Simulation of Ground-Water Flow and Evaluation of Water-Management Alternatives in the Assabet River Basin, Eastern Massachusetts

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Abstract

Water-supply withdrawals and wastewater disposal in the Assabet River Basin in eastern Massachusetts alter the flow and water quality in the basin. Wastewater discharges and streamflow depletion from ground-water withdrawals adversely affect water quality in the Assabet River, especially during low-flow months (late summer) and in headwater areas. Streamflow depletion also contributes to loss of aquatic habitat in tributaries to the river. In 1997–2001, water-supply withdrawals averaged 9.9 million gallons per day (Mgal/d). Wastewater discharges to the Assabet River averaged 11 Mgal/d and included about 5.4 Mgal/d that originated from sources outside of the basin. The effects of current (2004) and future withdrawals and discharges on water resources in the basin were investigated in this study.

Steady-state and transient ground-water-flow models were developed, by using MODFLOW-2000, to simulate flow in the surficial glacial deposits and underlying crystalline bedrock in the basin. The transient model simulated the average annual cycle at dynamic equilibrium in monthly intervals. The models were calibrated to 1997–2001 conditions of water withdrawals, wastewater discharges, water levels, and nonstorm streamflow (base flow plus wastewater discharges). Total flow through the simulated hydrologic system averaged 195 Mgal/d annually. Recharge from precipitation and ground-water discharge to streams were the dominant inflow and outflow, respectively. Evapotranspiration of ground water from wetlands and non-wetland areas also were important losses from the hydrologic system. Water-supply withdrawals and infiltration to sewers averaged 5 and 1.3 percent, respectively, of total annual out-flows and were larger components (12 percent in September) of the hydrologic system during low-flow months. Water budgets for individual tributary and main stem subbasins identified areas, such as the Fort Meadow Brook and the Assabet Main Stem Upper subbasins, where flows resulting from anthropogenic activities were relatively large percentages, compared to other subbasins, (more than 20 percent in September) of total out-flows. Wastewater flows in the Assabet River accounted for 55, 32, and 20 percent of total nonstorm streamflow (base flow plus wastewater discharge) out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively, in an average September.

The ground-water-flow models were used to evaluate water-management alternatives by simulating hypothetical scenarios of altered withdrawals and discharges. A scenario that included no water management quantified nonstorm streamflows that would result without withdrawals, discharges, septic-system return flow, or consumptive use. Tributary flows in this scenario increased in most subbasins by 2 to 44 percent relative to 1997–2001 conditions. The increases resulted mostly from variable combinations of decreased withdrawals and decreased infiltration to sewers. Average annual nonstorm streamflow in the Assabet River decreased slightly in this scenario, by 2 to 3 percent annually, because gains in ground-water discharge were offset by the elimination of wastewater discharges.

A second scenario quantified the effects of increasing withdrawals and discharges to currently permitted levels. In this simulation, average annual tributary flows decreased in most subbasins, by less than 1 to 10 percent relative to 1997–2001 conditions. In the Assabet River, flows increased slightly, 1 to 5 percent annually, and the percentage of wastewater in the river increased to 69, 42, and 27 percent of total nonstorm streamflow out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively, in an average September.

A third set of scenarios quantified the effects of ground-water discharge of wastewater at four hypothetical sites, while maintaining 1997–2000 wastewater discharges to the Assabet River. Wastewater, discharged at a constant rate that varied among sites from 0.3 to 1.5 Mgal/d, increased nonstorm streamflow in the tributaries adjacent to the sites and in down-stream reaches of the Assabet River. During low-flow months, flow increases in tributaries were less than the constant discharge rate because of storage effects and increased ground-water evapotranspiration. Average September flows, however, more than doubled in these scenarios relative to simulated 1997–2001 conditions in Fort Meadow, Taylor, Cold Harbor, and Stirrup Brooks. Increases in Assabet River flows were small, with reductions in the wastewater component of flow in September of 5 percent or less.

Simulation-optimization analysis was applied to the upper part of the basin to determine whether streamflow depletion could be reduced, relative to 1997–2001 conditions, by management of monthly withdrawals, with and without ground-water discharge. The analysis included existing supply wells, one new well (in use since 2001), and a hypothetical discharge site in the town of Westborough. Without ground-water discharge, simulated nonstorm streamflow in September in the Assabet River about doubled at the outlet of the Main Stem Headwaters subbasin and increased by about 4 percent at the outlet of the Main Stem Upper subbasin. These increases were obtained by using water-supply sources upstream of lakes, which appeared to buffer the temporal effect of withdrawals, in low-flow months, and by using water-supply sources adjacent to streams, which immediately affected flows, in high-flow months. With ground-water discharge, simulated flows nearly tripled at the outlet of the Assabet Main Stem Headwaters subbasin, increased by 18 percent at the outlet of the main stem Upper subbasin, and more than doubled in a tributary stream. The general principles illustrated in the simulation-optimization analysis could be applied in other areas of the basin where streamflow depletion is of concern.

