Prepared in cooperation with the
Massachusetts Executive Office of Environmental Affairs
Department of Conservation and Recreation

Effects of Water Use and Land Use on Streamflow and Aquatic Habitat in the Sudbury and Assabet River Basins, Massachusetts

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U.S. Department of the Interior
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By Phillip J. Zarriello, Gene W. Parker, David S. Armstrong, and Carl S. Carlson

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	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)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per acre per year (in/acre/yr)	0.006276	millimeter per square meter per year ($mm/m^2/yr$)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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).

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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Effects of Water Use and Land Use on Streamflow and Aquatic Habitat in the Sudbury and Assabet River Basins, Massachusetts

By Phillip J. Zarriello, Gene W. Parker, David S. Armstrong, and Carl S. Carlson

Abstract

Water withdrawals from surface-water reservoirs and groundwater have affected streamflow in the Sudbury and Assabet River Basins. These effects are particularly evident in the upper Sudbury River Basin, which prompted the need to improve the understanding of water resources and aquatic habitat in these basins. In 2004, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Conservation and Recreation, developed a precipitation-runoff model that uses Hydrologic Simulation Program–FORTRAN (HSPF) to evaluate the effects of water use and projected future water-use and land-use change on streamflow. As part of this study, the aquatic habitat in the basins and the effects of streamflow alteration also were evaluated.

Chapter 1 of the report covers the development of the HSPF model that focuses on the upper Sudbury River Basin (106 square miles) but covers the entire Sudbury and Assabet River Basins (339 square miles). The model was calibrated to an 11-year period (1993–2003) using observed or estimated streamflow at four streamgages. The model was then used to simulate long-term (1960–2004) streamflows to evaluate the effects of average 1993–2003 water use and projected 2030 water-use and land-use change over long-term climatic conditions. Simulations indicate that the average 1993–2003 withdrawals most altered streamflow relative to no withdrawals in small headwater subbasins where the ratios of mean annual withdrawals to mean annual streamflow are the highest. The effects of withdrawals are also appreciable in other parts of the upper Sudbury River Basin as a result of the perpetuation of the effects of large withdrawals in upstream reaches or in subbasins that also have a high ratio of withdrawal to streamflow. The simulated effects of potential 2030 water-use and land-use change indicate small decreases in flows as a result of increased water demands, but these flow alterations were offset as a result of decreased evapotranspiration associated with the loss of deep-rooted vegetation. Simulations of reactivating production wells near the north end of Lake Cochituate indicate pumping could substantially affect lake levels and flows at the lake outlet or in nearby reaches in the Sudbury River during periods of low flow, but the effects vary depending on the source of the water to the wells, which is largely unknown.

Chapter 2 of the report covers the fish-community assessment and comparison of streamflow-setting standards for protecting aquatic habitat. The fish-community assessment indicates the main stems of the Sudbury and Assabet Rivers are dominated by macrohabitat generalists. Water temperatures recorded in seven free-flowing reaches in the upper Sudbury River Basin at three sites unaffected by withdrawals or impoundments are generally suitable for cold-water fish; however, summer temperatures often rose to a level considered critical to long-term survival of brook trout. At four sites downstream from withdrawals or reservoirs, or both, summer water temperatures were often in the upper critical range for brook trout survival.

Physically and statistically based methods for determining streamflows for protecting aquatic habitat were applied at 10 selected riffle sites in the Sudbury and Assabet River Basins. Physically based methods, R2Cross and Wetted-Perimeter, use site-specific physical and hydraulic information and a one-dimensional hydraulics model, HEC-RAS, to determine flows that meet the criteria set forth by the method. The median flow that meets 2-of-3 of the R2Cross hydraulic criteria (percentage of bankfull wetted perimeter, average velocity, and mean depth) ranged from about 0.07 to 0.72 cubic feet per second per square mile ($ft^3/s/mi^2$) with an overall median of about 0.24 $ft^3/s/mi^2$; the median Wetted-Perimeter target flow ranged from about 0.10 to 0.51 $ft^3/s/mi^2$ with an overall median of about 0.25 $ft^3/s/mi^2$. Statistically based methods—Tennant, New England Aquatic Base Flow (ABF), and the Range-of-Variability Approach (RVA)—utilized HSPF simulated long-term streamflow (1960–2004) with no withdrawals to determine target flows or the monthly streamflow variability. The Tennant 30-percent of the mean annual flow (Q_{MA}) ranged from about 0.56 to 0.61 $ft^3/s/mi^2$ with an overall median of 0.58 $ft^3/s/mi^2$; the ABF low-flow target ranged from about 0.14 to 0.62 $ft^3/s/mi^2$ with an overall median of 0.32 $ft^3/s/mi^2$. The frequency and duration target flows were not met were evaluated using HSPF simulated

flows with and without water withdrawals. The median annual duration and total number of days flows were below the target were about three times greater for statistically based standards (Tennant 30 Q_{MA} and ABF) than for physically based targets (Wetted-Perimeter and R2Cross 2-of-3 criteria). Overall, physically based target flows were slightly more sensitive to flow alterations than the statistically based target flows.

Introduction

Water resources in the Sudbury and Assabet River Basins are of concern to Federal, State, and local government agencies, non-government organizations (NGOs), and citizens. Both basins are densely populated and have a long history of water alterations by industry, water supply, wastewater return flows, and other uses. These changes have altered the natural flow conditions and have affected aquatic habitats in the basins.

The effects of water withdrawals are particularly evident in the upper Sudbury River Basin during the summer when flows are naturally at their lowest. The Sudbury River Watershed Organization reported that a reach in the main stem of the upper Sudbury River went dry (Frederica Gillespie, Sudbury River Watershed Organization, written commun., June 2004). The Massachusetts Water Resource Commission (2001) classifies the upper Sudbury River Basin as moderately "stressed." Additional land development could further degrade aquatic habitat in the Sudbury and Assabet River Basins. The Massachusetts Department of Environmental Protection (MADEP) regulates over 80 public-supply withdrawals and 5 wastewater return flows in these basins; in addition, the Massachusetts Water Resource Authority (MWRA) and the Massachusetts Department of Conservation and Recreation (MADCR) manage several reservoirs for recreation, flood control, and emergency water supply. The Metropolitan Area Planning Council (MAPC) has shown that permitted withdrawals in 2006 in the towns of Hopkinton, Ashland, Wayland, and Sudbury may not be sufficient to meet projected demands in 2030 (M. Pillsbury, Metropolitan Area Planning Council, written commun., 2006).

In 2004, the U.S. Geological Survey (USGS) entered into a cooperative agreement with MADCR to improve the understanding of water resources and aquatic habitat in the Sudbury and Assabet River Basins. The study was also conducted in collaboration with MAPC, Massachusetts Division of Fisheries and Wildlife (MADFW), and other governmental and non-governmental stakeholders who share concern over the water resources and aquatic habitat in these basins. The study entailed the development of a precipitation-runoff model, using Hydrologic Simulation Program–FORTRAN (HSPF), to evaluate the effects of recent water use and projected water-use and land-use change on streamflow and to evaluate aquatic-habitat conditions in the basins.

Purpose and Scope

This report includes information about the Sudbury and Assabet River Basin study area, climate, streamflow, water use, and the methods used to obtain the data. These data provide background information on water resources and aquatic habitat in the basin used in the development of the precipitation-runoff model and habitat analysis. Chapter 1 describes the development and calibration of the HSPF precipitation-runoff model for the Sudbury and Assabet River Basins. The model was developed to evaluate the effects of water withdrawals and wastewater return flows on streamflow and to simulate the effects of water-use and land-use change primarily for the upper Sudbury River Basin. Chapter 2 describes fish communities, stream-water temperature, and streamflow targets by standard-setting methods for aquatic-habitat protection in the upper Sudbury and Assabet River Basins. This chapter focuses primarily on streamflows for aquatic-habitat protection, part of which included use of flows simulated through the HSPF model for the Assabet and Sudbury River Basins. A more detailed description of the purpose and scope of the individual aspects of the study are provided in the respective report chapters.

Description of the Sudbury and Assabet River Basins

The Sudbury and Assabet River Basins are in eastern Massachusetts about 25 mi west of the Boston metropolitan area (fig. 1). The Sudbury River flows eastward from its headwaters and then northward from the USGS streamgage at Ashland (01097480) for about 33 mi until it joins the Assabet River to form the Concord River (fig. 1). The Assabet River, located to the west of the Sudbury River, generally flows in a northeasterly direction for about 30 mi to its confluence with the Sudbury River. The Sudbury River Basin (162 mi^2) and the Assabet River Basin (177 mi^2) comprise about 44 and 47 percent of the Concord River Basin drainage area, respectively.

Thirty-one towns lie within or partially within the Sudbury and Assabet River Basins (fig. 1). The towns of Framingham and Southborough are completely within the Sudbury River Basin; portions of 16 other towns (Ashland, Concord, Holliston, Hopkinton, Hudson, Lincoln, Marlborough, Natick, Northborough, Stow, Sudbury, Sherborn, Upton, Wayland, Westborough, and Weston) are in the Sudbury River Basin. The towns of Acton, Hudson, Maynard, Northborough, and Stow are completely or nearly completely within the Assabet River Basin; portions of 14 other towns (Berlin, Bolton, Boylston, Boxborough, Carlisle, Clinton, Concord, Grafton, Littleton, Marlborough, Shrewsbury, Sudbury, Westford, and Westborough) are within the Assabet River Basin. Seven towns (Concord, Hudson, Marlborough, Northborough, Stow, Sudbury, and Westborough) straddle the drainage divide between the Sudbury and Assabet River Basins.

Base from Massachusetts Executive Office of Energy and Environmental Affairs digital data;
EOTROADS_ARC, 1:5,000, 2006; HYDRO25K_ARC , 1:25,000, 2005; MAJPOND_POLY, 1:100,000, 1998; SUBBASINS_POLY, 1:25,000, 2007; TOWNS_POLY, 1:25,000, 2002
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone 1998;

Figure 1. Towns, streamgages, and climate stations in and near the Sudbury and Assabet River Basins, Massachusetts.

Population

Collectively, the population of towns in, or partially within, the Sudbury and Assabet River Basins totaled nearly 0.5 million in 2000 (U.S. Bureau of the Census, 2005). The 2000 census town population (table 1) ranged from 4,200 in Sherborn to 66,910 in Framingham in the Sudbury River Basin, and from 4,008 in Boylston to 36,255 in Marlborough in the Assabet River Basin. On average, town populations increased by 13 percent from 1990 to 2000 in both basins, but several towns were among the fastest growing in the state. These towns include Hopkinton, in the Sudbury River Basin, and Boxborough, in the Assabet River Basin, which increased in population by about 45 percent between 1990 and 2000. Towns with larger established urban areas experienced minor changes in population between 1990 and 2000; these included the towns of Clinton, Concord, Framingham, Hudson, and Maynard. The town of Harvard experienced about a 50-percent decrease in population between 1990 and 2000 because of a military-base closure.

Populations within basins were estimated from the intersection of census tract data, land-use data, and the basin boundary. In 2000, an estimated 185,200 people lived in the Sudbury River Basin and 129,000 people lived in the Assabet River Basin (table 1). Average 2000 town population in the Sudbury River Basin was about 40 percent greater than in the Assabet River Basin. Population per unit area in the Sudbury River Basins (1,140 people/mi^2) was estimated to be about 60 percent greater than in the Assabet River Basin (730 people/mi^2).

Climate

Climate information was compiled from the National Weather Service (NWS) station in Worcester, the closest first-order weather station located about 22 mi southwest from the center of the Sudbury and Assabet River Basins (fig. 1). Monthly precipitation from 1892 to 2002 at this station (National Oceanic and Atmospheric Administration, 2009b) had a mean and median annual precipitation of 43.1 and 41.8 in., respectively. During that period, the recorded minimum and maximum annual rainfall ranged from 27.9 to 71.7 in., respectively. Monthly mean precipitation during 1892 to 2002 was generally evenly distributed throughout the year (standard deviation was 0.23 in.), but varied from 3.04 in. in February to 3.88 in. in November. During 1993 to 2002, the period that is nearly coincident with the model calibration period (1993 to 2003), the mean and median annual precipitation was 42.1 and 43.0 in., respectively.

Mean annual air temperature from 1892 to 2002 (National Oceanic and Atmospheric Administration, 2009a) was 48°F; minimum and maximum monthly mean temperature ranged from 25°F in January and February to 70°F in July. During 1993 to 2002, the mean annual, mean monthly, and minimum and maximum mean monthly temperatures were nearly identical to the long-term values.

Annual snowfall reported at the Worcester NWS station over the 1892 to 1996 period (National Oceanic and Atmospheric Administration, 2009c) averaged 58 in. and ranged from 17 to 120 in. Snowfalls reported in 1997 through 2002 are suspect, or were not reported, and were not included in the summary. During the 1993–96 period, average snowfall was above normal (78 in/yr), but the range (25 to 100 in/yr) was nearly identical to the long-term range.

Surface-Water Resources and Streamflow

Utilization of surface-water resources for mill power and water supply in the Sudbury and Assabet River Basins has a long history dating back to the 1700s. Impoundments constructed to utilize water resources vary in size and influence on streamflow in the basin. The upper Sudbury River Basin was once a major source of drinking water for the Boston metropolitan area. During the mid to late 1800s, eight reservoirs were built in the basin to meet the rapidly growing demand for water. These reservoirs include Lake Cochituate, Ashland, Hopkinton, Whitehall, Sudbury, Foss, Brackett, and Stearns Reservoirs. Soon after these water resources were completed, it was realized that additional sources of water were needed to meet Boston's growing demand, which lead to the development of two major reservoirs outside of the basin—Wachusett Reservoir to the northwest that began filling in 1905 followed by the Quabbin Reservoir to the west that began filling in 1939 (Massachusetts Water Resources Authority, 2008). After the Quabbin Reservoir was constructed, water from the Sudbury system (Cochituate, Sudbury, Foss, Brackett, and Stearns Reservoirs) was no longer needed and was of less desirable quality. Whitehall, Hopkinton, Ashland, and Cochituate Reservoirs were turned into State Parks in 1947, and in 1976, the entire Sudbury system was officially reclassified as an emergency water supply. Today, only the Sudbury and Foss Reservoirs are classified as a reserve water supply by the MWRA (Massachusetts Department of Conservation and Recreation, 2008). Although withdrawals are no longer made from these reservoirs, their operation for recreation and maintenance can still affect streamflow in this part of the basin. Sandra Pond has been a public water supply for the town of Westborough since the late 1800s.

The Assabet River Basin contains several water-supply reservoirs—Lake Williams and Millham Reservoir that, along with MWRA, supply water to the city of Marlborough, and Gates Pond that supplies water to the town of Hudson. A number of other reservoirs were built in the 18th and 19th centuries for mill power including Warner Pond in Concord, Lake Boon in Stow, and Fort Meadow Reservoir in Marlborough that are still regulated for recreational purposes. More recently built reservoirs, such as A1 in Westborough, provide flood control.

Streamflow below impoundments can be directly altered by flow regulation and indirectly through evaporation losses. Natural features such as wetlands, which are extensive in parts of the basin, can similarly affect streamflow through storage

Table 1. Population and percent change in population in towns in or partially within the Sudbury and Assabet River Basins, Massachusetts.

[Basin, A, Assabet, S, Sudbury; --, not determined separately by basin, the first set of numbers are the total for the town]

Town	Basin	U.S. Census town population					Estimated 2000 population in basin	Percent change	
		1960	1970	1980	1990	2000		1960 to 2000	1990 to 2000
Acton	A	7,238	14,770	17,544	17,872	20,331	20,300	181	14
Ashland	S	7,779	8,882	9,165	12,066	14,674	13,400	89	22
Berlin	A	1,742	2,099	2,215	2,293	2,380	2,380	37	3.8
Bolton	A	1,264	1,905	2,530	3,134	4,148	2,630	228	32
Boxborough	A	744	1,451	3,126	3,343	4,868	3,560	554	46
Boylston	A	2,367	2,774	3,470	3,517	4,008	560	69	14
Carlisle	A	1,488	2,871	3,306	4,333	4,717	1,600	217	8.9
Clinton	A	12,848	13,383	12,771	13,222	13,435	1,320	4.6	1.6
Concord	S	12,517	16,148	16,293	17,076	16,993	4,750	36	-0.5
Concord	A	--	--	--	--	--	8,430	--	--
Framingham	S	44,526	64,048	65,113	64,989	66,910	66,900	50	3.0
Grafton	A	10,627	11,659	11,238	13,035	14,894	150	40	14
Harvard	A	2,563	13,426	12,170	12,329	5,981	1,580	133	-52
Holliston	S	6,222	12,069	12,622	12,926	13,801	0	122	6.8
Hopkinton	S	4,932	5,981	7,114	9,191	13,346	10,200	171	45
Hudson	S	9,666	16,084	16,408	17,233	18,113	220	87	5.1
Hudson	A	--	--	--	--	--	17,900	--	--
Lincoln	S	5,613	7,567	7,098	7,666	8,056	1,430	44	5.1
Littleton	A	5,109	6,380	6,970	7,051	8,184	3,280	60	16
Marlborough	S	18,819	27,936	30,617	31,813	36,255	24,200	93	14
Marlborough	A	--	--	--	--	--	12,000	--	--
Maynard	A	7,695	9,710	9,590	10,325	10,433	10,400	36	1.0
Natick	S	28,831	31,057	29,461	30,510	32,170	15,600	12	5.4
Northborough	S	6,687	9,218	10,568	11,929	14,013	0	110	18
Northborough	A	--	--	--	--	--	14,000	--	--
Sherborn	S	1,806	3,309	4,049	3,989	4,200	650	133	5.3
Shrewsbury	A	16,622	19,196	22,674	24,146	31,640	11,500	90	31
Southborough	S	3,996	5,798	6,193	6,628	8,781	8,780	120	32
Stow	S	2,573	3,984	5,144	5,328	5,902	0	129	11
Stow	A	--	--	--	--	--	5,900	--	--
Sudbury	S	7,447	13,506	14,027	14,358	16,841	14,500	126	17
Sudbury	A	--	--	--	--	--	2,320	--	--
Upton	S	3,127	3,488	3,886	4,677	5,642	20	80	21
Wayland	S	10,444	13,461	12,170	11,874	13,100	12,000	25	10
Westborough	S	9,599	12,594	13,619	14,133	17,997	12,100	88	27
Westborough	A	--	--	--	--	--	5,660	--	--
Westford	A	6,261	10,368	13,434	16,392	20,754	3,510	232	27
Weston	S	8,261	10,870	11,169	10,200	11,469	440	39	12

and evapotranspiration (ET) losses. In addition, withdrawals, diversions, and wastewater-treatment facility discharges can also affect streamflow. All these factors affect the observed streamflow to varying degrees at streamgages in the basin.

Streamflow has been continuously measured by the USGS at Assabet River at Maynard (01097000) since 1941, at Nashoba Brook near Acton (01097300) since 1963, and at Sudbury River at Saxonville (01098530) since 1979 (fig. 1). Streamflow has also been sporadically measured by the USGS at Sudbury River at Ashland (01097480) with a continuous streamgage operating from April 1994 through October 1995, May 2004, October 2004 through May 2005, and October 2006 through July 2009.

Assabet River at Maynard (01097000), hereafter referred to as the Maynard streamgage, is the only long-term monitoring streamgage on the main stem of the Assabet River. Drainage area to the Maynard streamgage is 114 mi^2 and covers about 64 percent of the Assabet River Basin area. Annual streamflow at the Maynard streamgage over the period of record (water years 1942–2006; a water year spans from October 1 through September 30) averaged 192 ft^3/s (1.66 $ft^3/s/mi^2$) and ranged from 73 to 320 ft^3/s; during water years 1993 to 2003, annual flow averaged 200 ft^3/s (1.75 $ft^3/s/mi^2$) and ranged from 88 to 286 ft^3/s. Mean annual flow at the Maynard streamgage (fig. 2) tended to increase over the period of record as indicated by the Loess line (Cleveland and Devlin, 1988); part of this increase is attributed to increased discharge of treated wastewater above the streamgage over the period of record.

Nashoba Brook near Acton (01097300), hereafter referred to as the Nashoba streamgage, has provided long-term streamflow information on one of the main tributaries in the northern part of the Assabet River Basin since 1963. Drainage area to the Nashoba streamgage is 12.8 mi^2 and covers about 7 percent of the Assabet River Basin area. Mean annual flow at Nashoba streamgage over the period of record (water years 1964–2006) averaged 20 ft^3/s (1.60 $ft^3/s/mi^2$) and ranged from 7.1 to 36 ft^3/s. During water years 1993–2003, annual flow averaged about 19 ft^3/s (1.46 $ft^3/s/mi^2$) and ranged from 10 to 25 ft^3/s. The reason the Nashoba streamgage has a lower mean annual flow per unit area relative to the Assabet and Saxonville streamgages is believed to be related to a higher percentage of wetlands and a lower percentage of sand and gravel deposits relative to the other basins.

Sudbury River at Saxonville (01098530), hereafter referred to as the Saxonville streamgage, is the only long-term continuously operated streamgage in the Sudbury River Basin. The 106-mi^2 drainage area to the Saxonville streamgage, which includes the Sudbury reservoir system, covers about 65 percent of the Sudbury River Basin area. Mean annual flow at Saxonville streamgage over water years 1981–2006 averaged 200 ft^3/s (1.89 $ft^3/s/mi^2$) and ranged from 90 to 281 ft^3/s. During water years 1993–2003, annual flow averaged 194 ft^3/s (1.83 $ft^3/s/mi^2$) and ranged from 90 to 241 ft^3/s. The record low mean annual flow (90 ft^3/s) occurred during the 2002 water year.

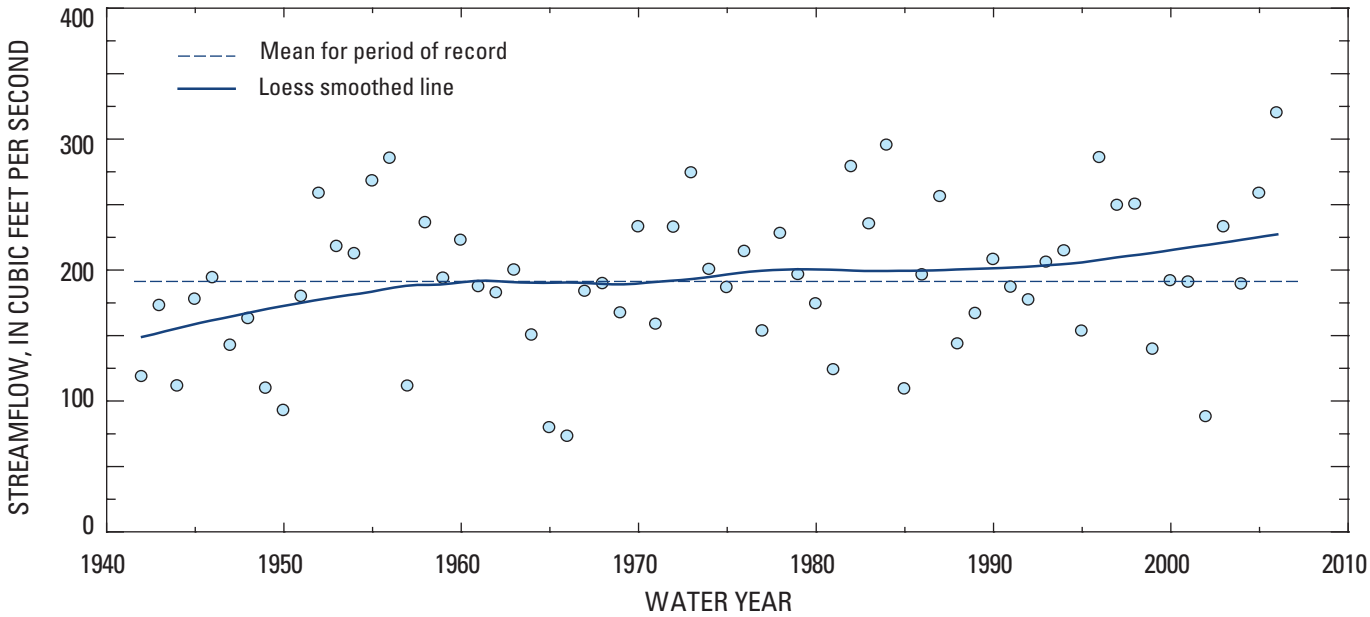


Figure 2. Mean annual streamflow, water years 1942–2006, Assabet River at Maynard, Massachusetts.

Topography

The Sudbury and Assabet River Basins are in the coastal lowlands near the border with the central highlands along the southwestern portion of the basin (Denny, 1982). The central lowlands are characterized by low relief with gently rolling hills that is more prevalent on the eastern side of the basins, particularly the Sudbury River Basin (fig. 3, inset). The hillier terrain more common in the central highlands is more prevalent in the southwestern part of the basin, particularly in the Assabet River Basin, which lies further to the west. Drumlins, low hills of glacial origin, are found throughout the region.

The Sudbury River drops from a maximum elevation of about 700 ft to about 100 ft at its confluence with the Assabet River. Along its 33 mi length, the river gradient averages about 5.2 ft/mi, but low-gradient reaches are common in wetlands and reservoirs found in many reaches. Upstream from the Saxonville streamgage, the river gradient averages about 9.0 ft/mi; downstream from the Saxonville streamgage, the river gradient flattens and averages about 1.4 ft/mi.

The Assabet River Basin is topographically similar to the Sudbury River Basin. The Assabet River drops from a maximum elevation of about 750 ft to about 100 ft at its confluence with the Sudbury River. Over its 32 mi length, the river gradient averages about 6.8 ft/mi, but low-gradient reaches behind impoundments are common. The river gradient flattens considerably below the Maynard streamgage.

Surficial Geology

Most of the uplands in the Sudbury and Assabet River Basins are glacial till with areas of fine- and coarse-grained glacial deposits in the valleys (Flanagan and others, 1999). The valley fill was deposited mostly by meltwater from the last glacial retreat that are stratified by the sorting processes that occurred during transport. Often, the coarse-grained sand and gravel deposits are interspersed with fine sands, silts, and clays that were deposited in temporary pools and lakes during the glacial retreat (Brackley and Hansen, 1985). Hence, valley-fill deposits are often discontinuous and heterogeneous, but typically provide the most productive aquifers in the basin (DeSimone, 2004).

Valley-fill glacial sands and gravels are more extensive toward the mouths of the basins (fig. 3). These deposits are upwards of 160 ft thick, but typically are less than 75 ft thick with an average thickness of about 35 ft in the Assabet River Basin (Brackley and Hansen, 1985; DeSimone, 2004). Glacial valley-fill deposits are overlain by recent fine-grained alluvial deposits along stream and river channels. For the purposes of this study, the alluvial deposits were grouped with the sand and gravel deposits because they are generally thin and comprise only a small percentage of the basin area. Sand and gravel compose about 52 and 40 percent of the Sudbury and Assabet River Basin areas, respectively.

Till is also a glacial deposit that consists of a heterogeneous mix of clays, sands, pebbles, cobbles, and boulders. Tills commonly blanket upland areas (fig. 3) and are typically thin with low transmissive properties limiting their use as a water supply even for single-family homes. In steep upland areas, bedrock outcrops are also present. Areas classified as till and bedrock comprise about 48 and 60 percent of the Sudbury and Assabet River Basin areas, respectively.

Wetlands

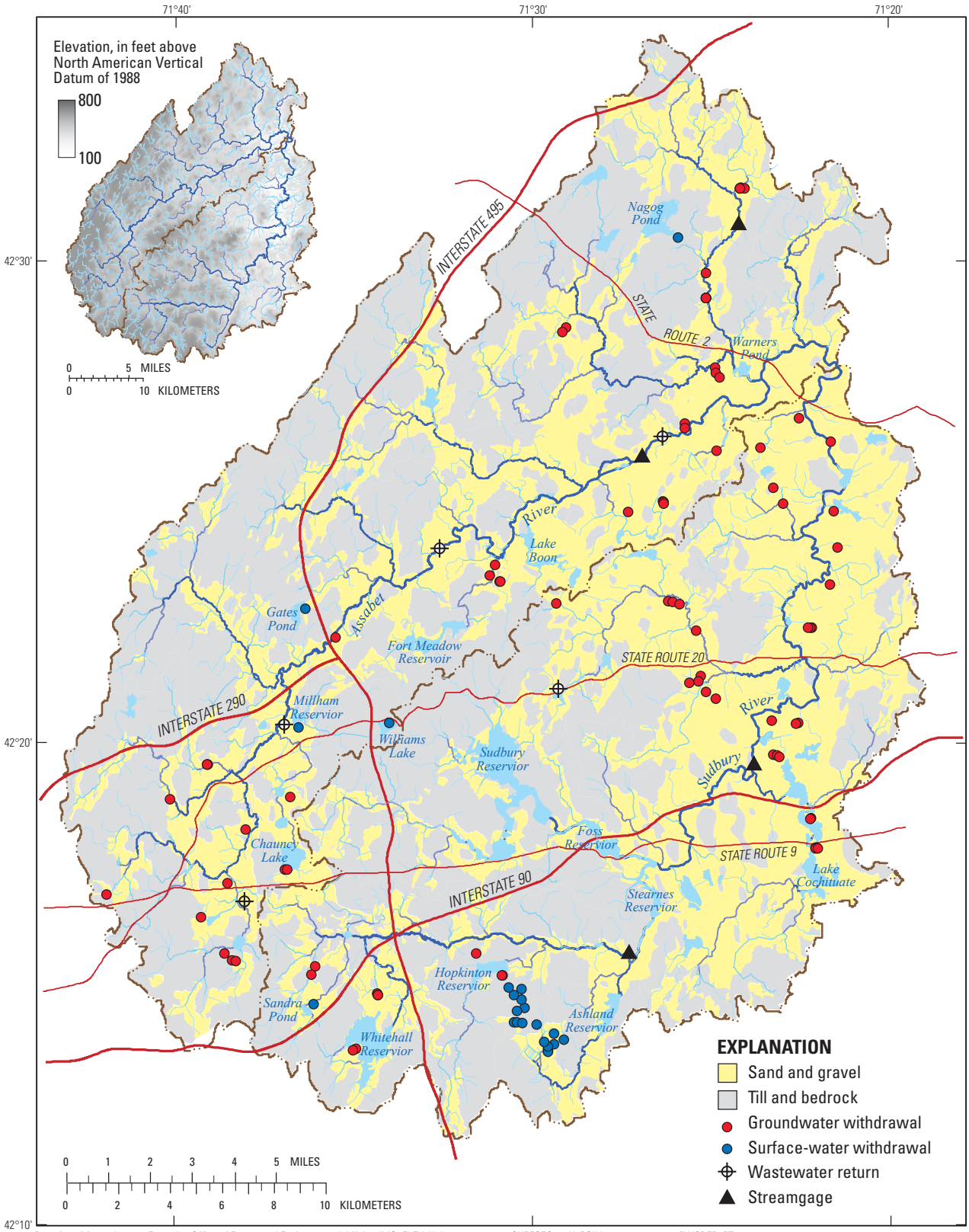
Wetlands are a prominent hydrological feature in the Sudbury and Assabet River Basins (fig. 4). Wetland information obtained from Massachusetts Geographic Information System (2007) was simplified into two groups, forested and nonforested, for this study. Forested wetlands are wooded swamps with deciduous trees, coniferous trees, or both. Nonforested wetlands include bogs, shallow marsh, meadow or fen, and shrub swamp.

Collectively, wetlands cover about 13 percent of the basin area and are about equally distributed between the Sudbury and Assabet River Basins. Forested wetlands are the most prevalent, covering about 10.5 and 9.8 percent of Sudbury and Assabet River Basin area, respectively; nonforested wetlands cover about 2.5 and 2.8 percent of the Sudbury and Assabet River Basin area, respectively. Upstream from the Saxonville streamgage, about 10.6 percent of the basin area is wetland, of which 8.9 percent is forested and 1.7 percent is nonforested. Upstream from the Ashland streamgage, about 13.8 percent of the basin area is wetland, of which 11.9 percent is forested and 1.9 percent is nonforested. Cedar Swamp, an extensive mostly nonforested wetland, comprises about half of the wetland area above Ashland streamgage. Wetlands upstream from the Maynard streamgage comprise about 11.6 percent of the basin area.

Land use

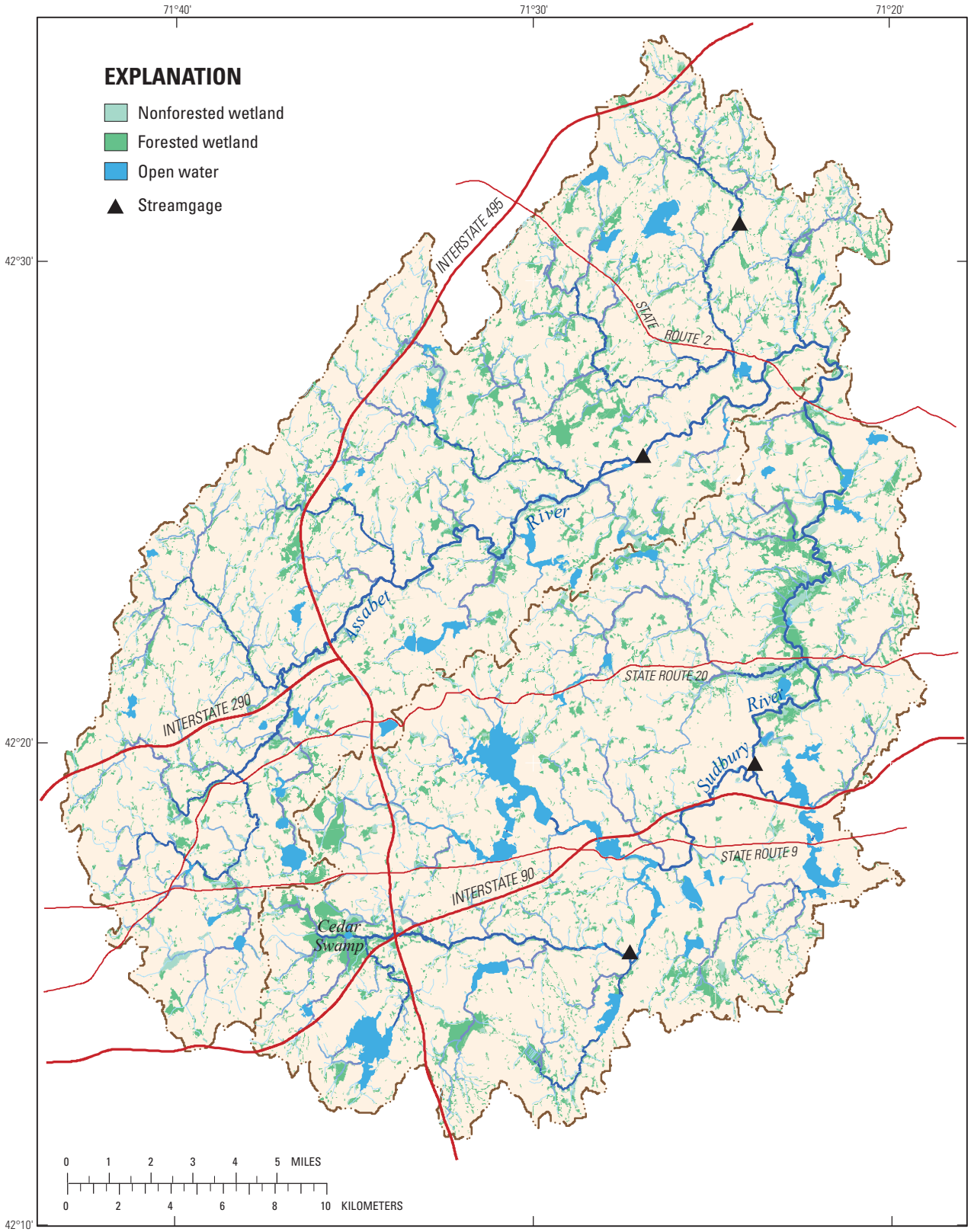
Land-use information classified from 1997, 1:25,000 scale aerial photographs was obtained from Massachusetts Geographic Information System (2009). In general, the Sudbury and Assabet River Basins are considered urbanized with about 29 percent of the basin area classified as residential (fig. 5). About 38 percent of the basin area was classified as forested with most of the undeveloped area in the western part of the Assabet River Basin.

In the Sudbury River Basin, land use was classified as about 33 percent forested, 32 percent residential, 10 percent forested wetlands, 9 percent open, 8 percent commercial, industrial, and transportation, 5 percent open water, and 2 percent nonforested wetland. Above the Saxonville streamgage, a greater percentage of the basin area (about 11 percent) is classified as commercial, industrial, and transportation because of the highly developed area along the Route 9 corridor and Interstates 90 and 495.



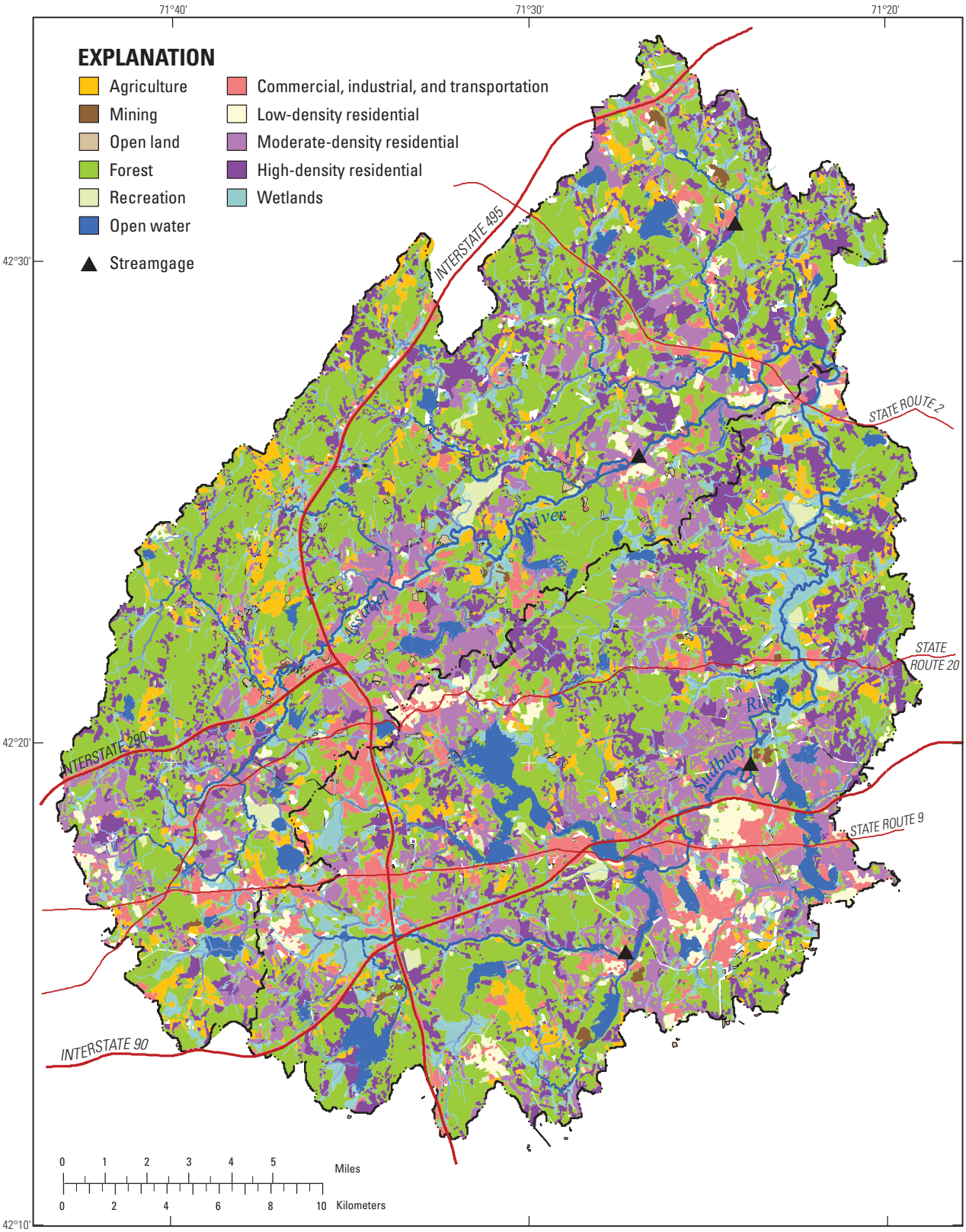
Base from Massachusetts Executive Office of Energy and Environmental Affairs, IMG_ELEV5K_I, 1:5,000, 2005; SURFGEO250K_POLY, 1:250,000, 1999, PWSDEP_PT, 2002
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 3. Elevation, simplified surficial geology, and major water withdrawals and return flows in the Sudbury and Assabet River Basins, Massachusetts.



Base from Massachusetts Executive Office of Energy and Environmental Affairs, WETLANDSDEP_POLY, 1:12,000, 2007
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 4. Forested and nonforested wetlands in the Sudbury and Assabet River Basins, Massachusetts.



Base from Massachusetts Executive Office of Energy and Environmental Affairs, LANDUSE_POLY, 1:25,000, 1999
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 5. Land use classified from 1997 aerial photography in the Sudbury and Assabet River Basins, Massachusetts.

In the Assabet River Basin, land use was classified as about 42 percent forested, 26 percent residential, 10 percent forested wetlands, 10 percent open, 6 percent commercial, industrial, and transportation, 3 percent water, and 3 percent nonforested wetland. The largest differences in land use between the Sudbury River and Assabet River Basins are in the size of the forested and residential areas.

Water Withdrawals and Wastewater Returns

Data on registered and permitted municipal withdrawals and non-municipal withdrawals (non-public supplies that withdraw more than 100,000 gal/d) were obtained directly from the supplier or from MADEP for the 1993–2003 period. Withdrawals are mostly for municipal water supply (table 2); withdrawals include 33 from groundwater and 4 from surface water in the Sudbury River Basin and 32 from groundwater and 9 from surface water in the Assabet River Basin. These withdrawals provide all or part of the municipal water supply to 17 of the 31 towns in, or partly in, the Assabet and Sudbury River Basins. Most of the major supply wells are finished in sand and gravel.

Registered and permitted non-municipal withdrawals are mostly for agriculture or golf course irrigation and are mostly in the town of Hopkinton. During the peak growing season (June through August), irrigation withdrawals composed up to a third of the total withdrawals in the Sudbury River Basin and up to 15 percent of the total withdrawals in the Assabet River Basin, but on average, municipal withdrawals account for most withdrawals. The total annual water withdrawals during 1993–2003 averaged about 12 Mgal/d from the Sudbury River Basin and about 9 Mgal/d from the Assabet River Basin.

Treated wastewater is returned to the basin at five locations from different sewer districts operating within the Sudbury and Assabet River Basins—one outfall is in the Sudbury River Basin and four are in the Assabet River Basin (fig. 3). Two of the wastewater treatment plants (WWTPs), Marlborough West and Westborough, in the Assabet River Basin, are connected to regional wastewater systems. WWTPs in Hudson and Maynard in the Assabet River Basin, and Marlborough East in the Sudbury River Basin, service only their respective communities.

Daily discharge records were obtained from the five WWTPs in the basin (table 3) and cross checked with the monthly wastewater discharges reported to the U.S. Environmental Protection Agency (USEPA) for the period January 1, 1993, through December 31, 2003. Average annual return flows ranged from 0.8 to 5.0 Mgal/d at Maynard and Westborough, respectively. Monthly average return flows peaked in March and were generally lowest in August; the higher return flows in the spring reflect additional water that enters the sewer infrastructure through direct inflow and groundwater infiltration, which is referred to as I&I. Average March return flows accounted for 11 to 16 percent of the average annual return flows; average August return flows accounted for 2.7 to 7.0 percent of the average annual return flows. Overall, annual wastewater discharge averaged 7.8 Mgal/d in the Sudbury River Basin and 12.4 Mgal/d in the Assabet River Basin. Thus, the average WWTP return flows to the Assabet River Basin are almost double the return flows to the Sudbury River Basin.

In addition to the direct effect of water withdrawals or return flows on streamflows, water and sewer systems can affect hydrology by importing or exporting water from a basin. Areas that import water are served by public water systems, but have on-site septic systems. Areas that export water are served by sewers that provide a conduit for I&I losses. Monthly records from wastewater treatment systems indicate that average March wastewater discharge increased by 30 to 91 percent relative to the mean annual discharge. Early spring is typically the period of highest groundwater infiltration to the sewer system because this is typically when the groundwater table is at its seasonal high.

Stream Habitat

The stream habitats along much of the Sudbury and the Assabet Rivers are characterized by low-gradient, slow-moving channels with pools, glides, and runs. Riffles, characterized by fast, turbulent water, are few, in part because dams were built at riffles and other riffles were submerged by the impoundment. More riffles are located on the tributaries than on the main-stem reaches of the river because steeper stream gradients are more common.

Previous Studies

Groundwater resources in the Assabet River Basin were investigated by DeSimone (2004). Information from Campbell (1925), Jahns (1953), Hansen (1956), Perlmutter (1962), Koteff (1966), Shaw (1969), Pollock and others (1969), Brackley and Hansen (1985), and Bratton and Parker (1995) was compiled to characterize the hydrogeology of the area. A number of small-scale hydrogeologic investigations by consultants were also compiled; these studies were typically undertaken for the purpose of locating water-supply sources, determining well-protection areas, locating groundwater contamination, or for specific development projects for towns. In addition to the hydrogeologic information, partial-record stations were established for low-flow studies by Ries (1993, 1994, 1999) and Ries and Friesz (2000). DeSimone (2004) reactivated many of these partial-record stations to provide estimates of baseflow from tributary streams to develop a groundwater-flow model of the Assabet River Basin used to evaluate the effects of water-management alternatives on baseflow. Many of these streamgages were reactivated again for this study.

Streamflow targets for protection of aquatic habitat were investigated by Parker and others (2004) at six sites in the Assabet River Basin. Water use in the Assabet, Concord, and Sudbury River Basins was compiled for 1996 through 2000 by Barlow and others (2009). Colman and others (1999) and Waldron and others (2000) investigated total mercury and

Table 2. Registered and permitted water withdrawals from 1993 to 2003 in the Sudbury and Assabet River Basins, Massachusetts.

[DSN, data-set number in Watershed Data Management (WDM) database; SWWD, DEPL, PUMP, WDM identification attribute (IDCONS) for surface-water withdrawal, streamflow depletion, and pumped groundwater well, respectively; Distance, length from the pumped well to nearest surface-water body in feet (ft); Mgal/d, million gallons per day; MDEP, Massachusetts Department of Environmental Protection; GW, groundwater; SW, surface water; --, not applicable]

Reach number	Town	Source	Name	DSN		Distance (ft)	Annual average withdrawal 1993–2003 (Mgal/d)	MDEP identification or registration number
				SWWD or DEPL	PUMP			
			Sudbury River Basin					
1	Westborough	GW	Morse St. well	1011	2011	33	0.214	2328000-02G
1	Westborough	GW	Hopkinton Rd. well	1012	2012	7	0.263	2328000-01G
2	Westborough	SW	Sandra Pond	1021	--	--	0.774	2328000-01S
3	Hopkinton	GW	McIntyre GP wells 4 and 5	1031	2031	768	0.234	2139000-04G, -05G
5	Hopkinton	GW	Fruit St. GP wells 1, 2, 3	1051	2051	62	0.482	2139000-01G, -02G, -03G
5	Westborough	GW	Industry well	1052	2052	1,250	0.008	21432803
8	Hopkinton	GW	Nursery (isolated irrigation ponds) 15, 16, 17, 18	1081	2081	2,500	0.001	21413902
8	Ashland	GW	Howe St. well 4, 5, 6, 8, 9	1082	2082	809	1.435	3014000-04G, -5G, -06G, -08G, -09G
9	Hopkinton	GW	Nursery (isolated irrigation pond) 14	1091	2091	3,000	0.001	21413902
10	Hopkinton	SW	Nursery (in-stream ponds and canals) 2, 3, 4, 6, 9, 13	1101	--	--	0.003	21413902
10	Hopkinton	GW	Nursery (isolated irrigation ponds) 1, 5, 7, 8,10, 11	1102	2102	250	0.013	21413902
17	Natick	GW	Springvale well 1	1171	2171	565	0.354	3198000-01G
17	Natick	GW	Springvale wells 3, 4, 5	1173	2173	405	1.254	3198000-02G, -07G, -08G
17	Natick	GW	Evergreen wells 1 and 2	1172	2172	450	1.317	3198000-09G, -10G
31	Hudson	GW	Cranberry bog well	1311	2311	509	0.558	2141000-02G
31	Sudbury	GW	Hop Brook well and well 3	1312	2312	79	0.253	3288000-01G, 03G
31	Sudbury	GW	Well 8	1313	2313	302	0.152	3288000-08G
31	Sudbury	GW	Well 10	1314	2314	203	0.099	3288000-10G
32	Sudbury	GW	Well 2A	1321	2321	885	0.210	3288000-02G
32	Sudbury	GW	Well 4	1322	2322	400	0.149	3288000-04G
32	Sudbury	GW	Well 6	1323	2323	538	0.494	3288000-06G
32	Sudbury	GW	Well 7	1324	2324	217	0.301	3288000-07G
32	Sudbury	GW	Well 9	1325	2325	217	0.269	3288000-09G
33	Concord	GW	Jennie Dugan well	1331	2331	394	0.267	3067000-01G
33	Concord	GW	Deaconess well	1332	2332	328	0.671	3067000-03G
33	Concord	GW	White Pond well	1333	2333	951	0.194	3067000-04G
33	Concord	GW	Robinson well	1334	2334	315	0.164	3067000-06G
33	Sudbury	GW	Well 5	1335	2335	164	0.119	3288000-05G
33	Wayland	GW	Campbell well 1	1336	2336	144	0.152	3315000-02G
33	Wayland	GW	Happy Hollow well 1	1337	2337	623	0.320	3315000-03G
33	Wayland	GW	Happy Hollow well 2	1338	2338	866	0.457	3315000-04G
33	Wayland	GW	Meadowview well 1	1339	2339	886	0.155	3315000-05G
33	Wayland	GW	Baldwin Pond well 1 and 3	1340	2340	325	0.226	3315000-01G, -07G
33	Wayland	GW	Baldwin Pond well 2	1341	2341	280	0.243	3315000-06G
33	Concord	GW	Golf course (isolated irrigation pond)	1342	2342	800	0.003	31406708
33	Concord	SW	Golf course	1343	--	--	0.003	31406702
33	Concord	SW	Farm withdrawal	1344	--	--	0.001	31406707

Table 2. Registered and permitted water withdrawals from 1993 to 2003 in the Sudbury and Assabet River Basins, Massachusetts.—Continued

[DSN, data-set number in Watershed Data Management (WDM) database; SWWD, DEPL, PUMP, WDM identification attribute (IDCONS) for surface-water withdrawal, streamflow depletion, and pumped groundwater well, respectively; Distance, length from the pumped well to nearest surface-water body in feet (ft); Mgal/d, million gallons per day; MDEP, Massachusetts Department of Environmental Protection; GW, groundwater; SW, surface water; --, not applicable]

Reach number	Town	Source	Name	DSN		Distance (ft)	Annual average withdrawal 1993–2003 (Mgal/d)	MDEP identification or registration number
				SWWD or DEPL	PUMP			
			Assabet River Basin					
51	Westborough	GW	Andrews I well	1511	2511	1,080	0.363	2328000-03G
51	Westborough	GW	Andrews II well	1512	2512	460	0.251	2328000-04G
51	Westborough	GW	Wilkinson well	1513	2513	1,290	0.113	2328000-06G
52	Shrewsbury	GW	South St. well	1521	2521	187	0.001	2271000-01G
52	Northborough	GW	Farm well	1522	2522	1,170	0.001	21428601
52	Northborough	GW	Nursery well	1523	2523	1,200	0.004	21421502
53	Northborough	GW	Crawford St. well	1531	2531	200	0.275	2215000-03G
53	Northborough	GW	Howard St. well 1, 2, and 3	1532	2532	500	0.091	2215000-04G, -05G, -06G
54	Northborough	GW	Brigham St. well	1541	2541	1,200	0.295	2215000-01G
54	Westborough	GW	Otis St. well	1542	2542	535	0.314	2328000-05G
54	Westborough	GW	Indian Meadow well	1543	2543	282	0.004	2328000-10G
54	Northborough	SW	Golf course	1544	--	--	0.003	21400205
55	Westborough	GW	Chauncy Lake wells 1 and 2	1551	2551	1,150	0.198	2328000-07G, -08G
56	Marlborough	SW	Millham Reservoir	1561	--	--	1.386	2170000-01S
58	Berlin	SW	Gates Pond	1581	--	--	0.135	2141000-01S
60	Stow	SW	Golf course	1601	--	--	0.002	21428602
61	Hudson	GW	Chestnut St. well 2	1611	2611	580	0.640	2141000-05G
61	Hudson	GW	Chestnut St. well 3	1612	2612	245	0.429	2141000-06G
61	Hudson	GW	Chestnut St. well 1 and Kane well	1613	2613	610	0.531	2141000-03G, 04G
62	Maynard	SW	White Pond	1621	--	--	0.244	2174000-01S
63	Hudson	GW	Industry well	1631	2631	1,550	0.000	21414101
63	Stow	SW	Golf course	1632	--	--	0.002	21428602
64	Maynard	GW	Well 1 Old Marlboro Rd.	1641	2641	361	0.306	2174000-01G
64	Maynard	GW	Well 1A Old Marlboro Rd.	1642	2642	197	0.033	2174000-02G
64	Maynard	GW	Well 3 Old Marlboro Rd	1643	2643	98	0.107	2174000-03G
64	Maynard	GW	Well 4 Great Rd	1644	2644	541	0.079	2174000-04G
66	Acton	GW	Assabet well 1	1661	2661	770	0.280	2002000-05G
66	Acton	GW	Assabet well 2	1662	2662	1,030	0.345	2002000-06G
66	Concord	GW	Second Division well	1663	2663	480	0.511	3067000-05G
66	Acton	SW	Sand and gravel withdrawal	1664	--	--	0.005	21400205
67	Acton	GW	Whitcomb well	1671	2671	290	0.143	2002000-01G
67	Acton	GW	Lawsbrook well	1672	2672	1,070	0.077	2002000-03G
67	Acton	GW	Christofferson well	1673	2673	256	0.320	2002000-04G
67	Acton	GW	Clapp well	1674	2674	575	0.037	2002000-07G
67	Acton	GW	Scribner well	1675	2675	320	0.028	2002000-08G
67	Maynard	GW	Bedrock well 5	1676	2676	725	0.064	2174000-07G
67	Acton	SW	Farm withdrawal	1677	--	--	0.002	21400202
68	Acton	GW	Marshall well	1681	2681	249	0.008	2002000-09G
68	Acton	GW	Kennedy wells 1, 2, 3, 4	1682	2682	615	0.356	2002000-10G,-11G, 12G,13G
69	Acton	GW	Conant well	1691	2691	125	0.115	2002000-02G
69	Acton	GW	Conant II wells 1, 2, 3, 4, 5	1692	2692	430	0.059	2002000-14G, 15G,16G, 17G, 18G
69	Acton	SW	Nagog Pond	1693	--	--	0.446	3067000-01S

Table 3. Wastewater returns from 1993 to 2003 from public-sewer systems in the Sudbury and Assabet River Basins, Massachusetts.

[Mgal/d, million gallons per day; DSN, data-set number in Watershed Data Management (WDM) database; locations shown on fig. 1]

Reach number	Wastewater treatment facility	Communities served	Receiving water	Average return flow (Mgal/d)			DSN
				Annual	March	August	
Sudbury River Basin							
31	Marlborough East	Marlborough	Hop Brook	3.3	4.6	2.4	81
Assabet River Basin							
54	Westborough	Westborough Shrewsbury Hopkinton	Assabet River	5.0	6.6	4.1	82
58	Marlborough West	Marlborough Northborough	Assabet River	2.0	2.5	1.6	83
60	Hudson	Hudson	Assabet River	1.5	2.9	0.5	84
66	Maynard	Maynard	Assabet River	0.8	1.4	0.3	85

methylmercury in 4 reservoir cores and 12 wetland cores from Sudbury River Basin. During that study, a short-term continuous-record streamgage was established on the Sudbury River at Ashland, which was reestablished for use in this study. The effects on the groundwater resources of channelization of the Sudbury River through Cedar Swamp were investigated by Walker (1973).

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Chapter 1—Simulated Effects of Water Use, and Projected Water-Use and Land-Use Change on Streamflow with a Precipitation-Runoff Model

Withdrawals from reservoirs and the aquifer have affected streamflows in the Sudbury River and its tributaries, especially in the 106-mi^2 upper basin upstream from the USGS streamgage at Saxonville (01098530, fig. 1). These effects are particularly evident in the summer when flows are naturally at their lowest. A precipitation-runoff model, HSPF, was developed as part of this study to examine effects of current (1993–2003) water use and the effects of potential future (2030) water-use and land-use changes on streamflow. The model also provided simulated streamflows for the protection of aquatic habitat at critical riffle sites in the basin as described in Chapter 2 of this report.

The HSPF model (Bicknell and others, 2000) was chosen as the appropriate modeling tool to simulate runoff in response to precipitation and the complex water-withdrawal patterns in the basin. The HSPF modeling software is publicly available and has been successfully used in similar New England basins to assist water-resources managers in basins with similar streamflow issues (Zarriello and Ries, 2000; Zarriello and Bent, 2004; Barbaro and Zarriello, 2007; Barbaro, 2007).

Purpose and Scope

This chapter describes the development and calibration of the HSPF precipitation-runoff model for the Sudbury and Assabet River Basins. The model was calibrated to the 1993–2003 period primarily for the upper Sudbury River Basin using streamflow data from Sudbury River at Ashland (01097480) and at Saxonville (01098530). The upper Sudbury River Basin is the contributing area above the streamgage at Saxonville. Streamflow data at Assabet River Basin near Maynard (01097000) and Nashoba Brook near Acton (01097300) were also used in the model calibration. This chapter also describes long-term simulations (1960–2004) made with, or modifications to, the calibrated model and the results of simulations that examine the effects of average recent withdrawals (1993–2003) relative to no withdrawals on streamflows, the effects of groundwater only and surface-water only withdrawals on streamflow, and the effects of projected 2030 land-use and water-use changes on streamflow. This chapter also discusses simulations that examine the potential effects on streamflow and lake levels of reactivating supply wells near Lake Cochituate.

Time-Series Data

Climate, water-use (water withdrawals and returns), and streamflow time-series data are necessary for developing a precipitation-runoff model of a basin. Climate and water-use data are required inputs to the model. Hourly precipitation, air temperature, dew-point temperature, solar radiation, and wind-speed data were used to simulate flows. Daily water-use data were used to account for water withdrawals and return flows and to simulate alternative water-management conditions. Observed streamflow data were used for model calibration, but are not needed to run the model.

These time-series data along with model-generated time-series data are stored in a Watershed Data Management (WDM) file. The WDM database is a binary file accessed by ANNIE (Flynn and others, 1995), GenScn (Kittle and others, 1998), or WDMUtil (Hummel and others, 2001). These programs are used to manage, display, transform, plot, and analyze time-series data stored in the WDM file. Within the WDM database, time-series data are organized by data-set number (DSN). Each DSN has attribute information that describes the data type, time step, location, and other important characteristics of the data. In the Sudbury and Assabet River Basin HSPF model, the associated WDM file was organized into groups by data type (table 4). The first 68 DSNs were for observed climate and streamflow time-series data.

The combined withdrawals for a reach from direct surface-water withdrawals and streamflow depletion from groundwater withdrawals (described later) are stored in DSNs 101 to 168; the last two digits of the DSN correspond to the model reach numbers 1 through 68. The combined withdrawals are identified by the WDM attribute IDCON as WSPD. Individual time series of streamflow depletion from pumped wells and direct surface-water withdrawals are stored separately in DSNs 1011 to 1693; the second and third digits correspond to the reach number and the last digit corresponds to an individual withdrawal from the reach. The streamflow depletions by pumped wells or direct surface-water withdrawals are individually identified by the attribute DEPL or SWWD, respectively. This scheme allows identification of up to 10 wells along a reach. In the Sudbury and Assabet River Basin HSPF model, only reach 33 had more than 10 simulated withdrawals points; therefore, the 11th withdrawal was numbered

Table 4. General contents and organization of the Watershed Data Management (WDM) database.

[DSN, data-set number in WDM]

DSN	Purpose
1–68	Observed climate and streamflow data
81–85	Discharge to a reach (input) from wastewater treatment plants
101–172	Combined water withdrawals from a reach
1xx–1xx	xx corresponds to model reach number, ranges from 1 to 72
2xx–2xx	Simulated streamflow output, observed water use
1011–1723	Individual streamflow depletion by well or surface withdrawal
1xx1–1xx9	xx corresponds to model reach number, ranges from 1 to 72
101x–172x	x corresponds to individual withdrawal point
2011–2722	Pumpage from individual wells
2xx1– 2xx9	xx corresponds to model reach number, ranges from 1 to 72
201x–272x	x corresponds to individual withdrawal point
6101–6972	Simulated streamflow from different scenarios
61xx–69xx	xx corresponds to model reach number, ranges from 1 to 72
6x01–6x72	x corresponds to scenario identification number incremented by 100

with the successive reach number (DSN 1340) because there were no withdrawals from this reach. Actual withdrawal rates from individual pumped wells are stored in DSNs 2011 to 2692 using the same numbering scheme described above and identified by the attribute PUMP. Daily discharge records from five WWTP are stored in DSNs 81–85 and identified by the WDM attribute IDCON as WWRE.

Climate

Climate data were obtained from the National Oceanographic and Atmospheric Administration (NOAA) National Weather Service (NWS) first-order weather station at Worcester, MA, about 8 mi from the southwest edge of the study area (fig. 1). The data include hourly precipitation, air temperature, dew-point temperature, solar radiation, and wind speed for the period January 1, 1960, through December 31, 2004. Potential evapotranspiration (PET) was calculated from daily minimum and maximum temperature and daily solar radiation by the Jensen-Haise method (Jensen and Haise, 1963) using the WDMUtil utility “compute meteorological time-series” program. Worcester climate data stored in the WDM database are identified by the location attribute, IDLOCN, as WORCLIM.

Daily precipitation data were also obtained from four NWS second-order climate stations in or within 20 mi to the south and east of the study area (fig. 1). These data were used for comparison with the Worcester data. Although the second-order climate data often differed from the Worcester data, the differences were not consistent; therefore, no adjustments were made to the precipitation input to the model.

Water Withdrawals and Wastewater Returns

Water withdrawals and WWTP discharges were explicitly accounted for in the model by time-series data collected from various sources. The water withdrawals and treated wastewater return flows are described in the introduction and summarized in tables 2 and 3, respectively.

Daily withdrawals were obtained from water suppliers, when possible, for the period January 1, 1993, through December 31, 2003. If daily withdrawal data could not be obtained, daily withdrawals were calculated from monthly water-use records reported to the MADEP. The daily withdrawal information provided by the water suppliers was used as a pattern to disaggregate monthly withdrawal records when only monthly data were available. Estimated daily values may differ from the actual withdrawals, but the total monthly withdrawals agree with the withdrawals reported to MADEP. Withdrawals specified in the long-term (1960–2004) simulations outside of the 1993–2003 model calibration period were determined on the basis of the mean monthly observed withdrawals during 1993–2003. Long-term (1960–2004) WWTP returns specified in the simulations outside of the 1993–2003 period were determined from the mean monthly observed return during 1993–2003. Mean monthly withdrawals and returns were disaggregated into a daily time step.

The amount of withdrawal eventually equals the amount of streamflow depletion, but the rate of streamflow depletion can differ from a varying rate of withdrawal because of the lag effects of moving water through an aquifer. The effect of groundwater withdrawals on streamflow was calculated with

the analytical program STRMDEPL (Barlow, 2000; Zarriello and Ries, 2000), which accounts for the time varying pumping rates on streamflow depletion from individual withdrawals on the basis of aquifer properties, distance of the well from the stream, and a resistance factor representing the stream-aquifer boundary. Most supply wells are finished in sand and gravel and were assigned a diffusivity (transmissivity divided by storativity) of 14,700 ft^2/d on the basis of values reported by Brackley and Hansen (1985). One supply well is finished in bedrock and was assigned a diffusivity of 41,500 ft^2/d on the basis of hydraulic properties of bedrock in the area reported by Lyford and others (2003). The resistance term representing the stream-aquifer boundary was assigned a value of zero for all wells, meaning the stream channel is in good hydraulic connection with the aquifer.

While STRMDEPL provides a reasonable approximation of the effect of a pumped well on streamflow, the interaction between a well and a stream can be very complex. Some of the factors affecting the action between a pumped well and a stream include (1) heterogeneous transmissivity and storage properties of the aquifer, (2) types and relative position of aquifer boundaries, (3) penetration of the pumped well and stream in the aquifer, and (4) transient conditions such as a change in recharge. Many authors have described factors that affect flow to a well that are summarized by Theis (1940), Reilly and Pollock (1993), and Franke and others (1998).

Streamflow

Streamgages operated continuously by the USGS in the Sudbury and Assabet River Basins served as the primary calibration points (fig. 1; table 5); these include Sudbury River at Ashland (01097480) and at Saxonville (01098530), Assabet River at Maynard (01097000), and Nashoba Brook near Acton (01097300). Daily mean flow records are available from Saxonville, Maynard, and Nashoba streamgages for the entire October 1993 through September 2003 calibration period. Flows at Sudbury River at Ashland were measured from May 12, 1994, through October 1, 1995; thus, daily mean flows had to be estimated for the other parts of the 1993–2003 calibration period.

Estimated flows at the Ashland streamgage were determined by the Maintenance Of Variance Extension type 3 (MOVE-3) method (Vogel and Stedinger, 1985). MOVE-3 uses statistical moments determined from 641 days of concurrent record with an index station (Maynard streamgage). Flows above 100 ft^3/s at the Ashland streamgage were adjusted because the MOVE-3 analysis indicated a nonlinear relation between concurrent high flows measured at the Ashland and Maynard streamgages that indicate flows at Ashland were increasingly overestimated as flow increases. This nonlinear relation is believed to be caused by dampening of high flows by storage in extensive wetlands above the Ashland

Table 5. Streamgages in the Sudbury and Assabet River Basins, Massachusetts.

