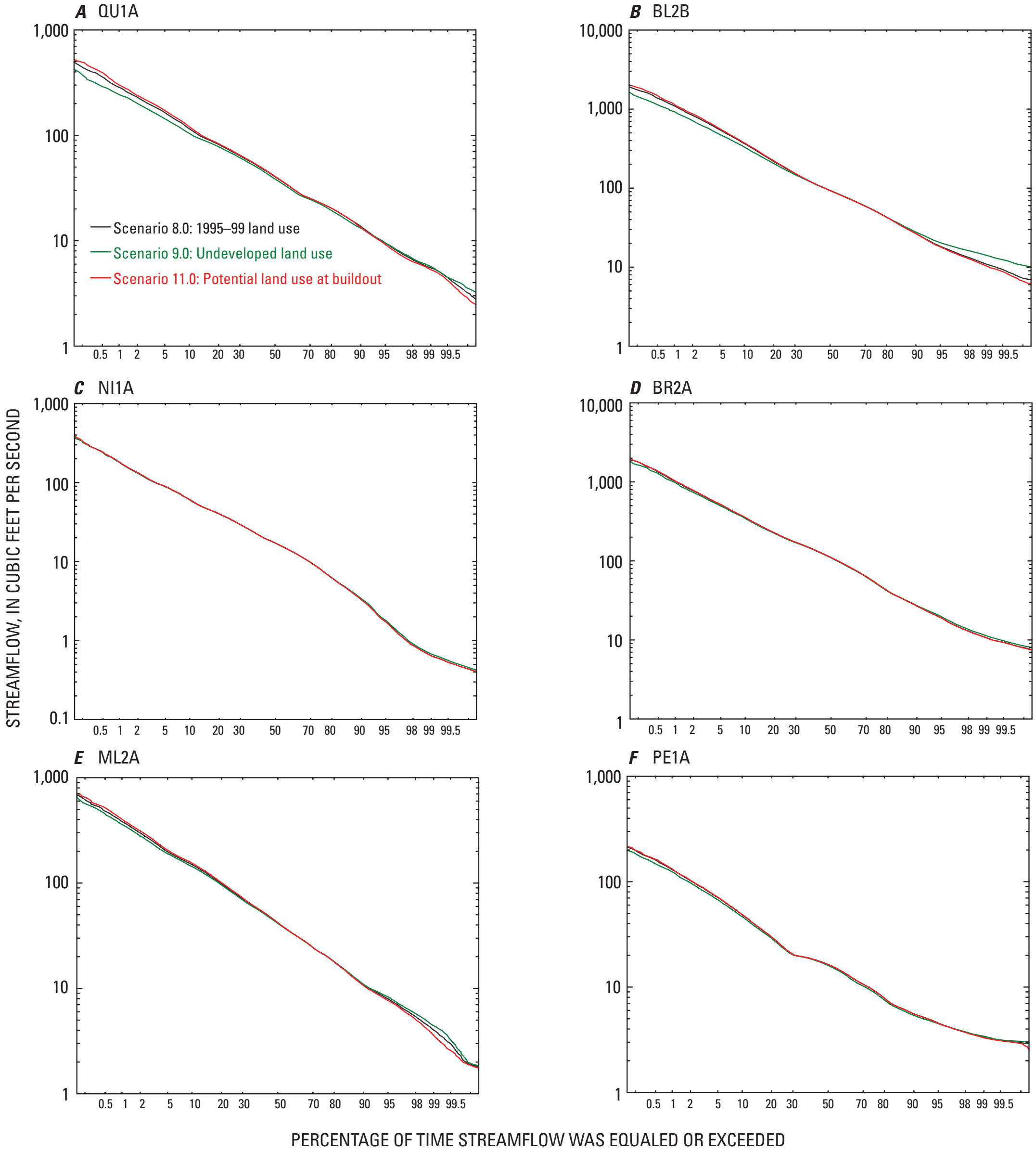


Figure 13. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with undeveloped land use (scenario 9.0), 1995–1999 land use (scenario 8.0), and potential land use at buildout (scenario 11.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*C*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*D*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*E*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*F*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*G*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*H*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); (*I*) Blackstone River at Pawtucket, R.I. (BL13, 01113895); and (*J*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged). Streamflow was simulated with no water use for all three scenarios.

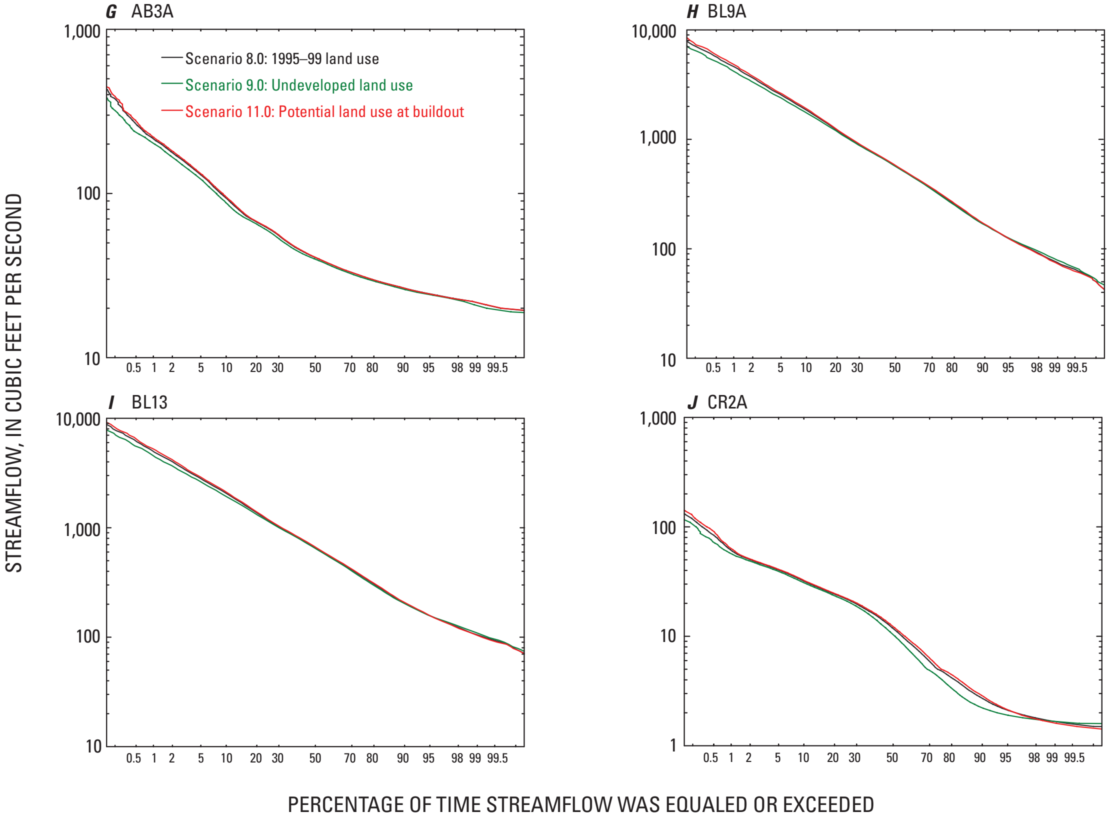


Figure 13. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with undeveloped land use (scenario 9.0), 1995–1999 land use (scenario 8.0), and potential land use at buildout (scenario 11.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*C*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*D*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*E*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*F*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*G*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*H*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); (*I*) Blackstone River at Pawtucket, R.I. (BL13, 01113895); and (*J*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged). Streamflow was simulated with no water use for all three scenarios.—Continued

Flow-duration curves[3] for 1960–2004 were similar, indicating that land-use change, as represented in the HSPF model, generally had a modest effect on streamflow (fig. 13). Differences in high and low flows were greatest in the most urban parts of the basin, such as the Worcester, Mass. area (fig. 13A, B). For example, at the Blackstone River at Millbury, Mass. station, the flow-duration curve for the undeveloped land-use scenario differed from the curves for 1995–1999 and buildout land-use scenarios by a factor of nearly 2 at the 99-percent flow duration (fig. 13B). This part of the basin had more effective impervious area (10.1 percent in 1995–1999 and 13.0 percent at buildout) than the basin average. In contrast, the flow-duration curves for the Nipmuc River near Harrisville, R.I. and Branch River near Forestdale, R.I. sites (figs. 13C, D), were similar because the drainage areas had relatively little development in 1995–1999 and, on the basis of current zoning codes, would have less future development at buildout than other parts of the basin. Flow-duration curves also were similar for the Mill River, Peters River, and Abbott Run (figs. 13E, F, G) which had moderate residential development in 1995–1999 and, on the basis of current zoning codes, would have substantial increases in medium- to low-density residential development at buildout (fig. 10). The simulated effects of these potential future land-use changes were small because medium- to low-density residential development was assumed in the HSPF simulations to add only 2 to 5 percent effective impervious area. Simulation results for the Blackstone River stations near the mouth of the basin (Blackstone River at Woonsocket, R.I. and Blackstone River at Pawtucket, R.I.; fig. 13H, I) indicated that basin-wide land-use changes associated with urbanization (particularly increases in effective impervious area) do not substantially change low flows in the Blackstone River in the Rhode Island part of the basin.

Differences in flow-duration curves generally were greatest between the undeveloped scenario (9.0) and the two developed scenarios (8.0 and 11.0). Flow-duration curves for the developed scenarios did not differ greatly. This result is consistent with the extent of differences in land use among the three scenarios (table 14 at back of report); the undeveloped land-use scenario included no effective impervious area and about 78 percent forest, whereas the developed land-use scenarios included 4.7 to 7.9 percent effective impervious area and a similar distribution of the other land-use categories. The major change in land use from 1995–1999 to buildout (table 14) was estimated to be the conversion of forest (50.7 percent to 36.0 percent) to medium- to low-density residential (14.7 percent to 27.7 percent), and these two land-use categories were assigned similar parameter sets in the HSPF model, which produced similar simulation results (Barbaro and Zarriello, 2006).

The results of HSPF simulations of the effects land-use change on streamflow are inherently uncertain because model calibration and performance reflect the combined response of the PERLNDs, IMPLNDs, and reaches used to represent the basin. Most HSPF parameters, as well as IMPLND areas, cannot be measured independently and are estimated through the calibration process. In general, hydrologic experience and results from previous HSPF studies are used to estimate initial parameter values for individual HRUs. Although the calibrated parameter values for individual HRUs are considered physically realistic and accurate in a relative sense (for example, lower-zone ET is assumed to be greater in areas with deep-rooted vegetation), the uncertainty in absolute values of parameters for individual HRUs leads to uncertainty in simulation results when the one HRU is converted into another (for example, forest to medium-to low-density residential land uses). Thus, results are best viewed as representative of relative rather than absolute responses to land-use change. For example, the actual changes in flow duration in response to the conversion of forest to medium-to low-density residential may turn out to be somewhat greater than shown in figure 13. In addition, the effects of development (particularly increased effective impervious area) on the hydrology, water quality, and aquatic habitat of streams may be more substantial at smaller spatial and temporal (that is, within-day responses to precipitation) scales (Wang and others, 2001; Seaburn, 1969).

Effects of Water Use on Streamflow

The effects of water use on streamflow were evaluated by comparing the results of long-term simulations. Flow-duration curves for scenarios with no water use (scenario 8.0), 1996–2001 water use (scenario 7.0 or 10.0), and potential increased water use at buildout (scenario 12.0) were compared. For each simulation, land use was held constant to isolate the effects of water use. Flow-duration curves for the same 10 streamflow-gaging stations previously discussed were used to show the effects of water use on streamflow in the basin. The spatial distributions of withdrawals and return flows by model subbasin are discussed further in the "Withdrawals and wastewater-return flows in relation to simulated streamflow" section of this report.

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[3] A flow-duration curve is a cumulative frequency curve that shows the percentage of time that specified discharges were equaled or exceeded during a given period. For example, the discharge at the 90-percent flow duration is exceeded 90 percent of the time, and thus is a low flow. Flow-duration curves do not show the chronological sequence of flows.

1996–2001 Water Use

The effects of recent (1996–2001) water use on streamflow were evaluated by comparing two long-term scenarios simulated with 1995–1999 land use: 1996–2001 water use (scenario 7.0) and no water use (scenario 8.0). The net effect of 1996–2001 withdrawals and return flows differed by location in the basin (fig. 14). Of the 10 sites shown on figure 14, flow-duration curves differed the most at the Quinsigamond River at North Grafton, Mass. station (fig. 14A), the Crookfall Brook at Woonsocket station (fig. 14B), and the Abbott Run at Pawtucket station (fig. 14C). Generally, flows under no-water-use conditions were greater than under 1996–2001 water-use conditions for all flows, but the differences became increasingly pronounced above the 50-percent flow duration; at lower flows, water use was a greater proportion of available streamflow. The total withdrawal rates from these subbasins were large, and return flows to public sewer systems were diverted out of the subbasins for treatment. In contrast, at the Blackstone River at Millbury, Mass. station, flows above the 20-percent flow duration were greater under recent water-use conditions than under no-water-use conditions because of return flows from the Upper Blackstone Wastewater Treatment Facility (UBWWTF) operated by the Upper Blackstone Water Pollution Abatement District (UBWPAD) (fig. 14D). The flow-duration curves for the Blackstone River at Millbury, Mass. station indicated that flows increased by about 75 percent (about 10 ft^3/s for no water use and about 40 ft^3/s for 1996–2001 water use) at the 99-percent flow duration.

At the Nipmuc River near Harrisville, R.I. station (fig.14E), the Branch River at Forestdale, R.I. station (fig. 14F), the Mill River at Woonsocket, R.I. station (fig. 14G), and Peters River at Woonsocket, R.I., station (fig. 14H), 1996–2001 withdrawals and return flows had a smaller effect on low flows than at the stations discussed above because withdrawals were smaller and wastewater was returned within the contributing areas to some of these stations (to the Hopedale, Mass. WWTP in the Mill River subbasin and to the Burrillville, R.I. WWTP in the Branch River subbasin). For example, the flow-duration curves for the Branch River at Forestdale, R.I. station indicated that flows decreased by about 17 percent (12 ft^3/s for no water use and 10 ft^3/s for 1996–2001 water use) at the 99-percent flow duration. At the Blackstone River at Woonsocket, R.I. station (fig. 14I), wastewater-return flows increased low flows, but the effect was not as great as at the Blackstone River at Millbury, Mass. station (fig. 14D). At the farthest downstream station, the Blackstone River at Pawtucket, R.I., additional withdrawals from the Abbott Run subbasin were large enough to offset the gain in low flow from wastewater-return flow to flows near those for no-water-use conditions (fig. 14J). Withdrawals and return flows had little effect on medium and high flows at all of these stations (fig. 14). Overall, the results show that the location and magnitude of wastewater-return flows play an important role in offsetting the effects of withdrawals on streamflow in the Blackstone River Basin.

The net effect of 1996–2001 withdrawals and return flows on low flows across the basin also was evaluated by calculating a ratio of the long-term (1960–2004) simulated flow with 1996–2001 water use (scenario 7.0) to the long-term simulated flow with no water use (scenario 8.0). The ratios of the flows at the 90-percent flow duration for all of the reaches in the basin are shown on figure 15. Flow ratios represent total contributing areas upstream of the HSPF subbasins, and thus reflect the cumulative effects of upstream water use. The flow equaled or exceeded 90 percent of the time (90-percent flow duration) represented the minimum daily mean flow expected to occur annually for 1960–2004 climatological conditions. Simulated flows from scenario 8.0 approximated natural flows that would occur in the absence of water use in the basin. If the ratio was less than 1.0, then the net effect of 1996–2001 water use was to deplete streamflow at the 90-percent flow duration relative to streamflow in the absence of water use. Alternatively, if the ratio was greater than 1.0, then the net effect of water use was to increase streamflow relative to streamflow in the absence of water use. Figure 15 shows that the ratios for many reaches, particularly in the southwestern quadrant of the basin, were above about 0.9, indicating that 1996–2001 water use in their respective drainage areas did not deplete low flows substantially. In contrast, flows were more severely depleted in the reaches that contained surface-water supplies for the larger cities in the basin (Worcester, Mass. water supply, KE1A and TA1A; Woonsocket, R.I. water supply, CR1A and CR2A; Pawtucket, R.I. water supply, AB3A). In these reaches, flows with 1996–2001 water use were about 10 percent of flows in the absence of water use; however, it should be noted that these simulated flows did not include reservoir management actions that may have been taken to increase low flows from these subbasins. Along the main stem of the Blackstone River, the ratios were greater than 1.0, decreasing from 2.6 in the headwaters to 0.98 at the mouth. This pattern reflected the large discharge of treated wastewater to the Blackstone River by the UBWWTF in reach 15 and subsequent dilution by nonwastewater inflows in the downstream direction.

It should be noted that, although entire HSPF subbasins are shaded for illustrative purposes, the ratios shown on figure 15 are most applicable to the rivers and larger tributary streams in their respective subbasins, and that the values of the ratios represent flows at the downstream ends of these subbasins, where streamflow is computed by the model; moreover, it should be noted that the effects of water use may be substantially different (more or less severe) on the smaller streams within the HSPF subbasins.

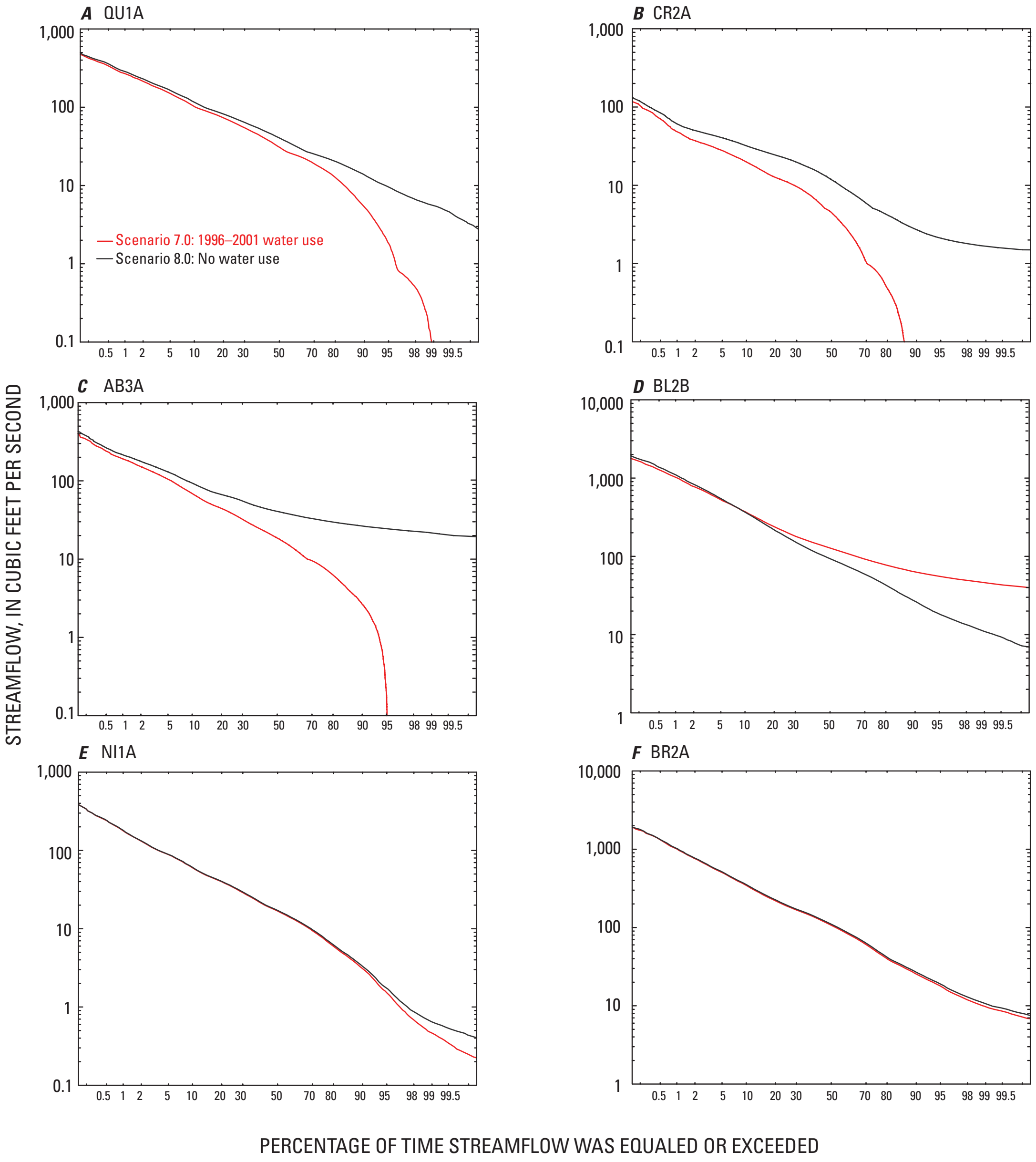


Figure 14. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with no water use (scenario 8.0), and 1996–2001 water use (scenario 7.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged); (*C*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*D*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*E*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*F*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*G*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*H*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*I*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); and (*J*) Blackstone River at Pawtucket, R.I. (BL13, 01113895). Streamflow was simulated with 1995–1999 land use for both scenarios.

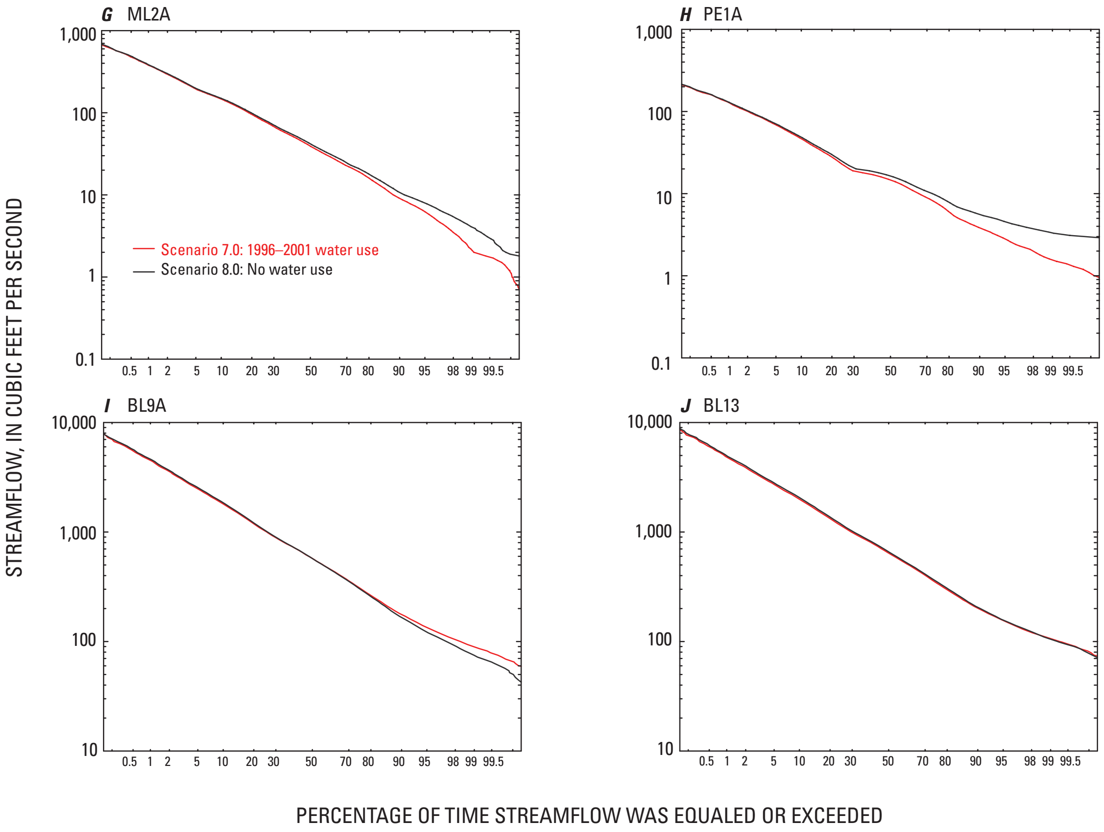
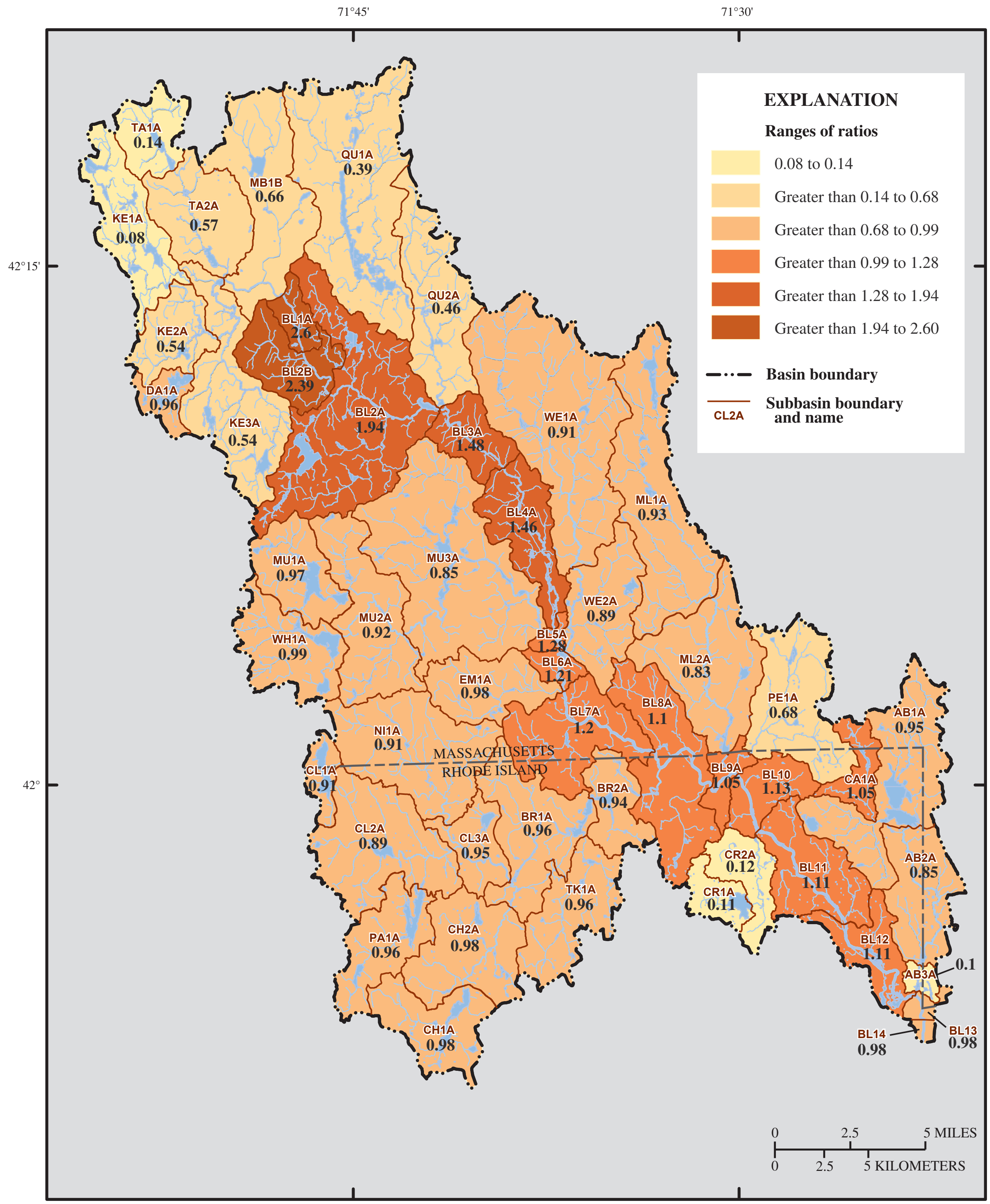


Figure 14. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with no water use (scenario 8.0), and 1996–2001 water use (scenario 7.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged); (*C*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*D*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*E*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*F*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*G*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*H*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*I*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); and (*J*) Blackstone River at Pawtucket, R.I. (BL13, 01113895). Streamflow was simulated with 1995–1999 land use for both scenarios.—Continued



Base from U.S. Geological Survey, 1:24,000, 1995
Massachusetts state plane projection, NAD83

Figure 15. Ratios of long-term (1960–2004) simulated flows with 1996–2001 water use (scenario 7.0) to long-term simulated flows with no water use (scenario 8.0) for the Hydrological Simulation Program—FORTRAN (HSPF) reaches in the Blackstone River Basin. Simulated flows are daily mean flows equaled or exceeded 90 percent of the time. Ratios represent total contributing areas upstream of HSPF subbasins. Low values indicate decreases and high values increases in streamflow with 1996–2001 water use relative to streamflow with no water use.