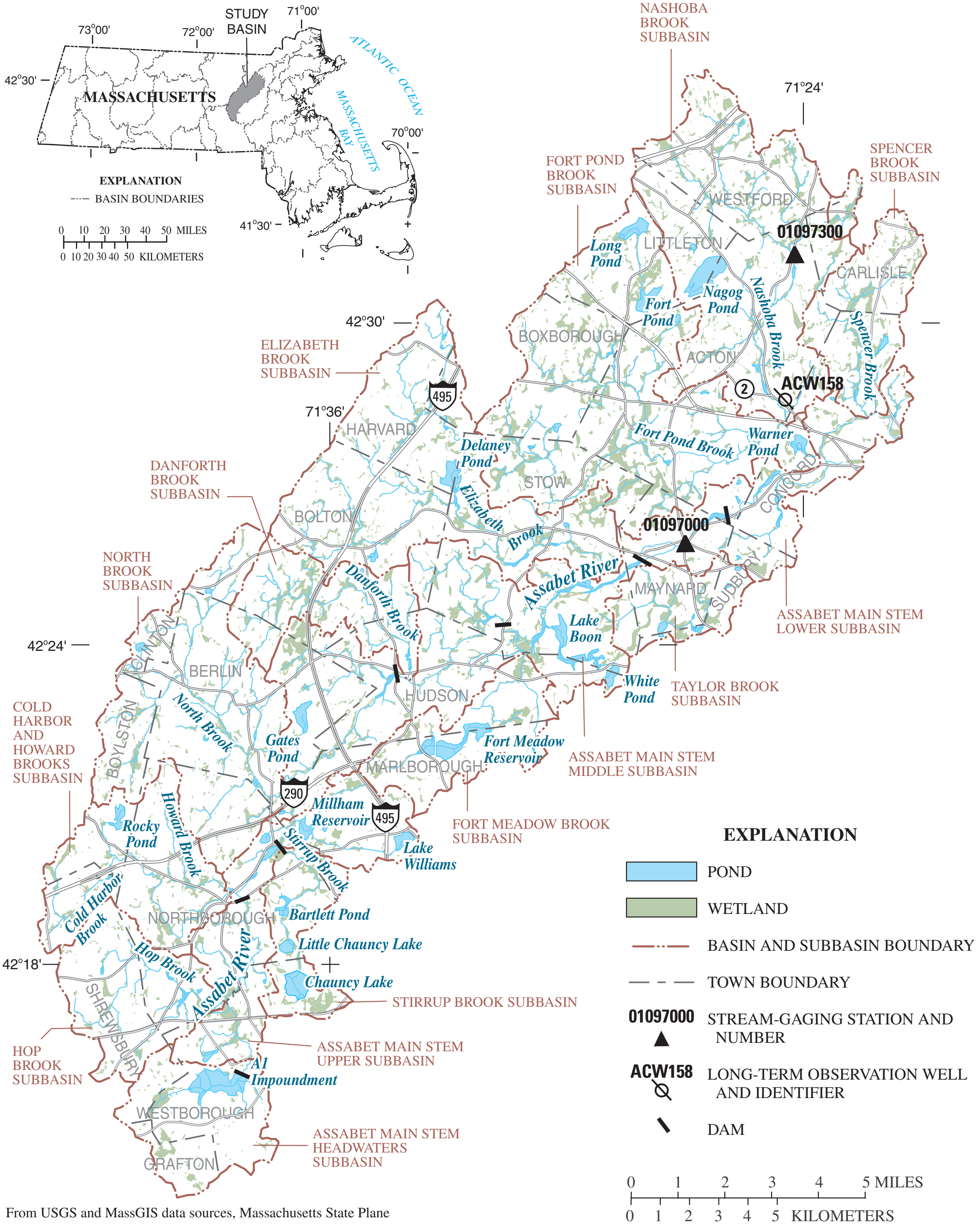
Introduction

Water-supply withdrawals and wastewater disposal in the Assabet River Basin, an area of about 177 mi^2 in eastern Massachusetts (fig. 1), have altered the flow and quality of ground- and surface water in the basin. Ground water is withdrawn for municipal supply from the discontinuous glacial aquifers along the tributaries and main stem of the Assabet River. Because these aquifers are in direct hydraulic connection with surface waters, the withdrawals typically reduce ground-water discharge to streams and wetlands and deplete streamflow (Winter and others, 1998; Randall, 2001). Along with water imported from outside the basin, private wells, and a few water-supply reservoirs, these ground-water sources supply a growing population of about 130,000 in the basin. Publicly supplied water typically is transferred within or outside of the basin after use to downstream treatment facilities, where it is discharged to the main stem of the Assabet River. These water withdrawals, transfers, and discharges adversely affect water resources by reducing flows required to maintain aquatic habitat, degrading water quality, and altering wetlands.

Currently (2004), the Assabet River is eutrophic during the summer and fails to meet most applicable water-quality standards (Massachusetts Department of Environmental Protection, 2003). These conditions result from discharges from the four municipal wastewater-treatment facilities along the river, from nonpoint sources, and from past waste-disposal practices (Richardson, 1964; ENSR International, 2001; Earth Tech, 2002a; Organization for the Assabet River, 2003b). Ground-water withdrawals also affect water quality and quantity. Natural ground-water discharge to streams, either to tributaries or directly to the main stem river, provides high-quality base flow that dilutes wastewater discharges. Reduced ground-water discharge to streams resulting from withdrawals for water supply may exacerbate the poor water-quality conditions common during low-flow periods. Reductions in current waste loads to the river are planned, primarily through the TMDL (Total Maximum Daily Load) process (Massachusetts Department of Environmental Protection, 2003). Actions to achieve waste-load reductions are costly, however, and alternative approaches to improving water quality in the river that involve ground-water management also are being considered (Earth Tech, 2002a).

Demands on water resources in the Assabet River Basin for water supply and wastewater disposal are likely to increase. The basin is along the rapidly developing Interstate 495 corridor, where a growing technology industry has spurred residential, commercial, and industrial development (Massachusetts Technology Collaborative, 1998). Between 1985 and 1999, 7.5 percent of the total basin area was converted from forested or agricultural uses to developed uses, with areas of residential and commercial or industrial land use increasing by 27 and 22 percent, respectively (MassGIS, 2001). Average population growth between 1990 and 2000 in towns in the basin, at 15 percent, was nearly 3 times the statewide average, and exceeded 30 percent in some towns (U.S. Census Bureau, 2003). These trends are likely to continue, resulting in the need for additional water supplies and wastewater discharges beyond current conditions (Massachusetts Technology Collaborative, 1999).

A better understanding of the effects of current and future water withdrawals and discharges on streamflows in the Assabet River and its tributaries will help water-resource managers make decisions about water supply, wastewater disposal, and waste-load reduction. Evaluating the effects of water-management practices on streamflows in a regional context also will aid management decisions, because these effects accumulate downstream. Recognition of this need by State agencies and others prompted a study by the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Conservation and Recreation (MADCR). The objective was to evaluate the effects on streamflows in the basin of withdrawals, discharges, and water-management alternatives, such as ground-water disposal of wastewater. Ground-water-flow models were developed to meet this objective because of the important role of ground-water discharge to streams and because most water withdrawals in the basin are from ground water. To ensure that the investigation adequately addressed issues of concern in the basin, representatives from Federal and State agencies, towns, a watershed association, and other organizations participated in a Technical Advisory Committee (TAC) for the study. The water-use and management issues of concern in the Assabet River Basin are common to many other basins in eastern Massachusetts and adjacent States, where communities are striving to balance growth and the available water resources. The methods and results of this study provide tools that can be used to address these issues.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 1. The Assabet River Basin, subbasins, streamflow-gaging stations, and long-term observation well, eastern Massachusetts.