[USGS, U.S. Geological Survey; mi^2, square mile; location shown in fig. 1; no., number; IDLOCN, location attribute in Watershed Data Management (WDM) database; DSN, data-set number in WDM; --, not used]

USGS streamgage no.	Streamgage name	Drainage area (mi^2)	Type	Model reach		WDM DSN
				No.	IDLOCN	
		Sudbury River Basin				
01097459	Whitehall Brook near Hopkinton	6.64	Partial	4	WBHK	24
01097460	Sudbury River at Fruit St. near Hopkinton	19.3	Partial	5	SRHK	25
01097466	Sudbury River at Howe St. near Ashland	23.9	Partial	6	SRAS1	26
01097468	Indian Brook near Hopkinton	4.73	Partial	7	IBHK	27
01097469	Indian Brook near Ashland	6.75	Partial	8	IBAS	--
01097480	Sudbury River at Front St. at Ashland	35.4	Continuous[1]	9	SRAS2	30, 31
01097540	Baiting Brook near Framingham	3.41	Partial	15	BBFR	35
01098530	Sudbury River at Saxonville	106	Continuous	19	SRSX	39
		Assabet River Basin				
01096600	Assabet River near Westborough	6.88	Partial	51	ARWB	51
01096853	Danforth Brook near Hudson	7.04	Partial	59	DBHU	59
01096880	Fort Meadow Brook near Hudson	6.39	Partial	61	FMBH	61
01096945	Elizabeth Brook near Stow	20	Partial	63	EBST	63
01097000	Assabet River at Maynard	116	Continuous	65	ARMY	65
01097300	Nashoba Brook near Acton	12.3	Continuous	68	NBAC	68

[1]Continuous data from June 1994 to October 1995 and from May 2004 to July 2009; two methods used to estimate record, stored in separate data sets.

streamgage. To compensate, a simple linear regression was developed from measured flows above 80 ft^3/s at the Ashland streamgage to concurrent flows at the Maynard streamgage to adjust MOVE-3 estimated flows above 100 ft^3/s; the regression relation had a coefficient of determination (r^2) of 0.88. Although the estimated record at Ashland streamgage had a root mean square error (RMSE) of 11 ft^3/s, the estimated flows are still considered to be poor because the observed flow data are generally rated poor (the estimated flow differs from the true flow by more than 15 percent), which perpetuates through the record-extension method.

Use of streamflow data for model calibration is subject to the uncertainties associated with the flow records. Flows affected by rating shifts and other factors or extrapolated from other records to fill periods of missing record are generally considered of poor quality and are subject to greater uncertainty. Flows at Ashland streamgage have a relatively high degree of uncertainty because the majority of the calibration period was estimated. Flows at Nashoba streamgage also are subject to a high degree of uncertainty, particularly at low flows, because beaver activity disrupts the stage-discharge rating stability. In addition, simulated flows at all the calibration sites can appear to have large error because of flow regulation that is unaccounted for in the model. This is a particular issue at the Saxonville streamgage because flows can be affected by regulation from numerous upstream reservoirs; most of these regulated flows are unaccounted for in the model because there was no set pattern of regulation or continuous record of how flows were regulated. The one exception to this is the out-of-basin transfer of water from the Wachusett Reservoir into the Sudbury Reservoir; these transfers are accounted for during the model calibration period from records obtained from MWRA. To minimize the uncertainty of calibrating the model to flow records that were estimated or affected by an unknown amount of regulation, or both, the Assabet River Basin was included in the model to provide two additional continuous-record calibration sites. These sites helped constrain the range of acceptable values for the model variables, and the extension of the model area also proved useful in the second part of the study.

Streamflow information at 10 partial-record stations (6 in the Sudbury River Basin and 4 in the Assabet River Basin) that ranged in size from 3.41 to 23.9 mi^2 was used in this study (fig. 1, table 5). Daily flows at these streamgages were determined from comparison of point streamflow measurements at the partial-record stations during this study or in previous studies, or both, to concurrent daily flows at two to nine index streamgages using MOVE-3 (table 6). The number of streamflow measurements at the partial-record stations ranged from 7 to 78 with a median of 16. Index stations were chosen on the basis of their proximity to the partial-record station and degree of flow regulation; the final selection was made on the basis of their correlation to flow measurements made at the partial-record station. If more than one index station was used in the MOVE-3 analysis, the selected index stations were weighted by the root mean square difference between measured and estimated flows. Flow measurements at the partial-record stations were typically made at low to moderate flows; thus, there is greater uncertainty in estimated moderate to high flows.

All other partial-record stations generally correlated best to the Maynard streamgage, which was used in all the record-extension analyses, except Indian Brook at Ashland (01097469), which did not correlate well with any of the selected index stations. The correlation generally improved when the flows at the Maynard streamgage were adjusted for WWTP return flows (effluent was subtracted from the recorded flow at the streamgage prior to the MOVE-3 analysis). Although estimated flows at the partial-record stations are subject to a large degree of uncertainty, the additional data from these sites provided useful information for evaluating and adjusting the model calibration.

Precipitation-Runoff Model

The HSPF model (Bicknell and other, 2001) was used to simulate runoff in response to climate and water use in the Sudbury and Assabet River Basins. HSPF is a well-documented non-proprietary model that can represent the hydrology and complex water-withdrawal patterns in the basin. The computer code for HSPF and its companion programs (U.S. Environmental Protection Agency, 2009) can be modified as necessary; however, no modification of the code was needed for this study. The general steps followed to complete the modeling effort were to (1) compile, collect, and process needed data; (2) build the model to represent the Sudbury and Assabet River Basins; (3) calibrate the model to streamflow data; (4) create and examine selected water-withdrawal scenarios; and (5) document the model and results.

Functional Description of the HSPF Model

HSPF is a continuous simulation model based on the principle of conservation of water mass; that is, inflow equals outflow plus or minus any change in storage. In HSPF, the land-surface areas are segmented into hydrologic response units (HRUs) that flow into streams, lakes, and reservoirs defined by model reaches (RCHRESs). Water budgets (inflows, outflows, and changes in storage) are calculated for each time step specified in the model for each HRU and for each RCHRES. HRUs reflect areas of relatively homogeneous hydrologic response to climate on the basis of similar land use, soil, surficial geology, wetlands, and other factors considered important to the hydrology of the watershed. HRUs are divided into pervious-area land segments (PERLNDs) and impervious-area land segments (IMPLNDs). RCHRESs represent stream channels, lakes, and reservoirs. The downstream end of each RCHRES is referred to as a node. Nodes are typically placed in the model to define channel segments with

Table 6. Correlation of partial-record stations in the Sudbury and Assabet River Basins to index streamgages.

[USGS, U.S. Geological Survey; No., number; IDLOCN, location attribute in Watershed Data Management (WDM) database; **Bold numbers** indicate index stations used to estimate daily flows at the partial-record station; DSN, WDM data-set number where estimated flows are stored; index stations are ranked by the number of partial-record stations they were used in, then by the average mean square difference between measured and estimated flow]

USGS station no.	Model reach		No. of measurements	Correlation coefficient to index streamgages (identified by USGS streamgage no.)								
	No.	IDLOCN		01097000	01111300	01097300	01105730	01096000	01103500	01105600	01175670	01098530
Sudbury River Basin												
01097459	4	WBHK	27	**0.866**	**0.873**	**0.848**	0.744	**0.816**	**0.817**	0.742	**0.803**	0.736
01097460	5	SRHK	10	**0.938**	**0.909**	0.655	**0.927**	0.714	0.837	**0.937**	0.755	0.803
01097466	6	SRAS1	21	**0.964**	0.718	**0.903**	0.859	0.770	0.717	0.876	0.794	0.828
01097468	7	IBHK	16	**0.924**	**0.977**	0.903	**0.917**	0.827	0.868	**0.951**	0.857	0.801
01097469	8	IBAS	17	0.516	0.412	0.463	0.480	0.573	0.580	0.296	0.507	0.433
01097480	9	SRAS2	[1]641	**0.955**	0.883	0.891	0.903	0.917	0.914	0.848	0.858	0.868
01097540	15	BBFR	15	**0.929**	**0.936**	**0.957**	**0.901**	**0.929**	0.873	**0.926**	**0.953**	**0.920**
Assabet River Basin												
01096600	51	ARWB	14	**0.961**	**0.907**	**0.901**	**0.900**	0.883	**0.920**	0.888	0.784	0.670
01096853	59	DBHU	78	**0.825**	0.756	**0.857**	0.649	**0.868**	0.794	0.572	0.853	0.652
01096880	61	FMBH	7	**0.974**	**0.956**	0.871	**0.975**	**0.966**	**0.929**	**0.950**	0.747	**0.913**
01096945	63	EBST	62	**0.909**	0.695	**0.849**	0.553	0.741	0.728	0.480	0.799	0.712

[1]Number of days of concurrent record used in analysis.

similar physical properties, at junctures with tributary streams, at the downstream end of lakes and reservoirs, at data-collection sites, and at other locations where estimates of streamflow are desired, such as the aquatic-habitat study sites.

HSPF requires two primary input files for its operation, the User Control Input (*uci*) file and the WDM file. The *uci* file directs process actions used by the model and sets values for input variables. Process actions or algorithms in the model calculate the movement of water and changes in storage. The *uci* file is structured in blocks that simulate different processes. The three main blocks of the *uci* file simulate (1) PERLNDs, (2) IMPLNDs, and (3) RCHRESs. Within each block are modules and sub-modules, some of which are mandatory for simulations and others are optional. For example, the PWATER module is required to simulate the hydrology of pervious areas, but the SNOW module is optional for simulating snowpack buildup and melt on pervious areas. A number of modules are used for administrative functions, such as controlling the operational sequence of the program and directing the model to external sources and output of time-series data.

The WDM file contains the input time series needed by the model and time series generated by the model. Simulations of streamflow require precipitation and PET as time series. Simulation of snowpack buildup and melt, which was done in this model, requires time series of air temperature, dew-point temperature, and solar radiation. Output time series can be generated for any component in the simulation process that is defined in the Time Series Catalog section of the user's manual, but time series were output mostly for streamflow.

PERLND and IMPLND water-budget calculations include surface runoff, but only PERLND water-budget calculations include interflow (shallow groundwater flow that responds rapidly to precipitation), baseflow (deep groundwater flow that remains relatively constant), and optionally, a deep groundwater-flow component that discharges outside of the basin. Process actions that control the rate of infiltration and change in subsurface storage make the simulation of PERLNDs considerably more complex than the water-budget calculations for IMPLNDs. A complete description of the process actions and input model variables is given in the HSPF Users Manual by Bicknell and others (2000).

Precipitation is the principal inflow to a basin; however, inflows can also include wastewater return flows and other sources. Precipitation and other sources of moisture supply to impervious and pervious areas can be retained at or above the surface as interception storage and as snowpack storage, but only pervious areas retain water in the subsurface. PERLNDs store soil water in two zones: (1) the upper-zone storage, generally considered the upper-soil horizon, and (2) the lower-zone storage, representing a deep-soil zone that only allows outward movement of water through ET by deep-rooted vegetation. In addition, water is held in groundwater storage that is eventually released to streams and is controlled by recession variables. Stream channels, lakes, and reservoirs also have a storage component defined by their geometry.

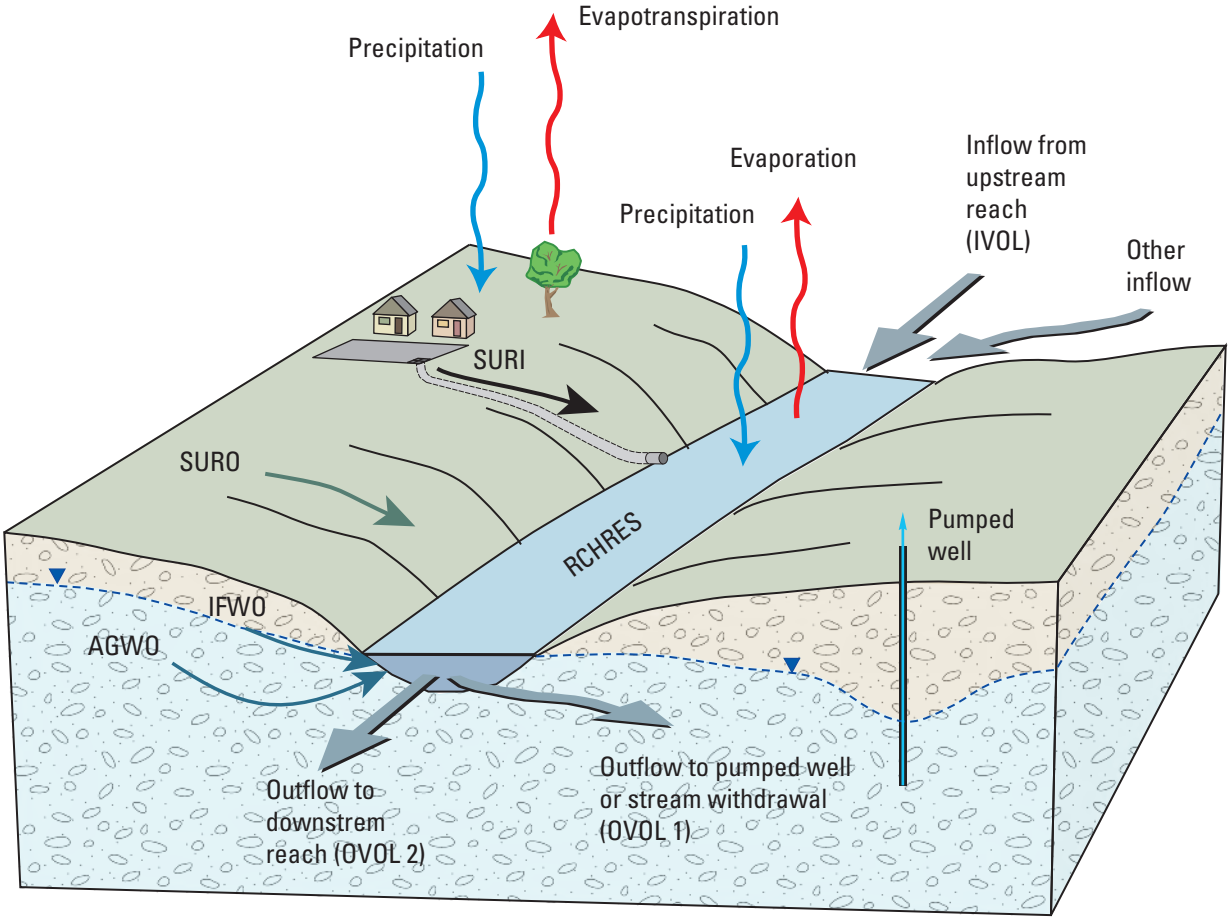
Precipitation that is not held in storage or is lost to ET (or optionally exits through deep groundwater) is discharged to RCHRESs as surface runoff from IMPLNDs and PERLNDs and as subsurface outflows from PERLNDs. The area of IMPLND and PERLND that drain to a RCHRES and the linkage of one RCHRES to another are specified in the SCHEMATIC block and associated MASSLINK block or the NETWORK block, or both. The SCHEMATIC or NETWORK blocks are used to represent the physical layout of the watershed. Relations among stage, storage, surface area, and discharge are specified for each RCHRES in user-supplied function tables (FTABLEs). Primary inflows to a RCHRES are (1) surface runoff from PERLNDs and IMPLNDs, (2) interflow and baseflow from PERLNDs, and (3) inflow from other RCHRESs. Inflow as direct precipitation and outflow as ET can be simulated for RCHRESs when specified by the user and were done only in RCHRES that represent large wetlands, lakes, or reservoirs. Inflows and outflows from other sources, such as wastewater effluent or water withdrawals were specified for RCHRES where applicable.

The inflows to and outflows from a RCHRES are illustrated in figure 6. Surface runoff enters RCHRES from impervious surfaces (SURI) and pervious surfaces (SURO). Infiltrated precipitation can flow to the RCHRES as shallow quick-responding interflow (IFWO) or as a slow-responding active groundwater (baseflow) component (AGWO). Inflow can also be from upstream reaches (IVOLs). Two outflow exits (or gates) are illustrated (a RCHRES can have up to five exits). The first exit gate in figure 6 (OVOL 1) is the volume time series of water withdrawals (OUTDGT 1) for each RCHRES, read in by the EXTERNAL-SOURCE block. Specifying the first outflow gate for water withdrawals requires that these withdrawals be satisfied before water is routed through successive outflow gates. In the Sudbury and Assabet River Basin model, water usually is routed downstream through the second outflow gate (OVOL 2), as illustrated, but in one instance (Hopkinton Reservoir outflow), a third outflow gate was specified where the second outflow gate routes a controlled release from a reservoir and the third routes an uncontrolled flow (spillway) from the reservoir.

Water is routed through RCHRES using the kinematic-wave method that assumes a uniform steady flow through the RCHRES. In kinematic-wave routing, lateral and upstream inflows are continuously added to solve equations for continuity and uniform flow. The model solves equations for continuity from computed inflows to the RCHRES and from the RCHRES storage-discharge properties (FTABLE) at each time step specified in the model.

Representation of the Basin

The physical and spatial representation of the basin is represented in the model by HRUs (PERLNDs and IMPLNDs), their contributing area to a reach, and the linkage



EXPLANATION

SURI–Surface runoff from impervious areas

SURO–Surface runoff from pervious areas

IFWO–Interflow (subsurface flow that responds rapidly to precipitation)

AGWO–Active groundwater flow (baseflow)

RCHRES–Stream reach or reservoir segment

IVOL–Inflow volume

OVOL x–Outflow volume through individual exits (x = 1 to 5)

Figure 6. Simplified schematic representation of the Hydrologic Simulation Program–FORTRAN (HSPF) inflows and outflows to a stream.

of one reach to another. The process of defining HRUs, their linkage to reaches, and the linkage of reaches to each other is commonly referred to as the model schematization or discretization. A Geographic Information System (GIS) was used to aid in this process. Basin boundaries for many of the reaches in the model were available from a statewide digital data layer constructed by the USGS and the Massachusetts Geographic Information System (MassGIS). Basin boundaries for reaches that were not available from this data layer were delineated from 1:25,000-scale Digital Elevation Model (DEM) data or were digitized by hand from 1:25,000-scale USGS topographic maps. Other data layers used in the discretization process were obtained from MassGIS and include 1:250,000-scale surficial geology, 1:25,000-scale 1999 land use, 1:25,000-scale hydrography, and 1:12,000-scale wetlands. These data layers, including detailed descriptions, can be obtained at MassGIS (Massachusetts Geographic Information System, 2009). Two additional GIS data layers used in the model development—public-water lines and public-sewer lines—were compiled from individual towns in the basin (L. Barlow, U.S. Geological Survey, written commun., 2004).

Development of Hydrologic Response Units

The spatial data were simplified and grouped to obtain categories that were considered important to the hydrology of the basin. The surficial-geology data layer was simplified from seven categories into two types of material on the basis of permeability and storage characteristics—sand and gravel or till and bedrock (fig. 3). Till and bedrock is herein referred to simply as till because bedrock is seldom exposed. The 1999 land-use cover (fig. 5), developed from aerial photography flown in 1997, was combined with the wetland data layer and then simplified from 37 categories to 9 categories: (1) forest, (2) open area, (3) open water, (4) forested wetland, (5) nonforested wetland, (6) low-density residential, (7) medium-density residential, (8) high-density residential, and (9) commercial, industrial, and transportation. Commercial, industrial, and transportation areas are generally referred to herein as commercial because this is the dominant land-use type. The simplified combinations of surficial geology and developed land uses (7, 8, and 9) were intersected with basinwide data layers of water and sewer infrastructure obtained from the towns to determine areas with net imports or exports of water as explained later.

Out of a potential combination of 54 unique pervious area HRUs, half were dropped because individually they account for less than about 1 percent of the basin area. A total of 27 pervious area HRUs and 2 unique impervious area HRUs were identified to represent the basin (table 7). The dropped HRUs were grouped into the retained HRUs with the most similar characteristics.

Impervious Areas (IMPLNDs)

Impervious areas, such as building roofs, paved roads, and parking lots, block infiltration of water into the ground. Runoff from some impervious surfaces can eventually infiltrate into the ground because these surfaces drain onto surrounding pervious surfaces that allow infiltration. In the HSPF model, IMPLNDs are used to simulate effective impervious areas, which are impervious surfaces that drain directly to streams and thus produce only surface runoff. Not all impervious surfaces drain directly to streams, however. Impervious surfaces that drain to pervious surfaces are considered non-effective impervious areas and are incorporated into one of several “disturbed” PERLND types as described later. In large basins such as the Sudbury and Assabet River Basins, values for effective imperviousness are difficult to obtain and were estimated from broad land-use categories that were adjusted during the model calibration.

Two IMPLND types were used in the model—commercial and residential. The residential IMPLNDs represent the combined impervious area from low-, medium-, and high-density residential areas. Initial estimates of effective impervious area were obtained from Zarriello and Ries (2000) for similar land-use types. Final IMPLND areas ranged from 70 percent for commercial, transportation, and industry to 15 percent for high-density residential, 8 percent for medium-density residential, 2.5 percent for low-density residential, and 0.1 percent for open space. Other factors were also considered in the calibration of effective impervious area, including the overall responsiveness of the hydrograph to precipitation, particularly for summer storms.

Overall, about 36 percent of the basin is classified as developed, but only about 6.7 percent of the basin area is simulated as effective impervious area. The average subbasin effective impervious area ranged from less than 1 to 37 percent with a median of 5.3 percent. In the Sudbury River Basin, about 40 percent is classified as developed and about 7.8 percent of the basin area is simulated as effective impervious area. In the Assabet River Basin, about 32 percent is classified as developed and about 5.4 percent of the basin area is simulated as effective impervious area. Above Saxonville streamgage, the area that is the focus of the model simulations, about 42 percent of the basin is developed and about 10 percent of the basin is simulated as effective impervious area.

Pervious Areas (PERLNDs)

Of the 27 unique PERLND HRUs defined for the basin (table 7), 4 represent open space or forested areas over sand and gravel or till. Three HRUs represent nonforested wetlands, forested wetlands, and open water; unlike other HRUs, these three HRUs are not further distinguished by the underlying surficial geology. Open-water HRUs represent small areas of

Table 7. Hydrologic Response Units (HRUs) used to develop the Hydrologic Simulation Program–FORTRAN (HSPF) model for the Sudbury and Assabet River Basins, Massachusetts.

[HRU ID, identifier number; PERLND, pervious area; IMPLND, impervious area; Comm., Commercial; transp., transportation; S&G, sand and gravel; Self, private well; Septic, on-site septic system; Public, public water or sewer system; NA, not applicable]

HRU ID	Land use	Surficial geology	Water supply source	Waste-water disposal	HRU ID	Land use	Surficial geology	Water supply source	Waste-water disposal
				PERLND					
1	Comm./industrial/transp.	S&G	Self	Septic	31	Comm./industrial/transp.	Till	Self	Septic
4	High-density residential	S&G	Self	Septic	34	High-density residential	Till	Self	Septic
7	Medium-density residential	S&G	Self	Septic	37	Medium-density residential	Till	Self	Septic
10	Low-density residential	S&G	Self	Septic	40	Low-density residential	Till	Self	Septic
8	Medium-density residential	S&G	Public	Septic	38	Medium-density residential	Till	Public	Septic
11	Low-density residential	S&G	Public	Septic	41	Low-density residential	Till	Public	Septic
3	Comm./industrial/transp.	S&G	Public	Sewer	33	Comm./industrial/transp.	Till	Public	Sewer
6	High-density residential	S&G	Public	Sewer	36	High-density residential	Till	Public	Sewer
9	Medium-density residential	S&G	Public	Sewer	39	Medium-density residential	Till	Public	Sewer
12	Low-density residential	S&G	Public	Sewer	42	Low-density residential	Till	Public	Sewer
13	Open	S&G	NA	NA	43	Open	Till	NA	NA
14	Forest	S&G	NA	NA	44	Forest	Till	NA	NA
51	Shrub-scrub wetlands	NA	NA	NA					
52	Forested wetlands	NA	NA	NA					
53	Water	NA	NA	NA					
				IMPLND					
60	Residential	NA	NA	NA					
61	Comm./industrial/transp.	NA	NA	NA					

water not explicitly accounted for in model reaches described later. Sixteen HRUs represent various combinations of residential-area densities, surficial geology, and water supply and wastewater disposal. Four HRUs represent commercial areas over two combinations of surficial geology intersected with two types of water supply and wastewater disposal. Commercial HRUs include industrial and transportation areas, but most area in these HRUs was originally classified as commercial. The 16 residential and 4 commercial HRUs represent disturbed pervious areas and the non-effective impervious areas associated with these types of land use.

HRUs for residential areas represent low-, medium-, and high-density development. High-density residential HRUs represent multi-family residential and single-family residential on lots smaller than or equal to 0.25 acre. Medium-density residential HRUs represent single-family homes on lots between 0.25 and 0.5 acre. Low-density residential HRUs represent single-family homes on lots larger than 0.5 acre.

Excluding the various combinations of water imports or exports in commercial and residential areas, the distribution of HRU types is shown in figure 7. Forest HRUs are the dominate HRU type in the basin (38 percent), but collectively, the developed HRUs are nearly equal to the area of forest HRUs (36 percent). Most developed areas are classified as low- to medium-density residential (27 percent).

In general, hydrologic characteristics are similar for PERLNDs with similar surficial geology; however, upper- and lower-zone storage and infiltration are less for developed PERLNDs than for forested PERLNDs. The decreased storage allows developed PERLNDs to respond more rapidly to precipitation than the same surficial geology type undisturbed by development. The rapid response to precipitation mimics the

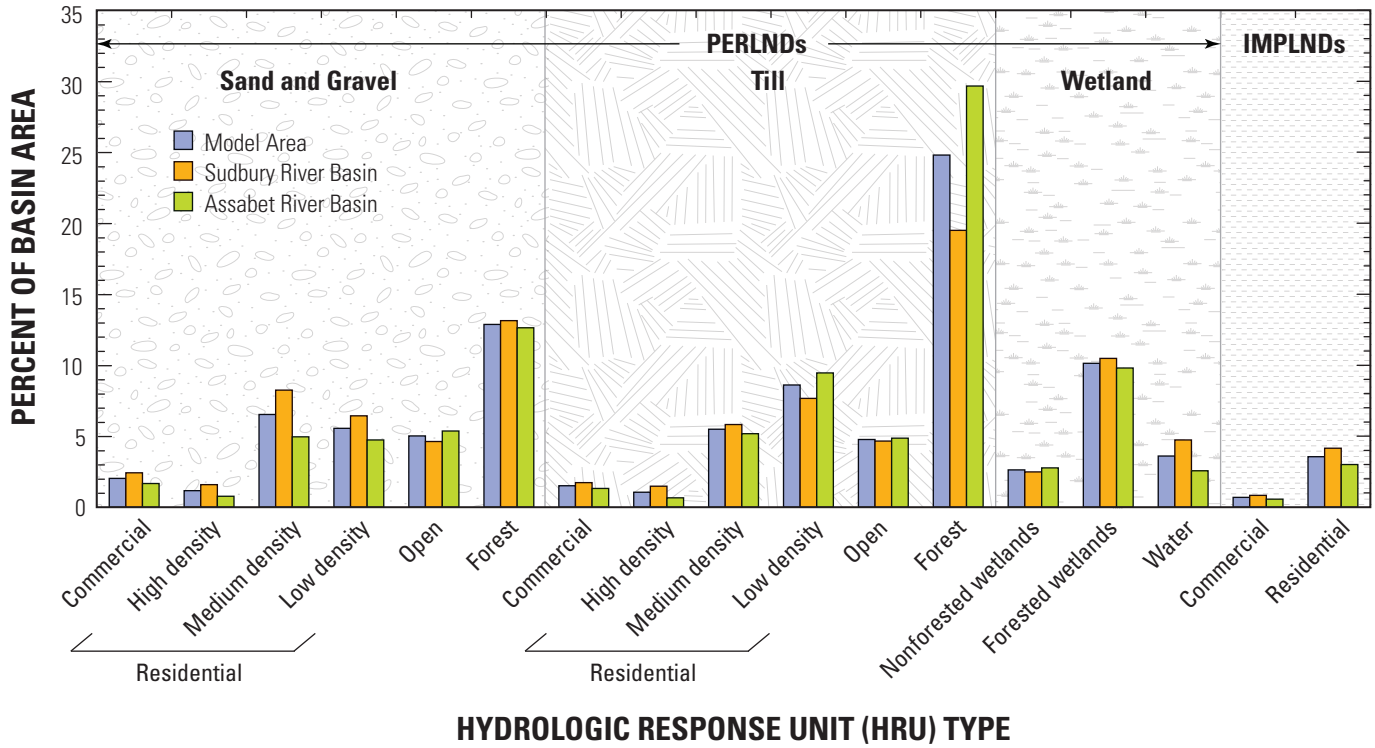
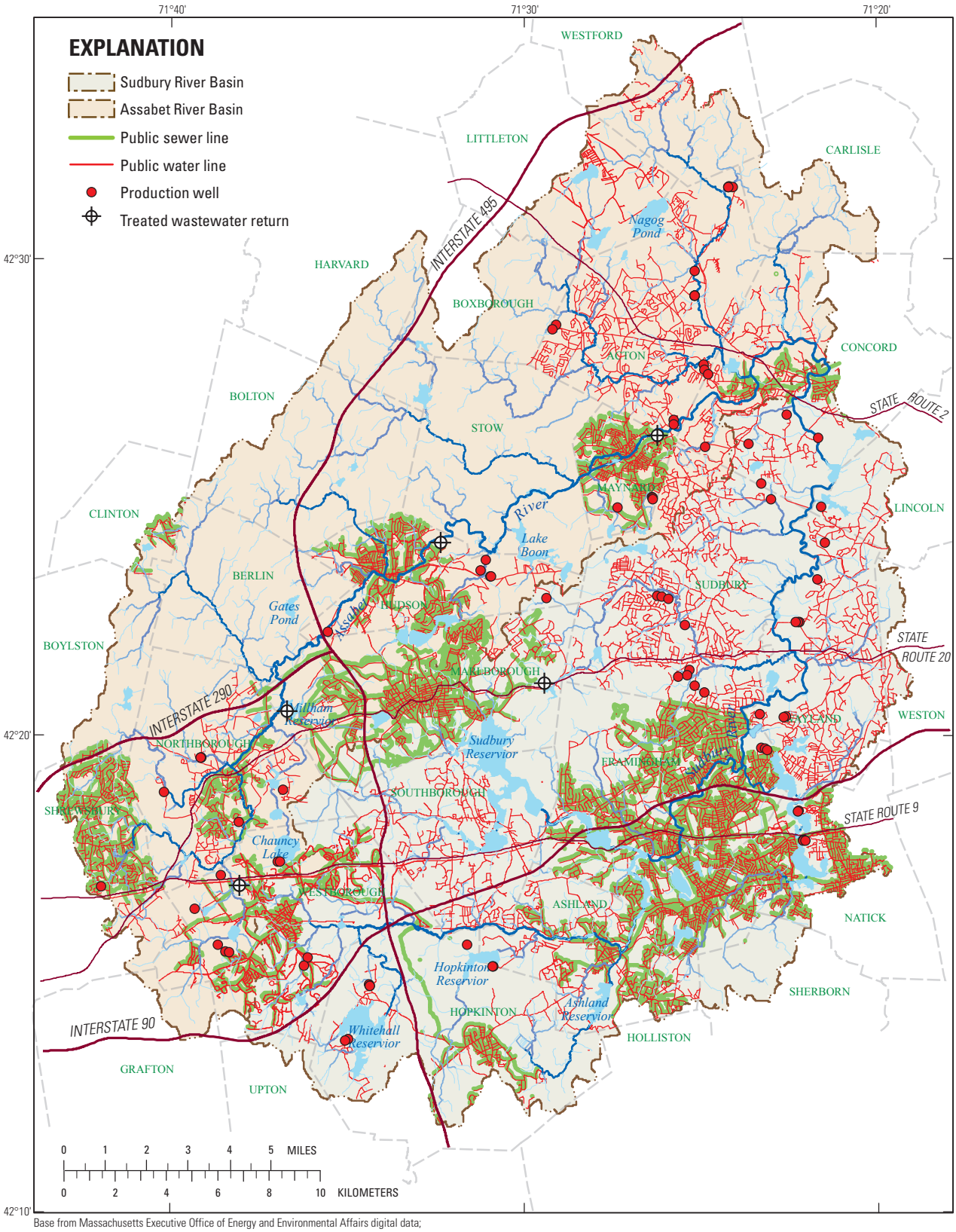


Figure 7. Distribution of general Hydrologic Response Unit (HRU) types for pervious area (PERLNDS) and impervious area (IMPLNDS) used to develop the Hydrologic Simulation Program–FORTRAN (HSPF) for the Sudbury and Assabet River Basins, Massachusetts.

effect of the more rapid depletion of available storage when the area receives lateral inflow from non-effective impervious areas or compaction of the native soil associated with development, or both.

Residential and commercial HRUs were further divided by water source (self supplied or public supply) and wastewater disposal (on-site septic or public sewer). These HRUs represent net water imports (public water and on-site septic), exports (private wells and public sewer), or no net gain or loss of water to the basin (private wells with on-site septic and public water with sewer). Developed areas with no net water gains or losses compose about 9.1 and 13 percent of the Sudbury and Assabet River Basin areas, respectively. Areas on public sewer can lose water from the basin through I&I. Areas served by public water and sewer compose (fig. 8) about 16 and 7.1 percent of the Sudbury and Assabet River Basin areas, respectively. Maps of water and sewer infrastructure indicate few areas where withdrawals from private wells are disposed of through public sewer (net imports). Therefore, separate HRUs were not developed for these areas and were combined with similar HRUs that export water from the basin. Water imports from areas served by public water and on-site septic were limited to medium- and low-density residential areas and compose about 6.3 and 6.2 percent of the Sudbury and Assabet River Basin areas, respectively. Commercial and high-density residential areas on public water with on-site septic combined comprised less than 1 percent of the basin area and were combined with similar HRUs with public water and sewer.

Imports and exports of water from the basin through the water and sewer infrastructure were estimated by first defining areas on public water and sewer from town water and sewer maps. A 250-ft buffer was added to each side of the water and sewer line features to indicate areas of net import, export, or no net change in the water budget. The rate of water input to areas on public water and on-site septic was determined from 2000 Topologically Integrated Geographic Encoding and Referencing system (TIGER) census-tract data (U.S. Census Bureau, 2009) to obtain an average number of households per acre and the average occupancy per household. The average occupancy per household ranged from 2.38 to 3.03 for the towns in the basin with an average occupancy of 2.73 persons per household over the basin. The average occupancy was multiplied by an average water use of 70 gal/d per person



Base from Massachusetts Executive Office of Energy and Environmental Affairs digital data;
EOTROADS_ARC, 1:5,000, 2006; HYDRO25K_ARC, 1:25,000, 2005; MAJPOND_POLY, 1:100,000, 1998; SUBBASINS_POLY, 1:25,000, 2007; TOWNS_POLY, 1:25,000, 2002
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 8. Public water and sewer infrastructure in the Sudbury and Assabet River Basins, Massachusetts.

times 5, 2.5, or 1.25 units per acre for high-, medium-, and low-density residential areas minus a 20-percent consumptive loss. This amounts to a net import of about 13, 6.4, and 3.2 in/acre/yr for high-, medium-, and low-density residential areas, respectively, on public water and on-site septic.

The town of Southborough has the highest percentage of medium-density residential land area on public water and on-site septic in the study area. Initial model calibration runs indicated peak flows and runoff volume in the reach associated with this area were oversimulated. Import of water in Southborough was modified because further investigation determined the average lot size is reported to be about two to four times that allowed by zoning and most households in the town are single occupancy (43 percent) or double occupancy (26 percent) (Chorey and others, 2004). The number of units per acre in Southborough was adjusted down to 1.0 and 0.5 from 2.5 and 1.25 units per acre used in other parts of the basin for medium- and low-density areas, respectively. An average occupancy of 2.73 people per unit and 70 gal/d per person minus a 20-percent consumptive loss was still used, which resulted in a net import of 1.3 and 2.6 in/acre/yr on low- and moderate-density residential areas on public water and on-site septic in Southborough.

Water imports from HRUs representing areas on public water and on-site septic are not linked to any particular source and account for withdrawals made from within the basins that are returned or imported from outside of the basin. Water imports on areas served by public supply and on-site septic are simulated as a lateral inflow to the lower-soil zone (LZLI), because septic leach fields are typically installed in this part of the soil horizon. Inflow to the lower-soil zone in the model is not available for discharge to streams, rather, septic effluent decreases the opportunity for infiltrated moisture from precipitation to be held in the lower-zone storage because the lateral inflow keeps this storage component closer to its capacity than would otherwise occur. As a result, more infiltrated water goes into active groundwater storage that eventually discharges to streams as baseflow than similar areas without septic effluent.

Sewer I&I by town reported by Barlow and others (2008) for the 1996–2000 period were extrapolated to the 1993–2003 period (table 8) to estimate the exports of water from the basin; annual I&I losses ranged from 0.26 Mgal/d in Ashland to 3.86 Mgal/d in Framingham and averaged 9.53 Mgal/d. I&I losses were highest during the spring when the groundwater table at its normal high with estimated average losses during March, April, and May of 20.9 Mgal/d. Exported water was simulated by the PWATER variable DEEPFR that is used to represent the fraction of groundwater lost from an HRU. DEEPFR was estimated at 0.22 (22-percent loss) for eight HRUs representing sewered areas in commercial, high-, medium-, and low-density residential areas over sand and gravel or till. The actual rate of export varies by HRU because the groundwater contribution to streamflow varies by HRU and season. Overall, about 11 percent of the basin is sewered—14 percent in the Sudbury River Basin and 8.1 percent in the Assabet River Basin.

Table 8. Estimated average 1993–2003 annual and spring inflow and infiltration (I&I) into public sewers by town in the Sudbury and Assabet River Basins, Massachusetts.

[Mgal/d, million gallons per day; Spring I&I, average for months of March, April, and May; MWRA, Massachusetts Water Resources Authority; WWTP, wastewater treatment plant; --, no data available]

Town	Facility or agency	Annual I&I		Spring I&I	
		Mgal/d	Percent of total effluent	Mgal/d	Percent of total effluent
Ashland	MWRA	0.26	36	0.61	83
Clinton	WWTP	0.71	--	1.5	--
Framingham	MWRA	3.86	45	7.1	83
Hopkinton	WWTP	--	--	--	--
Hudson	WWTP	0.62	27	1.01	44
Marlborough West	WWTP	0.57	36	3.89	55
Marlborough East	WWTP	1.13	45	1.87	65
Maynard	WWTP	0.27	26	0.46	35
Natick	MWRA	0.86	55	1.76	114
Northborough	WWTP	0.28	37	0.36	60
Shrewsbury	WWTP	0.69	--	1.45	--
Westborough	WWTP	0.28	17	0.88	35
Total		9.53		20.9	

Stream Reaches (RCHRES)

The Sudbury and Assabet River Basins were discretized (divided) into 44 stream reaches (fig. 9) on the basis of hydrologic features, availability of streamflow data, or where simulated flow information is desired. The Sudbury River Basin was divided into 23 reaches, 19 of which are upstream from the Saxonville streamgage (table 9). Four of the 19 upstream Sudbury River reaches are on the main stem. Four tributaries upstream from the Saxonville streamgage (Whitehall Brook, Indian Brook, Cold Spring Brook, and Lake Cochituate Outlet Brook) were subdivided to create reaches at reservoirs, major tributary confluences, or habitat sites. The Assabet River Basin was divided into 21 reaches, 7 of which are on the main stem of the river. RCHRESs are identified by a four-character attribute name (IDLOCN) and number (fig. 9 and table 9). RCHRESs are numbered in downstream order; the upper Sudbury River Basin RCHRESs are numbered 1 through 19, RCHRESs below the Saxonville streamgage are numbered 30 through 33; RCHRESs in the Assabet River Basin are numbered 51 through 72.

Linkage of reaches to one another is made in the model SCHEMATIC block to target outflow from the upstream reaches as inflow to the downstream reaches. In most cases, the linkage of one reach to another is easily identified in figure 9 and by the reach identification number, which ascends from upstream to downstream. In a few instances, the linkage between tributaries and the main stem are less obvious because of the juxtaposition of the confluence and reach node. For example, in the upper Sudbury River Basin, reach 18 (Lake Cochituate Outlet Brook) joins the Sudbury River just upstream (about 0.15 mi) of the Saxonville streamgage. Specifying outflow from reach 18 as an inflow to reach 19 would artificially elevate flows along most of the 5.8-mi length of reach 19 except near its outlet. To better represent flows in most of reach 19, while appropriately representing flows at the streamgage, flows from reaches 18 and 19 were combined using the model COPY operation to output simulated flows at the streamgage. Similar types of COPY operations were used in reaches 63, 64, and 65 (combines flows from Elizabeth Brook, Taylor Brook, and Assabet River to represent flows at the Maynard streamgage), reaches 67 and 69 (combines flows from Fort Pond Brook and Nashoba Brook), and reaches 33 and 72 (combined flows from the Sudbury and Assabet River Basins). A COPY operation was also used in reach 8 (Hopkinton Reservoir outlet) to combine the 2nd exit gate flow, which represents controlled releases from the reservoir, with the 3rd exit gate flow, which represents uncontrolled flow over the spillway; collectively, these flows represent flow in Indian Brook below the reservoir.

RCHRES in the Sudbury and Assabet River Basin HSPF model mostly had one or two exit gates to route water from the reach (table 9). For about half the reaches, one exit gate was specified. In most other reaches, two exit gates were specified; the 1st exit gate is used to satisfy the water demand when withdrawals are made from the reach and the 2nd is used to route water downstream. As previously noted, reach 8 has three exit gates.

Hydraulic Characteristics (FTABLEs)

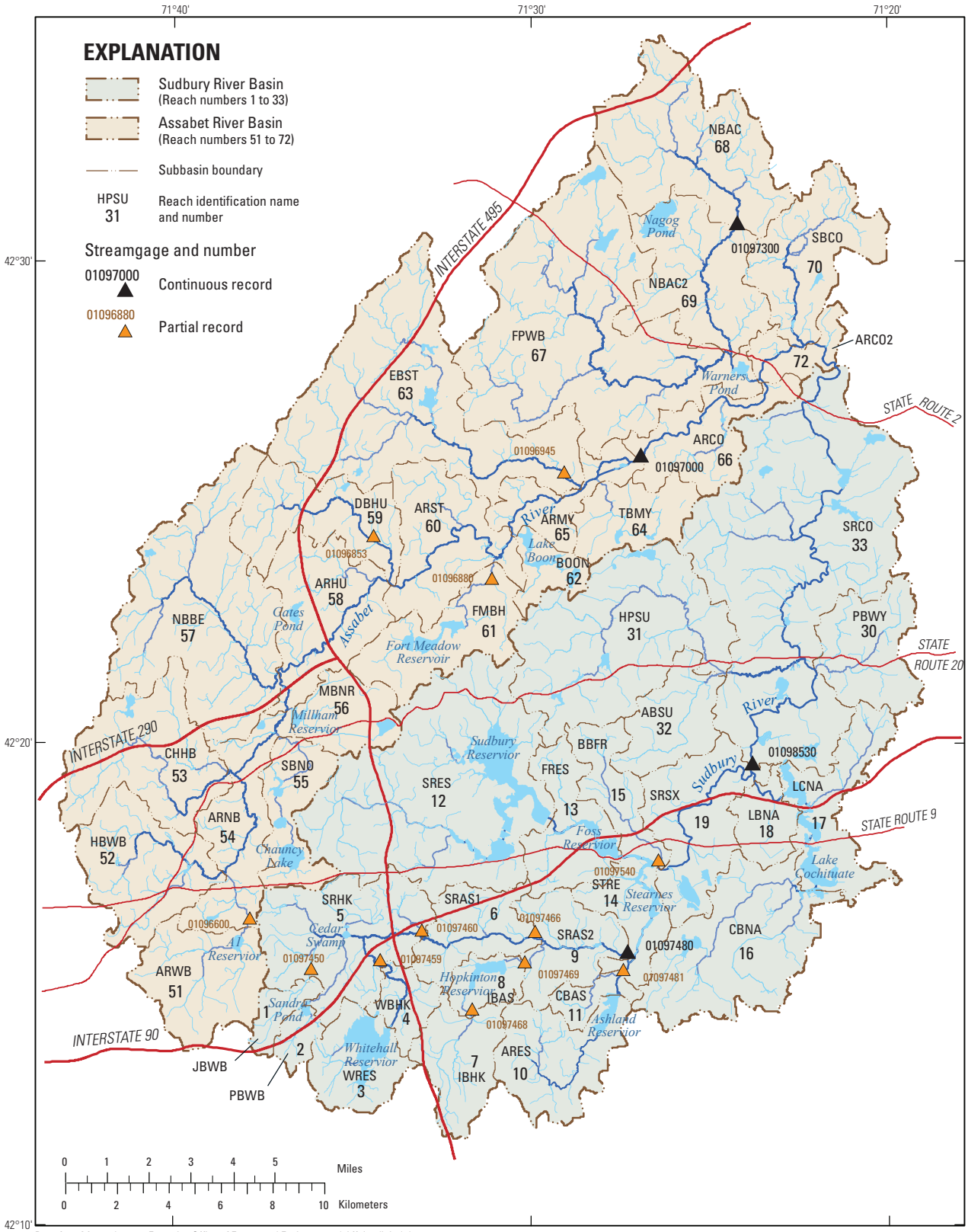
Stage-storage-discharge relations (FTABLEs) were developed for each RCHRES with the channel-geometry analysis program (CGAP) by Regan and Schaffranek (1985) and a supplemental program, GENFTBL. GENFTBL calculates discharge by Manning's equation from the hydraulic properties of the channel computed by CGAP from specified cross-section channel geometry and elevations. The cross-section geometry was obtained from surveys conducted at river reaches for flood-insurance studies, and from streamflow measurements made at continuous- and partial-record stations in the basin. When this detailed information was not available, channel widths and cross-section elevations were obtained from USGS 1:24,000-scale digital topographic maps and field observations. At a minimum, three cross sections were used to define the storage-discharge relations for each reach. GENFTBL requires Manning's roughness coefficients for each cross section; these coefficients were estimated from published guidelines by Chow (1959), Arcement and Schneider (1989), and Coon (1998).

Lakes and Impoundments

Lakes and impoundments are widely scattered throughout the Sudbury and Assabet River Basins (fig. 9). The presence of a major lake or impoundment can appreciably effect water movement through a reach. In these cases, the FTABLE was developed from depth, storage, surface area, and outlet discharge of the principal water body in the reach. In the Sudbury River Basin, FTABLES specifically represent Whitehall Reservoir (RCHRES 3), Hopkinton Reservoir (RCHRES 8), Ashland Reservoir (RCHRES 10), Sudbury Reservoir (RCHRES 12), Strearnes Reservoir (RCHRES 13), Foss Reservoir (RCHRES 14), and Lake Cochituate (RCHRES 17). In the Assabet River Basin, FTABLES represent A-1 Reservoir (RCHRES 51), Millham Reservoir (RCHRES 56), Fort Meadow Reservoir (RCHRES 61), Lake Boon (RCHRES 62), and Warner Pond (RCHRES 67). Information on depth, surface area, and volume of these water bodies and the shape and dimensions of their outlet structures were obtained from the MWRA, MADCR, or MADFW or from onsite measurements.

Wetlands

Wetland hydrology is complex and can be an important influence on stream hydrology (Lent and others, 1997; Hunt and others, 1996; Krabbenhoft and Webster, 1995; Anderson and Cheng, 1993; Mills and Zwarich, 1986; Zarriello and Reis, 2000). Wetlands account for about 13 percent of the total basin area, which is about equally distributed between the Sudbury River and Assabet River Basins. To account for storage and ET losses, wetlands were represented as "virtual" RCHRESs or incorporated into the reach FTABLE. Virtual RCHRESs,



Base from Massachusetts Executive Office of Energy and Environmental Affairs digital data;
EOTROADS_ARC, 1:5,000, 2006; HYDRO25K_ARC, 1:25,000, 2005; MAJPOND_POLY, 1:100,000, 1998; SUBBASINS_POLY, 1:25,000, 2007; TOWNS_POLY, 1:25,000, 2002
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 9. Discretization of the stream reaches used in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

Table 9. Subbasins and reaches (RCHRES) used in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

[Locations shown in fig. 9; IDLOCN, attribute in the Watershed Data Management (WDM) database that identifies the reach; --, not applicable or no streamgage; USGS, U.S. Geological Survey; mi², square mile; p, indicates partial-record station]

Reach number	IDLOCN	Stream or streamgage name	Number of exit gates	Upstream reach numbers	USGS streamgage number	Reach drainage area (mi²)	Cumulative drainage area (mi²)
		Sudbury River Basin					
1	JBWB	Jackstraw Brook near Westborough	1	--	01097450p	1.46	1.46
2	PBWB	Piccadilly Brook	1	--	--	1.21	1.21
3	WRES	Whitehall Reservoir	2	--	--	4.54	4.54
4	WBHK	Whitehall Brook at Fruit St. near Hopkinton	2	3	01097459p	2.1	6.64
5	SRHK	Sudbury River at Fruit St. near Hopkinton	2	1, 2, 4	01097460p	9.99	19.31
6	SRAS1	Sudbury River at Howe St. near Ashland	2	5	01097466p	4.56	23.86
7	IBHK	Indian Brook near Hopkinton	1	--	01097468p	4.73	4.73
8	IBAS	Indian Brook near Ashland (Hopkinton Res. outlet)	3	7	01097469p	2.02	6.75
9	SRAS2	Sudbury River at Front St. at Ashland	1	6, 8	01097480	4.73	35.35
10	ARES	Ashland Reservoir	2	--	--	6.43	6.43
11	CBAS	Cold Spring Brook near Ashland	1	10	01097481p	1.45	7.88
12	SRES	Sudbury Reservoir	2	--	01097466p	22.54	22.54
13	FRES	Foss Reservoir (no 3)	2	12	--	5.32	27.86
14	STRE	Stearnes Reservoir (no 1)	2	9, 10, 13	01097500p	3.84	74.94
15	BBFR	Baiting Brook near Framingham	1	--	01097540p	3.41	3.41
16	CBNA	Course Brook	1	--	--	11.4	11.4
17	LCNA	Lake Cochituate	2	16	--	6.17	17.57
18	LBNA	Lake Cochituate Outlet Brook	1	17	--	2.54	20.11
19	SRSX	Sudbury River at Saxonville	1	14, 15, 18	01098530	7.5	105.96
30	PBWY	Pine Brook	1	--	--	5.69	5.69
31	HBSU	Hop Brook near Sudbury	2	--	--	15.6	15.6
32	ABSU	Allowance Brook	2	--	--	4.6	4.6
33	SRCO	Sudbury River at Concord	2	19, 30, 31, 32	--	30.63	162.49
		Assabet River Basin					
51	ARWB	Assabet River near Westborough	2	--	01096600p	6.88	6.88
52	HBWB	Hop Brook at Westborough	2	--	--	7.89	7.89
53	CHHB	Cold Harbor/Howard Brook	2	--	--	9.55	9.55
54	ARNB	Assabet River at Northborough	2	51, 52, 53	--	4.36	4.36
55	SBNO	Stirrup Brook near Northborough	2	--	--	3.86	3.86
56	MBMR	Millham Brook near Marlborough	1	--	--	6.74	39.28
57	NBBE	North Brook near Berlin	1	--	--	16.89	16.89
58	ARHU	Assabet River at Hudson	2	54, 55, 56, 57	--	8.01	64.18
59	DBHU	Danforth Brook near Hudson	1	--	01096853p	7.04	7.04
60	ARST	Assabet River near Stow	1	58, 59	--	7.8	79.02
61	FMBH	Fort Meadow Brook near Hudson	2	--	01096880p	6.39	6.39
62	BOON	Boon Lake complex	2	--	--	2.07	2.07
63	EBST	Elizabeth Brook near Stow	1	--	01096945p	20.04	20.04
64	TBMY	Taylor Brook near Maynard	2	--	--	4.21	4.21
65	ARMY	Assabet River at Maynard	1	60, 61, 62, 63, 64	01097000	3.78	115.51
66	ARCO	Assabet River near Concord	2	65	--	5.58	121.09
67	FPBW	Fort Pond Brook	2	--	--	25.52	25.52
68	NBAC	Nashoba Brook near Acton	2	--	01097300	12.28	12.28
69	NBAC2	Nashoba Brook at Acton	1	67, 68	--	8.75	46.54
70	SBCO	Spencer Brook near Concord	1	--	--	7.51	7.51
72	ARCO2	Assabet River at Concord	1	66, 69, 70	--	2.27	177.41

described by Zarriello and Ries (2000), simulate wetland storage and ET loss without affecting the upstream channel flow through a reach. A virtual RCHRES allows for greater ET loss than a wetland treated as an HRU because the available moisture is not limited to precipitation falling on the HRU; rather, the available moisture supply is controlled by the amount of contributing area from surrounding HRUs that are directed into it. In the final model, only the reach representing Cedar Swamp (RCHRES 105) was used as a virtual reach because this was a focus area of the model and because large wetlands in most other areas are in headwater reaches (RCHRESs 3, 7, 51, 55, 56, 59, 61, 62, 63, 67, and 68) or reaches with large open-water features (RCHRESs 8, 13, 14, and 17). In headwater reaches and in reaches with large open-water features, the wetland areas were incorporated into the reach FTABLE. A separate virtual RCHRES in headwater reaches and in reaches with large open-water features would result in no or little difference in the simulation. It should be noted that RCHRES 7 (fig. 9), a headwater reach, was initially simulated with a virtual RCHRES (RCHRES 107) because it was in the focus area of the model but was converted to a single reach in the final model (RCHRES 107) that retained its virtual-reach numbering scheme.

The surface area of wetlands represented in RCHRES was set equal to the corresponding area of wetlands previously simulated as HRUs to maintain the same basin area. Precipitation on and ET from these reaches is directly proportional to the surface area specified in the FTABLE. At very low flows, the surface area was decreased in some FTABLES to limit the potential ET loss from the reach to achieve a satisfactory model calibration. Although this introduces some structural error into the model (because the simulated area of these subbasins decreases at very low flows), this modification was considered a necessary compromise to better simulate low flows. Storage-discharge characteristics of the wetland RCHRESs were adjusted empirically to minimize differences between simulated and observed streamflows. The wetland storage-discharge characteristics, flow-path characteristics, and the interaction between groundwater and surface water are largely unknown; however, they could be refined when wetland processes and their effects on the hydrology of the basin are better understood.

Water Withdrawals and Wastewater Returns

All water withdrawals from, and wastewater returns to, a reach are specified in the EXT SOURCE block of the *uci* file. For all major withdrawals within a reach (table 2), the combined streamflow depletion from groundwater withdrawals and direct surface-water withdrawals were specified in a single DSN (101 to 172) corresponding to RCHRESs 1 to 72, respectively. Twenty-four RCHRESs are affected by withdrawals as indicated by more than one exit gate for the reach (table 6). The combined water withdrawals are taken through the first outflow gate in a RCHRES (OUTDGT 1) and must be satisfied before water exits from the next outflow gate that typically routes water to the next downstream reach. Return flows from WWTP discharge to RCHRES 31, 54, 58, 60, and 66 are specified as an inflow to the reach (IVOL) from DSN 81, 82, 83, 84, and 85, respectively.

Model Calibration

The model was calibrated to an 11-year period, January 1, 1993, to December 31, 2003, by minimizing the differences between simulated and observed streamflow at the four streamgages in the model area. Values of variables that control runoff, infiltration, storage, and ET from HRUs were determined from spatial data to the extent possible. Many variables were initially assigned values similar to those used for comparable HRUs in the Ipswich River Basin HSPF model (Zarriello and Ries, 2000). An iterative process was then used to adjust variable values for grouped HRUs representing sand and gravel, till, and wetlands; the variable values were then refined for different land-use types within each group. Storm runoff and snowmelt were not given detailed consideration because the primary purpose of the model is to simulate the effects of withdrawals during low-flow periods. The calibrated-model variable values are given in the partial listing of the *uci* file in appendix 1.

Discharge measured at Sudbury River at Ashland (01097480) and at Saxonville (01098530), Assabet River at Maynard (01097000), and Nashoba Brook near Acton (01097300) provided the main data sets for model calibration. Estimates of daily flows at nine partial-record stations (five in the Sudbury River Basin and four in the Assabet River Basin) were also used to evaluate the model calibration. The estimated flows at partial-record stations were used mostly as a check of the calibration and to refine the FTABLE values in their corresponding upstream reaches (fig. 9).

The model fit was evaluated by graphical and statistical comparisons of the simulated and observed annual, monthly, and daily mean flows at the four principal streamgages. Hydrographs and flow-duration curves of the daily mean flow reflect climate, topography, and hydrogeologic conditions of the basin. Summary statistics including the differences and percent difference between simulated and observed streamflow means and medians, the RMSE, the r^2, and the Nash-Sutcliffe model-fit efficiency coefficient (E) were used to measure the quality of the model fit. The r^2 and E provide measures of the variation in the simulated value explained by the observed value (Neilson and others, 2003). The Nash-Sutcliffe E provides a more rigorous evaluation of the fit quality than r^2 does because E is sensitive to differences between the observed and simulated means and variances, whereas r^2 measures only the differences between mean values (Legates and McCabe, 1999). In cases where the observed values and model residuals are normally distributed, the value of r^2 and E should be equal (Duncker and Melching, 1998). Mean spring and summer simulated and observed flows over the calibration period were also compared to evaluate the model fit during seasonal high-flow and low-flow months.

The model was developed primarily for use in the upper Sudbury River Basin above the Saxonville streamgage (01098530; fig. 9); therefore, calibration focused on minimizing differences between simulated and observed flows at the streamgages at Saxonville and upstream at Ashland. Calibration also focused on summer low flows when streamflow stresses are most prevalent and flow alterations are of most concern. Unknown flow regulation in the observed streamflow at the Saxonville streamgage can cause unexplained differences between observed and simulated flows. Flows at the Ashland streamgage have a high degree of uncertainty because most of the record was estimated and the short period of actual record (641 days) was of questionable quality. Hence, fitting the model to the Saxonville and Ashland streamgages was weighed against the benefits of fitting the model to the Maynard streamgage, which was less affected by reservoir operations, and the Nashoba streamgage, which was least affected by regulation. However, flows at the Nashoba streamgage, particularly low flows, were often rated of fair to poor quality because of unstable control conditions, a factor that was also considered in the overall model calibration. Eventually, a point of diminishing returns is reached in the calibration process where any improvement in the model fit for one period or one location, or both, results in a deterioration of the model fit at another period or location, or both.

Some of the model error can be explained by the precipitation variability over the basin. Mean annual flow was oversimulated when annual precipitation measured at the Worcester climate station (model input climate data) was greater than the collective average precipitation measured at nearby climate stations (includes the Worcester station and four 2nd order stations in or near the basin) and undersimulated when Worcester precipitation was less than the collective average precipitation (fig. 10A). The r^2 between precipitation variability and model error ranged between 0.36 and 0.51. The regression line for Sudbury River at Saxonville had the lowest r^2 and also deviated most from the other stations, which may reflect the unaccounted for releases or diversions from the Sudbury Reservoir system, or both. In general, flows were oversimulated the most in 1993 and 1994 and undersimulated the most in 1998 and 2001, when precipitation recorded at Worcester was the greatest and least, respectively, relative to surrounding climate stations.

A similar pattern was observed between monthly model errors in relation to monthly precipitation variability (fig. 10B); however, the pattern is not as distinct as the relation between the annual model error and precipitation variability. The wide scatter in the relation between monthly model error and precipitation variability indicates other potential reasons for model error. These reasons include uncertainty of the estimated or observed flow data, flow regulation (including withdrawals and return flows) not accounted for in the model, particularly at the Saxonville streamgage, and representativeness of the input climate data. Model error can also result from variable values used in the model; the goodness of these values is dependent on the data used to calibrate the model. These factors are discussed in the model calibration at the four principal streamgages below.

Sudbury River at Ashland

Simulated streamflows at the Sudbury River at Ashland streamgage (SRAS2, RCHRES 9; fig. 9) were compared to observed data (when available) and estimated flows (January 1993 through April 1994 and July 1995 through December 2003) made using MOVE-3 as previously described in the Time-Series Data Streamflow section. Estimated flows were unadjusted (DSN 31) and adjusted (DSN 30) to correct for potential overestimation of flows above 100 ft^3/s. In general, the simulated flows are in good agreement with observed and estimated flows for the 11-year calibration period (table 10), but the simulated flows are in slightly better agreement with observed and adjusted estimated flows than to the observed and unadjusted flows.

The simulated mean daily flow during the calibration period (57 ft^3/s) was about midway between observed and estimated unadjusted and adjusted mean daily flow (54 and 59 ft^3/s, respectively); the difference between simulated and adjusted and unadjusted estimated daily mean flow was about 2.6 and -2.3 percent, respectively (table 10). Scatter plots of simulated daily mean flow in relation to observed and adjusted estimated flows (fig. 11A) generally indicate an equal distribution around the line of equality. Monthly and annual mean flow scatter plots (fig. 11B and C, respectively) indicate the simulated flows are slightly oversimulated relative to observed and adjusted estimated flows and slightly undersimulated relative to observed and unadjusted estimated flows. The split between the simulated and the adjusted and unadjusted flows is particularly evident in the daily mean flow-duration curves (fig. 11D) above 100 ft^3/s, or flows that are exceeded less than about 10 percent of the time; the simulated flow-duration curve is about mid-way between the unadjusted and adjusted "observed" flow-duration curves in this range. This suggests that the linear regression used to adjust high flows for the estimated record may overcompensate for the effects of wetland storage because the equation was developed from a limited period of actual record that generally had lower seasonal high flows than the remainder of the calibration period.

The model fit improved substantially when simulated flows were compared to the period of actual streamflow record (May 1994 through June 1995). The model fit for the period of actual record relative to the 11-year calibration period (using the adjusted estimated flows) increased the r^2 from 0.60 to 0.78, increased E from 0.50 to 0.75, and decreased RMSE from 38 to 27 ft^3/s (table 10). The model fit especially improved during the normal high-flow period (March and April); the difference between simulated flows and observed flows was about half for the period of actual record (-7.3 percent) relative to the 11-year calibration period record (-13 percent). The model fit during the summer months (June through September), however, was better for the 11-year calibration period than the period of actual record (summers

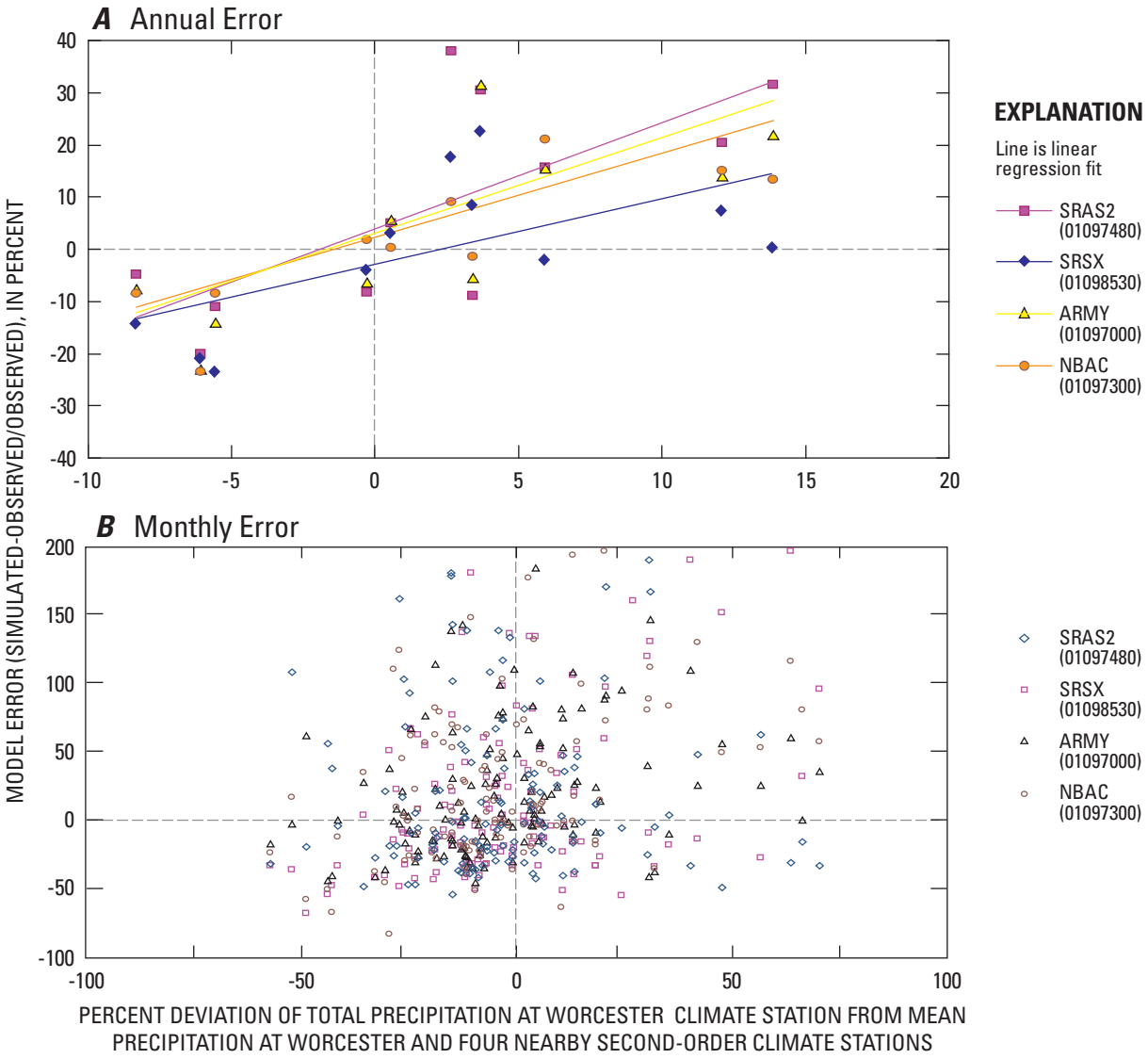


Figure 10. Annual (*A*) and monthly (*B*) precipitation variability in relation to model error at streamgages on the Sudbury River at Ashland (01097480; SRAS2) and Saxonville (01098530; SRSX), Assabet River at Maynard (01097000; ARMY), and Nashoba Brook near Acton (01097300; NBAC), Massachusetts, 1993 to 2003. Locations shown in figure 9.