Potential Water Use at Buildout

The effects of possible increases in withdrawals and wastewater-return flows were evaluated by comparing two long-term scenarios, both with potential land use at buildout: 1996–2001 water use (scenario 10.0) and potential water use at buildout (scenario 12.0). Although withdrawals were estimated to increase in most subbasins at buildout (table 11 at back of report), corresponding increases in wastewater-return flows resulted in similar flow-duration curves for the two scenarios at most of the stations shown on figure 16. The exceptions were the Quinsigamond River at North Grafton, Mass. station (fig. 16A), the Mill River at Woonsocket, R.I. station (fig. 16B), the Peters River at Woonsocket, R.I. station (fig. 16C), and the Abbott Run at Pawtucket station (fig. 16D). In the contributing areas to these stations, new demands were mainly in areas with public sewer systems and new return flows were exported out of the subbasins for treatment (table 12). As a result, low flows at buildout increasingly declined at flow durations above 50 percent compared to flows for 1996–2001 water-use conditions. Under the assumptions used to develop the buildout scenario, all potential new demands in the areas served by the Woonsocket surface-water supply system in Crookfall Brook (CR2A) would be met by increased rates of transfer from the supplemental surface-water supply at Harris Pond on the Mill River (ML2A) because Crookfall Brook had little spare capacity to meet new demands. Consequently, potential new withdrawals at buildout in the Mill River reflected new demands both in the Mill River drainage area (mainly from medium- to low-density residential development) and the greater Woonsocket area, and increased from an annual average of 1.3 Mgal/d in 1996–2001 to 3.8 Mgal/d at buildout. Thus, for this scenario, low flows in the Mill River were substantially reduced at buildout (fig. 16B), whereas low flows in Crookfall Brook remained largely unchanged (fig. 16E).

The smaller declines in low flows at the Branch River at Forestdale, R.I, (fig. 16F) and Nipmuc River near Harrisville, R.I. (fig. 16G) stations were caused by small consumptive losses in potential new residential areas with private wells and on-site septic systems. The flow-duration curves for the Blackstone River at Millbury, Mass. station (fig. 16H) were similar because it was assumed that all of the new demand in the area served by the Worcester water supply would be satisfied by increased rates of transfer from Kendall Reservoir in the Nashua River Basin. The flow-duration curves for the Blackstone River at Woonsocket, R.I. (fig. 16I) and the Blackstone River at Pawtucket, R.I. stations (fig. 16J) reflected a rough balance between new withdrawals and wastewater-return flows at buildout; the resulting effect on low flows was therefore small, and flow-duration curves for potential buildout water use were similar to the curves for 1996–2001 water use. In general, because the buildout simulations were based on the assumption that nearly all of the new water withdrawals would be returned to the Blackstone River Basin at WWTPs or septic systems, buildout had only small effects on simulated low flows in the Blackstone River and most of the major tributary streams. The effects of potential buildout water use as represented by scenario 12.0, however, may be more substantial in the smaller tributaries within the HSPF subbasins. The potential effects of buildout are discussed in greater detail in the following section.

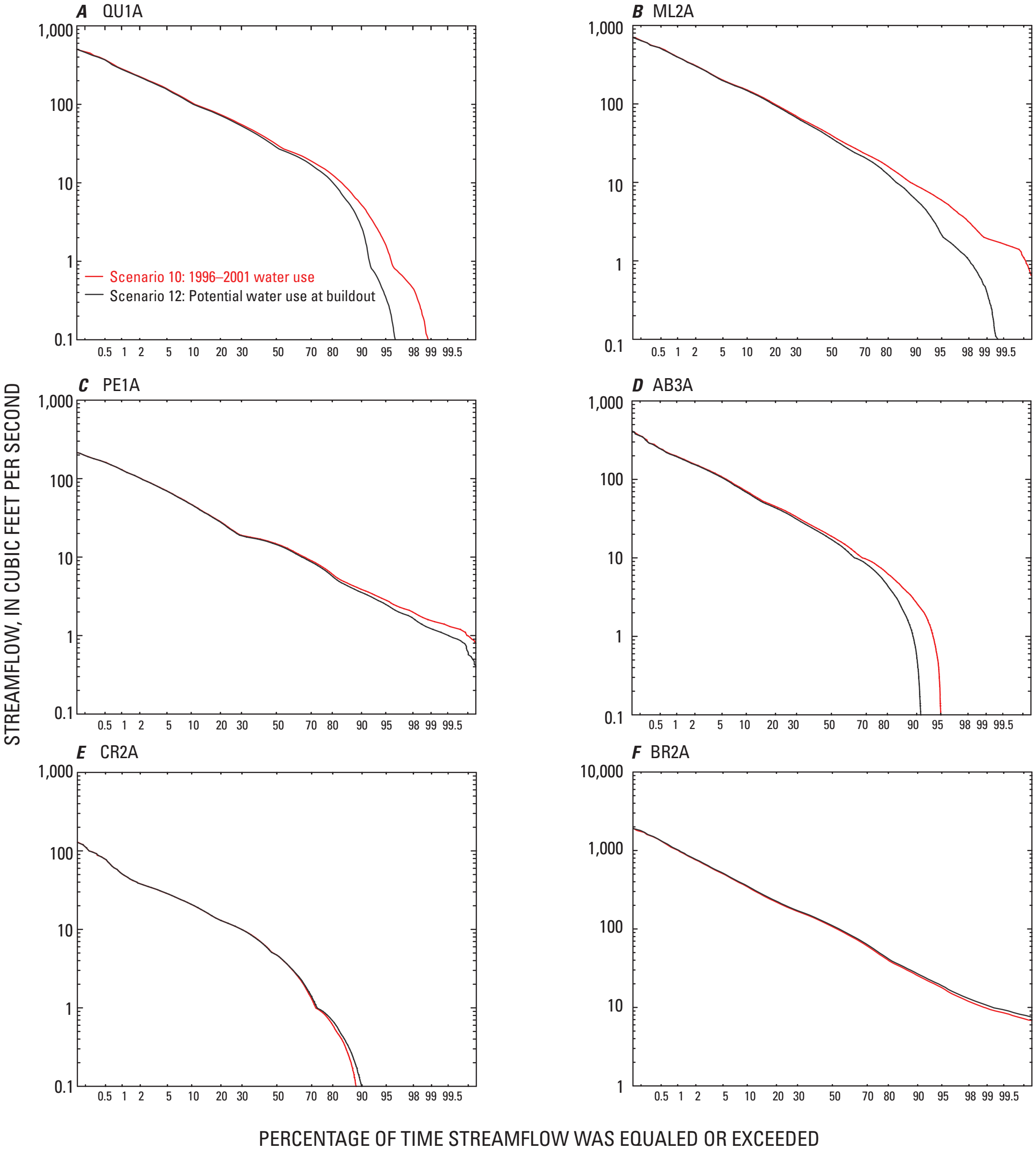


Figure 16. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with 1996–2001 water use (scenario 10.0) and potential water use at buildout (scenario 12.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*C*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*D*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*E*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged); (*F*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*G*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*H*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*I*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); and (*J*) Blackstone River at Pawtucket, R.I. (BL13, 01113895). Streamflow was simulated with potential land use at buildout for both scenarios.

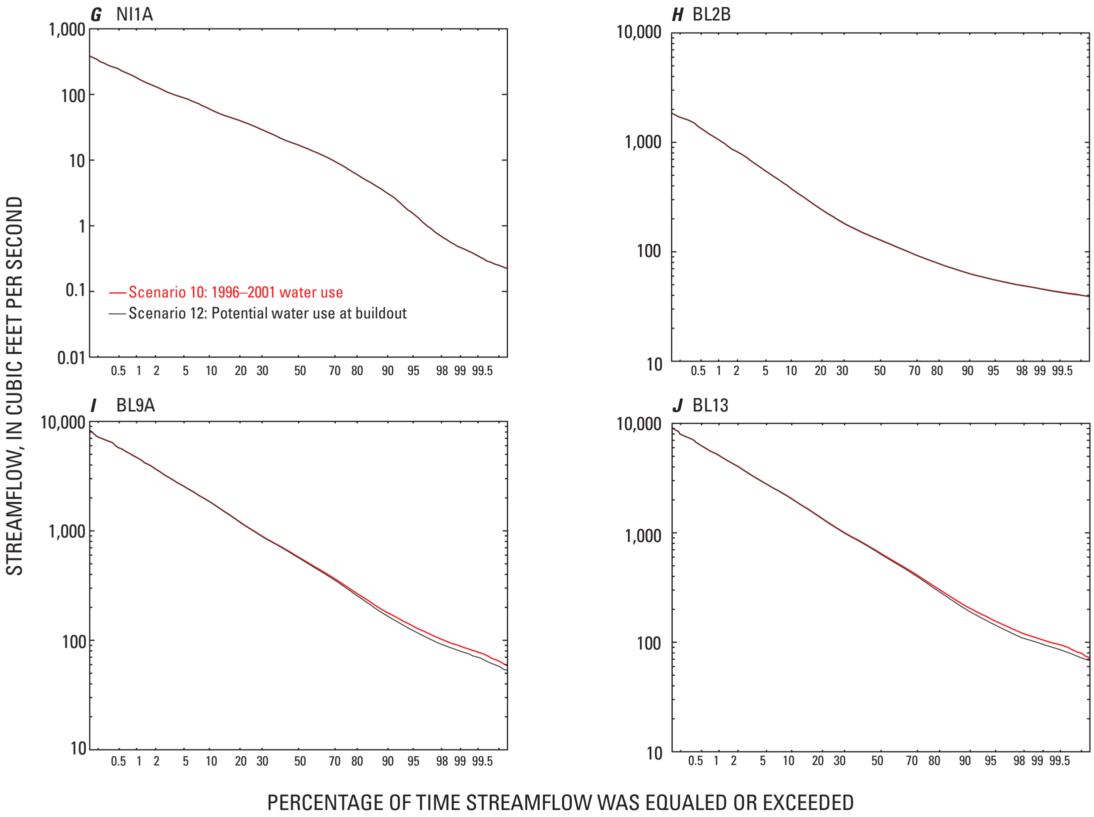


Figure 16. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with 1996–2001 water use (scenario 10.0) and potential water use at buildout (scenario 12.0) at streamflow-gaging stations (*A*) Quinsigamond River at North Grafton, Mass. (QU1A, 01110000); (*B*) Mill River at Woonsocket, R.I., (ML2A, 01112268); (*C*) Peters River at Woonsocket, R.I. (PE1A, 01112382); (*D*) Abbott Run at Pawtucket, R.I. (AB3A, ungaged); (*E*) Crookfall Brook, at Woonsocket, R.I. (CR2A, ungaged); (*F*) Branch River at Forestdale, R.I. (BR2A, 01111500); (*G*) Nipmuc River near Harrisville, R.I. (NI1A, 01111300); (*H*) Blackstone River at Millbury, Mass. (BL2B, 01109730); (*I*) Blackstone River at Woonsocket, R.I. (BL9A, 01112500); and (*J*) Blackstone River at Pawtucket, R.I. (BL13, 01113895). Streamflow was simulated with potential land use at buildout for both scenarios.—Continued

Scenarios Focused on the Rhode Island Part of the Basin

A series of water-resources management issues affecting the Rhode Island part of the Blackstone River Basin was identified by the USGS in consultation with the TAC formed for the project. These issues generally involve changes in streamflow caused by withdrawals and wastewater-return flows. Results from the simulations of the basin-scale scenarios described above and specific scenarios that are focused on subbasins in Rhode Island were used to evaluate these issues.

Withdrawals and Wastewater-Return Flows in Relation to Simulated Streamflow

Rates of water withdrawals and wastewater-return flows are not evenly distributed across the basin. To evaluate the effects of water use on streamflow in the rivers and major tributary streams in the Rhode Island part of the basin in greater detail, the magnitudes of water withdrawals and wastewater-return flows were calculated in relation to streamflow as unique ratios for individual HSPF subbasin contributing areas, and total contributing areas to major tributary streams. Dimensionless ratios of total water-withdrawal rates, total wastewater-return-flow rates, and total withdrawal rates minus total return-flow rates (net rates) to simulated streamflow with no water use (all rates in ft^3/s) were calculated for recent (1996–2001) water use and potential water use at buildout; all streamflows were computed from long-term (1960–2004) simulations. Ratios were computed for individual HSPF subbasins, the total contributing areas to HSPF subbasins (representing the cumulative effects of all withdrawals and return flows), and the contributing areas to the major tributaries in Rhode Island: Chepachet River, Clear River, Branch River, Crookfall Brook, Mill River, Peters River, and Abbott Run.

Ratios are a measure of the magnitudes of the rates of withdrawals or return flows relative to streamflow in the absence of water use. A withdrawal ratio of 0.5 indicates that average summer withdrawals deplete the median of average summer streamflow by 50 percent (methods used to calculate withdrawals, return flows, and streamflow are described below). Although the absolute values of withdrawal ratios based on medians of average summer streamflows are not appropriate for assessing water availability during the lowest-flow periods of the year, the spatial distribution of the ratios among the subbasins provides relative information about the effects of withdrawals on streamflow in the Rhode Island part of the basin. In a relative sense, subbasins with high withdrawal ratios have the lowest potential for future development of water supplies, whereas subbasins with low ratios have the highest potential for development; however, it should be noted that site-specific investigations are needed to determine the optimal location for new supplies and to estimate the effects of new and existing withdrawals on nearby stream reaches. A return-flow ratio of 0.5 indicates that average summer wastewater-return flows are 50 percent of the median of average summer streamflow. Wastewater-return flows from septic systems and WWTPs can offset the effects of withdrawals on low flows (depending on the location of the withdrawals and return flows in relation to the point of interest on the stream), but the offset can have deleterious effects on water quality. Thus, the spatial distribution of return-flow ratios among the subbasins provides relative information about the effects of wastewater-return flows on both streamflow and water quality in the Rhode Island part of the basin.

Computing ratios for withdrawals and return flows separately shows the relative effects of each of these types of water use on a stream reach but provides no information on the net effect of water use on the rate of streamflow. The ratios of net rates (withdrawals minus return flows) to streamflow represent the combined effects of withdrawals and return flows and identify reaches where, although the overall effect on streamflow is small, water quality may be affected by the return flow of wastewater. For example, a reach with a withdrawal ratio of 0.5 and a return-flow ratio of 0.5 has a net ratio of zero (no effect on streamflow relative to no-water-use conditions), but 50 percent of the streamflow is composed of treated wastewater. A negative net ratio indicates that return flows exceed withdrawals, so that there is a net gain of water to the reach and actual flows are larger than flows in the absence of water use.

Total withdrawal, return-flow, and simulated streamflow information was compiled for the summer season (June through September) to calculate ratios for low-flow periods when demands peak. Average June through September (hereafter referred to as "summer") withdrawal rates generally were about 20 percent higher than average annual withdrawal rates (table 15 at back of report). The summer season is when withdrawals have the greatest effect on streamflow and wastewater-return flows have the greatest effect on water quality. Average June through September (summer) streamflow was used in this analysis to represent low-flow conditions. Streamflow was simulated for long-term (1960–2004) climatological conditions to represent (1) 1995–1999 land use with no withdrawals or wastewater-return flows (scenario 8.0), and (2) buildout land use with no withdrawals or wastewater-return flows (scenario 11.0). For each subbasin in Rhode Island, the average summer streamflow was calculated as the mean of the monthly mean flows for each year in the long-term simulation. The median (50th percentile) of these flows then was used to represent typical summer streamflow (tables 16 and 17 at back of report). For the analysis of individual subbasins, median flows from upstream subbasins were subtracted to represent streamflow produced by runoff from the subbasin area only.

It should be noted that the ratios discussed below are most applicable to the rivers and larger tributary streams in their respective HSPF subbasins, and that the values of the ratios represent flows at the downstream ends of these subbasins, where streamflow is computed for the reach by the model; moreover, it should be noted that the effects of water use may be substantially different (more or less severe) on the smaller streams within the HSPF subbasins.

Withdrawal Ratios in HSPF Subbasins

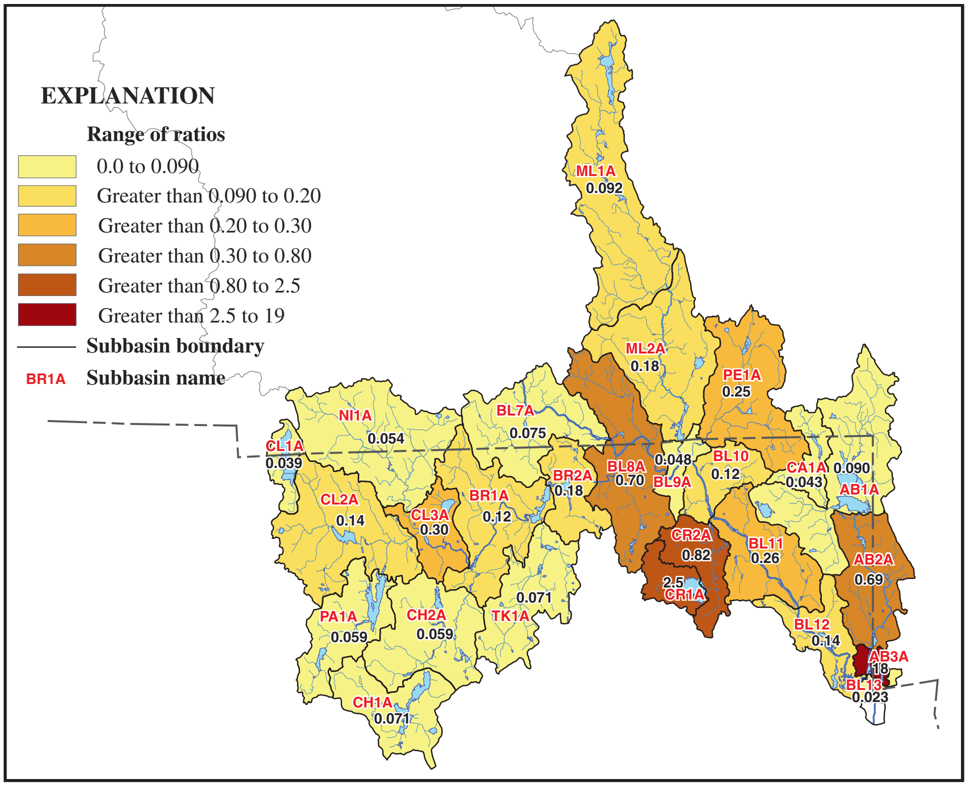
The total withdrawal rate from an area was calculated as the sum of the withdrawals explicitly represented in the HSPF model: municipal and commercial/industrial withdrawals, residential withdrawals from areas with private wells and public sewer systems (exports), and the infiltration of water into the public sewer system (Barbaro and Zarriello, 2006). For each subbasin, the average summer withdrawal rate was calculated from the monthly mean withdrawal rate from the subbasin. Average withdrawal rates for 1996–2001 were used to represent recent conditions, whereas potential increases in withdrawals at buildout were used to represent buildout conditions. Residential withdrawals from areas with private wells and public sewer systems were represented by a constant rate. (See the “Water Use” section of this report). Because residential land use potentially increases at buildout, residential withdrawal rates were higher in most subbasins at buildout compared to recent conditions. The baseline model accounted for infiltration of water into public sewer systems (Barbaro and Zarriello, 2006). For each subbasin, an annual average sewer-infiltration rate was calculated from a long-term (1960–2004) simulation. Because it was assumed that the sewer system would not expand to a great extent into rural areas at buildout, the total sewer-infiltration rate for the basin was held constant. In most subbasins, the municipal and commercial withdrawals were substantially larger than either the residential withdrawals or the sewer infiltration.

Ratios of total withdrawals to the medians of average summer streamflows for recent conditions (1996–2001 withdrawals and 1995–1999 land use) ranged from 0.023 to 18 with a median value of 0.12 for individual HSPF subbasins (fig. 17A; table 16). These withdrawal ratios (hereafter referred to as W/Q ratios) were largest in the subbasins with major municipal water-supply withdrawals. If the W/Q ratio is greater than 1.0, withdrawals exceed average summer streamflow in the subbasin, indicating that water is withdrawn from reservoir storage (in headwater subbasins) or that streamflow from upstream subbasins is required to meet the demand. For example, the largest W/Q ratios were calculated in the Crookfall Brook subbasins where summer water-supply withdrawals for Woonsocket, R.I. averaged 5.5 Mgal/d (CR1A, ratio=2.5 and CR2A, ratio=0.82), and the Abbott Run subbasin where summer water-supply withdrawals for Pawtucket, R.I. averaged 13.6 Mgal/d (AB3A, ratio=18). The large W/Q ratio for AB3A indicated that water in surface-water reservoirs in subbasin AB1A was used during the summer. Other subbasins with high W/Q ratios included BL8A (ratio=0.70), where Ocean State Power withdrawals from the Blackstone River averaged 2.3 Mgal/d, and AB2A (ratio=0.69), where summer water-supply withdrawals for North Attleboro, Mass., Cumberland, R.I., and Pawtucket, R.I averaged 2.8 Mgal/d. Municipal and commercial withdrawal rates are listed in table 15.

A comparison of W/Q ratios for individual subbasins (fig. 17A) with those reflecting streamflow and withdrawals for total contributing areas (fig.17B) shows that, with the exception of the headwaters subbasins, decreased when upstream flows and withdrawals were included. W/Q ratios for total contributing areas ranged from 0.039 to 2.5 with a median value of 0.11. W/Q ratios decreased the most for subbasins along the Blackstone River because of the large volume of streamflow from upstream runoff compared to cumulative upstream withdrawals (fig. 17B; table 16. For example, the ratio for subbasin BL8A dropped from 0.70 to 0.18 when cumulative upstream flows and withdrawals were included (fig. 17B). W/Q ratios for the Crookfall Brook subbasins (CR1A and CR2A) remained above 1.0 even when streamflow from the total contributing area was included (fig. 17B); this result indicates that the average summer withdrawal rate remained greater than the average summer streamflow. Thus, on average, additional water would be necessary to meet demand. In this instance, water was obtained from simulated transfers from Harris Pond (subbasin ML2A) and reservoir storage. Figure 17 illustrates that the smallest W/Q ratios were calculated for the rural areas in the Branch River drainage area in the southwestern part of the basin (for example, subbasins CL1A, CL2A, CL3A, NI1A, PA1A, CH1A, CH2A, and TK1A.

Barlow (2003) calculated ratios of average monthly withdrawals from surface and ground water for 1995–1999 to estimates of available water for six large subbasins in the lower part of the basin. Available water was computed as monthly base flows estimated from flows at the Branch River at the Forestdale, R.I., streamflow-gaging station (01111500) minus specific minimum instream flows. In the current study, simulated streamflow values were available for many more locations (that is, at the downstream ends of the model reaches), and the emphasis of the analysis was on the spatial distribution of the W/Q ratios in the Rhode Island part of the basin rather than the relation between monthly withdrawals and water availability in the subbasins of the major tributary streams. Although the drainage areas and methods used to calculate the ratios of withdrawals to streamflow differed somewhat between the two studies, the spatial distribution and magnitudes of the ratios for the contributing areas to the major tributary streams are consistent (table 16; Barlow, 2003, fig. 13, p. 44).

A INDIVIDUAL HSPF SUBBASINS



B TOTAL CONTRIBUTING AREAS

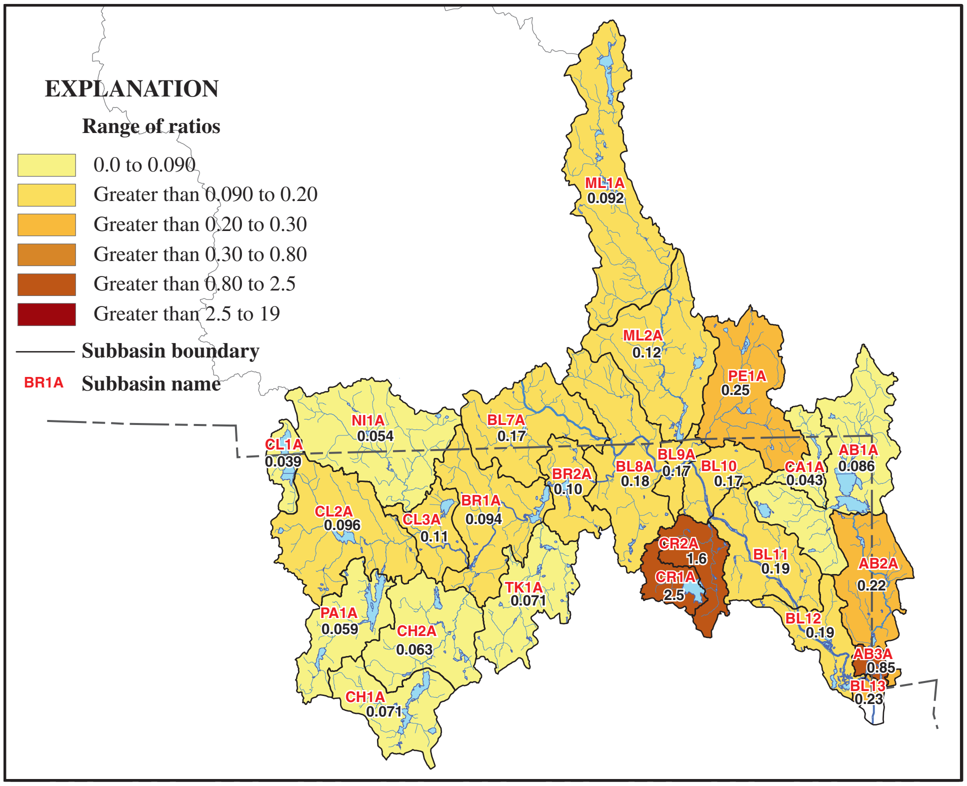


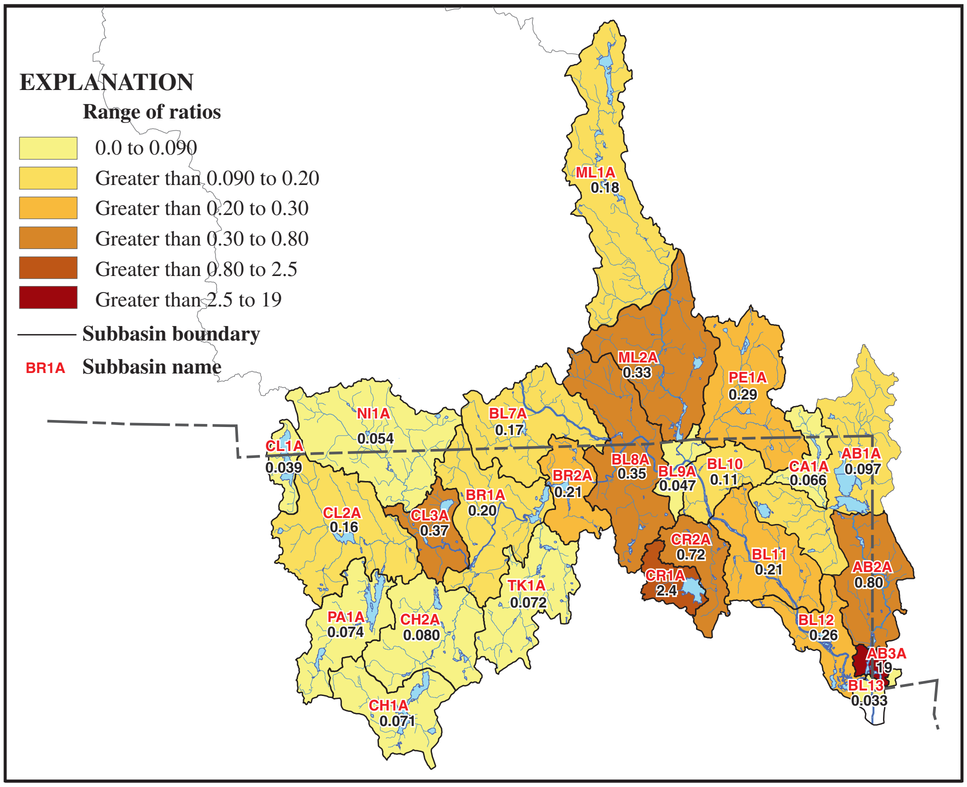
Figure 17. Ratios of average summer withdrawals for 1996–2001 to the medians of simulated average summer streamflows for the period 1960–2004 for (*A*) individual Hydrological Simulation Program—FORTRAN (HSPF) subbasin contributing areas, and (*B*) total contributing areas to HSPF subbasins in the Rhode Island part of the Blackstone River Basin. Streamflow was simulated with 1995–1999 land use and no withdrawals or wastewater-return flows.