Purpose and Scope

This report describes current water-resource conditions in the Assabet River Basin, the development, calibration, and limitations of numerical ground-water-flow models for the basin, and simulations made with the models to evaluate the effects of water withdrawals and discharges on streamflows. It also presents the data collected to define water resources in the basin, and upon which the steady-state and transient models were developed. The models include average water withdrawals and discharges for a 5-year period, 1997–2001, which was near long-term average hydrologic conditions. Simulation results of several scenarios of altered withdrawals, discharges, or other water-management practices also are described. Finally, the report describes the use of optimization techniques to investigate the potential for reduced streamflow depletion through altered water-management practices in the upper part of the basin.

Description of the Study Area

The Assabet River Basin (fig. 1) encompasses an area of 177 mi^2 within the Merrimack River Basin in eastern Massachusetts. The study area includes all or part of 20 towns. The basin is elongate in the northeast-southwest direction, parallel to regional geologic features (Zen and others, 1983). Topography varies from gently rolling to hilly, with elevations ranging from about 100 to 750 ft above NGVD 29. Higher elevations and steeper slopes are along the northwestern boundaries of the basin. The Assabet River flows northeastward from Westborough, through lowlands near the eastern basin boundary, about 31 mi to its confluence with the Sudbury River in Concord, MA. The climate is humid and temperate. Precipitation averages 47 in/yr, and average temperature ranges from 25°F in January to 71°F in July, according to records from nearby weather stations (National Oceanic and Atmospheric Administration, 2002).

Land use in the Assabet River Basin in 1999 was primarily forested or open (51 percent) and residential (28 percent, mostly low and medium density), with agricultural (8 percent), commercial or industrial (5 percent), water and wetlands (5 percent) representing small fractions of the basin area (MassGIS, 2001). Land use and population density varied widely among towns. Population density ranged from about 200 to nearly 2,000 people/mi^2 in 2000 (U.S. Census Bureau, 2003). Towns varied in residential land use from 13 to 39 percent, and in commercial or industrial land use and in agricultural land use from less than 1 to 14 percent each (1999 data; MassGIS, 2001). Forest cover varied from 34 to 66 percent, in 1999. Densely developed areas clustered along the main stem Assabet River and near the southeastern boundary of the basin. The most rapidly growing towns, however, were in the headwaters and along the northwestern upland parts of the basin; these include Bolton, Boxborough, Shrewsbury, Westborough, and Westford (fig. 1). Population increased in these towns from 27 to 46 percent between 1990 and 2000 (U.S. Census Bureau, 2003).

Previous Studies

Information on the hydrogeology and water resources of the Assabet River Basin is available from many sources. Several publications describe the surficial geology of parts of the study area (Campbell, 1925; Jahns, 1953; Hansen, 1956; Perlmutter, 1962; Koteff, 1966; and Shaw, 1969). Basic hydrogeologic data, including well and boring logs, water levels, and the locations of high transmissivity zones, are described in Pollock and Fleck (1964), Pollock and others (1969), and Brackley and Hansen (1985). An analysis of aquifer yields developed on the basis of streamflow data was completed by Bratton and Parker (1995). Continuous-record streamflow data for the Assabet River and for Nashoba Brook, a tributary of the Assabet River, are available from two long-term USGS streamflow-gaging stations (fig. 1; Socolow and others, 2003). Historical streamflow data also were collected at partial-record stations in the basin that were used for USGS low-flow studies (Ries, 1993, 1994, and 1999; Ries and Friesz, 2000). Streamflow and other hydrologic data for the Assabet River and its tributaries were collected for a recently completed TMDL study, in support of a surface-water model of the basin (ENSR International, 2001, 2004). Data also were being collected at the time of this study by the Organization for the Assabet River (2003a), as part of a stream monitoring and public-outreach program. Streamflow requirements for the protection of aquatic habitat were recently assessed by Parker and others (2004) at six sites in the basin. A water-use investigation of the Assabet, Concord, and Sudbury River Basins (L.K. Barlow, U.S. Geological Survey, oral commun., 2003) was ongoing at the time of this study. Information on existing conditions of water use and disposal for communities in the Assabet Consortium were available in the Comprehensive Wastewater Management Plans for these towns (Camp, Dresser, & McKee, 2001; 2002; Dufresne-Henry, 2001, 2002; Earth Tech 2001a, 2001b, 2001c, 2001d, 2001e, 2002b, 2002c, 2002d; Fay, Spofford, and Thorndike, 2001a, 2001b, 2002a, 2002b). The Assabet River Consortium includes the six towns (Hudson, Marlborough, Maynard, Northborough, Shrewsbury, and Westborough) in the basin that discharge wastewater to the river (Earth Tech, 2001a). Also, consultants to the towns have completed many small-scale hydrogeologic investigations. These studies were completed to locate water-supply sources, to determine wellhead protection areas for public-supply wells, to investigate ground-water contamination, or to support specific development projects. Information available from these reports include well and boring logs, hydrogeologic maps and sections, and results of aquifer tests and numerical simulations. Consultant reports used in this study include ABB Environmental Services (1996), Camp, Dresser, & McKee (1990), Dufresne-Henry (1981, 1989, 1993, 1996, 1999), Earth Tech (2000a, 2000b, 2000c, 2000d, 2000e), Ecology and Environment (1994), Epsilon Associates (2000, 2002a, 2002b), Geologic Services Corporation (1984, 1985, 1987, 1989, 1995a, 1995b, 1996, 2000), GeoScience Consultants (1988), GeoTrans (2001), Goldberg-Zoino & Associates (1985), Goldberg, Zoino, Dunnicliff & Associates (1980a, 1980b), HMM Associates (1987), Keystone Environmental Resources (1991), McCulley, Frick, & Gilman (1997), Metcalf & Eddy (1994), Rizzo Associates (1990), Sasaki Associates (1989), Weston & Sampson Engineers (1997), and Whitman & Howard (1986, 1987a, 1987b, 1987c).