Table 10. Model-fit statistics calculated from observed flows and Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows at four streamgages in the Sudbury and Assabet River Basins, Massachusetts, 1993 to 2003.

[Streamgage location shown on fig. 9; ft^3/s, cubic feet per second; r^2, coefficient of determination; E, Nash-Sutcliffe model-fit efficiency coefficient; RMSE, Root Mean Square Error]

	Calibration period January 1993 to December 2003								Summer (June–Sept.)		Spring (March–April)	
	Mean daily flow (ft^3/s)	Difference (percent)	Daily mean			Monthly mean			Mean daily flow (ft^3/s)	Difference (percent)	Mean daily flow (ft^3/s)	Difference (percent)
			r^2	E	RMSE (ft^3/s)	r^2	E	RMSE (ft^3/s)				
Sudbury River at Ashland (01097480)												
Observed	[1]54/59								[1]24/25		[1]114/134	
Simulated	57	2.6	0.60	0.50	38	0.72	0.70	24	26	8.3	99	-13
		-2.3	0.56	0.55	44	0.69	0.68	30		4.0		-26
May 1994 through September 1995 (period of measured streamflow)												
Observed	40								16		41	
Simulated	46	5.1	0.78	0.70	27	0.90	0.88	12	21	31	38	-7.3
Sudbury River at Saxonville (01098530)												
Observed	193								85		387	
Simulated	187	-5.9	0.53	0.49	143	0.68	0.68	90	92	7.5	275	-22
Assabet River at Maynard (01097000)												
Observed	201								92		433	
Simulated	208	3.4	0.52	0.48	39	0.72	0.72	90	107	16	354	-18
Nashoba Brook near Acton (01097300)												
Observed	19								7.1		42	
Simulated	19	0	0.31	0.23	24	0.68	0.67	10	9.3	31	33	-21

[1]A portion of the record was estimated, one was adjusted (DSN 30) and the other unadjusted (DSN 31) for high flows; the model-fit statistics that follow correspond to these data sets in sequential order.

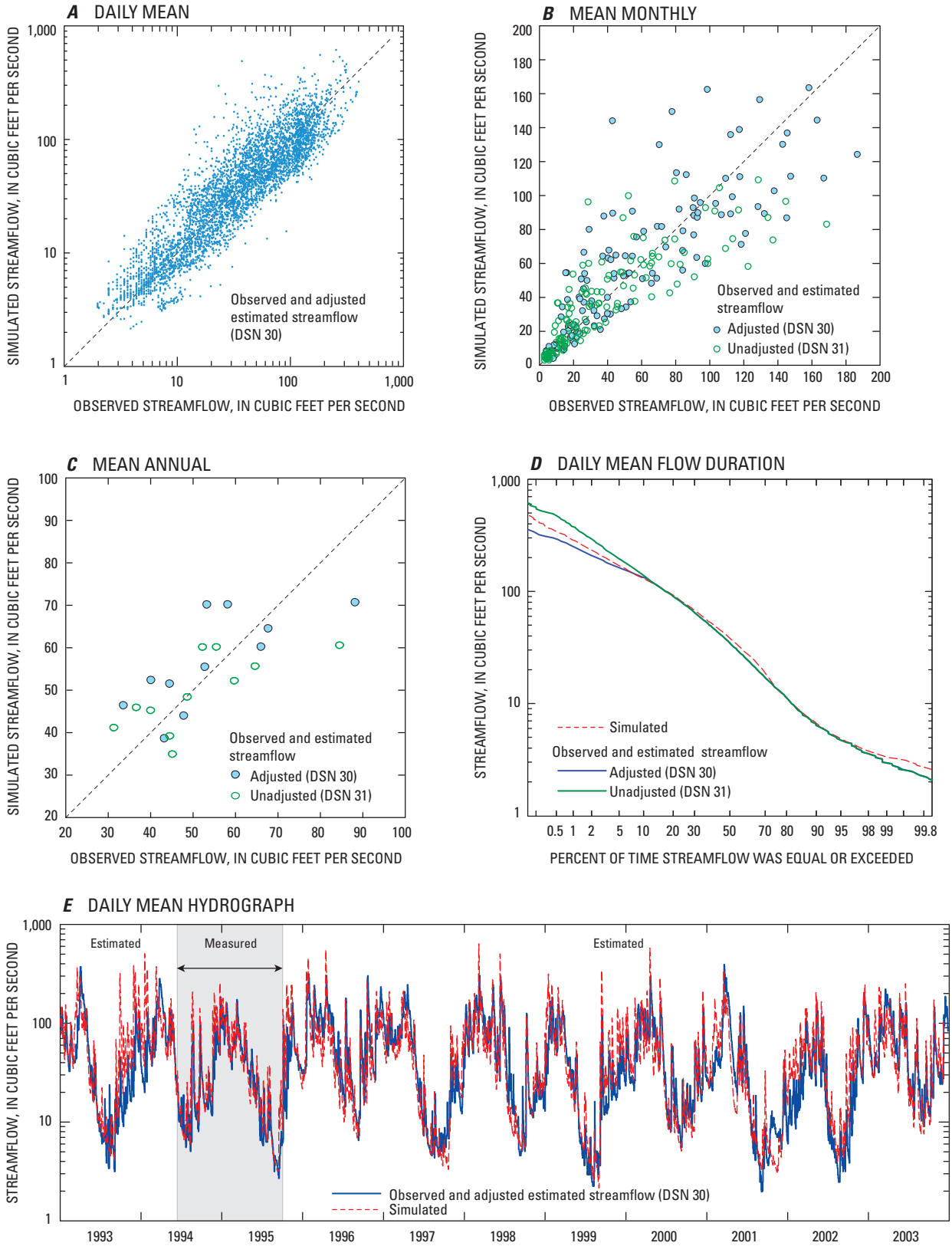


Figure 11. Simulated flow in relation to observed and estimated (adjusted and unadjusted for high flow) flow for (*A*) daily mean, (*B*) mean monthly, (*C*) mean annual, (*D*) daily mean flow-duration curves, and (*E*) daily mean hydrographs, at Sudbury River at Ashland, Massachusetts, 1993 to 2003 (01097480, RCHRES 9; fig. 9). (DSN, Data-set number in Watershed Data Management (WDM) database).

of 1994 and 1995). Again, it should be noted that the measurements of flows below 20 ft^3/s reported during this period were rated poor, which means the recorded values may differ from the actual values by more than 15 percent. In addition, precipitation during August 1994 at the Worcester station (data used for the simulation) was 1.16 to 2.54 in. greater than precipitation recorded at the surrounding stations, indicating precipitation from localized convective storms was unevenly distributed and could potentially result in an oversimulation of streamflow.

Sudbury River at Saxonville

Simulated streamflow in the Sudbury River at the Saxonville streamgage is generally in good agreement with observed flow over a wide range of flow conditions and seasons (fig. 12). Scatter plots of simulated flows in relation to observed flows (fig. 12 A–C) indicate a slight undersimulation of high flows and a slight oversimulation of low flows. Years with undersimulated or oversimulated flows are consistent with the difference in annual precipitation recorded at the Worcester station relative to precipitation recorded at nearby surrounding climate stations. Differences between simulated and observed flows may also be caused by uncounted transfers of water into the Sudbury Reservoir from outside the basin or by uncounted regulation of the Sudbury Reservoir system.

Daily mean flow hydrographs (fig. 12E) indicate the simulated flows vary more than the observed flows, suggesting a possible underestimation of storage in upstream reservoirs; however, when storage was added to the reaches representing the reservoirs, the daily mean flow-duration curve indicated an undersimulation of high flows and an oversimulation of moderate flows. Because of unknown reservoir operations, the storage-discharge representing the Sudbury reservoirs was adjusted to best fit the scatter of daily flows along the line of equality with observed flows (fig. 12A).

On average, the mean daily flow over the calibration period was undersimulated by about 5.9 percent (table 10), which is largely attributed to the representativeness of precipitation over the basin or inaccurate accounting of transfers of water into the basin, or both. Flows, on average, during spring months were undersimulated by about 22 percent and oversimulated by about 7.5 percent during the summer months. This difference also may be caused by unaccounted reservoir operations. The model fit for the daily mean and monthly mean flow had an r^2 of 0.53 and 0.68, respectively, and an E of 0.49 and 0.68, respectively; the RMSE was 143 and 90 ft^3/s, respectively (table 10).

Assabet River at Maynard

Simulated streamflow in the Assabet River at the Maynard streamgage is generally in good agreement with the observed flow over a wide range of flow conditions and seasons (fig. 13). The difference between simulated and observed flows over the calibration period for daily, monthly, and annual mean flows (fig. 13 A–C) was the most tightly grouped around the line of equality of the four main model calibration sites; this is believed to reflect the quality of the flow record and the lack of unaccounted flow regulation in the measured flows relative to the other calibration sites. Simulated and observed flow-duration curves are closely matched over the entire exceedence probability (fig. 13D).

On average, the mean daily flow over the calibration period was oversimulated by about 3.4 percent (table 10). In addition, the close agreement in simulated and observed mean daily flows is also attributed to a better representation of precipitation at the Worcester climate station for this part of the basin, which is geographically closer in position and elevation than the contributing areas to the other calibration sites. Flows, on average, were undersimulated by 18 percent during spring months and oversimulated by about 16 percent during the summer months. The model fit for the daily mean and monthly mean flow had an r^2 of 0.52 and 0.72, respectively, and an E of 0.48 and 0.72, respectively; the RMSE was 39 and 90 ft^3/s, respectively (table 10).

Nashoba Brook near Acton

Streamflows at Nashoba streamgage are affected by occasional regulation of an upstream pond that is unaccounted for in the model and by alteration of the stage-discharge relation by beavers, resulting in streamflow records that are often rated as poor during the calibration period, particularly at low flows. These factors are believed to be the primary reason for the large scatter between simulated and observed daily and monthly mean flows below 10 ft^3/s (fig. 14 A–B). Simulated and observed flow-duration curves (fig. 14D) are generally in close agreement, however.

On average, the simulated mean daily flow over the calibration period was the same as the observed (table 10). The model fit for the daily mean and monthly mean flow had an r^2 of 0.31 and 0.68, respectively, and an E of 0.23 and 0.67, respectively; the RMSE was 24 and 10 ft^3/s, respectively (table 10). Flows, on average, during spring months were undersimulated by 21 percent and oversimulated by about 31 percent during the summer months. Although the seasonal differences between simulated and observed flows at Nashoba Brook and Assabet River at Maynard streamgages are relatively consistent (table 10), the differences between streamgages were not always consistent from year to year or in relation to precipitation variability. For example, 1996 summer flows were consistently undersimulated by an average of about 11 percent at the Maynard streamgage and oversimulated by an average of 74 percent at the Nashoba streamgage. Spring flows in 2002, on average, were oversimulated by about 56 percent at the Maynard streamgage and undersimulated by about 1.1 percent at the Nashoba streamgage. Although the seasonal model errors are considered large at times, the inconsistent differences did not warrant further changes to the model because these changes could adversely affect the model calibration in the Sudbury River Basin.

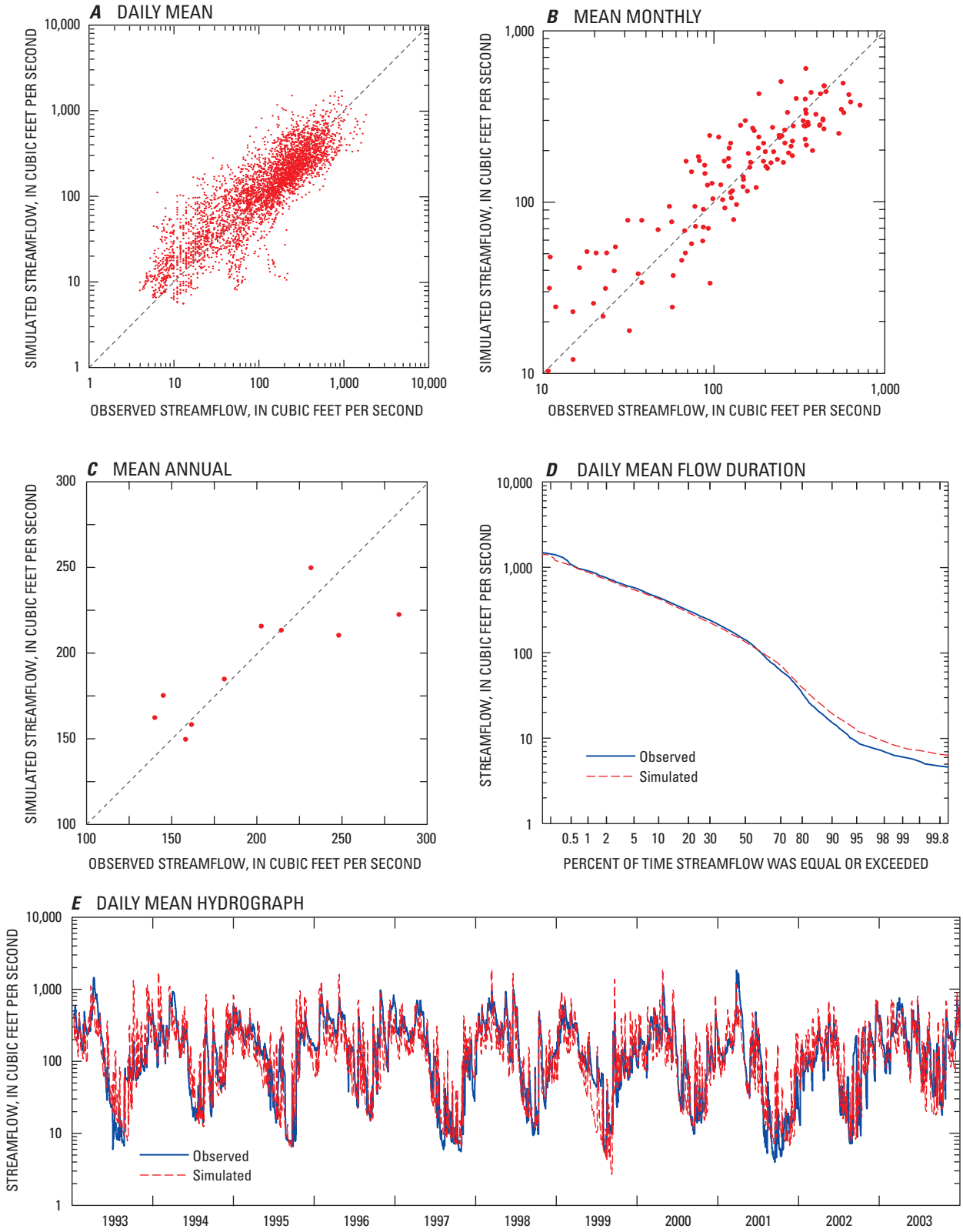


Figure 12. Simulated flow in relation to observed flow for (*A*) daily mean, (*B*) mean monthly, (*C*) mean annual, (*D*) daily mean flow-duration curves, and (*E*) daily mean hydrographs, at Sudbury River at Saxonville, Massachusetts, 1993 to 2003 (01098530, RCHRES 19; fig. 9).

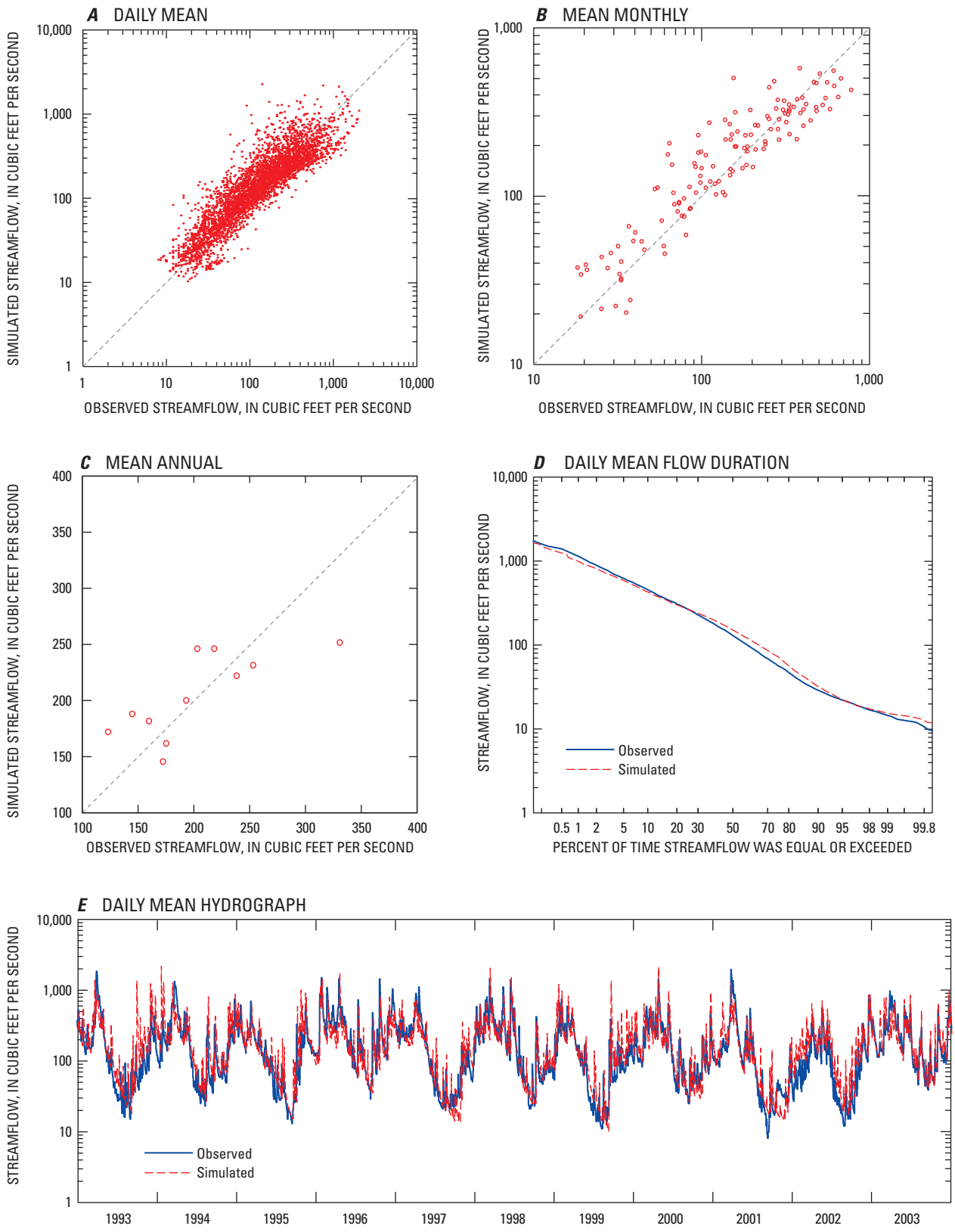


Figure 13. Simulated flow in relation to observed flow for (*A*) daily mean, (*B*) mean monthly, (*C*) mean annual, (*D*) daily mean flow-duration curves, and (*E*) daily mean hydrographs, at Assabet River at Maynard, Massachusetts, 1993 to 2003 (01097000, RCHRES 65; fig. 9).

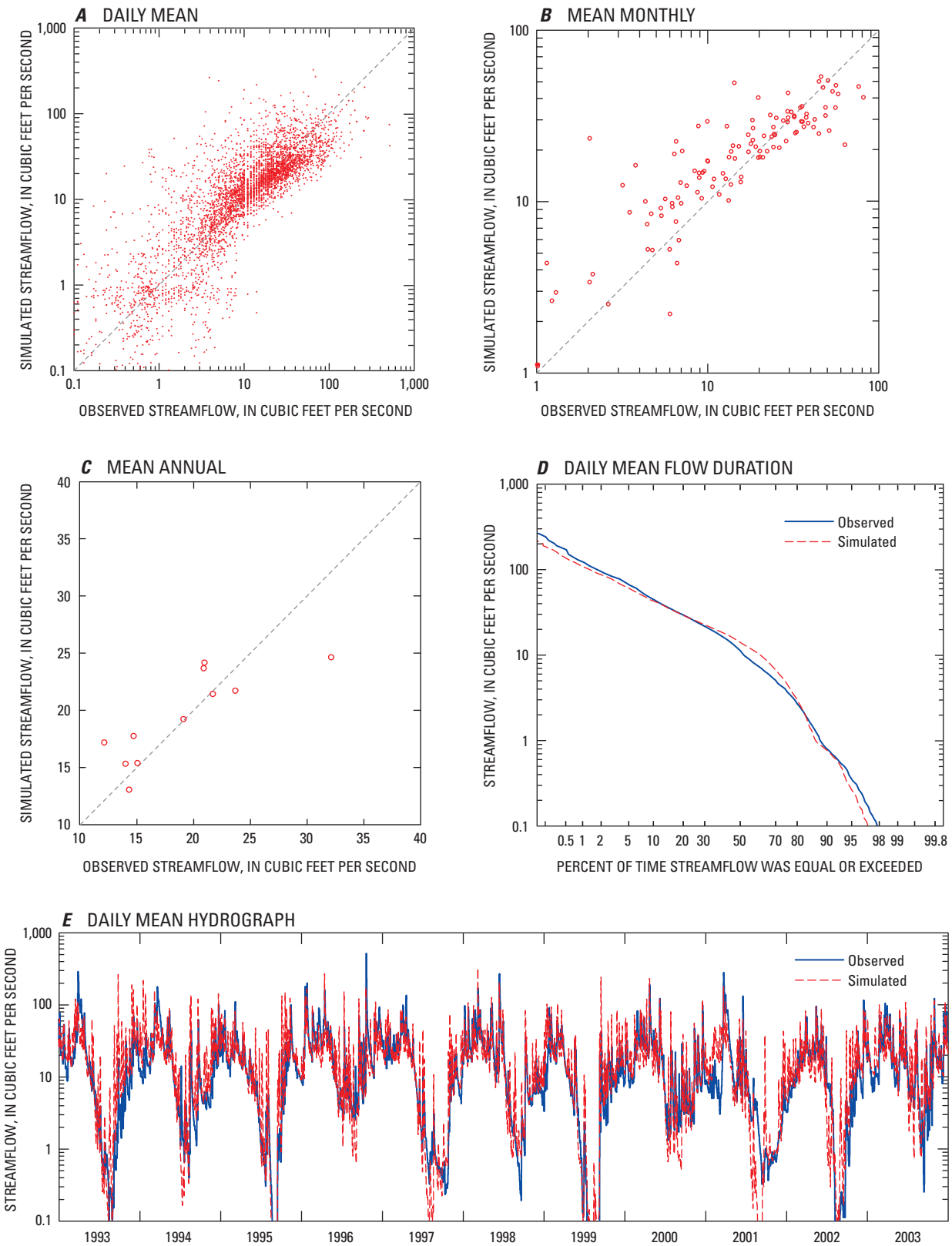


Figure 14. Simulated flow in relation to observed flow for (*A*) daily mean, (*B*) mean monthly, (*C*) mean annual, (*D*) daily mean flow-duration curves, and (*E*) daily mean hydrographs, at Nashoba Brook near Acton, Massachusetts, 1993 to 2003 (01097300, RCHRES 68; fig. 9).

Hydrologic Flow Components and Water Budgets

Discharge to streams and the loss of water through ET for each HRU compose the majority of the outflows in the water budget. Outflows are characterized by various hydrologic flow components that include discharge to streams through surface runoff, interflow, and active groundwater, and ET losses through interception, upper-zone, lower-zone, and active groundwater storages. These flow components are controlled by the variable values assigned to the HRUs. In addition to these components, the model also includes lateral inflows to lower-zone storage from areas served by public water with on-site septic and areas that lose water through sewer I&I. Outflow to streams and water losses by component are illustrated (figs. 15–17) for the various HRUs developed to simulate the Sudbury and Assabet River Basins. It should be noted that the HRU water budgets do not include the gains or losses in reaches, such as in large wetlands or water bodies that are specified as direct precipitation gains and evaporation losses, or from withdrawals from reaches.

Flow components for each of the HRUs were computed from the annual means for the calibration period (January 1993 through December 2003) and from the monthly means for March, the normal high-flow month, and August, the normal low-flow month, for the 1993–2003 period. Annual water budgets per unit area are generally similar for HRUs with similar surficial geology types, but still differ among land-use types (fig. 15A). Annually, discharge to streams per unit area from HRUs overlying sand and gravel averaged about 87 percent from active groundwater flow, about 13 percent from interflow, and a negligible amount from surface runoff. Discharge to streams from HRUs overlying till averaged about 50 percent from active groundwater, 38 percent from interflow, and 12 percent from surface runoff. Discharge components to streams from wetland HRUs are relatively evenly distributed between active groundwater flow, interflow, and surface runoff (about 30, 40, and 30 percent, respectively). All discharge to streams from impervious area HRUs (IMPLND) is from surface runoff.

On average, about 45 in. of precipitation fell on the basin during 1993–2003, of which about 49, 54, and 61 percent per unit area discharged to streams from HRUs overlying sand and gravel, till, and wetlands, respectively. The remainder was mostly lost to ET, per unit area, from lower-zone storage (LZET) that ranged from 24 to 19 percent for sand and gravel and till HRUs, respectively. ET loss per unit area from interception and upper-zone storages (CEPE and UZET, respectively) accounts for about 16 to 18 percent of the annual moisture supply to the basin. ET loss per unit area from active groundwater (AGWET) accounts for about 3 to 6 percent of the annual moisture supply to the basin.

Additional moisture supply on HRUs representing areas on public water and on-site septic systems is not directly represented in the water budgets shown on figure 15; rather, these gains are reflected in additional outflows to streams or ET losses relative to similar HRUs without these gains or losses. The additional moisture supply to areas on public water and on-site septic systems amounts to about 11 and 5.7 percent of the total mean annual precipitation during the 1993–2003 period in medium- and low-density residential HRUs, respectively. Water gains on these HRUs are represented as lateral inflows to lower-zone storage that do not discharge directly to streams; rather, it allows more precipitation on these HRUs to infiltrate and discharge to streams mostly as active groundwater. Discharge to streams from areas on public water and on-site septic compared to similar HRU types without lateral inflows increased the mean annual groundwater discharge, per unit area, by about 21 and 26 percent for medium-density residential areas overlying sand and gravel, and tills, respectively, and by about 10 and 12 percent for low-density residential area overlying sand and gravel, and tills, respectively. Interflow also increased slightly as a result of lateral inflows compared to similar HRU types by about 11 and 7 percent for medium-density residential areas overlying sand and gravel, and tills, respectively, and by about 6 and 3 percent for low-density residential areas overlying sand and gravel, and tills, respectively. The basin is comprised of about 4.0 and 3.6 percent medium- and low-density residential area on public water and on-site septic, respectively; the discharge to streams from lateral inflows from these areas was minor over the basin, accounting for less than 1 percent of the total discharge to streams.

On average, annual ET losses account for 40 to 50 percent of the moisture supply, per unit area. In areas served by public sewer, additional losses were simulated to account for sewer I&I; these losses were offset by decreases in active groundwater discharge to streams. Mean annual I&I loss is about 25 percent greater in sewered areas overlying sand and gravel than in sewered areas overlying till, per unit area. Excluding withdrawals, mean annual I&I loss accounted for about 2 percent of the total water loss from the basin; about 11 percent of the basin area is sewered.

Forested HRUs compose the major portion of the basin water budget (fig. 15B), expressed in inches over the basin, because forested HRUs represent about 48 percent of the total basin area. Forested HRUs contributed about 11 in. (44 percent), mostly from active groundwater, of the 24.7 in. of total mean annual discharge to streams. Discharge to streams from forested areas came predominantly from HRUs overlying till (5.7 in.) and about equal amounts from forested HRUs overlying sand and gravel, and forested wetlands (about 2.5 and 2.7 in., respectively). The amount of forested area over till is about the same as the combined forested area over sand and gravel and forested wetland. Combined, forested HRUs accounted for about 50 percent (10.6 in.) of the total ET losses (20.7 in.) from the basin. Mean annual loss from lower-zone storage was about equal to the combined losses from interception, upper-zone, and active groundwater storages.

During the normal seasonal high flow, the mean March discharge to streams is proportionally similar to the mean annual discharge to streams (fig. 16A). In HRUs overlying

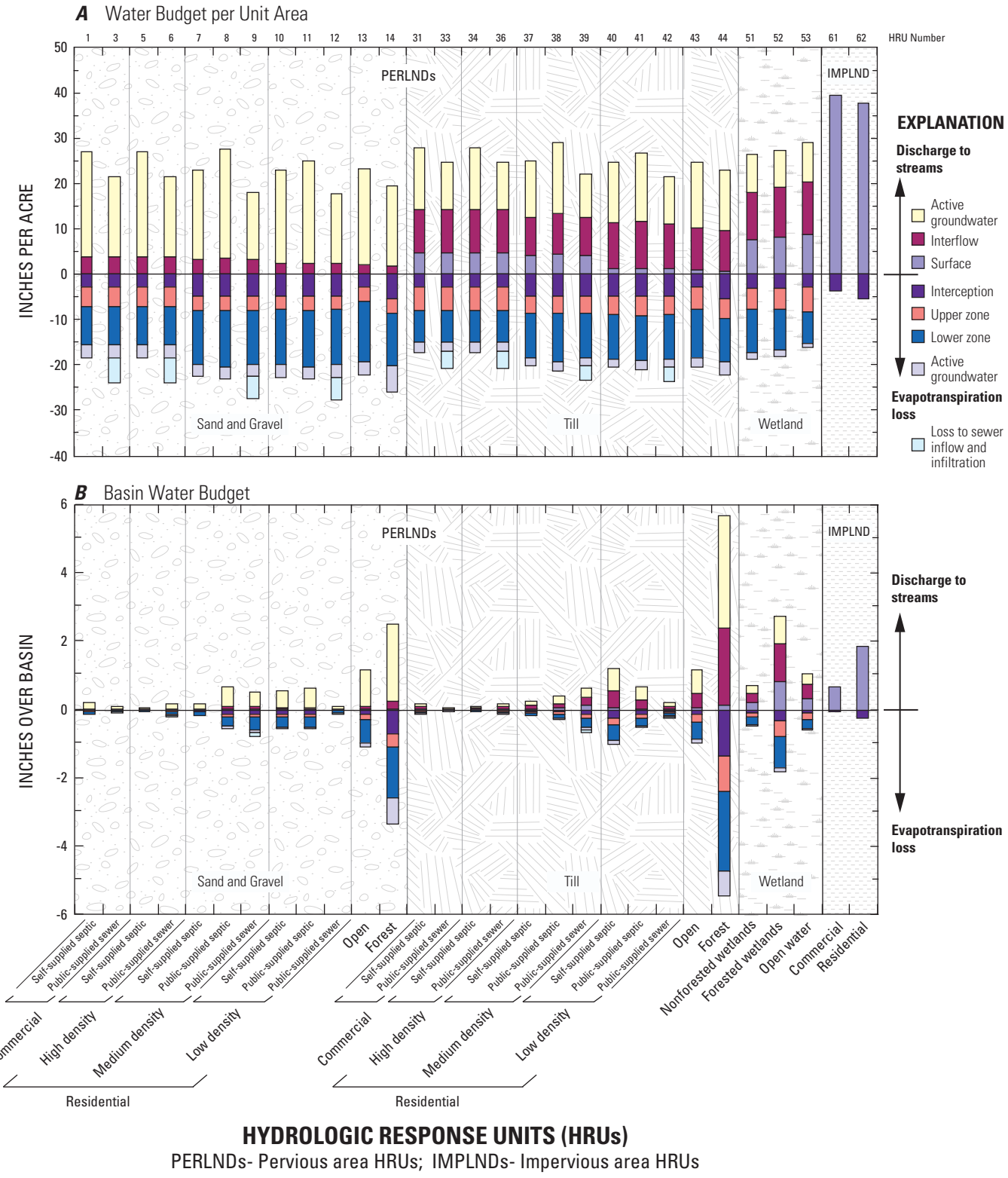


Figure 15. Mean annual 1993–2003 water-budget outflow components (*A*) in inches per acre and (*B*) in inches over the basin from each Hydrologic Response Unit (HRU) simulated by the Hydrological Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

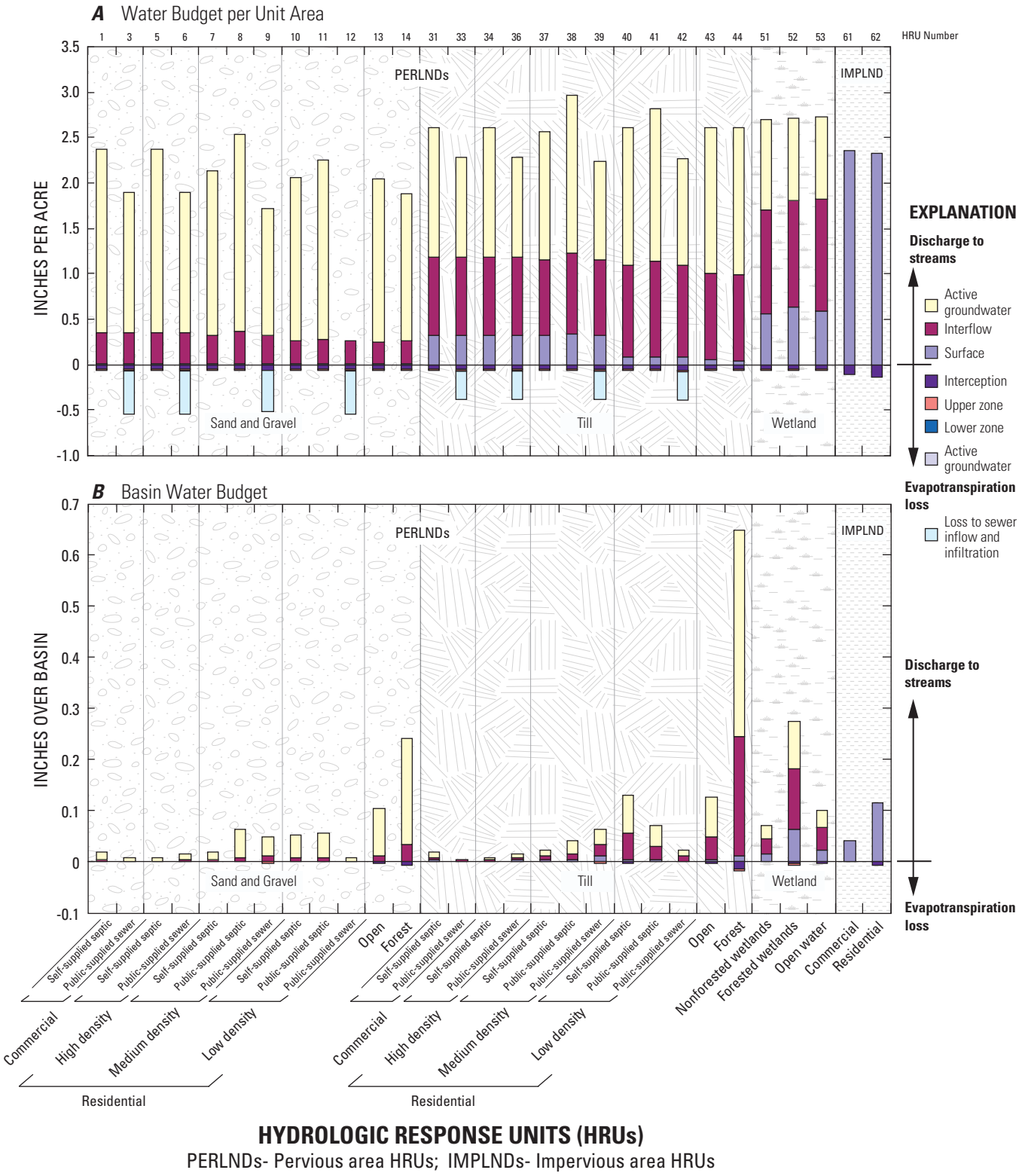


Figure 16. Mean 1993–2003 March water-budget outflow components (*A*) in inches per acre and (*B*) in inches over the basin from each Hydrologic Response Unit (HRU) simulated by the Hydrological Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

sand and gravel, discharge to streams per unit area averages about 80 percent from active groundwater flow, 20 percent from interflow, and a negligible amount from surface runoff. In HRUs overlying till, discharge to streams is about equally split between active groundwater flow and interflow (about 44 percent each), and 11 percent from surface runoff. Discharge to streams from wetland PERLND HRUs is relatively evenly distributed between active groundwater flow, interflow, and surface runoff (25, 45, and 29 percent, respectively). The water loss to ET during March differs appreciably from the mean annual ET losses, accounting for about 2 to 3 percent of the water budget per unit area. In HRUs where I&I loss is specified, the water loss per unit area accounts for 12 to 20 percent of the water budget in low- and medium-density residential areas, respectively.

The mean moisture supply to the basin during March 1993–2003 was about 4.3 in., and on average, about 57 percent was from precipitation and 43 percent was from snowmelt. Overall, on average, about 47 percent of the available moisture is discharged to streams (2.4 in.), about 1.6 percent is lost to ET (0.2 in.), and the remainder goes into storage (about 1.7 in.). Expressed in inches over the basin, about 48 percent of the average streamflow contribution comes from forested HRUs (fig. 16B), about half of which was from forested areas overlying till. Overall, discharge to streams in March was mostly from active groundwater (about 58 percent), followed by interflow (30 percent) and surface runoff (12 percent). ET losses were minor during March and were mostly from interception storage. In HRUs where I&I loss is specified, the water loss per unit area accounts for 14 to 27 percent of the water budget losses in low- and medium-density residential areas, respectively.

The mean August water budget per unit area during 1993–2003 (fig. 17A) is markedly different from the mean annual (fig. 15A) and March (fig. 16A) water budgets. Discharge to streams per unit area in August is mostly from active groundwater (about 80 percent), followed by interflow (about 14 percent) and surface runoff (about 6 percent). In HRUs representing areas overlying sand and gravel, active groundwater accounts for 99 percent of the discharge to streams.

During August 1993–2003, in inches over the basin (fig. 17B), the average combined discharge to streams (0.9 in.) and ET loss (4.6 in.) amount to nearly twice the average moisture supply to the basin (3.3 in.); the excess discharge and ET loss relative to the moisture supply reflect losses from storage mostly from the lower-soil zone. About 70 percent of total discharge to streams was from active groundwater mostly from forested HRUs. Water loss from I&I represents a small fraction (0.3 percent) of the total water loss during August.

The magnitude of simulated flow components, in inches over the basin, for the annual mean and the monthly means for March and August during 1993–2003 are readily apparent when compared side by side (fig. 18). Annually, the average total discharge to streams (24.7 in.) is about 20 percent more than the average total ET loss (20.7 in.); combined, they are about equal to the total average moisture supply to the basin (45.2 in). The slight discrepancy between moisture supply and the combined streamflow and ET loss is caused by lateral inflows to lower-zone storage that are not accounted for in the available moisture supply in these numbers (but are accounted for in the model) and minor change in storage components over the 1993–2003 period. The average March and average August water budgets stand out in sharp contrast to the annual average discharge to streams and ET losses and especially in contrast to each other. In March, the average discharge to streams is about 2.4 in. and losses to ET are about 0.1 in.; whereas, in August, the average discharge to streams is about 0.9 in. and losses to ET are about 4.6 in.

Sensitivity Analysis

Sensitivity analysis typically measures the response of the model-simulated discharges to changes in the value of variables representing the hydrologic processes in the basin. Thus, for the model structure under consideration, the most influential variables can be revealed by iteratively changing the value of a particular model variable.

The Sudbury and Assabet River Basins HSPF model structure and HRUs are similar to the HSPF models developed for the Ipswich River Basin (Zarriello and Ries, 2000) and the Usquepaug-Queen River Basin (Zarriello and Bent, 2004). Hydrologic budgets by flow component from these models indicate that the dominant discharge to streams is from active groundwater (AGWO) and interflow (IFWO) and the dominant loss of water is through ET from lower-zone storage. Therefore, the sensitivity analyses conducted for the Ipswich River Basin and Usquepaug-Queen models, which produced similar results, are considered applicable to the Sudbury and Assabet River Basin model. Details of iteratively changing HSPF variable values on various metrics of the model fit are given in tables for the Ipswich River Basin model (Zarriello and Ries, 2000) and graphically for the Usquepaug-Queen River Basin model (Zarriello and Bent, 2004).

In general, the Ipswich River and Usquepaug-Queen River Basin model sensitivity analyses indicated that the changes in the variables that affect groundwater and interflow recession cause the largest changes in various measures of model fit. The groundwater discharge to streams is most affected by the groundwater recession constant (AGWRC), the groundwater recession variable that determines the degree of nonlinearity of the recession rate (KVARY). The interflow discharge to streams is most affected by the coefficient that determines the amount of water that enters the ground from surface storage and becomes interflow (INTFLW) and the interflow recession constant (IRC). Uncertainties in these groundwater and interflow variables, thus, have a large effect on the performance of the HSPF model relative to most other model variables. Model results were also sensitive to changes in variables that determined the amount of precipitation that would eventually discharge as groundwater or interflow. These variables include the infiltration (INFILT), the lower-zone

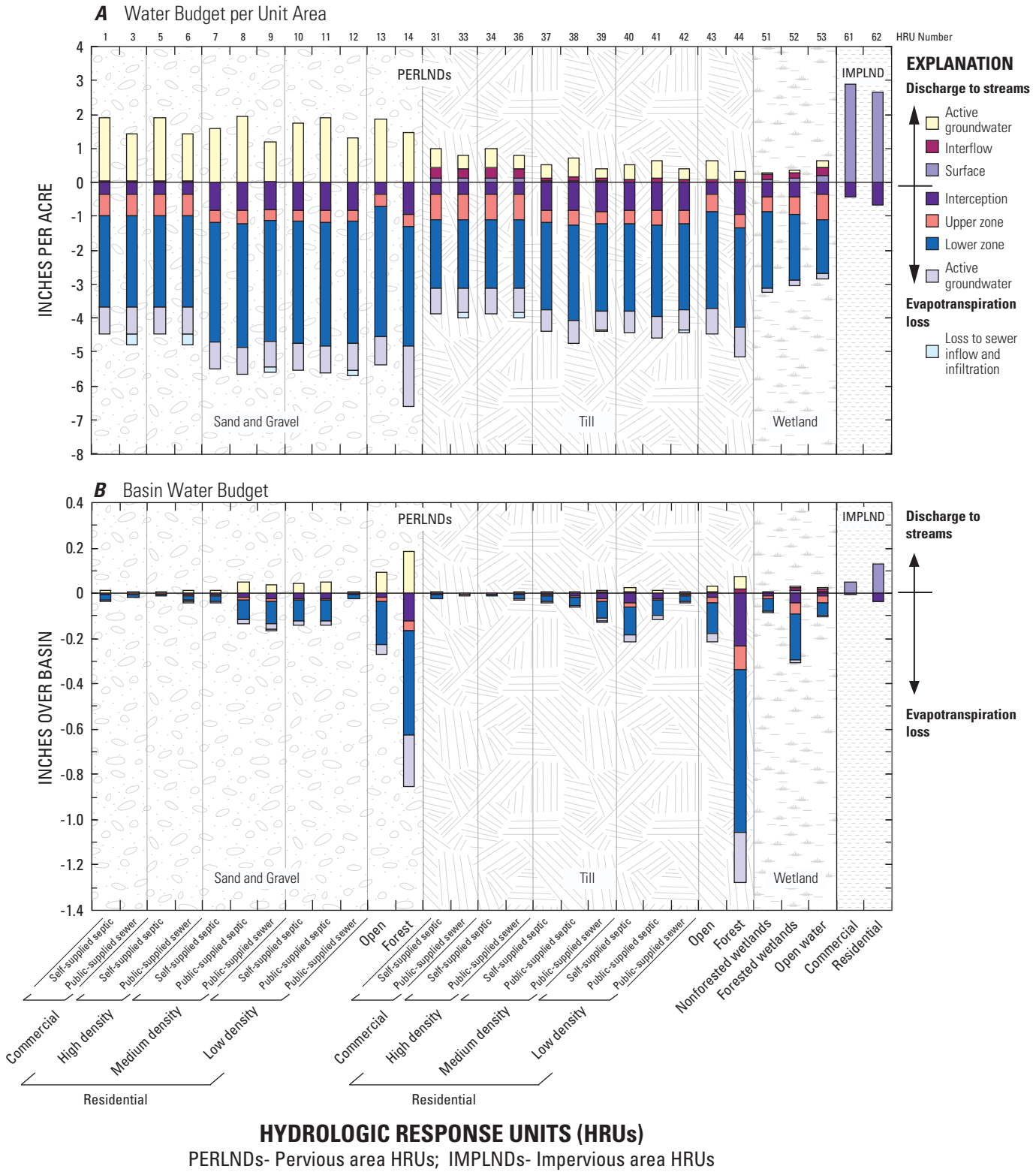


Figure 17. Mean 1993–2003 August water-budget outflow components (*A*) in inches per acre and (*B*) in inches over the basin from each Hydrologic Response Unit (HRU) simulated by the Hydrological Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

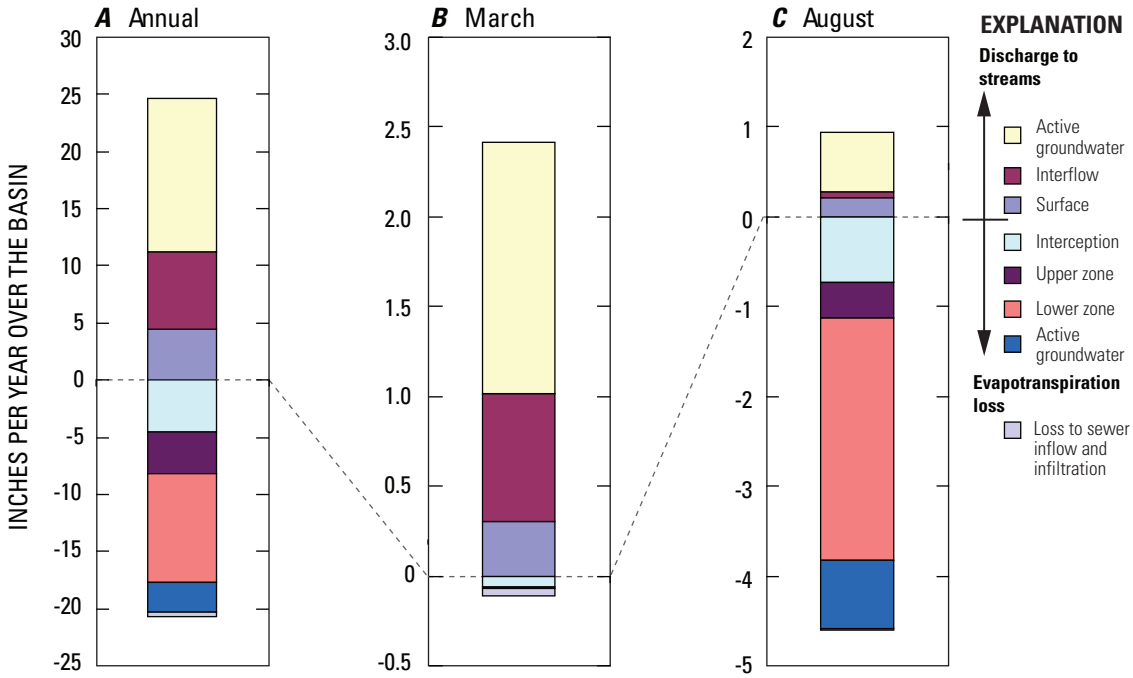


Figure 18. Summary of 1993–2003 mean (*A*) annual, (*B*) March, and (*C*) August water-budget outflow components simulated by the Hydrological Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

storage (LZSN), and the lower-zone ET (LZETP). LZETP is the dominant flow component during dry periods and exerts a large influence on other hydrologic components. More detailed explanation of all these variables can be found in Bicknell and others (2000). The Ipswich River Basin model analysis also indicated that model results were sensitive to how the wetlands were represented, especially during low-flow periods, because of differences in the amount of moisture supply available or ET.

Model Uncertainty and Limitations

The Sudbury and Assabet River Basins HSPF model should be used with an understanding of the model limitations, the uncertainty of the data used, and the possibility of alternate model structures. Numerical-simulation models use simplifications of complex hydrologic processes and physical basin characteristics to approximate streamflow in response to climatic conditions. Despite these limitations, models can be useful tools to evaluate the hydrologic responses of a basin, provided that the model structure and variable values adequately reflect the hydrologic responses of the system to the stresses evaluated. The uncertainty associated with data and the possibility that alternative model structures and variable values may produce similar results have been described by Beven (1993) and Beven and Binley (1992).The use of the climate data from the Worcester NWS station, located about 20 mi west of the study basin, has been shown to affect the model calibration. Extrapolation of a point measurement to define spatially varied precipitation and potential ET over the basin adds uncertainty to the identification of the best-fit variable values. For example, the lowest flows during the calibration period were in 1999. Total precipitation between May 29 and June 28, 1999, of 0.13 in. recorded at the Worcester NWS station (data used for model calibration) is less than the 0.23, 0.17, and 0.21 in. recorded at daily precipitation stations closer to the basin (Bedford, Natick, and West Medway, respectively). The spatial precipitation differences could explain some of the difference between simulated and observed flows during this time. Additionally, model variables that control the rate of ET loss could have been skewed to compensate for spatial differences in precipitation. This is one example of how the representativeness of a point value can influence the performance of a model that spans a large area.

Water-use information is another area of data uncertainty. Known water withdrawals are subtracted directly from simulated streamflow. Once withdrawals are accounted for, the model variable values are adjusted to calibrate the response of the basin to precipitation and ET. Unaccounted withdrawals, or inaccurate withdrawal information, can skew model variable values to compensate for these data deficiencies

during the calibration process. In addition, the model does not account for withdrawals in excess of streamflow, which means the simulated amount of water withdrawn does not exceed streamflow to maintain the mass balance of water. Withdrawals in excess of streamflow can be represented in the HSPF model through the use of Special Actions (Zarriello and Ries, 2000) that accounts for withdrawals in excess of streamflow and satisfies the excess withdrawals by decreasing streamflow later when it rises above the withdrawal rate as a surrogate measure of lost groundwater-storage and replenishment. This feature was not utilized in the Sudbury and Assabet River Basin HSPF model because it adds complexity to the model and was not considered a factor in most reaches. Where withdrawals deplete groundwater storage, streamflow may be oversimulated at times because the process of replenishing lost storage is not simulated; this condition is mostly a factor in headwater basins where the ratio of withdrawals to streamflow is largest.

The HRUs are simplifications of hydrologically complex and spatially variable land use, soils, surficial-geology types, and anthropogenic infrastructure. The model calibration reflects the combined interaction of various HRUs (PERLNDs and IMPLNDs) and reaches. Best hydrologic judgment was used to represent the responses of different PERLND and IMPLND HRUs. Although a reasonable fit was generally obtained between simulated and observed flows over a wide range of conditions, information was not available to calibrate individual HRUs explicitly. Thus, simulation results from ungaged areas or those that reflect changes of one type of HRU to another (such as projected 2030 land-use changes) have a high degree of uncertainty, and therefore, simulated flows for different scenarios are best viewed as a relative change instead of an absolute value.

Uncertainty in the stage, storage, and discharge characteristics of reaches (including wetlands) affects simulated streamflow and stage. These characterizations are determined from measured channel geometry to the extent possible, but many factors, such as channel roughness and the large number of changes in channel geometry along a river reach, could not be measured. Uncertainties in the reach stage-storage-discharge relation could be a factor in simulated flows in the late summer of 1999 at Sudbury River near Hopkinton at Fruit Street (RCHRES 5, WBHK; fig. 9), which reached a minimum of 0.2 ft^3/s (the lowest flow simulated during the calibration period) that is nearly consistent with an observation of no flow reported by the Sudbury River Watershed Organization (Frederica Gillespie, Sudbury River Watershed Organization, written commun., June 2004). The small difference between simulated and observed flows could also be attributed to underflow, or subsurface flow, at an observation point. In HSPF, water that flows to a reach as baseflow or interflow is routed downstream through the reach channel; however, under certain geohydrologic settings, a portion of groundwater may continue to pass an observation point through the subsurface. As a result, during very low flows, the model may appear to oversimulate flow in the reach that could be unaccounted underflow at the streamgage.

The HSPF model was conceptualized and calibrated to evaluate the effects of withdrawals on streamflow. Many water-resource-management questions can be addressed by model simulations, but the model may not be appropriate for some analyses. For example, groundwater withdrawals were represented in the model by an analytical solution that may not represent the actual flow path or source of water to a well. A pumped well that captures groundwater from an adjacent basin or subbasin could result in oversimulated flows in one basin and undersimulated flow in the other basin. As with all models, care should be taken to consider the model uncertainties and limitations to ensure that the simulation results do not lead to inaccurate conclusions.

Simulated Effects of Water Use and Land Use on Streamflow

Model results provide a quantitative assessment of flow and flow alterations under various conditions. Although measured data are preferable, obtaining data takes considerable time and expense, and often the data are not available in the time needed to make appropriate planning decisions. Further, the data represent the climate and withdrawal conditions under which the data were collected, often making the evaluation of water-management alternatives difficult because conditions can change over time. Use of simulated flows is often the only practical means to evaluate the effects of water-management practices over a wide range of climatic conditions.

Although many types of hydrologic issues or questions can be posed within the bounds of the model's limitations and uncertainties, the initial application of the model was limited to six scenarios agreed to by the Technical Advisory Committee (TAC). In addition to these scenarios, six additional simulations were made to examine projected 2030 water- and land-use change on streamflow and the effects of reactivating production wells near the northern end of Lake Cochituate. These scenarios entailed various combinations of land-use and water-use change simulated with an hourly time step over a wide range of climate conditions spanning the 1960–2004 period. Simulation focused on the upper Sudbury River Basin (area above the Saxonville streamgage—01097300; fig. 9), where flows were of greatest concern; however, the model was constructed to output results for any of the subbasins represented in the Sudbury and Assabet River Basins, with the exception of the land-use change simulations that were limited to the upper Sudbury River Basin and the simulations of reactivating production wells near Lake Cochituate.

Each scenario required modification of the calibrated model to change water-use rates or HRUs representing land-use change, or both. Each scenario is uniquely identified by the *uci* file name, the IDSCEN attribute, and the data-set number (table 11). The two baseline simulations characterize

Table 11. Summary of model-run files (*uci*) and target data-set numbers (DSNs) for output of Hydrologic Simulation Program–FORTRAN (HSPF) results of the Assabet and Sudbury River Basin, Massachusetts.

[IDSCEN, scenario-identification attribute in the Watershed-Data-Management (WDM) database; water use refers to withdrawals and return flows]

uci and IDSCEN name	Output DSN	Description
		Baseline simulations–1999 land use
AVGWU	6101–6173	Average 1993–2003 water use
NOWU	6201–6273	No water use (no withdrawals, return flows, or imports and exports)
		1999 land use and specified water-use change
GWoWU	6301–6373	Groundwater withdrawals only (surface-water withdrawals stopped)
SWoWU	6401–6473	Surface-water withdrawals only (groundwater withdrawals stopped)
		Projected 2030 water-use or land-use conditions, or both
30WU99LU	6501–6573	2030 water use and 1999 land use
30WULU	6601–6673	2030 water use and land use (limited to upper Sudbury River Basin)
30WULUalt	6701–6773	2030 water-use alternative (distributed water use–20 percent consumptive loss) and 2030 land use
30WUa99LU	6801–6873	2030 water-use alternative (distributed water use–20 percent consumptive loss) and 1999 land use
		Reactivation of Framingham Birch Road supply wells
BIR_LC	6901–6904	Assumes all water is from Lake Cochituate
BIR_LC66	6906–6909	Assumes two thirds of the water is from Lake Cochituate and the remainder is from Sudbury River
BIR_LC33	6911–6914	Assumes one third of the water is from Lake Cochituate and the remainder is from Sudbury River
BIR_SU	6916–6919	Assumes all water is from Sudbury River

long-term streamflow under current (1993–2003) average water-use conditions (AVGWU) and under no water use (NOWU). The NOWU simulation approximates a natural flow condition in which withdrawals and wastewater return flows are removed from the simulation; however, the 1997 land-use conditions represented in the calibrated model were not changed. The AVGWU simulation reflects the average calibration period (1993–2003) withdrawals and return flows. These flows were averaged by month and repeated over the simulation period, except for the calibration period, in which the actual water-use information was used. The NOWU simulation affects point withdrawals, point return flows, and distributed water gains or losses incorporated into HRUs associated with water supply or wastewater infrastructure, including water imports in areas on public-water supply and on-site septic, and water exports from sewer I&I losses; flow alterations that result from these features were essentially turned off.

Effects of Current Water Use on Streamflow

Streamflow simulated with no withdrawals, I&I loss, or return flows (NOWU) relative to average 1993–2003 conditions (AVGWU) provides a relative basis for comparison of other simulation results. Average annual withdrawal in 1993–2003 in the upper Sudbury River Basin varied; withdrawals occurred in 8 of the 19 subbasins and ranged from about 0.001 to 2.92 Mgal/d with a median annual withdrawal of 0.48 Mgal/d (table 12). The degree to which streamflow is affected by withdrawals is determined by the magnitude of the withdrawals relative to the flow in the reach. Hence, reaches most susceptible to flow alteration are in headwater basins, but the effects of withdrawals can be transmitted downstream for some distance depending on the magnitude of the losses relative to the gains in streamflow.

The change in AVGWU simulated streamflows relative to NOWU simulated streamflows was most pronounced in Piccadilly Brook (PBWB, RCHRES 2) and Jackstraw Brook (JBWB, RCHRES 1). These are relatively small headwater subbasins where the ratios of mean annual withdrawals to mean annual streamflow are the highest in the basin (0.25 and 0.48, respectively). Daily mean flow-duration curves (fig. 19A and B) developed from the 1960–2004 simulated flows indicate that AVGWU simulated flows begin to noticeably depart from NOWU simulated flows at about the 20- to 30-percent exceedence interval and are appreciably altered by about the 50-percent exceedence interval. AVGWU simulated flows are less than 0.01 ft^3/s about 20 percent of the time in Jackstraw Brook and about 30 percent of the time in Piccadilly Brook, whereas NOWU simulated flows maintain a minimum flow of about 0.05 ft^3/s in both brooks.

Table 12. Water-use change by reach from average 1993–2003 withdrawals to projected 2030 demands simulated in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the Sudbury and Assabet River Basins, Massachusetts.

[External target is the file read from the Watershed Data Management (WDM) database that reflects withdrawals from a reach; withdrawals in million gallons per day]

Reach number	Average annual withdrawals				Distributed demand with 80-percent return	
	1993–2003	2030	Percent change	External target multiplier	2030 annual withdrawal	External target multiplier
Sudbury River Basin						
1	0.476	0.549	15	1.152	0.491	1.030
2	0.774	0.899	16	1.161	0.799	1.032
3	0.234	0.258	10	1.101	0.239	1.020
5	0.490	0.567	16	1.157	0.505	1.031
8	1.436	1.760	23	1.227	1.441	1.003
9	0.001	0.000	-100	0.0	0.030	[1]0.0209
10	0.016	0.000	-100	0.0	0.030	[1]0.0209
17	2.925	3.132	7.1	1.071	2.966	1.014
31	1.061	1.182	11	1.114	1.085	1.023
32	1.423	1.594	12	1.120	1.458	1.024
33	2.974	3.305	11	1.111	3.040	1.022
Assabet River Basin						
51	0.727	0.838	15	1.153	0.749	1.031
52	0.006	0.006	0	1.000	0.006	1.000
53	0.366	0.399	9.1	1.091	0.373	1.018
54	0.616	0.692	12	1.122	0.631	1.024
55	0.198	0.227	15	1.146	0.204	1.029
56	1.386	1.386	0	1.000	1.386	1.000
58	0.135	0.151	12	1.119	0.138	1.024
60	0.002	0.002	0	1.000	0.002	1.000
61	1.599	1.769	11	1.106	1.633	1.021
62	0.244	0.244	0	1.000	0.244	1.000
63	0.002	0.002	0	1.000	0.002	1.000
64	0.525	0.570	8.6	1.086	0.534	1.017
66	1.141	1.309	15	1.147	1.175	1.029
67	0.672	0.783	16	1.165	0.694	1.033
68	0.364	0.426	17	1.170	0.377	1.034
69	0.620	0.667	7.6	1.076	0.629	1.015

[1]Multiplier applies to projected municipal demand from reach 8.

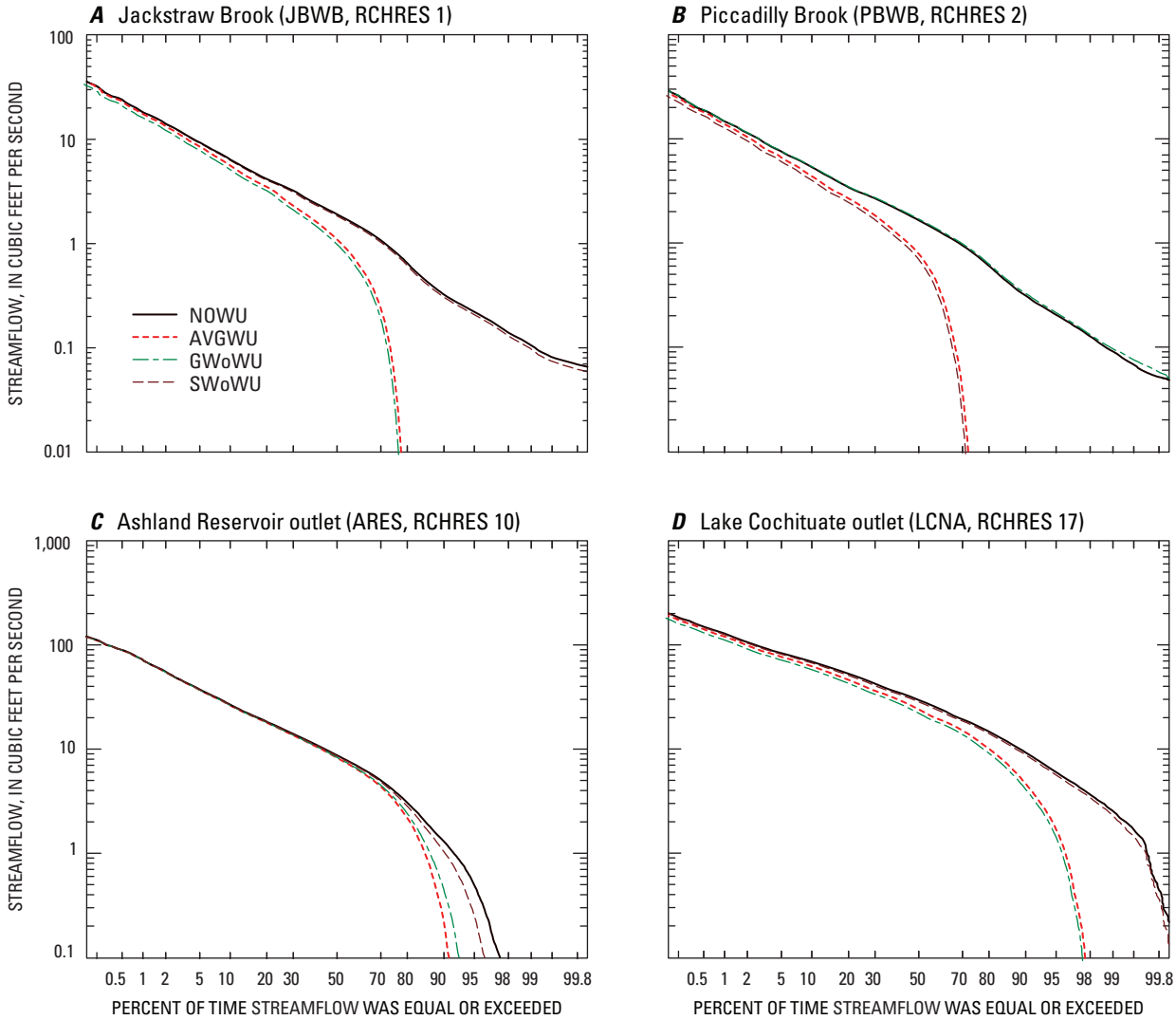


Figure 19. Daily mean flow-duration curves from long-term (1960–2004) simulations with no withdrawals (NOWU), average 1993–2003 withdrawals (AVGWU), groundwater-only withdrawals (GWoWU), and surface-water-only withdrawals (SWoWU) at (*A*) Jackstraw Brook (JBWB, RCHRES 1), (*B*) Piccadilly Brook (PBWB, RCHRES 2), (*C*) Ashland Reservoir Outlet (ARES, RCHRES 10), and (*D*) Lake Cochituate outlet (LCNA, RCHRES 17), upper Sudbury River Basin, Massachusetts. Locations are shown in figure 9.

The change in AVGWU simulated streamflows relative to NOWU simulated streamflows was also appreciable at the Ashland Reservoir outlet (ARES, RCHRES 10) and Lake Cochituate outlet (LCNA, RCHRES 16). Although these reaches drain larger areas than Jackstraw and Piccadilly Brooks, the ratios of mean annual withdrawals to mean annual streamflow are also high for Lake Cochituate outlet (0.13) and seasonally high for Ashland Reservoir outlet. Withdrawals from the Ashland Reservoir subbasin are mostly for irrigation; thus, on an annual basis, the ratio of mean annual withdrawals to mean annual streamflow is low (0.002), but during the peak irrigation period (June through August), the ratio of withdrawals to streamflow is large (0.13). Daily mean flow-duration curves (fig. 19C and D) developed from the 1960–2004 simulated flows indicate that flows under AVGWU conditions begin to noticeably depart from NOWU flows at about the 70-percent exceedence interval. AVGWU simulated flows are less than 0.1 ft^3/s about 10 percent of the time in Ashland Reservoir outlet (fig. 19C) and about 2 percent of the time in Lake Cochituate outlet (fig. 19D). Under NOWU simulated flows, Lake Cochituate outlet maintains a minimum flow of about 0.2 ft^3/s, whereas Ashland Reservoir outlet flows fall below 0.1 ft^3/s about 2 percent of the time.