At buildout, W/Q ratios ranged from 0.033 to 19 with a median value of 0.19 in individual subbasins (fig. 18A; table 17 in back of report). In comparison to recent conditions, W/Q ratios increased for 18 of 26 subbasins, remained unchanged for 3 subbasins, and decreased for the remaining 5 subbasins (tables 16 and 17). W/Q ratios remained constant or declined because of negligible new withdrawals or higher average summer streamflow computed from long-term simulations with potential land use at buildout (scenario 11.0) or both. W/Q ratios decreased mostly for subbasins along the main stem of the Blackstone River where new demands were estimated to be relatively modest and average summer streamflows simulated with potential land use at buildout were estimated to be higher than average summer streamflows simulated with 1995–1999 land use. When total contributing areas were included, W/Q ratios increased for 21 of 26 subbasins, remained constant for 3 subbasins, and decreased for 2 subbasins (figs. 17B and 18B). Thus, W/Q ratios generally were higher at buildout; this result indicates the potential for greater effects on streamflow compared to recent conditions. The pattern of potential new withdrawals generally corresponded to the pattern of potential new residential and commercial development, which generated the new demand.

The relative change in W/Q ratios, calculated for total contributing areas to the subbasins and expressed as percent differences between recent and potential buildout conditions, ranged in magnitude from -13 percent (CR2A) to 67 percent (ML2A) (fig. 19). Small absolute differences in W/Q ratios between recent and potential buildout conditions may result in large changes in the percent difference if the W/Q ratio is small. It should be noted that the large percent increases for subbasins with small W/Q ratios in 1996–2001 would likely have only minor effects on streamflow. The largest percent increases were for the subbasins to the Mill River (ML1A and ML2A) and Catamint Brook (CA1A). The increases were in response to substantial potential new residential development in the Mill River subbasin, and increased rates of water transfer from Harris Pond in ML2A to Crookfall Brook Reservoir No. 1 in response to new demands in the Woonsocket area. W/Q ratios decreased slightly in the Crookfall Brook subbasins (CR1A and CR2A) because it was assumed in the buildout scenario that all new demands on this reservoir system would be met by interbasin transfers, and because the simulated average summer streamflow was slightly higher at buildout. The assumption that new demands in the Woonsocket area would be met by increased transfer rates from Harris Pond is consistent with the analysis of Barlow (2003), who showed that the 5-yr average demand for 1995–1999 was 136 percent of the safe yield of the Crookfall Brook reservoir system; thus, the system would have little capacity to meet new demands.

Subbasins for the Branch River (BR1A and BR2A) and the Blackstone River near the state line (BL7A, BL8A, BL9A, and BL10) also had large changes in the W/Q ratios, but these changes generally were more substantial in absolute terms. Changes in these subbasins were mostly in response to potential new development in the Branch River subbasins and in Massachusetts.

A INDIVIDUAL HSPF SUBBASINS



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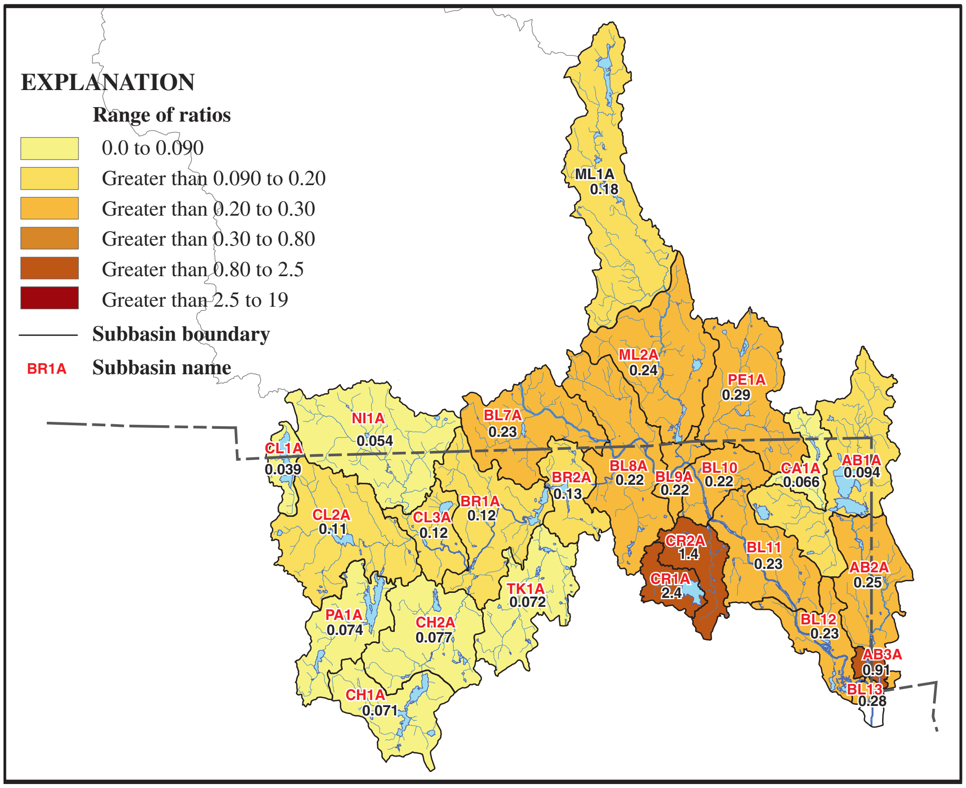


Figure 18. Ratios of potential average summer withdrawals at buildout to the medians of simulated average summer streamflows for the period 1960–2004 for (*A*) individual Hydrological Simulation Program—FORTRAN (HSPF) subbasin contributing areas, and (*B*) total contributing areas to HSPF subbasins in the Rhode Island part of the Blackstone River Basin. Streamflow was simulated with potential land use at buildout and no withdrawals or wastewater-return flows.

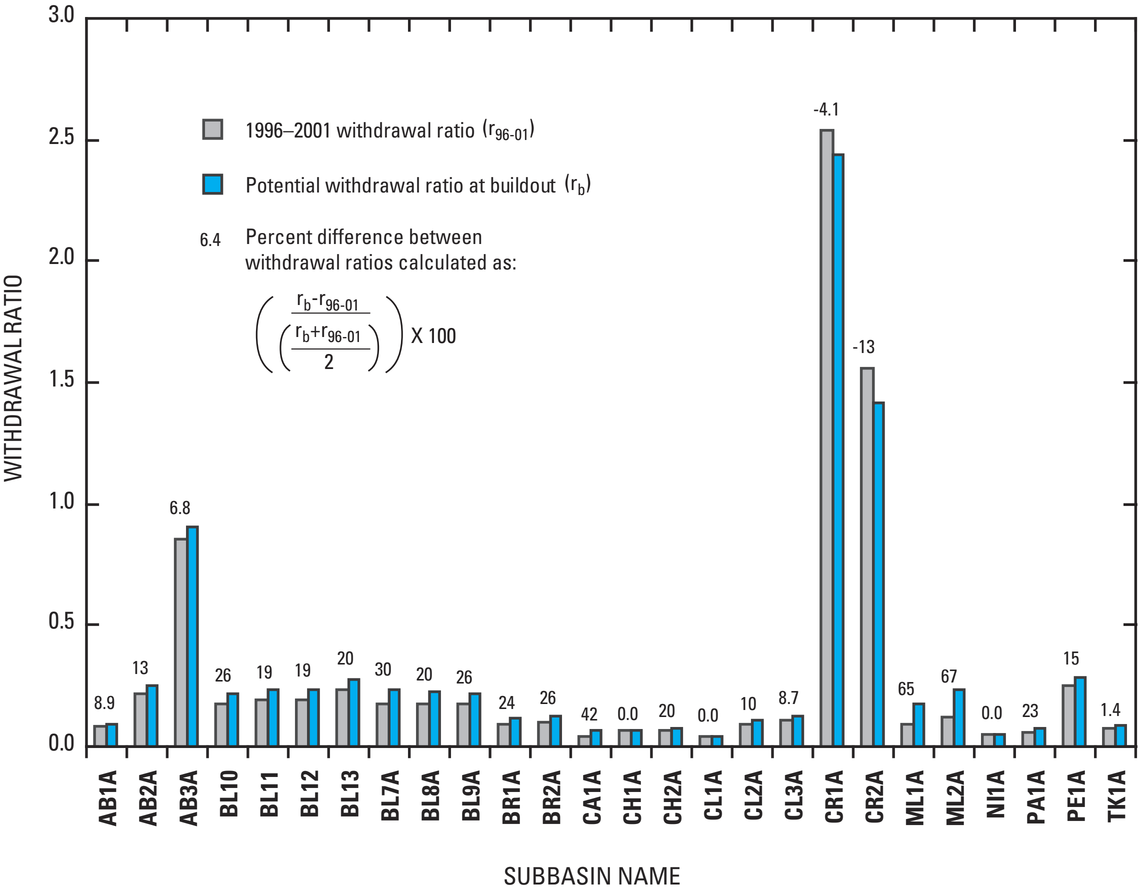


Figure 19. Comparison between withdrawal ratios in 1996–2001 and potential withdrawal ratios at buildout for total contributing areas to Hydrological Simulation Program—FORTRAN (HSPF) subbasins in the Rhode Island part of the Blackstone River Basin. Numbers are percent differences between the 1996–2001 ratios and buildout ratios.

Return-Flow Ratios in HSPF Subbasins

The total return-flow rate to an area was calculated as the sum of the return flows that are explicitly represented in the HSPF model: municipal and commercial/industrial wastewater-return flows, and residential return flows from areas with public water and on-site septic systems (imports). For each subbasin, the average summer return-flow rate was calculated from the monthly mean return-flow rate to the subbasin (table 15). Averages were computed for 1996–2001 return flows and potential return flows at buildout. In contrast to withdrawal rates, average summer return-flow rates generally were about 10 percent less than average annual return-flow rates (table 15). This is believed to reflect decreases in infiltration of ground water to public sewers because the water table typically is lower during the summer months and possibly losses of effluent from the sewer system to the subsurface in areas where the water table falls below the sewer invert. Residential septic return flows to areas with public water and on-site septic systems were represented by a constant rate. (See the “Water Use” section of this report). Because the analysis indicated an increase in the percentage of residential land in most subbasins, residential wastewater-return-flow rates were higher at buildout than under recent conditions.

Ratios of total return flows to the medians of average summer streamflows (herein referred to as the R/Q ratio) for recent conditions (1996–2001 return flows and 1995–1999 land use) ranged from 0.0 to 1.8 with a median value of 0.012 for individual HSPF subbasins (fig. 20A; table 16). The R/Q ratios were largest for subbasins on the Clear River and Blackstone River where municipal WWTPs are located (BL10, ratio=1.8, Woonsocket WWTP; CL3A, ratio=0.36, Burrillville WWTP; and BL7A, ratio=0.12, Uxbridge WWTP) and for the downstream subbasin on Abbott Run (AB3A, ratio=0.36). The R/Q ratios generally were low for the other subbasins and were zero for NI1A, CL1A, and CH1A (table 16). In comparison to individual subbasins, the R/Q ratios calculated for total contributing areas increased for the Blackstone River and Branch River subbasins, and generally remained unchanged for the other subbasins (figs. 20A and 20B). R/Q ratios for total contributing areas ranged from 0.0 to 0.20 with a median value of 0.029. In contrast to the W/Q ratios, R/Q ratios were largest for the subbasins along the Blackstone River (fig. 20B) because of upstream wastewater-return flows from WWTPs in Massachusetts. R/Q ratios calculated for the total contributing areas in the Blackstone River subbasins were roughly five times higher than for the surrounding subbasins. Thus, of the major rivers in the Rhode Island part of the basin, the main stem of the Blackstone River was most affected by wastewater-return flows.

At buildout, R/Q ratios ranged from 0.0 to 1.8 with a median value of 0.019 for individual HSPF subbasins. (fig. 21A; table 17). R/Q ratios increased compared to recent conditions for 14 of 26 subbasins, remained unchanged for 8 subbasins, and decreased for 4 subbasins (tables 16 and 17). Similar to changes in W/Q ratios, the R/Q ratios increased the least for subbasins along the Blackstone River as a result of slightly higher summer streamflows simulated with potential land use at buildout. For total contributing areas, R/Q ratios increased for 22 of 26 subbasins and remained constant for the remaining 4 subbasins. Thus, as indicated by potential land-use changes, the buildout analysis indicated the potential for spatially widespread increases in wastewater-return flows to rivers and tributary streams in response to development.

The relative change in R/Q ratios, calculated for total contributing areas to the subbasins and expressed as percent differences between the ratios for recent and potential buildout conditions, ranged in magnitude from 0 percent (CL1A, NI1A, CH1A, and TK1A) to 183 percent (CR1A) (fig. 22). The largest percent increases were for the Mill River (ML1A and ML2A), Branch River (BR1A and BR2A), Chepachet River (PA1A), and Crookfall Brook (CR1A and CR2A) subbasins in response to potential new residential development at buildout. The absolute change in the R/Q ratio in most subbasins with a large percentage change, however, was relatively low (for example, CR1A, CR2A and PA1A). The changes in R/Q ratios for subbasins along the Blackstone River were small as percentage changes but large as absolute changes compared to most other subbasins. For the older, established urban centers such as Worcester, percent increases in rates of wastewater-return flow over 1996–2001 rates were small compared to increases for areas with more extensive new growth; for example, the percent increase for the return-flow rate to UBWWTF in Millbury, Mass. potentially will be 9 percent, whereas the percent increase for the return-flow rate to the Northbridge WWTP potentially will potentially be 102 percent. The absolute increase in the wastewater-return flow rate at the UBWWTF, however, likely will be larger at buildout than the increases at the other WWTPs in the basin (table 12).

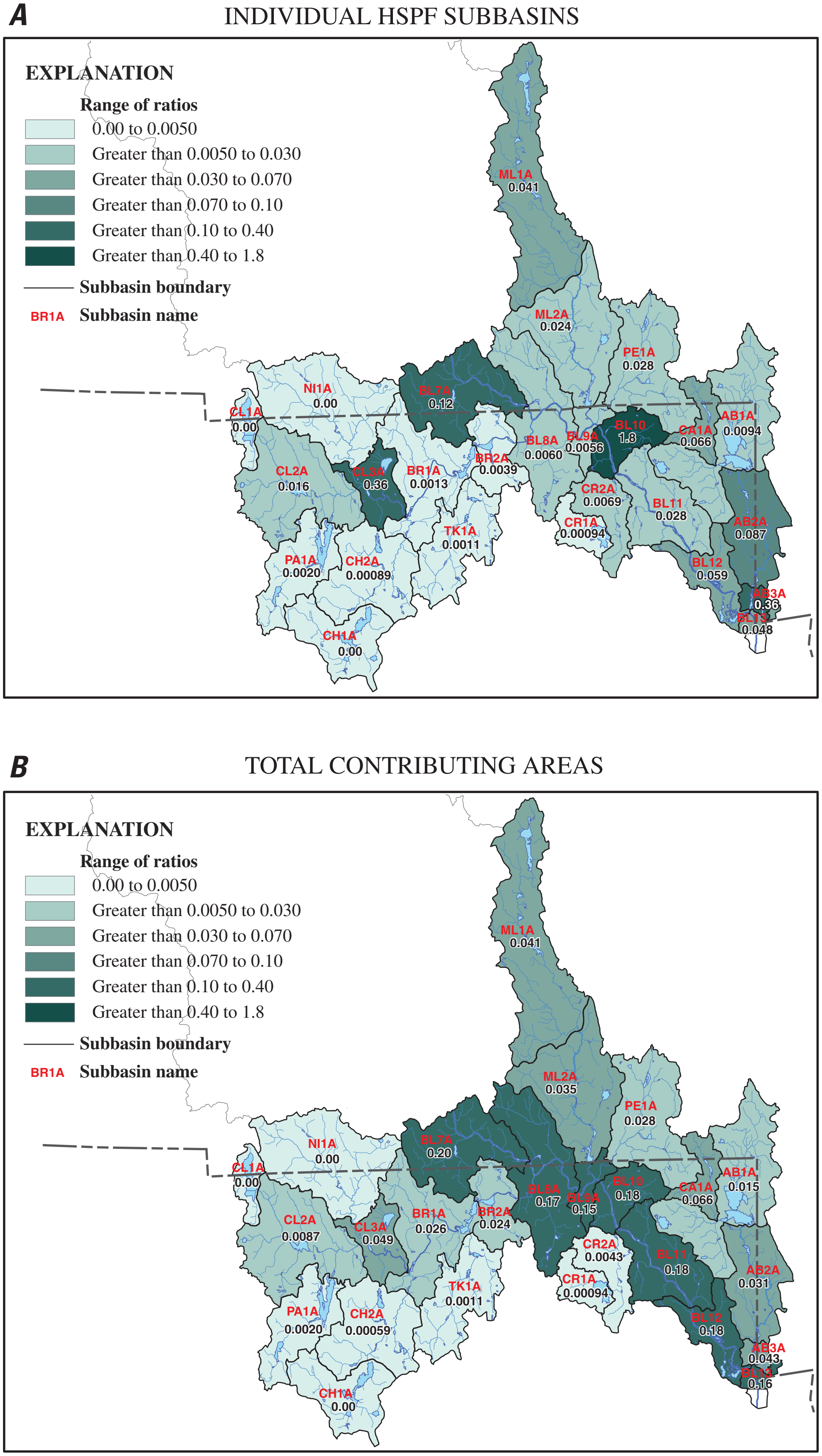
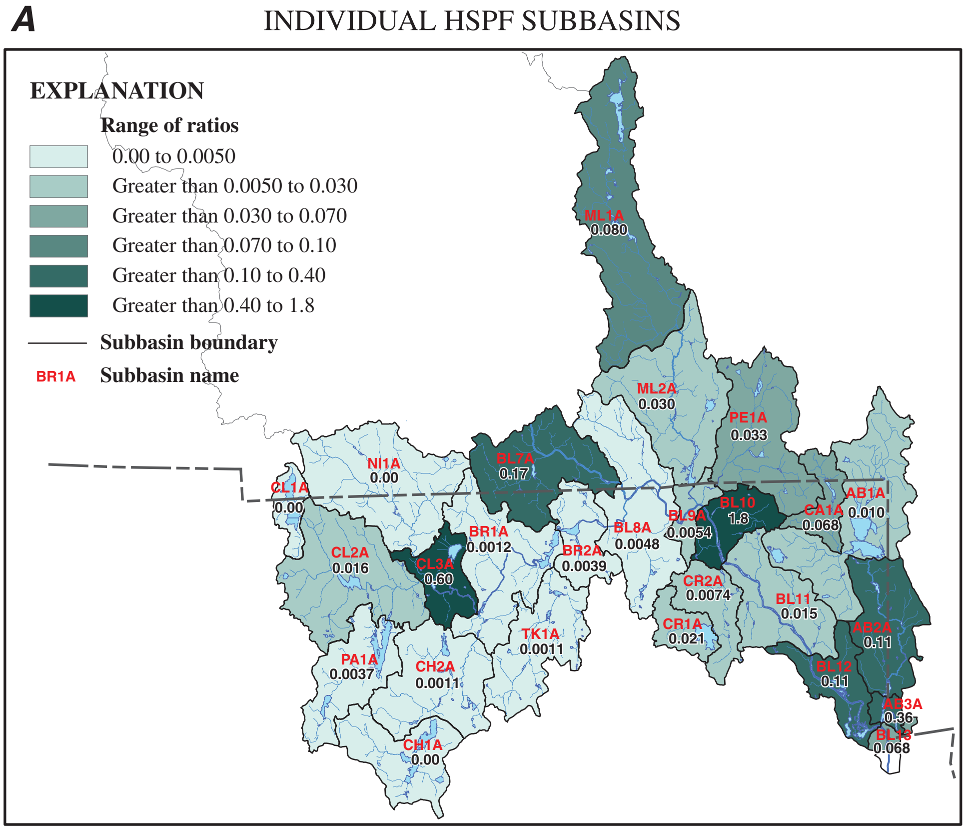


Figure 20. Ratios of average summer wastewater-return flows for 1996–2001 to the medians of simulated average summer streamflow for the period 1960–2004 for (*A*) individual Hydrological Simulation Program—FORTRAN (HSPF) subbasin contributing areas, and (*B*) total contributing areas to HSPF subbasins in the Rhode Island part of the Blackstone River Basin. Streamflow was simulated with 1995–1999 land use and no withdrawals or wastewater-return flows.



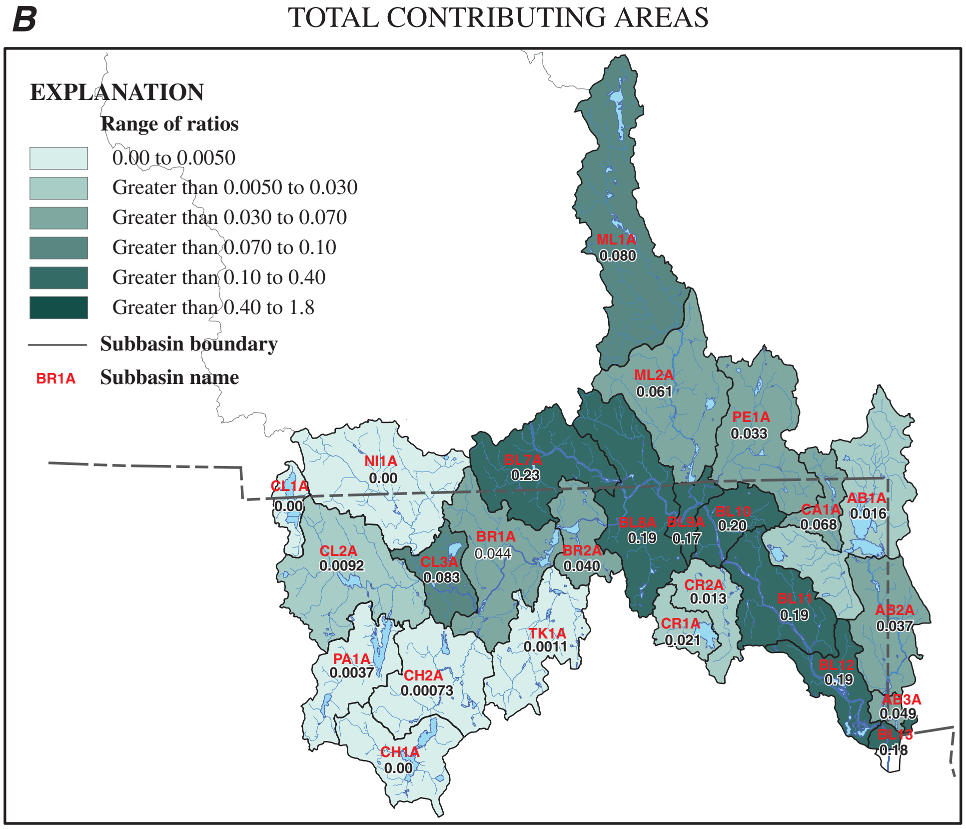


Figure 21. Ratios of potential average summer wastewater-return flows at buildout to the medians of simulated average summer streamflow for the period 1960–2004 for (*A*) individual Hydrological Simulation Program—FORTRAN (HSPF) subbasin contributing areas, and (*B*) total contributing areas to HSPF subbasins in the Rhode Island part of the Blackstone River Basin. Streamflow was simulated with potential land use at buildout and no withdrawals or wastewater-return flows.

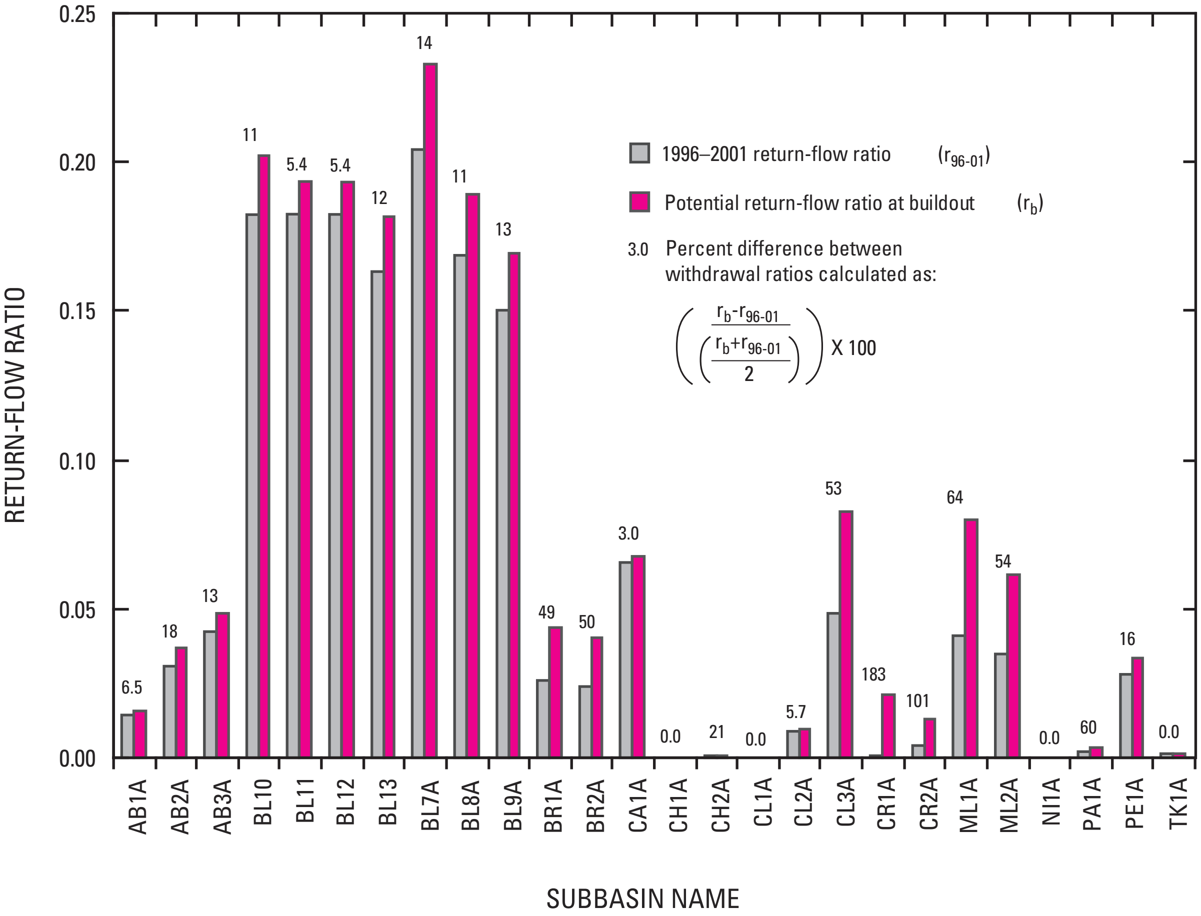


Figure 22. Comparison between wastewater-return-flow ratios in 1996–2001 and potential wastewater-return-flow ratios at buildout for total contributing areas to Hydrological Simulation Program—FORTRAN (HSPF) subbasins in the Rhode Island part of the Blackstone River Basin. Numbers are percent differences between the 1996–2001 ratios and buildout ratios.