Ground- and Surface-Water Resources

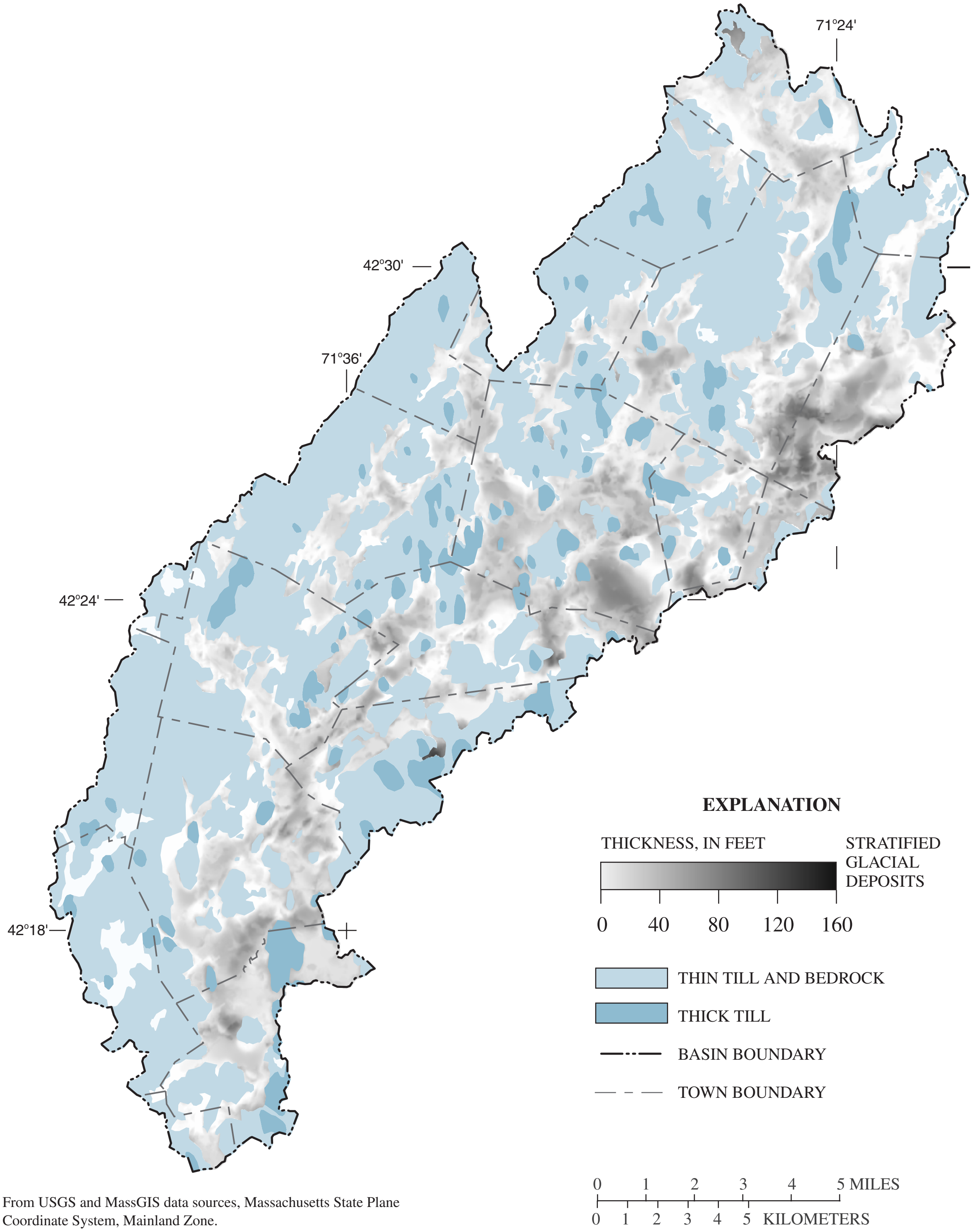
Many factors affect water resources in the Assabet River Basin. Ground-water flow is influenced by the hydraulic properties of the geologic units in which it occurs and the timing and quantity of recharge. Impoundments, ponds, and wetlands, as well as climate and topography, affect surface-water flow. Ground-water- and surface-water-flow systems are in close hydraulic connection, especially in the surficial geologic materials.

Geologic Setting

Ground water occurs in three major geologic units in the Assabet River Basin—stratified glacial deposits, glacial till, and bedrock (fig. 2). The stratified glacial deposits consist of sorted and layered sand, gravel, silt, and clay deposited by meltwater in streams or lakes in valleys and lowlands during the last glacial period. The till is generally an unsorted, unstratified mixture of clay, silt, sand, gravel, cobbles, and boulders, deposited directly by the glacial ice. Locally, till forms thick deposits in uplands or in areas of stratified glacial deposits and covers uplands in a thin layer. Crystalline bedrock underlies the stratified glacial deposits and till, and consists primarily of metasedimentary, metavolcanic, and metaintrusive rocks (Zen and others, 1983). Alluvium and swamp deposits are relatively minor components of the hydrogeologic system in the basin, and are not areally extensive and (or) form relatively thin surficial layers.

Although the stratified glacial deposits are discontinuous and heterogeneous, they are the most productive aquifers in the basin. They occur along the Assabet River and its major tributaries and cover about 43 percent of the study area (fig. 2). The areal extent of stratified glacial deposits in the basin was determined from published and unpublished surficial geologic maps (J.R. Stone, U.S. Geological Survey, written commun., 2002). The thickness of the stratified glacial deposits was mapped by contouring the elevation of the underlying bedrock or till surface (J.R. Stone, U.S. Geological Survey, written commun., 2002) and subtracting that elevation from the land-surface elevation. Data on depth to bedrock, till, or drilling refusal were obtained from about 830 well logs or borings, available from USGS files, from the reports by private consultants cited previously, and from wells installed during this study. The thickness of the stratified glacial deposits ranges from 0 at its edges to about 160 ft (fig. 2). Typically, the deposits are less than 75 ft thick, and average only about 35 ft thick throughout the mapped area. Stratified glacial deposits are relatively thick in southeastern Stow, where a bedrock valley may represent the preglacial route of the Assabet River (Hansen, 1956; Perlmutter, 1962), and in Concord and southeastern Acton (fig. 2).