Flows are better sustained under NOWU in Jackstraw and Piccadilly Brooks than in Ashland Reservoir and Lake Cochituate outlets because of subtle differences in basin

characteristics. Jackstraw and Piccadilly Brooks maintain about the same minimum flow when normalized for drainage area (about 0.46 and 0.41 $ft^3/s/mi^2$, respectively); each of these subbasins has a comparable percentage of contributing area of sand and gravel (18 percent each), forest (51 and 60 percent, respectively), and wetlands (8.2 and 5.1 percent, respectively). Although the percentages of the drainage area underlain by sand and gravel, which generally helps sustain low flows relative to other areas, are larger in the Ashland Reservoir and Lake Cochituate outlet subbasins (29 and 40 percent, respectively) than in Jackstraw and Piccadilly Brooks, the area of lakes and wetlands, which generally loses a greater amount of water to ET relative to other areas, is greater in Ashland Reservoir and Lake Cochituate outlet subbasins (16 and 18 percent, respectively) compared to Jackstraw and Piccadilly Brooks. Moreover, flow in the Ashland Reservoir and Lake Cochituate outlets is affected by large surface-water bodies and wetland areas (4.7 and 16 percent of the subbasin area, respectively) that are represented in the model as RCHRESs (10 and 17, respectively), which receive direct precipitation and lose water at the potential evaporation rate. This allows for greater evaporation loss per unit area in the Ashland Reservoir and Lake Cochituate outlet subbasins resulting in lower flows per unit area relative to the Jackstraw and Piccadilly Brooks, in which ET losses were limited by water availability in HRUs representing open water and wetlands.

The effects of withdrawals on streamflow in other subbasins in the upper Sudbury River Basin are less pronounced than those shown for Jackstraw and Piccadilly Brooks, and Ashland Reservoir and Lake Cochituate outlets (fig. 19). In other subbasins, the largest differences in streamflow with and without withdrawals are in reaches immediately downstream from the four reaches noted above. To illustrate the effects of withdrawals over the entire upper Sudbury River Basin, the change in streamflow under average 1993–2003 withdrawals (AVGWU) relative to no withdrawals (NOWU) is shown for the mean annual flow (fig. 20) and for the median of the August mean flow (fig. 21) simulated over the 1960–2004 period.

Withdrawals decreased the mean annual streamflow in the upper Sudbury River subbasins from 0.6 to 31 percent—the largest changes are in Piccadilly Brook (31 percent; PBWB, RCHRES 2), Jackstraw Brook (24 percent; JBWB, RCHRES 1), Indian Brook (17 percent; IBAS, RCHRES 8), and Lake Cochituate outlet (15 percent; LCNA, RCHRES 17), followed by reaches immediately downstream from these reaches (fig. 20). Minor changes between simulations with and without withdrawals are indicated in subbasins with no withdrawals because these reaches are affected by upstream reaches or by small I&I losses to sewer lines, or both.

The effects of withdrawals on streamflow are generally more pronounced in the summer low flows as indicated by the median of the August mean flows, which decreased from 83 to 0 percent (fig. 21). The largest changes in streamflow are generally in the same reaches as previously noted, except for Ashland Reservoir outlet (ARES, RCHRES 10), which now ranks among the reaches most affected by withdrawals because of the seasonal irrigation use. The median of the August mean flows with and without withdrawals decreased by 83 percent in Piccadilly Brook (PBWB, RCHRES 2), 67 percent in Jackstraw Brook (JBWB, RCHRES 1), and 31 percent in Lake Cochituate outlet (LCNA, RCHRES 17). Similar to the changes in the mean annual flow, changes in the median of the August mean flows with and without withdrawals in most other reaches reflect the cumulative effects of withdrawals on streamflow or small I&I losses to sewer lines, or both.

At Ashland Reservoir outlet (ARES, RCHRES 10), simulations with and without withdrawals indicate the median of the August mean flows decreased by 34 percent, whereas the mean annual flows decreased by only 4.4 percent. Withdrawals within the Ashland Reservoir subbasin are mostly for irrigation and, thus, are typically at a maximum during August when streamflow is typically at a minimum. As a result, differences between median of the August mean flows with and without withdrawals are large relative to differences in the annual mean flows with and without withdrawals.

At Indian Brook (IBAS, RCHRES 8), simulations with and without withdrawals indicate a large change (-17 percent) in mean annual flows (fig. 20) relative to the change (-5.0 percent) in the median of the August mean flows (fig. 21). Streamflow in the lower part of Indian Brook (IBAS, RCHRES 8) is affected by Hopkinton Reservoir, which is a State recreational resource. The reservoir outflow can be regulated but was assumed to be released through a lower outflow gate at a relatively constant rate of 2 ft^3/s when the water level in the reservoir falls below its spillway (outflows from the reservoir still decrease somewhat as the head in the reservoir drops). The flow-duration plot (fig. 22) indicates that streamflow below the reservoir is maintained at 2 ft^3/s or more about 80 percent of the time under NOWU and about 65 percent of the time under AVGWU. The relatively small change in the median of the August mean flow under NOWU (2.0 ft^3/s) and under AVGWU (1.9 ft^3/s) likely reflects a change in reservoir storage because withdrawals from supply wells adjacent to the reservoir typically peak during August. Streamflow in RCHRES 8 over 1960–2004 averaged about 11 and 13 ft^3/s with and without withdrawals, respectively; flows of this magnitude affect the flow-duration curve, but the difference between duration curves continues to widen (fig. 22) as streamflow decreases until the lines converge corresponding to the release from the lower outflow gate of the reservoir (about 2 ft^3/s). It should be noted that releases from the reservoir can be regulated for recreation or other purposes and that downstream flows can be appreciably altered in response to this regulation.

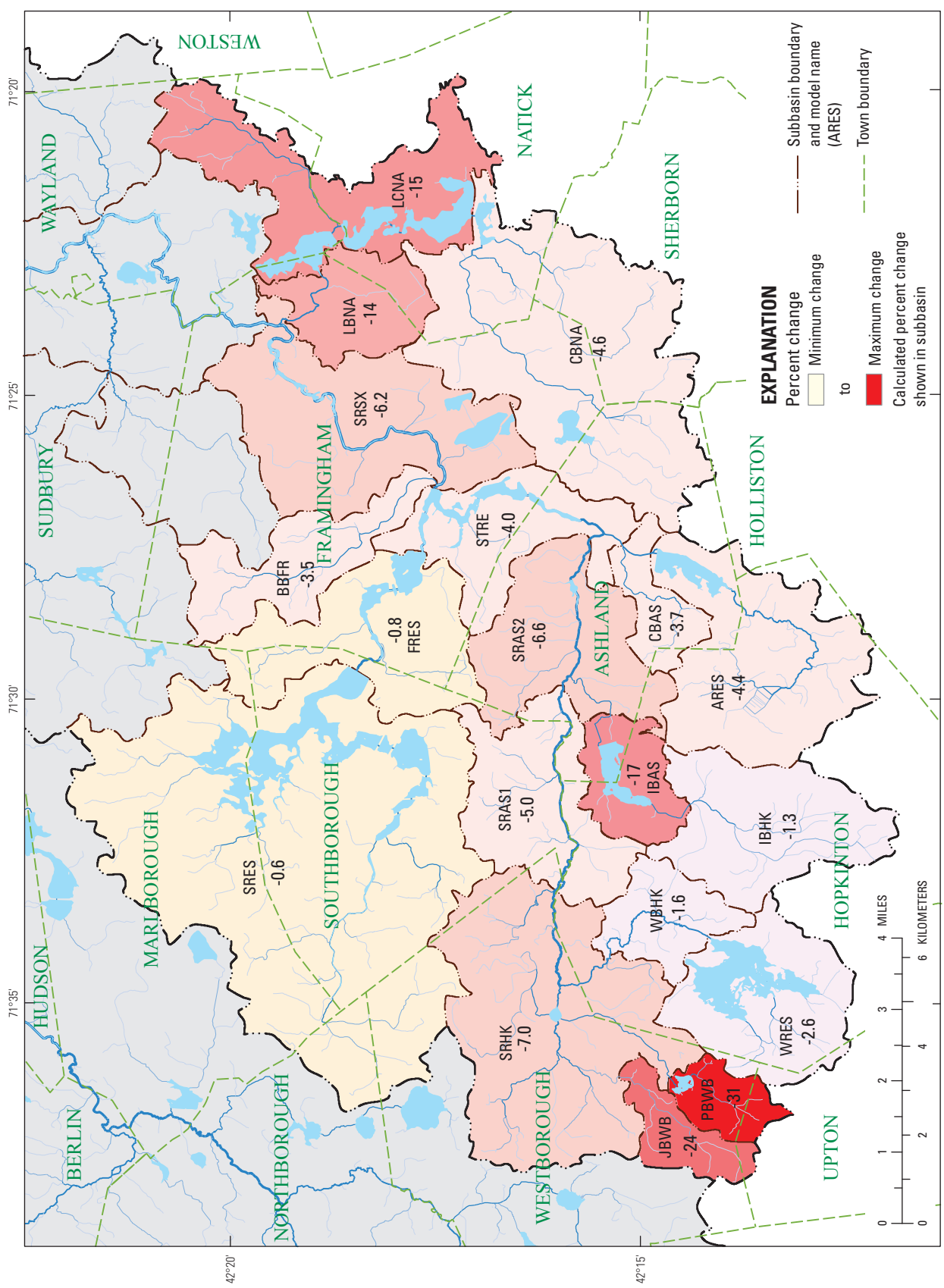
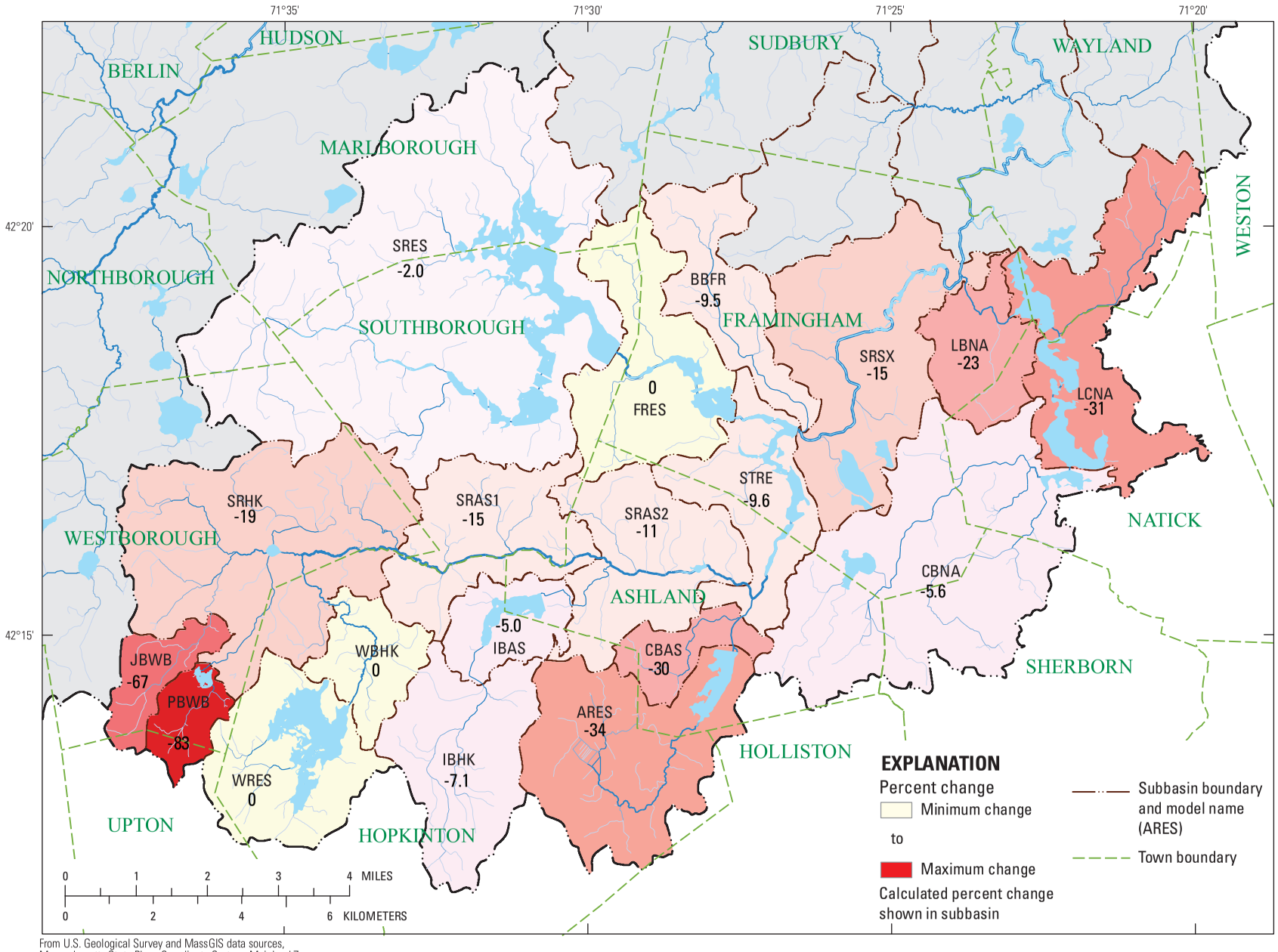


Figure 20. Percent change in the simulated long-term (1960–2004) mean annual streamflows with average 1993–2003 withdrawals (AVGWU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.



From U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone Polyconic projection

Figure 21. Percent change in the simulated long-term (1960–2004) median of the August mean streamflows with average 1993–2003 withdrawals (AVGWU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.

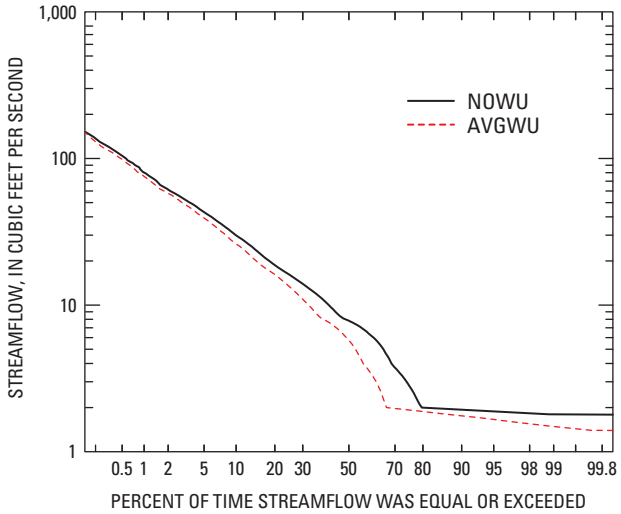


Figure 22. Daily mean flow-duration curves from long-term (1960–2004) simulations with no withdrawals (NOWU) and average 1993–2003 withdrawals (AVGWU), at Indian Brook (IBAS, RCHRES 8), upper Sudbury River Basin, Massachusetts. Location is shown in figure 9.

Effects of Groundwater and Surface-Water Withdrawals on Streamflow

Groundwater-only (GWoWU) and surface-water only (SWoWU) withdrawals were simulated to isolate their effects on streamflow. These simulations held return flows, net water gains through public water supply and on-site septic, and net I&I losses the same as the AVGWU scenario. Most of the upper Sudbury River Basin is unaffected by these factors, but additional changes to the model *uci* file may be warranted when simulating other parts of the Sudbury and Assabet River Basins.

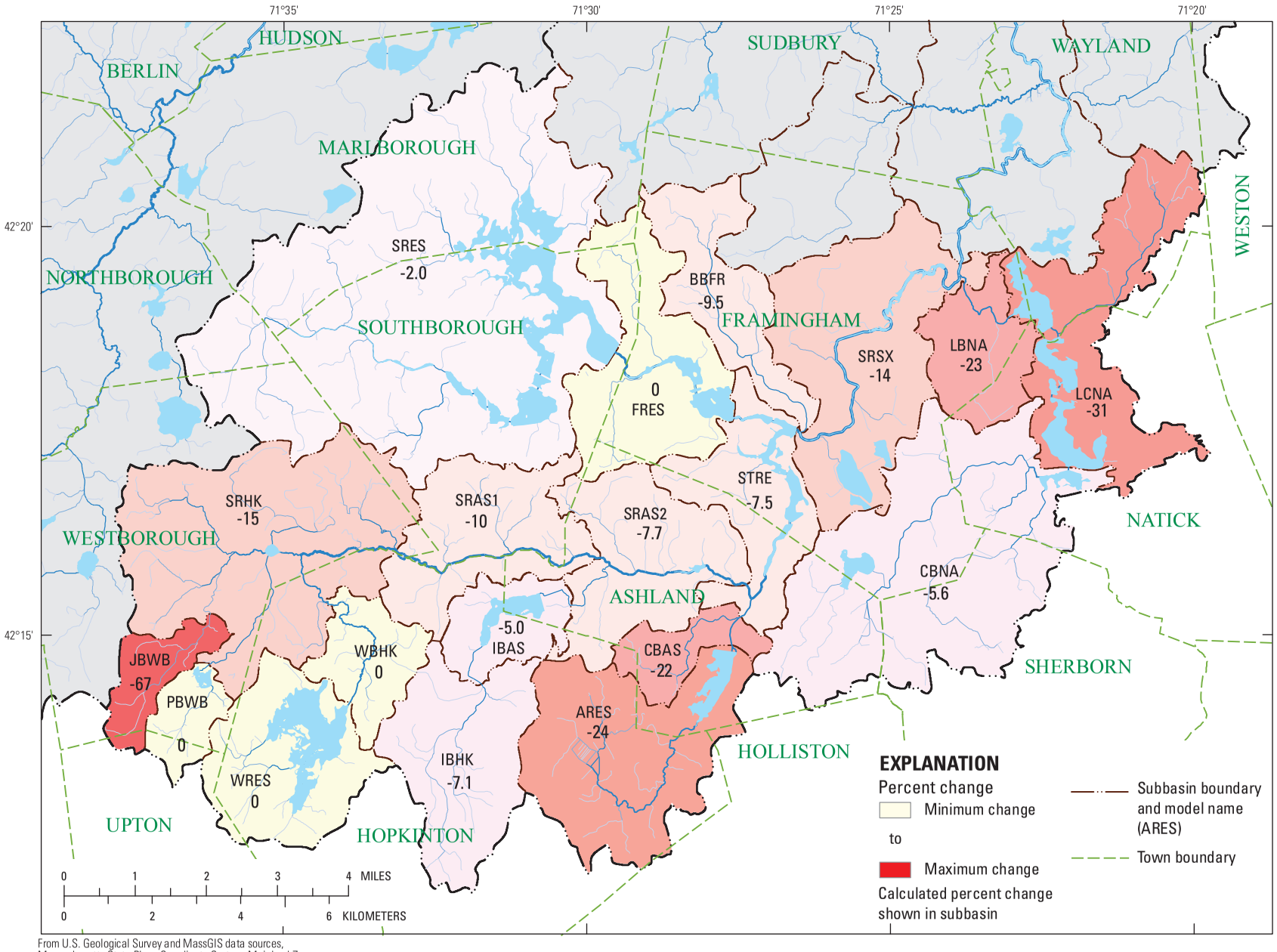
In general, the percent change in the median of the August mean flows with GWoWU relative to NOWU (fig. 23) are similar to that for AVGWU relative to NOWU (fig. 21) because most withdrawals in the upper Sudbury River Basin are from groundwater sources. Conversely, the percent change in the median of the August mean flows with SWoWU relative to NOWU are mostly small, except in Piccadilly Brook (fig. 24). Most changes in the median of the August mean flows with SWoWU and in many of the subbasins with GWoWU, relative to NOWU (fig. 23), result from sewer I&I losses.

Flow-duration curves developed from simulated streamflow in Jackstraw Brook and Lake Cochituate outlet indicate that GWoWU are the same as AVGWU and that SWoWU are the same as NOWU (fig. 19); flow-duration curves are slightly offset for clarity. This indicates groundwater is the sole source of water withdrawn from these basins. In Piccadilly Brook, the opposite is true; flow-duration curves (fig. 19B) indicate that surface water is the sole source of water withdrawn from the subbasin. At Ashland Reservoir outlet (fig. 19C), flow-duration curves developed from GWoWU and SWoWU simulated streamflows are between that developed from NOWU and AVGWU—the GWoWU curve is closer to the AVGWU curve and the SWoWU curve is closer to the NOWU curve. As previously noted, however, most withdrawals from this subbasin are from surface-water sources, but a number of these sources are isolated ponds (disconnected from the streams) and were treated as a groundwater withdrawal because they indirectly affect streamflows much like a pumped large-diameter shallow well would. Turning off all direct and indirect surface-water withdrawals in this subbasin would result in streamflows being similar to the no-withdrawal simulation.

Effects of Potential Water- and Land-Use Change on Streamflow

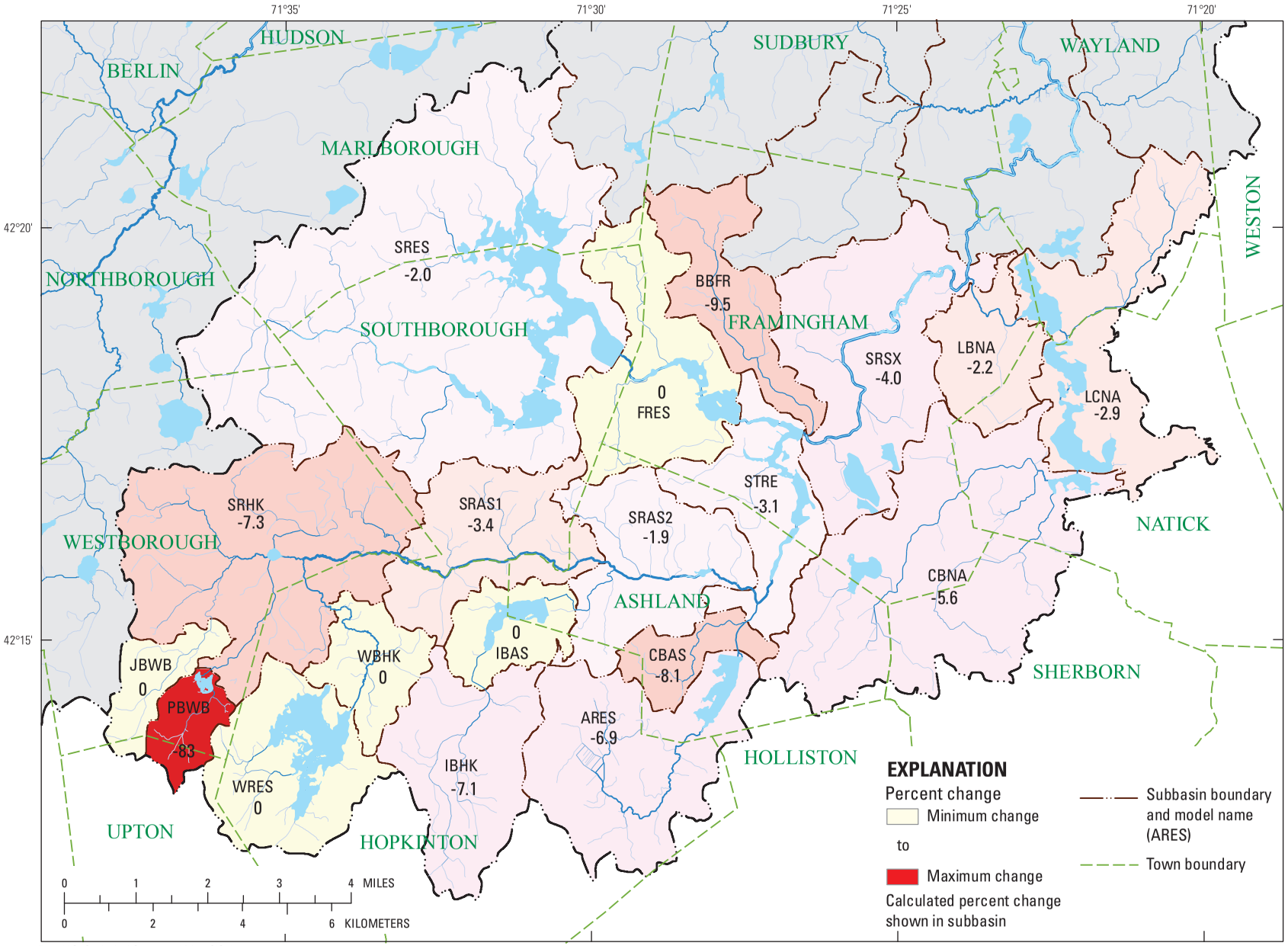
Four simulations examined the effects on streamflow of potential 2030 water- and land-use change (table 11) projected by the MAPC (M. Pillsbury, Metropolitan Area Planning Council, written comm., 2006). Two simulations (30WU99LU and 30WUa99LU) reflect changes in withdrawals and wastewater return-flow rates to projected 2030-use rates, but land use remained unchanged from the calibrated model (1997 land-use conditions). In the 30WU99LU simulation, changes in water use were distributed among existing supply sources, and in the 30WUa99LU simulation, changes in water use were distributed among dispersed domestic supply sources. In the other two simulations (30LUWU and 30WULUalt), both water and land use were changed to reflect projected 2030 conditions. In these simulations, land-use change was the same, but water-use change was simulated as described above; the 30LUWU simulation distributed the water-use change among existing sources and the 30WULUalt simulation distributed water change among dispersed domestic sources.

In the 30WU99LU and 30WULU simulations, the MAPC-projected 2030 water demands by town were distributed among existing sources in proportion to the average amount each source supplied in 1993–2003. The projected 2030 demand, in excess of the average 1993–2003 demand, was used as a multiplier in the *uci* file *External Source Block* to reflect the total projected withdrawals from a reach; this approach maintains the same pattern of withdrawals over the 1960–2004 climatic conditions as was used in the simulation of long-term average 1993–2003 withdrawals (AVGWU). The projected 2030 withdrawals in the upper Sudbury River Basin relative to the average 1993–2003 withdrawals changed by -100 to 23 percent with a median increase of about 13 percent (table 12). In RCHRES 9 and 10, current withdrawals are for irrigation purposes that were projected to be converted to residential land use resulting in no withdrawals from these reaches (-100 percent change) when distributed among existing supply



From U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone Polyconic projection

Figure 23. Percent change in the simulated long-term (1960–2004) median of the August mean flows with average 1993–2003 groundwater withdrawals (GWoWU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.



From U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone Polyconic projection

Figure 24. Percent change in the simulated long-term (1960–2004) median of the August mean flows with average 1993–2003 surface-water withdrawals (SWoWU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.

sources. Discharge from WWTPs in the 30WU99LU and 30WULU simulations was increased in proportion to the additional projected withdrawals in the areas served by the facility.

In the 30WULUalt and 30WUa99LU simulations, the MAPC-projected 2030 water demands were distributed as dispersed domestic wells that return most water through on-site septic disposal. It was assumed that 80 percent of the projected increase in withdrawals would be returned through on-site septic systems; that is, 20 percent is lost from the basin, which is often referred to as consumptive use. These values were considered to reflect an end-member condition that is considered appropriate for peak summer consumptive use, but this value likely overestimates consumptive use during other periods of the year. The majority of land-use change (described later) is from forest to low-density residential development, and dispersed withdrawals will likely reflect much of the water-use change associated with the land-use change.

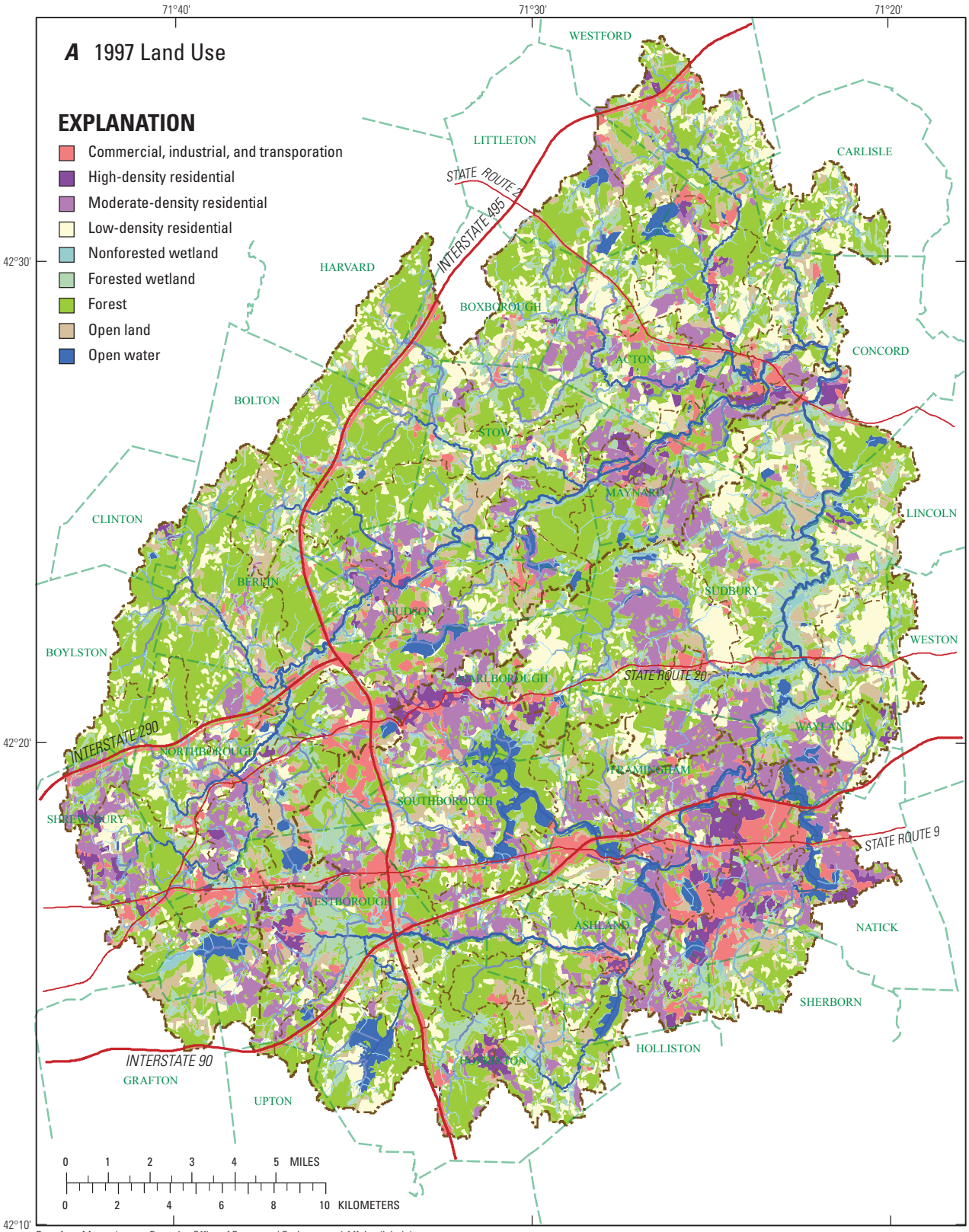
To simulate the dispersed withdrawals in the 30WULUalt and 30WUa99LU simulations, the projected change in withdrawals from a reach were increased by 20 percent of the projected 2030 withdrawal rate (table 12), except for RCHRESs 8, 9, and 10. In these three reaches, the projected public-supply withdrawal was assumed to come from RCHRES 8, the reach with the closest public supply source; therefore, the projected increase in demand from RCHRES 8 was distributed in proportion to the land-use change among RCHRESs 8, 9, and 10. Return flows, net water gains through public-water supply and on-site septic, and net I&I losses in the 30WULUalt and 30WUa99LU simulations were held the same as the AVGWU simulation.

Land-use change from 1997 to the MAPC-projected 2030 conditions are illustrated in figures 25A and 25B for the simplified land-use categories used to develop the model HRUs. In general, the majority of land-use change was from forest to low-density residential development. In the upper Sudbury River Basin, forest area decreased by about 52 percent and low-density residential area increased by about 145 percent (table 13). As a percentage of the upper Sudbury River Basin area, forested area decreased by about half (from about 33 to 16 percent); whereas low-density residential area more than doubled (from about 10 to 25 percent).

Overall, the area of the upper Sudbury River Basin classified as some type of developed land-use category was projected to increase from about 42 percent in 1997 to about 64 percent in 2030. Only modest changes were made to the amount of effective impervious area because most of the anticipated development is low-density residential and most new development is designed to minimize the effects of imperviousness on streamflow. Collectively, the effective impervious area in the upper Sudbury River Basin increased from 10 to 13 percent from 1997 to 2030, respectively. The projected land-use change was generally similar in the Assabet River Basin—overall areas classified as some type of developed land increased from about 32 percent in 1997 to about 60 percent in 2030. It should be noted, however, that the *uci* file was modified to only reflect projected land-use change in the upper Sudbury River Basin (RCHRES 1 through 19). It should also be noted that the exact nature of land-use change is unknown and that the model variables associated with different types of land use are largely unknown because the model is calibrated to points that represent a mix of many land-use types. As a result, the simulations of land-use change have a large degree of uncertainty. Changes in streamflow as a result of changes in water use also have a large degree of uncertainty—in particular, how water is withdrawn from the basin (existing supply wells or dispersed domestic wells) and disposed (public sewer or on-site septic). Although the simulations presented cover a range of possible land- and water-use conditions, the results of the simulations should be used with these uncertainties in mind.

In general, simulations of projected water-use change only (30WU99LU, fig. 26 and 30WUa99LU, fig. 27) produced results similar to those shown for the effects of average 1993–2003 withdrawals (AVGWU, fig. 21). Streamflow simulated under estimated 2030 demands distributed among existing supply sources (30WU99LU) indicates only minor decreases (1 to 5 percent) in the median of the August mean flows relative to AVGWU (figs. 26 and 21, respectively). The largest decrease (5 percent) relative to AVGWU was in lower Indian Brook (IBAS, RCHRES 8) because the supply well in this subbasin was assumed to cover RCHRES 9 and 10. The median August mean streamflow did not change appreciably in other reaches even though projected 2030 withdrawals increased. In these reaches, such as Jackstraw Brook (JBWB, RCHRES 1) and Piccadilly Brook (PBWB, RCHRES 2), expected 2030 withdrawals increased by 15 to 16 percent, respectively, relative to AVGWU, but no change in the median August mean streamflow was indicated. The mean annual streamflow in these reaches decreased by about 3 percent, however. This indicates that the streamflow in August was already less than the average 1993–2003 withdrawals most of the time and any increases in withdrawals, therefore, would have little or no effect on streamflow. Withdrawals from these reaches are met through changes in groundwater storage, which generally decrease streamflow later in the fall when streamflow exceeds the withdrawal rate and water would be available to replenish that lost from storage. This condition is accounted for in lost storage from the surface-water reservoir in Jackstraw Brook, but not in lost groundwater storage from pumped wells as previously described.

The median of the August mean flows simulated under projected 2030 water demands distributed among existing supply sources (30WU99LU) indicate Ashland Reservoir outlet (ARES, RCHRES 10) and the next downstream reach, Cold Spring Brook (CBAS, RCHRES 11), increased substantially relative to AVGWU (figs. 26 and 21, respectively). The median of the August mean flow under AVGWU decreased by 34 and 30 percent relative to NOWU in RCHRES 10 and 11, respectively. Simulated flows under 30WU99LU indicate no change from the NOWU in RCHRES 10 and 11. As previously described, withdrawals in ARES are largely for irrigation; if irrigated lands are converted to low-density



Base from Massachusetts Executive Office of Energy and Environmental Affairs digital data;
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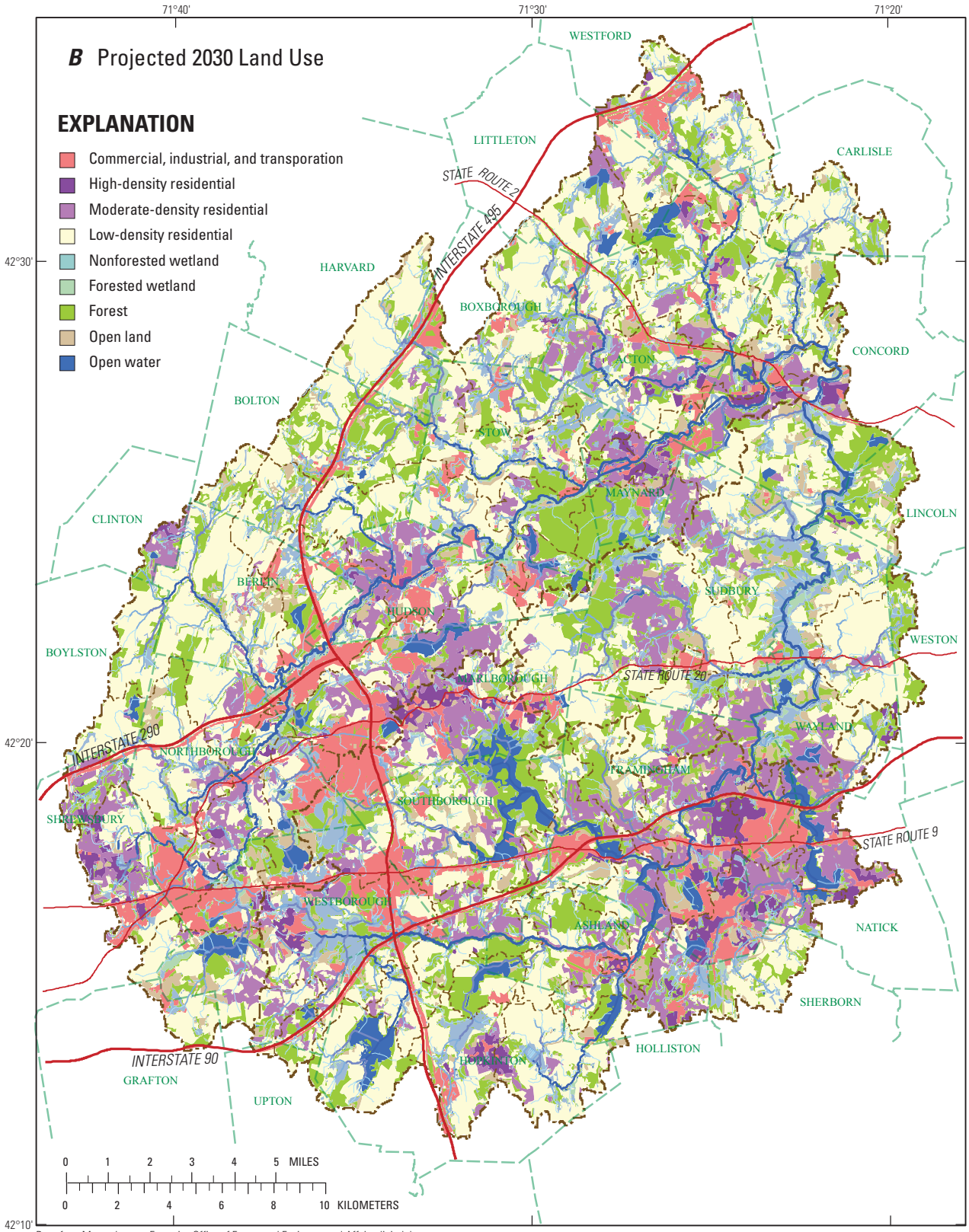
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 25. Generalized land use as (*A*) classified from 1997 interpreted 1:25,000 aerial photographs, and (*B*) projected 2030 buildout analysis by the Metropolitan Area Planning Council (M. Pillsbury, Metropolitan Area Planning Council, written commun., 2006), upper Sudbury River Basin, Massachusetts.



Base from Massachusetts Executive Office of Energy and Environmental Affairs digital data;
EOTROADS_ARC, 1:5,000, 2006; HYDRO25K_ARC , 1:25,000, 2005; MAJPOND_POLY, 1:100,000, 1998; SUBBASINS_POLY, 1:25,000, 2007; TOWNS_POLY, 1:25,000, 2002
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 25. Generalized land use as (*A*) classified from 1997 interpreted 1:25,000 aerial photographs, and (*B*) projected 2030 buildout analysis by the Metropolitan Area Planning Council (M. Pillsbury, Metropolitan Area Planning Council, written commun., 2006), upper Sudbury River Basin, Massachusetts.—Continued

Table 13. Summary of Hydrologic Response Unit (HRU) changes simulated in the Hydrologic Simulation Program–FORTRAN (HSPF) model of the upper Sudbury River Basin, Massachusetts.

[Percent area may not add to 100 because of rounding]

HRU type	Area (acres)		Percent change	Percent of basin area	
	1997	2030		1997	2030
Commercial-industrial-transportation	2,263	2,975	31	3.3	4.4
High-density residential	2,797	3,429	23	4.1	5.1
Moderate-density residential	9,642	10,914	13	14	16
Low-density residential	6,973	17,086	145	10	25
Open	5,911	2,621	-56	8.7	3.9
Forest	22,165	10,593	-52	33	16
Nonforested wetland	1,166	1,166	0	1.7	1.7
Forested wetland	6,045	6,045	0	8.9	8.9
Water	4,007	4,007	0	5.9	5.9
Effective impervious area					
Residential	1,512	1,992	32	2.2	2.9
Commercial-industrial-transportation	5,289	6,942	31	7.8	10

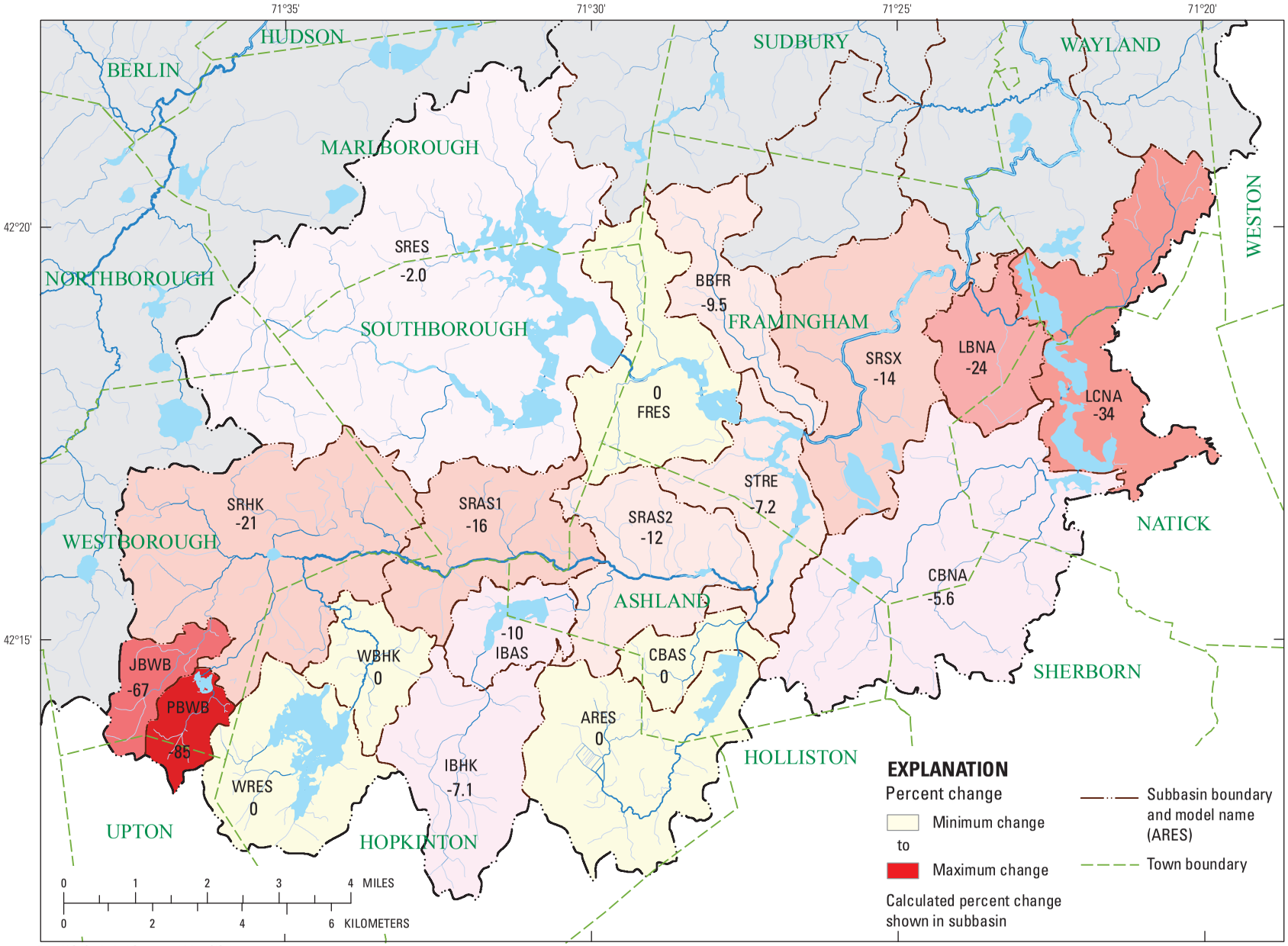
residential development that imports water from a neighboring subbasin, streamflow in the basin would be about the same as the no-withdrawal condition. Water demands in ARES in the 30WU99LU simulation were assumed to be met through increased withdrawals in the Indian Brook subbasins (IBAS, RCHRES 8; fig. 26), but without any net import of water through on-site septic disposal.

When 2030 demands are met through dispersed domestic-well withdrawals (30WUa99LU) that are mostly returned through on-site septic disposal (assuming a 20-percent consumptive loss), streamflow in Ashland Reservoir outlet (ARES, RCHRES 10) and in downstream Cold Spring Brook (CBAS, RCHRES 11) increased substantially relative to AVGWU simulated streamflows (figs. 27 and 21, respectively), but not to the extent of NOWU simulated streamflow (fig. 19). The 30WUa99LU simulated median of the August mean flows still indicates a modest reduction in flow in these reaches relative to NOWU of 3.4 and 2.7 percent, respectively. Most other changes in streamflow simulated under 30WUa99LU conditions indicate little change relative to AVGWU simulated flows (figs. 27 and 21, respectively).

The effects of land-use and water-use change (30WULU and 30WULUalt) on streamflow are markedly different from AVGWU and from projected water-use change only simulations (30WU99LU and 30WUa99LU). However, changes are not in the direction normally expected as a result of development because many reaches indicate an increase in the median of the August mean flows relative to the NOWU (figs. 28 and 29). In subbasins with large municipal withdrawals, the median of the August mean flows under 30WULU and 30WULUalt decreased by a comparable amount to that simulated for AVGWU conditions (fig. 21) because municipal withdrawals remained unchanged. In most other subbasins, the median of the August mean flows for 30WULU and 30WULUalt simulated flows increased substantially relative to AVGWU simulated flows and in 13 of 19 subbasins increased above the NOWU simulated flows.

Typically, low flows are expected to decrease with development as a result of increased impervious area that decreases the opportunity for precipitation to infiltrate into the groundwater, thereby, decreasing the baseflow contribution to streams. The amount of precipitation diverted from infiltration is largely a function of the impervious area directly connected to the streams, or effective impervious area. However, development can also cause a loss in deep-rooted vegetation that decreases ET losses and increases baseflow to streams. The balance between decreased baseflow and ET determines the streamflow response associated with development.

As previously noted, MAPC-projected land-use change in upper Sudbury River Basin was predominantly from forest to low-density residential development. As a result, all reaches in the upper Sudbury River Basin indicate an increase in the long-term (1960–2004) median of the August mean flows under projected 2030 land use (30WULU and 30WULUalt) relative to 1997 land use (figs. 28 and 29, respectively, compared to fig. 21), despite increased water withdrawals. The changes in the median of the August mean flows were modest in reaches where withdrawals have the greatest effect on streamflows, but in reaches where withdrawals do not greatly affect streamflows, the effect of land-use change is pronounced, often resulting in streamflows above the NOWU simulated flows. For example, in upper Indian Brook (IBHK,



From U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone Polyconic projection

Figure 26. Percent change in the simulated long-term (1960–2004) median of the August mean flows with estimated 2030 water withdrawals distributed among existing supply sources (30WU99LU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.

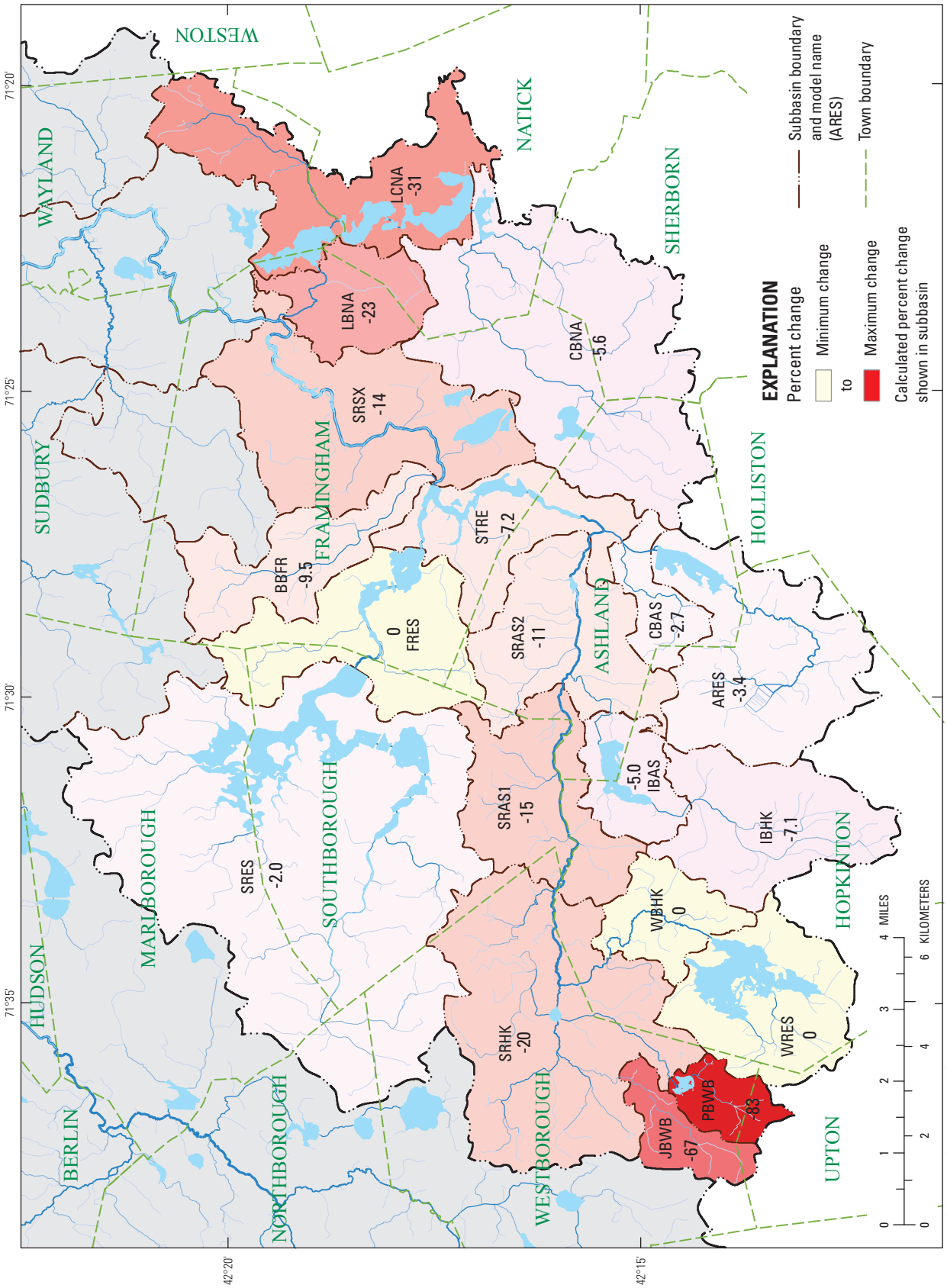
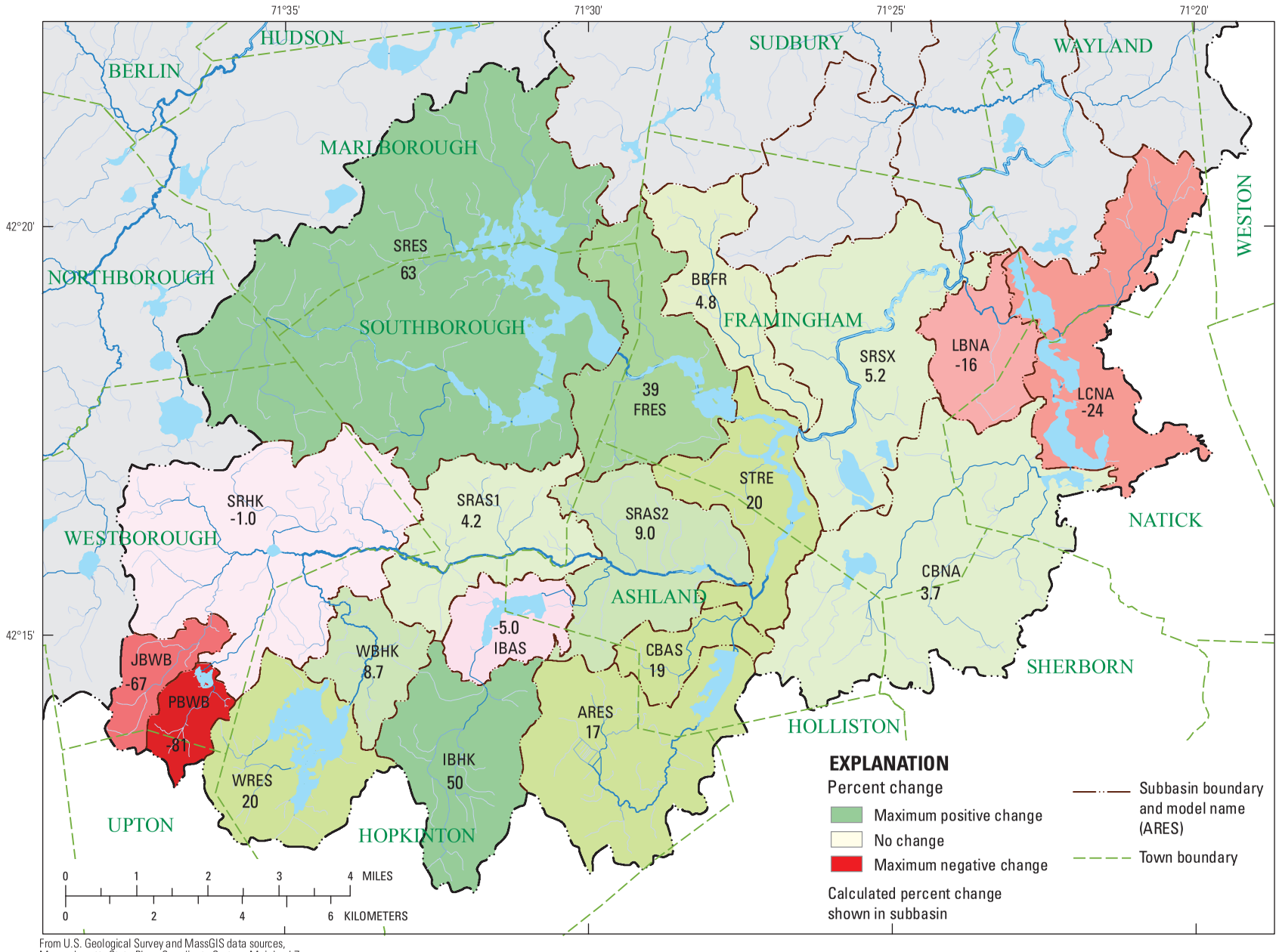


Figure 27. Percent change in the simulated long-term (1960–2004) median of the August mean flows with estimated 2030 water withdrawals dispersed among self-supply sources and a 20-percent consumptive use (30WUa99LU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.



From U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone Polyconic projection

Figure 28. Percent change in the simulated long-term (1960–2004) median of the August mean flows with estimated 2030 land use and water withdrawals distributed among existing supply sources (30WULU) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.

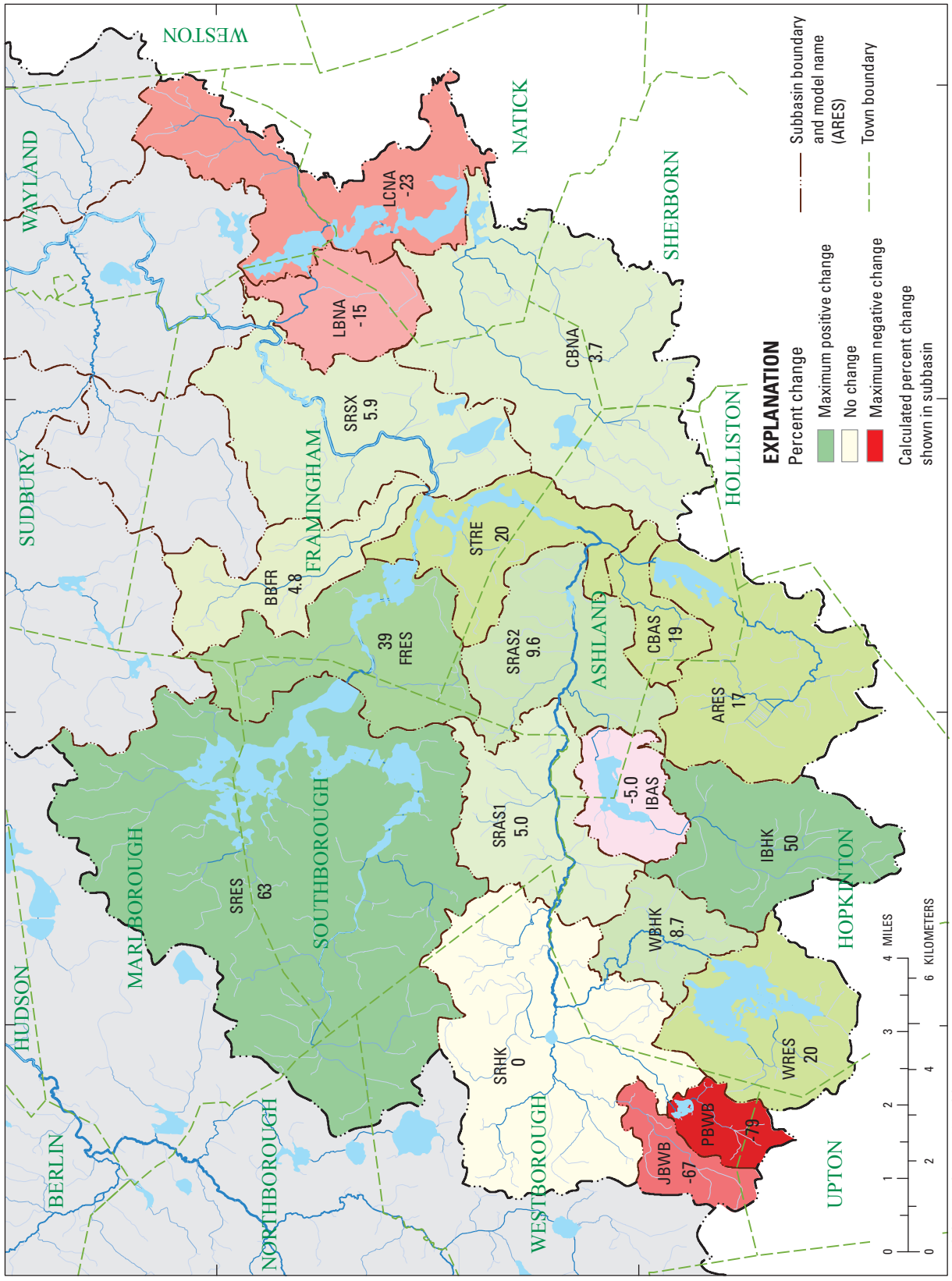


Figure 29. Percent change in the simulated long-term (1960–2004) median of the August mean flows with estimated 2030 land use and water withdrawals dispersed among self-supply sources with a 20-percent consumptive loss (30WULUalt) relative to no withdrawals (NOWU) in the upper Sudbury River Basin, Massachusetts.

RCHRES 7), the long-term median of the August mean flows was 50 percent greater under projected 2030 land use simulated flows (30WULU and 30WULUalt; figs. 28 and 29, respectively) than NOWU flows (fig. 21). The median of the August mean AVGWU simulated flows in upper Indian Brook (fig. 23) are about 7.1 percent less than NOWU simulated flows (fig. 21). No withdrawals were specified from this subbasin; therefore, the net loss shown in figure 21 is from groundwater routed out of the basin to represent sewer I&I losses. The same losses to sewer I&I are specified in the projected 2030 simulations (30WULU and 30WULUalt), but the decrease in ET losses more than offsets these losses, resulting in an increase in the median of the August mean flows relative to 1997 land-use conditions.

Examination of the water-budget outflows for August reveals why the simulated land-use change resulted in an increase in the median of the August mean flows. In upper Indian Brook (IBHK, RCHRES 7), projected 2030 land use decreased forested HRUs by about 72 percent, and medium- and low-density residential HRUs increased by about 300 and 430 percent, respectively. The August mean water-budget outflows (fig. 17) indicate that ET losses from medium- and low-density residential HRUs are about 15 percent less than ET losses from forested HRUs per unit area. When these values are applied to the distribution of HRU types in upper Indian Brook (IBHK) under 1997 land use (fig. 30A) and under the projected 2030 land use (fig. 30B), it becomes more apparent why the simulated median of the August mean flows increased. The resulting subbasin water-budget outflows indicate that the average 1993–2003 August inflow to streams increased by about 20 percent, and ET losses decreased by about 11 percent under project 2030 land use relative to 1997 land use.

In Course Brook (CBNA, RCHRES 16), the long-term median of the August mean flows increased by 3.7 percent under projected 2030 land use (figs. 28 and 29) relative to 1997 land use (fig. 23). Similar to simulations in upper Indian Brook, withdrawals in Course Brook are not a factor and the small decrease in AVGWU simulated streamflow (7.1 percent) relative to NOWU simulated streamflow (fig. 21) is attributed to sewer I&I losses. Projected 2030 land use in the Course Brook subbasin decreased forested HRUs by about 64 percent, and medium- and low-density residential HRUs increased by about 412 and 166 percent, respectively. Water-budget outflows computed from the distribution of HRU types under 1997 land use (fig. 31A) and projected 2030 land use (fig. 31B) indicate that the average 1993–2003 median of the August mean flows increased by about 7.5 percent, and ET losses decreased an equal amount.

Although changes in the median of the August mean flows associated with development can be pronounced, the changes in the long-term mean annual flows associated with development are relatively modest. Simulations of projected 2030 water-use change only (30WU99LU and 30WUa99LU) indicate flow in most reaches remained about the same as AVGWU simulated flows; at most, long-term mean annual flows associated with water-use change only were about 3 percent more than the change in AVGWU simulated flows relative to NOWU simulated flows. The long-term mean annual flows simulated with projected 2030 water-use and land-use change (30WULU and 30WULUalt) generally increased relative to the AVGWU simulated flows (fig. 21); the change in mean annual flows decreased as the effect of withdrawals increased, but these changes were small relative to changes in the median of the August mean flows.

The simulations of projected 2030 water-use and land-use change on streamflow reflect several possibilities, none of which can be viewed with certainty, however. The exact nature of future development is unknown, thus, the representation of these changes in the model are unknown. Given the projected land-use change in the upper Sudbury River Basin is predominantly from forest to medium- and low-density residential development, the increased water demands associated with development will likely be partially offset by decreased ET losses from the loss of deep-rooted vegetation also associated with development. The degree increased demands are offset by decreased ET losses will vary locally and may be reflected in one simulation more than another. However, the potential for increased low flows associated with low- to medium-density development is not a rationale for development because the effect of development on water quality, stream-water temperature, and other factors should also be considered.

Potential Effects of Reactivating Production Wells near Lake Cochituate

During the course of the study, reactivating production wells by the town of Framingham became of interest as did concern over their potential effects on streamflow and Lake Cochituate water levels. The production wells consist of a cluster of three wells in the Sudbury River Basin near the Saxonville streamgage about 1,400 ft from the northern edge of Lake Cochituate and about 600 ft from the upstream boundary of the SRCO (RCHRES 33) subbasin (fig. 3). Collectively, these wells are referred to as the Birch Road wells and were discontinued in 1979 when the town converted entirely to MWRA water supply. The town maintained the wells for emergency use and in June 2009 submitted a Draft Environmental Impact Report (DEIR) with the Commonwealth to reactivate the Birch Road wells for regular supply use.