Ratios Based on the Difference between Withdrawals and Wastewater-Return Flows (Net Ratios) in HSPF Subbasins

Nearly all of the subbasins in the Rhode Island part of the Blackstone River Basin had both withdrawals and return flows. The net ratios, defined as the differences between withdrawals and wastewater-return flows divided by the medians of the average streamflow for June through September, are listed in tables 16 and 17 for the Rhode Island subbasins. For most of these subbasins, withdrawals were considerably larger than return flows, so the offset by return flows was small. For the subbasins along the Blackstone River, however, net ratios computed for total contributing areas were negative to slightly above zero for recent and potential buildout conditions (tables 16 and 17). Thus, wastewater return flows mainly from the Massachusetts part of the basin appear to largely offset the effects of withdrawals on the rate of streamflow during the summer months. This result is also observable in the ratios of the simulated 1996–2001 flows to no-water-use flows at the 90-percent flow duration (fig. 15), and is discussed further in the “Contribution of Wastewater-Return Flows to Streamflow in the Blackstone River” section of the report.

Effects of Conservation Measures on Streamflow

A simulation was run to evaluate the effects of potential water-conservation measures on low flows in rivers and major tributary streams in the Rhode Island part of the Blackstone River Basin (table 13). During the summer months (June through September) when streamflows are at seasonal lows, withdrawals typically increase and wastewater-return flows typically decrease. For example, for 1996–2001, average annual municipal and commercial/industrial withdrawals in Rhode Island totaled 27.9 Mgal/d (43.2 ft^3/s), whereas average summer withdrawals for these categories totaled 31.7 Mgal/d (49.0 ft^3/s), a percent increase of about 14 percent (table 15). For the same period, average annual municipal and commercial wastewater-return flows totaled 13.2 Mgal/d (20.5 ft^3/s), whereas average summer return flows totaled 12.3 Mgal/d (19.0 ft^3/s), a percent decrease of 8 percent (table 15). The coincidence of peak demands and reduced return flows with normally low streamflows may create conditions in parts of the basin where stream habitat, recreational activities, and wastewater dilution are adversely affected. During drought conditions in particular, streams in the reaches with the highest W/Q ratios may have little or no flow, and ground-water levels may decline appreciably. Under these circumstances, water-conservation measures can be critical in maintaining streamflow.

A long-term (1960–2004) simulation (scenario 13.0) was run to obtain streamflow over a range of climatological conditions, including several drought years. To simulate reduced withdrawals with the HSPF model, all withdrawals explicitly simulated in the model for 1996–2001 were reduced by 20 percent to represent greater efficiency in water use. A reduction of 20 percent is in the range of 10 to 30 percent reductions in water use considered feasible for residents of Rhode Island (Rhode Island Water Resources Board, oral commun., 2006). The simulated withdrawals included the total municipal, commercial/industrial and golf-course withdrawals and the withdrawals from residential areas with private wells and public sewer systems. Average 1996–2001 monthly municipal, commercial/industrial, and golf-course withdrawals for the months of June, July, August, and September are listed in table 18 (at back of report). A 20-percent reduction in withdrawals during these months reduced the total withdrawal rate in the Rhode Island part of the basin from about 32 Mgal/d to 25 Mgal/d (table 18). To maximize the effects of conservation on streamflow, the reductions in water use were assumed to be achieved by limiting consumptive-use activities such as lawn and garden watering. For this reason, wastewater-return flows in the HSPF model were not reduced by a corresponding 20 percent.

To reduce withdrawal rates, the total municipal, commercial/industrial and golf-course withdrawals specified for a model reach in the External Sources block of the UCI file were altered by use of a multiplication factor; individual withdrawals were not altered for this analysis. The multiplication factor reduced every withdrawal value in the hourly time series by 20 percent, effectively reducing demand year round. Residential withdrawals simulated in the model also were reduced year round by reducing the water use for each resident by 20 percent, from the privately supplied water-use rate of 71 gallons per day per person used in other simulations to 57 gallons per day per person. Because constant year-round reductions of 20 percent likely would exceed actual reductions enacted during the dry summer months, this simulation generated a best-case estimate of the effects of water-conservation measures on streamflow. Simulations showed, however, that the reduced withdrawals had a negligible effect on high flows during late fall through early spring; consequently, the following discussion focuses on the effects of conservation measures on summertime low flows.

To evaluate the potential benefits of reducing withdrawals by 20 percent, subbasins were ranked on the basis of their W/Q ratios for total contributing areas (fig. 17B). Conservation measures would have the greatest effect on flows in subbasins with the highest W/Q ratios. Results are shown by the differences between flow-duration curves from 1960–2004 simulations with 1996–2001 water use and 1995–1999 land use (scenario 7.0) and 1996–2001 water use with reduced withdrawals and 1995–1999 land use (scenario 13.0) (table 13, fig. 23). Figure 23 includes five subbasins with high W/Q ratios: Crookfall Brook above the outlet of Woonsocket Reservoir No. 1 (CR2A, ratio=1.6), Abbott Run above the outlet of Happy Hollow Pond (AB3A, ratio=0.85), Peters River above the Route 114 bridge (PE1A, ratio=0.25), Blackstone River above the Elizabeth Webbing Dam (BL13, ratio=0.23), and Branch River above the streamflow gaging station at Forestdale, R.I. (BR2A, ratio=0.10) (table 16). Figure 23 also includes results for the subbasin on the Blackstone River just upstream of the Massachusetts-Rhode Island state line (BL7A, ratio=0.17) to show the simulated effects of conservation measures in Massachusetts on streamflow entering Rhode Island. Flow-duration curves show that conservation measures had a strong effect on low flows in the subbasins with the highest W/Q ratios (ratios above about 0.85) (figs. 23A and 23B); conservation measures had only a modest effect on flows in the subbasins with lower W/Q ratios (ratios between 0.10 and 0.25) (figs. 23C through 23F). Changes in streamflows at the 90-percent flow duration (the 90-percent flow duration was considered representative of a typical annual low flow) are summarized in table 19 at the back of the report. At BL13 (fig. 23D) and BR2A (fig. 23E), 20-percent reductions in withdrawals increase streamflow at the 90-percent flow duration from 202 ft^3/s to 219 ft^3/s and 25.5 ft^3/s to 25.9 ft^3/s, respectively. The streamflow response to conservation measures in the remaining subbasins in Rhode Island (fig. 17B) is expected to be about the same or less than that for BL13 and BR2A on the basis of their similar W/Q ratios.

At CR2A, streamflow was below 0.1 ft^3/s 14 percent of the time under average 1996–2001 withdrawals, but under reduced withdrawal conditions streamflow was below 0.1 ft^3/s only 4 percent of the time (fig. 23A). At AB3A, streamflow was below 0.1 ft^3/s 5 percent of the time under average 1996–2001 withdrawals, but under reduced-withdrawal conditions streamflow was below 0.1 ft^3/s only 0.2 percent of the time (fig. 23B).

Simulated daily-mean hydrographs at CR2A and AB3A for 1960–2004 indicate that a 20-percent reduction in withdrawals increased flows during the summer and, at AB3A, prevented flows from falling below 0.1 ft^3/s during most years (data not shown). At AB3A, the number of years when streamflow fell below 0.1 ft^3/s dropped from 15 to 2 when average 1996–2001 withdrawals were reduced by 20 percent. Model-simulated flows below 0.1 ft^3/s are considered to represent no-flow conditions. It should be noted that the simulated occurrence and duration of streamflow below 0.1 ft^3/s represents average 1996–2001 withdrawals and not the actual withdrawals during 1960–2004 and that reservoir-management activities were not simulated. Thus, these simulations illustrate the response of unmanaged reservoir systems to average 1996–2001 withdrawals for 1960–2004 climatological conditions. If average 1996–2001 withdrawals are assumed to represent the long-term period, the results of these simulations indicate how often these streams can be expected to run dry under long-term climatological conditions. In addition, the results indicate that active conservation measures and reservoir management can have a critical influence in maintaining streamflow during dry periods, especially in subbasins with high W/Q ratios.

For 1996–2001, about 79 percent of the total withdrawals from the Rhode Island part of the basin were from surface water and the remaining 21 percent were from ground water (table 5). When the withdrawal rate from a ground-water supply is reduced to conserve water, there is a time lag between the change in withdrawal rate and the corresponding reduction in streamflow depletion (Barlow and others, 2003). The length of the lag is determined by the properties of the aquifer and the distance between the well and stream (Barlow, 2000). As a consequence of the lag period, reducing ground-water withdrawals during the summer in response to low-flow conditions may not yield timely increases in streamflow. Lag effects associated with ground-water withdrawals were not accounted for in this study. Rather, the approach effectively represents a best-case scenario for evaluating the effects of conservation measures on streamflow because the reductions in withdrawals were applied at a constant rate; the effect is comparable to achieving a uniform 20-percent reduction in streamflow depletion throughout the summer months. This approach is considered to represent actual conditions in the basin because (1) 79 percent of the withdrawals were direct withdrawals from surface water, and (2) the median distance of the water-supply wells in the Rhode Island part of the basin from the nearest stream was 210 ft. As a result of this short distance, the lag time between adjustments of withdrawal rates and responses of streamflows also will be short (days to weeks).

Simulations with 20-percent reductions in withdrawals demonstrate that conservation measures of this magnitude should increase low flows in the subbasins with the highest W/Q ratios in the Rhode Island part of the Blackstone River Basin. Effects on streamflow were much less pronounced in subbasins with lower withdrawal rates. It should be noted, however, that the effects of withdrawals and conservation measures on flows in the smaller tributary streams within the HSPF subbasins could not be evaluated with the model. Other issues that arise under drought conditions, such as unacceptably low ground-water or reservoir levels, also could create conditions for which conservation measures would be beneficial, even in areas with low W/Q ratios.

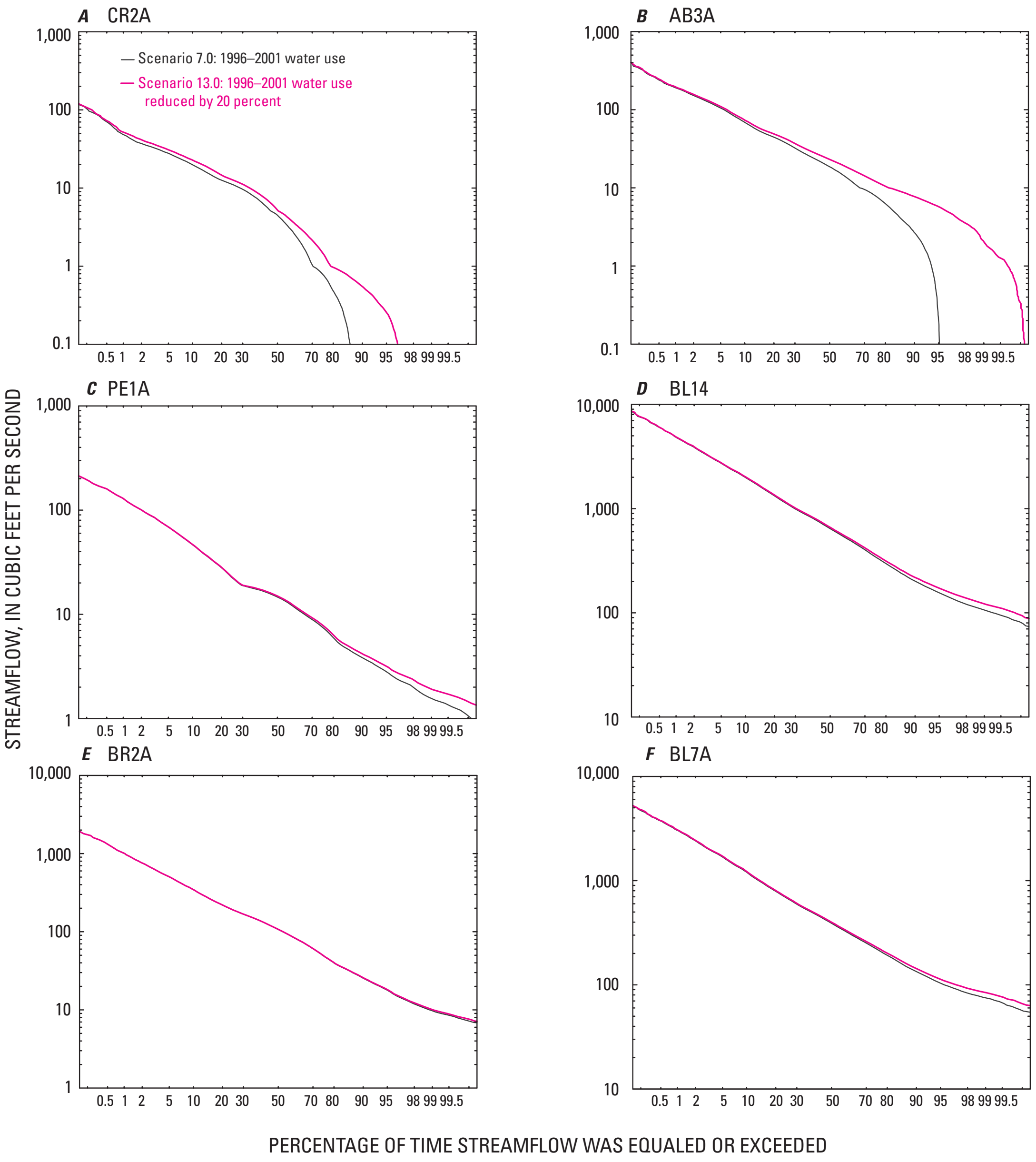


Figure 23. Flow-duration curves of daily mean streamflow from long-term (1960–2004) simulations with 1996–2001 water use (scenario 7.0) and 1996–2001 water use with withdrawals reduced by 20 percent to represent conservation measures (scenario 13.0) in Hydrological Simulation Program—FORTRAN (HSPF) subbasins: (*A*) Crookfall Brook above outlet of Woonsocket Reservoir No. 1 (CR2A); (*B*) Abbott Run above Happy Hollow Pond (AB3A); (*C*) Peters River above the Route 114 bridge (PE1A); (*D*) Blackstone River above Elizabeth Webbing Dam (BL13); (*E*) Branch River above the streamflow-gaging station at Foresdale, R.I. (BR2A); and (*F*) Blackstone River north of the Mass.-R.I. state line (BL7A). Streamflow was simulated with 1995–1999 land use.

Contribution of Wastewater-Return Flows to Streamflow in the Blackstone River

The HSPF model was used to assess the contribution of wastewater-return flows to streamflow in the Blackstone River. The rate of wastewater-return flow from 11 municipal WWTPs[4] in the basin averaged about 53 Mgal/d (82 ft^3/s) for 1996–2001. The city of Worcester and surrounding communities contributing to the UBWWTF operate the largest public sewer system in the basin. Accordingly, UBWWTF was the largest source of treated wastewater, accounting for about 69 percent of the total return-flow rate (fig. 24A). Of the 11 WWTPs in the basin, 9, including the Worcester Combined Sewer Overflow plant, are in Massachusetts, and these facilities accounted for about 81 percent of the total municipal wastewater-return flow in the basin for 1996–2001.

The Blackstone River receives treated wastewater from three facilities along its 17.8-mi length in Rhode Island: the Burrillville, R.I., WWTP discharges to the Branch River (10.7 mi upstream of the confluence), which flows into the Blackstone River 17.4 mi from the mouth; the Hopedale, Mass., WWTP discharges to the Mill River (in Massachusetts 9.9 mi upstream of the confluence), which flows into the Blackstone River 13.2 mi from the mouth; and the Woonsocket, R.I., WWTP discharges directly to the Blackstone River 12.2 mi from the mouth (fig. 24B). All of these municipal return flows and tributary flows entered the Blackstone River within 5.6 mi of the Mass.-R.I. state line; no additional municipal return flows enter the river in the 12.2-mi segment between the Woonsocket facility and the mouth of the river. Wastewater discharged to public sewer systems in the lower part of the basin (mainly in the towns of Lincoln, Cumberland, and Central Falls) was exported out of the basin to the Narragansett Bay Commission facility at Bucklin Point. Rates of nonpoint-source wastewater-return flows from septic systems were substantially lower than direct return flows from municipal WWTPs, and are not considered in this section.

Hydrographs of daily mean flows for 1996–2001 in the Blackstone River near the Mass.-R.I state line (in subbasin BL7A; the downstream end of the reach is in Blackstone, Mass. about 0.2 mi north of the state line; fig. 25A) and the mouth of the river (in subbasin BL14; the downstream end of the reach is in Pawtucket, R.I., at Slater Mill; fig. 25B) show the contribution of wastewater-return flows to streamflow at different times of the year. Under typical summer low-flow conditions, treated wastewater was a substantial component of streamflow in the Blackstone River; treated wastewater accounted for about 35 to 50 percent of the flow in the lower part of the basin, and the percentage of treated wastewater was larger during the driest periods. For example, simulation results indicated that for a brief period of time during the summer of 1999, wastewater accounted for about 59 ft^3/s out of 60 ft^3/s of the flow at BL7A (fig. 25A). In other words, only about 1 ft^3/s or about 2 percent of the total streamflow was generated from runoff (mainly ground-water discharge); however, this value also reflects streamflow depletion from withdrawals in Massachusetts, and therefore the percentage of runoff to return flow would be slightly larger without withdrawals. At the mouth of the river, the percentage of streamflow from wastewater was somewhat smaller than at the state line because little wastewater was discharged to the river in Rhode Island relative to the increase in streamflow from runoff. For example, during the summer of 1999, the nonwastewater component of flow at BL14 did not fall below about 10 ft^3/s (fig. 25B). These daily flow data are consistent with the ratios of return-flow rates to streamflow in the total contributing areas to the HSPF subbasins (fig. 20B); these ratios declined between the state line and the mouth of the basin. The percentage of wastewater in streamflow was much smaller under medium- to high-flow conditions (figs. 25A and 25B).

At buildout, municipal wastewater-return flows in the Blackstone River Basin were estimated to increase by about 9 Mgal/d, or about 17 percent over 1996–2001 return-flow rates (table 12). Septic return flows also would increase in response to low-density residential development in areas that do not have public sewer systems. In addition, wastewater-return flows will likely constitute a greater percentage of streamflow in the Blackstone River and tributaries with WWTPs, such as the Branch River and Mill River, at buildout. Although wastewater-return flows play a positive role in maintaining streamflow during dry conditions, they can have an adverse effect on stream-water quality. An assessment of the nature and magnitude of the effects of treated wastewater on water quality is beyond the scope of this report.

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[4] The Millbury WWTP in Millbury, Mass. currently (2006) is not in operation, and wastewater from the service area of this plant is currently being treated at UBWWTF. Simulations of return flows described in this report treat the Millbury WWTP as a separate return flow. Because UBWWTF and the Millbury WWTP discharge wastewater to adjacent HSPF reaches on the Blackstone River, the transfer of wastewater from the Millbury WWTP to UBWWTF would have a negligible effect on the simulation results presented in this report.

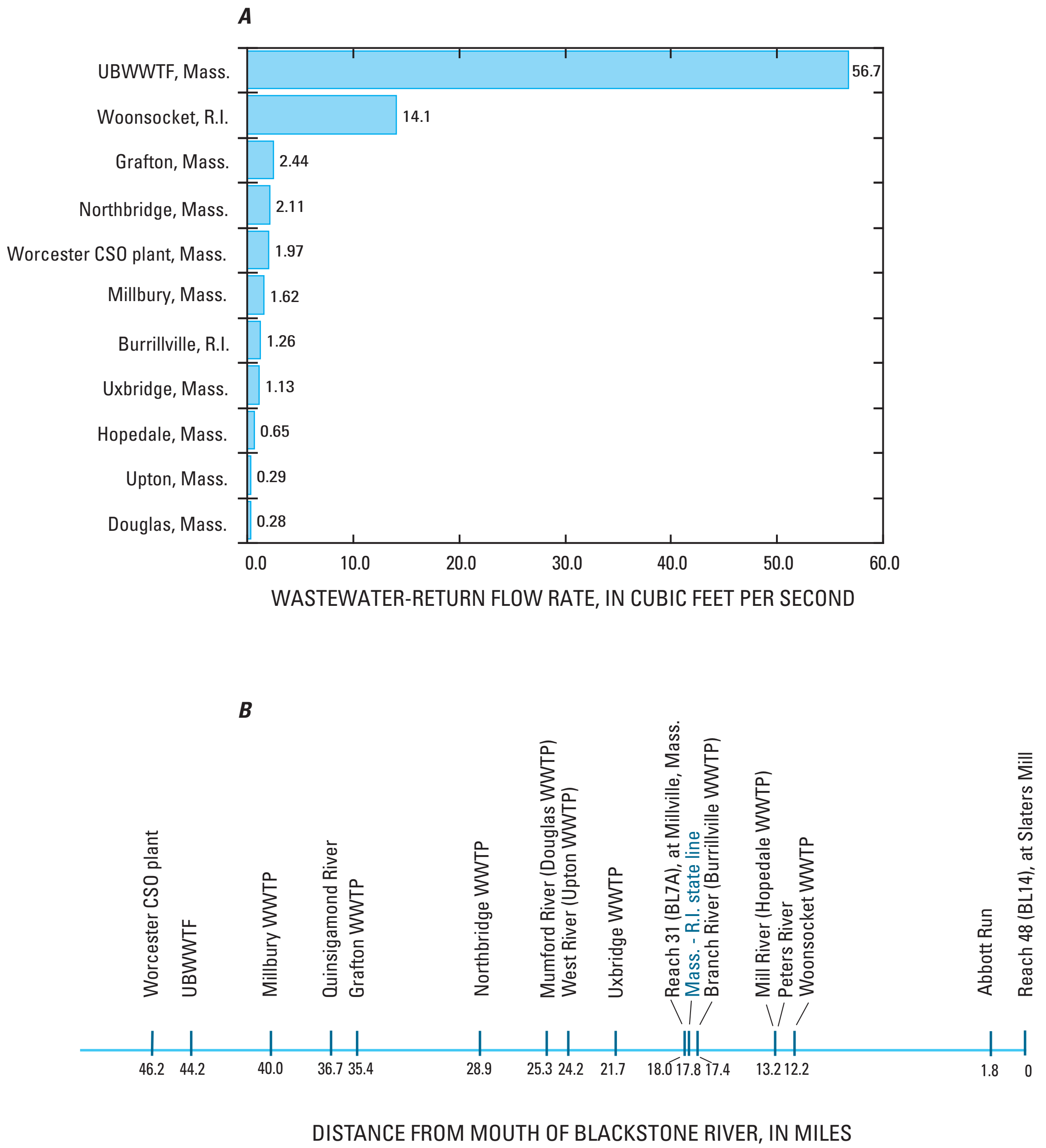

Figure 24. (*A*) Average 1996–2001 wastewater return-flow rates, and (*B*) distances of the mouths of major tributaries and of municipal wastewater-treatment plant outfalls from the mouth of the Blackstone River. The names of wastewater-treatment plants that discharge to tributary streams to the Blackstone River are shown in parentheses. UBWWTF, Upper Blackstone Wastewater Treatment Facility; CSO, combined sewer overflow; WWTP, wastewater-treatment facility; BL7A and BL14, subbasin names; Mass., Massachusetts; R.I., Rhode Island.

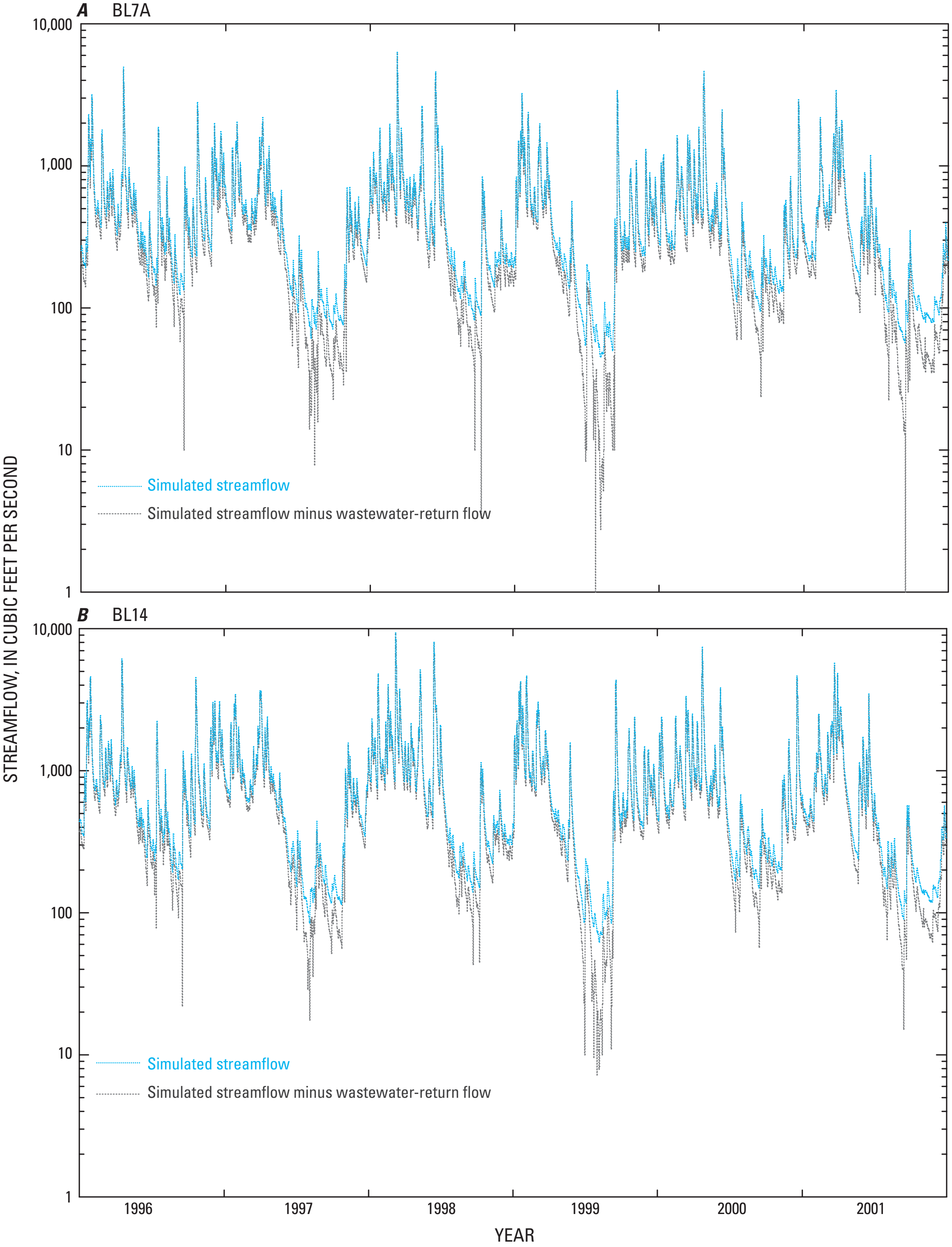

Figure 25. Hydrographs of daily mean streamflow and daily mean streamflow minus municipal wastewater-return flows for simulations with 1996–2001 water use for the (*A*) Blackstone River near the Massachusetts-Rhode Island state line (subbasin BL7A); and (*B*) the mouth of the Blackstone River at Pawtucket, Rhode Island (subbasin BL14).

Effect of Withdrawals from the Tuspani Well, North Smithfield

The Tuspani well is about 120 ft from the southern edge of the Slatersville Reservoir in North Smithfield (fig. 8). Results of an aquifer test after installation of the well in 2003 indicated that the well was capable of producing about 1,000 gallons per minute (gal/min) from the sand and gravel aquifer. This high-capacity well was not in service in 2006, but because it was considered a potentially important source of water for municipal or industrial needs, a simulation was done to evaluate the effects of withdrawals on low flows in the Branch River.

To simulate withdrawals from the Tuspani well, a long-term (1960–2004) time series based on a hypothetical annual average withdrawal rate of 1,000 gal/min was developed. A seasonal pattern, developed by Granato and Barlow (2004, fig. 13) from an analysis of monthly water-supply withdrawals as a percentage of total annual withdrawals from six water-supply systems in Rhode Island, was applied to the time series. This pattern increases demands in the summer months compared to the annual average demand. STRMDEPL then was used to develop a time series of streamflow depletion for the Branch River. Because the well is only 120 ft from the reservoir, the time lag is short, and the streamflow depletion and ground-water-withdrawal time series were similar. The streamflow-depletion time series from the Tuspani well withdrawals then was added to the time series of total withdrawals from reach 36 (subbasin BR1A). Withdrawals from the Tuspani well increase the total withdrawal rate from the reach from 0.031 Mgal/d to 1.5 Mgal/d.