The stratified glacial deposits in the Assabet River Basin were deposited during successive pauses of the retreating ice margin in association with two meltwater lakes, glacial Lakes Assabet and Sudbury (Campbell, 1925; Hansen, 1956; Koteff, 1966; J.R. Stone, U.S. Geological Survey, oral commun., 2002). They include glacial stream, deltaic, and lake-bottom deposits. Distinct sequences of these units, as have been identified elsewhere in New England (Stone and others, 1998; Randall, 2001), have not been identified in the Assabet River Basin, and geologic mapping has not distinguished sediment packages based on lithology or depositional setting. Ice-contact deposits, variable in thickness, grain size, and sorting, are common throughout the basin. These stratified glacial deposits are characteristic of the low-relief, narrow valleys in southern New England (Randall, 2001). The areas of thick stratified glacial deposits in southeastern Stow and Concord, mapped as outwash plain and delta deposits, include sediments that were deposited farther from the ice margin and are better sorted than the more proximal ice-contact deposits (Hansen, 1956; Koteff, 1963). Also, near the Assabet River from Stow to Concord, thick layers of fine sand, silt, and clay underlie coarser-grained sediments. Fine-grained sediments also occur at depth farther south in Northborough and Westborough; fine-over-coarse sequences also are common in Westborough. These fine-grained sediments probably are lake-bottom sediments (Koteff, 1963); their distribution, however, is discontinuous. In areas of coarse-grained deposits, depressions left by melting ice blocks are common and often are occupied by kettle lakes or isolated wetlands.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 2. Surficial geology of the Assabet River Basin, eastern Massachusetts.

Till in the Assabet River Basin consists of a thin upper till and a discontinuous, thick lower till. The upper or younger till forms a thin surficial layer over bedrock throughout the basin. The till is loosely consolidated, relatively permeable, characterized by abundant boulders, and typically 10 to 15 ft thick or less (Campbell, 1925; Jahns, 1953; Hansen, 1956; Koteff, 1966). The lower or older till forms hills with deposits that often are 50 to 80 ft thick, and may exceed 100 or 200 ft thick. The thick lower till is compacted tightly and relatively impermeable. Hills of thick till (drumlins) are rounded and commonly elongate in the north-south direction, parallel to the direction of regional ice flow. Because of its low transmissivity, till rarely is used for water supply in the basin, even by domestic water users.

Bedrock consists of Proterozoic or Lower Paleozoic metasedimentary, metavolcanic, and intrusive igneous rocks, including the Nashoba Formation, Andover Granite, and Marlboro Formation (Zen and others, 1983; Goldsmith, 1991a). Typical rock types are mica schist and gneiss, granite, diorite, and amphibolite. The basin lies in a structural zone between two major fault zones, which trend northeast-southwest across the State. Within this zone, beds dip steeply and faulting is pervasive and complex (Goldsmith, 1991b; Walsh, 2001). Two regional faults within the basin, the Assabet River and Spencer Brook faults, extend northeast-southwest from Northborough to West Concord. Faults and joints are important hydrologically, because most water in bedrock is stored and flows in these openings; the unbroken rock is nearly impermeable.

Hydraulic Properties

Information about the hydraulic properties of hydrogeologic units in the basin is most readily available for the stratified glacial deposits than for the other geologic units, because large water supplies commonly are developed in these deposits. Horizontal hydraulic conductivity values at public-supply wells, determined from analysis of aquifer tests, averaged about 190 ft/d (median value equal to 140 ft/d) and ranged from 80 to 675 ft/d (table 1). These values likely represent the most permeable and most productive deposits in the basin. Well logs, distributed throughout the stratified glacial deposits, are another source of information about hydraulic properties of sediments. Brackley and Hansen (1985) used horizontal hydraulic conductivity values estimated from well logs, along with other data, to map transmissivity (hydraulic conductivity multiplied by aquifer thickness) in the basin. The estimates were based on values for sediments of various grain size and sorting in New England, compiled from aquifer tests and other sources (B.P. Hansen, U.S. Geological Survey, oral commun., 2002). The values determined by Brackley and Hansen (1985), and similar values calculated for well logs inventoried in this study, were used to characterize horizontal hydraulic conductivity in the stratified glacial deposits (fig. 3). Spatially, hydraulic conductivity values from well logs and aquifer tests are variable, which reflects the vertical and horizontal heterogeneity of sediment characteristics (for well logs) because the values are depth-weighted averages. Hydraulic conductivity values, however, were significantly different among the mapped transmissivity zones, with geometric mean values of 46, 72, and 108 ft/d for low-, medium-, and high-transmissivity zones, respectively.

Little information about vertical hydraulic conductivity is available for stratified glacial deposits in the study area, but values can be estimated from reported ratios of vertical to horizontal conductivity. Reported ratios range from 1:3 to 1:5, for coarse-grained stratified glacial deposits, and from 1:30 to 1:100, for fine-grained deposits (Dickerman and others, 1990; Masterson and Barlow, 1997; Masterson and others, 1998; Stone and Dickerman, 2002). Reported values of specific yield, or unconfined storage coefficient, of stratified glacial deposits ranges from 0.16 to 0.47, with typical values of 0.25 to 0.33 for medium to coarse sand and gravel, 0.21 to 0.33 for fine sand, and 0.02 to 0.08 for silt and clay (Johnson, 1967; Morris and Johnson, 1967; Moench and others, 2000; Kontis and others, in press). Storage coefficients from aquifer tests in coarse-grained deposits in the basin range from 0.07 to 0.14 (table 1); these values may be representative of short-term aquifer responses to stress. Less information is available for confined storage coefficient for stratified glacial deposits than for specific yield. Typical values of specific storage are 1×10^{-4} ft^{-1} for fine-grained deposits and 1×10^{-6} ft^{-1} for coarse-grained deposits in the glaciated northeastern United States (Kontis and others, in press); these values would need to be multiplied by aquifer thickness to determine the storage coefficient.