The source of water to these wells is not readily defined because the wells are near the border of several subbasin boundaries and pumping these wells will likely affect local groundwater flow paths so that the subsurface-water divides are no longer coincident with the surface-water divides. The potential sources of water to these wells is further complicated by the hydrogeology of the area. Gay (1985) shows a confining layer below the northern end of Lake Cochituate that pinches out as it slopes northward toward the production wells. Gay (1985) also shows that the hydraulic head in the confined aquifer on June 5, 1979 (it is not known if the

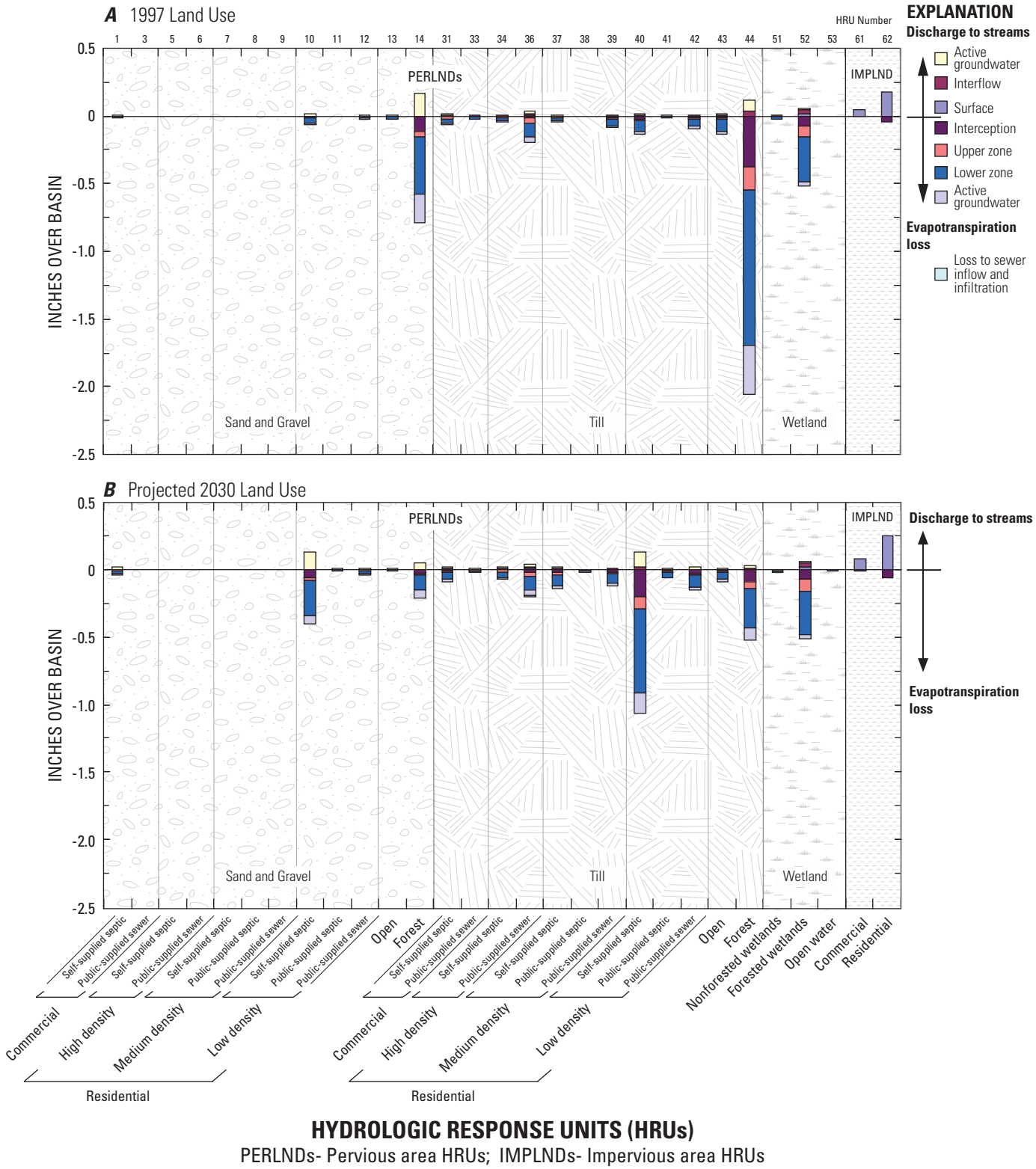


Figure 30. Mean August (1993–2003) water-budget outflow components by Hydrologic Response Unit (HRU) simulated by the Hydrological Simulation Program–FORTRAN (HSPF) in upper Indian Brook (IBHK, RCHRES 7) under (*A*) 1997 land use and (*B*) projected 2030 land use, upper Sudbury River Basin, Massachusetts. Location shown in figure 9.

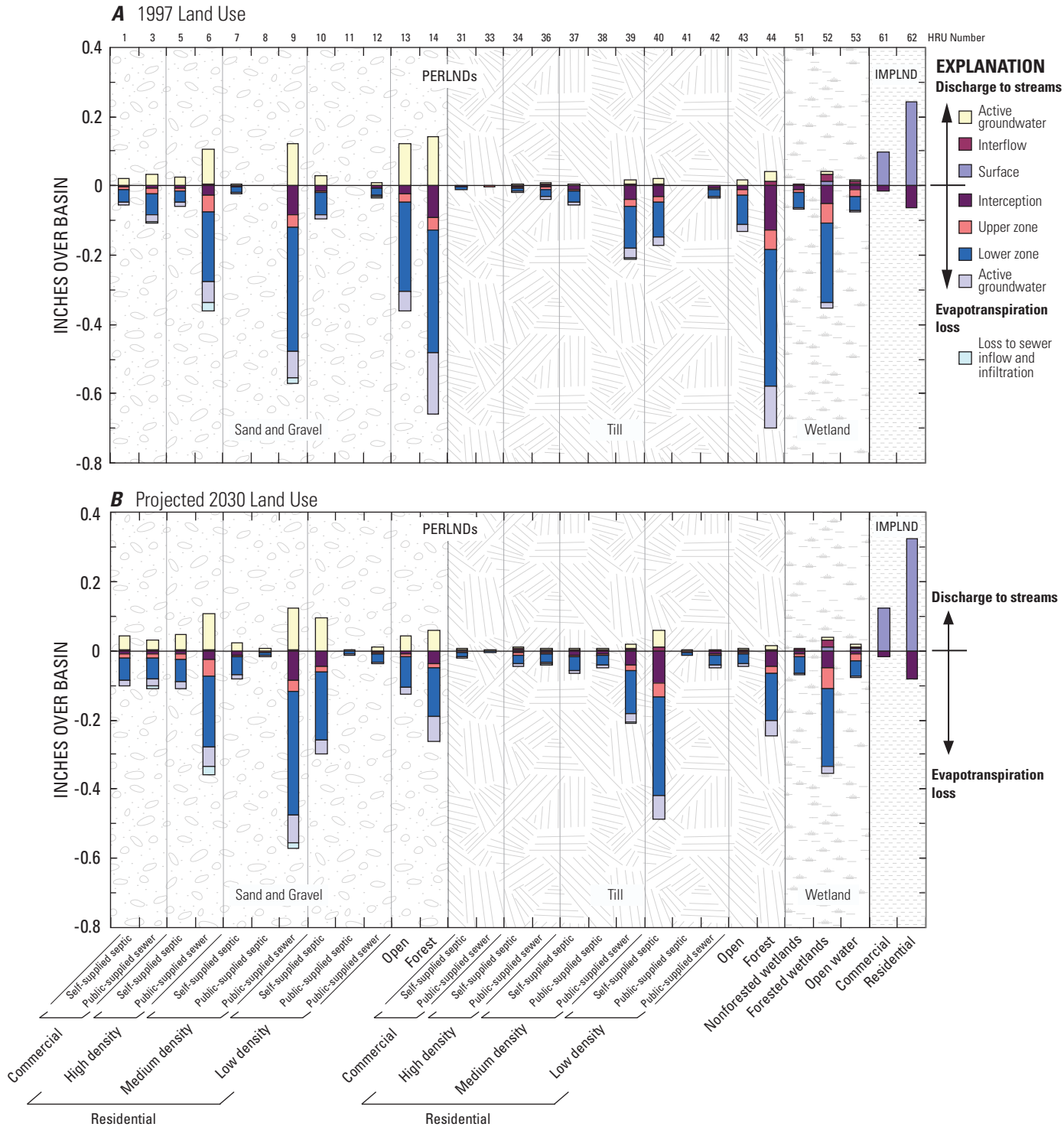


Figure 31. Mean August (1993–2003) water-budget outflow components by Hydrologic Response Unit (HRU) simulated by the Hydrological Simulation Program–FORTRAN (HSPF) in Course Brook (CBNA, RCHRES 16) under (*A*) 1997 land use and (*B*) projected 2030 land-use conditions, upper Sudbury River Basin, Massachusetts. Location is shown in figure 9.

Birch Road wells were active at this time), was below the lake level, indicating a downward gradient from the lake to the lower aquifer, which may have been caused by pumping of the Birch Road wells. Additional information is needed to understand and quantify the subsurface-water movement in this area, possibly requiring a multi-layer groundwater model to simulate the hydrologic response of a pumping stress in this complex hydrogeologic setting. Lacking this information, the HSPF model was used to simulate a steady-state pumping of 4.3 Mgal/d (6.65 ft^3/s), which was proposed in the DEIR, assuming four possible sources of water to the wells from induced infiltration or captured baseflow, or both, from (1) Lake Cochituate (BIR_LC) only, (2) Sudbury River (BIR-SU) only, (3) one third of the water is from Lake Cochituate and two thirds is from Sudbury River (BIR-LC33), and (4) two thirds of the water is from Lake Cochituate and one third is from Sudbury River (BIR-LC66). Whether water is from induced infiltration or captured baseflow that would normally discharge to the water feature is not distinguished in these simulations. These simulations were compared to long-term simulations reflecting average 1993–2003 water use (AVGWU), during which time the Birch Road wells were not active, and no water use (NOWU); the AVGWU and NOWU simulated conditions apply throughout the Sudbury and Assabet River Basins.

Although the entire Sudbury and Assabet River Basin hydrology was simulated in each of these scenarios, the output of the model was restricted to Lake Cochituate water level, and flows at the lake outlet (LCNA, RCHRES 17), the lake outlet brook near the confluence with the Sudbury River (LBNA, RCHRES 18), and Sudbury River at Saxonville (SRSX, RCHRES 19). Flow at the Saxonville streamgage was considered the most representative flow in the river near the withdrawals, although the effects of these withdrawals may occur mostly below the streamgage. In addition, simulated lake levels may not reflect actual levels because the lake outflow can be manually regulated. Simulations of lake levels, therefore, should be viewed as a relative change for comparison to other simulations. In addition, the FTABLE representing Lake Cochituate was modified to better represent changes in the stage-storage relation below the spillway. The FTABLE modification to RCHES 17 was limited to the *uci* files associated with the reactivation of production wells near Lake Cochituate.

Effects of reactivating the Birch Road wells on the water level of Lake Cochituate, its outflow, and in downstream reaches depend on the hydraulic connection of the well with the aquifer, the aquifer properties, and the distance of the pumped wells from these water features. Again, it should be noted that the simulation results presented assume a steady withdrawal rate of 4.3 Mgal/d (6.65 ft^3/s) and the lake levels are not managed. Unsteady withdrawal rates and active management of the lake levels can yield different results from those shown.

Assuming all water to the wells is from induced infiltration from or captured baseflow to Lake Cochituate (BIR_LC), long-term (1961–2004) outflow from the lake (LNCA, RCHRES 17) equals or exceeds 0.1 ft^3/s about 80 percent of the time; in other words, streamflow ceases, or nearly ceases, about 20 percent of the time (fig. 32A). Under average 1993–2003 withdrawals (AVGWU), in which Birch Road wells are inactive, outflow from the lake equals or exceeds 0.1 ft^3/s about 95 percent of the time. Under NOWU, simulated outflows equals or exceeds about 1 ft^3/s all the time. Assuming all water to the Birch Road wells is induced infiltration from or captured baseflow to the Sudbury River (BIR_SU), outflows from the lake are identical to the AVGWU simulated flows, as would be expected (fig. 32A). Simulations that assume one third of the water to the wells is from Lake Cochituate and two thirds is from Sudbury River (BIR-LC33) and, alternatively, two thirds of the water is from Lake Cochituate and one third is from Sudbury River (BIR-LC66) result in flow-duration curves at the lake outlet that are proportionally spaced between simulations that assume all water to the wells is from the lake (BIR_LC) and none of the water to the wells is from the lake (BIR_SU). Flow-duration curves affected by withdrawals begin to noticeably depart from one another at about the 30-percent exceedence interval. These simulations illustrate the potential range of effects from reactivating the Birch Road wells on the lake outflows and flow in the Sudbury River near the pumped wells.

The simulated long-term (1961–2004) streamflow at the Saxonville streamgage (SRSX, RCHRES 19) under average 1993–2003 withdrawals (AVGWU) is about 6 ft^3/s or greater and under no withdrawals (NOWU) streamflow is about 8 ft^3/s or greater. If all water to the Birch Road wells is induced infiltration from or captured baseflow to the Sudbury River, the simulated long-term streamflow at the Saxonville streamgage is about 1 ft^3/s or less about 1 percent of the time (fig. 32B). It should be noted that flow at the Saxonville streamgage is a proxy for changes in flow that would likely be realized near, but downstream from the streamgage if the source water to the wells is induced infiltration from or captured baseflow that normally flows to the Sudbury River.

Changes in flow in the Sudbury River that result from pumping the Birch Street wells, unlike the changes in flow at Lake Cochituate outlet, do not change proportionally on the basis of the assumed source of water (fig. 32). This is because flows in the Sudbury River at the Saxonville streamgage are affected by flows from Lake Cochituate outlet. When the source of water to the Birch Street wells is assumed to come solely from Lake Cochituate, the changes in the lake outflow equally affect flows in the Sudbury River except when the rate of depletion (the pump rate that is assumed to come from Lake Cochituate) exceeds the rate of streamflow at which point water comes from lake storage. Changes in storage that result from depletion rates that exceed streamflow were simulated as a change in lake storage but may also result in a change in groundwater storage.

Regardless of the assumed source of water in these simulations, flow-duration curves (fig. 32) indicate that the effects of pumping the Birch Street wells on streamflows at

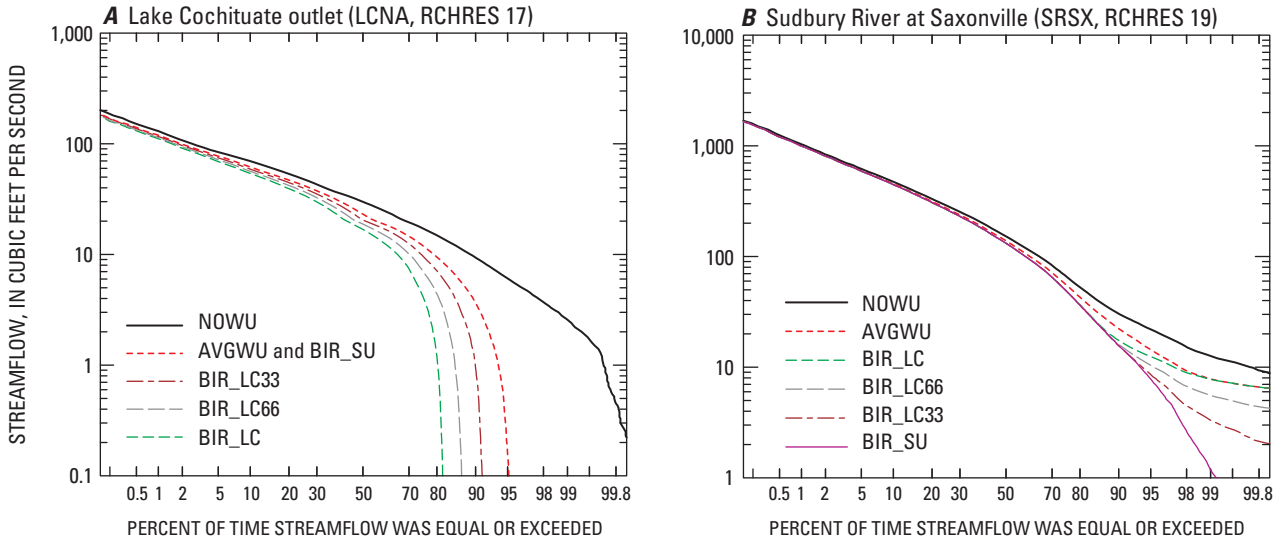


Figure 32. Daily mean flow-duration curves developed from 1960–2004 simulated flows under no withdrawals (NOWU), average 1993–2003 withdrawals (AVGWU), and reactivating production wells north of Lake Cochituate assuming water is induced infiltration from or captured baseflow to Lake Cochituate only (BIR_LC), Sudbury River only (BIR-SU), one third of the water is from Lake Cochituate and two thirds is from Sudbury River (BIR-LC33), and two thirds of the water is from Lake Cochituate and one third is from Sudbury River at (*A*) Lake Cochituate outlet, and (*B*) Sudbury River at Saxonville, upper Sudbury River Basin, Massachusetts. Locations shown in figure 9.

Saxonville are nearly identical up to the 90-percent duration interval. At this point, the flow-duration curve developed from the BIR_LC simulated flows begins to move toward the flow-duration curve for AVGWU simulated flows and are nearly the same at about the 98-percent duration interval. This indicates that, for the BIR_LC simulation, the streamflow contribution from the Lake Cochituate outflow to the Sudbury River diminishes when the flow in the river is below about 20 ft^3/s and there is no appreciable contribution when the flow in the river is below about 9 ft^3/s.

The Sudbury River flow in response to pumping the Birch Street wells incrementally changes in proportion to the source of water to the wells from the lake and the river (BIR_LC33 and BIR_LC66) at the lowest flows (fig. 32). Otherwise, the effects of pumping the wells on the Sudbury River are the same regardless of the sources of water simulated. The differences in the flow-duration curves at the lowest flows are proportional to the rate of depletion assumed to come from the Sudbury River, with the remainder of the total withdrawal coming from lake storage.

Simulated stage in Lake Cochituate, when not managed, indicates water levels periodically fall below the spillway under average 1993–2003 withdrawals. For example, during 1999, which had below-normal precipitation during the late spring and early summer, lake levels fell below the spillway for about 13 days in late June, recovered in early July, then fell below the spillway for about 56 days as dry-weather conditions continued until early September (fig. 33). As the pumped wells induce more infiltration from the lake, the number of episodes (a continuous period when water levels are below the spillway) and the length of the time the lake stage fell below the spillway increased. Over the 1961–2004 period, simulated water levels in Lake Cochituate under no withdrawals (NOWU) fell below the spillway five times lasting a total of 29 days (the longest episode lasting 12 days in 1999 (table 14). For the same period, under average 1993–2003 withdrawals, the lake level fell below the spillway 53 times lasting a total of 731 days. The number of times (episodes) the lake fell below the spillway relative to average 1993–2003 withdrawals increased by 38, 60, and 77 percent for simulations that obtain one third (BIR_LC33), two thirds (BIR_LC66), and all water (BIR_LC) from induced infiltration from the lake, respectively (table 14). The total number of days lake levels fell below the spillway also increased substantially as more water is induced from lake infiltration as indicated in table 14 and as illustrated in figure 33.

Simulations of withdrawals from reactivation of the Birch Road wells indicate that the lake stage and streamflow at the lake outlet and in the Sudbury River just below the Saxonville streamgage could be substantially affected during periods of low flow. These effects vary depending on the source of the water to the wells and are largely unknown. It should also be noted that the simulation results represent a constant pumping rate. If pumping rates varied, the effects on lake stage and flow could be mitigated if withdrawals were decreased at the appropriate times and by the appropriate amounts because the effects on lake level and flow were relatively small during periods of average or above-average discharge.

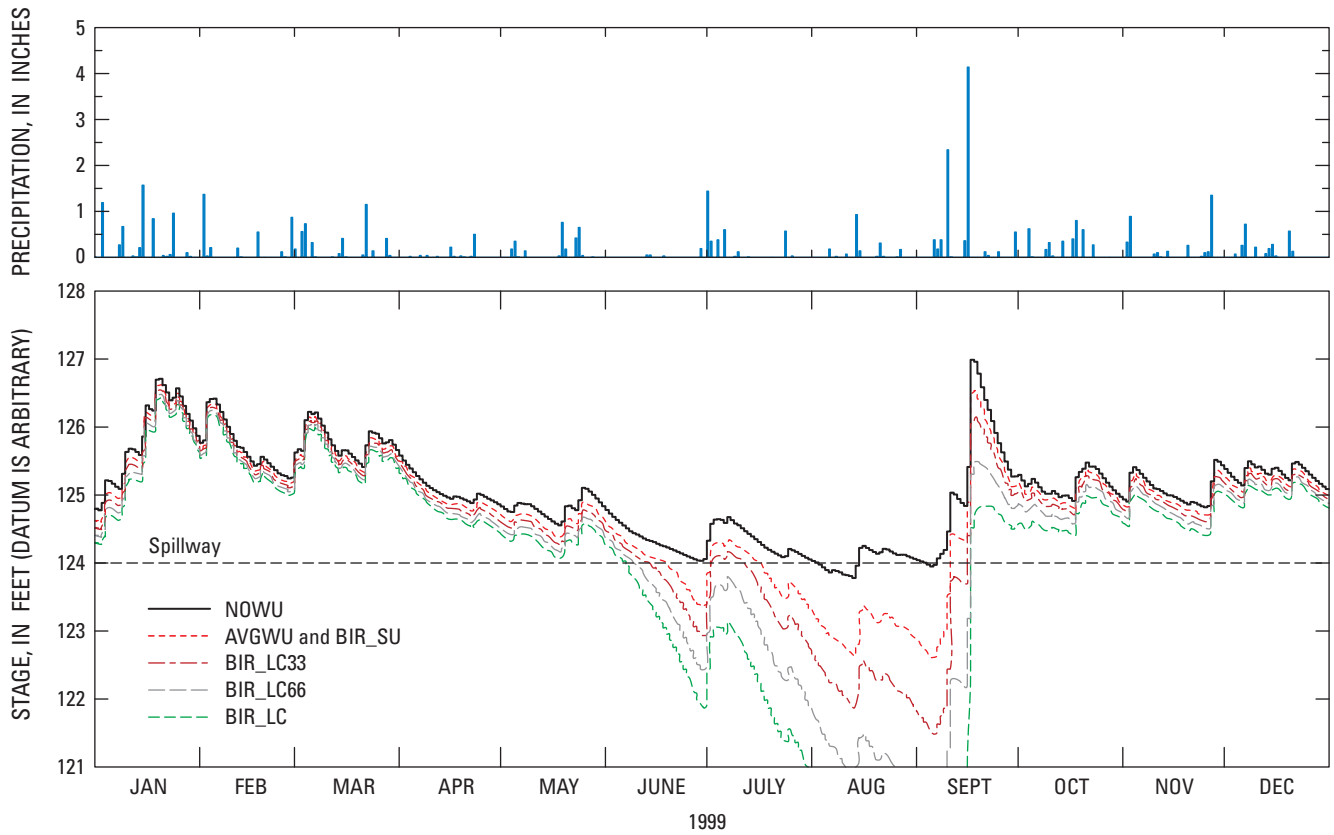


Figure 33. Daily mean stage of Lake Cochituate in 1999 simulated under no withdrawals (NOWU), average 1993–2003 withdrawals (AVGWU), and reactivating production wells north of Lake Cochituate assuming water is induced infiltration from or captured baseflow to Lake Cochituate only (BIR_LC), Sudbury River only (BIR_SU), one third of the water is from Lake Cochituate and two thirds is from Sudbury River (BIR_LC33), and two thirds of the water is from Lake Cochituate and one third is from Sudbury River (BIR_LC66), upper Sudbury River Basin, Massachusetts. Location shown in figure 9.

Table 14. Summary of the frequency and duration the Lake Cochituate water levels fell below the outflow spillway from 1961 through 2004 simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) under average 1993–2003 withdrawals (AVGWU), without withdrawals (NOWU), and reactivating production wells north of Lake Cochituate assuming water is induced infiltration or captured baseflow from Lake Cochituate only (BIR_LC), Sudbury River (BIR_SU) only, one third of the water is from Lake Cochituate and two thirds is from Sudbury River (BIR_LC33), and two thirds of the water is from Lake Cochituate and one third is from Sudbury River (BIR_LC66), upper Sudbury River Basin, Massachusetts.

[Episode, a period of continuous days water levels were below the spillway]

	NOWU	AVGWU and BIR_SU	Percent change relative to NOWU	BIR_LC33	Percent change relative to AVGWU	BIR_LC66	Percent change relative to AvgWU	BIR_LC	Percent change relative to AvgWU
Number of episodes	5	53	960	73	38	85	60	94	77
Longest episode (days)	12	58	383	128	121	162	179	220	279
Total number of days water level below spillway	29	731	2,421	1,390	90	2,103	188	2,968	306
Mean duration of annual episodes (days)	0.49	8.4	1,616	15	85	28	232	32	277
Mean duration of annual episodes with non-zero values (days)	5.8	14	138	19	38	25	79	14	0

Summary

Water withdrawals from reservoirs and the aquifer have affected streamflows in the Sudbury and Assabet River Basins, especially the upper Sudbury River Basin upstream from the USGS Saxonville streamgage. These effects are particularly evident in the summer when flows are at their lowest. A precipitation-runoff model, Hydrologic Simulation Program–FORTRAN (HSPF), was developed as part of this study to examine effects of current (1993–2003) water use and the effects of potential future (2030) water use and land use on streamflow.

The HSPF model was developed for the entire Sudbury and Assabet River Basins (339 mi^2), but focused on the 106-mi^2 upper Sudbury River Basin, which was the primary interest of the study. The model was calibrated to daily streamflow records at four continuous-record streamgages operated by the USGS—Sudbury River at Ashland (01097480) and at Saxonville (01098530), Assabet River at Maynard (01097000), and Nashoba Brook near Acton (01097300)—for an 11-year period from January 1, 1993, through December 31, 2003. Flows at Sudbury River at Ashland were measured from May 12, 1994, through October 1, 1995, but were estimated for the other parts of the 1993–2003 calibration period primarily by the Maintenance Of Variance Extension type 3 (MOVE-3) method. Nine partial-record stations (five in the Sudbury River Basin and four in the Assabet River Basin) were also used to evaluate and modify the model calibration.

The HSPF model is developed from hydrologic response units (HRUs) that are divided into pervious (PERLNDs) and impervious (IMPLNDs) areas to reflect relatively homogeneous hydrologic responses to climate on the basis of similar land use, surficial geology, and other factors. From each HRU, water is lost to evapotranspiration or routed into streams, lakes, and reservoirs defined by model reaches (RCHRESs). The HSPF model of the Sudbury and Assabet River Basins was represented by 27 PERLNDs and 2 IMPLNDs that connect to a network of 44 RCHRESs—23 represent the Sudbury River Basin, of which 21 represent the upper basin above the Saxonville streamgage. An hourly time step was used for all simulations.

The HRUs were developed from 1997 land-use information that was simplified into nine classes and intersected with two types of surficial geology. Developed lands were further divided into areas of net water imports and exports determined from public water and sewer infrastructure. Collectively, land use in the Sudbury and Assabet River Basins is primarily forested (38 percent) or developed (36 percent), mostly as low- to medium-density residential (26 percent); forested and nonforested wetlands, and open water, compose about 13 and 3.6 percent of the basin area, respectively. Open areas compose about 9.8 percent of the basin area. About 52 percent of the basin is underlain by sand and gravel, and the remainder is underlain by till and bedrock. Generally, the distribution of HRUs in the upper Sudbury River Basin is similar to other parts of the basin with the exception of open water (5.9 percent), which is a more dominant feature because of the large reservoirs. Effective impervious area (impervious area directly connected to streams) exerts a large influence on the hydrologic response of a basin; overall, 6.7 percent of the basin area was simulated as effective impervious area; in the upper Sudbury River Basin, about 10 percent of the basin area was simulated as effective impervious.

Water-withdrawal information from January 1, 1993, through December 31, 2003, obtained from water suppliers for 17 towns and from the Massachusetts Water Resource Authority (MWRA), was entered into the associated model database, the Watershed Data Management (WDM) system. Discharge data from five wastewater treatment plants were obtained for the same period from sewer districts for six towns in the Sudbury and Assabet River Basins and entered into the WDM database. Water withdrawals and wastewater return flows were applied to the appropriate reaches in the model; the lag effect of groundwater withdrawals on streamflow depletion was estimated through the analytical program STRMDEPL. Net imports of water through areas served by public supply and on-site septic disposal, and net exports of water through sewer inflow and infiltration (I&I) were simulated by additional HRU types modified from appropriate HRUs representing developed areas.

Simulated streamflows for the 11-year calibration period generally agree well with observed streamflows at the four continuous-record streamgages given the potential error in observed data and by regulation of streamflow not accounted for in the model. The Nash-Sutcliffe model-fit efficiency coefficient (E) ranged from 0.23 to 0.55 for daily mean flows and from 0.67 to 0.72 for monthly mean flows; E appreciably improved at Sudbury River at Ashland to 0.70 for daily mean flows and 0.88 for monthly mean flows for the 1.5-year period of observed record. The difference between simulated and observed mean daily flow over the calibration period ranged from -5.9 to 5.1 percent. Much of the model error could be explained by spatial variability of precipitation over the basin.

The calibrated model was modified to simulate the effects on streamflow for various water uses, and for projected 2030 water-use and land-use change, over long-term (1960–2004) climatic conditions. Additional simulations were made to simulate the effects of reactivating a cluster of production wells north of Lake Cochituate. The model results focused on the effects on streamflow in the upper Sudbury River basin (RCHRESs 1 through 19).

Water uses simulated include no withdrawals (NOWU), average 1993–2003 withdrawals (AVGWU), groundwater-only withdrawals (GWoWU), and surface-water-only withdrawals (SWoWU). The NOWU scenario shut off all withdrawals, return flows (discharges from wastewater treatment plants), water imports from areas on public water supply and on-site septic disposal, and water exports through sewer

I&I losses. Average water use (AVGWU) applied the mean monthly withdrawals from 1993 through 2003 and computed streamflow depletion to the long-term (1960–2004) period except when actual withdrawals and associated streamflow depletion data were available. GWoWU and SWoWU simulations are similar to the AVGWU simulation except for turning off surface-water withdrawals and groundwater withdrawals, respectively.

The change in AVGWU simulated streamflows relative to NOWU simulated streamflows was most pronounced in Piccadilly Brook (PBWB, RCHRES 2) and Jackstraw Brook (JBWB, RCHRES 1). These are relatively small headwater subbasins where the ratios of mean annual withdrawals to mean annual streamflow are the highest. Daily mean flow-duration curves developed from 1960–2004 simulated flows indicate that the AVGWU curve noticeably departs from the NOWU curve at about the 20- to 30-percent exceedence interval and is appreciably altered by about the 50-percent exceedence interval in these reaches. Current withdrawals result in flows of 0.01 ft^3/s or less about 20 percent of the time in Jackstraw Brook and about 30 percent of the time in Piccadilly Brook, whereas under no withdrawals, both brooks maintain a minimum flow of about 0.4 $ft^3/s/mi^2$. AVGWU simulated flows were also appreciably smaller than NOWU simulated flows in Ashland Reservoir outlet (ARES, RCHRES 10) and Lake Cochituate outlet (LCNA, RCHRES 16). Flow-duration curves developed from 1960–2004 simulated flows indicate that the AVGWU curve begins to noticeably depart from the NOWU curve at about the 70-percent exceedence interval in these reaches. AVGWU simulated flows indicate that flows are less than 0.1 ft^3/s about 10 percent of the time in Ashland Reservoir outlet and about 2 percent of the time in Lake Cochituate outlet. NOWU simulations indicate Lake Cochituate outlet maintains a minimum flow of about 0.2 ft^3/s, whereas in the Ashland Reservoir, outlet flows fall below 0.1 ft^3/s about 2 percent of the time. The effects of withdrawals on streamflow in other subbasins in the upper Sudbury River Basin are less pronounced and mainly reflect the perpetuation of the effects of withdrawals from the reaches noted above. In general, the change in streamflow associated with groundwater-only withdrawals (GWoWU) relative to no withdrawals is similar to that for average 1993–2003 withdrawals relative to NOWU because most withdrawals in the upper Sudbury River Basin are from groundwater sources. The change in streamflow with surface-water-only withdrawals (SWoWU) relative to NOWU was only notable in Piccadilly Brook.

Four simulations examined the effects of potential 2030 water- and land-use change projected by the Metropolitan Area Planning Council (MAPC). Two simulations evaluated the effects of water-use change only—30WU99LU, changes in water demand were distributed among existing supply sources, and 30WUa99LU, changes in water demand were simulated as dispersed domestic wells with a 20-percent consumptive-loss rate. In 30WUa99LU simulations, the remaining 80 percent was assumed to be returned through on-site septic disposal. Two other simulations evaluated the effects of both land-use and water-use change—30LUWU, which distributed projected withdrawals among existing sources, and 30WULUalt, which dispersed withdrawals among domestic wells and returns as described above. Simulations of land-use change redistributed the HRU areas to reflect the projected 2030 land-use conditions. In general, the majority of land-use change was from forest to low-density residential development. In the upper Sudbury River Basin, open forest area decreased by about 52 percent and low-density residential area increased by about 145 percent. Overall, the area classified in some type of developed land-use category in the upper Sudbury River Basin changed from about 42 percent in the calibrated model (1997 land use) to about 64 percent in 2030. Because most of the anticipated development is low-density residential and new development employs techniques that minimize the effects of imperviousness, the simulated change in effective impervious area increased only by 3 percent in the upper Sudbury River Basin (from 10 to 13 percent).

Streamflow simulated under estimated 2030 withdrawal demands distributed among existing supply sources (30WU99LU) indicates only minor decreases in the median of the August mean flows relative to AVGWU (1 to 5 percent). In the two headwater basins with large withdrawals (Jackstraw and Piccadilly Brooks), the small decreases reflect that the model does not account for withdrawals in excess of streamflow, which is a limitation of the model. The median August mean streamflow simulated under estimated 2030 withdrawal demands (30WU99LU and 30WUa99LU) indicates Ashland Reservoir outlet (ARES, RCHRES 10) and the next downstream reach, Cold Spring Brook (CBAS, RCHRES 11), increased substantially relative to AVGWU. Withdrawals from the ARES subbasin are largely for irrigation purposes; those agricultural lands were converted to low-density residential development. Under average 1993–2003 withdrawals, the median August mean streamflow decreased by 34 and 30 percent relative to NOWU in RCHRES 10 and 11, respectively. Projected 2030 demands distributed among existing supply sources (30WU99LU) indicate no change from the NOWU simulation in these reaches and modest reduction in flow of 3.4 and 2.7 percent in reaches 10 and 11, respectively, relative to the NOWU when 2030 demands are from dispersed domestic well withdrawals (30WUa99LU).

The effects of land-use and water-use change (30WULU and 30WULUalt) are markedly different from AVGWU and from simulations of projected water-use change only. In subbasins with large municipal withdrawals, the median of the August mean streamflow decreased by an amount comparable to AVGWU simulated flows. In most other subbasins, the median of the August mean streamflow increased substantially relative to the AVGWU simulated flows; streamflows

increased above the NOWU simulated flow in 13 of 19 subbasins. The increase in low flow is attributed to a decrease in evapotranspiration loss associated with a loss of deep-rooted vegetation. Changes in the long-term mean annual flows associated with development (30WU99LU and 30WUa99LU) indicate flow in most reaches remained about the same as AVGWU simulated flows. At most, long-term mean annual flow associated with water-use change only was about 3 percent more than the change in AVGWU simulated flow relative to NOWU simulated flows.

Simulations of withdrawals from reactivation of the Birch Road production wells near the north end of Lake Cochituate indicate lake stage and discharge at the lake outlet and in the Sudbury River at the Saxonville streamgage (a proxy for changes in flow below the streamgage) could be substantially affected during periods of low flow. These effects vary depending on the sources of the water to the wells, which are unknown. It should also be noted that the simulation results are based on a constant pumping rate, but if pumping rates were varied, the effects on lake stage and flow could be mitigated if withdrawals were decreased at the appropriate times and by the appropriate amounts.

The HSPF model was conceptualized and calibrated to evaluate the effects of withdrawals on streamflow. Many water-resource-management questions can be addressed by model simulations, but the model may not be appropriate for some analyses. Care should be taken to consider the model uncertainties and limitations to ensure that the simulation results do not lead to inaccurate conclusions. Simulations of projected 2030 water-use and land-use changes on streamflows have inherent limitations and uncertainty because the exact nature of future development is unknown. The extent to which increased water demands are offset by decreased evapotranspiration losses will vary locally and may be reflected by one simulation more than another. Although tools such as HSPF are designed to simulate the effects of alternative water-management strategies and basin changes on water resources, it is necessary to determine whether model results can be appropriately used in making a specific water-resources management decision.

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Chapter 2—Fish Communities, Stream Temperature, and Assessment of Minimum Streamflow Targets for Aquatic Habitat at Selected Sites in the Sudbury and Assabet River Basins, Massachusetts

When streamflows are naturally low, typically during the summer between July and September, a conflict for water often arises between the needs of humans and those of aquatic life. This conflict is often veiled but is increasingly moving to the forefront as government agencies, nongovernment agencies, and water suppliers try to find the appropriate balance to meet conflicting water needs. The quality and quantity of the habitat that supports the biological integrity of the Sudbury and Assabet River Basins in eastern Massachusetts are of growing concern because of streamflow alterations by water withdrawals and wastewater returns.

To help address these concerns, streamflows, fish communities, and stream temperatures were characterized at selected sites in the Sudbury and Assabet River Basins to evaluate the current condition of the aquatic habitat. These types of studies provide critical information for policy makers and other interested stakeholders that can assist in the determination of an appropriate balance between the needs for human water supply and aquatic habitat. These studies also help provide quantitative measures of some of the common aquatic stresses and their potential causes that could inform the management-decision process.

Purpose and Scope

This chapter describes fish communities, variation in stream-water temperature, and the streamflow needed to support aquatic habitat in the upper Sudbury and Assabet River Basins. The fish-community data, collected by the MADFW, are summarized for flowing reaches (not impounded) at five sites in the Sudbury River main stem and eight sites in the Assabet River main stem. Additional cold-water fish-community data are summarized for tributary reaches to these rivers. Water-temperature data were collected at seven sites in the upper Sudbury River Basin between August 2004 and June 2006. These data are summarized and characterized with respect to water-temperature tolerances of brook trout, a cold-water fish.

Streamflow targets intended to preserve aquatic habitat were determined by standard-setting methods at riffle reaches at six sites in the Sudbury River Basin and four sites in the Assabet River Basin. Standard-setting methods included the Wetted-Perimeter, R2Cross, Tennant, Aquatic Base Flow (ABF), and the Range-of-Variation (RVA) for a select set of hydrologic statistics; the last three methods relied on simulated unaltered streamflows determined by the HSPF precipitation-runoff model developed for the Sudbury and Assabet River Basins described in the first chapter of this report. Streamflows simulated by the HSPF model at the riffle sites were also used to determine and contrast the frequency and the duration that streamflows were below the flow thresholds determined by the various standard-setting methods.

Fish Communities

Fish-community composition is generally considered a good measure of the ecological condition of a river because fish are sensitive to a wide range of stresses that reflect conditions over time. Although fish can live in different aquatic habitats, many species of fish are adapted to life in flowing waters and are considered riverine or fluvial fish. Ecologically healthy rivers have fish communities that are predominantly fluvial (Bain and Meixler, 2000, 2008). Many fluvial fish species require riffle habitat for part or all of their life cycle. Most streams in coastal Massachusetts naturally lack riffle habitat because of low gradients. Although streams in central Massachusetts have abundant riffles, many of these riffles have been hydrologically altered for many years by past mill dams, road crossings, and other uses. Fish-community composition can also be influenced by water temperature and quality. Data on fish-community composition in free-flowing reaches of the Sudbury and Assabet River Basins collected by the MADFW as part of their Statewide Fisheries Assessment Program were compiled to better understand the condition of river habitat.

Fish were sampled during the summer during low to moderate flows because fish-community assemblages at this time are relatively stable and reflect the range of resident species (Gibson and others, 1996). The fish-community assessment was designed to characterize the diversity and relative abundance of fish species. The MADFW fish data also include the length-frequency distribution; however, these characteristics were not examined as part of this study. Sampling was conducted in selected free-flowing reaches on the river main stem and on tributaries. Where possible, a minimum reach length of 300 ft was sampled by electrofishing with pulsed direct current (DC) backpack units and barges. Backpack electrofishing units are best used in small or shallow streams and were used for sampling most tributary and headwater reaches in the Assabet and Sudbury River Basins. Barge electrofishing units (fig. 34) were used in many of the main-stem reaches of the Assabet and Sudbury Rivers where a strong power supply was needed.

Figure 34. Massachusetts Department of Fish and Game, Division of Fisheries and Wildlife (MADFW) barge electrofishing to assess river-fish community composition. Photo courtesy of MADFW.

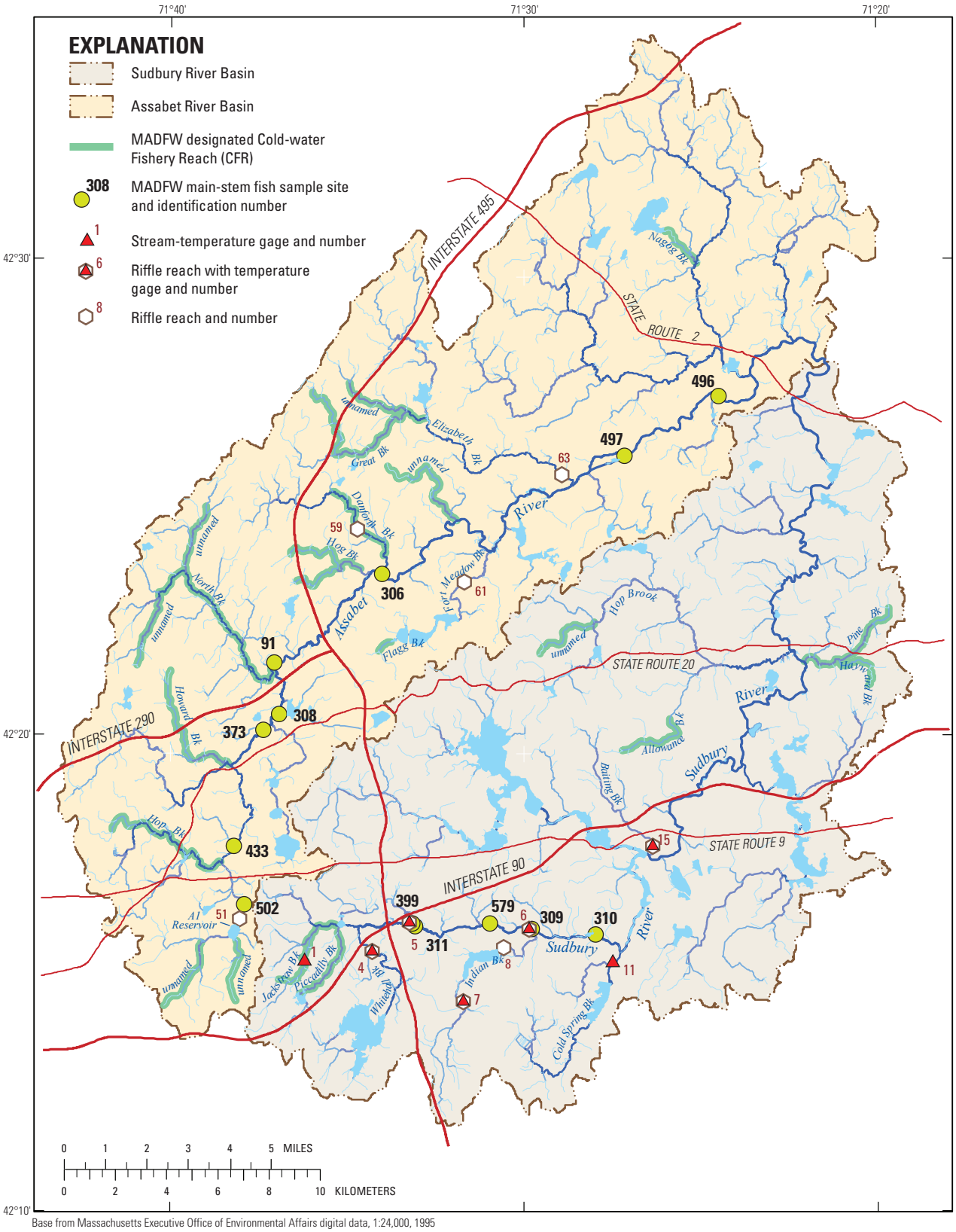
Fish were classified into three habitat-use categories—macrohabitat generalists, fluvial dependents, and fluvial specialists (Bain and Knight, 1996; Bain and Meixler, 2000, 2008). Macrohabitat-generalist fish species use a broad range of habitat to complete their life cycle and are commonly found in lakes, reservoirs, and streams. Fluvial-dependent fish species require access to flowing-water habitats for a specific life stage, but can complete part of their life cycle in non-flowing waters such as lakes and reservoirs. Fluvial-specialist fish species require flowing-water habitats throughout their life cycle and, therefore, are limited to free-flowing reaches (Bain and Travnichek, 1996).

Fish can live in different habitat conditions in different geographic areas. For the purposes of this study, habitat-use classifications were modified from Bain and Meixler (2000) to accommodate regional differences in habitat requirements. For example, the creek chub was reclassified from macrohabitat generalist to fluvial specialist on the basis of its habitat use in Massachusetts streams (M. Kearns, Massachusetts Department of Fish and Game, written commun., 2006).

Main-Stem River Fish Communities

Fish-community samples were collected at five locations on the main stem of the Sudbury River in July and August 2001 (fig. 35). The sampled reaches are downstream from Whitehall Brook and upstream from Cold Spring Brook in the upper part of the basin. A total of 390 fish of 14 species were collected (table 15); of these, nearly 71 percent were macrohabitat generalists (fig. 36A).

Fish-community samples were collected at eight locations on the main stem of the Assabet River (fig. 35); most sampling was done in June through August 2001 and one sample (91) was collected in August 1999. A total of 1,065 fish of 22 species were collected (table 15), including a tiger trout that is a cross species of brown and brook trout. Stocked salmonids,



Base from Massachusetts Executive Office of Environmental Affairs digital data, 1:24,000, 1995
Polyconic projection. North American Datum of 1983
Massachusetts coordinate system mainland zone

Figure 35. Main-stem fish-sampling sites, cold-water fishery reaches, stream-temperature gages, and riffle study locations in the Sudbury and Assabet River Basins, Massachusetts. MADFW, Massachusetts Division of Fisheries and Wildlife.

Table 15. Fish species and numbers captured at selected free-flowing reaches in the main stem of the Sudbury and Assabet Rivers, Massachusetts.

[Data courtesy of Massachusetts Division of Fisheries and Wildlife; Habitat class; FD, fluvial dependent; FS, fluvial specialist; MG, macrohabit generalist]

Common name	Species name	Count	Habitat class	Percent	
				Total	Total in habitat class
Sudbury River					
White sucker	*Catostomus commersoni*	20	FD	5.1	100
Fallfish	*Semotilus corporalis*	93	FS	34	99
Rainbow trout[1]	*Oncorhynchus mykiss*	1	FS	0.3	1.1
Redfin pickerel	*Esox americanus americanus*	154	MG	39	56
Largemouth bass	*Micropterus salmoides*	30	MG	11	11
Rock bass	*Ambloplites rupestris*	23	MG	7.7	8.3
Yellow bullhead	*Ameiurus natalis*	19	MG	5.9	6.9
Redbreast sunfish	*Lepomis auritus*	16	MG	4.9	5.8
Bluegill	*Lepomis macrochirus*	9	MG	3.3	3.3
Yellow perch	*Perca flavescens*	9	MG	3.3	3.3
Pumpkinseed	*Lepomis gibbosus*	7	MG	2.5	2.5
Chain pickerel	*Esox niger*	5	MG	1.3	1.8
Brown bullhead	*Ameiurus nebulosus*	3	MG	0.8	1.1
Golden shiner	*Notemigonus crysoleucas*	1	MG	0.3	0.4
Assabet River					
White sucker	*Catostomus commersoni*	305	FD	29	100
Fallfish	*Semotilus corporalis*	78	FS	7.3	38
Blacknosed dace	*Rhinichthys atratulus*	74	FS	6.9	36
Brown trout[1]	*Salmo trutta*	20	FS	1.9	9.7
Rainbow trout[1]	*Oncorhynchus mykiss*	16	FS	1.5	7.8
Creek chubsucker	*Erimyzon oblongus*	15	FS	1.4	7.3
Brook trout[1]	*Salvelinus fontinalis*	2	FS	0.2	1.0
Tiger trout[1]	*Salvelinus fontinalis X Salmo trutta*	1	FS	0.1	0.5
Largemouth bass	*Micropterus salmoides*	82	MG	7.7	15
Bluegill	*Lepomis macrochirus*	77	MG	7.2	14
American eel	*Anguilla rostrata*	75	MG	7.0	14
Golden shiner	*Notemigonus crysoleucas*	71	MG	6.7	13
Redbreast sunfish	*Lepomis auritus*	56	MG	5.3	10
Yellow bullhead	*Ameiurus natalis*	56	MG	5.3	10
Redfin pickerel	*Esox americanus americanus*	55	MG	5.2	9.9
Pumpkinseed	*Lepomis gibbosus*	33	MG	3.1	6.0
Chain pickerel	*Esox niger*	16	MG	1.5	2.9
Spottail shiner	*Notropis hudsonius*	11	MG	1.0	2.0
Yellow perch	*Perca flavescens*	8	MG	0.8	1.4
Black crappie	*Pomoxis nigromaculatus*	6	MG	0.6	1.1
Brown bullhead	*Ameiurus nebulosus*	6	MG	0.6	1.1
Banded sunfish	*Enneacanthus obesus*	2	MG	0.2	0.4

[1]Stocked salmonid.

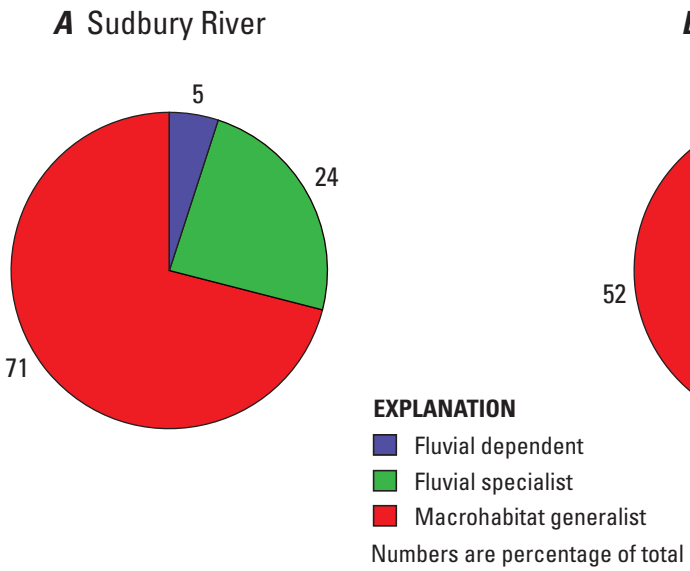


Figure 36. Proportion of the fish community comprised of fluvial specialists, fluvial dependents, and macrohabitat generalists collected in the main stem of the (*A*) upper Sudbury and (*B*) Assabet Rivers, Massachusetts.

which included 20 brown trout, 16 rainbow trout, 2 brook trout, and 1 tiger trout, were removed from the description of the fish-community assessment below because they were stocked in the stream or adjacent waters by the MADFG and are not considered part of the self-sustaining native fish population. White suckers, a pollution-tolerant species, dominated the fish community in the main stem of the Assabet River (29 and 100 percent of the total and fluvial communities, respectively), indicating that water quality may be a factor affecting the fish-community composition. Although the Assabet River contains a diversity of species similar to that expected in a natural river in southern New England (Kashiwagi and Richards, 2009), macrohabitat generalists still dominated the river (52 percent; fig. 36B), indicating other hydrologic alterations may be affecting the fish community.

Cold-Water Fishery Resources

The fish communities sampled in the main stem of the Sudbury and Assabet Rivers were primarily composed of fish that could tolerate warmer summer water temperatures. The tributaries to the Sudbury and Assabet Rivers vary greatly with respect to the degree of habitat, flow, and water-quality alteration. Some of these streams maintain a population of native cold-water fish, in this case brook trout, which is identified in the Massachusetts Wildlife Action Plan (Massachusetts Division of Fisheries and Wildlife, 2006) as a species in greatest need of conservation.

The status of brook trout in the Sudbury and Assabet River tributaries was characterized by the Conservation Strategy Work Group Eastern Brook Trout Joint Venture (2005) as greatly reduced or even extirpated in some areas. The Eastern Brook Trout Joint Venture identified that stresses to populations of brook trout in Massachusetts were primarily caused by hydrologic alterations from dams, roads, and urbanization. These alterations result in increases in temperature and sedimentation, and changes to the natural flow regime.

Although the presence of brook trout in a water body does not mean the stream is pristine, it does indicate that the water quantity, water quality, and physical habitat are sufficient to maintain this sensitive species. The MADFG has identified 21 tributary reaches (fig. 35) as Cold-water Fishery Resources (CFRs) in the Sudbury (6 reaches) and Assabet (15 reaches) River Basins. Other CFRs may exist in the basin but have not yet been sampled. Many CFRs in the Sudbury and Assabet River Basins have drainage areas in or near Interstate 495 that are increasingly affected by urbanization. Even though some of these reaches have fish communities dominated by cold-water species, other reaches have been impacted by flow and water-quality alteration to the point that the cold-water community is reduced or absent in recently collected samples by the MADFG.

Stream Temperature

Water-temperature data were collected at seven sites in the upper Sudbury River Basin between August 2004 and June 2006 (fig. 35). Data were collected at 30-minute intervals with instream data loggers installed inside perforated PVC pipes mounted about 0.5 ft above the streambed on staff gages, trees, or a steel bar set in the streambed. Because water withdrawals and impoundment releases have been shown to

effect the downstream water temperature (Poole and Berman, 2001), the seven water-temperature sites were divided into two groups related to their position relative to impoundments and water withdrawals. Three sites were on free-flowing tributaries upstream from water withdrawals and impoundments: (1) Jackstraw Brook near Westborough, (7) Indian Brook near Hopkinton, and (15) Baiting Brook near Framingham. Jackstraw Brook is identified by the MADFW as a CFR. Four sites were downstream from impoundments or water withdrawals, or both: (4) Whitehall Brook near Hopkinton, (5) Sudbury River near Hopkinton, (6) Sudbury River near Ashland, and (11) Cold Spring Brook near Ashland. Note the number in parentheses above refers to the gage identification number shown in figure 35, which is referenced to the reach number (RCHRES) in the HSPF model.

Stream temperatures were evaluated relative to the tolerances of brook trout because of State and local concerns regarding maintenance of these native fish and their sensitivity to water temperature. In general, summer stream temperatures below 66°F are considered favorable for brook trout, and temperatures in the range of 68–84°F are considered precarious for brook-trout survival (Elliot, 1994). Although brook trout can tolerate temperatures in the 68–84°F range, their normal behavior is affected and can vary from cessation of feeding to death. These physiological effects increase in intensity as stream temperatures rise and are sustained for longer periods. During prolonged warm periods, populations of brook trout can exist in thermally marginal streams if sufficient cold-water refuges exist, such as shaded margins, springs, or pools that receive cool groundwater discharge. However, the distribution and abundance of brook trout in relation to temperatures of local cold-water refuges were not determined in this study. Stream temperatures recorded at the study sites provide a general indication of the suitability of summer stream temperatures for cold-water fish species (figs. 37 and 38). A 7-day moving mean of daily maximum stream temperature was computed to illustrate differences in stream temperatures between the study sites and to more easily evaluate the duration and magnitude of stream temperatures in the critical range for brook trout.

The 7-day mean maximum daily temperature in Jackstraw Brook was generally below the critical range for brook trout (68–84°F) for all but a few days during the summer. When the temperatures were above the critical threshold, it was usually near the lower limit. In addition, the 7-day mean maximum daily temperatures in Jackstraw Brook were near or below the upper optimum summer temperature (66°F) for brook trout. The minimum daily temperatures were generally in the optimum range (55–66°F) for most of the summer period, but the daily maximums still rose into the critical range during part of the day. The cool stream temperatures in this segment of Jackstraw Brook are believed to be caused by the combined effects of groundwater discharge and shading of the stream channel. Jackstraw Brook provided the best water-temperature habitat for brook trout of the seven sites examined.

Stream temperatures recorded at Indian and Baiting Brooks, the other two sites unaffected by dams or withdrawals, were in the critical temperature range for longer periods and at higher temperatures than at Jackstraw Brook (fig. 37), but temperatures were less than those recorded at the four sites affected by dams or withdrawals, or both (fig. 38). The higher 7-day mean maximum daily temperature and intradaily temperatures in Indian and Baiting Brooks relative to Jackstraw Brook are believed to be caused by the large wetlands in the headwaters of Indian Brook subbasin, the removal of riparian vegetation, and the greater amount of impervious area in the Baiting Brook subbasin.

The cooler summer water temperatures measured in the three unregulated tributary streams could potentially support a cold-water fishery, and brook trout have been found in samples collected at Jackstraw Brook by MADFW in the area of the temperature recorder. Although stream temperatures measured in Indian Brook and Baiting Brook were also near or within the summer optimum water-temperature range for brook trout, other conditions such as altered habitat, water quality, low flows, and impairments to stream passage may limit the ability of brook trout to find survivable habitat or move between suitable habitats.

The 7-day mean maximum daily temperatures observed at four study sites downstream from reservoirs and withdrawals (Whitehall Brook near Hopkinton, Sudbury River near Hopkinton, Sudbury River near Ashland, and Cold Spring Brook near Ashland) are generally similar and tend to be in the upper end of the critical range for brook trout survivability for a substantial time during the summer (fig. 38). Further, the temperature fluctuations during the day tend to be less at these sites compared to sites unaffected by reservoirs or withdrawals. This is likely caused by warm water released from the epilimnion (upper stratified water layer in the reservoir), whereas streams unaffected by dams have relatively large diurnal temperature fluctuations that are caused by discharge of cool groundwater to the stream, which warms during the day from solar radiation and increased daytime air temperatures. Hence, stream-water temperature can increase if the amount of groundwater discharging to a stream is reduced (Baevsky, 1991; Stark and others, 1994; Picard, 1995). This may be a factor at the temperature monitoring sites in the Sudbury River. The small daily temperature fluctuations likely result in fewer temporary refuges from warmer waters creating a more-stressed environment for temperature-sensitive fish. Overall, the 7-day mean maximum daily temperatures at the four sites affected by dams or withdrawals, or both, indicate that habitat for brook trout was marginal or poor in these reaches.

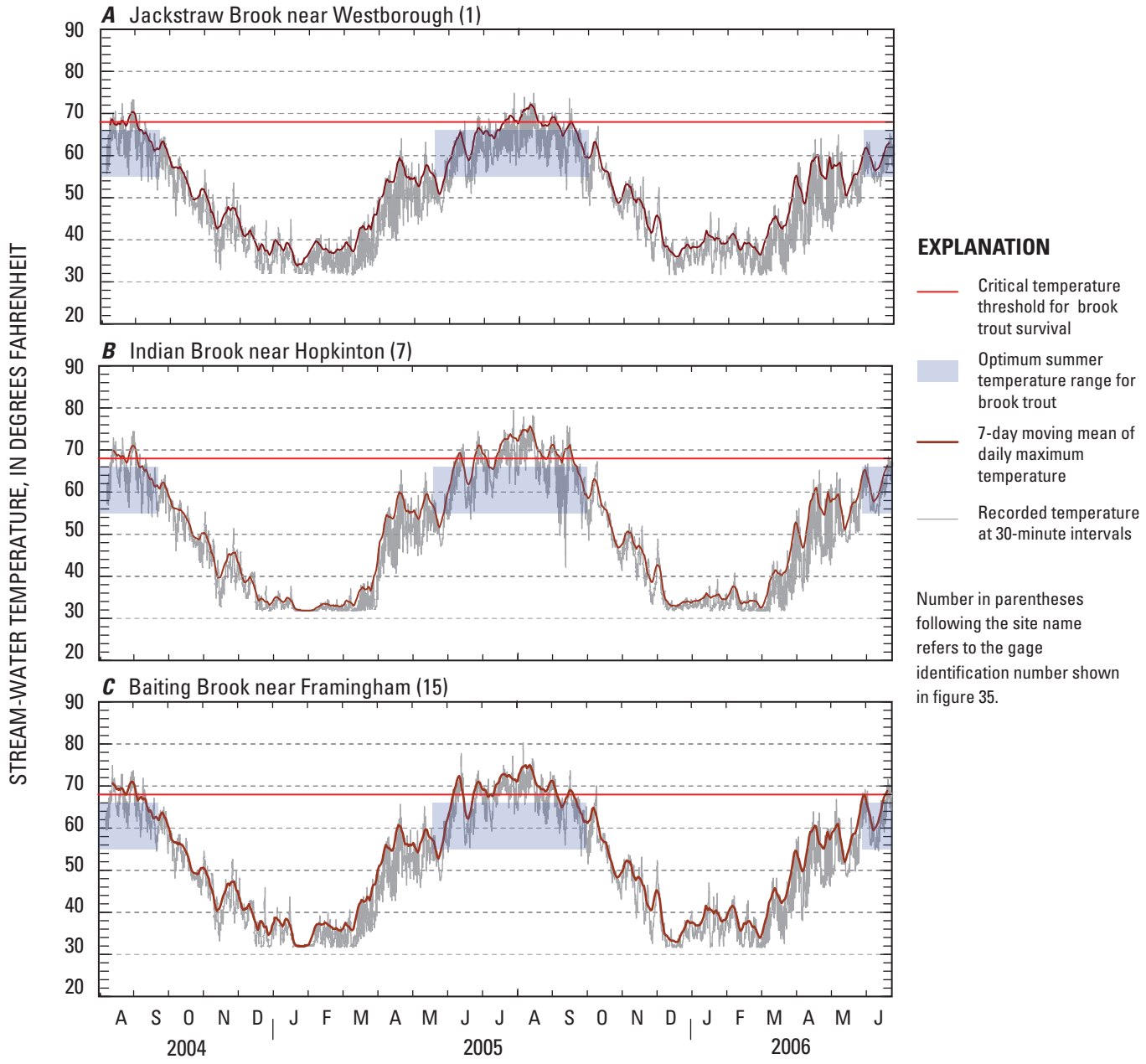


Figure 37. Stream-water temperature recorded between August 2004 and June 2006 in reaches unaffected by dams or withdrawals at (*A*) Jackstraw Brook near Westborough, (*B*) Indian Brook near Hopkinton, and (*C*) Baiting Brook near Framingham, Sudbury River Basin, Massachusetts.

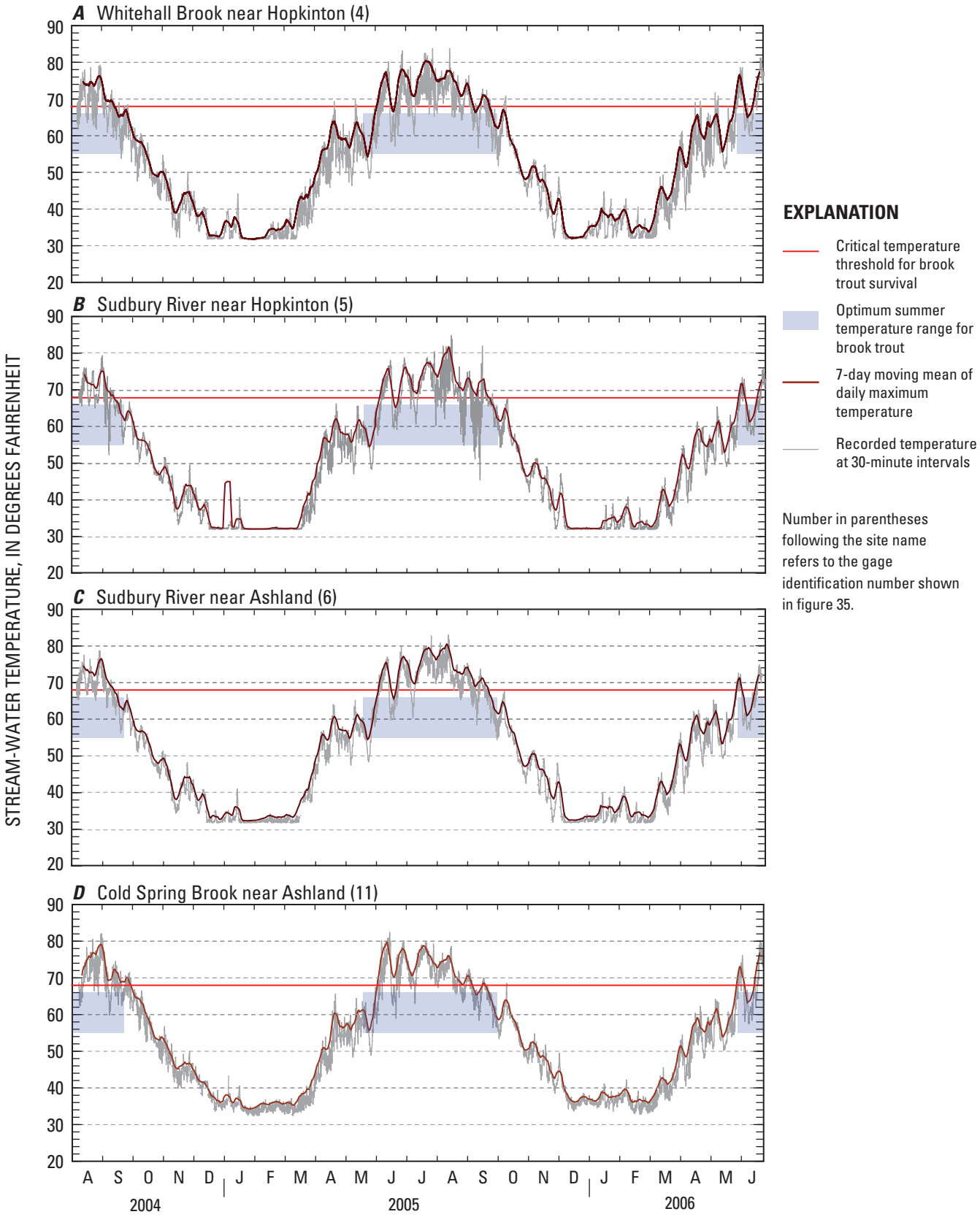


Figure 38. Stream-water temperature recorded between August 2004 and June 2006 in reaches below dams or withdrawals, or both, at (*A*) Whitehall Brook near Hopkinton, (*B*) Sudbury River near Hopkinton, (*C*) Sudbury River near Ashland, and (*D*) Cold Spring Brook near Ashland, Sudbury River Basin, Massachusetts.

Determination and Assessment of Target Streamflows for Aquatic Habitat at 10 Riffle Sites

Streamflow needs to maintain a healthy aquatic habitat were determined at 10 selected riffle sites in the Sudbury and Assabet River Basins (fig. 35) using 5 standard-setting methods. Five of these sites (4, 5, 6, 7, and 15) are coincident with the stream-temperature monitoring sites. The riffle identification number is the HSPF-model reach number associated with the riffle site. Streamflows computed by standard-setting methods are considered the minimal flow necessary to protect aquatic habitat and are referred to in this report as target streamflows. Most methods identify target streamflows appropriate for normal seasonal low- and high-flow periods.

The standard-setting methods were divided into two categories—physically based and statistically based methods. Physically based methods included Wetted-Perimeter (Nelson, 1984; Leath and Nelson, 1986; Lohr, 1993) and the R2Cross (Nehring, 1979; Espegren, 1996, 1998); statistically based methods included Tennant (Tennant, 1976) and New England ABF (U.S. Fish and Wildlife Service, 1981; Lang, 1999). A limited set of statistics from the RVA method (Richter and others, 1996) was also used. The RVA method is considered a diagnostic flow-assessment technique by the Instream Flow Council (2004) but was grouped with the statistical methods because only a limited set of flow statistics from the method were used in the analysis. The physical characteristics of the riffle reaches are described with the results of the physically based target flow determinations because they are inherently linked.