Results from long-term simulations indicate that withdrawals from the Tuspani well would have an observable effect on low flows in the Branch River downstream of Slatersville Reservoir (BR1A; fig. 8). Flow-duration curves for recent conditions (baseline long-term scenario 7.0 with 1996–2001 water use and 1995–1999 land use) and recent conditions plus withdrawals from the Tuspani well became noticeably different for flow durations above 70 percent (fig. 26). At the 90-percent flow duration, streamflow declined from 23.6 ft^3/s to 21.1 ft^3/s (or about 11 percent) with the Tuspani well pumping at an annual average rate of 1,000 gal/min. At the 99-percent flow duration, streamflow declined from 8.91 ft^3/s to 6.21 ft^3/s (or about 30 percent). These reductions in streamflow indicate that withdrawals from the Tuspani well would reduce typical summer low flows, but with the exception of the lowest flows that occur infrequently, reductions in flow would be modest. The effects would be negligible for medium and high flows because the constant withdrawal rate is a smaller percentage of these higher streamflows (fig. 26).

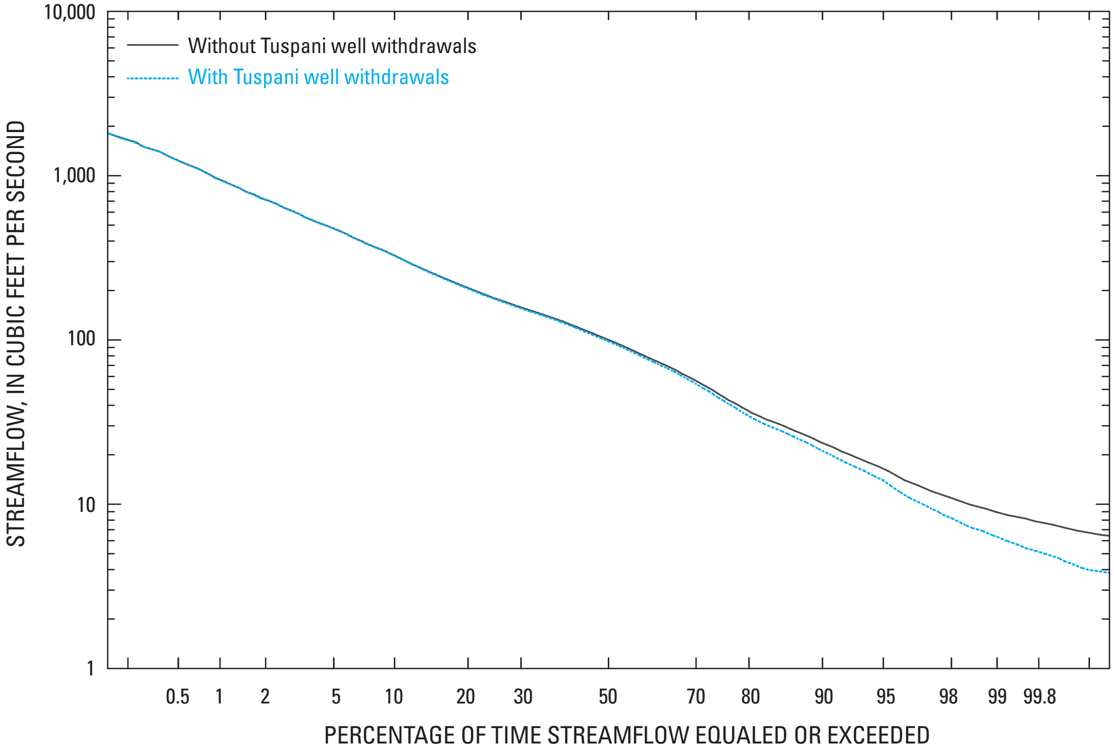

Figure 26. Flow-duration curves of daily mean streamflow in the Branch River downstream of Slatersville Reservoir (Hydrological Simulation Program—FORTRAN (HSPF) subbasin BR1A) from long-term (1960–2004) simulations for recent conditions (1996–2001 water use and 1995–1999 land use) and for recent conditions plus hypothetical annual average withdrawals of 1,000 gallons per minute from the Tuspani well, North Smithfield, Rhode Island.

Effects of Connecting North Smithfield to the Woonsocket Water-Supply System

In 2006, the municipal wells serving the town of North Smithfield were taken out of service, and the town was connected to the city of Woonsocket water-supply system. North Smithfield was withdrawing about 0.12 Mgal/d from three wells in the sand and gravel aquifer near the Slatersville Reservoir to a service population of 1,600 (Richard Amirault, Rhode Island Department of Health, oral commun., 2006). The TAC requested information on the effect of this change on flows in the Branch River and Crookfall Brook.

It should be noted that the information on the North Smithfield water-supply withdrawals supplied by the TAC late in the study was different from the withdrawal rate used in the baseline model (table 5). The withdrawals in the baseline model were represented by only one municipal well pumping at 0.06 Mgal/d (Barlow, 2003) in Branch River subbasin BR2A, reach 37 rather than multiple wells pumping at 0.12 Mgal/d; however, because the difference in rates (0.06 Mgal/d) was small, the baseline simulation was not re-run with increased withdrawals from subbasin BR2A.

The change in the water supply was simulated in two ways with the HSPF model. First, the ground-water withdrawal rate of 0.06 Mgal/d from subbasin BR2A (reach 37) representing the North Smithfield ground-water supply was removed from the model. Second, a constant rate of 0.12 Mgal/d was added to the time series of withdrawals from Reservoir No. 1 on Crookfall Brook, the location of the Woonsocket water-supply system in subbasin CR2A, reach 42 (fig. 7). The North Smithfield water demand (0.12 Mgal/d) was about 2 percent of the 1996–2001 annual average withdrawal rate from Crookfall Brook (5.0 Mgal/d). To incorporate these changes, modifications were made to scenario 7.0, the long-term (1960–2004) baseline simulation.

Long-term simulations indicated that changing the source of the municipal water supply for the town of North Smithfield from wells in the Branch River subbasin to surface water in the Crookfall Brook subbasin would have only a small effect on low flows in these subbasins. The effect was small mainly because the withdrawal rate for the North Smithfield municipal supply was small compared to runoff rates in these subbasins. The addition of 0.12 Mgal/d (0.19 ft^3/s) to the 1996–2001 withdrawal rates from CR2A (reach 42) led to observable decreases in low flows; for 1996–2001 withdrawal rates, flows were above 0.1 ft^3/s about 86 percent of the time, whereas for 1996–2001 withdrawals plus North Smithfield demands, flows were above 0.1 ft^3/s about 83 percent of the time. The cessation of the ground-water withdrawal of 0.06 Mgal/d (0.09 ft^3/s) from BR2A had a negligible effect on streamflow in the Branch River; flow at the 90-percent flow duration increased from 25.5 ft^3/s when the North Smithfield well was withdrawing water to 25.6 ft^3/s when the withdrawal was removed from the model. Although the total municipal withdrawal rate for the town of North Smithfield apparently was underestimated in the baseline model, this scenario indicated that withdrawals of this magnitude would have only a small effect on low flows in the lower part of the Branch River, which receives runoff from a 91-mi^2 drainage area.

Summary and Conclusions

The Blackstone River Basin encompasses an area of 474.5 square miles (mi^2) in south-central Massachusetts and northern Rhode Island. Streamflow in many parts of the basin currently (2006) is altered by water-supply withdrawals, wastewater-return flows, and land-use change associated with a growing population. Withdrawals deplete streamflow and potentially have an adverse effect on aquatic habitat, water quality, and the scenic and recreational value of the streams and rivers in the basin. Wastewater-return flows lessen the effects of withdrawals on streamflow depletion but may degrade water quality by adding nutrients and other detrimental constituents. Managing the water resources of the basin to provide sustainable water supplies while maintaining adequate flows for aquatic habitat and other uses is of increasing concern to government agencies, environmental organizations, and groups of concerned citizens. The need for water-resources management is intensified by rapid population growth and land-use change in the basin. The U.S. Geological Survey (USGS), in cooperation with the Rhode Island Water Resources Board (RIWRB), developed and calibrated a Hydrological Simulation Program–FORTRAN (HSPF) precipitation-runoff model for the Blackstone River Basin to simulate the effects of increased water withdrawals, increased wastewater-return flows, and land-use change on streamflow. Most of the simulations described in this report were conducted for recent (1996–2001) and buildout conditions to provide a long-range assessment of the effects of potential future human activities on water resources in the basin.

Information from a buildout analysis conducted by the Massachusetts Executive Office of Environmental Affairs, Rhode Island Department of Environmental Management, and Blackstone River Valley National Heritage Corridor Commission was incorporated into the HSPF model to simulate the effects of potential future development on streamflow. The buildout analysis shows how a community might fully develop in accordance with recent (1990s) zoning codes. Potential changes in land use were determined relative to the 1995–1999 land-use data in the baseline HSPF model. The analysis of the buildout information indicated that the major change in land use would be the conversion of forested areas to medium- to low-density residential development. Forested areas decreased from 50.7 percent in 1995–1999 to 36.0 percent at buildout, whereas medium- to low-density residential areas increased from 14.7 percent in 1995–1999 to 27.7 percent at buildout. Simulated effective impervious area increased from 4.7 percent to 7.9 percent.

An estimated 86,000 new dwelling units and 152 million square feet of new commercial floor space would accompany the changes in land use, and population in the basin potentially will increase from about 436,000 persons in 1990 to 651,000 persons at buildout. The total new water demand associated with this development was estimated to be 26.0 Mgal/d, of which 15.2 Mgal/d would be from residential development and 10.8 Mgal/d from commercial development. The spatial pattern of potential new demands at buildout was determined by the underlying changes in land use. Approximately 71 percent of the growth in residential land use is expected to be in areas that had no public water or public sewer systems in 2000. After accounting for the water withdrawals from private wells that would be returned locally to on-site septic systems (and not simulated explicitly in the HSPF model), 16.3 Mgal/d of new withdrawals were incorporated into the HSPF model. An additional withdrawal of 0.25 Mgal/d from the Abbott Run subbbasin was simulated to satisfy new demands from the city of Pawtucket, which is mainly outside the basin. After accounting for consumptive use, water withdrawn from private wells that would be returned locally to on-site septic systems, and the export of wastewater from the towns in the lower part of the basin to the Narragansett Bay Commission Bucklin Point Wastewater Treatment Facility, 10.1 Mgal/d of new wastewater-return flows were incorporated into the HSPF model. Of this total return flow, 8.7 Mgal/d were from municipal wastewater-treatment plants and 1.4 Mgal/d were from on-site septic systems in residential areas served by public water-supply systems. The HSPF model was used to simulate the effects of these potential land-use and water-use changes on streamflow in the basin.

The effects of land-use change on streamflow were evaluated by comparing the results of long-term (1960–2004) simulations with (1) undeveloped land use, (2) 1995–1999 land use, and (3) potential buildout land use at selected sites across the basin. Flow-duration curves for these land-use scenarios were similar, indicating that land-use change, as represented in the HSPF model, had little effect on streamflow in the major tributaries and rivers in the basin; however, land-use change—particularly increased effective impervious area—could potentially have greater effects on the hydrology, water quality, and aquatic habitat of smaller streams in the basin.

The effects of increased water withdrawals and wastewater-return flows were evaluated by comparing the results of long-term simulations with (1) no withdrawals and return flows, (2) actual (measured) 1996–2001 withdrawals and return flows, and (3) potential withdrawals and return flows at buildout. Overall, the results indicated that water use had a much larger effect on streamflow than did land use and that the location and magnitude of wastewater-return flows were important for lessening the effects of withdrawals on streamflow in the Blackstone River Basin. Ratios of long-term (1960–2004) simulated flows with 1996–2001 water use (representing the net effect of withdrawals and wastewater-return flows) to long-term simulated flows with no water use indicated that, for many reaches, particularly in the southwestern part of the basin, 1996–2001 water use did not deplete low flows at the 90-percent flow duration substantially compared to flows unaffected by water use. Flows were more severely depleted in the reaches that include surface-water supplies for the larger cities in the basin (Kettle and Tatnuck Brooks, Worcester, Mass. water supply; Quinsigamond River, Shrewsbury, Mass. water supply; Crookfall Brook, Woonsocket, R.I. water supply; and Abbott Run, Pawtucket, R.I. water supply). These reaches did not have substantial wastewater-return flows that could offset withdrawals. In contrast, wastewater-return flows from the Upper Blackstone Wastewater Treatment Facility in Millbury, Mass. increased flows at the 90-percent flow duration in the main stem of the Blackstone River compared to no-water-use conditions. Under the assumptions used to develop the buildout scenario, nearly all of the new water withdrawals were returned to the Blackstone River Basin at municipal wastewater-treatment plants or on-site septic systems. Consequently, buildout generally had small effects on simulated low flows in the Blackstone River and most of the major tributary streams compared to flows with 1996–2001 water use. As for land use, however, potential new withdrawals and return flows at buildout may have larger effects on streamflow in the smaller streams in the basin.

To evaluate the effects of water use on flows in the rivers and major tributary streams in the Rhode Island part of the basin in greater detail, the magnitudes of water withdrawals and wastewater-return flows in relation to simulated streamflow were calculated as unique ratios for individual HSPF subbasins, the total contributing areas to HSPF subbasins (representing the cumulative effects of all withdrawals and return flows), and the contributing areas to the major tributaries in Rhode Island: Chepachet River, Clear River, Branch River, Crookfall Brook, Mill River, Peters River, and Abbott Run. Dimensionless ratios of total water-withdrawal rates, total wastewater-return flow rates, and total withdrawal rates minus total return-flow rates (net rates) to simulated streamflow in the absence of water use were calculated for the summer months (June through September) when streamflows are low and demands peak. For recent conditions (1996–2001 withdrawals and 1995–1999 land use), ratios of average summer withdrawals to long-term (1960–2004) medians of average summer streamflow simulated in the absence of water use ranged from 0.039 to 2.5 with a median value of 0.11 for total contributing areas to HSPF subbasins. The largest ratios of withdrawal rates to streamflow were in the subbasins with major withdrawals for municipal water supply, such as Crookfall Brook and Abbott Run. Ratios for these subbasins were near or greater than 1.0, indicating that water was being used from reservoir storage to meet summer demands. The smallest withdrawal-to-streamflow ratios were for the rural areas in the Branch River drainage area in the southwestern part of the basin. Ratios also were small for the subbasins along the Blackstone River because of the large volume of upstream runoff in comparison to upstream withdrawals.

For recent conditions, ratios of average summer return flows to the long-term (1960–2004) medians of average summer streamflows simulated in the absence of water use ranged from 0.0 to 0.20 with a median value of 0.029 for total contributing areas to HSPF subbasins. The largest ratios of wastewater-return flows to streamflows were for the subbasins that received return flows from municipal wastewater-treatment plants. In contrast to the withdrawal ratios, return-flow ratios also were large for the subbasins along the Blackstone River because of high wastewater-return-flow rates from upstream wastewater-treatment plants. Thus, of the major rivers in the Rhode Island part of the basin, the main stem of the Blackstone River appeared to be most affected by wastewater-return flows.

Under the assumptions used to develop the buildout analysis, withdrawal and return-flow ratios were estimated to increase for most of the HSPF subbasins in the Rhode Island part of the basin. Ratios more than doubled for some subbasins, but the large increases mainly were for subbasins that had low ratios in 1996–2001. Large increases in ratios generally corresponded to subbasins with the greatest potential for medium- to low-density residential development.

The effects of potential water-conservation measures on low flows in rivers and major tributary streams in the Rhode Island part of the basin were evaluated with the HSPF model by reducing 1996–2001 withdrawals by 20 percent, which decreased the average total summer withdrawal rate from about 32 Mgal/d to 25 Mgal/d. The results of long-term simulations indicate that the effects on streamflow would be most evident for the subbasins with the highest withdrawal rates compared to streamflow. For example, streamflow in Crookfall Brook fell below 0.1 ft^3/s (simulated flows below 0.1 ft^3/s were considered to represent no-flow conditions) 14 percent of the time under average 1996–2001 withdrawals, but only 4 percent of the time under conditions in which demands were reduced by 20 percent. Simulations indicated that conservation measures would have more modest effects in subbasins with lower withdrawal rates. For example, at the streamflow-gaging station at the Branch River at Forestdale, R.I., a 20-percent reduction in demand increased streamflow at the 90-percent flow duration from 25.5 ft^3/s to 25.9 ft^3/s. Overall, simulations with 20-percent reductions in withdrawal rates indicated that conservation measures may result in appreciable increases in low flows in the subbasins with the highest ratios of withdrawals to streamflows in the Rhode Island part of the Blackstone River Basin. Although the effects on streamflow appear to be much smaller in the subbasins with lower rates of withdrawals, other issues that arise under drought conditions, such as unacceptably low ground-water or reservoir levels, could create conditions for which conservation measures would be beneficial.

The contribution of wastewater-return flows to streamflow in the Blackstone River was assessed with the HSPF model by comparing simulated flows with and without municipal wastewater-return flows. The total rate of wastewater-return flow from the 11 municipal WWTPs operating in the basin in 1996–2001 averaged about 53 Mgal/d (82 ft^3/s). Of the 11 facilities in the basin, 9 were in Massachusetts and approximately 81 percent of the total municipal wastewater-return flow to the basin was from the Massachusetts facilities. Under typical summer low-flow conditions, treated wastewater was a substantial component of streamflow in the Blackstone River; treated wastewater accounted for about 35 to 50 percent of the flow in the lower part of the basin, and the percentage of treated wastewater was larger during the driest periods. For example, for a brief period of time during the summer of 1999, wastewater accounted for about 59 ft^3/s of the total streamflow rate of 60 ft^3/s near the Mass.-R.I. state line. Because little wastewater was discharged to the Blackstone River along its 18-mile length in Rhode Island, the percentage of streamflow from wastewater was lower at the mouth of the basin than at the state line. At buildout, municipal wastewater-return flows to the Blackstone River Basin were estimated to increase by about 9 Mgal/d, or 17 percent of 1996–2001 return-flow rates. Septic-system return flows also were estimated to be greater at buildout in response to low-density residential development in areas that do not have public sewer systems. Consequently, wastewater-return flows will likely constitute a greater percentage of streamflow at buildout.

Two local water-supply issues in Rhode Island were evaluated with the HSPF model. The effect of withdrawals from an inactive well (Tuspani well) on flows in the Branch River was evaluated by use of a long-term simulation. The Tuspani well is about 120 ft from the southern edge of the Slatersville Reservoir in North Smithfield and is capable of producing about 1,000 gal/min from the sand and gravel aquifer. The results of the simulation indicated that withdrawals from the Tuspani well would reduce low flows in the Branch River, but with the exception of very low flows that occur infrequently, reductions in flow rates would be modest. Streamflow at the 90-percent flow duration in the Branch River downstream of the Tuspani well declined from 23.6 ft^3/s to 21.1 ft^3/s. The effect of connecting the town of North Smithfield to the Woonsocket water-supply system also was evaluated by use of a long-term simulation. In 2006, North Smithfield was providing about 0.12 Mgal/d from three wells in the sand and gravel aquifer near the Slatersville Reservoir to a service population of 1,600. To simulate the change in water supply with the HSPF model, the ground-water withdrawals for the town of North Smithfield were removed from the model, and 0.12 Mgal/d was added to the surface-water withdrawals from Reservoir No. 1 on Crookfall Brook, the location of the intake for the Woonsocket water-supply system. Results from the simulation indicate that withdrawals of this magnitude would have only a small effect on low flows in these subbasins.

Numerical watershed models necessarily simplify the complex processes and physical characteristics of a basin. Consequently, there are limitations to the types of questions that can be addressed by the model. Nonetheless, the model can be used effectively to address many water-resource-management questions, if the limitations and uncertainties are considered. The assumptions, estimation procedures, and data used to develop and calibrate the HSPF model for the Blackstone River Basin, the spatial resolution of the model, the possible applicability of alternative model structures and parameter values, and the assumptions used to develop land-use and water-use scenarios should be considered when evaluating the model and using its results for water-management decisions. For example, a number of assumptions were made to incorporate the buildout information into the HSPF model and estimate the potential future patterns of land use and water use in the basin; these assumptions and the limitations of the HSPF model should be considered when evaluating the results of the buildout-model scenarios.

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Tables 1–19

Table 1. Streamflow-gaging stations in the Blackstone River Basin, Massachusetts and Rhode Island.

[Period of record represents the streamflow data available at the time of model development; USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; mi^2, square miles; Mass., Massachusetts; R.I., Rhode Island; $(ft^3/s)/mi^2$, cubic feet per second per square mile of drainage area]

Station location	USGS station number	Period of record	Average discharge for period of record (ft^3/s)	Drainage area (mi^2)	Average discharge for period of record ($(ft^3/s)/mi^2$)	Number of dams in drainage area
[1] Kettle Brook, Auburn, Mass.	01109439	10/1/2003–9/30/2004	28.2	18.4	1.53	10
Quinsigamond River, North Grafton, Mass.	01110000	10/1/1939–9/30/2004	40.8	25.6	1.59	5
Blackstone River, Millbury, Mass.	01109730	7/24/2002 –9/30/2004	175	72.2	2.42	27
Blackstone River, Northbridge, Mass.	01110500	12/7/1939–9/30/2003	269	140	1.92	48
[1] Mumford River, Uxbridge, Mass.	01111050	10/1/2003–9/30/2004	92.3	56.2	1.64	22
West River, Uxbridge, Mass.	01111200	3/23/1962–9/30/1990	48.9	27.9	1.75	4
Nipmuc River, Harrisville, R.I.	01111300	3/1/1964–9/30/2004	30.3	15.6	1.94	1
[1] Chepachet River, Gazzaville, R.I.	01111410	1/13/2004–9/30/2004	32.0	19.2	1.66	5
Branch River, Forestdale, R.I.	01111500	1/24/1940–9/30/2004	174	91.3	1.91	19
[1] Mill River, Woonsocket, R.I.	01112268	1/13/2004–9/30/2004	49.8	33.1	1.51	6
[1] Peters River, Woonsocket, R.I.	01112382	1/13/2004–9/30/2004	21.2	12.3	1.72	0
Blackstone River, Woonsocket, R.I.	01112500	2/22/1929–9/30/2004	775	416	1.86	109
Catamint Brook, Cumberland, R.I.	01113695	7/30/1999–9/30/2004	6.20	3.5	1.79	1
[1] Abbott Run, Valley Falls, R.I.	01113760	12/9/2003–9/30/2004	51.9	27.7	1.87	5
[1] Blackstone River, Pawtucket, R.I.	01113895	10/1/2003–9/30/2004	852	474	1.80	124

[1] Streamflow-gaging stations installed and operated for this study.

Table 2. Definitions and areas of hydrologic response units (HRUs), wetlands, and open water used to represent the Blackstone River Basin in the baseline Hydrological Simulation Program—FORTRAN (HSPF) model, Massachusetts and Rhode Island.

[Private water refers to private wells and private sewer refers to on-site septic systems. Public water refers to municipal water-supply systems and public sewer refers to municipal wastewater-disposal systems. HRU, hydrologic response unit; PERLND, pervious land segment; IMPLND, impervious land segment; --, not applicable]

HRU	Surficial geology	Water imported or exported from stream reach	Acres in basin before computation of impervious area	Acres in basin after computation of impervious area	Percentage of total basin area	Description
[1]PERLND1	--	--	17,572	8,216	2.7	Commercial/industrial/transportation
PERLND 2	Till	--	21,789	21,229	7.0	Open, nonresidential
PERLND 3	Till	--	123,084	123,084	40.6	Forest
[2]PERLND 4	Till	--	23,932	23,312	7.7	Medium- to low-density residential on private water-private sewer and public water-public sewer
PERLND 5	Till	Export	1,095	1,065	0.4	Medium- to low-density residential on private water-public sewer
PERLND 6	Till	Import	5,266	5,126	1.7	Medium- to low-density residential on public water-private sewer
[2]PERLND 7	Till	--	11,981	10,191	3.4	High-density residential on private water-private sewer and public water-public sewer
PERLND 8	Till	Export	298	254	.08	High-density residential on private water-public sewer
PERLND 9	Till	Import	742	633	.2	High-density residential on public water-private sewer
PERLND 10	Sand and gravel	--	10,706	10,422	3.4	Open, nonresidential
PERLND 11	Sand and gravel	--	30,652	30,652	10.1	Forest
[2]PERLND 12	Sand and gravel	--	10,164	9,896	3.3	Medium- to low-density residential on private water-private sewer and public water-public sewer
PERLND 13	Sand and gravel	Export	449	436	.1	Medium- to low-density residential on private water-public sewer
PERLND 14	Sand and gravel	Import	3,724	3,627	1.2	Medium- to low-density residential on public water-private sewer
[2]PERLND 15	Sand and gravel	--	6,337	5,381	1.8	High-density residential on private water-private sewer and public water-public sewer
PERLND 16	Sand and gravel	Export	247	210	.07	High-density residential on private water-public sewer
PERLND 17	Sand and gravel	Import	417	357	.1	High-density residential on public water-private sewer
IMPLND 30	--	--	0	9,356	3.1	Mixed commercial development
IMPLND 31	--	--	0	5,006	1.7	Residential development and urban open space
--	--	--	23,395	23,395	7.7	Wetland
--	--	--	11,392	11,392	3.8	Open water

[1] PERLND 1 includes areas underlain by both till and sand and gravel because surface soils are likely to be disturbed and backfilled.

[2] PERLNDs 4, 7, 12, and 15 include residential areas served by both private water/private sewer and public water/public sewer.

Table 3. Residential densities used in the baseline Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.

[HRU, hydrologic response unit; <, less than; >, greater than]

Reclassified residential categories from state land-use data layers	Number of house-holds per acre	Population per acre	Consolidated residential categories for HRU development	Percentage of consolidated residential area	Weighted number of households per acre	Weighted population per acre
High-density residential (<1/8-acre lots)	8.0	20.0	High-density residential	24.1	5.7	14.3
Medium-high density residential (1/8- to 1/4-acre lots)	5.0	12.5		75.9		
Medium-density residential (>1/4- to 1-acre lots)	2.5	6.3	Medium- to low-density residential	49.8	1.5	3.7
Low-density residential (>1-acre lots)	0.5	1.3		50.2		

Table 4. Descriptions of stream reaches in the Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.