Hydraulic properties of till are not well known. Horizontal hydraulic conductivity of till in the study area probably ranges from 0.01 to 10 ft/d (Allen and others, 1963; Randall and others, 1988; Melvin and others, 1992; Tiedeman and others, 1997; Lyford and others, 2003; Kontis and others, in press), with the thin till at the upper end of the reported range. The ratio of vertical to horizontal hydraulic conductivity may range from 1:1 to 1:100. The vertical hydraulic conductivity of thin surficial deposits, consisting of lake-bottom silt, fine sand, and thin till, as determined from an aquifer test for municipal supply wells in Maynard, ranges from 0.13 to 1.35 ft/d, averaging 0.48 ft/d (Lyford and others, 2003). Specific yield values of 0.06 to 0.26 have been reported for silty and sandy till (Allen and others, 1963; Morris and Johnson, 1967).

Table 1. Hydraulic properties of stratified glacial deposits as determined by analysis of aquifer tests at public-supply wells in the Assabet River Basin, eastern Massachusetts.

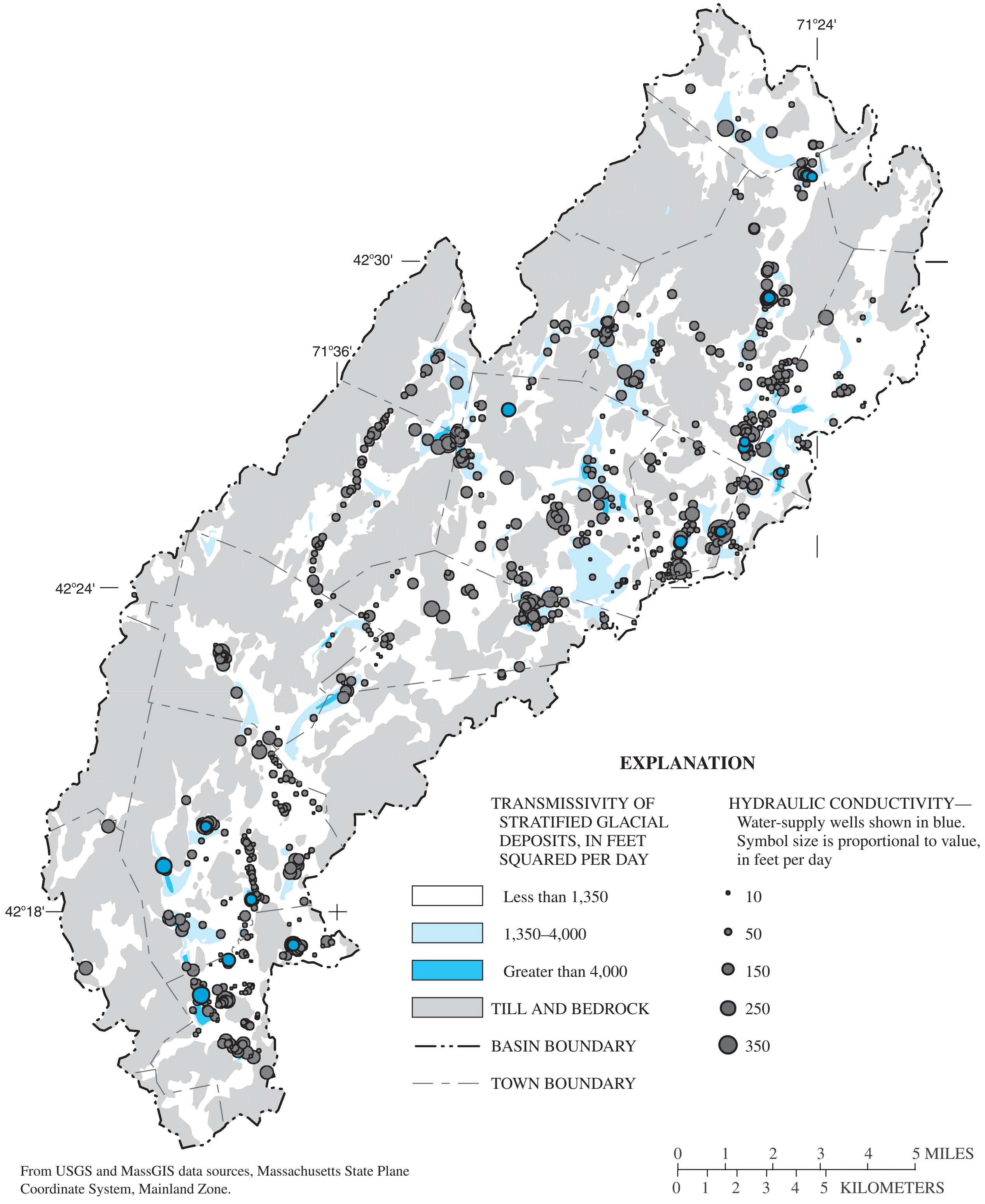
[**Well site:** See table 8 for additional identification information; site locations shown on figure 16 unless otherwise indicated. **Transmissivity:** Mean of reported values or a value otherwise considered representative; ft, foot; ft/d, foot per day; ft^2/d, square foot per day; gal/min, gallons per minute; --, not available]

Well site	Predominant grain size of tested interval	Year of test	Length of test (days)	Well discharge (gal/min)	Transmissivity (ft^2/d)	Saturated thickness (ft)	Hydraulic conductivity (ft/d)	Storage coefficient	Reference
AN-06G	Fine to coarse sand and gravel	1970	19	500	5,290	--	85	0.14	Goldberg, Zoino, Dunnicliff & Associates, 1980a,b
AN-05G	Fine to coarse sand and gravel	1970	13	265	6,220	--	110	.07	Goldberg, Zoino, Dunnicliff & Associates, 1980a,b
AN-09G	Sand and gravel	1980	5	171	4,390	40	110	--	Dufresne-Henry, 1996
AN-10G	Sand and gravel	1979	10	365	5,610	40	140	--	Dufresne-Henry, 1996
		1980	7	269					
AN-11G	Fine to coarse sand and gravel	1991	9	395	7,730	30	258	--	Dufresne-Henry, 1993
BSC[1]	Silt and clay	1989	3	1.75	53	40	1.3	.001	Rizzo Associates, 1990
ARNWR[2]	Sand and gravel	1955	2	603	4,500	45	101	.2	Perlmutter, 1962
CN-01G	Medium to coarse sand and gravel	1966	1.5	--	4,400	70–90	80	--	Weston and Sampson, 1997
HD-01G	Sand and gravel	1967	2	710	23,600	35	675	--	Earth Tech, 2000c
MCC[3]	Fine to coarse sand and gravel	1989	1	229	8,300	51	163	--	Sasaki Associates, 1989
NB-01G	Medium to coarse sand and gravel	1955	7	350	8,600	60	140	--	Earth Tech, 2000b
NB-03G	Sand and gravel	1969	--	--	5,050	53	95	--	Earth Tech, 2000b
WB-05G and WB-06G	Fine to coarse sand and gravel	1984	7	450	9,210	50	184	--	Geologic Services Corporation, 1985
WB-07G	Coarse sand and gravel	1994	8	393	9,700	50	194	.10	Geologic Services Corporation, 1995
WB-03G	Sand and gravel	1981	2	600	11,200	35	320	--	Earth Tech, 2000e