Physically Based Streamflow Targets

The physically based target standard-setting methods, R2Cross and Wetted-Perimeter, were applied at six riffle reaches in the Sudbury River Basin and at four riffle reaches in the Assabet River Basin. These methods require site-specific physical and hydraulic data and can be applied at ungaged or flow-altered sites. However, values obtained by these methods are still subject to limitations as described later. Cross-section data and measurements of water-surface elevations in a riffle over a range of flows were used to develop and calibrate a one-dimensional hydraulic flow model, HEC-RAS (Brunner, 2006), for each site. The HEC-RAS model was used to compute streamflows that satisfy criteria for the R2Cross and Wetted-Perimeter methods. In general, the HEC-RAS models, documented in appendix 2 for the Sudbury River Basin sites and in Parker and others (2004) for the Assabet River Basin sites, were well calibrated to the observed water-surface gradients.

Streamflow needed to satisfy the criteria for the physically based methods was determined from HEC-RAS simulations at one to five cross sections within each riffle that varied on the basis of their suitability for inclusion in the analysis. The streamflows reported for each method are the minimum flows needed to satisfy the method. The number of cross sections used for determining streamflow targets was typically less than the number of cross sections used for developing the HEC-RAS models. This was mostly because downstream cross sections were dropped from the determination of streamflow targets because of backwater conditions. The channel in each study reach was generally trapezoidal and its geometry was generally not a limiting factor in determining streamflow targets with physically based methods.

Physically based methods assume that a streamflow chosen to maintain a riffle habitat is sufficient to maintain the habitat in nearby pools and runs for most life stages of fish and aquatic invertebrates (Nehring, 1979; Annear and Conder, 1984; Lohr, 1993; Nelson, 1984). The R2Cross method considers three channel hydraulic properties in the determination of a streamflow target—average velocity, mean depth, and a percentage of the bankfull wetted perimeter; the latter two variables vary according to the bankfull top width of the stream (table 16). The wetted perimeter of a stream is defined as the cross-sectional length of channel (streambed and banks) in contact with water, but in R2Cross, this variable is defined as the flow necessary to maintain between 50 and 70 percent of the bankfull wetted perimeter in contact with water, depending on the bankfull top width. Bankfull refers to the normal channel incision into the landscape for conveying all but the highest streamflows.

To account for seasonal streamflow variability, the R2Cross method establishes different streamflow targets for the summer and winter seasons on the basis of the number of criteria met. The R2Cross streamflow targets in Colorado (Espegren, 1996), where the method was developed, are based

Table 16. R2Cross method hydraulic criteria in relation to channel bankfull top width.

[ft, feet; ft/s, foot per second]

Bankfull top width (ft)	Average depth[1] (ft)	Bankfull wetted perimeter[2] (percent)	Average velocity (ft/s)
1–20	0.2	50	1
21–50	0.2–0.5	50	1
51–60	0.5–0.6	50–60	1
61–100	0.6–1.0	70	1

[1] Values are scaled between 21 and 100 feet for the ranges shown.

[2] Values are scaled between 51 and 61 feet for the range shown.

on flows that meet or exceed any two of the three criteria (2-of-3) during the normal low-flow period and all three criteria (3-of-3) during the normal high-flow period. The R2Cross 2-of-3 and 3-of-3 criteria flows are reported, but as explained later, flows required to meet the 3-of-3 criteria do not appear to be applicable to seasonal high flows in this region.

In the Wetted-Perimeter method, the flow necessary to keep the channel cross section in contact with water at the lower edges of the streambanks is the streamflow target. In trapezoidal-shaped channels with steep banks, the flow needed to maintain a wetted perimeter to the bottom edges of the streambanks is usually easily identifiable by a sharp break in the wetted perimeter-discharge relation. In triangular, bowl-shaped, or gently sloping trapezoidal-shaped channels, a clear breakpoint in the wetted perimeter-discharge relation may not be easily identifiable. An example of a breakpoint in the wetted perimeter-streamflow relation that cannot be easily identified is shown in figure 39D for cross section XS4 in Fort Meadow Brook. In these types of situations, breakpoints in the water-surface elevation in relation to the wetted perimeter were used as a surrogate measure to define the flow corresponding to the wetted perimeter extending to the edges of the streambanks (fig. 39C). A cross check was made of the field-surveyed elevations of the bottom edges of the streambank with the elevation-wetted perimeter breakpoint. If these were reasonably consistent, the flow corresponding to that wetted perimeter determined at the breakpoints was used as the streamflow requirement for that cross section. If no distinct breakpoints were observed in the elevation-wetted perimeter relation, or if the points didn't reasonably correspond to the field observations, a streamflow requirement was not determined for that cross section.

It should be noted that application of the R2Cross and Wetted-Perimeter methods requires careful selection of riffle sites. A riffle is a section of channel, usually between pools, that has gravel-to-cobble-sized bed material and a relatively steep channel slope. Differences in channel geometry throughout the riffle create variability in the determination of the flow needed to satisfy the method. To minimize some of the variability, cross sections in riffles that have large boulders or woody debris in the channel or altered streambeds or streambanks were avoided. For each method, flow targets were determined at each cross section used in the analysis, but to minimize the variability of these values, a median value was computed from the individual target values within a reach.

Artificial widening or narrowing of the stream channel, such as bank reinforcement with riprap, affects the wetted perimeter, average velocity, and average depth; hence, altered channels were avoided in the selection of riffle cross sections. Flow targets computed by physically based methods in artificially restricted channels may be excessive compared to nearby natural riffle sites; conversely, flow targets determined for natural riffle sites may not be sufficient to protect habitat in artificially widened channels.

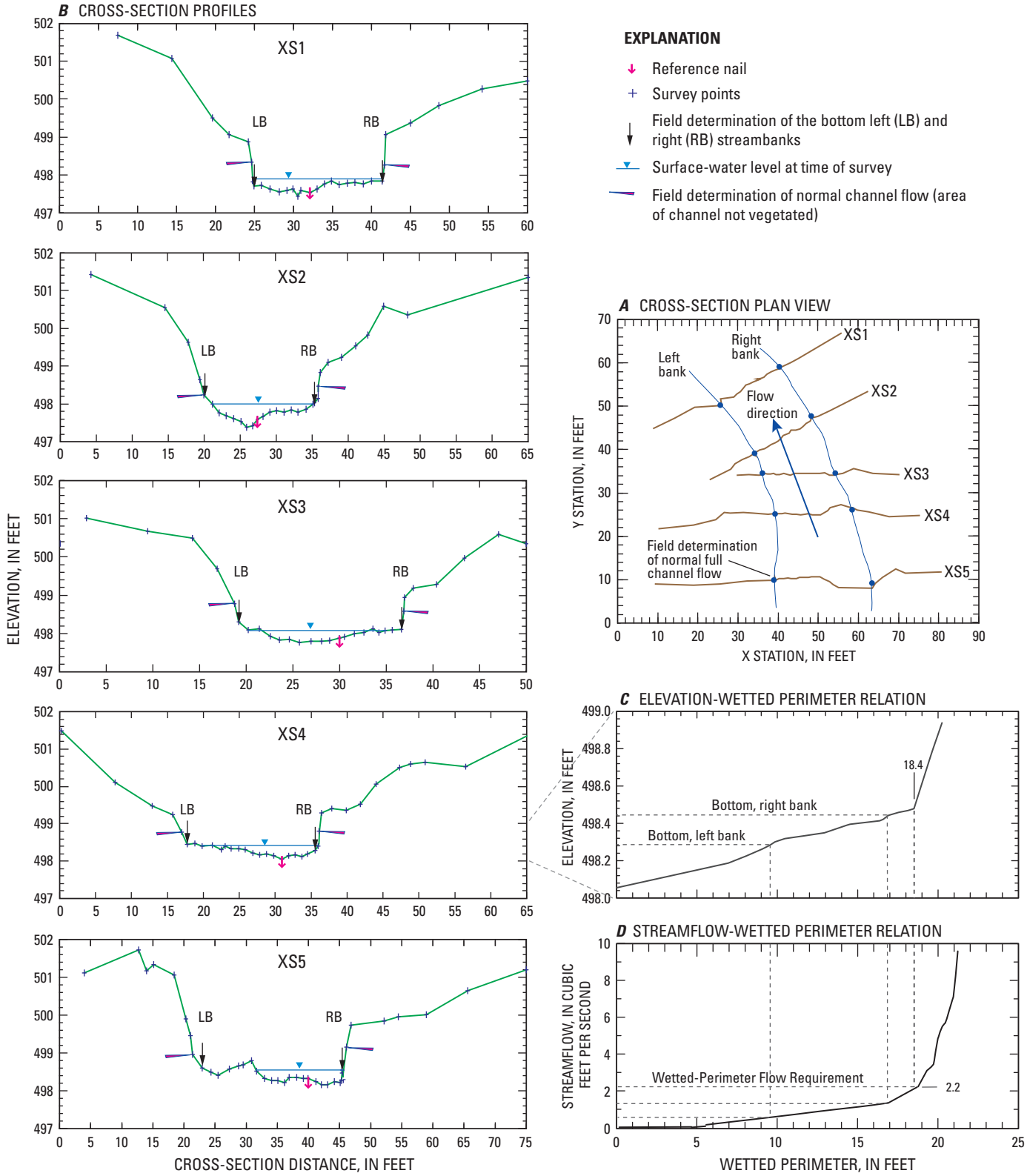


Figure 39. Riffle-reach study section showing (*A*) position of cross-section surveys, (*B*) cross-section profiles, (*C*) elevation and wetted perimeter relation, and (*D*) streamflow and wetted perimeter, Fort Meadow Brook near Hudson, Massachusetts. Elevation is an arbitrary reference datum.

Whitehall Brook near Hopkinton

The riffle reach on Whitehall Brook (fig. 40; reach 4, fig. 35) is about 60 ft downstream from the Fruit Street Bridge near Hopkinton. Four cross sections were surveyed in September 2003 along a 90-ft reach. The streambed is primarily sand and gravel with a few cobbles; about 90 percent or more of the bed is covered by eel grass with an open section through the middle of the reach. Channel banks are primarily silt and sand with a mix of organic material. The left bank is covered by grass and sedge with a narrow border of hardwood trees; the right bank is covered by scattered trees, wetland shrubs, and lawn grass. The water-surface gradient in the reach is moderately sloped with a measured drop of about 0.5 ft for streamflows ranging from 1.1 to 196 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 118, 128, and 136 were unaffected by backwater during low to moderate flows and were used in the R2Cross analysis. The top width at normal channel flow (the stream channel that is mostly void of vegetation) in these sections ranged from about 16 to 23 ft with a median width of about 21 ft. The limiting hydraulic metric (depth, velocity, or wetted perimeter) varied with the R2Cross 3-of-3 and 2-of-3 criteria at the three cross sections (table 17). Overall, depth was the most limiting factor, followed by wetted perimeter and velocity. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 3.3 to 4.2 ft^3/s with a median of 3.6 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged from 1.1 to 1.4 ft^3/s with a median of 1.2 ft^3/s.

The same three cross sections were used in HEC-RAS simulations for the Wetted-Perimeter method analysis; target streamflows ranged from 1.5 to 2.1 ft^3/s with a median of 1.8 ft^3/s (table 17). The median Wetted-Perimeter streamflow target was about 50 percent greater than the median determined from the R2Cross 2-of-3 criteria method.

Sudbury River near Hopkinton

The riffle reach on the Sudbury River near Hopkinton (fig. 41; reach 5, fig. 35) is about 100 ft downstream from the Fruit Street Bridge. Three cross sections were surveyed in September 2003 along a 15-ft reach. The streambed is primarily sand and gravel with cobbles and a few small boulders. Channel banks are composed of silt and sand mixed with organic material. The left bank is covered by a narrow border of hardwood trees and shrubs; the right bank is covered by scattered trees, wetland shrubs, and grasses. A railroad-bed embankment constricts the left-bank flood plain but does not directly affect the riffle habitat. The surface-water gradient in the reach is moderately sloped with a measured drop of 0.4 to 0.2 ft for streamflows of 5.2 to 32 ft^3/s, respectively. The riffle is short and becomes a run (a flooded riffle) at moderate to high flows. Longer riffles that are located downstream may provide suitable habitat, but because of channel alterations, these cross sections were not surveyed for use in the determination of flow standards.

The HEC-RAS simulations indicate that only one of the three sections surveyed (station 128) was unaffected by

Figure 40. Downstream view of riffle on Whitehall Brook at Fruit Street near Hopkinton, Massachusetts. Location (site 4) shown in figure 35.

Table 17. Streamflow targets determined by the R2Cross and Wetted-Perimeter methods at 10 selected riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[Reach location shown on fig. 35; mi², square miles; ft³/s, cubic foot per second; ft³/s/mi², cubic foot per second per square mile; R2Cross limiting criterion- D, depth, V, velocity, WP, wetter perimeter; ~, means cross section not used]

Reach number	Reach name	Drainage area (mi²)	Cross-section station[1]	R2Cross 3-of-3 criterion			R2Cross 2-of-3 criterion			Wetted Perimeter	
				Discharge		Limiting variable	Discharge		Limiting variable	Discharge	
				(ft³/s)	(ft³/s/mi²)		(ft³/s)	(ft³/s/mi²)		(ft³/s)	(ft³/s/mi²)
				Sudbury River Basin							
4	Whitehall Brook near Hopkinton	6.64	118	4.2	0.633	D	1.4	0.211	WP	1.5	0.226
			128	3.3	0.497	D	1.1	0.166	WP	2.1	0.109
			136	3.6	0.542	V	1.2	0.181	D	1.8	0.093
5	Sudbury River near Hopkinton	19.3	128	18	0.933	WP	14	0.725	D	7.0	0.363
6	Sudbury River near Ashland	23.9	157	20	0.837	V	7.0	0.293	D	6.8	0.282
			171	~	~	~	~	~	~	10	0.418
			192	30	1.255	V	8.0	0.335	D	3.0	0.126
			209	25	1.046	D	6.1	0.255	WP	23	0.962
			223	15	0.628	V	13	0.561	D	4.5	0.188
7	Indian Brook near Hopkinton	4.73	222	26	5.497	V	0.4	0.093	D	0.2	0.049
			225	14	2.960	V	1.0	0.211	D	2.0	0.423
			230	14	2.960	V	0.3	0.055	D	1.4	0.296
8	Indian Brook near Ashland	6.75	157	9.5	1.407	V	0.4	0.059	D	0.6	0.089
			181	8.0	1.185	V	0.6	0.089	D	0.8	0.119
			196	5.6	0.830	V	0.2	0.030	D	0.6	0.089
			214	4.0	0.593	V	0.6	0.089	WP	1.1	0.163
15	Baiting Brook near Framingham	3.41	198	5.7	1.663	V	1.9	0.548	D	0.6	0.164
			218	6.0	1.748	V	0.9	0.252	D	1.1	0.323
			245	~	~	~	~	~	~	0.8	0.220
			265	8.2	2.390	V	1.2	0.340	D	0.2	0.067
			285	5.7	1.663	V	3.0	0.868	D	0.9	0.267
	Median (Sudbury River Basin)				**1.185**			**0.211**			**0.188**

Table 17. Streamflow targets determined by the R2Cross and Wetted-Perimeter methods at 10 selected riffle sites in the Sudbury and Assabet River Basins, Massachusetts.—Continued

[Reach location shown on fig. 35; mi², square miles; ft³/s, cubic foot per second; ft³/s/mi², cubic foot per second per square mile; R2Cross limiting criterion- D, depth, V, velocity, WP, wetter perimeter; ~, means cross section not used]

Reach number	Reach name	Drainage area (mi²)	Cross-section station[1]	R2Cross 3-of-3 criterion			R2Cross 2-of-3 criterion			Wetted Perimeter	
				Discharge		Limiting variable	Discharge		Limiting variable	Discharge	
				(ft³/s)	(ft³/s/mi²)		(ft³/s)	(ft³/s/mi²)		(ft³/s)	(ft³/s/mi²)
				Assabet River Basin							
51	Assabet River near Westborough	6.79	117	5.8	0.854	V	0.6	0.088	D	0.6	0.088
			128	6.8	1.001	V	0.4	0.059	D	0.2	0.029
			136	8.0	1.178	V	0.5	0.066	D	0.2	0.029
59	Danforth Brook at Hudson	5.12	26	14	2.813	V	0.2	0.035	D	0.5	0.195
			52	10	1.973	V	0.4	0.078	D	~	~
			61	8.1	1.582	V	1.2	0.234	D	~	~
			69	10	2.031	V	0.9	0.176	D	~	~
			82	12	2.246	V	2.0	0.391	D	2.0	0.820
61	Fort Meadow Brook near Hudson	4.85	134	7.3	1.505	V	2.2	0.454	D	1.7	0.351
63	Elizabeth Brook near Stow	18.7	202	10	0.535	D	5.0	0.267	V	3.5	0.187
			214	9.0	0.481	V	6.5	0.348	D	1.8	0.096
			229	11	0.561	D	3.6	0.193	V	5.5	0.294
			241	12	0.642	D	10	0.548	V	3.0	0.160
	Median (Assabet River Basin)				**1.178**			**0.193**			**0.174**
	Overall median				**1.182**			**0.211**			**0.187**

[1]Station position rounded to nearest foot.

Figure 41. Upstream view of riffle on Sudbury River at Fruit Street near Hopkinton, Massachusetts. Location (site 5) shown in figure 35.

backwater and was used in the R2Cross and Wetted-Perimeter analyses. The top width in this section at bankfull flow is about 15 ft. The limiting R2Cross hydraulic factor at this section was wetted perimeter (streamflow of 18 ft^3/s) for the 3-of-3 criteria and depth (streamflow of 14 ft^3/s) for the 2-of-3 criteria (table 17). A streamflow of 7 ft^3/s was needed to meet the criteria for the Wetted-Perimeter method for the same reach (table 17), which is half that determined by the R2Cross 2-of-3 criteria method.

Sudbury River near Ashland

The riffle reach at the Sudbury River near Ashland (fig. 42; reach 6, fig. 35) is about 400 ft downstream from the Howe Street Bridge. Six cross sections were surveyed in September 2003 along a 100-ft reach. The streambed is primarily sand, gravel, and cobbles with emergent vegetation in the pool areas. Channel banks are composed of silt and sand mixed with organic material and an occasional boulder. The left bank is lined with shrubs that overhang the stream and thick forested vegetation further inland. The right bank at the downstream-most section is composed of natural riparian vegetation, but most of the natural vegetation on the right bank is replaced by a mowed lawn. The water-surface gradient in the reach is moderately sloped with a measured drop of 0.8 to 0.4 ft for streamflows ranging from 4.7 to 70 ft^3/s.

The HEC-RAS simulations at stations 157, 192, 209, and 223 were used in the R2Cross analysis. The top width at normal full channel flow in these sections ranged from about 36 to 47 ft with a median width of about 42 ft. Velocity was the limiting hydraulic factor for the R2Cross 3-of-3 criteria in three of the four sections and depth was the limiting

Figure 42. Downstream view of riffle on Sudbury River near Ashland, Massachusetts. Location (site 6) shown in figure 35.

factor in the other section (table 17). Streamflows meeting the R2Cross 3-of-3 criteria varied from 15 to 30 ft^3/s with a median of 22 ft^3/s. Depth was the limiting hydraulic factor for the R2Cross 2-of-3 criteria in three of the four sections and wetted perimeter was the limiting factor in the other section (table 17). Streamflow meeting the 2-of-3 criteria varied from 6.1 to 13 ft^3/s with a median of 7.5 ft^3/s and was about a third of the flow meeting the 3-of-3 criteria.

The same four cross sections, plus one additional section (station 171), were used in HEC-RAS simulations to determine streamflow targets by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria ranged from 3.0 to 23 ft^3/s with a median of 6.8 ft^3/s (table 17). The median Wetted-Perimeter streamflow target was similar to the median flow target determined from the R2Cross 2-of-3 criteria method.

Indian Brook near Hopkinton

The riffle reach at the Indian Brook near Hopkinton (fig. 43; reach 7, fig. 35) is about 1,600 ft upstream from Hopkinton Reservoir and 1,300 ft west of Cedar Street along a walking trail near the Hopkinton State Park Headquarters. Seven cross sections were surveyed in October 2004 along a 100-ft reach. At about the middle of the reach, the walking trail crosses the brook over a bridge with a center pier that was also surveyed and included in the HEC-RAS model. The streambed is primarily cobbles with a few boulders, gravel, and silt. Channel banks are composed of silt over sand mixed with cobbles, boulders, and organic material. Shrubs and hardwood trees border both banks. The water-surface gradient is gently sloped with a measured drop of about 0.2 ft through the reach at streamflows ranging from 0.34 to 41 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 222, 225, and 230 were unaffected by backwater and were used in the R2Cross analysis. The top width at normal channel flow in these sections ranged from about 15 to 18 ft with a median width of about 17 ft. Velocity was the limiting hydraulic factor for all sections meeting the R2Cross 3-of-3 criteria and depth was the limiting factor in all sections meeting the 2-of-3 criteria. Streamflow meeting the R2Cross 3-of-3 criteria ranged from 14 to 26 ft^3/s with a median of 14 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged from 0.3 to 1.0 ft^3/s with a median of 0.4 ft^3/s (table 17). The large difference in the streamflow requirement between the 3-of-3 and the 2-of-3 criteria is attributed to the low gradient in the reach, which required a high flow to meet the velocity criteria.

The same three cross sections were used to determine streamflow targets by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria ranged from 0.2 to 2.0 ft^3/s with a median of 1.4 ft^3/s (table 17). The median Wetted-Perimeter streamflow target was about three times larger than that determined from the R2Cross 2-of-3 criteria method.

Indian Brook near Ashland

The riffle reach at Indian Brook near Ashland (fig. 44; reach 8, fig. 35) is about 2,600 ft downstream from Hopkinton Reservoir and about 600 ft upstream from Cross Street. Five cross sections were surveyed in November 2004 along a 100-ft reach. The streambed is primarily gravel with a few cobbles. Channel banks are primarily silt over sand mixed with cobbles, gravel, and organic material. Shrubs and hardwood trees cover both banks, although some shrubs have been removed from the left bank. The water-surface gradient is moderately sloped with a measured drop of about 0.4 ft through the reach at streamflows ranging from 1.1 to 6.6 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 157, 181, 196, and 214 were unaffected by backwater and were used in the R2Cross analysis. The top width at

Figure 43. Upstream view of riffle from bridge on Indian Brook near Hopkinton, Massachusetts. Location (site 7) shown in figure 35.

Figure 44. Downstream view of riffle on Indian Brook near Ashland, Massachusetts. Location (site 8) shown in figure 35.

normal channel flow in these sections ranged from about 14 to 16 ft with a median width of about 14 ft. Velocity was the limiting hydraulic factor for all sections meeting the R2Cross 3-of-3 criteria; depth was the limiting factor in three of four sections meeting the 2-of-3 criteria and wetted perimeter was the limiting factor in the other section. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 4.0 to 9.5 ft^3/s with a median of 6.8 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged to 0.2 to 0.6 ft^3/s with a median of 0.5 ft^3/s (table 17).

The same four cross sections were used to determine streamflow targets by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria ranged from 0.6 to 1.1 ft^3/s with a median of 0.7 ft^3/s (table 17). The median wetted-perimeter streamflow target was similar to that determined by the R2Cross 2-of-3 criteria method.

Baiting Brook near Framingham

The riffle reach at Baiting Brook near Framingham (fig. 45; reach 15, fig. 35) is about 400 ft downstream from Maple Street and about 250 ft upstream from its mouth on the Sudbury River. Nine cross sections were surveyed in October 2004 along a 170-ft reach. The streambed is primarily gravel with a few cobbles. Channel banks are composed of silt over sand mixed with cobbles, gravel, and organic material.

Figure 45. Upstream view of riffle on Baiting Brook near Framingham, Massachusetts. Location (site 15) shown in figure 35.

Channel banks are bounded by shrubs and hardwood trees. The water-surface gradient is moderately sloped with a measured drop of about 1.5 ft through the reach for streamflows ranging from 0.4 to 9.6 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 198, 218, 245, 265, and 285 were unaffected by backwater and were used in the R2Cross analysis. The top width at normal full channel flow in these sections ranged from about 22 to 36 ft with a median width of about 24 ft. Velocity was the limiting hydraulic factor for all sections meeting the R2Cross 3-of-3 criteria, and depth was the limiting factor in all sections meeting the 2-of-3 criteria. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 5.7 to 8.2 ft^3/s with a median of 5.8 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged from 0.9 to 3.0 ft^3/s with a median of 1.5 ft^3/s (table 17).

The same four cross sections were used to determine streamflow targets by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria ranged from 0.2 to 1.1 ft^3/s (table 17) with a median of 0.8 ft^3/s. The median wetted-perimeter streamflow target was about half that determined by the R2Cross 2-of-3 criteria method.

Assabet River near Westborough

The riffle reach at the Assabet River near Westborough (fig. 46; reach 51, fig. 35) is about 100 ft downstream from Fisher Street Bridge. Five cross sections were surveyed on July 2002 along a 100-ft reach. The streambed is primarily silt and sand with a few cobbles. Channel banks are composed of silt and sand mixed with organic material. The banks are bounded by a narrow border of shrubs then hardwood forest. The water-surface gradient is moderately sloped with a measured drop of 0.5 to 0.1 ft through the reach for flows ranging from 0.05 to 27 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 117, 128, and 136 were unaffected by backwater and were used in the R2Cross analysis. The top width at normal channel flow in these sections ranged from about 14 to 21 ft with a median width of about 15 ft. Velocity was the limiting hydraulic factor for all sections meeting the R2Cross 3-of-3 criteria and depth was the limiting factor in all sections meeting the 2-of-3 criteria. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 5.8 to 8.0 ft^3/s with a median of 6.8 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged to 0.4 to 0.6 ft^3/s with a median of 0.5 ft^3/s (table 17).

The same three cross sections were used to determine streamflow targets by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria ranged from 0.2 to 0.6 ft^3/s with a median of 0.2 ft^3/s (table 17). The median wetted-perimeter streamflow target was about half that determined by the R2Cross 2-of-3 criteria method.

Danforth Brook at Hudson

The riffle reach on Danforth Brook (fig. 47; reach 59, fig. 35) is about 300 ft upstream from the Route 85 culvert in a conservation area owned by the town of Hudson. Seven cross sections were surveyed in September 2001 along an 80-ft reach of pool and riffle habitats. The streambed is primarily cobbles with a few scattered large boulders. Channel banks are composed of rich organic soil, silt, sand, and cobbles. The banks are bounded by scattered trees and shrubs. The channel takes a shallow bend to the left looking downstream along the study reach. The water-surface gradient is moderately steep with a measured drop of 1.8 to 1.6 ft through the reach for flows ranging from 0.01 to 28 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 26, 52, 61, 69, and 82 were unaffected by backwater and were used in the R2Cross analysis. The top width

Figure 46. Downstream view of riffle on Assabet River near Westborough, Massachusetts. Location (site 51) shown in figure 35.

Figure 47. Upstream view of riffle on Danforth Brook at Hudson, Massachusetts. Location (site 59) shown in figure 35.

at normal channel flow in these sections ranged from about 20 to 25 ft with a median width of about 23 ft. Velocity was the limiting hydraulic factor for all sections meeting the R2Cross 3-of-3 criteria and depth was the limiting factor in all sections meeting the 2-of-3 criteria. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 8.1 to 14 ft^3/s with a median of 10 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged from 0.2 to 2.0 ft^3/s with a median of 0.9 ft^3/s (table 17).

The target flows were determined at only two cross sections (26 and 82) by the Wetted-Perimeter method. Streamflows meeting the Wetted-Perimeter criteria were 0.5 and 2.0 ft^3/s at cross sections 26 and 82, respectively (table 17). The median Wetted-Perimeter streamflow target (1.2 ft^3/s) was about equal to that determined from the R2Cross 2-of-3 criteria method.

Fort Meadow Brook near Hudson

The riffle reach on Fort Meadow Brook (fig. 48; reach 61, fig. 35) is 1,350 ft upstream from the Shay Street culvert in Hudson. Five cross sections were surveyed in July 2002 along a 90-ft reach. The streambed is primarily cobble and gravel. Channel banks are composed of rich organic material bordered by large pine trees. The water-surface gradient is moderately sloped with a measured drop of about 0.6 ft through the reach for flows ranging from 0.84 to 6.8 ft^3/s.

The HEC-RAS simulations indicate that only one cross section (station 134) was unaffected by backwater and was used in the R2Cross and Wetted-Perimeter analyses. The bankfull top width was about 19 ft at this section. Velocity was the limiting hydraulic factor meeting the R2Cross 3-of-3 criteria and depth was the limiting factor meeting the 2-of-3

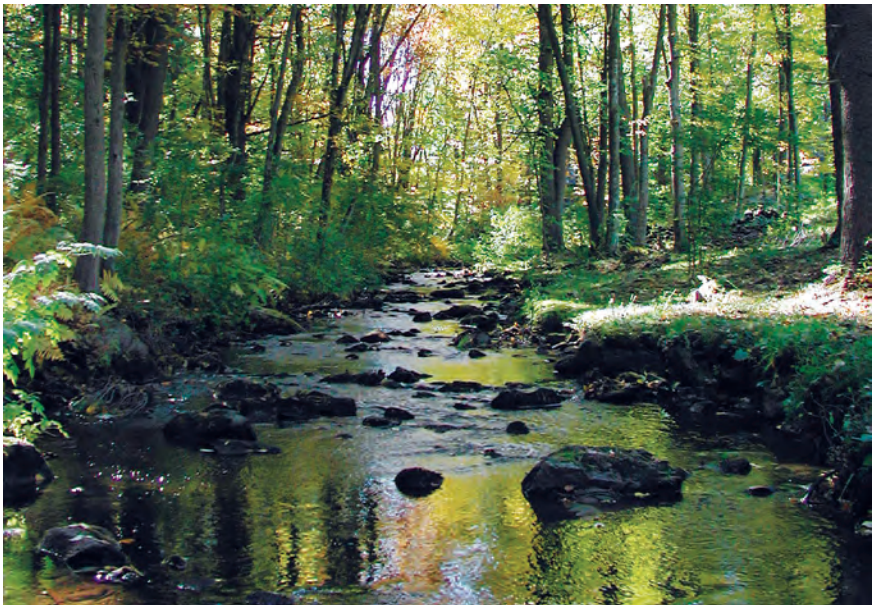


Figure 48. Upstream view of riffle on Fort Meadow Brook near Hudson, Massachusetts. Location (site 61) shown in figure 35.

criteria. Streamflows meeting the R2Cross 3-of-3 and 2-of-3 criteria were 7.3 and 2.2 ft^3/s, respectively (table 17). Streamflow meeting the Wetted-Perimeter target (1.7 ft^3/s; table 17) is about 23 percent less than that determined by the R2Cross 2-of-3 criteria method.

Elizabeth Brook near Stow

The riffle reach on Elizabeth Brook (fig. 49; reach 63, fig. 35) is about 0.2 mi south of White Pond Road in Stow and just downstream from an unnamed washed-out road that still has three culverts in the channel. Six cross sections were surveyed in September 2001 along a 70-ft reach. The streambed is primarily gravel and cobbles. Channel banks are composed of a mixture of rich organic soil, sand, and cobbles and are bordered by shrubs and larger deciduous trees further from the channel. The channel bends slightly to the right looking downstream in the study reach. The water-surface gradient is moderately sloped with a measured drop of 0.7 to 1.1 ft through the reach at streamflows ranging from 1.8 to 50 ft^3/s.

The HEC-RAS simulations indicate that cross sections at stations 202, 214, 229, and 241 were unaffected by backwater and were used in the R2Cross analysis. The top width at normal channel flow in these sections ranged from about 23 to 32 ft with a median width of about 27 ft. Depth was the limiting hydraulic factor for all but one section meeting the R2Cross 3-of-3 criteria, and velocity was the limiting factor in all but one section meeting the 2-of-3 criteria. In the one section, the limiting hydraulic factor was reversed from that of the other sections. Streamflows meeting the R2Cross 3-of-3 criteria ranged from 9.0 to 12 ft^3/s with a median of 10 ft^3/s; streamflows meeting the R2Cross 2-of-3 criteria ranged to 3.6 to 10 ft^3/s with a median of 5.8 ft^3/s (table 17).

The same four cross sections were used to determine target flows by the Wetted-Perimeter analysis. Streamflows meeting the Wetted-Perimeter criteria ranged from 1.8 to 5.5 ft^3/s with a median of 3.2 ft^3/s (table 17). The median Wetted-Perimeter flow target was half that determined from the R2Cross 2-of-3 criteria method.

Figure 49. Downstream view of riffle on Elizabeth Brook near Stow, Massachusetts. Location (site 63) shown in figure 35.

Statistically Based Streamflow Targets

Tennant and New England ABF methods calculate streamflow targets from statistical measures of long-term daily flow values at a site. The RVA also calculates statistical properties of long-term streamflows that reflect natural streamflow variability, which is considered important to preserve the ecological integrity of the stream. RVA is mainly used in the following analysis for comparative purposes with the other statistically based streamflow methods.

In general, these methods are applicable only at unregulated sites where long-term daily streamflow data are available. Typically, the availability of this type of data, particularly in streams affected by withdrawals, limits their use, but because unregulated long-term daily flows were simulated with the HSPF model, the methods could be applied to all 10 selected riffle reaches in this study. The HSPF simulated long-term daily flows (1960–2004) under no water use (NOWU) were used to determine flow targets. The NOWU simulation zeros out surface-water withdrawals and streamflow depletion from groundwater withdrawals in each model reach; the NOWU simulation also excludes other water imports and exports, such as areas on public water and on-site septic systems (net import), sewer inflow and infiltration losses (net export), and treatment-facility wastewater returns.

Streamflows for the analyses were simulated at model nodes (end of a reach) at or near the riffle sites. In the Sudbury River Basin, riffles were close enough to model nodes that no adjustment to the simulated flows was necessary. In the Assabet River Basin, riffles 51, 59, 61, and 63 (fig. 35) were sufficiently upstream from model nodes to warrant adjustment of the simulated flows by the drainage-area ratio at the node and riffle. It should be noted that flow targets determined from simulated flows are subject to the model uncertainties and limitations described previously. Statistically based target flows were normalized by drainage area to facilitate comparisons between sites.

Tennant Method

The Tennant method (Tennant, 1976) calculates streamflow targets as percentages of the mean annual flow (Q_{MA}). Seasonally variable streamflow targets are identified by the Tennant method by assigning different percentages of the Q_{MA} for the summer and winter periods (table 18). The method was developed in the Rocky Mountain region of the United States, which has distinctly different high- and low-flow seasons from southern New England. Thus, the October through March flow condition described by Tennant (1976) is more applicable to the summer through early fall flows in southern New England. The percentages of Q_{MA} that reflect the quality of stream habitat (table 18) were determined at each of the riffle sites from HSPF simulated flows without withdrawals (table 19). This study focused primarily on the 30- and 50-percent Q_{MA} flows, which Tennant considered an excellent flow for aquatic habitat for seasonal low and high flows, respectively. However, the magnitude of the high-flow standard in relation to the percentage of Q_{MA} does not appear to reflect the high-flow regime in this region as discussed later.

At 30 percent of the Q_{MA}, flows ranged from about 0.56 to 0.61 $ft^3/s/mi^2$ in the Sudbury and Assabet River Basins with an overall median of about 0.58 $ft^3/s/mi^2$. Flows at 10 and 20 percent of the Q_{MA}, considered poor to fair for seasonal low-flow habitat (Tennant, 1976), had overall medians of about 0.19 and 0.39 $ft^3/s/mi^2$, respectively. These values are closest to the overall medians of the flow standards determined by the physically based R2Cross 2-of-3 criteria (0.24 $ft^3/s/mi^2$) and Wetted-Perimeter (0.25 $ft^3/s/mi^2$) methods. At 50 percent of the Q_{MA}, the overall median was about 0.97 $ft^3/s/mi^2$, which is close to the overall median flow (1.18 $ft^3/s/mi^2$) computed by the R2Cross 3-of-3 criteria method.

New England Aquatic Base Flow Method (ABF)

The U.S. Fish and Wildlife Service developed the ABF method to establish standards for seasonal low (summer), moderate (fall and winter), and high flow (spring) for different life stages of the aquatic biota (U.S. Fish and Wildlife Service, 1981; Lang, 1999). Default standards for these flow regimes (0.5, 1.0, and 4.0 $ft^3/s/mi^2$, respectively) were developed from streamflow records at 48 unregulated streamgages throughout New England to provide flow standards at ungaged sites or at gaged sites that have short-term records or are affected by regulation. It should be noted that these defaults were not intended for sites with contributing areas less than 50 mi^2. Where long-term unregulated flow information is available, ABF standards can be directly calculated from site-specific

Table 18. Condition of aquatic habitat in relation to streamflow as a percentage of the mean annual flow (Q_{MA}) described by Tennant (1976) for small streams in the Rocky Mountain Region of the United States.

[<, less than]

Rated aquatic-habitat condition	Percentage of Q_{MA}	
	April–September[1]	October–March[2]
Excellent	50	30
Good	40	20
Fair	30	10
Poor	10	10
Degraded	<10	<10

[1] Generally reflects seasonal high flows.

[2] Generally reflects seasonal low flows.

Table 19. Streamflow targets determined by the Tennant method as percentages of the means of the mean annual flows (Q_{MA}) computed from long-term (1960–2004) simulated streamflow with the Hydrologic Simulation Program–FORTRAN with no water use (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[Reach location shown on fig. 35; mi², square mile; ft³/s/mi², cubic foot per second per square mile]

Reach number	Reach	Drainage area (mi²)	Flow as a percentage of Q_{MA} (ft³/s/mi²)				
			10	20	30	40	50
			Sudbury River Basin				
4	Whitehall Brook near Hopkinton	6.64	0.191	0.381	0.572	0.762	0.953
5	Sudbury River near Hopkinton	19.3	0.197	0.394	0.591	0.788	0.985
6	Sudbury River near Ashland	23.9	0.198	0.396	0.595	0.793	0.991
7	Indian Brook near Hopkinton	4.73	0.196	0.391	0.587	0.783	0.979
8	Indian Brook near Ashland	6.75	0.193	0.386	0.579	0.772	0.965
15	Baiting Brook near Framingham	3.41	0.204	0.407	0.611	0.814	1.018
	Median		**0.196**	**0.393**	**0.589**	**0.786**	**0.982**
			Assabet River Basin				
51	Assabet River near Westborough	6.79	0.191	0.381	0.572	0.762	0.953
59	Danforth Brook at Hudson	5.12	0.189	0.378	0.567	0.756	0.945
61	Fort Meadow Brook near Hudson	4.85	0.194	0.388	0.582	0.777	0.971
63	Elizabeth Brook near Stow	18.7	0.187	0.375	0.562	0.749	0.936
	Median		**0.190**	**0.380**	**0.569**	**0.759**	**0.949**
	Overall median		**0.194**	**0.387**	**0.581**	**0.774**	**0.968**

data, which were made possible by HSPF simulated flows under no water use (NOWU) at each of the 10 riffle sites.

The ABF low-flow target is calculated as the median of the August mean flows over the period of record. August was chosen as the low-flow target because it's typically the month with the lowest flow. The original ABF fall-winter target was calculated from the median of the February mean flows that limits favorable aquatic habitat on the basis of low flows, cold temperatures, and icing. Examination of the simulated hydrographs at the riffle sites indicates that the median of the January mean flow best represented these limiting winter conditions in this area and, thus, was used for the ABF fall-winter flow target. The spring flow target was intended to address flow needs for fish spawning and incubation that, for some species, require overbank flooding. The spring flow target was originally computed from the mean of the median April and May mean monthly flows. Examination of the simulated hydrographs at the riffle sites indicates the highest monthly flows, which often result in overbank flooding, typically occur during March and April and, thus, the mean of the median of these monthly mean flows was used as the ABF high-flow target.

The ABF low-flow target computed from NOWU simulated flows varied from about 0.14 to 0.62 ft³/s/mi² among the 10 riffle sites (table 20); riffles in the Sudbury River Basin had a median value that was about 32 percent larger than the median of the riffle sites in the Assabet River Basin (0.41 and 0.28 ft³/s/mi², respectively). The computed ABF low-flow target was below the default target (0.5 ft³/s/mi²) at 9 of the 10 riffle sites; the overall median (0.32 ft³/s/mi²) was about 36 percent less than the default target. Excluding outliers on Whitehall Brook and Sudbury River near Hopkinton and near Ashland, the computed ABF low-flow target is moderately correlated (r^2 0.68) with the percentage of the basin underlain by sand and gravel. The area underlain by sand and gravel at the riffle sites, excluding Whitehall Brook and the two Sudbury River sites, ranged from about 13 to 34 percent and yielded computed ABF low-flow targets of 0.43 to 0.59 ft³/s/mi², respectively. The outliers at Whitehall Brook and the Sudbury River sites have relatively low ABF target flows compared to the other riffle sites, but comparatively similar area, in percent, underlain by sand and gravel. The outliers likely reflect a greater percentage of the basin area classified as water and wetlands, which is weakly inversely correlated (r^2 -0.27) with the ABF low-flow target. The positive correlation with area underlain by sand and gravel reflects the larger sustained baseflow from these deposits relative to other surficial deposits; the negative correlation with area of

the basin in water and wetlands reflects the greater ET losses relative to other land-use types. It should be noted that the correlations were made from simulated flows that have an inherent degree of circularity between flow standards and basin characteristics; thus, conclusions drawn this analysis should be used with caution.

The computed ABF winter- and spring-flow targets were less variable than the low-flow targets among riffle sites, but were considerably different than the ABF default target flows. The median of the January mean flows (winter) were about 2.4 and 2.5 $ft^3/s/mi^2$ at selected riffles in the Sudbury and Assabet River Basins, respectively (table 20); this is about two and a half times greater than the default ABF fall-winter flow target (1.0 $ft^3/s/mi^2$). The ABF spring-flow target (high flow) was also less variable than the low-flow target among the riffle sites. The median spring-flow target was 3.1 $ft^3/s/mi^2$ for 10 riffles in the Sudbury and Assabet River Basins (table 20); this is about 22 percent less than the default ABF spring-flow target (4.0 $ft^3/s/mi^2$).

Range of Variability Approach (RVA)

RVA was developed by the Nature Conservancy (Richter and others, 1996) to characterize natural flow variability considered necessary to preserve the ecological integrity of the stream. RVA considers the interquartile ranges of 33 indicators of hydrologic alteration (IHA) that are a suite of statistical measures calculated from daily streamflow values (The Nature Conservancy, 2009). About half the statistics measure the central tendency of various flow conditions and the other half focus on the magnitude, duration, timing, and frequency of extreme events.

The RVA analyses for all 33 IHA statistics are presented in appendix 3, but only the medians and upper and lower quartiles of the mean monthly flows are presented in the following section because they represent the monthly flow variation that the other standard-setting methods can be compared to. The medians and upper and lower quartiles of the mean monthly flows were computed from HSPF simulated unregulated flows (NOWU scenario) for a 45-year period (1960–2004). The values presented herein were calculated from the medians of the monthly mean values calculated at each of the 10 riffle sites; 25th, 50th, and 75th percentiles represent the combined values among the riffle sites. For clarity, only the percentiles are referred to.

The 50th-percentile flow at 10 riffle sites (table 21) was lowest in August (0.32 $ft^3/s/mi^2$) and slightly larger in July and September (0.42 and 0.47 $ft^3/s/mi^2$, respectively); the 50th-percentile flow was highest in March (3.41 $ft^3/s/mi^2$) and somewhat lower in February and April (2.80 and 2.85 $ft^3/s/mi^2$,

Table 20. Streamflow standards determined by the New England Aquatic Baseflow (ABF) method from the median of the monthly mean flow (1960–2004) simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with no water use (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[Reach location shown on fig. 35; $ft^3/s/mi^2$, cubic foot per second per square mile]

Reach number	Reach	Median of mean monthly flow ($ft^3/s/mi^2$)		
		August	January	March–April[1]
	Sudbury River Basin			
4	Whitehall Brook near Hopkinton	0.331	2.425	3.110
5	Sudbury River near Hopkinton	0.492	2.430	2.964
6	Sudbury River near Ashland	0.499	2.452	3.041
7	Indian Brook near Hopkinton	0.296	2.474	3.129
8	Indian Brook near Ashland	0.296	2.533	3.222
15	Baiting Brook near Framingham	0.616	2.346	3.211
	Median	**0.412**	**2.441**	**3.119**
	Assabet River Basin			
51	Assabet River near Westborough	0.247	2.355	3.183
59	Danforth Brook at Hudson	0.142	2.500	3.168
61	Fort Meadow Brook near Hudson	0.329	2.535	3.059
63	Elizabeth Brook near Stow	0.314	2.470	3.036
	Median	**0.281**	**2.470**	**3.119**
	Overall median	**0.322**	**2.461**	**3.119**

[1]Mean of the median monthly mean flow.

respectively). Differences between the 75th percentile and the 50th percentile were proportionally greater in the low-flow months (about twice the 50th percentile) than in the high-flow months (about 25 to 50 percent greater than the 50th percentile). The differences between the 25th and the 50th percentiles were also proportionally larger in the low-flow months than in the high-flow months, but to a lesser degree. In effect, streamflow standards based on the median monthly or seasonal flows would less likely be met during the low-flow season than during the high-flow season because the variation around the median (as a percentage) is greater in the normal low-flow period than in the normal high-flow period.

Comparison of Computed Target Flows

Computed target flows determined by standard-setting methods for aquatic-habitat protection at 10 riffle sites in the Sudbury and Assabet River Basins yielded variable results when normalized for drainage area (table 22 and fig. 50). In general, the variability in the target flows was larger among sites for physically based methods than for statistically based methods. Physically based methods also yielded lower flow targets than statistically based methods, with the exception of the R2Cross 3-of-3 criteria.

Table 21. Quartiles of medians of the monthly mean streamflows determined from Hydrologic Simulation Program–FORTRAN (HSPF) simulated flow (1960–2004) with no water use (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts

[$ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Streamflow ($ft^3/s/mi^2$)		
	25th percentile	50th percentile	75th percentile
October	0.451	1.022	1.652
November	1.322	1.718	2.491
December	1.524	2.437	3.270
January	1.632	2.461	3.759
February	2.108	2.795	3.499
March	2.475	3.413	4.160
April	2.078	2.854	3.822
May	1.381	1.790	2.495
June	0.609	0.976	1.837
July	0.301	0.421	0.827
August	0.215	0.322	0.729
September	0.224	0.468	0.915

Table 22. Summary of target flows determined by standard-setting methods at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ABF, aquatic base flow median of August monthly mean flow; Q_{MA}, mean annual flow]

Reach number	Reach	Flow standard, in cubic feet per second per mile square ($ft^3/s/mi^2$)					
		Physically based methods[1]			Statistically based methods[2]		
		Wetted Perimeter	R2Cross		Tennant		ABF
			2-of-3 criteria	3-of-3 criteria	30-percent Q_{MA}	50-percent Q_{MA}	
	Sudbury River Basin						
4	Whitehall Brook near Hopkinton	0.109	0.181	0.542	0.572	0.953	0.331
5	Sudbury River near Hopkinton	0.363	0.725	0.933	0.591	0.985	0.492
6	Sudbury River near Ashland	0.282	0.314	0.942	0.595	0.991	0.499
7	Indian Brook near Hopkinton	0.296	0.093	2.960	0.587	0.979	0.296
8	Indian Brook near Ashland	0.104	0.074	1.008	0.579	0.965	0.296
15	Baiting Brook near Framingham	0.220	0.444	1.706	0.611	1.018	0.616
	Median	**0.251**	**0.247**	**0.975**	**0.589**	**0.982**	**0.412**
	Assabet River Basin						
51	Assabet River near Westborough	0.029	0.066	1.001	0.572	0.953	0.247
59	Danforth Brook at Hudson	0.508	0.176	2.031	0.567	0.945	0.142
61	Fort Meadow Brook near Hudson	0.351	0.454	1.505	0.582	0.971	0.329
63	Elizabeth Brook near Stow	0.174	0.308	0.548	0.562	0.936	0.314
	Median	**0.262**	**0.242**	**1.253**	**0.569**	**0.949**	**0.281**
	Overall Median	**0.251**	**0.244**	**1.005**	**0.581**	**0.968**	**0.322**

[1] Median target flows determined at multiple cross sections.

[2] Determined from Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows without water use (NOWU scenario).

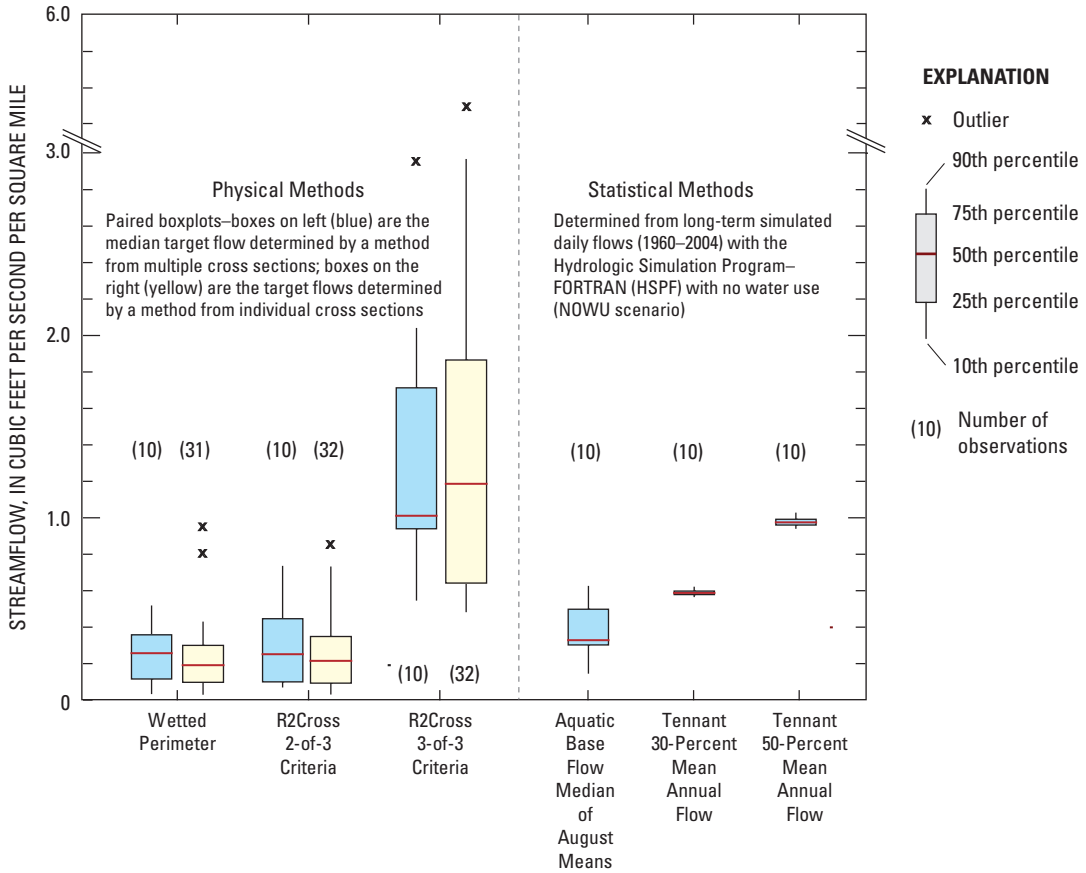


Figure 50. Variation in target flows determined by standard-setting methods at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

The R2Cross 3-of-3 criteria yielded the highest (with one exception) and most variable flows among the methods examined; the median flow determined from the multiple cross sections within a riffle reach ranged from about 0.54 to 3.0 $ft^3/s/mi^2$ (table 22) with an overall median of 1.0 $ft^3/s/mi^2$ and an interquartile range of about 0.94 to 1.7 $ft^3/s/mi^2$. The variation in the target flows determined by this method was much larger for the individual cross sections (fig. 50), indicating individual cross sections may underrepresent or overrepresent the flow required to protect aquatic habitat in the reach. Again, it should be noted that the R2Cross 3-of-3 criteria was designed as a seasonal high-flow target for the Rocky Mountain region and may not be applicable to this region.

The R2Cross 2-of-3 criteria target flow was substantially lower and less variable than that produced from the 3-of-3 criteria, but the variability of the target flows computed by this method was still the 2nd highest relative to the flows computed by the other methods. Although the interquartile range of target flows determined by R2Cross 2-of-3 criteria method from 32 individual cross sections was about equal to that determined from medians of the multiple cross sections at each of the 10 riffle sites, the relatively large variability underscores that too few cross sections may not yield a representative target flow for aquatic-habitat needs. The median target flows computed from individual cross sections determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods were in closest agreement among the methods examined with an overall median of about 0.24 and 0.25 $ft^3/s/mi^2$, respectively, and an interquartile range of about 0.13 to 0.38 and 0.14 to 0.32 $ft^3/s/mi^2$, respectively. These findings are comparable to target flows determined by these methods at riffle sites in the Charles River Basin (Parker and others, 2004) and in other basins throughout the state (Armstrong and others, 2004).

The R2Cross and Wetted-Perimeter methods are direct measures of stream-channel features such as width, depth, slope, roughness, and other features. Channel geometry usually obtains a state of quasi-equilibrium over time in response to normal conveyance needs for water and sediment, but a new state of quasi-equilibrium will develop in response to long-term changes in the conveyance need (Leopold and Maddock, 1953). For example, changes in land use, such as urbanization, can increase runoff and result in increased channel width, whereas impoundments can mitigate high flows that could decrease downstream channel cross-section area (Jacobson and others, 2001).

The degree to which a channel adjusts to altered flows and the effects these adjustments have on physically based methods for determining target flows are not well understood.

The physically based target flows at Indian Brook near Ashland, in contrast to the upstream riffle site near Hopkinton, suggest that the Hopkinton Reservoir may have decreased the downstream conveyance needs, resulting in a target flow that was lower below the reservoir than above the reservoir (table 17). The median flows determined by the R2Cross 2-of-3 criteria and the Wetted-Perimeter methods decreased from the upstream to the downstream riffle sites on Indian Brook (from about 0.09 to 0.07 $ft^3/s/mi^2$ and from about 0.30 to 0.10 $ft^3/s/mi^2$, respectively). Further evidence of a decreased channel conveyance is indicated by the median top width of the channel that decreased by about 18 percent (from 17 to 14 ft) from the upstream to the downstream riffle sites on Indian Brook. Development of regional flow targets from physically based methods underscores the need to consider channels that may have been directly or indirectly altered in response to upstream changes that affect the downstream hydrology.

Of the statistically based methods, the computed ABF low-flow target was closest to the target flows determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods; these physically based methods were about 22 to 24 percent less than the computed ABF low-flow target. The overall median ABF low flow (0.32 $ft^3/s/mi^2$) was about 45 percent less than the Tennant 30-percent Q_{MA} (0.58 $ft^3/s/mi^2$). The ABF target low-flow interquartile range (0.30 to 0.45 $ft^3/s/mi^2$) was smaller than that determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods but larger than that determined by the Tennant method.

Streamflow targets determined by the Tennant method varied least among standard-setting methods over the 10 riffle sites. The interquartile target flows ranged from about 0.57 to 0.59 $ft^3/s/mi^2$ and from 0.95 to 0.98 $ft^3/s/mi^2$ determined by the Tennant 30-percent Q_{MA} and 50-percent Q_{MA} methods, respectively. The small variability in target flows determined by the Tennant method relative to other methods is expected because the value is computed from the mean annual flow that, when normalized for drainage area, tends to be comparable in similar hydrogeologic settings. It should be noted that medians of the R2Cross 2-of-3 criteria and Wetted-Perimeter target flows were between 10 and 20 percent of the Q_{MA} (table 19), which Tennant (1976) ranked as fair to poor for seasonal low flows (table 18).

The R2Cross 3-of-3 criteria and the Tennant 50-percent Q_{MA} methods, designed for setting high-flow targets, yielded comparable median target flows. The overall median determined by the Tennant 50-percent Q_{MA} (0.97 $ft^3/s/mi^2$) is about 3 percent less than the overall median determined by the R2Cross 3-of-3 criteria (1.00 $ft^3/s/mi^2$). However, the upper quartile of median flows determined by the R2Cross 3-of-3 criteria (1.66 $ft^3/s/mi^2$) is about twice that determined by the Tennant 50-percent Q_{MA} (0.98 $ft^3/s/mi^2$) (fig. 50).

Simulated streamflows at the 25th, 50th, and 75th percentiles of median monthly mean flows represent the normal range in flow variability during the year (fig. 51). The ABF median of the August mean flow (0.32 $ft^3/s/mi^2$) is between the 25th- and 50th-percentile flows for the July through September period (0.22 and 0.42 $ft^3/s/mi^2$, respectively) at the 10 riffle sites. This indicates that unregulated summer streamflows are below the ABF target low flow about 35 percent of the time. The Tennant 30-percent Q_{MA} criterion flow (0.58 $ft^3/s/mi^2$) is between the 50th and 75th percentiles for the July through September period (0.42 and 0.83 $ft^3/s/mi^2$, respectively) at the 10 riffle sites. The median R2Cross 2-of-3 criteria and Wetted-Perimeter flow targets (0.24 and 0.25 $ft^3/s/mi^2$, respectively) were about equal to the 25th-percentile flows for the July through September period at the 10 riffle sites.

The Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria target flows are well above the 75th-percentile flows during the normally low-flow period (July through September) and well below the 25th-percentile flows during the normally high-flow period (March and April). This underscores that target flows determined by the Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria methods have limited applicability to the seasonal flow regimes in this region because they were intended to represent the Rocky Mountain region.

Statistically based target flows cannot be met 100 percent of the time because they reflect statistical properties of the observed or simulated streamflows they were derived from. Physically based target flows also are not typically met 100 percent of the time, but are more likely to be met because they are derived from physical characteristics of a stream reach. Regardless of the method used to set a target flow, two important questions are often asked that can be addressed by the use of simulated flows—(1) how often do unaltered flows meet, or not meet, a target flow, and (2) how would this change in response to flow alterations. Regulation at the riffle sites examined in this study was limited to the effects of water withdrawals, which affected 6 of the 10 sites. Affected riffle reaches (fig. 35) included Whitehall Brook near Hopkinton (4), Sudbury River near Hopkinton (5), Sudbury River near Ashland (6), and Indian Brook near Ashland (8) in the Sudbury River Basin, and Assabet River at Westborough (51) and Fort Meadow Brook near Hudson (61) in the Assabet River Basin. Elizabeth Brook near Stow (63) is also affected by withdrawals, but these withdrawals were minor; therefore, this reach was not included in the comparison of reaches with and without flow alteration.

Frequency and Duration Streamflows were below Target Flows

Flow-duration curves are a useful method for determining the percentage of flows that fall below a given threshold, but they reflect the flows over the entire period of record that the curves were developed from. Duration curves do not provide information on the magnitude, frequency, and duration that streamflows were below a specified threshold. Marsh and others (2003) developed the River Analysis Package (RAP)

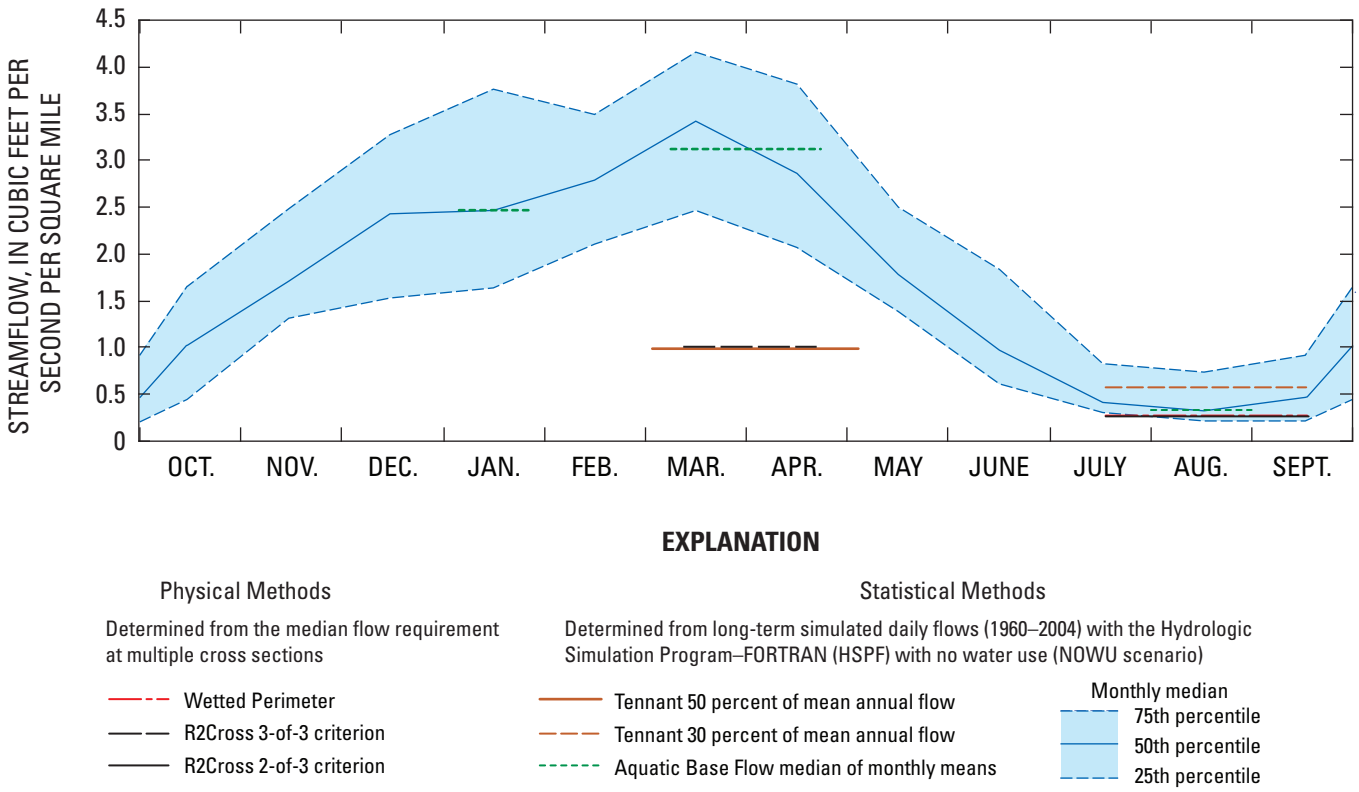


Figure 51. Median and quartiles of the monthly median flow in comparison to standard-setting method target flows determined at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

to compute a suite of quantitative measures of flow, some of which were used to determine the number of continuous days (duration) and the number of episodes (frequency) streamflows fell below specified thresholds. An episode is a period of continuous days a flow target was not met.

Flow thresholds used in the RAP analysis were determined from standard-setting methods for each of the 10 riffle sites examined in the Sudbury and Assabet River Basins previously described. Flow thresholds for physically based methods (R2Cross and Wetted-Perimeter) represent the median target flows from multiple cross sections at each riffle site. Flow thresholds for statistically based methods (Tennant and ABF) are a unique value for each riffle site.

For each site, the duration and frequency that streamflows fell below a threshold were determined from the long-term (1960–2004) HSPF simulated flows without withdrawals (NOWU) and with average 1993–2003 withdrawals (AVGWU). Withdrawals affected flows in 7 of the 10 riffle reaches. For each riffle site, the ability to meet the target flow over the 45-year simulation period was evaluated by (1) the median number of episodes per year the flow threshold was not met, (2) the median number of days per year the flow threshold was not met, (3) the median duration (days) of the longest annual episode the flow threshold was not met, (4) the longest continuous duration the flow threshold was not met, and (5) the total number of days the flow threshold was not met.

The frequency and duration NOWU simulated streamflows fell below a given threshold varied by method and by site (appendix 4, fig. 52). Flow thresholds determined by the Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria methods are not met at a greater frequency and for a longer duration of time than other flow thresholds determined by the other methods (appendix 4, tables 4-1 to 4-6 and fig. 52); thus, their applicability requires greater consideration to the flow regimes they are intended to be used for. Overall, flow thresholds determined by the Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria methods were not met about 40 percent of the time over the 45-year period (appendix 4; tables 4-3 and 4-5). In general, the frequency and duration the R2Cross 3-of-3 criteria flow target was not met varied more among sites than the other target flows (fig. 52). The frequency and duration target flows determined by the Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria methods are not met are excluded from

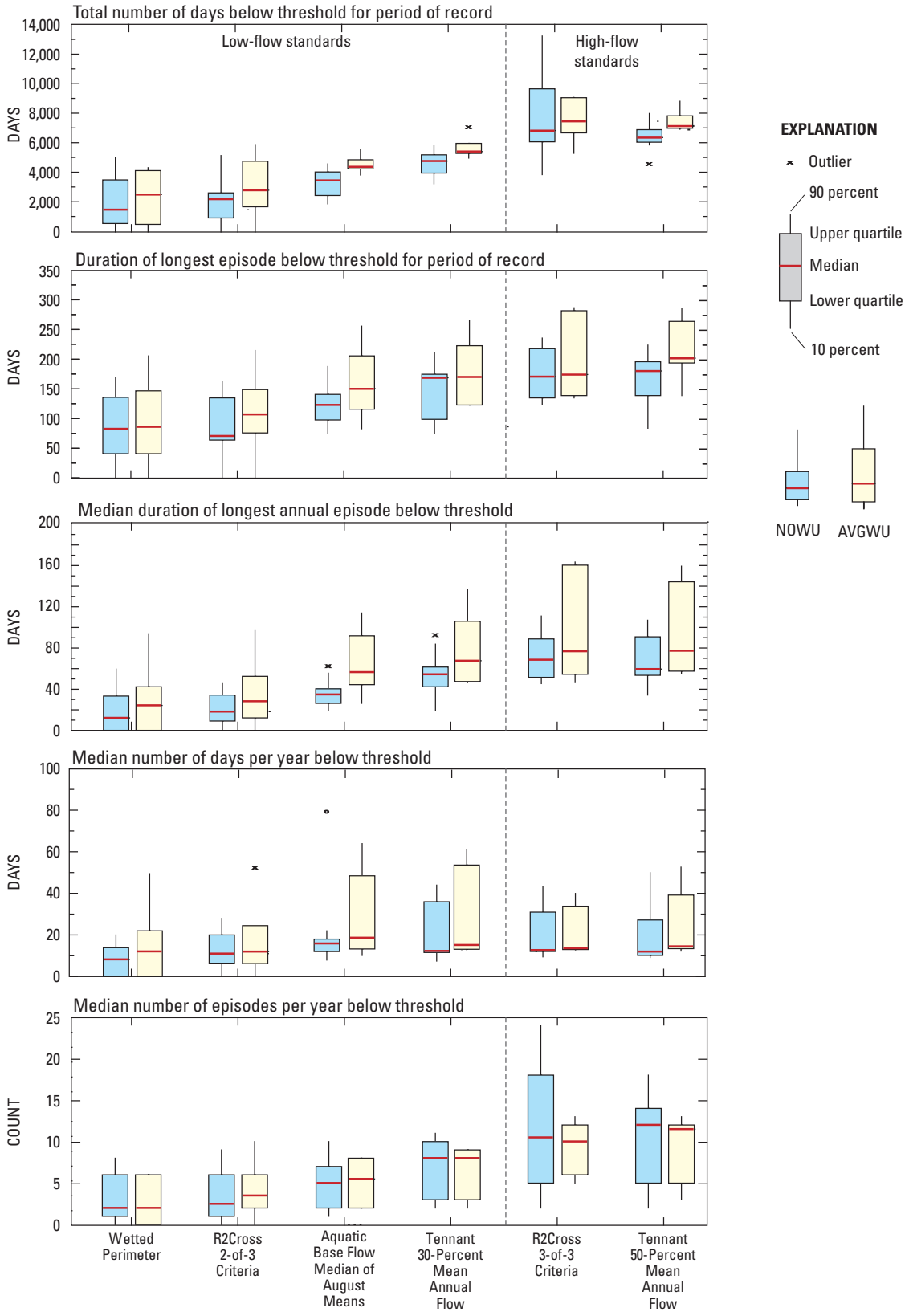


Figure 52. Frequency and duration that long-term (1960–2004) streamflows simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with (AVGWU) and without (NOWU) withdrawals were below target flows determined by six standard-setting methods at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

the remainder of the analyses because they are not intended to reflect a low-flow target and are not comparable to results from the other methods.