[Data from climatological stations used to simulate streamflow. Percent effective impervious areas obtained from calibration of baseline model (1995-1999 land use). Reaches and subbasins shown in fig. 7; --, not applicable; UBWPAD, Upper Blackstone Water Pollution Abatement District; KORH, Worcester Regional Airport climatological station; KPVD, T.F. Green Airport climatological station]

Model reach number	Subbasin name and (streamflow-gaging station identification number)	Reach description	Direct drainage area (acres)	Percent effective impervious area in direct drainage area	Total drainage area (acres)	Upstream reach number(s)	Climatological station
11	KE1A	Kettle and Lynde Brook above Smiths Pond	6,287	3.4	6,287	--	KORH
19	DA1A	Dark Brook at Dark Brook Reservoir outlet	1,701	6.2	1,701	--	KORH
16	KE2A (01109439)	Kettle Brook above Rockland Road bridge	3,813	3.8	11,801	11, 19	KORH
14	KE3A	Kettle Brook above confluence with Middle River	9,085	8.9	20,886	16	KORH
5	TA1A	Tatnuck Brook above Holden Reservoir No. 2 outlet	3,363	0.2	3,363	--	KORH
6	TA2A	Tatnuck Brook above confluence with Middle River	6,384	11.3	9,747	5	KORH
3	MB1B	Mill Brook and Middle River	9,562	21.5	40,196	14, 6	KORH
15	BL1A	Blackstone River above UBWPAD wastewater return	1,535	21.1	41,731	3	KORH
49	BL2B (01109730)	Blackstone River above station at Millbury	4,497	6.3	46,228	15	KORH
13	BL2A	Blackstone River above confluence with Quinsigamond River	16,075	3.5	62,302	49	KORH
1	QU1A (01110000)	Quinsigamond River above station at North Grafton	16,402	9.3	16,402	--	KORH
7	QU2A	Quinsigamond River above confluence with Blackstone River	7,853	5.4	24,255	1	KORH
20	BL3A (01110500)	Blackstone River above station at Northbridge	3,138	2.7	89,695	13, 7	KORH
22	BL4A	Blackstone River above confluence with Mumford River	5,392	2.1	95,087	20	KORH
50	WH1A	Unnamed tributary to Mumford River at Whitin Reservoir	5,748	0.1	5,748	--	KORH
18	MU1A	Mumford River above Stevens Pond	4,796	0.4	4,796	--	KORH
23	MU2A	Mumford River above East Douglas	8,075	0.7	18,619	50, 18	KORH
21	MU3A (01111050)	Mumford River above confluence with Blackstone River	17,321	3.6	35,940	23	KORH
25	BL5A	Blackstone River above confluence with West River	569	3.3	131,596	22, 21	KPVD
17	WE1A (01111200)	West River above West Hill Dam	17,883	1.1	17,883	--	KORH
24	WE2A	West River above confluence with Blackstone River	6,045	1.5	23,928	17	KPVD
28	BL6A	Blackstone River above confluence with Emerson Brook	1,075	1.6	156,600	25, 24	KPVD
27	EM1A	Emerson Brook above confluence with Blackstone River	4,811	2.3	4,811	--	KPVD
31	BL7A	Blackstone River above confluence with Branch River	7,201	2.9	168,612	28, 27	KPVD
9	CL1A	Clear River at Wallum Lake	1,551	0.7	1,551	--	KPVD
2	PA1A	Pascoag River at Pascoag Reservoir	5,221	0.6	5,221	--	KPVD

Table 4. Descriptions of stream reaches in the Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Data from climatological stations used to simulate streamflow. Percent effective impervious areas obtained from calibration of baseline model (1995-1999 land use). Reaches and subbasins shown in fig. 7; --, not applicable; UBWPAD, Upper Blackstone Water Pollution Abatement District; KORH, Worcester Regional Airport climatological station; KPVD, T.F. Green Airport climatological station]

Model reach number	Subbasin name and (streamflow-gaging station identification number)	Reach description	Direct drainage area (acres)	Percent effective impervious area in direct drainage area	Total drainage area (acres)	Upstream reach number(s)	Climatological station
10	CL2A	Clear River above confluence with Nipmuc River	9,251	1.8	16,023	9, 2	KPVD
32	NI1A (01111300)	Nipmuc River above station at Harrisville	10,003	0.4	10,003	--	KPVD
39	CL3A	Clear River above confluence with Branch River	3,080	3.1	29,106	10, 32	KPVD
34	CH1A	Chepachet River at Smith and Sayles Reservoir	5,227	0.7	5,227	--	KPVD
4	CH2A (01111410)	Chepachet River above station at Gazzaville	7,085	1.9	12,312	34	KPVD
43	TK1A	Tarkiln Brook above Slatersville Reservoir	6,072	0.7	6,072	--	KPVD
36	BR1A	Branch River above Slatersville Reservoir outlet	7,540	2.4	55,030	39, 4, 43	KPVD
37	BR2A (01111500)	Branch River above station at Forestdale	3,371	7.4	58,401	36	KPVD
30	BL8A	Blackstone River above Woonsocket Falls	8,948	6.7	235,962	31, 37	KPVD
12	ML1A	Mill River above Bellingham Street, South Milford	12,204	3.1	12,204	--	KORH
8	ML2A (01112268)	Mill River above station at Harris Pond Outlet	8,951	1.5	21,155	12	KPVD
26	PE1A (01112382)	Peters River above station at Route 114 bridge	7,870	2.8	7,870	--	KPVD
35	BL9A (01112500)	Blackstone River above station at Woonsocket	1,544	28.4	266,530	30, 8, 26	KPVD
38	BL10	Blackstone River above confluence with Crookfall Brook	3,065	13.7	269,596	35	KPVD
44	CR1A	Crookfall Brook above Woonsocket Reservoir No. 3 outlet	1,999	1.7	1,999	--	KPVD
42	CR2A	Crookfall Brook above Woonsocket Reservoir No. 1 outlet	3,197	10.5	5,196	44	KPVD
40	BL11	Blackstone River above Route 116 at Cumberland	5,929	10.5	280,721	42, 38	KPVD
45	BL12	Blackstone River above confluence with Abbott Run	3,537	14.1	284,258	40	KPVD
33	CA1A (01113695)	Catamint Brook above station at Cumberland	2,216	2.4	2,216	--	KPVD
29	AB1A	Abbott Run above Arnold Mills Pond outlet	9,832	1.7	12,048	33	KPVD
41	AB2A (01113760)	Abbott Run above station at Robin Hollow Pond outlet	5,669	5.7	17,717	29	KPVD
46	AB3A	Abbott Run above Happy Hollow Pond outlet	730	12.8	18,447	41	KPVD
47	BL13 (01113895)	Blackstone River above Elizabeth Webbing dam	626	35.2	303,331	45, 46	KPVD
48	BL14	Blackstone River above Old Slater Mill	310	44.8	303,642	47	KPVD

Table 5. Municipal, commercial/industrial, and golf-course withdrawals in the Blackstone River Basin, Massachusetts and Rhode Island.

[Aquifer refers to the geologic unit from which ground water was withdrawn. Distance to stream refers to the distance used to compute streamflow depletion for time-varying ground-water withdrawals. Shading indicates that streamflow depletion was not computed because only a constant ground-water withdrawal rate was available. Reach locations shown on fig. 7. WDM, watershed data management; DSN, dataset number; s&g, sand and gravel aquifer; b, bedrock aquifer; Mass., Massachusetts; R.I., Rhode Island; NA, not available; ft, feet; Mgal/d, million gallons per day; --, not applicable because the withdrawal was from surface water]

Reach number	Sub-basin name	WDM database DSN	Identification or permit number	Source name	Location	Aquifer	Distance to stream (ft)	Average withdrawal rate for 1996-2001 (Mgal/d)
1	QU1A	2010	2039000-01G	Well 1	Boylston, Mass.	s&g	950	0.141
1	QU1A	2011	2039000-02G	Well 2	Boylston, Mass.	s&g	1,470	0.0120
1	QU1A	2012	2039001-01G	Well 1	Boylston, Mass.	s&g	380	0.122
1	QU1A	2013	21211001	Wyman-Gordon, four wells and Hovey Pond combined	North Grafton, Mass.	--	--	0.0167
1	QU1A	2014	2271000-02G	Sewell Street Well 4	Shrewsbury, Mass.	s&g	480	0.837
1	QU1A	2015	2271000-04G	Lambert's Sand Pit Well 3.1	Shrewsbury, Mass.	s&g	1,330	0.369
1	QU1A	2016	2271000-05G	Lambert's Sand Pit Well 3.2	Shrewsbury, Mass.	s&g	1,330	0.0458
1	QU1A	2017	2271000-06G	Sewell Street Well 5	Shrewsbury, Mass.	s&g	670	0.00363
1	QU1A	2018	2271000-07G	Home Farm Well 6.1	Shrewsbury, Mass.	s&g	80	0.753
1	QU1A	2019	2271000-08G	Home Farm Well 6.2	Shrewsbury, Mass.	s&g	30	1.71
1	QU1A	9110	9P21227102	Well 1	Shrewsbury, Mass.	s&g	330	0.224
1	QU1A	9111	NA	Worcester Green Hill Municipal Golf Club	Worcester, Mass.	s&g	1,000	[1]0.0341
1	QU1A	9112	NA	Worcester Country Club	Worcester, Mass.	--	--	0.0366
3	MB1B	2030	21234801	Norton Company, five wells combined	Worcester, Mass.	s&g	980	0.209
5	TA1A	2050	2348000-06S	Holden Reservoir No. 1 surface-water intake	Holden, Mass.	--	--	23.2
6	TA2A	2060	NA	Tatnuck Country Club	Worcester, Mass.	s&g	1,000	0.0210
7	QU2A	2070	2110000-02G	Worcester Street Gravel Packed Well 1	Grafton, Mass.	s&g	70	0.619
7	QU2A	2071	2110000-03G	East Street Gravel Packed Well 2	Grafton, Mass.	s&g	50	0.126
7	QU2A	2072	2110000-04G	East Street Gravel Packed Well 3	Grafton, Mass.	s&g	70	0.196
7	QU2A	2073	2110004-01G	Countryside Condos Well 1	Grafton, Mass.	s&g	520	0.000472
8	ML2A	2080	2032000-01G	Well 1	Blackstone, Mass.	s&g	200	0.189
8	ML2A	2081	2032000-02G	Well 2	Blackstone, Mass.	s&g	20	0.0499
8	ML2A	2082	2032000-04G	Well 4	Blackstone, Mass.	s&g	130	0.221
8	ML2A	2083	2032000-05G	Well 5	Blackstone, Mass.	s&g	110	0.282
8	ML2A	2084	NA	Harris Pond surface-water intake	Woonsocket, R.I.	--	--	0.159
9	CL1A	2090	RI0100129	Wallum Lake surface-water intake	Burrillville, R.I.	--	--	0.0853
10	CL2A	2100	1592020-02	Well 2	Burrillville, R.I.	s&g	740	0.105
10	CL2A	2101	1592020-03&3A	Wells 3 and 3A combined	Burrillville, R.I.	s&g	760	0.191

Table 5. Municipal, commercial/industrial, and golf-course withdrawals in the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Aquifer refers to the geologic unit from which ground water was withdrawn. Distance to stream refers to the distance used to compute streamflow depletion for time-varying ground-water withdrawals. Shading indicates that streamflow depletion was not computed because only a constant ground-water withdrawal rate was available. Reach locations shown on fig. 7. WDM, watershed data management; DSN, dataset number; s&g, sand and gravel aquifer; b, bedrock aquifer; Mass., Massachusetts; R.I., Rhode Island; NA, not available; ft, feet; Mgal/d, million gallons per day; --, not applicable because the withdrawal was from surface water]

Reach number	Sub-basin name	WDM database DSN	Identification or permit number	Source name	Location	Aquifer	Distance to stream (ft)	Average withdrawal rate for 1996-2001 (Mgal/d)
11	KE1A	2110	2151000-01G	Well 1	Paxton, Mass.	b	280	0.0405
11	KE1A	2111	2151000-02G	Well 2	Paxton, Mass.	b	100	0.0476
11	KE1A	2112	2151000-03G	Well 3	Paxton, Mass.	b	260	0.0505
11	KE1A	2113	2348000-01S	Lynde Brook Reservoir surface-water intake	Leicester, Mass.	--	--	4.18
12	ML1A	2120	2138000-01G	TWF Mill Street Well	Hopedale, Mass.	s&g	250	0.277
12	ML1A	2121	2138000-02G	Green Street Well	Hopedale, Mass.	s&g	70	0.0953
12	ML1A	2122	NA	Hopedale Country Club	Hopedale, Mass.	--	--	0.0299
12	ML1A	2123	NA	Milford Country Club	Milford, Mass.	s&g	1,000	[1]0.0105
13	BL2A	2130	2110000-05G	Follette Street Gravel Packed Well 4	Grafton, Mass.	s&g	440	0.0328
13	BL2A	2131	NA	Pleasant Valley Country Club	Sutton, Mass.	--	--	0.0549
13	BL2A	2132	2186000-01G	Millbury Avenue Well	Millbury, Mass.	s&g	70	0.535
13	BL2A	2133	2186000-02G	Oak Pond Well	Millbury, Mass.	s&g	220	0.400
13	BL2A	2134	2290014-01G	Hatchery Road Well	Sutton, Mass.	s&g	1,350	0.123
13	BL2A	2135	2290015-01G	Pleasant Valley Country Club	Sutton, Mass.	b	480	0.0125
13	BL2A	2136	2290015-02G	Pleasant Valley Country Club	Sutton, Mass.	b	410	0.00372
14	KE3A	2140	2017000-01G	Well 1	Auburn, Mass.	s&g	170	0.361
14	KE3A	2141	2017000-03G	Well 3	Auburn, Mass.	s&g	400	0.148
14	KE3A	2142	2017000-04G	Well 4	Auburn, Mass.	s&g	300	0.190
14	KE3A	2143	2017000-05G	Well 5	Auburn, Mass.	s&g	160	0.246
14	KE3A	2144	2017000-06G	Well 6	Auburn, Mass.	s&g	270	0.143
14	KE3A	2145	2017000-07G	Well 7	Auburn, Mass.	s&g	590	0.145
14	KE3A	2146	2017000-08G	Well 8	Auburn, Mass.	s&g	490	0.0579
14	KE3A	2147	2017000-09G	Satellite Well # 6 West (Well 9)	Auburn, Mass.	s&g	220	0.0410
14	KE3A	2148	2017000-10G	Satellite Well # 6 North (Well 10)	Auburn, Mass.	s&g	240	0.00679
15	BL1A	2150	NA	Clearview Country Club	Millbury, Mass.	s&g	1,000	[1]0.0143
16	KE2A	2160	2151009-01G	Rock Well 1	Leicester, Mass.	b	670	0.00269
16	KE2A	2161	2151009-02G	Rock Well 2	Leicester, Mass.	b	690	0.00269
16	KE2A	2162	2151009-03G	Rock Well 3	Leicester, Mass.	b	600	0.00269
17	WE1A	2170	21217902	Well 1	Mendon, Mass.	b	520	0.0434
17	WE1A	2171	2303000-01G	TWF Glen Avenue Well	Upton, Mass.	s&g	260	0.0896
17	WE1A	2172	2303000-02G	West River Well	Upton, Mass.	s&g	260	0.317
20	BL3A	2200	2110001-01G	Providence Road Gravel Packed Well 1	Grafton, Mass.	s&g	70	0.0697

Table 5. Municipal, commercial/industrial, and golf-course withdrawals in the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Aquifer refers to the geologic unit from which ground water was withdrawn. Distance to stream refers to the distance used to compute streamflow depletion for time-varying ground-water withdrawals. Shading indicates that streamflow depletion was not computed because only a constant ground-water withdrawal rate was available. Reach locations shown on fig. 7. WDM, watershed data management; DSN, dataset number; s&g, sand and gravel aquifer; b, bedrock aquifer; Mass., Massachusetts; R.I., Rhode Island; NA, not available; ft, feet; Mgal/d, million gallons per day; --, not applicable because the withdrawal was from surface water]

Reach number	Sub-basin name	WDM database DSN	Identification or permit number	Source name	Location	Aquifer	Distance to stream (ft)	Average withdrawal rate for 1996-2001 (Mgal/d)
20	BL3A	2201	2110001-02G	Ferry Street Well 1	Grafton, Mass.	s&g	240	0.0669
20	BL3A	2202	2110001-03G	Ferry Street Well 2	Grafton, Mass.	s&g	120	0.0934
21	MU3A	2210	9P321207702	Gilboa Pond surface-water intake	Douglas, Mass.	--	--	0.255
21	MU3A	2211	2216000-01G	Meadow Pond Tubular Well Field	Northbridge, Mass.	s&g	10	0.675
21	MU3A	2212	2216000-02G	Cook Allon Brook Tubular Well Field	Northbridge, Mass.	s&g	40	0.790
21	MU3A	2213	NA	Whitinsville Golf Club	Whitinsville, Mass.	--	--	0.0330
21	MU3A	2214	NA	Edgewood Golf Club	Uxbridge, Mass.	s&g	500	[1]0.00592
22	BL4A	2220	21221602	Well 2	Northbridge, Mass.	s&g	290	0.213
23	MU2A	2230	2077000-01G	West Street Tubular Well Field	Douglas, Mass.	s&g	50	0.0827
23	MU2A	2231	2077000-02G	West Street Gravel Packed Well	Douglas, Mass.	s&g	640	0.0669
23	MU2A	2232	2077000-03G	Glenn Street Well 1	Douglas, Mass.	s&g	540	0.0512
23	MU2A	2233	2077000-04G	Glenn Street Well 2	Douglas, Mass.	s&g	480	0.0579
23	MU2A	2234	NA	Blackstone National Golf Club	Sutton, Mass.	s&g	1,000	[1]0.0358
23	MU2A	2235	2290001-01G	Well 1	Sutton, Mass.	b	140	0.0402
24	WE2A	2240	2304000-01G	Well 1	Uxbridge, Mass.	s&g	80	0.0698
24	WE2A	2241	2304000-02G	Well 2	Uxbridge, Mass.	s&g	70	0.0629
24	WE2A	2242	2304000-03G	Well 3	Uxbridge, Mass.	s&g	110	0.0842
25	BL5A	2250	2304000-04G	Well 4 (Bernat well field)	Uxbridge, Mass.	s&g	690	0.416
25	BL5A	2251	2304000-05G	Well 5 (Bernat well field)	Uxbridge, Mass.	s&g	420	0.107
25	BL5A	2252	2304000-06G	Well 6 (Bernat well field)	Uxbridge, Mass.	s&g	550	0.116
26	PE1A	2260	2025000-01G	Well 1	Bellingham, Mass.	s&g	210	0.207
26	PE1A	2261	2025000-02G	Well 2	Bellingham, Mass.	s&g	100	0.0835
26	PE1A	2262	2025000-03G	Well 3	Bellingham, Mass.	s&g	20	0.0530
26	PE1A	2263	2025000-04G	Well 4	Bellingham, Mass.	s&g	210	0.320
26	PE1A	2264	2025000-11G	Well 11	Bellingham, Mass.	s&g	410	0.157
26	PE1A	2265	2025000-12G	Well 12	Bellingham, Mass.	s&g	360	0.168
26	PE1A	2266	NA	Bungay Brook Golf Club	Bellingham, Mass.	s&g	500	[1]0.0221
26	PE1A	2267	NA	The New England Country Club	Bellingham, Mass.	--	--	0.0348
29	AB1A	2290	1647530	Sneech Pond surface-water intake	Cumberland, R.I.	--	--	0.883
29	AB1A	2291	NA	Wentworth Hills Golf and Country Club	Plainville, Mass.	s&g	500	[1]0.0424
29	AB1A	2292	41235001	Big Apple Realty Trust, four ponds and two wells combined	Wrentham, Mass.	b	430	0.0273

Table 5. Municipal, commercial/industrial, and golf-course withdrawals in the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Aquifer refers to the geologic unit from which ground water was withdrawn. Distance to stream refers to the distance used to compute streamflow depletion for time-varying ground-water withdrawals. Shading indicates that streamflow depletion was not computed because only a constant ground-water withdrawal rate was available. Reach locations shown on fig. 7. WDM, watershed data management; DSN, dataset number; s&g, sand and gravel aquifer; b, bedrock aquifer; Mass., Massachusetts; R.I., Rhode Island; NA, not available; ft, feet; Mgal/d, million gallons per day; --, not applicable because the withdrawal was from surface water]

Reach number	Sub-basin name	WDM database DSN	Identification or permit number	Source name	Location	Aquifer	Distance to stream (ft)	Average withdrawal rate for 1996-2001 (Mgal/d)
30	BL8A	2300	NA	Seville Dyeing/Dorado Processing surface-water intake	Woonsocket, R.I.	--	--	2.036
30	BL8A	2301	NA	Ocean State Power surface-water intake	Woonsocket, R.I.	--	--	2.310
32	NI1A	2320	NA	Blissful Meadows Golf Club	Uxbridge, Mass.	s&g	500	[1]0.0468
36	BR1A	2360	1559519	Wells 1 and 4 combined	Burrillville, R.I.	s&g	10	0.00601
36	BR1A	2361	1583825	Glendale Water Association Wells	Burrillville, R.I.	b	1,030	0.00789
36	BR1A	2362	1592019	Oakland Water Associaton Well	Burrillville, R.I.	s&g	210	0.0170
37	BR2A	2370	1615614	Driven Well Field	North Smithfield, R.I.	s&g	160	0.0600
39	CL3A	2390	1858411-02	Well 2	Burrillville, R.I.	s&g	150	0.109
39	CL3A	2391	1858411-03	Well 3	Burrillville, R.I.	s&g	70	0.121
40	BL11	2400	1647530	Manville well 1	Cumberland, R.I.	s&g	210	0.191
40	BL11	2401	1647530	Manville well 2	Cumberland, R.I.	s&g	250	0.170
40	BL11	2402	RI12980071	Autocrat Well	Lincoln, R.I.	b	1,400	0.0460
40	BL11	2403	NA	Kirkbrae Country Club	Lincoln, R.I.	s&g	1,000	[1]0.0469
41	AB2A	2410	1647530	Abbott Run well 2	Cumberland, R.I.	s&g	70	0.00376
41	AB2A	2411	1647530	Abbott Run well 3	Cumberland, R.I.	s&g	40	0.00380
41	AB2A	2412	4211001-01G	Well 1	North Attleboro, Mass.	s&g	400	0.0294
41	AB2A	2413	4211000-08G	Adamsdale well	North Attleboro, Mass.	s&g	420	0.202
41	AB2A	2414	4211000-09G	Hillman well	North Attleboro, Mass.	s&g	280	0.811
41	AB2A	2415	NA	Chemawa Golf Course	North Attleboro, Mass.	s&g	500	[1]0.0413
41	AB2A	2416	1592021	Well 6	Pawtucket, R.I.	s&g	10	0.171
41	AB2A	2417	1592021	Well 7	Pawtucket, R.I.	s&g	150	0.229
41	AB2A	2418	1592021	Well 8	Pawtucket, R.I.	s&g	80	0.250
41	AB2A	2419	1592021	Well 9	Pawtucket, R.I.	s&g	10	0.247
42	CR2A	2420	NA	Reservoir No. 1 surface-water intake	Woonsocket, R.I.	--	--	1.49
43	TK1A	2430	1900034	Nasonville Well field B	Burrillville, R.I.	s&g	120	0.00931
44	CR1A	2440	NA	Reservoir No. 3 surface-water intake	Woonsocket, R.I.	--	--	3.48
45	BL12	2450	1858423	Lonsdale Well 4	Lincoln, R.I.	s&g	200	0.119
45	BL12	2451	NA	Lincoln Country Club	Lincoln, R.I.	s&g	1,000	[1]0.0413
46	AB3A	2460	1592021	Happy Hollow surface-water intake	Pawtucket, R.I.	--	--	11.7
46	AB3A	2461	1592021	Well 2	Pawtucket, R.I.	s&g	10	0.120
46	AB3A	2462	1592021	Well 3	Pawtucket, R.I.	s&g	110	0.296

Table 5. Municipal, commercial/industrial, and golf-course withdrawals in the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Aquifer refers to the geologic unit from which ground water was withdrawn. Distance to stream refers to the distance used to compute streamflow depletion for time-varying ground-water withdrawals. Shading indicates that streamflow depletion was not computed because only a constant ground-water withdrawal rate was available. Reach locations shown on fig. 7. WDM, watershed data management; DSN, dataset number; s&g, sand and gravel aquifer; b, bedrock aquifer; Mass., Massachusetts; R.I., Rhode Island; NA, not available; ft, feet; Mgal/d, million gallons per day; --, not applicable because the withdrawal was from surface water]

Reach number	Sub-basin name	WDM database DSN	Identification or permit number	Source name	Location	Aquifer	Distance to stream (ft)	Average withdrawal rate for 1996-2001 (Mgal/d)
46	AB3A	2463	1592021	Well 4	Pawtucket, R.I.	s&g	450	0.0243
49	BL2B	2490	2017003-01G	Rock Well 1	Auburn, Mass.	b	280	0.0115
49	BL2B	2491	2017003-02G	Rock Well 2	Auburn, Mass.	b	280	0.00347
49	BL2B	2492	2017003-04G	Rock Well 4	Auburn, Mass.	b	300	0.00156
49	BL2B	2493	NA	Pakachoag Golf Course	Auburn, Mass.	s&g	1,000	[1]0.00428
49	BL2B	2494	2186000-03G	No. 1 North Main Street Well	Millbury, Mass.	s&g	180	0.469
49	BL2B	2495	2186000-04G	No. 2 North Main Street Well	Millbury, Mass.	s&g	280	0.244

[1] Measured withdrawals not available. Estimated withdrawals described in Barbaro and Zarriello (2006).

Table 6. Wastewater-return flows in the Blackstone River Basin, Massachusetts and Rhode Island.

[Reaches shown on fig. 7; WDM, watershed data management; DSN, dataset number; Mgal/d, million gallons per day; Mass., Massachusetts; R.I., Rhode Island]

Reach number	Subbasin name	WDM database DSN	Identification or permit number	Source name	Location	Average return-flow rate for 1996–2001 (Mgal/d)
3	MB1B	3030	MA0000817	Norton Company	Worcester, Mass.	0.160
3	MB1B	3031	MA0102997	Worcester Combined Sewer-Overflow Plant	Worcester, Mass.	1.27
3	MB1B	3032	MA0001112	Wyman Gordon	Worcester, Mass.	0.350
10	CL2A	3100	RI0100129	Eleanor Slater Hospital, Zambarano Unit	Burrillville, R.I.	0.0709
12	ML1A	3120	MA0102202	Hopedale Wastewater-Treatment Plant	Hopedale, Mass.	0.422
13	BL2A	3130	MAG250969	Lewcott Corporation	Millbury, Mass.	0.00915
13	BL2A	3131	MA0100650	Millbury Wastewater-Treatment Plant	Millbury, Mass.	1.05
15	BL1A	3150	MA0102369	Upper Blackstone Wastewater-Treatment Facility	Millbury, Mass.	36.7
17	WE1A	3170	MA0100196	Upton Wastewater-Treatment Plant	Upton, Mass.	0.186
20	BL3A	3200	MA0101311	Grafton Wastewater-Treatment Plant	Grafton, Mass.	1.57
21	MU3A	3210	MA0101095	Douglas Wastewater-Treatment Plant	Douglas, Mass.	0.182
22	BL4A	3220	MA0100722	Northbridge Wastewater-Treatment Plant	Northbridge, Mass.	1.36
30	BL8A	3300	RI0000566	Atlantic Thermoplastics Company, Incorporated	North Smithfield, R.I.	0.000962
30	BL8A	3301	RI0000485	Blackstone Smithfield Corporation	North Smithfield, R.I.	0.00326
31	BL7A	3310	MA0102440	Uxbridge Wastewater-Treatment Facility	Uxbridge, Mass.	0.732
35	BL9A	3350	RI0021466	CNC International	Woonsocket, R.I.	0.0499
36	BR1A	3360	RI0000116	Turex Incorporated	Burrillville, R.I.	0.00595
37	BR2A	3370	RI0000019	Philips Components	North Smithfield, R.I.	0.00297
38	BL10	3380	RI0021393	ACS Industries Incorporated	Woonsocket, R.I.	0.199
38	BL10	3381	RI0100111	Woonsocket Wastewater-Treatment Facility	Woonsocket, R.I.	9.10
38	BL10	3382	RI0001627	Woonsocket Water Division (filter backwash)	Woonsocket, R.I.	0.990
39	CL3A	3390	RI0100455	Burrillville Wastewater-Treatment Facility	Burrillville, R.I.	0.817
42	CR2A	3420	RI0000124	A.T. Cross, Outfall 001	Lincoln, R.I.	0.00850
45	BL12	3450	RI0020451	Air Products and Chemicals Incorporated	Cumberland, R.I.	0.147
45	BL12	3451	RI0020141	Okonite Company	Cumberland, R.I.	0.123
45	BL12	3452	RI0021865	Fleet National Bank	Lincoln, R.I.	0.000119
45	BL12	3453	RI0023132	Blackstone Valley Electric Company	Lincoln, R.I.	0.00434
46	AB3A	3460	RI0001589	Pawtucket Water Supply Board (filter backwash)	Cumberland, R.I.	0.271
47	BL13	3470	RI0001180	Osram Sylvania	Central Falls, R.I.	0.301

Table 7. Relations between regionalized zoning codes and land-use categories used to develop the Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin at buildout, Massachusetts and Rhode Island.