[1] Bay State Circuits, Northborough, MA; test well location at 42°19′09″ latitude and 71°36′38″ longitude. This well was installed for remediation, not public supply.

[2] Assabet Valley National Wildlife Refuge, Sudbury, MA; test well location at 42°24′40″ latitude and 71°29′15″ longitude.

[3] Marlboro Corporate Center, Marlborough, MA; test well location at 42°22′01″ latitude and 71°35′47″ longitude.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 3. Depth-weighted hydraulic conductivity from well logs and transmissivity zones in stratified glacial deposits in the Assabet River Basin, eastern Massachusetts. Transmissivity zones from Brackley and Hansen (1985).

Hydraulic properties of bedrock generally are low but variable. Median values of hydraulic conductivity of crystalline bedrock for large and small supply wells in New England and adjacent areas range from 0.45 to 0.9 ft/d (Randall and others, 1966; Randall and others, 1988). Hydraulic conductivity in fractured crystalline bedrock in the Mirror Lake area, New Hampshire, varies over 6 orders of magnitude; representative values determined through model calibration were 0.02 and 0.09 ft/d (Tiedeman and others, 1997). Aquifer tests of four industrial supply wells in Acton and Hudson yielded hydraulic conductivity values of 0.18, 0.24, 0.97, and 2.8 ft/d (Epsilon Associates, 2000, 2002a, 2002b). The values for supply wells in bedrock, in the study area and elsewhere, likely represent the more permeable bedrock zones. Little information is available on vertical conductivity or storage properties of bedrock, which are likely to be highly variable. Vertical conductivity at the Maynard supply-well site ranged from 0.13 to 1.35 ft/d (Lyford and others, 2003). Storage coefficients for the industrial supply wells in Hudson and Acton ranged from 3×10^{-6} to 0.067 (Epsilon Associates, 2000, 2002a, 2002b), and a median value for large supply wells in New England was about 2×10^{-4} (Randall and others, 1988).

Ground-Water Flow

Ground water in the study area generally flows from topographic highs in the uplands toward stream channels and toward the stratified glacial deposits in valleys and lowlands. The water table mimics topography, such that surface- and ground-water divides typically coincide, especially in uplands. Precipitation recharges ground water in till and bedrock upland areas and in the stratified glacial deposits; surface runoff from uplands also recharges the stratified glacial deposits at the edges of valleys. Ground-water levels and flow directions, particularly in the stratified glacial deposits, are strongly influenced by the locations and elevations of streams, which, along with wetlands and pumping wells, are the discharge points for the ground-water-flow system (Winter and others, 1998; Randall and others, 2001).

Recharge

Recharge rates for the Assabet River Basin were estimated from two approaches and data sources—streamflow records and climate data. The recharge estimates were made to characterize the overall water budget for the basin and to guide calibration of the ground-water-flow models. The recession-curve displacement method was applied to mean daily streamflow records from the two continuous-record streamflow-gaging stations (fig. 1) in the basin. The computer program RORA, developed by Rutledge (1993, 1998) on theory by Rorabaugh (1964), was used to estimate recharge rates. In this method, recharge is quantified from the upward displacement of the streamflow-recession hydrograph after streamflow peaks. Individual recharge events are summed over yearly and monthly intervals. Several simplifying assumptions about the flow system are made, including the assumption of uniform aquifer properties and an instantaneous and uniform aquifer response to recharge events throughout the basin.

A water-balance method also was used to calculate daily recharge from climate data as:

$$R = P - ET - \Delta SM - DR, \qquad (1)$$

where

R is recharge;
P is precipitation;
ET is evapotranspiration;
ΔSM is change in soil moisture; and
DR is direct runoff.

Climate data from the nearby Bedford and West Medway, MA, weather stations (about 5 and 15 mi, respectively, from the basin) were used for this analysis because they were considered most representative of conditions in the study area. Potential evapotranspiration (PET) for use in the water-balance method was calculated by using methods for estimating evaporation in settings where actual evaporation equals PET. The Hamon (1961) method (Lumb and Kittle, 1995) and the available climate data (mean daily temperature and hours of sunlight) initially were used. Because the Hamon method underestimates actual evaporation (Winter and others, 1995), values from this method were adjusted upward based on a comparison of monthly PET values calculated by Hamon and Penman methods for a basin in southern Rhode Island (P.J. Zarriello, U.S. Geological Survey, written commun., 2003). The Penman equation (Penman, 1948) more completely characterizes the driving forces of evaporation because it includes temperature, solar radiation, and wind speed; therefore, it is considered a better approximation of actual evaporation (Penman, 1948; Veihmeyer, 1964; Winter and others, 1995). The difference between mean daily streamflow and mean daily base flow (estimated with the automated hydrograph-separation method, PART; Rutledge, 1993, 1998) at the Assabet River streamflow-gaging station (fig. 1) was used as an estimate of direct runoff. Use of PART in an estimate of direct runoff assumes that anthropogenic effects on streamflow (for example, increased wastewater discharge to the river from storm inflow to sewers) are negligible compared to those resulting directly from precipitation. The water-balance method was applied by using a FORTRAN computer program (D.R. LeBlanc, U.S. Geological Survey, written commun., 2002) that calculates ET, soil moisture deficit, and recharge on a daily basis, as described by Thornthwaite and Mather (1957). ET is set equal to PET when precipitation exceeds PET and is equal to precipitation and available soil moisture when precipitation is less than PET. The remaining available water first goes to satisfy the soil moisture deficit, then to recharge. A maximum soil storage capacity of 2 in. was assumed (Thornthwaite and Mather, 1957). No lag time is applied between precipitation and recharge to the water table, such that unsaturated-zone travel time is assumed negligible. As with the results produced by the RORA method, the water-balance method results in basin-wide recharge rates that simplify and homogenize recharge, runoff, and ET processes.