The median frequency and duration NOWU simulated streamflows fell below a flow threshold for a given method (fig. 52) indicate that the statistically based methods (Tennant 30-percent Q_{MA} and ABF) tend to have a greater number of episodes that were of longer duration than the physically based methods (Wetted-Perimeter and R2Cross 2-of-3 criteria). Flow thresholds determined by the Wetted-Perimeter and R2Cross 2-of-3 criteria methods have a median of about 0.25 $ft^3/s/mi^2$, which is about 45 percent less than the flow thresholds determined by the Tennant 30-percent Q_{MA} and the ABF, which have a median of about 0.45 $ft^3/s/mi^2$. As a result, the median annual duration of an episode and total number of days simulated flows were below the flow threshold were about three times greater for statistically based standards than for physically based standards.

In almost all cases, as would be expected, the frequency and duration flows fell below a given threshold were greater for AVGWU simulated streamflows than for NOWU simulated streamflows (appendix 4, fig. 52). The only exception to this was the median annual number of episodes (continuous periods when flows were below a threshold). In a few instances, the number of episodes was less for AVGWU simulated flows than for NOWU simulated flows because the duration flows fell below the threshold was greater, resulting in fewer breaks between episodes. Differences in the frequency and duration AVGWU simulated streamflows fell below a given threshold relative to NOWU simulated streamflows largely depend on the degree of flow alteration. The total number of days the long-term (1960–2004) AVGWU simulated streamflows fell below a threshold relative to NOWU increased from 17 to 130 percent at the seven riffle sites affected by withdrawals (table 23). The median difference in total number of days that NOWU and AVGWU simulated flows were below physically based target flows (58 percent) was nearly three times that for statistically based target flows (20 percent) (table 23). This indicates that overall, physically based target flows are more sensitive to flow alterations than statistically based target flows because the flow targets are generally lower.

Overall, the differences between frequency and duration simulated flows with and without withdrawals fell below a given flow threshold were significant at the 95-percent confidence interval as determined by the paired two-sample t-test or by the Wilcoxon signed-rank test (TIBCO Spotfire S+®, 2008; 30 matched pairs that represent 5 RAP metrics measured at 6 sites). In addition to the three sites not affected by withdrawals (Indian Brook near Hopkinton, Baiting Brook near Framingham, and Danforth Brook at Hudson), Elizabeth Brook near Stow was excluded from the paired-test analysis because withdrawals from this subbasin minimally affect streamflow. Paired differences were not always significant at the 95-percent confidence interval for individual sites (combined RAP metrics at a site) or for individual RAP metrics (combined sites for individual RAP metrics). Differences between simulated flows with and without withdrawals were not significant, by either test, at the 95-percent confidence interval at Whitehall Brook near Hopkinton (reach 4) for all RAP metrics or for the median number of annual episodes at all sites except Sudbury River near Ashland (reach 6). Additional sites with paired information on the ability to meet flow targets with and without withdrawals are needed to better determine statistically valid differences in the frequency and duration flow targets are not met.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Conservation and Recreation (MADCR), began a study in 2004 of the Sudbury and Assabet River Basins to determine the condition of fisheries and to assess target streamflows determined by standard-setting methods intended to protect aquatic habitat. Fish-community data, collected by the Massachusetts Division of Fisheries and Wildlife (MADFW), for flowing (not impounded) reaches in the main stem of the Sudbury and Assabet Rivers were compiled and assessed. Stream-temperature data were collected at seven sites in the upper Sudbury River Basin and evaluated with respect to habitat for brook trout. Two of the water-temperature monitoring sites are coincident with the river fish-sampling sites on the main stem. The main focus of the habitat study was the determination and comparison of target streamflows at 10 riffle reaches in the Sudbury and Assabet River Basins determined by standard-setting methods designed to protect aquatic habitat. These flow targets were evaluated with respect to the frequency and duration streamflows were not met using HSPF simulated flows developed for the Sudbury and Assabet River Basins.

The fish-community assessment characterized the diversity and relative abundance of fish species in the main stems of the Sudbury and Assabet Rivers. These rivers have a diversity of species expected in rivers in southern New England; however, the community is dominated by macrohabitat generalists, indicating the fish community is under some degree of stress. A total of 390 fish of 14 species were captured at 5 sites on the main stem of the Sudbury River; nearly 71 percent of the fish captured are classified as macrohabitat generalists. A total of 1,065 fish of 21 species were captured at 8 sites on the main stem of the Assabet River; 54 percent of the fish captured are macrohabitat generalists. White suckers, a fluvial species that is pollution tolerant, composed 30 and 60 percent of the total and fluvial communities, respectively, indicating that water quality may be a factor affecting community composition. The main-stem fish communities of the Sudbury and Assabet Rivers were primarily composed of species that could tolerate the warmer summer water temperatures.

Twenty-one tributary stream reaches in the Sudbury and Assabet River Basins have been identified by the MADFG as a cold-water fishery resource (CFR); 7 are in the Sudbury River Basin and 15 are in the Assabet River Basin. Cold-water fish

Table 23. Median frequency and duration long-term (1960–2004) streamflows simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with (AVGWU) and without (NOWU) withdrawals were below target flows determined by four standard-setting methods at seven riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[Episode, a period of continuous days a target flow was not met; n, number of observations used to determine the median; $ft^3/s/mi^2$, cubic feet per second per square mile; Q_{MA}, mean annual flow]

	n	Median annual			Period of Record		Median flow threshold ($ft^3/s/mi^2$)
		Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)	
Wetted Perimeter (WP)							
NOWU	7	1.5	7.0	5	67	999	0.251
AVGWU	7	2.0	9.8	22	97	2,302	
Percent difference		33	40	340	45	130	
R2Cross 2-of-3 criteria							
NOWU	7	2.0	10	21	73	2,087	0.244
AVGWU	7	2.0	13	26	134	2,585	
Percent difference		0	31	24	84	24	
Tennant 30-percent Q_{MA}							
NOWU	7	8.0	12	50	168	4,611	0.581
AVGWU	7	8.0	17	83	176	5,395	
Percent difference		0	33	66	4.8	17	
Aquatic Baseflow (ABF)							
NOWU	7	4.0	18	39	112	3,434	0.322
AVGWU	7	4.0	23	45	141	4,260	
Percent difference		0	25	15	26	24	
Median of the medians for physically based methods (WP & R2Cross 2-of-3)							
NOWU	7	1.8	8.5	13.0	70	1,543	0.248
AVGWU	7	2.0	11.5	24.0	116	2,444	
Percent difference		14	35	85	65	58	
Median of the medians for statistically based methods (Tennant 30-Q_{MA} & ABF)							
NOWU	7	6.0	15.0	44.5	140	4,023	0.452
AVGWU	7	6.0	19.5	64.0	159	4,828	
Percent difference		0	30	44	13	20	

species were dominant in some CFR reaches; however, other CFR reaches that had contained cold water species in the past contained few, if any, cold-water species during recent sampling efforts. Cold-water fish species in many CFR reaches are between these extremes because of stress from hydrologic alterations, increasing stream temperature, and sedimentation from rapid urbanization around the Interstate-495 corridor in which these basins are located.

Stream temperature was recorded in seven free-flowing reaches in the upper Sudbury River Basin to provide a general indication of the suitability for cold-water fish species, particularly brook trout. Three of the sites were unaffected by upstream water withdrawals or impoundments—Jackstraw Brook near Westborough, Indian Brook near Hopkinton, and Baiting Brook near Framingham. The other four sites were affected by withdrawals or impoundments, or both—Whitehall Brook near Hopkinton, Sudbury River near Hopkinton, Sudbury River near Ashland, and Cold Spring Brook at Ashland. The sites unaffected by withdrawals or impoundments generally maintained water temperatures that could potentially sustain brook trout; however, daily water temperatures at these sites often rose to levels considered precarious to the long-term survival of brook trout. Summer water temperatures in Jackstraw Brook were more favorable for brook trout (cooler) than Indian and Baiting Brook because the reach generally had a denser canopy cover and was affected less by wetlands and

urbanization. The 7-day mean of the maximum daily stream temperatures during the summer at the four sites downstream from withdrawals or reservoirs, or both, were warmer (often in the upper range for brook-trout survivability) for longer periods of time compared to the unaffected sites. These sites also had smaller fluctuations in daily temperature that combined with the warmer temperatures provide less opportunity for cold-water fish to find temporary refuge during warm periods. Stream temperatures in the reaches examined below reservoirs or withdrawals, or both, were marginal to poor for supporting brook trout.

Standard-setting methods for determining flows to protect aquatic habitat were applied at 10 riffle sites; 6 in the Sudbury River Basin and 4 in the Assabet River Basin. Drainage areas to these sites ranged in size from 3.4 to 24 mi^2. The methods were divided into two general categories—physical and statistical; flows determined by these methods are referred to as target flows and are intended to represent the minimal flow needed to protect aquatic habitat. Target flows vary to reflect normal seasonal low- and high-flow periods.

The physically based methods used included R2Cross and Wetted-Perimeter. These methods require site-specific physical and hydraulic data and can be applied to reaches that are ungaged or altered by withdrawals (subject to some constraints). A calibrated one-dimensional hydraulics model, HEC-RAS, was developed for each riffle reach to determine flows that meet the criteria set forth by the method. Models were developed for the six riffle reaches in the Sudbury River Basin for this study; HEC-RAS models developed previously were used for the Assabet River Basin riffle reaches. The HEC-RAS models were developed from multiple cross sections and calibrated to measured water levels over a range of flows, but not all cross sections were used in the determination of physically based target flows.

The R2Cross method establishes flow targets on the basis of three channel hydraulic characteristics—average velocity, wetted perimeter, and mean depth; the latter two variables vary according to the top width of the stream. To account for seasonal streamflow variability, summer and winter target flows vary according to the number of hydrologic criteria met. Flows that meet 2-of-3 criteria were considered applicable to low-flow conditions in southern New England. Flows that meet all three hydraulic criteria, intended to reflect seasonal high flows for the Rocky Mountain region, were not considered representative of seasonal high flows in southern New England. The Wetted-Perimeter method defines the target flow as the flow necessary to keep the riffle cross section between the lower streambank edges in contact with water. The flow required to satisfy the wetted-perimeter variable in the R2Cross method is defined as a percentage of the bankfull wetted perimeter. The median flow targets developed with the R2Cross 2-of-3 criteria at the 10 riffle sites ranged from about 0.07 to 0.72 $ft^3/s/mi^2$ with an overall median of about 0.24 $ft^3/s/mi^2$. The Wetted-Perimeter flow targets at the same riffle sites ranged from about 0.10 to 0.51 $ft^3/s/mi^2$ with an overall median of about 0.25 $ft^3/s/mi^2$.

The statistically based methods used included Tennant and New England Aquatic Baseflow (ABF), and although not considered a standard-setting method, the Range-of-Variability Approach (RVA) was used to characterize the monthly streamflow variability. These methods typically are limited to unregulated sites with long-term daily streamflow data. It was possible to employ these statistically based methods at the 10 riffle sites by using the HSPF simulated long-term (1960–2004) daily flows with no water use (NOWU scenario). The simulated unregulated flows were also used to characterize monthly flow variability at the 25th, 50th, and 75th percentiles of median monthly flow.

The Tennant method flow target is calculated as a percentage of the mean annual flow (Q_{MA}). Seasonal flow targets are identified by the Tennant method by assigning different percentages of the Q_{MA}. The Tennant high-flow target (50-percent Q_{MA}), like the R2Cross 3-of-3 criteria method, was not considered representative of seasonal high flows in southern New England. The 30-percent Q_{MA}, considered by the Tennant method to be an excellent low-flow target, ranged from about 0.56 to 0.61 $ft^3/s/mi^2$ with an overall median of 0.58 $ft^3/s/mi^2$ at the 10 riffle sites.

The ABF low-flow standard is calculated as the median of the August mean flow for each year over the period of record. ABF flow targets were calculated for winter and spring as the median of the January mean flows and the mean of the median monthly mean flows in March and April, respectively. The computed ABF low-flow targets ranged from about 0.14 to 0.62 $ft^3/s/mi^2$ among the 10 riffle sites; the overall median low-flow target, 0.32 $ft^3/s/mi^2$, was about 36 percent less than the ABF default standard (0.50 $ft^3/s/mi^2$). The computed ABF low-flow target was moderately correlated (r^2 0.62) with the percentage of the contributing area underlain by sand and gravel, excluding Whitehall Brook, which is affected by Whitehall Reservoir. The computed ABF low-flow targets were weakly inversely correlated (r^2 -0.27) with the percentage of the basin area classified as water and wetlands, reflecting greater evapotranspiration losses from these areas. Computed ABF winter and spring flow targets at the riffle sites ranged from about 2.4 to 2.5 $ft^3/s/mi^2$ and 3.0 to 3.2 $ft^3/s/mi^2$, respectively. The overall median ABF winter flow target (2.5 $ft^3/s/mi^2$) was about two and a half times greater than the default ABF fall-winter standard (1.0 $ft^3/s/mi^2$), and the overall median spring flow target (3.1 $ft^3/s/mi^2$) was about 22 percent less than the default ABF spring flow standard (4.0 $ft^3/s/mi^2$).

RVA is considered a diagnostic tool for evaluating hydrologic variability necessary to preserve the ecological integrity of a stream. Of the 33 statistical measures determined by this method, the median (50th percentile), upper (75th percentile), and lower (25th percentile) quartiles of the median monthly flows were used to reflect the normal seasonal flow variability, which the other methods could be compared to. The 50th-percentile flow at 10 riffle sites was lowest in August (0.32 $ft^3/s/mi^2$) and highest in March (3.4 $ft^3/s/mi^2$).

Flow targets determined by the various methods at the 10 riffle sites, normalized for drainage area, yielded a broad

range of flows. In general, the variability was larger among sites for physically based methods than for statistically based methods, and the physically based methods generally yielded lower flow targets than the statistically based methods. The R2Cross 3-of-3 criteria yielded the largest flow target among the methods examined. Flows that satisfy all the R2Cross 3-of-3 criteria do not appear to reflect the normal magnitude of seasonal-low or seasonal-high flows in southern New England. The R2Cross 2-of-3 criteria flow target was substantially lower and less variable than the 3-of-3 criteria target flow, but with the exception of the 3-of-3 criteria target flow, the 2-of-3 criteria target flows varied the most among the sites and methods examined. This indicates that if an insufficient number of cross sections are used, the target flow determined by the R2Cross method may not represent the aquatic-habitat needs of the reach.

The target flows determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods were in closest agreement among the methods examined; the median values determined at the 10 riffle sites were about 0.24 and 0.25 $ft^3/s/mi^2$, respectively. Of the statistically based methods, the ABF low-flow target (median of about 0.32 $ft^3/s/mi^2$) was closest to the flow targets determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods. The Tennant 30-percent Q_{MA} target flow (median of about 0.58 $ft^3/s/mi^2$) was about 81 percent greater than the median ABF low-flow target. The Tennant method varied least among standard-setting methods over the 10 riffle sites. The flow targets determined by R2Cross 2-of-3 criteria and Wetted-Perimeter methods were between 10 and 20 percent of the Q_{MA}.

The ABF low-flow target (0.32 $ft^3/s/mi^2$) is between the 25th and 50th percentiles of the median monthly flow for the period July through September (0.22 and 0.42 $ft^3/s/mi^2$, respectively). The flow targets determined by the R2Cross 2-of-3 criteria and Wetted-Perimeter methods (0.24 and 0.25 $ft^3/s/mi^2$, respectively) were about equal to the 25th percentile of the median monthly flow for the period July through September. The target flow determined by the Tennant 30-percent Q_{MA} criteria method (0.58 $ft^3/s/mi^2$) is between the 50th and 75th percentiles of the median monthly flow for the period July through September (0.42 and 0.83 $ft^3/s/mi^2$, respectively). The target flows determined by the Tennant 50-percent Q_{MA} and the R2Cross 3-of-3 criteria methods are well above the upper quartile of median monthly flows during the summer and well below the lower quartile of monthly median flows during the normal high-flow period. This underscores that the target flows determined by these particular methods are not representative of the low- and high-flow regimes in southern New England.

Through use of HSPF simulated flows it was possible to evaluate the frequency and duration that flow targets were not met over a 45-year period (1960–2004) without water withdrawals (NOWU scenario) and with average 1998–2003 water withdrawals (AVGWU scenario). The ability to meet the flow targets over the long-term period was evaluated by (1) the median number of episodes (an episode is a continuous period that streamflow fell below a target flow) per year the flow target was not met, (2) the median number of days per year the flow target was not met, (3) the median duration (days) of the longest annual episode the flow target was not met, (4) the longest continuous duration the flow target was not met, and (5) the total number of days the flow target was not met.

At the 10 riffle sites, the NOWU simulated streamflows were below the statistically based target flows (Tennant 30-percent Q_{MA} and ABF), as measured by the median duration of annual episodes and total number of days below the flow target over the 45-year period, about three times more than that determined by physically based target flows (Wetted-Perimeter and R2Cross 2-of-3 criteria). This is because the median target flow determined by Wetted-Perimeter and R2Cross 2-of-3 criteria methods (about 0.25 $ft^3/s/mi^2$) is about 45 percent less than the median target flow determined by the Tennant 30-percent Q_{MA} and ABF methods (about 0.45 $ft^3/s/mi^2$).

The frequency and duration that flows fell below a given target flow were almost always greater for AVGWU simulated streamflows than for NOWU simulated streamflows. Paired two-sample t-test and Wilcoxon signed-rank tests indicate these differences were mostly significant at the 95-percent confidence interval except at Whitehall Brook near Hopkinton and, at most sites, for the median number of annual episodes. The reason the difference in the number of annual episodes was largely insignificant is because AVGWU simulated streamflows generally have more days in an episode, resulting in fewer breaks between episodes compared to episodes computed from NOWU simulated streamflows. Overall, physically based target flows were slightly lower than statistically based target flows, making them slightly more likely to not meet a flow target as a result of flow alteration.

The range of target flows determined by the different methods and among sites within the Sudbury and Assabet River Basins indicates additional information would be needed to determine regional flow standards for protection of aquatic habitat. The fish-community data, available at only two of the riffle sites examined (both along the upper Sudbury River), limits the conclusions that can be drawn among these data and the target flows. Further work would be needed to determine which methods are most sensitive to hydrologic alteration and fish-community composition to provide the appropriate balance between human water-supply needs and aquatic-habitat needs.

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Appendix 1

Partial Listing of the Hydrologic Simulation Program–FORTRAN (HSPF) Model Run File (*uci*)

Appendix 1. Partial Listing of the Hydrologic Simulation Program–FORTRAN (HSPF) Model Run File (*uci*)

```
      ***  HSPF model run for Sudbury-Assabet River Basin, MA
RUN

GLOBAL
  Sudbury-Assabet River Basin, MA, Base calibration
  START       1992/10/01 00:00  END    2003/12/31 24:00
  RUN INTERP OUTPUT LEVEL    4   6
  RESUME    0 RUN      1
END GLOBAL

FILES
<FILE>  <UN#>***<----FILE NAME--------------------------------------------------->
WDM        20   Sud1.WDM
MESSU      22   sud1.ech
              15   sud1.out
BINO       16   sud1.hbn
END FILES

OPN SEQUENCE
   INGRP            INDELT 01:00
     IMPLND      60
     IMPLND      61

     PERLND       1
     PERLND       3
     PERLND       4
     PERLND       6
     PERLND       7
     PERLND       8
     PERLND       9
     PERLND      10
     PERLND      11
     PERLND      12
     PERLND      13
     PERLND      14

     PERLND      31
     PERLND      33
     PERLND      34
     PERLND      36
     PERLND      37
     PERLND      38
     PERLND      39
     PERLND      40
     PERLND      41
     PERLND      42
     PERLND      43
     PERLND      44

     PERLND      51
```

```
    PERLND    52
    PERLND    53

    RCHRES     1
    RCHRES     2
    RCHRES     3
    RCHRES     4
    RCHRES   105
    RCHRES     5
    RCHRES     6
    RCHRES   107
    RCHRES     8
    RCHRES     9
    RCHRES    10
    RCHRES    11
    RCHRES    12
    RCHRES    13
    RCHRES    14
    RCHRES    15
    RCHRES    16
    RCHRES    17
    RCHRES    18
    RCHRES    19

    RCHRES    30
    RCHRES    31
    RCHRES    32
    RCHRES    33

    RCHRES    51
    RCHRES    52
    RCHRES    53
    RCHRES    54
    RCHRES    55
    RCHRES    56
    RCHRES    57
    RCHRES    58
    RCHRES    59
    RCHRES    60
    RCHRES    61
    RCHRES    62
    RCHRES    63
    RCHRES    64
    RCHRES    65
    RCHRES    66
    RCHRES    67
    RCHRES    68
    RCHRES    69
    RCHRES    70
    RCHRES    72
    RCHRES    73

      COPY     1
      COPY     5
  END INGRP
END OPN SEQUENCE
```

```
**************************************************
***         PERLND - Pervious land surface                    ***
***                                                           ***
**************************************************
PERLND
  ACTIVITY
    <PLS >         Active Sections (1=Active; 0=Inactive)            ***
  ### -### ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC ***
     1    53         0          1          1
  END ACTIVITY

  PRINT-INFO
    <PLS > <-*** Print-flags: 2-PIVL, 3-dy, 4-mn, 5-yr, 6-never                          ***-> PIVL  PYR
  ### -### ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC       ***
     1    53         5          5                                                                          1   12
  END PRINT-INFO

  BINARY-INFO ***
    <PLS > <-*** Print-flags: 2-PIVL, 3-dy, 4-mn, 5-yr, 6-never                          ***-> PIVL  PYR
  ### -### ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC       ***
      1    53         5          5                                                                          1   12
  END BINARY-INFO ***

  GEN-INFO
    <PLS ><-------Name------->NBLKS      Unit-systems      Printer      Binary    ***
  ###--###                                User  t-series   Engl   Metr  Engl  Metr ***
    1         S&G Comm/Ind                1      1      1      1      15      0      16      0
    2         S&G Comm/Ind  Imp           1      1      1      1      15      0      16      0
    3         S&G Comm/Ind  Exp           1      1      1      1      15      0      16      0
    4         S&G hi resid                       1      1      1      1      15      0      16      0
    5         S&G hi resid  Imp                  1      1      1      1      15      0      16      0
    6         S&G hi resid  Exp                  1      1      1      1      15      0      16      0
    7         S&G mod resid                      1      1      1      1      15      0      16      0
    8         S&G mod resid Imp                  1      1      1      1      15      0      16      0
    9         S&G mod resid Exp                  1      1      1      1      15      0      16      0
   10         S&G low resid                      1      1      1      1      15      0      16      0
   11         S&G low resid Imp                  1      1      1      1      15      0      16      0
   12         S&G low resid Exp                  1      1      1      1      15      0      16      0
   13         S&G Open                           1      1      1      1      15      0      16      0
   14         S&G Forest                         1      1      1      1      15      0      16      0

   31         Till Comm/Ind                      1      1      1      1      15      0      16      0
   32         Till Comm/Ind  Imp                 1      1      1      1      15      0      16      0
   33         Till Comm/Ind  Exp                 1      1      1      1      15      0      16      0
   34         Till hi resid                      1      1      1      1      15      0      16      0
   35         Till hi resid  Imp                 1      1      1      1      15      0      16      0
   36         Till hi resid  Exp                 1      1      1      1      15      0      16      0
   37         Till mod resid                     1      1      1      1      15      0      16      0
   38         Till mod resid Imp                 1      1      1      1      15      0      16      0
   39         Till mod resid Exp                 1      1      1      1      15      0      16      0
   40         Till low resid                     1      1      1      1      15      0      16      0
   41         Till low resid Imp                 1      1      1      1      15      0      16      0
   42         Till low resid Exp                 1      1      1      1      15      0      16      0
   43         Till Open                          1      1      1      1      15      0      16      0
```

```
 44        Till Forest                    1    1    1    1    15   0    16    0

 51        Non-forest wetland             1    1    1    1    15   0    16    0
 52        Forested wetland               1    1    1    1    15   0    16    0
 53        Water                          1    1    1    1    15   0    16    0
END GEN-INFO

*** ----------------------------------------------------------------------
***   PERLND -  Section SNOW

ICE-FLAG
  <PLS >  0= Ice formation not simulated, 1= Simulated ***
### -###ICEFG                                          ***
   1    53       1
END ICE-FLAG

SNOW-PARM1
  <PLS >  Snow input info: Part 1                                  ***
### -###      LAT    MELEV    SHADE   SNOWCF   COVIND ***
   1     6     42.4     281.     0.15     1.35     0.75
   7    12     42.4     281.     0.35     1.35     0.75
  13           42.4     281.     0.15     1.35     0.75
  14           42.4     281.     0.50     1.35     0.75
  31   36      42.4     281.     0.15     1.35     0.75
  37   42      42.4     281.     0.35     1.35     0.75
  43           42.4     281.     0.15     1.35     0.75
  44           42.4     281.     0.50     1.35     0.75
  51           42.4     281.     0.10     1.35     0.75
  52           42.4     281.     0.50     1.35     0.75
  53           42.4     281.     0.05     1.35     0.75
 END SNOW-PARM1

SNOW-PARM2
  <PLS >  Snow input info: Part 2                                                  ***
### -###     RDCSN     TSNOW    SNOEVP    CCFACT    MWATER    MGMELT ***
   1    53      0.15       32.      0.03      1.25      0.15    0.0200
END SNOW-PARM2


***-----------------------------------------------------------------------------*
***  PERLND -  Section PWATER

PWAT-PARM1
***     CSNO=1 snowmelt on   ;   1=varies monthly 0=does not
*** <PLS > <PWATER flags><monthly parameter value flags>< other proc >
***## -### CSNO RTOP UZFG  VCS  VUZ  VNN VIFW VIRC VLET IFFC  HWT IRRG
   1    13    1    0    1    1    0    0    1    0    1    0    0    0
  14         1    0    1    1    0    0    1    0    1    0    0    0
  31    43   1    0    1    1    0    0    1    0    1    0    0    0
  44         1    0    1    1    0    0    1    0    1    0    0    0
  51    53   1    0    1    1    0    0    1    0    1    0    0    0
END PWAT-PARM1

PWAT-PARM2
### -### ***FOREST     LZSN    INFILT     LSUR    SLSUR    KVARY    AGWRC
      ***        (none)      (in)      (in/hr)      (ft)      (none)    (l/in)          (l/in)
```

```
  1   9          0.050        4.60       0.400       150.       0.021       0.05       0.990
 10  12          0.100        4.80       0.480       200.       0.021       0.05       0.992
 13              0.050        4.90       0.500       300.       0.021       0.05       0.993
 14              0.250        5.00       0.520       300.       0.021       0.05       0.993
 31  39          0.050        2.70       0.100       150.       0.021       0.28       0.980
 40    42        0.100        2.50       0.120       200.       0.021       0.28       0.981
 43              0.050        2.70       0.130       300.       0.021       0.28       0.982
 44              0.250        2.70       0.140       300.       0.021       0.28       0.982
 51              0.050        1.70       0.050       100.       0.015       0.55       0.890
 52              0.250        1.20       0.050       100.       0.015       0.55       0.870
 53              0.010        1.20       0.050       100.       0.005       0.55       0.722
END PWAT-PARM2


PWAT-PARM3
  <PLS > ***  PWATER input info: Part 3
### -### ***PETMAX    PETMIN    INFEXP    INFILD    DEEPFR    BASETP    AGWETP
  1      2          40.       35.       2.0       2.0       0.00      0.000     0.120
  3                 40.       35.       2.0       2.0       0.22      0.000     0.120
  4      5          40.       35.       2.0       2.0       0.00      0.000     0.120
  6                 40.       35.       2.0       2.0       0.22      0.000     0.120
  7      8          40.       35.       2.0       2.0       0.00      0.000     0.120
  9                 40.       35.       2.0       2.0       0.22      0.000     0.120
 10  11             40.       35.       2.0       2.0       0.00      0.000     0.120
 12                 40.       35.       2.0       2.0       0.22      0.000     0.120
 13                 40.       35.       2.0       2.0       0.00      0.000     0.120
 14                 40.       35.       2.0       2.0       0.00      0.000     0.280
 31  32             40.       35.       2.0       2.0       0.00      0.000     0.120
 33                 40.       35.       2.0       2.0       0.22      0.000     0.120
 34  35             40.       35.       2.0       2.0       0.00      0.000     0.120
 36                 40.       35.       2.0       2.0       0.22      0.000     0.120
 37  38             40.       35.       2.0       2.0       0.00      0.000     0.120
 39                 40.       35.       2.0       2.0       0.22      0.000     0.120
 40  41             40.       35.       2.0       2.0       0.00      0.000     0.120
 42                 40.       35.       2.0       2.0       0.22      0.000     0.120
 43                 40.       35.       2.0       2.0       0.00      0.000     0.120
 44                 40.       35.       2.0       2.0       0.00      0.000     0.280
 51                 40.       35.       2.0       2.0       0.00      0.000     0.300
 52                 40.       35.       2.0       2.0       0.00      0.000     0.380
 53                 40.       35.       2.0       2.0       0.00      0.000     0.340
END PWAT-PARM3

PWAT-PARM4
  <PLS >     PWATER input info: Part 4                                    ***
varies monthly     Y        Y-N       NO        Y         Y         Y   ***
  Flag PARM1   VCS      VUZ       VUR       VMN       VIFW      VLE  ***
### -###      CEPSC     UZSN      NSUR    INTFW       IRC     LZETP ***
                (in)      (in)     (none)    (none)    (l/da)    (none)  ***
  1      9          0.020        0.21       0.190       2.60       0.65       0.18
 10  12             0.020        0.25       0.200       2.70       0.75       0.18
 13                 0.040        0.28       0.210       2.80       0.80       0.28
 14                 0.040        0.31       0.250       2.80       0.85       0.88
 31  39             0.040        0.12       0.180       2.00       0.55       0.18
 40  42             0.040        0.18       0.210       2.15       0.65       0.18
 43                 0.040        0.20       0.210       2.25       0.68       0.28
 44                 0.040        0.22       0.220       2.30       0.70       0.88
```

```
 51   52          0.020        0.12        0.250       1.00        0.75       0.88
 53               0.020        0.12        0.150       1.00        0.75       0.38
END PWAT-PARM4

MON-INTERCEP
  Monthly interception storage                                                  ***
  <PLS>   Only required if VCSFG=1 in PWAT-PARM1                              ***
### -###  Interception storage capacity at start of each month                  ***
              JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1    6      0.02  0.02  0.02  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.02  0.02
  7   12      0.02  0.02  0.02  0.03  0.05  0.10  0.12  0.10  0.10  0.08  0.02  0.02
 13           0.02  0.02  0.02  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.02  0.02
 14           0.02  0.02  0.02  0.02  0.05  0.12  0.14  0.12  0.14  0.10  0.04  0.03
 31   36      0.02  0.02  0.02  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.02  0.02
 37   42      0.02  0.02  0.02  0.03  0.05  0.10  0.12  0.10  0.10  0.08  0.02  0.02
 43           0.02  0.02  0.02  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.02  0.02
 44           0.02  0.02  0.02  0.02  0.05  0.12  0.14  0.12  0.14  0.10  0.04  0.03
 51   52      0.02  0.02  0.02  0.02  0.03  0.04  0.04  0.04  0.04  0.04  0.03  0.02
 53           0.02  0.02  0.02  0.02  0.03  0.03  0.03  0.03  0.03  0.02  0.02  0.02
END MON-INTERCEP


MON-INTERFLW
  Inc INTERFLW  inc interflow & dec surface runoff (1- 3.0 typical)  ***
  Interflow (range 0.0 to ~) Only required if VIFWFG=1 in PWAT-PARM1 ***
   inc.INTFW dec peak & extends recession                          ***
<  PLS >  Monthly interflow  at start of each month                 ***
              JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1    9      2.80  2.80  2.80  2.85  2.85  2.85  2.85  2.85  2.85  2.80  2.80  2.80
 10   13      3.00  3.00  3.00  3.05  3.05  3.05  3.05  3.05  3.05  3.00  3.00  3.00
 14           3.20  3.20  3.20  3.25  3.25  3.25  3.25  3.25  3.25  3.20  3.20  3.20
 31   39      1.20  1.20  1.20  1.35  1.35  1.35  1.35  1.35  1.35  1.20  1.20  1.20
 40   43      2.40  2.40  2.40  2.45  2.45  2.45  2.45  2.45  2.45  2.40  2.40  2.40
 44           2.80  2.80  2.80  2.85  2.85  2.85  2.85  2.85  2.85  2.80  2.80  2.80
 51   53      1.40  1.40  1.40  1.45  1.45  1.45  1.45  1.45  1.45  1.40  1.40  1.40
END MON-INTERFLW

MON-LZETPARM
  Lower zone ET                                          ***
  <PLS >  Only required if VLEFG=1 in PWAT-PARM1  (max < 1.0)       ***
### -###  Lower zone ET parameter at start of each month            ***
              JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
  1    6      .03   .03   .03   .06   .15   .35   .42   .42   .36   .26   .12   .08
  7   13      .04   .04   .04   .07   .19   .68   .68   .68   .64   .56   .32   .18
 14           .05   .05   .05   .08   .24   .70   .74   .74   .72   .66   .40   .22
 31   36      .03   .03   .03   .05   .15   .35   .40   .40   .34   .26   .10   .16
 37   43      .04   .04   .04   .06   .19   .68   .68   .68   .64   .56   .30   .16
 44           .06   .06   .06   .08   .24   .70   .74   .74   .72   .66   .40   .22
 51   52      .06   .06   .06   .08   .38   .75   .78   .78   .75   .62   .52   .32
 53           .04   .04   .04   .07   .26   .42   .45   .45   .40   .42   .32   .16
END MON-LZETPARM

PWAT-STATE1
  <PLS > *** Initial conditions at start of simulation
### -### ***  CEPS    SURS    UZS    IFWS    LZS   AGWS   GWVS
  1       13        0.02        0.00     0.50        0.055      9.63      6.40      3.58
```

```
 14        0.02     0.00     0.59        0.084     8.31      7.80     3.91
 31     43        0.02       0.00     0.30        0.108     4.78     2.19     2.34
 44        0.02     0.00     0.50        0.093     4.59      2.72     2.84
 51     53        0.02       0.00     0.40        0.425     4.55     0.83     0.44
 END PWAT-STATE1

END PERLND


**********************************************************************
***   IMPLND  - Impervious land
**********************************************************************
IMPLND
 ACTIVITY
  <ILS >  Active Sections (1-active, 0-inactive)                ***
 ### -### ATMP SNOW IWAT  SLD  IWG IQAL              ***
  60              0       1        1
  61              0       1        1
 END ACTIVITY

 PRINT-INFO
  2-PIVL, 3-dy, 4-mn, 5-yr, 6-never    user  end                          ***
  <ILS > <------ Print-flags --------->                PIVL  PYR          ***
 ### -### ATMP SNOW IWAT  SLD  IWG IQAL ####   ##                ***
  60              6       5                                  1   12
  61              6       5                                  1   12
 END PRINT-INFO

 BINARY-INFO   ***
  2-PIVL, 3-dy, 4-mn, 5-yr, 6-never    user  end                ***
  <ILS > <------ Print-flags --------> PIVL  PYR                ***
 ### -### ATMP SNOW IWAT  SLD  IWG IQAL ####   ##                ***
  60   61         5        5                                  1   12
 END BINARY-INFO ***

 GEN-INFO
  <ILS ><-------Name------->   Unit-systems     Printer   Binary ***
 ### -###                 User  t-series  Engl Metr     Engl Metr     ***
                            in  out i/o#                                ***
  60     Residential       1       1       1     15     0     16       0
  61     Commercial        1       1       1     15     0     16       0
 END GEN-INFO

 ICE-FLAG
  <PLS >  0= Ice formation not simulated, 1= Simulated ***
 ### -###ICEFG                                          ***
  60    61       1
 END ICE-FLAG

 SNOW-PARM1
  <PLS >  Snow input info: Part 1                                  ***
 ### -###      LAT     MELEV     SHADE    SNOWCF    COVIND ***
  60   61        42.          60.          0.20          1.35          0.75
 END SNOW-PARM1

 SNOW-PARM2
```

```
  <PLS >  Snow input info: Part 2                          ***
 ### -###    RDCSN    TSNOW   SNOEVP   CCFACT   MWATER   MGMELT ***
  60   61      0.15       32.     0.02     1.25     0.30   0.1100
 END SNOW-PARM2


*** ----------------------------------------------------------------------
***   IMPLND - Section IWATER i

 IWAT-PARM1
  <ILS >        Flags                          ***
 ### -### CSNO RTOP  VRS  VNN RTLI ***
  60          0        1        0
  61          0        1        0
 END IWAT-PARM1

 IWAT-PARM2
  <ILS >                                          ***
 ### -###     LSUR    SLSUR     NSUR    RETSC ***
  60              200.     .014     .010      .04
  61              100.     .010     .010      .08
 END IWAT-PARM2

 IWAT-PARM3
  <ILS >                          ***
 ### -###   PETMAX   PETMIN ***
  60              40.      35.
  61              40.      35.
 END IWAT-PARM3

 IWAT-STATE1
  <ILS >  IWATER state variables ***
 ### -###     RETS     SURS       ***
  60              .04      .00
  61              .08      .00
 END IWAT-STATE1
END IMPLND



*******************************************************************************
***     RCHRES Block
*******************************************************************************
RCHRES
 ACTIVITY
  RCHRES  Active Sections (1=Active, 0=Inactive)                          ***
 ### -### HYFG ADFG CNFG HTFG SDFG GQFG OXFG NUFG PKFG PHFG ***
   1     73      1
 105  112      1
 END ACTIVITY

 PRINT-INFO
  RCHRES <-Print-flags: 2-PIVL,3-dy,4-mn,5-yr,6-never                    ***> PIVL  PYR
 ### -### HYDR ADCA CONS HEAT    SED   GQL OXRX NUTR PLNK PHCB ****  ***
   1      8      6      6      6      6      6      6      6      6      6      6     1   12
   9             6      6      6      6      6      6      6      6      6      6     1   12
```

```
 10    18        6        6        6        6        6        6        6        6        6        6    1   12
 19              6        6        6        6        6        6        6        6        6        6    1   12
 30    64        6        6        6        6        6        6        6        6        6        6    1   12
 65              6        6        6        6        6        6        6        6        6        6    1   12
 66    67        6        6        6        6        6        6        6        6        6        6    1   12
 68              6        6        6        6        6        6        6        6        6        6    1   12
 69    73        6        6        6        6        6        6        6        6        6        6    1   12
105   112        6                                                                                 1   12
END PRINT-INFO

BINARY-INFO
  RCHRES <-Print-flags: 2-PIVL,3-dy,4-mn,5-yr,6-never                          ***> PIVL  PYR
### -### HYDR ADCA CONS HEAT  SED  GQL OXRX NUTR PLNK PHCB ****  ***
  1     73        6                                                                                 1   12
105   112        6                                                                                 1   12
END BINARY-INFO

GEN-INFO
  RCHRES<-------Name------->Nexit   Unit Systems   Printer        Binary  ***
### -###                    User t-series  Engl  Metr LKFG  Engl  Metr ***
                             in  out                                  ***
  1    Jackstraw Bk          2    1        1    15        0    16    0
  2    Piccadilly BK         2    1        1    15        0    16    0
  3    Whitehall Res         2    1        1    15        0    16    0
  4    Whitehall Bk          1    1        1    15        0    16    0
  5    Sudbury R Fruite St   2    1        1    15        0    16    0
  6    Sudbury R Howe St     1    1        1    15        0    16    0
  7    Indian Bk Hopkinton   1    1        1    15        0    16    0
  8    Hopkington Res outfl  3    1        1    15        0    16    0
  9    Sudbury R Front St    2    1        1    15        0    16    0
 10    Ashland Res           2    1        1    15        0    16    0
 11    Cold Spring Bk        1    1        1    15        0    16    0
 12    Sudbury Res           2    1        1    15        0    16    0
 13    Foss Res (no 3)       2    1        1    15        0    16    0
 14    Stearnes Res (no 1)   2    1        1    15        0    16    0
 15    Baiting Bk            1    1        1    15        0    16    0
 16    Course Bk             1    1        1    15        0    16    0
 17    Lake Cochituate       2    1        1    15        0    16    0
 18    Lake Cochituate Out   1    1        1    15        0    16    0
 19    Sudbury R Saxonvil    1    1        1    15        0    16    0
 30    Pine Bk               1    1        1    15        0    16    0
 31    Hop Bk Sudbury        2    1        1    15        0    16    0
 32    Allowance Bk          2    1        1    15        0    16    0
 33    Sudbury R Concord     2    1        1    15        0    16    0
 51    Assabet R Headwat     2    1        1    15        0    16    0
 52    Hop Bk Westboro       2    1        1    15        0    16    0
 53    ColdHarbor/Howard B   2    1        1    15        0    16    0
 54    Assabet R Northb      2    1        1    15        0    16    0
 55    Stirrup Bk Northb     2    1        1    15        0    16    0
 56    Millham Bk Marlb      2    1        1    15        0    16    0
 57    North Bk Berlin       1    1        1    15        0    16    0
 58    Abbabet R Hudson      2    1        1    15        0    16    0
 59    Danforth Bk           1    1        1    15        0    16    0
 60    Assabet R Stow        2    1        1    15        0    16    0
 61    Fort Meadow Bk        2    1        1    15        0    16    0
 62    Boon Lake complex     2    1        1    15        0    16    0
```

```
 63    Elizabeth Bk          2    1    1   15    0   16    0
 64    Taylor Bk Maynard     2    1    1   15    0   16    0
 65    Assabet R Maynard g   1    1    1   15    0   16    0
 66    Assabet R Concord     2    1    1   15    0   16    0
 67    Fort Pnd Bk           2    1    1   15    0   16    0
 68    Nashoba Bk Gage       2    1    1   15    0   16    0
 69    Nashoba Bk 2          2    1    1   15    0   16    0
 70    Spencer Bk            1    1    1   15    0   16    0
 72    Assabet R Low Main    1    1    1   15    0   16    0
 73    Confluence            1    1    1   15    0   16    0
105     Sudbury R Fruite St  2    1    1   15    0   16    0
107     Indian Bk Hopkinton  1    1    1   15    0   16    0
112     Sudbury Res          2    1    1   15    0   16    0
END GEN-INFO


*** ------------------------------------------------------------------------ ***
***    RECHRES - Section HYDR input

HYDR-PARM1
  RCHRES  Flags for HYDR section                    ***
### -###   VC   A1  A2  A3  ODFVFG for each     ODGTFG for each *** FUNCT  for each
            FG  FG  FG  FG  possible   exit    possible   exit *** possible   exit
                                     1    2    3    4    5     1  2  3  4  5 ***   1  2  3  4  5
  1      3      0    1    0    0    0    4    1                0  0  1
  4      0      1    0    0    4    0    0    1
  5      0      1    0    0    0    4    1    0                0  1
  6      7      0    1    0    0    4
  8      0      1    0    0    0    4    5    1                0  0  1
  9     10      0    1    0    0    0    4    1                0  1
 11      0      1    0    0    4
 12     14      0    1    0    0    0    4    1                0  0  1
 15     16      0    1    0    0    4
 17      0      1    0    0    0    4    1    0                0   1
 18     19      0    1    0    0    4
 30             0    1    0    0    4
 31     33      0    1    0    0    0    4    1                0  1
 51     56      0    1    0    0    0    4    1                0  0  1
 57             0    1    0    0    4
 58             0    1    0    0    0    4    1                0  0  1
 59             0    1    0    0    4
 60     64      0    1    0    0    0    4    1                0  0  1
 65             0    1    0    0    4
 66     69      0    1    0    0    0    4    1                0  0  1
 70     73      0    1    0    0    4
105             0    1    0    0    0    4    1                0  0  1
107             0    1    0    0    4
112             0    1    0    0    0    4    1                0  0  1
END HYDR-PARM1

HYDR-PARM2
  RCHRES ***
### -###  FTB  FTA        LEN     DELTH       STCOR              SED  ***
### -###  DSN  BNO     (miles)     (feet)       (feet)        KS    DB50 ***
   1                 1          1.629          222.          0.0          0.5
   2                 2          1.292           37.          0.0          0.5
```

3	3	1.910	11.	0.0	0.5
4	4	2.608	50.	0.0	0.5
5	5	2.659	168.	0.0	0.5
6	6	3.450	67.	0.0	0.5
7	7	2.940	113.	0.0	0.5
8	8	1.650	20.	0.0	0.5
9	9	2.758	33.	0.0	0.5
10	10	1.197	15.	0.0	0.5
11	11	0.790	14.	0.0	0.5
12	12	5.943	49.	0.0	0.5
13	13	2.130	22.	0.0	0.5
14	14	3.149	26.	0.0	0.5
15	15	3.515	99.	0.0	0.5
16	16	4.452	34.	0.0	0.5
17	17	3.591	13.	0.0	0.5
18	18	1.348	32.	0.0	0.5
19	19	5.811	42.	0.0	0.5
30	30	3.109	52.	0.0	0.5
31	31	8.502	110.	0.0	0.5
32	32	3.398	102.	0.0	0.5
33	33	16.62	41.	0.0	0.5
51	51	1 .05	1.3	0.0	0.5
52	52	4.445	194.	0.0	0.5
53	53	7.004	305.	0.0	0.5
54	54	4.754	62.	0.0	0.5
55	55	4.754	82.	0.0	0.5
56	56	4.386	109.	0.0	0.5
57	57	4.386	152.	0.0	0.5
58	58	4.774	94.	0.0	0.5
59	59	5.026	70.	0.0	0.5
60	60	8.387	99.	0.0	0.5
61	61	4.774	19.	0.0	0.5
62	62	7.361	62.	0.0	0.5
63	63	8.387	96.	0.0	0.5
64	64	1.886	53.	0.0	0.5
65	65	5.236	74.	0.0	0.5
66	66	5.236	74.	0.0	0.5
67	67	5.236	74.	0.0	0.5
68	68	5.236	74.	0.0	0.5
69	69	5.236	74.	0.0	0.5
70	70	5.236	74.	0.0	0.5
72	72	5.236	74.	0.0	0.5
73	73	5.236	74.	0.0	0.5
105	105	2 600	74.	0.0	0.5
107	107	2.900	74.	0.0	0.5
112	112	5.900	74.	0.0	0.5

END HYDR-PARM2

Appendix 2

Calibration of a One-Dimensional Channel Hydraulic Model (HEC-RAS) used to Determine Physically Based Target Flows at Six Riffle Reaches in the Sudbury River Basin

Water-Surface-Profile Model 124

Whitehall Brook near Hopkinton 125

Sudbury River near Hopkinton 127

Sudbury River near Ashland 128

Indian Brook near Hopkinton 132

Indian Brook near Ashland 135

Baiting Brook near Framingham 136

Appendix 2. Calibration of a One-Dimensional Channel Hydraulic Model (HEC-RAS) used to Determine Physically Based Target Flows at Six Riffle Reaches in the Sudbury River Basin

Water-Surface-Profile Model

Channel hydraulic properties were determined using HEC-RAS, a one-dimensional channel hydraulics model. The model entailed entering detailed cross-sectional information along a reach and initial values of channel roughness (Manning's "n" value), type of flow regime (subcritical or supercritical defined by the Froude number, which characterizes the energy gradient of the channel), and downstream hydraulic gradient. In all reaches, the computed Froude number indicated subcritical flow (value less than 1); therefore, the standard upstream-step energy method was used to simulate water-surface profiles. The hydraulic gradient at the downstream end of each reach was estimated from the measured difference in the water-surface elevation at the downstream section and surveyed reference points further downstream.

Final "n" values were empirically determined by altering their value until the simulated surface-water profile closely matched the observed profile over a range of flows. The variability in the calibrated "n" value over the range of flows at a cross section and between cross sections is because of the variability of the flow-path length. As the flow path lengthens, the energy gradient decreases. To compensate for the change in flow-path length that changes with flow, the only variable that can be altered in a one-dimensional model is the channel roughness.

The number of cross sections in a reach and the number and range of flows over which the water-surface profile was obtained varied by site. Occasionally, additional cross sections were needed to reduce simulated velocity head drops between surveyed cross sections to maintain model stability. When needed, these sections were interpolated and added to the model. Occasionally, several of the downstream cross sections were not used in the R2Cross and Wetted-Perimeter analysis because downstream backwater affected the hydraulic characteristics of the section.

The model was considered calibrated when the root mean square error (RMSE) between observed and simulated water-surface elevations was minimized. The calibrated model was then used to compute the flows that satisfied the hydraulic criteria for physically based target flow standard-setting methods. The tables in this appendix show by site the observed water-surface elevation over a range of flows and the calibrated water-surface elevation for those flows. Also shown are the calibrated "n" value and computed Froude number and other hydraulic properties over the range of flows.

Whitehall Brook near Hopkinton

Four cross sections (109, 118, 128, and 136) and water levels over 15 flows ranging from 1.1 to 198 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–1). A slope of 0.001 ft/ft was specified as the downstream boundary condition. The RMSE was 0.008 ft over the entire reach for all measured flows.

All four cross sections were used in the R2Cross analysis, but the flow standard was determined from the three upstream stations (118, 128, and 136) because the downstream section was affected by backwater. For the same reason, the three upstream cross sections were used for the Wetted-Perimeter analysis.

Table 2–1. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Whitehall Brook near Hopkinton, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
109	1.1	0.040	1.1	0.14	0.012	0.51	497.75	497.75
109	1.7	0.058	1.8	0.19	0.012	0.38	497.84	497.84
109	2.6	0.060	2.5	0.23	0.012	0.37	498.05	497.91
109	3.5	0.063	3.4	0.25	0.012	0.36	498.01	497.97
109	3.9	0.064	3.7	0.27	0.012	0.36	498.00	498.00
109	4.0	0.065	3.8	0.27	0.012	0.36	498.16	498.00
109	4.1	0.068	4.0	0.29	0.012	0.34	498.07	498.02
109	4.3	0.073	4.3	0.30	0.012	0.32	498.27	498.04
109	5.8	0.107	6.6	0.43	0.012	0.23	498.20	498.20
109	6.5	0.113	7.5	0.47	0.012	0.22	498.60	498.26
109	9.1	0.132	10	0.61	0.012	0.20	498.73	498.43
109	10	0.140	12	0.66	0.012	0.19	498.89	498.50
109	74	0.096	33	1.3	0.012	0.32	499.56	499.56
109	77	0.094	34	1.3	0.012	0.33	499.56	499.57
109	198	0.045	40	1.2	0.012	0.71	499.77	499.77
118	1.1	0.053	1.1	0.11	0.024	0.53	497.95	497.97
118	1.7	0.087	1.5	0.13	0.063	0.54	498.00	498.01
118	2.6	0.135	2.1	0.16	0.134	0.52	498.14	498.05
118	3.5	0.175	2.7	0.20	0.206	0.52	498.10	498.10
118	3.9	0.180	2.9	0.21	0.208	0.51	498.12	498.12
118	4.0	0.180	3.0	0.21	0.207	0.51	498.18	498.12
118	4.1	0.188	3.1	0.22	0.219	0.50	498.13	498.12
118	4.3	0.197	3.2	0.23	0.228	0.50	498.29	498.13
118	5.8	0.121	4.8	0.31	0.045	0.38	498.27	498.24
118	6.5	0.100	5.5	0.35	0.026	0.35	498.61	498.29
118	9.1	0.100	8.1	0.48	0.015	0.29	498.75	498.45
118	10	0.100	9.3	0.52	0.013	0.27	498.90	498.52
118	74	0.002	33	1.2	0.000	0.35	499.54	499.56
118	77	0.002	34	1.2	0.000	0.36	499.57	499.57
118	198	0.002	43	1.4	0.000	0.66	499.80	499.89

Table 2–1. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Whitehall Brook near Hopkinton, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
128	1.1	0.032	1.1	0.10	0.011	0.59	498.17	498.13
128	1.7	0.032	1.4	0.12	0.012	0.62	498.16	498.16
128	2.6	0.058	2.2	0.18	0.020	0.48	498.23	498.23
128	3.5	0.051	2.7	0.21	0.015	0.49	498.27	498.26
128	3.9	0.081	3.3	0.25	0.027	0.42	498.33	498.31
128	4.0	0.084	3.3	0.25	0.029	0.42	--	498.31
128	4.1	0.094	3.5	0.26	0.033	0.41	498.32	498.32
128	4.3	0.108	3.7	0.28	0.041	0.39	498.43	498.34
128	5.8	0.197	4.9	0.35	0.101	0.35	498.43	498.43
128	6.5	0.195	5.3	0.37	0.097	0.35	--	498.46
128	9.1	0.174	7.1	0.47	0.061	0.33	--	498.58
128	10	0.165	7.9	0.51	0.050	0.32	498.90	498.64
128	74	0.039	27	1.1	0.004	0.47	--	499.55
128	77	0.038	27	1.1	0.004	0.48	499.56	499.56
128	198	0.025	33	1.2	0.007	0.98	499.77	499.79
136	1.1	0.150	1.9	0.15	0.046	0.27	498.25	498.25
136	1.7	0.121	2.2	0.18	0.038	0.32	498.28	498.28
136	2.6	0.139	2.9	0.22	0.050	0.33	498.36	498.33
136	3.5	0.150	3.5	0.26	0.060	0.34	498.38	498.38
136	3.9	0.095	3.8	0.28	0.024	0.35	498.43	498.40
136	4.0	0.094	3.8	0.28	0.024	0.35	498.40	498.40
136	4.1	0.101	3.9	0.28	0.028	0.35	498.44	498.41
136	4.3	0.130	4.1	0.30	0.041	0.33	498.77	498.42
136	5.8	0.160	5.4	0.37	0.050	0.31	498.54	498.51
136	6.5	0.160	5.8	0.40	0.049	0.31	498.65	498.54
136	9.1	0.160	7.4	0.49	0.044	0.30	498.78	498.65
136	10	0.160	8.1	0.53	0.042	0.30	498.92	498.70
136	74	0.160	23	0.97	0.094	0.52	499.56	499.55
136	77	0.159	23	0.98	0.098	0.53	--	499.56
136	198	0.013	40	1.1	0.001	0.77	499.79	500.10

Sudbury River near Hopkinton

Three cross sections (112, 121, and 128) and water levels over 10 flows ranging from 5.1 to 32 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–2). A slope of 0.006 ft/ft was specified as the downstream boundary condition. The RMSE was 0.000 ft over the entire reach for all measured flows.

All three cross sections were used in the R2Cross analysis, but the flow standard was determined from the upstream station (128) because the downstream sections were affected by backwater during low to moderate flows. For the same reason, only the most upstream cross section was used for the Wetted-Perimeter analysis.

Table 2–2. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Sudbury River near Hopkinton, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
112	5.1	0.022	3.2	0.18	0.006	0.68	497.95	497.95
112	5.5	0.034	4.5	0.23	0.006	0.45	498.02	498.02
112	6.2	0.035	5.0	0.24	0.006	0.45	--	498.04
112	8.9	0.035	6.3	0.29	0.006	0.46	--	498.10
112	9.1	0.035	6.4	0.30	0.006	0.46	--	498.11
112	14	0.067	14	0.44	0.006	0.27	--	498.38
112	15	0.068	14	0.47	0.006	0.26	--	498.41
112	20	0.075	19	0.58	0.006	0.25	498.54	498.54
112	25	0.080	22	0.68	0.006	0.24	498.65	498.65
112	32	0.080	28	0.61	0.006	0.24	--	498.74
121	5.1	0.900	3.7	0.26	4.318	0.48	498.17	498.14
121	5.5	0.589	4.4	0.29	1.267	0.41	--	498.19
121	6.2	0.439	4.6	0.30	0.816	0.44	498.20	498.20
121	8.9	0.257	5.3	0.33	0.369	0.51	--	498.25
121	9.1	0.244	5.4	0.33	0.336	0.52	498.25	498.25
121	14	0.021	8.4	0.36	0.002	0.47	498.39	498.39
121	15	0.022	8.9	0.38	0.002	0.47	498.42	498.42
121	20	0.020	12	0.49	0.001	0.42	498.54	498.54
121	25	0.020	14	0.58	0.001	0.39	498.65	498.65
121	32	0.180	23	0.60	0.044	0.30	498.83	498.83
128	5.1	0.044	3.9	0.26	0.008	0.44	498.30	498.30
128	5.5	0.042	4.2	0.25	0.007	0.43	498.32	498.32
128	6.2	0.044	4.5	0.24	0.008	0.44	--	498.34
128	8.9	0.050	6.0	0.29	0.011	0.46	--	498.42
128	9.1	0.052	6.1	0.30	0.011	0.45	498.42	498.42
128	14	0.123	8.7	0.41	0.052	0.43	--	498.55
128	15	0.140	9.4	0.44	0.063	0.42	498.58	498.58
128	20	0.150	11	0.51	0.075	0.44	498.67	498.67
128	25	0.121	16	0.46	0.039	0.40	498.74	498.74
128	32	0.169	22	0.60	0.047	0.33	498.92	498.92

Sudbury River near Ashland

Six cross sections (120, 157, 171, 192, 209, and 223) and water levels over 22 flows ranging from 4.7 to 70 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–3). A slope of 0.002 ft/ft was specified as the downstream boundary condition. The RMSE was 0.021 ft over the entire reach for all measured flows.

All cross sections were used in the R2Cross analysis, but the flow standard was determined from the four upstream stations (157, 171, 192, and 209) that are unaffected by backwater during low to moderate flows. Stations 157, 171, 192, and 223 were used in the Wetted-Perimeter analysis.

Table 2–3. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Sudbury River near Ashland, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
120	4.7	0.060	6.7	0.38	0.002	0.20	498.19	498.07
120	6.1	0.060	8.1	0.42	0.002	0.20	498.17	498.15
120	6.8	0.062	8.9	0.44	0.002	0.20	498.19	498.19
120	8.9	0.051	10	0.45	0.002	0.24	498.22	498.22
120	12	0.056	12	0.52	0.002	0.23	498.35	498.35
120	13	0.056	14	0.55	0.002	0.23	498.44	498.41
120	14	0.056	14	0.56	0.002	0.23	498.34	498.42
120	17	0.054	16	0.59	0.002	0.24	498.44	498.48
120	17	0.053	16	0.60	0.002	0.24	498.46	498.49
120	20	0.050	17	0.62	0.002	0.26	498.46	498.53
120	20	0.050	17	0.63	0.002	0.26	498.54	498.54
120	22	0.050	18	0.66	0.002	0.26	498.53	498.57
120	23	0.052	20	0.69	0.002	0.25	498.58	498.63
120	27	0.056	25	0.56	0.002	0.25	498.63	498.72
120	27	0.056	26	0.57	0.002	0.25	498.73	498.73
120	32	0.057	30	0.56	0.002	0.25	498.71	498.81
120	33	0.058	31	0.56	0.002	0.25	498.65	498.84
120	34	0.058	32	0.57	0.002	0.25	498.69	498.85
120	37	0.059	34	0.60	0.002	0.24	498.75	498.90
120	64	0.066	56	0.82	0.002	0.21	499.25	499.25
120	69	0.074	65	0.90	0.002	0.19	499.22	499.37
120	70	0.076	67	0.92	0.002	0.18	499.40	499.40
157	4.7	0.067	6.7	0.27	0.005	0.23	498.30	498.19
157	6.1	0.068	8.6	0.33	0.004	0.22	498.26	498.26
157	6.8	0.068	10	0.35	0.004	0.21	498.28	498.30
157	8.9	0.069	11	0.38	0.005	0.23	498.34	498.34
157	12	0.070	14	0.48	0.004	0.21	498.42	498.46
157	13	0.070	16	0.53	0.004	0.20	498.52	498.52
157	14	0.069	16	0.54	0.004	0.20	498.45	498.53
157	17	0.065	18	0.59	0.003	0.21	498.55	498.59
157	17	0.064	18	0.59	0.003	0.21	498.60	498.60
157	20	0.062	19	0.62	0.003	0.22	498.60	498.63
157	20	0.062	20	0.64	0.003	0.23	498.67	498.65
157	22	0.061	21	0.66	0.003	0.23	498.66	498.68
157	23	0.058	22	0.70	0.003	0.22	498.72	498.72

Table 2–3. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Sudbury River near Ashland, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
157	27	0.047	24	0.75	0.002	0.22	498.79	498.79
157	27	0.047	25	0.77	0.002	0.22	498.84	498.81
157	32	0.047	27	0.82	0.002	0.22	498.82	498.88
157	33	0.047	28	0.85	0.002	0.23	498.84	498.91
157	34	0.047	29	0.86	0.002	0.23	498.92	498.92
157	37	0.049	30	0.89	0.002	0.23	498.94	498.97
157	64	0.064	43	1.2	0.003	0.24	499.34	499.34
157	69	0.057	47	1.3	0.002	0.23	499.29	499.45
157	70	0.056	47	1.3	0.002	0.23	499.47	499.47
171	4.7	0.274	12	0.36	0.016	0.11	498.37	498.31
171	6.1	0.266	15	0.40	0.015	0.11	498.38	498.37
171	6.8	0.224	16	0.41	0.012	0.12	498.39	498.39
171	8.9	0.146	17	0.43	0.007	0.14	498.43	498.42
171	12	0.104	21	0.48	0.003	0.14	498.51	498.51
171	13	0.102	23	0.54	0.003	0.14	498.62	498.57
171	14	0.101	23	0.55	0.003	0.14	498.54	498.58
171	17	0.089	26	0.60	0.003	0.15	498.64	498.64
171	17	0.083	26	0.60	0.002	0.15	498.67	498.64
171	20	0.064	27	0.63	0.002	0.16	498.67	498.67
171	20	0.068	28	0.65	0.002	0.16	498.75	498.69
171	22	0.076	29	0.68	0.002	0.16	498.75	498.72
171	23	0.083	31	0.72	0.002	0.15	498.79	498.77
171	27	0.083	34	0.77	0.003	0.16	498.85	498.83
171	27	0.082	35	0.78	0.002	0.16	498.93	498.84
171	32	0.081	38	0.85	0.002	0.16	498.89	498.92
171	33	0.080	39	0.87	0.002	0.16	498.91	498.95
171	34	0.080	40	0.88	0.002	0.16	499.01	498.96
171	37	0.079	42	0.92	0.002	0.16	499.01	499.01
171	64	0.098	61	1.2	0.004	0.16	499.41	499.40
171	69	0.098	66	1.3	0.003	0.16	499.39	499.50
171	70	0.098	67	1.3	0.003	0.16	499.58	499.53
192	4.7	0.108	12	0.35	0.003	0.12	498.51	498.43
192	6.1	0.109	14	0.41	0.003	0.12	498.51	498.50
192	6.8	0.108	14	0.43	0.004	0.13	498.51	498.52
192	8.9	0.107	15	0.45	0.005	0.15	498.55	498.54
192	12	0.105	17	0.50	0.006	0.17	498.63	498.60
192	13	0.104	19	0.54	0.006	0.17	--	498.65
192	14	0.103	19	0.55	0.006	0.17	498.67	498.66
192	17	0.101	21	0.60	0.006	0.18	498.73	498.71
192	17	0.101	21	0.60	0.006	0.19	498.76	498.71
192	20	0.100	22	0.61	0.007	0.20	498.76	498.73
192	20	0.099	22	0.63	0.007	0.20	498.82	498.75
192	22	0.097	24	0.66	0.006	0.20	498.84	498.79

Table 2–3. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Sudbury River near Ashland, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
192	23	0.095	25	0.69	0.005	0.19	498.86	498.83
192	27	0.092	28	0.74	0.005	0.20	498.92	498.90
192	27	0.091	28	0.75	0.005	0.20	498.96	498.91
192	32	0.088	31	0.80	0.005	0.20	498.99	498.98
192	33	0.087	32	0.82	0.005	0.20	499.01	499.01
192	34	0.085	32	0.83	0.005	0.20	499.05	499.02
192	37	0.082	34	0.87	0.004	0.20	499.07	499.07
192	64	0.047	50	1.1	0.001	0.21	499.43	499.44
192	69	0.047	54	1.2	0.001	0.20	499.43	499.53
192	70	0.047	55	1.2	0.001	0.20	--	499.56
209	4.7	0.020	4.0	0.18	0.002	0.48	498.55	498.47
209	6.1	0.020	5.4	0.23	0.002	0.42	498.54	498.53
209	6.8	0.022	5.9	0.24	0.002	0.41	498.55	498.55
209	8.9	0.035	7.6	0.26	0.004	0.40	498.61	498.61
209	12	0.037	10	0.28	0.004	0.40	498.71	498.68
209	13	0.038	11	0.31	0.004	0.38	498.72	498.72
209	14	0.039	12	0.33	0.004	0.37	498.68	498.74
209	17	0.047	14	0.37	0.005	0.35	498.75	498.79
209	17	0.047	14	0.38	0.005	0.35	498.80	498.80
209	20	0.046	15	0.40	0.005	0.37	498.80	498.83
209	20	0.045	16	0.41	0.005	0.36	498.84	498.84
209	22	0.043	17	0.42	0.004	0.35	498.89	498.87
209	23	0.040	18	0.44	0.003	0.34	498.90	498.90
209	27	0.040	20	0.48	0.003	0.34	498.96	498.96
209	27	0.040	21	0.49	0.003	0.33	499.02	498.97
209	32	0.040	23	0.54	0.003	0.32	499.09	499.03
209	33	0.040	25	0.57	0.003	0.32	499.03	499.06
209	34	0.040	25	0.58	0.003	0.31	499.07	499.07
209	37	0.040	27	0.61	0.002	0.31	--	499.11
209	64	0.036	42	0.91	0.001	0.28	499.45	499.45
209	69	0.036	47	0.99	0.001	0.26	--	499.55
209	70	0.036	48	1.0	0.001	0.26	--	499.57
223	4.7	0.066	6.6	0.21	0.007	0.27	498.84	498.56
223	6.1	0.064	8.0	0.25	0.006	0.27	498.82	498.60
223	6.8	0.064	8.6	0.27	0.006	0.27	498.84	498.62
223	8.9	0.062	11	0.32	0.005	0.26	498.86	498.69
223	12	0.061	12	0.37	0.005	0.27	498.94	498.74
223	13	0.060	14	0.41	0.005	0.27	499.01	498.78
223	14	0.060	14	0.42	0.005	0.26	498.78	498.80
223	17	0.059	16	0.47	0.005	0.26	499.00	498.85
223	17	0.059	16	0.48	0.005	0.27	499.02	498.86
223	20	0.059	17	0.51	0.005	0.28	499.02	498.89
223	20	0.059	18	0.52	0.005	0.28	499.02	498.90

Table 2–3. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Sudbury River near Ashland, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
223	22	0.058	19	0.54	0.005	0.28	499.04	498.93
223	23	0.058	19	0.56	0.005	0.28	499.10	498.95
223	27	0.058	21	0.60	0.005	0.28	499.13	499.01
223	27	0.058	22	0.61	0.005	0.28	499.14	499.02
223	32	0.057	24	0.66	0.004	0.28	499.14	499.08
223	33	0.057	25	0.68	0.004	0.28	499.17	499.11
223	34	0.057	25	0.69	0.004	0.28	499.23	499.12
223	37	0.057	27	0.72	0.004	0.28	499.19	499.15
223	64	0.072	39	0.99	0.006	0.28	499.63	499.49
223	69	0.076	43	1.1	0.006	0.27	499.50	499.58
223	70	0.077	44	1.1	0.006	0.27	499.86	499.60

Indian Brook near Hopkinton

Seven cross sections (125, 163, 182, 208, 222, 225, and 230) and water levels over 11 flows ranging from 0.3 to 41 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–4). A slope of 0.004 ft/ft was specified as the downstream boundary condition. The RMSE was 0.020 ft over the entire reach for all measured flows. About in the middle of the reach, the walking trail crosses the brook over a double-arched stone bridge that was also surveyed and included in the HEC-RAS model but does not appear to alter low to moderate flows.