[Letters in parentheses represent abbreviations and codes; Mass., Massachusetts; R.I., Rhode Island; HRU, hydrologic response unit; >, greater than; <, less than; ft^2, square feet]

Regionalized zoning codes	Consolidated Mass.-R.I. state land-use categories	HRU land-use categories
Limited business (LB)	Commercial and services	Commercial-industrial-transportation
General business (GB)		
Central business (CB)		
Highway business (HB)		
Office park (OP)		
Mixed use (MU)		
Light industrial (LI)	Industrial manufacturing, design, and assembly	
General Industrial (GI)		
Multifamily, high density (MH)	High-density residential, >8 dwelling units per acre	High-density residential
Multifamily, medium density (MM)		
Multifamily, low density (ML)	Medium-high-density residential, 4 to 8 dwelling units per acre	
Two family (R6)		
Residential, 5,000-15,000 ft^2 (R5)		
Residential, 15,000-20,000 ft^2 (R4)	Medium-density residential, 1 to <4 dwelling units per acre	Low-density residential
Residential, 20,000-40,000 ft^2 (R3)		
Residential, 40,000-80,000 ft^2 (R2)	Low-density residential, <1 dwelling unit per acre	
Residential, > 80,000 ft^2 (R1)	Undifferentiated forest	Forest
Residential/agricultural, > 2 acre (RA)		
Conservation/passive recreation (CP)		
Institutional (IN)	Urban, predominantly open space	Open, nonresidential
Health care (HC)		

Table 8. Potential new residential and commercial water demands at buildout, Blackstone River Basin, Massachusetts and Rhode Island.

[ft^2, square feet; Mgal/d, million gallons per day; Mass., Massachusetts; R.I., Rhode Island]

Town	State	Area in basin (percent)	New dwelling units in basin	New residential demand (Mgal/d)	New commercial floor area (ft^2)	New commercial demand (Mgal/d)	Total new demand (Mgal/d)
Inside basin							
Attleboro	Mass.	4.0	510	0.0905	339,600	0.0241	0.115
Auburn	Mass.	93.3	2,160	0.383	2,284,600	0.162	0.546
Bellingham	Mass.	48.0	880	0.156	10,325,000	0.733	0.889
Blackstone	Mass.	100.0	1,590	0.282	1,049,300	0.0745	0.357
Boylston	Mass.	20.5	470	0.0834	296,700	0.0211	0.104
Douglas	Mass.	86.3	4,780	0.848	10,687,000	0.759	1.61
Franklin	Mass.	9.3	370	0.0657	1,042,700	0.0740	0.140
Grafton	Mass.	93.3	4,790	0.850	5,150,400	0.366	1.22
Holden	Mass.	18.4	1,170	0.208	54,700	0.0039	0.212
Hopedale	Mass.	80.1	270	0.0479	2,199,800	0.156	0.204
Hopkinton	Mass.	12.6	580	0.103	609,700	0.0433	0.146
Leicester	Mass.	32.8	1,620	0.288	534,700	0.0380	0.326
Mendon	Mass.	98.3	3,520	0.625	185,900	0.0132	0.638
Milford	Mass.	14.2	330	0.0586	1,250,300	0.0888	0.147
Millbury	Mass.	99.6	3,060	0.543	3,031,200	0.215	0.758
Millville	Mass.	100.0	1,060	0.188	44,600	0.0032	0.191
North Attleboro	Mass.	20.4	1,190	0.211	2,466,700	0.175	0.386
Northbridge	Mass.	100.0	3,530	0.627	3,699,500	0.263	0.889
Oxford	Mass.	4.8	260	0.0462	315,300	0.0224	0.0685
Paxton	Mass.	24.2	670	0.119	3,100	0.0	0.119
Plainville	Mass.	13.8	380	0.0675	1,556,300	0.110	0.178
Shrewsbury	Mass.	63.2	3,850	0.683	18,036,000	1.28	1.96
Sutton	Mass.	98.1	6,110	1.08	11,191,000	0.795	1.88
Upton	Mass.	96.8	2,630	0.467	4,094,100	0.291	0.758
Uxbridge	Mass.	100.0	4,590	0.815	5,511,700	0.391	1.21
Webster	Mass.	0.9	23	0.0041	40,200	0.0028	0.0069
West Boylston	Mass.	8.0	110	0.0195	281,100	0.0200	0.0395
Westborough	Mass.	2.1	80	0.0142	246,600	0.0175	0.0317
Worcester	Mass.	99.3	10,920	1.94	20,620,000	1.46	3.40
Wrentham	Mass.	27.2	910	0.162	2,095,500	0.149	0.310
Burrillville	R.I.	85.2	7,600	1.35	5,791,100	0.411	1.76
Central Falls	R.I.	60.5	16	0.0028	84,700	0.0060	0.0088
Cumberland	R.I.	100.0	3,630	0.644	12,903,000	0.916	1.56
Glocester	R.I.	43.6	2,160	0.383	1,266,600	0.0899	0.473
Lincoln	R.I.	37.0	1,770	0.314	3,724,900	0.264	0.579
North Smithfield	R.I.	82.3	6,170	1.10	7,214,700	0.512	1.61
Pawtucket	R.I.	6.3	50	0.0089	111,300	0.0079	0.0168
Smithfield	R.I.	5.9	250	0.0444	1,483,000	0.105	0.150
Woonsocket	R.I.	100.0	1,600	0.284	9,810,000	0.697	0.981
	Total:		**85,659**	**15.2**	**151,630,000**	**10.8**	**26.0**
Outside basin							
Pawtucket[1]		93.7	740	0.131	1,649,800	0.117	0.25

[1] New demands from Pawtucket, including the city area outside the basin, were assumed to be satisfied by withdrawals from the Abbott Run subbasin.

Table 9. Potential increases in the areas and percentages of residential and commercial-industrial-transportation land use at buildout for the Blackstone River Basin, Massachusetts and Rhode Island.

[Mgal/d, million gallons per day; --, not applicable]

Land-use category	Area at buildout (acres)	Area in 1995–1999 (acres)	Area increase (acres)	Percentage of total increase in residential area	Total new demand at buildout (Mgal/d)
Residential areas with private wells and onsite septic systems	52,086	20,978	31,108	71.2	10.8
Residential areas with private wells and public sewer systems	3,318	2,090	1,228	2.8	0.427
Residential areas with public water systems and onsite septic systems	15,259	10,149	5,111	11.7	1.78
Residential areas with public water and public sewer systems	37,705	31,436	6,270	14.3	2.2
Commercial-industrial-transportation areas	28,360	17,572	10,788	--	10.8
Total:	**136,729**	**82,224**	**54,505**		**26.0**

Table 10. Potential increases in areas and percentages of residential and commercial-industrial-transportation land use at buildout compared to their actual values in 1995–1999 for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.

[Subbasins and reaches shown on fig. 7]

Reach number	Subbasin name	Subbasin area (acres)	Increase in residential area with private wells and onsite septic systems (acres)	Percentage of total increase in residential area with private wells and onsite septic systems	Increase in residential area with private wells and public sewer systems (acres)	Percentage of total increase in residential areas with private wells and public sewer systems	Increase in residential area with public water systems and onsite septic systems (acres)	Percentage of total increase in residential area with public water systems and onsite septic systems	Increase in residential area with public water and public sewer systems (acres)	Percentage of total increase in residential areas with public water and public sewer systems	Increase in commercial-industrial-transportation areas (acres)	Percentage of total increase in commercial-industrial-transportation areas
1	QU1A	16,326	1,065.2	3.42	73.2	5.96	647.2	12.66	822.2	13.11	752.6	6.98
2	PA1A	5,219	49.8	0.16	1.6	0.13	20.0	0.39	40.0	0.64	3.1	0.03
3	MB1B	9,557	80.3	0.26	4.5	0.36	87.0	1.70	496.2	7.91	30.4	0.28
4	CH2A	7,087	170.1	0.55	14.7	1.20	6.0	0.12	28.7	0.46	63.8	0.59
5	TA1A	3,359	1,074.4	3.45	0.0	0.0	64.1	1.25	49.8	0.79	0.0	0.0
6	TA2A	6,383	205.9	0.66	7.1	0.58	138.1	2.70	332.7	5.31	52.1	0.48
7	QU2A	7,830	1,571.2	5.05	140.8	11.46	250.4	4.90	443.4	7.07	811.5	7.52
8	ML2A	8,947	2,881.7	9.26	10.0	0.81	364.5	7.13	96.5	1.54	66.3	0.61
9	CL1A	1,532	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	CL2A	9,251	275.3	0.89	19.3	1.57	10.2	0.20	68.1	1.09	26.5	0.25
11	KE1A	6,256	50.7	0.16	58.3	4.74	2.7	0.05	116.5	1.86	94.3	0.87
12	ML1A	12,203	2,420.7	7.78	1.3	0.11	241.5	4.73	232.6	3.71	638.5	5.92
13	BL2A	16,072	1,562.1	5.02	187.0	15.23	214.6	4.20	444.3	7.09	659.2	6.11
14	KE3A	9,086	2,066.7	6.64	10.9	0.89	44.3	0.87	242.6	3.87	127.7	1.18
15	BL1A	1,536	63.2	0.20	22.7	1.85	51.6	1.01	50.9	0.81	47.2	0.44
16	KE2A	3,813	820.8	2.64	37.1	3.02	55.6	1.09	222.6	3.55	630.3	5.84
17	WE1A	17,877	3,055.6	9.82	11.6	0.94	107.2	2.10	164.8	2.63	520.8	4.83
18	MU1A	4,795	332.5	1.07	0.0	0.0	0.0	0.0	0.0	0.0	18.5	0.17
19	DA1A	1,699	542.6	1.74	10.2	0.83	34.9	0.68	80.3	1.28	125.0	1.16
20	BL3A	3,137	900.0	2.89	52.3	4.25	108.8	2.13	166.4	2.65	362.0	3.36
21	MU3A	17,323	1,728.2	5.56	31.1	2.53	457.2	8.95	447.4	7.14	773.5	7.17
22	BL4A	5,391	1,155.8	3.72	34.0	2.77	232.2	4.54	252.0	4.02	262.2	2.43
23	MU2A	8,076	255.1	0.82	7.6	0.62	270.2	5.29	99.2	1.58	200.6	1.86
24	WE2A	6,047	2,628.4	8.45	0.2	0.02	151.9	2.97	46.5	0.74	0.0	0.0
25	BL5A	570	37.6	0.12	1.3	0.11	0.2	0.0	57.8	0.92	74.5	0.69

Table 10. Potential increases in areas and percentages of residential and commercial-industrial-transportation land use at buildout compared to their actual values in 1995–1999 for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Subbasins and reaches shown on fig. 7]

Reach number	Subbasin name	Subbasin area (acres)	Increase in residential area with private wells and onsite septic systems (acres)	Percentage of total increase in residential area with private wells and onsite septic systems	Increase in residential area with private wells and public sewer systems (acres)	Percentage of total increase in residential areas with private wells and public sewer systems	Increase in residential area with public water systems and onsite septic systems (acres)	Percentage of total increase in residential area with public water systems and onsite septic systems	Increase in residential area with public water and public sewer systems (acres)	Percentage of total increase in residential areas with public water and public sewer systems	Increase in commercial-industrial-transportation areas (acres)	Percentage of total increase in commercial-industrial-transportation areas
26	PE1A	7,866	221.5	0.71	0.9	0.07	220.6	4.32	46.0	0.73	75.6	0.70
27	EM1A	4,809	342.3	1.10	2.9	0.24	2.9	0.06	0.0	0.0	52.5	0.49
28	BL6A	1,074	247.5	0.80	46.3	3.77	43.8	0.86	60.0	0.96	43.8	0.41
29	AB1A	9,765	704.8	2.27	7.8	0.63	69.6	1.36	18.0	0.29	98.3	0.91
30	BL8A	8,949	795.0	2.56	48.9	3.98	152.8	2.99	152.6	2.43	281.8	2.61
31	BL7A	7,201	567.1	1.82	22.5	1.83	81.4	1.59	0.0	0.0	444.8	4.12
32	NI1A	9,971	1.8	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
33	CA1A	2,196	23.8	0.08	0.0	0.0	41.1	0.80	0.0	0.0	77.4	0.72
34	CH1A	5,223	5.3	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	BL9A	1,545	10.7	0.03	0.2	0.02	0.9	0.02	7.8	0.12	22.0	0.20
36	BR1A	7,537	42.0	0.14	97.6	7.95	0.0	0.0	0.0	0.0	447.7	4.15
37	BR2A	3,374	102.7	0.33	54.3	4.42	2.2	0.04	22.2	0.35	99.2	0.92
38	BL10	3,064	63.6	0.20	4.5	0.36	24.9	0.49	93.2	1.49	302.9	2.81
39	CL3A	3,082	130.8	0.42	71.2	5.79	1.8	0.03	34.2	0.55	160.6	1.49
40	BL11	5,927	140.8	0.45	50.9	4.15	111.2	2.18	260.6	4.16	522.4	4.84
41	AB2A	5,603	880.7	2.83	20.7	1.68	577.5	11.30	125.0	1.99	70.5	0.65
42	CR2A	3,198	279.3	0.90	5.3	0.43	18.0	0.35	34.0	0.54	151.0	1.40
43	TK1A	6,070	6.7	0.02	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.04
44	CR1A	1,996	155.9	0.50	0.0	0.0	54.5	1.07	0.0	0.0	40.9	0.38
45	BL12	3,538	59.8	0.19	9.6	0.78	60.9	1.19	138.8	2.21	174.8	1.62
46	AB3A	729	4.2	0.01	0.0	0.0	1.6	0.03	26.5	0.42	10.5	0.10
47	BL13	627	0.0	0.0	0.0	0.0	0.0	0.0	5.1	0.08	11.8	0.11
48	BL14	308	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.02	0.0	0.0
49	BL2B	4,496	1,301.2	4.18	48.2	3.93	85.2	1.67	242.9	3.87	320.3	2.97
50	WH1A	5,735	27.4	0.09	0.0	0.0	0.0	0.0	0.0	0.0	1,051.2	9.74
	Total:	**303,256**	**31,108**	**100**	**1,228**	**100**	**5,111**	**100**	**6,270**	**100**	**10,788**	**100**

Table 11. Potential new demands for residential and commercial-industrial-transportation land use at buildout for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.

[New demands refer to increases relative to withdrawals for 1996–2001. Shading indicates subbasins that did not contain public sewer lines around the year 2000. Subbasins and reaches shown on fig. 7. All demands in million gallons per day (Mgal/d). Commercial means commercial-industrial-transporation land use]

A	B	C	D	E	F	G	H	I	J	K	L	
Reach number	Subbasin name	New demand from residential areas with private wells and onsite septic systems	Net new demand from residential areas with private wells and on-site septic systems (consumptive losses)	New demand from residential areas with private wells and public sewer systems	New demand from residential areas with public water systems and on-site septic systems	New demand from residential areas with public water and public sewer systems	New demand from commercial areas[1]	Net new demand from commercial areas[2]	Total new demand from residential and commerical areas with public sewer systems	Total new demand in residential and commercial areas with public water systems	Total new demand from all residential and commercial areas in subbasins	Comments
1	QU1A	0.370	0.0741	0.0254	0.225	0.286	0.751	0.751	1.06	1.26	1.36	
2	PA1A	0.0173	0.00346	0.000539	0.00696	0.0139	0.00310	0.00310	0.0176	0.0240	0.0280	
3	MB1B	0.0279	0.00558	0.00155	0.0302	0.173	0.0304	0.0304	0.204	0.233	0.240	New demand satisfied by withdrawals from reach 5
4	CH2A	0.0592	0.0118	0.00511	0.00209	0.0100	0.0637	0.0637	0.0788	0.0758	0.0927	
5	TA1A	0.374	0.0747	0.0	0.0223	0.0173	0.0	0.0	0.0	0.0396	0.114	New demand satisfied by transfers from Kendall Reservoir in Nashua River Basin
6	TA2A	0.0716	0.0143	0.00248	0.0480	0.116	0.0520	0.0520	0.170	0.216	0.232	New demand satisfied by withdrawals from reach 5
7	QU2A	0.546	0.109	0.0490	0.0871	0.154	0.810	0.810	1.01	1.05	1.21	
8	ML2A	1.00	0.200	0.00348	0.127	0.0336	0.0661	0.0661	0.103	0.226	0.430	
9	CL1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
10	CL2A	0.0958	0.0192	0.00673	0.00356	0.0237	0.0264	0.0264	0.0568	0.0536	0.0795	
11	KE1A	0.0176	0.00353	0.0203	0.000932	0.0405	0.0941	0.0941	0.155	0.136	0.159	
12	ML1A	0.842	0.168	0.0	0.0840	0.0809	0.637	0.637	0.719	0.802	0.971	

Table 11. Potential new demands for residential and commercial-industrial-transportation land use at buildout for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[New demands refer to increases relative to withdrawals for 1996–2001. Shading indicates subbasins that did not contain public sewer lines around the year 2000. Subbasins and reaches shown on fig. 7. All demands in million gallons per day (Mgal/d). Commercial means commercial-industrial-transporation land use]

A	B	C	D	E	F	G	H	I	J	K	L	
Reach number	**Subbasin name**	**New demand from residential areas with private wells and onsite septic systems**	**Net new demand from residential areas with private wells and on-site septic systems (consumptive losses)**	**New demand from residential areas with private wells and public sewer systems**	**New demand from residential areas with public water systems and on-site septic systems**	**New demand from residential areas with public water and public sewer systems**	**New demand from commercial areas[1]**	**Net new demand from commercial areas[2]**	**Total new demand from residential and commerical areas with public sewer systems**	**Total new demand in residential and commercial areas with public water systems**	**Total new demand from all residential and commercial areas in subbasins**	**Comments**
13	BL2A	0.543	0.109	0.0651	0.0746	0.155	0.658	0.658	0.877	0.887	1.06	
14	KE3A	0.719	0.144	0.00379	0.0154	0.0844	0.127	0.127	0.216	0.227	0.375	
15	BL1A	0.0220	0.00439	0.00789	0.0179	0.0177	0.0471	0.0471	0.0727	0.0827	0.0950	New demand satisfied by withdrawals from reach 5
16	KE2A	0.285	0.0571	0.0129	0.0193	0.0774	0.629	0.629	0.719	0.726	0.796	
17	WE1A	1.06	0.213	0.00402	0.0373	0.0573	0.520	0.520	0.581	0.614	0.831	
18	MU1A	0.116	0.0231	0.0	0.0	0.0	0.0184	0.00368	0.0	0.0	0.0268	
19	DA1A	0.189	0.0377	0.00356	0.0121	0.0279	0.125	0.125	0.156	0.165	0.206	New demand satisfied by withdrawals from reach 14
20	BL3A	0.313	0.0626	0.0182	0.0378	0.0579	0.361	0.361	0.437	0.457	0.538	
21	MU3A	0.601	0.120	0.0108	0.159	0.156	0.772	0.772	0.938	1.09	1.22	
22	BL4A	0.402	0.0804	0.0118	0.0808	0.0876	0.262	0.262	0.361	0.430	0.522	
23	MU2A	0.0887	0.0177	0.00263	0.0940	0.0345	0.200	0.200	0.237	0.329	0.349	
24	WE2A	0.914	0.183	0.0	0.0528	0.0162	0.0	0.0	0.0162	0.0690	0.252	

Table 11. Potential new demands for residential and commercial-industrial-transportation land use at buildout for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[New demands refer to increases relative to withdrawals for 1996–2001. Shading indicates subbasins that did not contain public sewer lines around the year 2000. Subbasins and reaches shown on fig. 7. All demands in million gallons per day (Mgal/d). Commercial means commercial-industrial-transporation land use]

A	B	C	D	E	F	G	H	I	J	K	L	
Reach number	Subbasin name	New demand from residential areas with private wells and onsite septic systems	Net new demand from residential areas with private wells and on-site septic systems (consumptive losses)	New demand from residential areas with private wells and public sewer systems	New demand from residential areas with public water systems and on-site septic systems	New demand from residential areas with public water and public sewer systems	New demand from commercial areas[1]	Net new demand from commercial areas[2]	Total new demand from residential and commerical areas with public sewer systems	Total new demand in residential and commercial areas with public water systems	Total new demand from all residential and commercial areas in subbasins	Comments
25	BL5A	0.0131	0.00261	0.0	0.0	0.0201	0.0744	0.0744	0.0949	0.0945	0.0976	
26	PE1A	0.0770	0.0154	0.0	0.0767	0.0160	0.0754	0.0754	0.0918	0.168	0.184	
27	EM1A	0.119	0.0238	0.00101	0.00101	0.0	0.0524	0.0105	0.0	0.00101	0.0363	
28	BL6A	0.0861	0.0172	0.0161	0.0152	0.0209	0.0437	0.0437	0.0807	0.0799	0.113	New demand satisfied by withdrawals from reach 25
29	AB1A	0.245	0.0490	0.00271	0.0242	0.00627	0.0981	0.0981	0.107	0.129	0.180	
30	BL8A	0.277	0.0553	0.0170	0.0531	0.0531	0.281	0.281	0.351	0.387	0.460	New demand satisfied by withdrawals from reach 44
31	BL7A	0.197	0.0394	0.00781	0.0283	0.0	0.444	0.444	0.452	0.472	0.519	
32	NI1A	0.000616	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
33	CA1A	0.00827	0.00165	0.0	0.0143	0.0	0.0772	0.0154	0.0	0.0143	0.0314	
34	CH1A	0.00186	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Table 11. Potential new demands for residential and commercial-industrial-transportation land use at buildout for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[New demands refer to increases relative to withdrawals for 1996–2001. Shading indicates subbasins that did not contain public sewer lines around the year 2000. Subbasins and reaches shown on fig. 7. All demands in million gallons per day (Mgal/d). Commercial means commercial-industrial-transporation land use]

A	B	C	D	E	F	G	H	I	J	K	L	
Reach number	Subbasin name	New demand from residential areas with private wells and onsite septic systems	Net new demand from residential areas with private wells and on-site septic systems (consumptive losses)	New demand from residential areas with private wells and public sewer systems	New demand from residential areas with public water systems and on-site septic systems	New demand from residential areas with public water and public sewer systems	New demand from commercial areas[1]	Net new demand from commercial areas[2]	Total new demand from residential and commerical areas with public sewer systems	Total new demand in residential and commercial areas with public water systems	Total new demand from all residential and commercial areas in subbasins	Comments
35	BL9A	0.00371	0.000742	0.0	0.0	0.00270	0.0220	0.0220	0.0248	0.0250	0.0258	New demand satisfied by withdrawals from reach 44
36	BR1A	0.0146	0.00292	0.0340	0.0	0.0	0.447	0.447	0.481	0.447	0.484	
37	BR2A	0.0357	0.00715	0.0189	0.000776	0.00773	0.0990	0.0990	0.126	0.107	0.134	
38	BL10	0.0221	0.00442	0.00155	0.00866	0.0324	0.302	0.302	0.336	0.343	0.349	New demand satisfied by withdrawals from reach 44
39	CL3A	0.0455	0.00910	0.0247	0.000619	0.0119	0.160	0.160	0.197	0.173	0.207	
40	BL11	0.0490	0.00979	0.0177	0.0387	0.0906	0.521	0.521	0.630	0.651	0.678	
41	AB2A	0.306	0.0613	0.00720	0.201	0.0435	0.0704	0.0704	0.121	0.315	0.383	
42	CR2A	0.0971	0.0194	0.00185	0.00627	0.0118	0.151	0.151	0.164	0.169	0.190	
43	TK1A	0.00232	0.0	0.0	0.0	0.0	0.00443	0.000886	0.0	0.0	0.00135	
44	CR1A	0.0542	0.0108	0.0	0.0189	0.0	0.0408	0.00817	0.0	0.0189	0.0380	New demand satisfied by transfers from reach 8
45	BL12	0.0208	0.00416	0.00332	0.0212	0.0483	0.174	0.174	0.226	0.244	0.251	New demand satisfied by withdrawals from reach 46

Table 11. Potential new demands for residential and commercial-industrial-transportation land use at buildout for Hydrological Simulation Program—FORTRAN (HSPF) subbasins, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[New demands refer to increases relative to withdrawals for 1996–2001. Shading indicates subbasins that did not contain public sewer lines around the year 2000. Subbasins and reaches shown on fig. 7. All demands in million gallons per day (Mgal/d). Commercial means commercial-industrial-transporation land use]

A	B	C	D	E	F	G	H	I	J	K	L	
Reach number	Subbasin name	New demand from residential areas with private wells and onsite septic systems	Net new demand from residential areas with private wells and on-site septic systems (consumptive losses)	New demand from residential areas with private wells and public sewer systems	New demand from residential areas with public water systems and on-site septic systems	New demand from residential areas with public water and public sewer systems	New demand from commercial areas[1]	Net new demand from commercial areas[2]	Total new demand from residential and commerical areas with public sewer systems	Total new demand in residential and commercial areas with public water systems	Total new demand from all residential and commercial areas in subbasins	Comments
46	AB3A	0.00147	0.0	0.0	0.000543	0.00920	0.0104	0.0104	0.0196	0.0202	0.0205	New demands from city of Pawtucket outside the basin satisfied by withdrawals from this reach
47	BL13	0.0	0.0	0.0	0.0	0.00178	0.0118	0.0118	0.0135	0.0135	0.0135	New demand satisfied by withdrawals from reach 46
48	BL14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
49	BL2B	0.453	0.0905	0.0168	0.0296	0.0845	0.320	0.320	0.421	0.434	0.541	
50	WH1A	0.00951	0.00190	0.0	0.0	0.0	1.05	0.210	0.0	0.0	0.212	
Total:		**10.8**	**2.16**	**0.427**	**1.78**	**2.18**	**10.8**	**9.79**	**12.1**	**13.5**	**16.3**	

[1] All new commercial-industrial-transportation demands were assumed to be in urban areas served by public water and public sewer systems, with the exception of the subbasins that did not contain public sewers around the year 2000 (shaded rows). New commercial-industrial-transportation development in these subbasins was assumed to be in areas served by private wells and on-site septic systems.

[2] New commercial-industrial-transportation demands in subbasins that did not contain public sewer lines around the year 2000 were reduced to 20 percent of total demands so that only consumptive losses were simulated by the model.

Table 12. Potential new wastewater-return flows to treatment plants at buildout, Blackstone River Basin, Massachusetts and Rhode Island.

[Subbasins and reaches shown on fig. 7. New return flows refer to increases relative to flows for 1996–2001. All return-flow rates in million gallons per day (Mgal/d). WWTP, wastewater-treatment plant; UBWWTF, Upper Blackstone Wastewater Treatment Facility; Mass., Massachusetts; R.I., Rhode Island]

WWTP	Reach number	Subbasin name	Annual average 1996–2001 return flow to WWTP (Mgal/d)	Reaches in WWTP service area	Potential new return flow from public sewers in reaches in WWTP service area (Mgal/d)	Potential new return flow minus 20 percent consumptive losses (Mgal/d)
Worcester Combined Sewer Overflow Plant	3	MB1B	1.27	1, 3, 6, 11, 14, 15, 16, 19, 49	0.0	0.0
Hopedale, Mass.	12	ML1A	0.422	12	0.719	0.575
Millbury, Mass.	13	BL2A	1.05	13	0.877	0.702
UBWWTF, Millbury, Mass.	15	BL1A	36.7	1, 3, 6, 11, 14, 15, 16, 19, 49	3.18	2.54
Upton, Mass.	17	WE1A	0.186	17	0.581	0.465
Grafton, Mass.	20	BL3A	1.57	7, 20	1.45	1.16
Douglas, Mass.	21	MU3A	0.182	23	0.237	0.190
Northbridge, Mass.	22	BL4A	1.36	21, 22, 25	1.39	1.12
Uxbridge, Mass.	31	BL7A	0.732	24, 28, 31	0.549	0.439
Woonsocket, R.I.	38	BL10	9.10	8, 26, 30, 35, 37, 38	1.03	0.830
Burrillville, R.I.	39	CL3A	0.817	2, 4, 10, 36, 39	0.831	0.665
		Total:	**53.4**		**10.8**	**8.68**

Table 13. Summary of basin-wide, long-term (1960–2004) scenarios simulated with Hydrological Simulation Program—FORTRAN (HSPF) model of the Blackstone River Basin, Massachusetts and Rhode Island.

[UCI, User Control File; DSN, dataset number in the watershed data management database]

Scenario number	Description	UCI file name	Output DSN
7.0	Baseline simulation—1996–2001 water use, 1995–1999 land use	black_7.0	6701-6750
8.0	No water use, 1995–1999 land use	black_8.0	6801-6850
9.0	No water use, undeveloped land use	black_9.0	6901-6950
10.0	Buildout simulation—1996–2001 water use, land use at buildout	black_10.0	8001-8050
11.0	Buildout simulation—no water use, land use at buildout	black_11.0	8101-8150
12.0	Buildout simulation—water use at buildout, land use at buildout	black_12.0	8201-8250
13.0	20-percent reduction in 1996–2001 water use, 1995–1999 land use	black_13.0	8301-8350

Table 14. Land use for Hydrological Simulation Program—FORTRAN (HSPF) scenarios 8.0 (1995–1999 land use), 9.0 (undeveloped land use), and 11.0 (potential land use at buildout), Blackstone River Basin, Massachusetts and Rhode Island.