All cross sections were used in the R2Cross analysis, but the flow standard was determined from the three upstream stations (222, 225, and 230) that are unaffected by backwater during low to moderate flows. For the same reason, the three upstream cross sections were used for the Wetted-Perimeter analysis.

Table 2–4. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Indian Brook near Hopkinton, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
125	0.3	0.031	0.5	0.10	0.004	0.36	495.04	495.04
125	0.8	0.068	2.0	0.15	0.004	0.18	495.23	495.22
125	0.8	0.070	2.1	0.16	0.004	0.17	495.23	495.23
125	0.9	0.075	2.3	0.17	0.004	0.16	495.36	495.25
125	1.2	0.095	3.3	0.23	0.004	0.13	495.32	495.32
125	1.4	0.124	4.2	0.28	0.004	0.11	495.39	495.39
125	2.7	0.135	7.0	0.40	0.004	0.10	495.57	495.57
125	5.2	0.140	11	0.60	0.004	0.10	495.80	495.80
125	7.7	0.135	14	0.73	0.004	0.11	495.96	495.96
125	29	0.092	24	1.2	0.004	0.18	496.57	496.57
125	41	0.072	26	1.3	0.004	0.23	496.65	496.68
163	0.3	0.497	4.4	0.41	0.002	0.02	495.16	495.16
163	0.8	0.303	5.8	0.52	0.002	0.03	495.32	495.32
163	0.8	0.288	5.8	0.52	0.002	0.03	495.33	495.32
163	0.9	0.213	5.9	0.52	0.001	0.03	495.34	495.33
163	1.2	0.074	6.0	0.53	0.000	0.04	495.34	495.34
163	1.4	0.178	7.1	0.60	0.001	0.04	495.46	495.46
163	2.7	0.062	8.4	0.68	0.000	0.06	495.60	495.60
163	5.2	0.055	11	0.80	0.000	0.08	495.84	495.84
163	7.7	0.020	12	0.86	0.000	0.10	495.97	495.97
163	29	0.034	19	1.1	0.001	0.21	496.63	496.63
163	41	0.036	21	1.2	0.002	0.27	496.70	496.76
182	0.3	0.200	14	0.68	0.000	0.01	495.17	495.16
182	0.8	0.200	17	0.81	0.000	0.01	495.33	495.32
182	0.8	0.200	17	0.82	0.000	0.01	495.34	495.32
182	0.9	0.200	17	0.82	0.000	0.01	495.36	495.33
182	1.2	0.200	17	0.84	0.000	0.01	495.37	495.35
182	1.4	0.037	20	0.93	0.000	0.01	495.46	495.46
182	2.7	0.168	22	1.1	0.000	0.02	495.64	495.60

Table 2–4. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Indian Brook near Hopkinton, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
182	5.2	0.108	27	1.3	0.000	0.03	495.86	495.84
182	7.7	0.100	30	1.4	0.000	0.04	496.01	495.98
182	29	0.044	43	1.9	0.000	0.08	496.64	496.67
182	41	0.182	47	2.0	0.005	0.10	496.86	496.84
208	0.3	0.200	9.3	0.55	0.000	0.01	495.17	495.16
208	0.8	0.200	12	0.67	0.000	0.01	495.33	495.32
208	0.8	0.200	12	0.67	0.000	0.01	495.34	495.32
208	0.9	0.200	12	0.68	0.000	0.02	495.37	495.33
208	1.2	0.200	12	0.69	0.000	0.02	495.37	495.35
208	1.4	0.038	14	0.79	0.000	0.02	495.46	495.46
208	2.7	0.185	17	0.90	0.000	0.03	495.62	495.61
208	5.2	0.200	22	1.1	0.001	0.04	495.86	495.84
208	7.7	0.200	24	1.2	0.002	0.05	496.01	495.98
208	29	0.047	38	1.6	0.000	0.10	496.64	496.67
208	41	0.194	42	1.7	0.007	0.12	496.86	496.85
222	0.3	0.050	2.0	0.15	0.000	0.08	495.09	495.16
222	0.8	0.050	4.1	0.28	0.000	0.06	495.33	495.32
222	0.8	0.050	4.2	0.29	0.000	0.06	495.35	495.32
222	0.9	0.050	4.3	0.29	0.000	0.07	495.36	495.33
222	1.2	0.050	4.5	0.31	0.000	0.08	495.37	495.35
222	1.4	0.035	6.2	0.39	0.000	0.06	495.46	495.46
222	2.7	0.048	8.6	0.52	0.000	0.08	495.63	495.61
222	5.2	0.050	13	0.72	0.000	0.08	495.88	495.85
222	7.7	0.050	15	0.82	0.000	0.10	496.03	495.99
222	29	0.022	27	1.3	0.000	0.15	496.64	496.67
222	41	0.035	31	1.4	0.001	0.18	496.86	496.86
225	0.3	0.350	0.9	0.15	0.104	0.17	495.36	495.36
225	0.8	0.350	1.4	0.15	0.200	0.24	495.44	495.42
225	0.8	0.350	1.5	0.16	0.201	0.25	495.44	495.43
225	0.9	0.350	1.6	0.16	0.203	0.25	495.48	495.44
225	1.2	0.350	1.9	0.18	0.208	0.26	495.50	495.47
225	1.4	0.350	2.3	0.20	0.173	0.24	495.54	495.50
225	2.7	0.350	4.1	0.29	0.119	0.21	495.69	495.64
225	5.2	0.350	7.6	0.49	0.068	0.17	495.94	495.88
225	7.7	0.350	9.7	0.61	0.068	0.18	496.04	496.02
225	29	0.026	21	1.1	0.001	0.22	496.66	496.68
225	41	0.100	24	1.3	0.009	0.25	496.88	496.88

Table 2–4. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Indian Brook near Hopkinton, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
230	0.3	0.110	1.6	0.18	0.003	0.09	--	495.39
230	0.8	0.110	2.4	0.24	0.004	0.12	--	495.48
230	0.8	0.108	2.5	0.24	0.004	0.12	495.48	495.48
230	0.9	0.099	2.5	0.25	0.004	0.13	495.52	495.49
230	1.2	0.071	2.7	0.26	0.003	0.15	495.51	495.51
230	1.4	0.109	3.4	0.26	0.005	0.14	495.57	495.57
230	2.7	0.111	5.2	0.37	0.005	0.15	495.70	495.70
230	5.2	0.160	8.7	0.59	0.008	0.14	495.95	495.95
230	7.7	0.090	10	0.68	0.004	0.16	496.05	496.05
230	29	0.053	19	1.1	0.002	0.23	--	496.68
230	41	0.040	23	1.2	0.002	0.26	496.89	496.89

Indian Brook near Ashland

Five cross sections (123, 157, 181, 196, and 214) and water levels over six flows ranging from 1.1 to 6.6 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–5). A slope of 0.003 ft/ft was specified as the downstream boundary condition. The RMSE was 0.029 ft over the entire reach for all measured flows.

All cross sections were used in the R2Cross analysis, but the flow standard was determined from the four upstream sections (157, 181, 196, and 214) that are unaffected by backwater during low to moderate flows. For the same reason, the four upstream cross sections were used for the Wetted-Perimeter analysis.

Table 2–5. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Indian Brook near Ashland, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Flow (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
123	1.1	0.169	5.1	0.35	0.003	0.07	498.03	498.03
123	1.2	0.161	5.3	0.36	0.003	0.07	498.22	498.04
123	2.0	0.125	6.1	0.41	0.003	0.09	498.23	498.10
123	2.4	0.112	6.4	0.43	0.003	0.10	498.12	498.12
123	2.9	0.105	6.9	0.46	0.003	0.11	498.15	498.15
123	6.6	0.073	9.3	0.58	0.003	0.16	498.32	498.32
157	1.1	0.100	3.4	0.28	0.003	0.11	498.12	498.12
157	1.2	0.095	3.5	0.28	0.003	0.12	498.25	498.13
157	2.0	0.070	4.2	0.33	0.002	0.15	498.23	498.18
157	2.4	0.060	4.4	0.34	0.002	0.16	498.20	498.20
157	2.9	0.041	4.6	0.35	0.001	0.19	498.21	498.22
157	6.6	0.058	7.3	0.50	0.003	0.22	498.41	498.41
181	1.1	0.020	2.8	0.23	0.000	0.15	498.14	498.14
181	1.2	0.029	3.0	0.24	0.000	0.15	498.25	498.15
181	2.0	0.088	4.2	0.32	0.004	0.15	498.25	498.25
181	2.4	0.111	4.6	0.35	0.006	0.16	498.23	498.28
181	2.9	0.128	5.0	0.37	0.010	0.17	498.30	498.30
181	6.6	0.030	7.1	0.51	0.001	0.23	498.46	498.46
196	1.1	0.150	2.8	0.25	0.011	0.14	498.26	498.26
196	1.2	0.149	2.9	0.26	0.011	0.15	498.36	498.27
196	2.0	0.140	3.7	0.29	0.013	0.18	498.34	498.34
196	2.4	0.076	3.9	0.30	0.005	0.20	498.35	498.35
196	2.9	0.045	4.2	0.33	0.002	0.21	498.36	498.38
196	6.6	0.045	6.0	0.45	0.003	0.29	498.52	498.52
214	1.1	0.040	2.3	0.18	0.002	0.21	498.49	498.40
214	1.2	0.040	2.4	0.19	0.002	0.21	498.52	498.41
214	2.0	0.040	3.2	0.25	0.002	0.22	498.48	498.47
214	2.4	0.040	3.4	0.26	0.002	0.24	498.51	498.49
214	2.9	0.040	3.6	0.27	0.003	0.27	498.57	498.50
214	6.6	0.040	4.7	0.35	0.006	0.42	498.58	498.59

Baiting Brook near Framingham

Nine cross sections (stations 116, 135, 156, 180, 198, 218, 245, 265, and 285) and water levels over 11 flows ranging from 0.4 to 9.6 ft^3/s were used to calibrate the HEC-RAS model in this reach (table 2–6). A slope of 0.017 ft/ft was specified as the downstream boundary condition. The RMSE was 0.020 ft over the entire reach for all measured flows.

All cross sections were used in the R2Cross analysis, but the flow standard was determined from the five upstream stations (198, 218, 245, 265, and 285) that are unaffected by backwater during low to moderate flows. For the same reason, the five upstream cross sections were used for the Wetted-Perimeter analysis.

Table 2–6. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Baiting Brook near Framingham, Massachusetts.

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
116	0.4	0.070	0.8	0.07	0.017	0.31	496.91	496.91
116	0.7	0.093	1.5	0.12	0.017	0.25	496.96	496.96
116	1.0	0.093	1.8	0.14	0.017	0.26	496.99	496.99
116	1.2	0.128	2.4	0.18	0.017	0.20	497.03	497.03
116	1.5	0.110	2.5	0.19	0.017	0.23	497.04	497.04
116	3.5	0.083	3.6	0.26	0.017	0.33	497.24	497.12
116	5.0	0.071	4.1	0.30	0.017	0.39	497.16	497.16
116	6.3	0.100	6.0	0.41	0.017	0.29	497.77	497.29
116	7.4	0.100	6.6	0.45	0.017	0.29	497.56	497.33
116	8.6	0.100	7.2	0.49	0.017	0.30	497.88	497.38
116	9.6	0.100	7.8	0.52	0.017	0.30	497.41	497.41
135	0.4	0.100	1.1	0.08	0.015	0.21	497.21	497.21
135	0.7	0.082	1.5	0.10	0.013	0.25	497.24	497.24
135	1.0	0.065	1.8	0.12	0.011	0.30	497.25	497.25
135	1.2	0.072	2.1	0.14	0.011	0.27	497.30	497.27
135	1.5	0.080	2.5	0.16	0.011	0.26	497.29	497.30
135	3.5	0.053	3.3	0.22	0.010	0.39	497.47	497.36
135	5.0	0.042	3.7	0.24	0.009	0.48	497.38	497.38
135	6.3	0.037	4.7	0.30	0.006	0.43	497.70	497.45
135	7.4	0.034	5.1	0.33	0.005	0.44	497.57	497.48
135	8.6	0.032	5.6	0.35	0.004	0.45	497.90	497.50
135	9.6	0.030	6.0	0.38	0.004	0.46	497.53	497.53
156	0.4	0.100	1.4	0.11	0.006	0.14	497.40	497.39
156	0.7	0.100	2.0	0.15	0.007	0.16	497.44	497.44
156	1.0	0.105	2.4	0.17	0.010	0.18	497.53	497.47
156	1.2	0.112	2.6	0.19	0.010	0.18	497.48	497.48
156	1.5	0.130	3.3	0.24	0.011	0.16	497.53	497.53
156	3.5	0.103	4.4	0.31	0.014	0.25	497.68	497.61
156	5.0	0.095	5.0	0.35	0.017	0.30	497.65	497.65

Table 2–6. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Baiting Brook near Framingham, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
156	6.3	0.175	5.8	0.40	0.054	0.30	497.82	497.71
156	7.4	0.227	6.4	0.44	0.094	0.30	497.81	497.75
156	8.6	0.263	6.8	0.46	0.142	0.33	497.93	497.78
156	9.6	0.273	6.9	0.47	0.184	0.36	497.79	497.79
180	0.4	0.035	1.6	0.22	0.000	0.09	497.41	497.41
180	0.7	0.020	1.9	0.24	0.000	0.13	497.45	497.45
180	1.0	0.010	2.0	0.26	0.000	0.17	497.53	497.47
180	1.2	0.008	2.1	0.27	0.000	0.18	497.48	497.49
180	1.5	0.008	2.5	0.30	0.000	0.19	497.53	497.53
180	3.5	0.006	3.1	0.34	0.000	0.32	497.68	497.61
180	5.0	0.005	3.4	0.37	0.000	0.41	497.65	497.65
180	6.3	0.005	3.9	0.40	0.000	0.43	497.82	497.71
180	7.4	0.006	4.3	0.39	0.000	0.46	497.81	497.75
180	8.6	0.006	4.7	0.35	0.000	0.53	497.93	497.78
180	9.6	0.006	4.8	0.35	0.000	0.59	497.79	497.79
198	0.4	0.220	1.5	0.10	0.033	0.15	497.85	497.77
198	0.7	0.220	2.5	0.13	0.026	0.14	497.83	497.83
198	1.0	0.247	3.5	0.18	0.023	0.12	497.88	497.88
198	1.2	0.232	3.7	0.19	0.023	0.13	497.91	497.89
198	1.5	0.206	3.9	0.20	0.025	0.15	497.90	497.90
198	3.5	0.102	4.9	0.25	0.015	0.25	498.02	497.95
198	5.0	0.070	5.3	0.27	0.011	0.32	497.97	497.97
198	6.3	0.068	6.1	0.30	0.011	0.33	498.03	498.01
198	7.4	0.067	6.8	0.34	0.010	0.33	498.05	498.05
198	8.6	0.066	7.4	0.36	0.010	0.34	498.10	498.08
198	9.6	0.065	7.8	0.38	0.011	0.35	498.10	498.10
218	0.4	0.200	2.6	0.20	0.003	0.06	497.91	497.91
218	0.7	0.100	2.9	0.22	0.002	0.09	497.93	497.93
218	1.0	0.109	3.8	0.26	0.002	0.09	497.99	497.99
218	1.2	0.106	3.9	0.26	0.003	0.10	498.03	498.00
218	1.5	0.099	4.2	0.28	0.003	0.12	498.02	498.02
218	3.5	0.070	5.3	0.34	0.004	0.20	498.17	498.09
218	5.0	0.062	5.6	0.36	0.005	0.26	498.12	498.12
218	6.3	0.051	6.0	0.38	0.005	0.30	498.14	498.14
218	7.4	0.042	6.2	0.39	0.004	0.33	498.19	498.16
218	8.6	0.036	6.4	0.40	0.004	0.37	498.20	498.17
218	9.6	0.030	6.6	0.41	0.003	0.39	498.18	498.18

Table 2–6. Simulated water-surface elevations made with the HEC-RAS model calibrated to observed water-surface elevations at multiple cross sections over a range of discharges at Baiting Brook near Framingham, Massachusetts.—Continued

[Elevation is an arbitrary datum; ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not determined]

Station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Water-surface elevation	
							Observed (ft)	Simulated (ft)
245	0.4	1.000	0.6	0.12	2.583	0.30	498.16	497.98
245	0.7	1.000	1.2	0.16	1.838	0.26	498.47	498.08
245	1.0	1.000	1.5	0.18	2.169	0.29	498.22	498.11
245	1.2	1.000	1.7	0.19	2.022	0.28	498.29	498.13
245	1.5	1.000	2.0	0.20	2.080	0.29	498.29	498.18
245	3.5	0.367	4.1	0.25	0.279	0.30	498.32	498.32
245	5.0	0.152	4.4	0.27	0.080	0.39	498.34	498.34
245	6.3	0.102	4.8	0.29	0.042	0.43	498.37	498.37
245	7.4	0.110	5.5	0.32	0.046	0.42	498.36	498.41
245	8.6	0.120	6.2	0.35	0.051	0.41	498.45	498.45
245	9.6	0.120	6.7	0.37	0.051	0.41	498.48	498.48
265	0.4	0.200	2.4	0.17	0.005	0.07	498.35	498.35
265	0.7	0.191	3.5	0.22	0.005	0.07	498.44	498.43
265	1.0	0.163	4.5	0.23	0.005	0.08	498.47	498.45
265	1.2	0.146	4.6	0.23	0.004	0.09	498.52	498.46
265	1.5	0.117	4.8	0.24	0.004	0.11	498.47	498.47
265	3.5	0.065	6.1	0.30	0.003	0.18	498.58	498.53
265	5.0	0.054	6.5	0.32	0.004	0.24	498.55	498.55
265	6.3	0.069	7.8	0.38	0.005	0.23	498.62	498.62
265	7.4	0.058	8.1	0.39	0.004	0.25	498.70	498.63
265	8.6	0.048	8.3	0.40	0.004	0.28	498.62	498.64
265	9.6	0.040	8.5	0.41	0.003	0.31	498.65	498.65
285	0.4	0.100	1.2	0.18	0.004	0.13	498.45	498.45
285	0.7	0.050	1.6	0.20	0.002	0.18	498.49	498.49
285	1.0	0.061	1.9	0.20	0.004	0.21	498.57	498.53
285	1.2	0.064	2.0	0.21	0.005	0.22	498.62	498.54
285	1.5	0.069	2.2	0.22	0.007	0.25	498.57	498.56
285	3.5	0.070	3.1	0.26	0.017	0.39	--	498.64
285	5.0	0.070	3.6	0.29	0.023	0.46	498.77	498.68
285	6.3	0.070	4.7	0.34	0.017	0.40	498.77	498.77
285	7.4	0.070	4.8	0.34	0.022	0.46	498.80	498.78
285	8.6	0.070	4.9	0.34	0.029	0.53	498.82	498.78
285	9.6	0.070	4.7	0.34	0.040	0.62	498.87	498.77

Appendix 3

Indicators of Hydrologic Alterations (IHA) Computed from Long-Term (1960–2004) Daily Streamflows Simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) without Withdrawals (NOWU) at 10 Riffle Reaches in the Sudbury and Assabet River Basins

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Table 3–10. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Fort Meadow Brook near Hudson, Massachusetts. 150

Table 3–11. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Elizabeth Brook near Stow, Massachusetts. 151

Appendix 3. Indicators of Hydrologic Alterations (IHA) Computed from Long-Term (1960–2004) Daily Streamflows Simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) without Withdrawals (NOWU) at 10 Riffle Reaches in the Sudbury and Assabet River Basins

Indicators of Hydrologic Alteration (IHA) Statistics

The tables in this appendix are output from the Indicators of Hydrologic Alteration (IHA) software, version 7.0.3 (The Nature Conservancy, 2009). The IHA program calculates the median of annual or monthly values (considered a nonparametric analysis by IHA). A low-flow pulse was defined by a flow less than or equal to the 25th percentile of all flows, and a high-flow pulse was defined by a flow greater than or equal to the 75th percentile of all flows. The input to the IHA program is the long-term (1960–2004) daily mean flow simulated with no water use (NOWU) by the Hydrologic Simulation Program—FORTRAN (HSPF) model developed for the Sudbury and Assabet River Basins. The model outputs flows at or near the 10 riffle sites. All metrics were computed using the water year (October 1 through September 30) except for the Group 2 minimum 1-, 3-, 7- , 30-, and 90-day low flows, which used the climate year (April 1 through March 31). The climate year was used for the low-flow metric because the extended periods of low flow commonly cross over the water year.

The IHA method was developed by The Nature Conservancy to characterize the variation in flow by a suite of 33 hydrologic statistics (Richter and others, 1996). The 33 IHA statistics are divided into five general groups (table 3–1). Group 1 represents the monthly flow variation. Group 2 reflects the magnitude of low and high flows for varying time spans. Group 3 measures when the annual low and high flows typically occur. Group 4 measures the frequency and duration that flows were below the 25th and above the 75th flow percentiles. Group 5 measures the rate of change in flow. About half the indices measure the central tendency of the magnitude or rate of change of flow and the other half focus on the magnitude, duration, timing, and frequency of extreme events.

References Cited

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The Nature Conservancy, 2009, Indicators of Hydrologic Alteration, Version 7.1 Users Manual: The Nature Conservancy with rPurview LLC, Totter Software Design, and Smythe Scientific Software, 76 p. (available online at *http://www.nature.org/initiatives/freshwater/conservationtools/art17004.html*)

Table 3–1. Hydrologic statistics computed by Indicators of Hydrologic Alteration (IHA).

[ft^3/s, cubic feet per second; ≤, less than or equal to; ≥, greater than or equal to]

Metric	Definition
Group 1–Percentiles of monthly median flow	
October (ft^3/s)	
November (ft^3/s)	
December (ft^3/s)	
January (ft^3/s)	
February (ft^3/s)	
March (ft^3/s)	Annual monthly median flow
April (ft^3/s)	
May (ft^3/s)	
June (ft^3/s)	
July (ft^3/s)	
August (ft^3/s)	
September (ft^3/s)	
Group 2–Percentiles of the n-day annual low and high flow	
1-day minimum (ft^3/s)	Annual 1-day minimum daily flow
3-day minimum (ft^3/s)	Annual mean 3-day minimum continuous daily flow
7-day minimum (ft^3/s)	Annual mean 7-day minimum continuous daily flow
30-day minimum (ft^3/s)	Annual mean 30-day minimum continuous daily flow
90-day minimum (ft^3/s)	Annual mean 90-day minimum continuous daily flow
1-day maximum (ft^3/s)	Annual 1-day maximum daily discharge
3-day maximum (ft^3/s)	Annual mean 3-day maximum continuous daily flow
7-day maximum (ft^3/s)	Annual mean 3-day maximum continuous daily flow
30-day maximum (ft^3/s)	Annual mean 3-day maximum continuous daily flow
90-day maximum (ft^3/s)	Annual mean 3-day maximum continuous daily flow
Number of zero days	Annual number of days with no flow
Baseflow index (ft^3/s)	Annual 7-day minimum flow divided by mean annual flow
Group 3–Percentiles of the timing of annual minimum and maximum flow	
Date of minimum (Julian date)	Julian date of annual daily maximum flow
Date of maximum (Julian date)	Julian date of annual daily minimum flow
Group 4–Percentiles of the frequency and duration of low and high flows	
Low-pulse count	Number of low-flow pulses each year (continuous period of flow ≤ 25th percentile)
Low-pulse duration (days)	Median annual duration of low-flow pulses
High-pulse count	Number of high-flow pulses each year (continuous period of flow ≥ 75th percentile)
High-pulse duration (days)	Median annual duration of high-flow pulses
Group 5–Percentiles of the rate of change in flow	
Rise rate	Annual median of all positive differences between consecutive daily mean flows
Fall rate	Annual median of all negative differences between consecutive daily mean flows
Number of reversals	Number of times in which flow switched from a rising period to a falling period or from a falling period to a rising period

Table 3–2. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Whitehall Brook near Hopkinton, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	0.70	1.5	3.8	7.3	13	1.5
November (ft^3/s)	3.2	6.2	9.1	13	18	0.71
December (ft^3/s)	6.8	8.2	11	16	23	0.68
January (ft^3/s)	5.7	7.8	13	17	25	0.72
February (ft^3/s)	8.1	11	14	17	25	0.49
March (ft^3/s)	11	13	18	23	30	0.53
April (ft^3/s)	7.9	11	16	20	23	0.56
May (ft^3/s)	3.6	6.6	9.6	12	18	0.61
June (ft^3/s)	2.0	2.4	3.8	7.5	15	1.3
July (ft^3/s)	1.2	1.5	1.9	2.7	4.3	0.61
August (ft^3/s)	0.85	1.1	1.6	2.0	2.6	0.56
September (ft^3/s)	0.70	0.96	1.4	2.0	3.7	0.74
Group 2						
1-day minimum (ft^3/s)	0.35	0.52	0.85	1.2	1.3	0.79
3-day minimum (ft^3/s)	0.35	0.55	0.88	1.2	1.4	0.74
7-day minimum (ft^3/s)	0.36	0.62	0.91	1.2	1.5	0.68
30-day minimum (ft^3/s)	0.55	0.88	1.3	1.6	2.1	0.55
90-day minimum (ft^3/s)	0.83	1.4	2.1	3.6	5.2	1.0
1-day maximum (ft^3/s)	70	79	110	150	190	0.65
3-day maximum (ft^3/s)	53	62	85	100	150	0.50
7-day maximum (ft^3/s)	36	45	55	72	99	0.50
30-day maximum (ft^3/s)	23	27	32	40	48	0.41
90-day maximum (ft^3/s)	17	20	23	28	32	0.38
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.04	0.05	0.07	0.09	0.10	0.47
Group 3						
Date of minimum (Julian date)	240	260	270	280	300	~
Date of maximum (Julian date)	340	24	64	110	170	~
Group 4						
Low-pulse count	4.0	6.0	8.0	10	14	0.50
Low-pulse duration (days)	3.2	5	6.2	11	15	0.96
High-pulse count	12	14	18	20	22	0.32
High-pulse duration (days)	2.0	2.0	3.0	4.0	5.0	0.67
Group 5						
Rise rate	1.5	2.2	2.5	3.1	4.2	0.35
Fall rate	-1.9	-1.7	-1.4	-1.1	-0.90	-0.44
Number of reversals	100	100	110	120	120	0.11

Table 3–3. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Sudbury River near Hopkinton, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	4.2	7.4	15	27	56	1.3
November (ft^3/s)	8.9	20	29	45	63	0.88
December (ft^3/s)	22	25	40	59	87	0.84
January (ft^3/s)	19	25	42	57	83	0.77
February (ft^3/s)	24	36	46	59	71	0.51
March (ft^3/s)	32	40	60	73	90	0.55
April (ft^3/s)	23	32	52	63	78	0.61
May (ft^3/s)	12	19	30	43	60	0.79
June (ft^3/s)	5.3	6.4	13	25	56	1.4
July (ft^3/s)	2.8	3.8	4.8	8.2	18	0.92
August (ft^3/s)	2.4	2.8	4.8	8.0	12	1.1
September (ft^3/s)	2.6	3.7	5.8	10	19	1.1
Group 2						
1-day minimum (ft^3/s)	1.3	1.6	2.4	2.7	3.0	0.45
3-day minimum (ft^3/s)	1.4	1.6	2.4	2.8	3.1	0.46
7-day minimum (ft^3/s)	1.6	1.8	2.6	3.0	3.5	0.45
30-day minimum (ft^3/s)	2.1	2.8	3.7	5.2	7.4	0.64
90-day minimum (ft^3/s)	3.5	4.7	8.2	13	17	1.0
1-day maximum (ft^3/s)	130	150	210	280	350	0.61
3-day maximum (ft^3/s)	120	140	190	240	320	0.57
7-day maximum (ft^3/s)	98	120	150	200	250	0.51
30-day maximum (ft^3/s)	70	80	93	120	140	0.39
90-day maximum (ft^3/s)	50	57	65	80	93	0.35
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.05	0.05	0.06	0.08	0.09	0.40
Group 3						
Date of minimum (Julian date)	200	220	240	250	270	~
Date of maximum (Julian date)	340	24	74	120	200	~
Group 4						
Low-pulse count	4.0	5.0	7.0	9.0	12	0.57
Low-pulse duration (days)	2.8	5.0	7.0	17	22	1.7
High-pulse count	8.0	10	13	15	18	0.38
High-pulse duration (days)	2.5	3.0	4.8	5.9	7.8	0.61
Group 5						
Rise rate	3.5	4.8	6.1	6.9	8.8	0.36
Fall rate	-5.4	-4.1	-3.2	-2.2	-1.7	-0.62
Number of reversals	86	90	95	100	110	0.13

Table 3–4. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Sudbury River near Ashland, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	5.1	9.2	18	32	64	1.3
November (ft^3/s)	11	25	35	59	76	0.98
December (ft^3/s)	27	31	50	73	100	0.83
January (ft^3/s)	23	33	51	68	100	0.69
February (ft^3/s)	29	43	56	71	90	0.49
March (ft^3/s)	40	51	74	90	110	0.52
April (ft^3/s)	29	40	64	80	97	0.63
May (ft^3/s)	17	25	37	51	74	0.69
June (ft^3/s)	8.4	10	19	31	67	1.2
July (ft^3/s)	4.4	5.5	7.4	12	23	0.90
August (ft^3/s)	3.4	3.8	6.8	11	16	1.0
September (ft^3/s)	3.1	4.5	7.6	12	23	0.97
Group 2						
1-day minimum (ft^3/s)	1.9	2.1	3.2	3.7	4.4	0.5
3-day minimum (ft^3/s)	2.0	2.2	3.4	3.8	4.4	0.49
7-day minimum (ft^3/s)	2.2	2.4	3.6	4.2	5.0	0.49
30-day minimum (ft^3/s)	2.7	3.7	5.2	7.1	8.8	0.65
90-day minimum (ft^3/s)	4.5	6.4	10	16	21	0.92
1-day maximum (ft^3/s)	160	180	260	350	440	0.63
3-day maximum (ft^3/s)	150	170	230	300	390	0.56
7-day maximum (ft^3/s)	120	150	190	240	320	0.46
30-day maximum (ft^3/s)	86	98	120	140	170	0.39
90-day maximum (ft^3/s)	62	71	82	100	120	0.36
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.05	0.06	0.07	0.09	0.10	0.40
Group 3						
Date of minimum (Julian date)	220	230	250	260	280	~
Date of maximum (Julian date)	340	24	74	120	200	~
Group 4						
Low-pulse count	3.0	4.2	7.0	8.8	11	0.64
Low-pulse duration (days)	3.0	5.0	7.8	17	26	1.5
High-pulse count	7.0	10	12	14	16	0.33
High-pulse duration (days)	3.0	3.6	5.0	6.9	8.5	0.65
Group 5						
Rise rate	5.0	5.4	6.7	8.3	9.8	0.43
Fall rate	-6.0	-4.6	-3.5	-2.5	-1.9	-0.61
Number of reversals	84	90	96	100	110	0.10

Table 3–5. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Indian Brook near Hopkinton, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	0.75	1.3	2.0	4.3	8.4	1.5
November (ft^3/s)	1.8	3.7	5.7	7.8	12	0.73
December (ft^3/s)	4.2	5.1	7.8	11	16	0.71
January (ft^3/s)	3.8	5.0	8.6	12	17	0.84
February (ft^3/s)	5.0	6.5	9.0	11	17	0.56
March (ft^3/s)	7.0	8.6	12	16	20	0.62
April (ft^3/s)	4.4	6.8	9.6	13	15	0.60
May (ft^3/s)	1.8	3.4	5.0	7.7	10	0.87
June (ft^3/s)	1.1	1.3	1.9	4.6	9.2	1.7
July (ft^3/s)	0.45	0.6	0.95	1.3	2.1	0.71
August (ft^3/s)	0.2	0.42	0.85	1.2	1.3	0.91
September (ft^3/s)	0.3	0.56	0.92	1.3	1.9	0.80
Group 2						
1-day minimum (ft^3/s)	0	0.10	0.25	0.48	0.7	1.5
3-day minimum (ft^3/s)	0.02	0.10	0.28	0.5	0.7	1.4
7-day minimum (ft^3/s)	0.04	0.11	0.32	0.56	0.76	1.4
30-day minimum (ft^3/s)	0.14	0.28	0.52	0.9	1.1	1.2
90-day minimum (ft^3/s)	0.37	0.62	1.2	2.6	3.7	1.6
1-day maximum (ft^3/s)	65	75	100	140	170	0.60
3-day maximum (ft^3/s)	45	52	68	89	110	0.54
7-day maximum (ft^3/s)	29	35	44	57	74	0.49
30-day maximum (ft^3/s)	18	21	24	30	36	0.40
90-day maximum (ft^3/s)	13	15	17	20	24	0.35
Number of zero days	0	0	0	0	4.5	0
Baseflow index (ft^3/s)	0.01	0.01	0.03	0.05	0.08	1.2
Group 3						
Date of minimum (Julian date)	200	210	240	260	280	~
Date of maximum (Julian date)	320	22	66	110	200	~
Group 4						
Low-pulse count	2.0	3.0	4.0	5.0	7.0	0.50
Low-pulse duration (days)	3.0	5.0	9.0	26	54	2.3
High-pulse count	18	20	23	28	30	0.35
High-pulse duration (days)	2.0	2.0	2.0	2.0	3.0	0
Group 5						
Rise rate	1.9	2.2	2.8	3.9	5.2	0.60
Fall rate	-1.6	-1.2	-1.0	-0.8	-0.6	-0.45
Number of reversals	94	100	110	120	130	0.15

Table 3–6. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Indian Brook near Ashland, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	1.8	1.9	4.0	7.4	13	1.4
November (ft^3/s)	1.9	4.7	8.1	13	18	1.1
December (ft^3/s)	6.7	8.2	13	17	23	0.70
January (ft^3/s)	6.6	8.0	13	18	25	0.72
February (ft^3/s)	7.7	12	14	18	24	0.42
March (ft^3/s)	11	14	18	23	30	0.56
April (ft^3/s)	7.8	11	16	19	23	0.51
May (ft^3/s)	4.6	7.0	9.0	13	18	0.65
June (ft^3/s)	2.8	3.5	5.3	7.6	15	0.77
July (ft^3/s)	2.0	2.0	2.0	3.5	6.0	0.72
August (ft^3/s)	1.9	1.9	2.0	2.6	3.8	0.35
September (ft^3/s)	1.8	1.9	2.0	2.8	4.6	0.48
Group 2						
1-day minimum (ft^3/s)	1.8	1.9	1.9	2.0	2.0	0.05
3-day minimum (ft^3/s)	1.8	1.9	1.9	2.0	2.0	0.05
7-day minimum (ft^3/s)	1.8	1.9	1.9	2.0	2.0	0.05
30-day minimum (ft^3/s)	1.8	1.9	1.9	2.0	2.9	0.06
90-day minimum (ft^3/s)	1.8	1.9	2.1	3.6	5.2	0.83
1-day maximum (ft^3/s)	74	91	120	170	210	0.66
3-day maximum (ft^3/s)	57	65	88	120	150	0.64
7-day maximum (ft^3/s)	39	48	58	79	100	0.54
30-day maximum (ft^3/s)	25	29	34	43	51	0.42
90-day maximum (ft^3/s)	18	21	24	29	34	0.35
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.11	0.13	0.15	0.18	0.21	0.36
Group 3						
Date of minimum (Julian date)	200	220	250	280	280	~
Date of maximum (Julian date)	340	22	56	100	150	~
Group 4						
Low-pulse count	1.0	1.0	2.0	2.0	3.0	0.50
Low-pulse duration (days)	5.5	25	61	99	120	1.2
High-pulse count	8.0	10	15	17	19	0.47
High-pulse duration (days)	3.0	3.5	4.0	5.0	7.0	0.38
Group 5						
Rise rate	1.2	1.8	2.7	3.7	4.6	0.72
Fall rate	-1.8	-1.4	-0.88	-0.62	-0.48	-0.87
Number of reversals	57	63	72	85	90	0.31

Table 3–7. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Baiting Brook near Framingham, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	0.80	1.2	2.4	3.9	7.2	1.1
November (ft^3/s)	1.6	3.0	4.2	6.8	9.2	0.89
December (ft^3/s)	3.4	3.9	5.6	8.0	12	0.73
January (ft^3/s)	3.2	4.1	6.2	8.2	12	0.66
February (ft^3/s)	4.2	5.3	7.3	9.3	13	0.55
March (ft^3/s)	6.0	7.0	9.6	12	15	0.55
April (ft^3/s)	4.6	6.2	8.6	11	12	0.52
May (ft^3/s)	3.4	4.8	5.9	7.6	10	0.47
June (ft^3/s)	2.5	3.1	4.1	5.9	9.1	0.69
July (ft^3/s)	1.2	1.6	2.2	3.4	4.6	0.81
August (ft^3/s)	0.75	1.0	1.6	2.2	3.0	0.73
September (ft^3/s)	0.60	0.92	1.5	2.0	2.9	0.69
Group 2						
1-day minimum (ft^3/s)	0.30	0.52	0.8	1.1	1.4	0.72
3-day minimum (ft^3/s)	0.30	0.52	0.82	1.1	1.4	0.73
7-day minimum (ft^3/s)	0.35	0.59	0.87	1.2	1.5	0.71
30-day minimum (ft^3/s)	0.61	0.93	1.4	1.7	2.2	0.56
90-day minimum (ft^3/s)	0.97	1.4	2.0	2.7	3.7	0.68
1-day maximum (ft^3/s)	33	39	59	81	110	0.71
3-day maximum (ft^3/s)	26	31	44	53	74	0.50
7-day maximum (ft^3/s)	18	22	30	38	52	0.56
30-day maximum (ft^3/s)	12	14	17	21	24	0.42
90-day maximum (ft^3/s)	9.2	10	12	15	17	0.35
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.07	0.10	0.12	0.15	0.18	0.48
Group 3						
Date of minimum (Julian date)	240	260	270	280	300	~
Date of maximum (Julian date)	360	22	51	100	160	~
Group 4						
Low-pulse count	5.5	8.0	10	14	18	0.57
Low-pulse duration (days)	3.2	4.0	5.0	6.4	10	0.48
High-pulse count	10	12	15	18	21	0.38
High-pulse duration (days)	2.0	2.6	4.0	4.5	5.8	0.47
Group 5						
Rise rate	1.1	1.2	1.4	1.6	2.2	0.28
Fall rate	-0.75	-0.60	-0.50	-0.40	-0.30	-0.40
Number of reversals	95	100	110	110	120	0.11

Table 3–8. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Assabet River near Westborough, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	0.95	1.7	3.8	7.2	14	1.5
November (ft^3/s)	2.8	6.1	9.0	13	18	0.82
December (ft^3/s)	7.2	8.4	12	16	23	0.65
January (ft^3/s)	5.8	8.0	13	17	25	0.67
February (ft^3/s)	8.3	11	14	18	26	0.55
March (ft^3/s)	12	14	18	25	31	0.59
April (ft^3/s)	8.2	11	17	20	24	0.55
May (ft^3/s)	4.6	7.5	10	14	19	0.60
June (ft^3/s)	1.8	2.8	5.2	8.8	16	1.2
July (ft^3/s)	0.55	0.72	1.6	3.1	5.7	1.5
August (ft^3/s)	0	0.32	1.2	1.8	2.5	1.3
September (ft^3/s)	0.05	0.60	1.3	2.0	4.0	1.1
Group 2						
1-day minimum (ft^3/s)	0	0	0.10	0.48	0.90	4.8
3-day minimum (ft^3/s)	0	0	0.18	0.50	0.93	2.7
7-day minimum (ft^3/s)	0	0	0.26	0.67	1.1	2.5
30-day minimum (ft^3/s)	0.01	0.14	0.70	1.2	2.1	1.6
90-day minimum (ft^3/s)	0.34	0.84	1.7	3.5	5.2	1.5
1-day maximum (ft^3/s)	64	81	100	130	170	0.51
3-day maximum (ft^3/s)	54	63	89	110	150	0.49
7-day maximum (ft^3/s)	38	47	61	78	100	0.52
30-day maximum (ft^3/s)	25	28	35	43	51	0.43
90-day maximum (ft^3/s)	18	21	24	30	34	0.36
Number of zero days	0	0	0	22	34	0
Baseflow index (ft^3/s)	0	0	0.02	0.04	0.07	2.4
Group 3						
Date of minimum (Julian date)	200	210	230	250	270	~
Date of maximum (Julian date)	340	19	54	110	160	~
Group 4						
Low-pulse count	2.5	4.0	6.0	7.8	11	0.62
Low-pulse duration (days)	2.0	3.1	6.5	13	26	1.5
High-pulse count	10	12	16	19	21	0.42
High-pulse duration (days)	2.0	2.6	3.0	4.0	5.8	0.46
Group 5						
Rise rate	1.2	1.8	2.1	2.7	3.5	0.45
Fall rate	-1.6	-1.3	-1.1	-0.82	-0.7	-0.43
Number of reversals	94	100	100	110	110	0.10

Table 3–9. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Danforth Brook near Hudson, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	0.50	1.5	3.0	5.9	13	1.5
November (ft^3/s)	2.6	5.7	8.0	13	18	0.90
December (ft^3/s)	6.6	8.1	12	16	25	0.68
January (ft^3/s)	5.8	8.0	13	19	23	0.81
February (ft^3/s)	8.2	11	14	18	25	0.5
March (ft^3/s)	12	14	19	24	33	0.56
April (ft^3/s)	7.8	11	16	20	24	0.57
May (ft^3/s)	3.2	6.0	8.9	13	18	0.81
June (ft^3/s)	1.0	1.8	3.3	7.0	15	1.6
July (ft^3/s)	0.30	0.40	0.85	1.6	3.1	1.4
August (ft^3/s)	0.10	0.30	0.60	1.1	1.8	1.3
September (ft^3/s)	0.12	0.32	0.78	1.5	2.3	1.5
Group 2						
1-day minimum (ft^3/s)	0	0.10	0.20	0.40	0.50	1.5
3-day minimum (ft^3/s)	0	0.10	0.22	0.40	0.57	1.4
7-day minimum (ft^3/s)	0.04	0.10	0.26	0.45	0.64	1.4
30-day minimum (ft^3/s)	0.11	0.17	0.4	0.77	1.3	1.5
90-day minimum (ft^3/s)	0.21	0.41	1.2	3.0	4.7	2.2
1-day maximum (ft^3/s)	85	100	130	190	250	0.68
3-day maximum (ft^3/s)	62	70	97	120	160	0.48
7-day maximum (ft^3/s)	41	49	62	81	110	0.52
30-day maximum (ft^3/s)	26	29	36	44	53	0.42
90-day maximum (ft^3/s)	19	21	25	31	36	0.37
Number of zero days	0	0	0	0	5.0	0
Baseflow index (ft^3/s)	0	0.01	0.02	0.03	0.04	1.1
Group 3						
Date of minimum (Julian date)	200	210	230	250	280	~
Date of maximum (Julian date)	340	25	76	130	200	~
Group 4						
Low-pulse count	1.5	2.2	4.0	6.0	8.0	0.94
Low-pulse duration (days)	3.2	4.5	10	26	74	2.1
High-pulse count	18	21	23	27	31	0.26
High-pulse duration (days)	1.0	1.0	2.0	2.0	3.0	0.50
Group 5						
Rise rate	2.0	2.6	3.5	4.3	6.0	0.48
Fall rate	-2.4	-1.8	-1.4	-1.1	-0.95	-0.48
Number of reversals	100	110	120	130	140	0.12

Table 3–10. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Fort Meadow Brook near Hudson, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	1.2	2.2	5.4	9.3	15	1.3
November (ft^3/s)	2.8	5.3	9.0	14	18	0.98
December (ft^3/s)	7.5	9.2	13	18	26	0.68
January (ft^3/s)	7.2	9.2	14	17	25	0.57
February (ft^3/s)	8.0	13	16	18	23	0.33
March (ft^3/s)	12	14	18	23	29	0.45
April (ft^3/s)	8.6	12	17	20	24	0.5
May (ft^3/s)	5.5	8.3	11	14	17	0.47
June (ft^3/s)	3.4	4.6	6.7	10	16	0.86
July (ft^3/s)	1.4	1.6	2.8	5.2	7.4	1.3
August (ft^3/s)	0.80	1.3	1.8	3.2	5.8	1.1
September (ft^3/s)	0.75	1.2	2.1	3.5	6.2	1.1
Group 2						
1-day minimum (ft^3/s)	0.55	0.70	1.1	1.4	2.2	0.64
3-day minimum (ft^3/s)	0.57	0.74	1.1	1.5	2.4	0.69
7-day minimum (ft^3/s)	0.59	0.78	1.2	1.7	2.5	0.77
30-day minimum (ft^3/s)	0.68	0.89	1.4	2.2	3.6	0.95
90-day minimum (ft^3/s)	0.86	1.5	2.1	4.1	5.7	1.2
1-day maximum (ft^3/s)	44	57	74	100	140	0.59
3-day maximum (ft^3/s)	38	49	66	87	120	0.57
7-day maximum (ft^3/s)	33	40	50	67	89	0.54
30-day maximum (ft^3/s)	23	26	31	39	46	0.41
90-day maximum (ft^3/s)	17	19	22	27	32	0.36
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.05	0.07	0.09	0.12	0.14	0.59
Group 3						
Date of minimum (Julian date)	210	230	250	270	280	~
Date of maximum (Julian date)	350	22	67	95	150	~
Group 4						
Low-pulse count	1.0	2.0	2.0	3.0	5.0	0.50
Low-pulse duration (days)	4.0	7.2	35	81	100	2.1
High-pulse count	4.0	6.0	8.0	11	13	0.62
High-pulse duration (days)	5.0	6.0	8.0	9.9	12	0.48
Group 5						
Rise rate	0.55	0.72	1.0	1.3	2.0	0.58
Fall rate	-0.90	-0.7	-0.55	-0.40	-0.30	-0.55
Number of reversals	69	73	80	90	97	0.21

Table 3–11. Indicators of Hydrologic Alteration (IHA) statistics determined from simulated long-term (1960–2004) daily flows with the Hydrologic Simulation Program–FORTRAN (HSPF) without withdrawals (NOWU) at Elizabeth Brook near Stow, Massachusetts.

[ft^3/s, cubic foot per second; ~, not applicable; metrics calculated for water years (October 1 through September 31), except for Group 2 minimum flows, which used climate years (April 1 through March 31)]

Metric	Percentile					
	10	25	50	75	90	(75-25)/50
Group 1						
October (ft^3/s)	3.4	6.6	14	25	43	1.3
November (ft^3/s)	8.4	15	27	42	56	1.0
December (ft^3/s)	23	28	40	54	87	0.64
January (ft^3/s)	20	27	43	55	85	0.64
February (ft^3/s)	27	37	45	58	73	0.47
March (ft^3/s)	36	44	60	73	92	0.48
April (ft^3/s)	28	39	52	66	78	0.51
May (ft^3/s)	15	27	35	41	57	0.42
June (ft^3/s)	10	13	18	33	48	1.1
July (ft^3/s)	3.8	5.3	8.3	13	21	0.94
August (ft^3/s)	1.5	3.6	5.5	9.8	14	1.1
September (ft^3/s)	1.4	3.2	6.0	9.6	14	1.1
Group 2						
1-day minimum (ft^3/s)	0.60	0.90	2.5	4.6	7.0	1.5
3-day minimum (ft^3/s)	0.62	0.98	2.6	5.0	7.0	1.5
7-day minimum (ft^3/s)	0.68	1.0	3.0	5.6	7.4	1.5
30-day minimum (ft^3/s)	1.1	1.9	4.4	7.1	9.7	1.2
90-day minimum (ft^3/s)	1.9	4.0	6.3	12	16	1.2
1-day maximum (ft^3/s)	120	150	240	340	480	0.76
3-day maximum (ft^3/s)	110	140	200	260	390	0.63
7-day maximum (ft^3/s)	98	120	150	190	280	0.5
30-day maximum (ft^3/s)	68	79	94	120	140	0.42
90-day maximum (ft^3/s)	52	59	68	84	97	0.37
Number of zero days	0	0	0	0	0	0
Baseflow index (ft^3/s)	0.02	0.04	0.07	0.11	0.14	0.9
Group 3						
Date of minimum (Julian date)	210	230	250	270	280	~
Date of maximum (Julian date)	360	20	54	88	140	~
Group 4						
Low-pulse count	1.0	1.0	2.0	3.0	4.0	1.0
Low-pulse duration (days)	4.5	11	37	84	100	2.0
High-pulse count	5.0	6.2	9.0	12	14	0.64
High-pulse duration (days)	4.0	5.5	7.0	8.4	10	0.41
Group 5						
Rise rate	1.7	1.9	3.0	3.9	5.9	0.65
Fall rate	-3.0	-2.2	-1.7	-1.0	-0.80	-0.71
Number of reversals	77	84	90	95	100	0.12

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Appendix 4

Duration and Frequency Long-Term (1960–2004) Daily Streamflow Simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with (AVGWU) and without (NOWU) Withdrawals were below Target Flows Determined by Six Standard-Setting Methods at 10 Riffle Sites in the Sudbury and Assabet River Basins

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Table 4–1. Duration and frequency the Wetted-Perimeter flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts. 155

Table 4–2. Duration and frequency the R2Cross 2-of-3 criterion flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts..... 156

Table 4–3. Duration and frequency the R2Cross 3-of-3 criterion flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts..... 157

Table 4–4. Duration and frequency the Tennant 30 percent of the mean annual flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts. 158

Table 4–5. Duration and frequency the Tennant 50 percent of the mean annual flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts. 159

Table 4–6. Duration and frequency the New England Aquatic Baseflow (ABF) low-flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts. 160

Appendix 4. Duration and Frequency Long-Term (1960–2004) Daily Streamflow Simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with (AVGWU) and without (NOWU) Withdrawals were below Target Flows Determined by Six Standard-Setting Methods at 10 Riffle Sites in the Sudbury and Assabet River Basins

Frequency and Duration Simulated Streamflows were below Target Flows

The tables in this appendix are summarized output from the River Analysis Package (RAP) by Marsh and others (2003) that determined the number of continuous days (duration) and the number of episodes (frequency) streamflows fall below a threshold. Thresholds were computed by six standard-setting methods—Wetted-Perimeter, R2Cross 2-of-3 criterion and 3-of-3 criterion, Tennant 30- and 50-percent mean annual flow, and Aquatic Base Flow (ABF). Flow thresholds were computed by each method for each of the 10 riffle sites examined. The Wetted-Perimeter and R2Cross flow thresholds were computed from site-specific hydrologic characteristics, typically determined from multiple cross sections, and a channel surface-water profile model (HEC-RAS). The Tennant and ABF flow thresholds were computed from statistical measures of long-term flows (1960–2004) simulated with the Hydrologic Simulation Program–FORTRAN (HSPF) with no withdrawals (NOWU).

The RAP program provides a number of measures of when threshold values are not met. Five measures were chosen that were considered a good representation of the duration and frequency a flow target could not be met. These include (1) the median annual number of episodes, (2) the median annual duration of an episode, (3) the median duration of the longest annual episode, (4) the longest duration of an episode for the 45-year simulated record, and (5) the total number of days over the 45-year period the threshold was not met. These metrics were determined by method, by site, and between simulated flows with and without withdrawals. The duration and frequency flows did not meet the flow target were determined from long-term simulated daily flows with (AVGWU) and without (NOWU) withdrawals. The median annual duration and frequency simulated flows were below the target flow were computed outside of the RAP because the program excludes years from the analysis the target flow was always met.

References Cited

Marsh, N.A., Stewardson, M.J., and Kennard, M.J., 2003, River Analysis Package (V2.0.4), Cooperative Research Center for Catchment Hydrology: Melbourne, Australia, Monash University [variously paged], accessed May 12, 2009, at *http://www.toolkit.net.au/Tools/RAP*.

Table 4–1. Duration and frequency the Wetted-Perimeter flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	0.7	[1]0	0	0	40	521
	AVGWU		[1]0	0	0	40	516
	Percent difference		0	0	0	0	-1
Sudbury River near Hopkinton	NOWU	7.0	6	12	33	97	3,514
	AVGWU		6	14	42	97	4,141
	Percent difference		0	16	27	0	18
Sudbury River near Ashland	NOWU	6.7	5	9	19	67	2,337
	AVGWU		6	10	22	74	2,755
	Percent difference		20	5	16	10	18
Indian Brook near Hopkinton[2]	NOWU	1.4	6	17	55	167	4,592
Indian brook near Ashland	NOWU	0.7	0	0	0	0	0
	AVGWU		0	0	0	0	0
	Percent difference		0	0	0	0	0
Baiting Brook near Framingham[2]	NOWU	0.8	0	0.0	0	25	570
Assabet River Basin							
Assabet River at Westborough	NOWU	0.2	1	4	3	59	621
	AVGWU		2	22	26	146	2,302
	Percent difference		100	450	767	147	271
Danforth Brook at Hudson[2]	NOWU	2.6	8	14	59	169	5,040
Fort Meadow Brook near Hudson	NOWU	1.7	2	20	25	135	2,005
	AVGWU		2	50	93	205	4,336
	Percent difference		0	148	272	52	116
Elizabeth Brook near Stow	NOWU	3.2	1	7	5	100	999
	AVGWU		1	8	5	100	1,047
	Percent difference		0	14	0	0	5
Median[3]	NOWU	1.7	1.5	7.0	5	67	999
	AVGWU		2.0	9.8	22	97	2,302
	Percent difference		33	40	340	45	130

[1]Fell below threshold once during period of record.

[2]No water withdrawals or returns in this subbasin.

[3]Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

Table 4–2. Duration and frequency the R2Cross 2-of-3 criterion flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	1.2	5	6.4	12	63	1,687
	AVGWU		5	6.2	12	79	1,701
	Percent difference		0	-3	0	25	1
Sudbury River near Hopkinton	NOWU	14	9	12	45	98	5,158
	AVGWU		10	13	52	134	5,898
	Percent difference		11	5	16	37	14
Sudbury River near Ashland	NOWU	7.5	6	9	21	73	2,637
	AVGWU		6	11	26	75	3,044
	Percent difference		0	23	24	3	15
Indian Brook near Hopkinton[1]	NOWU	0.4	1	12	9	63	945
Indian brook near Ashland	NOWU	0.5	0	0	0	0	0
	AVGWU		0	0	0	0	0
	Percent difference		0	0	0	0	0
Baiting Brook near Framingham[1]	NOWU	1.5	8	6.1	15	54	2,359
Assabet River Basin							
Assabet River at Westborough	NOWU	0.5	1	10	8	67	925
	AVGWU		2	25	30	148	2,585
	Percent difference		100	145	275	121	179
Danforth Brook at Hudson[1]	NOWU	1.2	3	20	43	162	2,992
Fort Meadow Brook near Hudson	NOWU	2.2	2	28	34	161	2,550
	AVGWU		2	53	96	214	4,773
	Percent difference		0	89	182	33	87
Elizabeth Brook near Stow	NOWU	6.2	2	20	25	134	2,087
	AVGWU	6.2	2	21	25	139	2,129
	Percent difference		0	5	0	4	2
Median[2]	NOWU		2.0	10	21	73	2,087
	AVGWU		2.0	13	26	134	2,585
	Percent difference		0	31	24	84	24

[1] No water withdrawals or returns in this subbasin.

[2] Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

Table 4–3. Duration and frequency the R2Cross 3-of-3 criterion flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	3.6	10	11	45	134	5,116
	AVGWU		9	13	46	134	5,302
	Percent difference		-10	15	2	0	4
Sudbury River near Hopkinton	NOWU	18	11	12	51	123	6,140
	AVGWU		12	13	54	138	6,902
	Percent difference		9	5	6	12	12
Sudbury River near Ashland	NOWU	22	10	13	51	123	6,079
	AVGWU		11	13	55	138	6,681
	Percent difference		10	0	8	12	10
Indian Brook near Hopkinton[1]	NOWU	14	24	12	88	217	13,214
Indian brook near Ashland	NOWU	6.8	5	31	110	235	7,160
	AVGWU		6	34	159	286	9,054
	Percent difference		20	8	45	22	26
Baiting Brook near Framingham[1]	NOWU	5.8	18	12	58	158	9,737
Assabet River Basin							
Assabet River at Westborough	NOWU	6.8	12	13	58	169	6,922
	AVGWU		13	14	97	209	8,028
	Percent difference		8	7	67	24	16
Danforth Brook at Hudson[1]	NOWU	10	23	9	79	171	9,649
Fort Meadow Brook near Hudson	NOWU	7.3	5	31	109	220	6,762
	AVGWU		5	40	162	281	9,075
	Percent difference		0	29	49	28	34
Elizabeth Brook near Stow	NOWU	10	2	44	78	174	3,870
	AVGWU		2	44	78	174	3,911
	Percent difference		0	0	0	0	1
Median[2]	NOWU		10	13	58	169	6,140
	AVGWU		9	14	78	174	6,902
	Percent difference		-10	3	34	3	12

[1] No water withdrawals or returns in this subbasin.

[2] Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

Table 4–4. Duration and frequency the Tennant 30 percent of the mean annual flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	3.8	10	11	46	134	5,241
	AVGWU		9	13	48	134	5,441
	Percent difference		-10	15	4	0	4
Sudbury River near Hopkinton	NOWU	11	8	12	41	98	4,611
	AVGWU		9	13	47	122	5,301
	Percent difference		13	4	15	24	15
Sudbury River near Ashland	NOWU	14	8	12	42	97	4,477
	AVGWU		8	14	46	122	4,981
	Percent difference		0	13	10	26	11
Indian Brook near Hopkinton[1]	NOWU	2.8	11	12	58	189	5,847
Indian brook near Ashland	NOWU	3.9	3	37	93	211	5,144
	AVGWU		3	54	136	265	7,145
	Percent difference		0	45	46	26	39
Baiting Brook near Framingham[1]	NOWU	2.1	10	7	19	74	3,352
Assabet River Basin							
Assabet River at Westborough	NOWU	3.9	9	12	50	168	4,960
	AVGWU		8	17	86	205	5,975
	Percent difference		-11	38	72	22	20
Danforth Brook at Hudson[1]	NOWU	2.9	8	14	61	169	5,205
Fort Meadow Brook near Hudson	NOWU	2.8	2	36	58	168	3,248
	AVGWU		2	61	105	222	5,395
	Percent difference		0	69	81	32	66
Elizabeth Brook near Stow	NOWU	10	2	44	83	174	3,972
	AVGWU		2	44	83	176	4,008
	Percent difference		0	0	0	1	1
Median[2]	NOWU		8.0	12	50	168	4,611
	AVGWU		8.0	17	83	176	5,395
	Percent difference		0	33	66	5	17

[1] No water withdrawals or returns in this subbasin.

[2] Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

Table 4–5. Duration and frequency the Tennant 50 percent of the mean annual flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	6.3	13	12	58	189	6,938
	AVGWU		13	12	59	193	7,142
	Percent difference		0	2	2	2	3
Sudbury River near Hopkinton	NOWU	19	12	12	51	123	6,400
	AVGWU		12	13	55	138	7,156
	Percent difference		0	13	8	12	12
Sudbury River near Ashland	NOWU	24	11	13	53	138	6,347
	AVGWU		11	14	57	193	6,925
	Percent difference		0	11	8	40	9
Indian Brook near Hopkinton[1]	NOWU	4.6	18	10	60	194	7,993
Indian brook near Ashland	NOWU	6.5	5	30	106	223	6,902
	AVGWU		5	39	158	285	8,815
	Percent difference		0	30	49	28	28
Baiting Brook near Framingham[1]	NOWU	3.5	14	9.1	34	83	5,869
Assabet River Basin							
Assabet River at Westborough	NOWU	6.5	12	12	58	169	6,713
	AVGWU		12	15	94	209	7,833
	Percent difference		0	22	62	24	17
Danforth Brook at Hudson[1]	NOWU	4.8	14	10	62	170	6,250
Fort Meadow Brook near Hudson	NOWU	4.7	2	50	90	195	4,670
	AVGWU		3	53	143	263	6,992
	Percent difference		50	5	59	35	50
Elizabeth Brook near Stow	NOWU	18	5	27	97	204	6,053
	AVGWU		5	27	97	204	6,065
	Percent difference		0	0	0	0	0
Median[2]	NOWU		12	12.4	58	179	6,557
	AVGWU		12	14.4	77	201	7,149
	Percent difference		0	17	32	12	9

[1] No water withdrawals or returns in this subbasin.

[2] Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

Table 4–6. Duration and frequency the New England Aquatic Baseflow (ABF) low-flow standard was not met using long-term (1960–2004) Hydrologic Simulation Program–FORTRAN (HSPF) simulated flows with (AVGWU) and without withdrawals (NOWU) at 10 riffle sites in the Sudbury and Assabet River Basins, Massachusetts.

[ft^3/s, cubic feet per second]

Site	Scenario	Flow threshold (ft^3/s)	Median annual			Period of record	
			Number of episodes (count)	Duration of episodes (days)	Duration of longest episode (days)	Longest episode (days)	Total days below threshold (days)
Sudbury River Basin							
Whitehall Brook near Hopkinton	NOWU	2.2	7	11	28	82	3,739
	AVGWU		8	10	26	82	3,841
	Percent difference		14	-9	-7	0	3
Sudbury River near Hopkinton	NOWU	9.5	7	13	40	97	4,259
	AVGWU		8	13	45	116	4,871
	Percent difference		14	3	13	20	14
Sudbury River near Ashland	NOWU	12	7	12	40	97	4,050
	AVGWU		7	14	44	115	4,519
	Percent difference		0	19	10	19	12
Indian Brook near Hopkinton[1]	NOWU	1.4	6	17	55	167	4,592
Indian brook near Ashland	NOWU	2.0	1	80	63	187	3,434
	AVGWU		2	64	113	255	5,581
	Percent difference		100	-20	79	36	63
Baiting Brook near Framingham[1]	NOWU	2.1	10	7.9	19	74	3,524
Assabet River Basin							
Assabet River at Westborough	NOWU	1.7	4	18	39	112	3,223
	AVGWU		4	23	67	183	4,260
	Percent difference		0	28	72	63	32
Danforth Brook at Hudson[1]	NOWU	0.7	3	15	30	140	2,463
Fort Meadow Brook near Hudson	NOWU	1.6	2	18	22	133	1,899
	AVGWU		2	49	91	205	4,257
	Percent difference		0	169	314	54	124
Elizabeth Brook near Stow	NOWU	5.9	2	22	26	140	2,171
	AVGWU		2	23	26	141	2,220
	Percent difference		0	2	0	1	2
Median[2]	NOWU		4	18	39	112	3,434
	AVGWU		4	23	45	141	4,260
	Percent difference		0	25	15	26	24

[1] No water withdrawals or returns in this subbasin.

[2] Medians determined from sites with both AVGWU and NOWU; excludes sites unaffected by withdrawals or returns.

For additional information, write to:
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