Land-use category	Scenario 9.0 Undeveloped		Scenario 8.0 1995–1999		Scenario 11.0 Buildout	
	Area (acres)	Percentage of total area	Area (acres)	Percentage of total area	Area (acres)	Percentage of total area
Commercial-industrial-transportation	0.0	0.0	8,216	2.7	11,460	3.8
High-density residential	0.0	0.0	17,026	5.6	20,641	6.8
Medium- to low-density residential	0.0	0.0	43,462	14.3	81,663	26.9
Open, nonresidential	32,495	10.7	31,650	10.4	21,977	7.2
Forest	235,960	77.8	153,736	50.7	109,046	36.0
Open water	11,392	3.8	11,392	3.8	11,432	3.8
Wetlands	23,395	7.7	23,395	7.7	23,396	7.7
Effective impervious area	0.0	0.0	14,362	4.7	23,639	7.9

Table 15. Average annual and average summer withdrawals and wastewater-return flows for Hydrological Simulation Program—FORTRAN (HSPF) subbasins for recent (1996–2001) conditions and potential conditions at buildout, Blackstone River Basin, Massachusetts and Rhode Island.-

[Average summer withdrawals and wastewater-return flows for 1996–2001 are the 6-year averages of average monthly rates for June through September. Potential rates at buildout were calculated by multiplying the 1996–2001 rates by a constant determined from analysis of buildout information. Total withdrawals are the sum of municipal, commercial/industrial, and golf-course withdrawals from the subbasin. Total wastewater-return flows are the sum of commercial and municipal return flows to the subbasin. Subbasins and reaches shown on fig. 7; ft^3/s, cubic feet per second]

Reach number	Subbasin name	1996–2001				Buildout			
		Average annual withdrawals, 1996–2001 (ft^3/s)	Average summer withdrawals, 1996–2001 (ft^3/s)	Average annual return flows, 1996–2001 (ft^3/s)	Average summer return flows, 1996–2001 (ft^3/s)	Average annual withdrawals, buildout (ft^3/s)	Average summer withdrawals, buildout (ft^3/s)	Average annual return flows, buildout (ft^3/s)	Average summer return flows, buildout (ft^3/s)
				Rhode Island subbasins					
2	PA1A	0.0	0.0	0.0	0.0	0.0425	0.0510	0.0	0.0
4	CH2A	0.0	0.0	0.0	0.0	0.136	0.162	0.0	0.0
8	ML2A	1.39	1.34	0.0	0.0	3.66	3.53	0.0	0.0
9	CL1A	0.132	0.126	0.0	0.0	0.132	0.126	0.0	0.0
10	CL2A	0.459	0.494	0.110	0.108	0.572	0.615	0.110	0.108
12	ML1A	0.638	0.793	0.653	0.571	2.14	2.66	1.54	1.35
26	PE1A	1.62	1.88	0.0	0.0	1.90	2.21	0.0	0.0
29	AB1A	1.48	1.64	0.0	0.0	1.63	1.81	0.0	0.0
30	BL8A	6.73	6.75	0.00653	0.00696	6.73	6.75	0.00653	0.00696
31	BL7A	0.0	0.0	1.13	0.990	0.791	0.947	1.81	1.58
32	NI1A	0.0724	0.143	0.0	0.0	0.0724	0.143	0.0	0.0
33	CA1A	0.0	0.0	0.0	0.0	0.0486	0.0580	0.0	0.0
34	CH1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	BL9A	0.0	0.0	0.0773	0.0773	0.0	0.0	0.0773	0.0773
36	BR1A	0.0480	0.0480	0.00920	0.00920	0.744	0.744	0.00920	0.00920
37	BR2A	0.0930	0.0930	0.00460	0.00460	0.270	0.270	0.00460	0.00460
38	BL10	0.0	0.0	15.9	14.7	0.0	0.0	17.2	15.9
39	CL3A	0.356	0.391	1.26	1.18	0.637	0.700	2.29	2.14
40	BL11	0.702	0.810	0.0	0.0	1.72	1.99	0.0	0.0
41	AB2A	3.08	4.32	0.0	0.0	3.66	5.14	0.0	0.0
42	[1]CR2A	2.07	2.47	0.0130	0.0120	2.07	2.47	0.0130	0.0120
43	TK1A	0.0145	0.0159	0.0	0.0	0.0166	0.0182	0.0	0.0
44	CR1A	5.38	6.06	0.0	0.0	5.38	6.06	0.0	0.0
45	BL12	0.248	0.548	0.423	0.445	0.248	0.548	0.423	0.445
46	AB3A	18.7	21.1	0.420	0.432	19.5	22.0	0.420	0.432
47	BL13	0.0	0.0	0.466	0.494	0.0	0.0	0.466	0.494
	Total:	**43.2**	**49.0**	**20.5**	**19.0**	**52.1**	**59.0**	**24.3**	**22.5**

Table 15. Average annual and average summer withdrawals and wastewater-return flows for Hydrological Simulation Program—FORTRAN (HSPF) subbasins for recent (1996–2001) conditions and potential conditions at buildout, Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Average summer withdrawals and wastewater-return flows for 1996–2001 are the 6-year averages of average monthly rates for June through September. Potential rates at buildout were calculated by multiplying the 1996–2001 rates by a constant determined from analysis of buildout information. Total withdrawals are the sum of municipal, commercial/industrial, and golf-course withdrawals from the subbasin. Total wastewater-return flows are the sum of commercial and municipal return flows to the subbasin. Subbasins and reaches shown on fig. 7; ft^3/s, cubic feet per second]

Reach number	Subbasin name	1996–2001				Buildout			
		Average annual withdrawals, 1996–2001 (ft^3/s)	Average summer withdrawals, 1996–2001 (ft^3/s)	Average annual return flows, 1996–2001 (ft^3/s)	Average summer return flows, 1996–2001 (ft^3/s)	Average annual withdrawals, buildout (ft^3/s)	Average summer withdrawals, buildout (ft^3/s)	Average annual return flows, buildout (ft^3/s)	Average summer return flows, buildout (ft^3/s)
				Massachusetts subbasins					
1	QU1A	6.65	7.95	0.0	0.0	8.71	10.4	0.0	0.0
3	MB1B	0.320	0.320	2.76	2.10	0.320	0.320	2.76	2.10
5	[1]TA1A	8.55	4.35	0.0	0.0	8.80	4.47	0.0	0.0
6	TA2A	0.0323	0.0729	0.0	0.0	0.0323	0.0729	0.0	0.0
7	QU2A	1.46	1.62	0.0	0.0	3.25	3.62	0.0	0.0
11	KE1A	6.66	8.84	0.0	0.0	6.88	9.12	0.0	0.0
13	BL2A	1.80	1.94	1.63	1.30	3.34	3.60	2.72	2.17
14	KE3A	2.07	2.32	0.0	0.0	2.96	3.31	0.0	0.0
15	BL1A	0.0220	0.0496	56.8	48.1	0.0220	0.0496	60.7	51.4
16	KE2A	0.0125	0.0129	0.0	0.0	1.22	1.26	0.0	0.0
17	WE1A	0.696	0.764	0.287	0.217	1.97	2.17	1.01	0.760
18	MU1A	0.0	0.0	0.0	0.0	0.0415	0.0495	0.0	0.0
19	DA1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	BL3A	0.355	0.393	2.44	2.20	1.16	1.28	4.24	3.82
21	MU3A	2.73	3.02	0.280	0.245	4.60	5.10	0.572	0.501
22	BL4A	0.330	0.327	2.11	1.73	1.12	1.11	3.84	3.15
23	MU2A	0.517	0.625	0.0	0.0	1.05	1.27	0.0	0.0
24	WE2A	0.335	0.395	0.0	0.0	0.724	0.853	0.0	0.0
25	BL5A	0.990	1.039	0.0	0.0	1.29	1.35	0.0	0.0
27	EM1A	0.0	0.0	0.0	0.0	0.0546	0.0650	0.0	0.0
28	BL5A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	BL2B	1.13	1.41	0.0	0.0	1.94	2.42	0.0	0.0
50	WH1A	0.0	0.0	0.0	0.0	0.328	0.392	0.0	0.0
	Total:	**34.7**	**35.5**	**66.3**	**55.9**	**49.8**	**52.3**	**75.9**	**63.9**
	Basin total:	**77.9**	**84.5**	**86.8**	**74.9**	**102**	**111**	**100**	**86.5**

[1] Transfers of water to these subbasins from other areas were subtracted from total withdrawal rates.

Table 16. Ratios of withdrawals and wastewater-return flows to streamflow for 1996–2001 water-use conditions in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.

[Streamflow was simulated for 1960–2004 with 1995–1999 land use and no water use. Average summer streamflow is defined as the average monthly streamflow for June through September. Total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September for 1996–2001, residential withdrawals from areas with private wells and public sewer systems, and the annual average simulated infiltration to public sewers. Total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows for 1996–2001 and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; (ft^3/s)/mi^2, cubic feet per second per square mile of drainage area; HSPF, Hydrologic Simulation Program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ((ft^3/s)/mi^2)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
Individual HSPF subbasins									
2	[1]PA1A	3.40	0.42	0.200	0.00694	0.193	0.059	0.0020	0.057
4	CH2A	7.80	0.70	0.463	0.00692	0.456	0.059	0.00089	0.058
8	ML2A	11.1	0.79	1.95	0.271	1.68	0.18	0.024	0.15
9	[1]CL1A	3.90	1.6	0.152	0.0	0.152	0.039	0.0	0.039
10	CL2A	7.70	0.53	1.09	0.121	0.965	0.14	0.016	0.13
12	[1]ML1A	19.5	1.0	1.80	0.803	1.00	0.092	0.041	0.051
26	[1]PE1A	9.40	0.76	2.38	0.263	2.11	0.25	0.028	0.22
29	AB1A	22.8	1.5	2.05	0.215	1.83	0.090	0.0094	0.080
30	BL8A	11.6	0.83	8.13	0.0691	8.06	0.70	0.0060	0.70
31	BL7A	8.70	0.77	0.652	1.01	-0.362	0.075	0.12	-0.042
32	[1]NI1A	8.90	0.57	0.479	0.0	0.479	0.054	0.0	0.054
33	[1]CA1A	2.30	0.66	0.0992	0.152	-0.0523	0.043	0.066	-0.023
34	[1]CH1A	3.90	0.48	0.276	0.0	0.276	0.071	0.0	0.071
35	BL9A	14.0	5.8	0.679	0.0787	0.600	0.048	0.0056	0.043
36	BR1A	6.90	0.59	0.803	0.00920	0.794	0.12	0.0013	0.12
37	BR2A	4.60	0.87	0.809	0.0181	0.791	0.18	0.0039	0.17
38	BL10	8.00	1.7	1.00	14.7	-13.7	0.12	1.8	-1.7
39	CL3A	3.30	0.69	1.00	1.19	-0.194	0.30	0.36	-0.059
40	BL11	6.40	0.69	1.67	0.178	1.49	0.26	0.028	0.23
41	AB2A	7.30	0.82	5.01	0.632	4.38	0.69	0.087	0.60
42	CR2A	3.20	0.64	2.64	0.0220	2.61	0.82	0.0069	0.82
43	[1]TK1A	6.00	0.63	0.429	0.00644	0.422	0.071	0.0011	0.070
44	[1]CR1A	2.40	0.77	6.10	0.0	6.10	2.5	0.00094	2.5
45	BL12	9.00	1.6	1.29	0.530	0.762	0.14	0.059	0.085
46	AB3A	1.20	1.1	21.4	0.434	21.0	18	0.36	18
47	BL13	10.4	11	0.241	0.498	-0.257	0.023	0.048	-0.025

Table 16. Ratios of withdrawals and wastewater-return flows to streamflow for 1996–2001 water-use conditions in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Streamflow was simulated for 1960–2004 with 1995–1999 land use and no water use. Average summer streamflow is defined as the average monthly streamflow for June through September. Total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September for 1996–2001, residential withdrawals from areas with private wells and public sewer systems, and the annual average simulated infiltration to public sewers. Total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows for 1996–2001 and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; (ft^3/s)/mi^2, cubic feet per second per square mile of drainage area; HSPF, Hydrologic Simulation Program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ((ft^3/s)/mi^2)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
Total contributing areas (excluding headwaters subbasins listed above)									
4	CH2A	11.7	0.61	0.739	0.00692	0.732	0.063	0.00059	0.063
8	ML2A	30.6	0.93	3.75	1.07	2.68	0.12	0.035	0.087
10	CL2A	15.0	0.60	1.44	0.128	1.31	0.096	0.0085	0.087
29	AB1A	25.1	1.3	2.15	0.366	1.78	0.086	0.015	0.071
30	BL8A	354	0.96	63.8	59.8	3.97	0.18	0.17	0.011
31	BL7A	286	1.1	49.9	58.4	-8.42	0.17	0.20	-0.029
35	BL9A	408	0.98	70.6	61.2	9.36	0.17	0.15	0.023
36	BR1A	51.8	0.60	4.88	1.34	3.54	0.094	0.026	0.068
37	BR2A	56.4	0.62	5.69	1.36	4.33	0.10	0.024	0.077
38	BL10	416	0.99	71.6	75.9	-4.35	0.17	0.18	-0.010
39	CL3A	27.2	0.60	2.91	1.32	1.59	0.11	0.048	0.059
40	BL11	428	0.98	82.0	76.1	5.85	0.19	0.18	0.014
41	AB2A	32.4	1.2	7.16	0.998	6.16	0.22	0.031	0.19
42	CR2A	5.60	0.69	8.74	0.0242	8.71	1.6	0.0043	1.6
45	BL12	437	0.98	83.3	76.6	6.61	0.19	0.18	0.015
46	AB3A	33.6	1.2	28.6	1.43	27.2	0.85	0.043	0.81
47	BL13	481	1.0	112	78.6	33.5	0.23	0.16	0.070
27	^{2}EM1A	5.30	0.71	0.0	0.0	0.0	0.0	0.0	0.0
28	^{2,3}BL6A	272	1.1	49.3	57.3	-8.06	0.18	0.21	-0.030
Tributary subbasins									
Abbott Run									
29, 33, 41, 46	AB1A, CA1A, AB2A, AB3A	33.6	1.2	28.6	1.43	27.2	0.85	0.043	0.81
Chepachet River									
4, 34	CH1A, CH2A	11.7	0.61	0.739	0.00692	0.732	0.063	0.00059	0.063

Table 16. Ratios of withdrawals and wastewater-return flows to streamflow for 1996–2001 water-use conditions in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Streamflow was simulated for 1960–2004 with 1995–1999 land use and no water use. Average summer streamflow is defined as the average monthly streamflow for June through September. Total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September for 1996–2001, residential withdrawals from areas with private wells and public sewer systems, and the annual average simulated infiltration to public sewers. Total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows for 1996–2001 and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile of drainage area; HSPF, Hydrologic Simulation Program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ($(ft^3/s)/mi^2$)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
Tributary subbasins (Continued)									
Clear River									
2, 9, 10, 32	PA1A, CL1A, CL2A, NI1A	23.9	0.59	1.92	0.128	1.79	0.080	0.0054	0.075
Branch River below confluence of Clear and Chepachet Rivers									
36, 37, 39, 43	BR1A, BR2A, CL3A, TK1A	20.8	0.66	3.04	1.22	1.81	0.15	0.059	0.087
Peters River									
26	PE1A	9.40	0.76	2.38	0.263	2.11	0.25	0.028	0.22
Mill River									
8, 12	ML2A, ML1A	30.6	0.93	3.75	1.074	2.68	0.12	0.035	0.087
Crookfall Brook									
42, 44	CR2A, CR1A	5.60	0.69	8.74	0.0242	8.71	1.6	0.0043	1.6

[1] Headwaters subbasin.

[2] Massachusetts subbasin.

[3] Represents cumulative streamflow, withdrawal rate, and wastewater-return flow rate from all subbasins above main stem reach 31 (BL7A).

Table 17. Ratios of withdrawals and wastewater-return flows to streamflow for potential water-use conditions at buildout in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.

[Streamflow was simulated for 1960–2004 with potential land use at buildout and no withdrawals or return flows. Average summer streamflow is defined as the average monthly streamflow for June through September. Potential total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September at buildout, residential withdrawals from areas with private wells and public sewer systems, and annual average simulated infiltration to public sewers. Potential total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows at buildout and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile of drainage area; HSPF, hydrologic simulation program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ($(ft^3/s)/mi^2$)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
				Individual HSPF subbasins					
2	[1]PA1A	3.40	0.42	0.251	0.0124	0.239	0.074	0.0037	0.070
4	CH2A	7.90	0.71	0.631	0.00858	0.622	0.080	0.0011	0.079
8	ML2A	12.4	0.89	4.15	0.371	3.77	0.33	0.030	0.30
9	[1]CL1A	3.90	1.6	0.152	0.0	0.152	0.039	0	0.039
10	CL2A	7.80	0.54	1.21	0.124	1.09	0.16	0.016	0.14
12	[1]ML1A	20.6	1.1	3.67	1.65	2.02	0.18	0.080	0.098
26	[1]PE1A	9.40	0.76	2.71	0.315	2.39	0.29	0.033	0.25
29	AB1A	22.8	1.5	2.22	0.233	1.99	0.097	0.010	0.087
30	BL8A	23.0	1.6	8.15	0.111	8.04	0.35	0.0048	0.35
31	BL7A	9.60	0.85	1.61	1.63	-0.0235	0.17	0.17	-0.0025
32	[1]NI1A	8.90	0.57	0.479	0.0	0.479	0.054	0.0	0.054
33	[1]CA1A	2.40	0.69	0.157	0.163	-0.00570	0.066	0.068	-0.0024
34	[1]CH1A	3.90	0.48	0.276	0.0	0.276	0.071	0.0	0.071
35	BL9A	14.6	6.1	0.679	0.0791	0.600	0.047	0.0054	0.041
36	BR1A	7.80	0.66	1.53	0.00920	1.52	0.20	0.0012	0.19
37	BR2A	4.80	0.91	1.01	0.0187	0.989	0.21	0.0039	0.21
38	BL10	9.00	1.9	1.00	15.9	-14.9	0.11	1.8	-1.7
39	CL3A	3.60	0.75	1.33	2.15	-0.820	0.37	0.60	-0.23
40	BL11	13.8	1.5	2.86	0.212	2.65	0.21	0.02	0.19
41	AB2A	7.30	0.82	5.83	0.809	5.02	0.80	0.11	0.69
42	CR2A	3.70	0.74	2.65	0.0272	2.63	0.72	0.0074	0.71
43	[1]TK1A	6.00	0.63	0.431	0.00644	0.425	0.072	0.0011	0.071
44	[1]CR1A	2.50	0.80	6.10	0.0533	6.05	2.4	0.021	2.4
45	BL12	5.00	0.90	1.30	0.550	0.75	0.26	0.11	0.15
46	AB3A	1.20	1.1	22.4	0.435	21.9	19	0.36	18
47	BL13	7.30	7.5	0.241	0.498	-0.257	0.033	0.068	-0.035

Table 17. Ratios of withdrawals and wastewater-return flows to streamflow for potential water-use conditions at buildout in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Streamflow was simulated for 1960–2004 with potential land use at buildout and no withdrawals or return flows. Average summer streamflow is defined as the average monthly streamflow for June through September. Potential total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September at buildout, residential withdrawals from areas with private wells and public sewer systems, and annual average simulated infiltration to public sewers. Potential total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows at buildout and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile of drainage area; HSPF, hydrologic simulation program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ($(ft^3/s)/mi^2$)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
				Full contributing area (excluding headwater subbasins listed above)					
4	CH2A	11.8	0.61	0.907	0.00858	0.898	0.077	0.00073	0.076
8	ML2A	33.0	1.0	7.81	2.02	5.79	0.24	0.061	0.18
10	CL2A	15.1	0.60	1.62	0.136	1.48	0.11	0.0090	0.098
29	AB1A	25.2	1.3	2.38	0.396	1.98	0.094	0.016	0.079
30	BL8A	374	1.0	83.7	70.7	13.1	0.22	0.19	0.035
31	BL7A	293	1.1	68.3	68.2	0.0730	0.23	0.23	0.00025
35	BL9A	431	1.0	94.9	73.1	21.9	0.22	0.17	0.051
36	BR1A	53.2	0.62	6.30	2.31	3.98	0.12	0.043	0.075
37	BR2A	58.0	0.64	7.30	2.33	4.97	0.13	0.040	0.086
38	BL10	440	1.0	95.9	89.0	6.96	0.22	0.20	0.016
39	CL3A	27.6	0.61	3.43	2.29	1.14	0.12	0.083	0.041
40	BL11	460	1.0	108	89.3	18.3	0.23	0.19	0.040
41	AB2A	32.5	1.2	8.21	1.20	7.01	0.25	0.037	0.22
42	CR2A	6.20	0.76	8.76	0.0805	8.68	1.4	0.013	1.4
45	BL12	465	1.0	109	89.8	19.0	0.23	0.19	0.041
46	AB3A	33.7	1.2	30.6	1.64	28.9	0.91	0.049	0.86
47	BL13	506	1.1	140	92.0	47.7	0.28	0.18	0.094
27	[2]EM1A	5.40	0.72	0.0	0.0	0.0	0.0	0.0	0.0
28	[2, 3] BL6A	278	1.1	66.7	66.6	0.0965	0.24	0.24	0.0
				Tributary subbasins					
Abbott Run									
29, 33 ,41 ,46	AB1A, CA1A, AB2A, AB3A	33.7	1.2	30.6	1.64	28.9	0.91	0.049	0.86

Table 17. Ratios of withdrawals and wastewater-return flows to streamflow for potential water-use conditions at buildout in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.—Continued

[Streamflow was simulated for 1960–2004 with potential land use at buildout and no withdrawals or return flows. Average summer streamflow is defined as the average monthly streamflow for June through September. Potential total withdrawals from a subbasin include average monthly municipal and commercial/industrial withdrawals for June through September at buildout, residential withdrawals from areas with private wells and public sewer systems, and annual average simulated infiltration to public sewers. Potential total return flows to a subbasin include average June through September municipal and commercial wastewater-return flows at buildout and residential return flows from areas with public water systems and on-site septic systems; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile of drainage area; HSPF, hydrologic simulation program—FORTRAN]

Reach number	Subbasin name	50th percentile (median) of average summer streamflow, 1960–2004 (ft^3/s)	50th percentile (median) of average summer streamflow, 1960–2004 ($(ft^3/s)/mi^2$)	Total withdrawal rate (ft^3/s)	Total return-flow rate (ft^3/s)	Total withdrawal rate minus total return-flow rate (net rate) (ft^3/s)	Ratio of total withdrawal rate to streamflow	Ratio of total return-flow rate to streamflow	Ratio of net rate to streamflow
Tributary subbasins (Continued)									
Chepachet River									
4, 34	CH1A, CH2A	11.8	0.61	0.907	0.0	0.898	0.077	0.00073	0.076
Clear River									
2, 9, 10, 32	PA1A, CL1A, CL2A, NI1A	24.0	0.59	2.10	0.136	1.96	0.087	0.0057	0.082
Branch River below confluence of Clear and Chepachet Rivers									
36, 37, 39, 43	BR1A, BR2A, CL3A, TK1A	22.2	0.71	4.30	2.19	2.11	0.19	0.10	0.10
Peters River									
26	PE1A	9.4	0.76	2.71	0.315	2.39	0.29	0.033	0.25
Mill River									
8, 12	ML2A, ML1A	33.0	1.0	7.81	2.02	5.79	0.24	0.061	0.18
Crookfall Brook									
42, 44	CR2A, CR1A	6.2	0.76	8.76	0.0805	8.68	1.4	0.013	1.4

[1] Headwaters subbasin.

[2] Massachusetts subbasin.

[3] Represents cumulative streamflow, withdrawal rate, and wastewater-return flow rate from all subbasins above main stem reach 31 (BL7A).

Table 18. Six-year (1996–2001) average withdrawal rates and 20-percent reductions in average withdrawal rates in Hydrological Simulation Program—FORTRAN (HSPF) subbasins for the months of June, July, August, and September in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.

[Withdrawals represent the sum of all municipal, commercial/industrial, and golf-course withdrawals in the subbasin. Subbasins and reaches shown in fig. 7; Mgal/d, million gallons per day]

Reach number	Subbasin name	June		July		August		September	
		Withdrawal rate (Mgal/d)	Withdrawal rate reduced by 20 percent (Mgal/d)	Withdrawal rate (Mgal/d)	Withdrawal rate reduced by 20 percent (Mgal/d)	Withdrawal rate (Mgal/d)	Withdrawal rate reduced by 20 percent (Mgal/d)	Withdrawal rate (Mgal/d)	Withdrawal rate reduced by 20 percent (Mgal/d)
2	PA1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	CH2A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	ML2A	0.903	0.722	0.806	0.645	0.909	0.727	0.855	0.684
9	CL1A	0.0826	0.0661	0.0840	0.0672	0.0756	0.0605	0.0851	0.0681
10	CL2A	0.309	0.247	0.316	0.253	0.324	0.260	0.328	0.262
12	ML1A	0.531	0.425	0.567	0.454	0.494	0.395	0.459	0.368
26	PE1A	1.24	1.00	1.29	1.03	1.18	0.945	1.15	0.918
29	AB1A	1.02	0.814	1.10	0.882	1.08	0.866	1.04	0.834
30	BL8A	4.43	3.54	4.43	3.54	4.27	3.41	4.32	3.46
31	BL7A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	NI1A	0.0683	0.0546	0.119	0.0954	0.101	0.0811	0.0810	0.0648
33	CA1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	CH1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	BL9A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	BR1A	0.0309	0.0247	0.0309	0.0247	0.0309	0.0247	0.0309	0.0247
37	BR2A	0.0600	0.0480	0.0600	0.0480	0.0600	0.0480	0.0600	0.0480
38	BL10	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0
39	CL3A	0.271	0.217	0.271	0.216	0.243	0.194	0.227	0.182
40	BL11	0.552	0.442	0.605	0.484	0.495	0.396	0.442	0.354
41	AB2A	2.39	1.91	3.12	2.50	3.21	2.57	2.44	1.95
42	CR2A	1.75	1.40	1.73	1.39	1.69	1.35	1.54	1.23
43	TK1A	0.0105	0.00841	0.0107	0.00854	0.0107	0.00858	0.00916	0.00733
44	CR1A	4.09	3.27	4.04	3.23	3.94	3.15	3.59	2.87
45	BL12	0.285	0.228	0.395	0.316	0.408	0.326	0.330	0.264
46	AB3A	14.4	11.5	14.4	11.5	13.4	10.8	12.5	10.0
47	BL13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Total:	**32.4**	**25.9**	**33.4**	**26.7**	**32.0**	**25.6**	**29.4**	**23.6**

Table 19. Simulated streamflow at the 90-percent flow duration for 1996–2001 withdrawals and 1996–2001 withdrawals reduced by 20 percent to represent conservation measures in selected subbasins with high ratios of withdrawals to streamflow in the Rhode Island part of the Blackstone River Basin, Massachusetts and Rhode Island.

[Streamflow at the 90-percent flow duration computed from long-term simulations (1960–2004). Subbasins and reaches shown on fig. 7. ft^3/s; cubic feet per second; Mass., Massachusetts; R.I., Rhode Island; <, less than]

Description of subbasin	Subbasin name	Simulated streamflow at the 90-percent flow duration (ft^3/s)	
		1996–2001 withdrawals	1996–2001 withdrawals reduced by 20 percent
Crookfall Brook above outlet of Woonsocket Reservoir No. 1	CR2A	<0.10	0.48
Abbott Run above outlet of Happy Hollow Pond	AB3A	2.67	7.64
Peters River above Route 114 bridge	PE1A	3.81	4.12
Blackstone River above Elizabeth Webbing Dam	BL13	202	219
Branch River above streamflow-gaging station at Forestdale, R.I.	BR2A	25.5	25.9
Blackstone River upstream of Mass.-R.I. state line	BL7A	133	142