Recharge rates of about 20 in/yr were calculated from streamflow records, for long-term conditions and for the 1997–2001 period (table 2). The water-balance method yielded rates of about 17 in/yr. These values are consistent with recharge rates of 17.5 to 25.5 in/yr, estimated from streamflow records and model calibration for basins in southern New England with variable percentages of stratified glacial deposits and till-covered uplands (Bent, 1995, 1999; Barlow, 1997; Barlow and Dickerman, 2001; DeSimone and others, 2002). Although average annual rates for 1997–2001 are similar to long-term rates, this 5-year period was unusual in that it contained relatively dry summers in 1997 and 1999 and an extended period of dry weather that began in September 2001 (fig. 4). Recharge rates of 17 to 20 in/yr for 1997–2001 correspond to total inflow volumes to the basin of 143 to 169 Mgal/d (222 to 261 ft^3/s).

Table 2. Average annual recharge rates and precipitation for the Assabet River Basin, eastern Massachusetts.

[in/yr, inches per year]

Period	Precipitation (in/yr)	Recharge (in/yr): Streamflow hydrograph displacement method: Assabet River station (01097000)	Recharge (in/yr): Streamflow hydrograph displacement method: Nashoba Brook station (01097300)	Recharge (in/yr): Water-balance method
Data source period of record[1]	46.4	20.6	19.8	17.3
1964–2002	46.4	20.6	19.8	17.2
1997–2001	47.1	20.3	16.4	17.1

[1] Assabet River streamflow-gaging station, 1941–2002; Nashoba Brook streamflow-gaging station, 1964–2002; water-balance method, 1958–2002.

The distribution of annual recharge among months from both methods (fig. 5) is consistent with conceptual models in which most aquifer recharge occurs during spring and winter months. Results of the two methods differ in that recharge rates from streamflow records have a distinct peak in the spring that may reflect the effects of snowmelt or aquifer storage that are not captured in the climate-based water-balance method. Unlike the annual average rates, deviations of 1997–2001 conditions from long-term average conditions are apparent in the monthly average rates. Average rates in October, November, and December for 1997–2001 are lower than long-term average rates for both methods because of the extended dry period in 2001. Average March and June rates for 1997–2001 are higher than the long-term average because of some unusually wet months in that 5-year period (figs. 4 and 5). Both methods, however, are more accurate for estimating long-term average rates than for estimating rates at shorter time scales, such as months (Rutledge, 1998, 2000).

Water Levels

Ground-water levels throughout the basin are strongly influenced by the locations and elevations of streams, ponds, and wetlands. Water-level fluctuations also are influenced by proximity to surface water. Annual fluctuations are smallest near streams and ponds, and are largest in the uplands, where thin surficial layers of till may dry out in summer (Randall and others, 1988). In this study, ground-water levels were measured only in the stratified glacial deposits; water levels and fluctuations in the till and bedrock upland areas were considered too variable to be characterized by the data-collection program.

Water levels were measured in 19 wells at about monthly intervals from September 2001 through December 2002 (fig. 6 and table 3). Data also were available from a long-term observation well, ACW158, with a continuous record since July 2001 and a 40-year record of intermittent measurements (Socolow and others, 2003). The wells all were screened in the stratified glacial deposits. Water levels throughout eastern Massachusetts during the measurement period were lower than normal, as shown by records at ACW158 (fig. 7) and at other long-term observation wells (table 4; Socolow and others, 2002, 2003). Measured annual fluctuations in observation wells generally ranged from less than 2 to more than 4 ft. Fluctuations generally were largest in wells near boundaries of stratified glacial deposits with uplands, such as ACW257 and WRW150, and smallest in wells near streams, such as HZW147 and WRW149 (fig. 8).

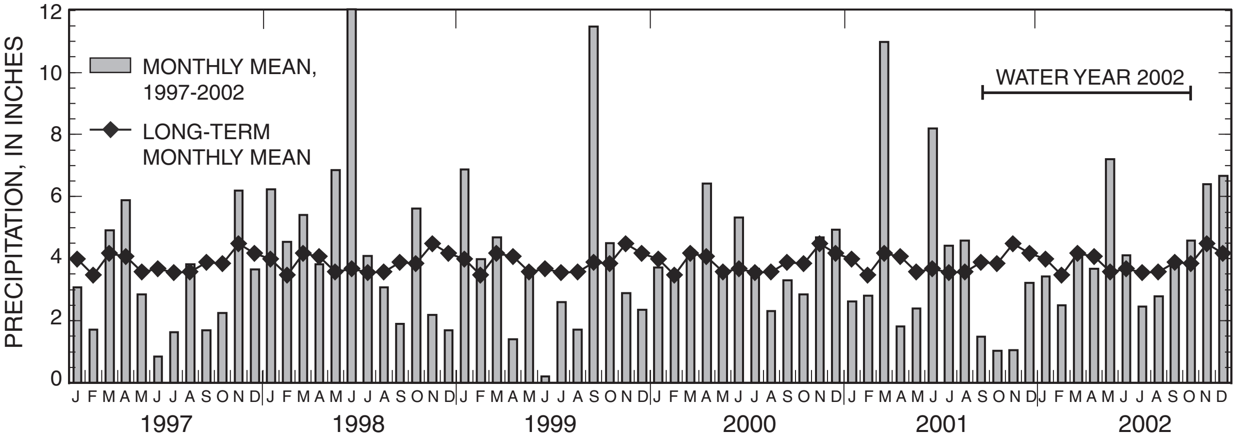


Figure 4. Monthly mean precipitation for long-term average conditions (1958–2002) and for 1997–2002 at National Oceanic and Atmospheric Administration weather stations in Bedford and West Medway, Massachusetts. Data shown are averages of daily values at the two stations.

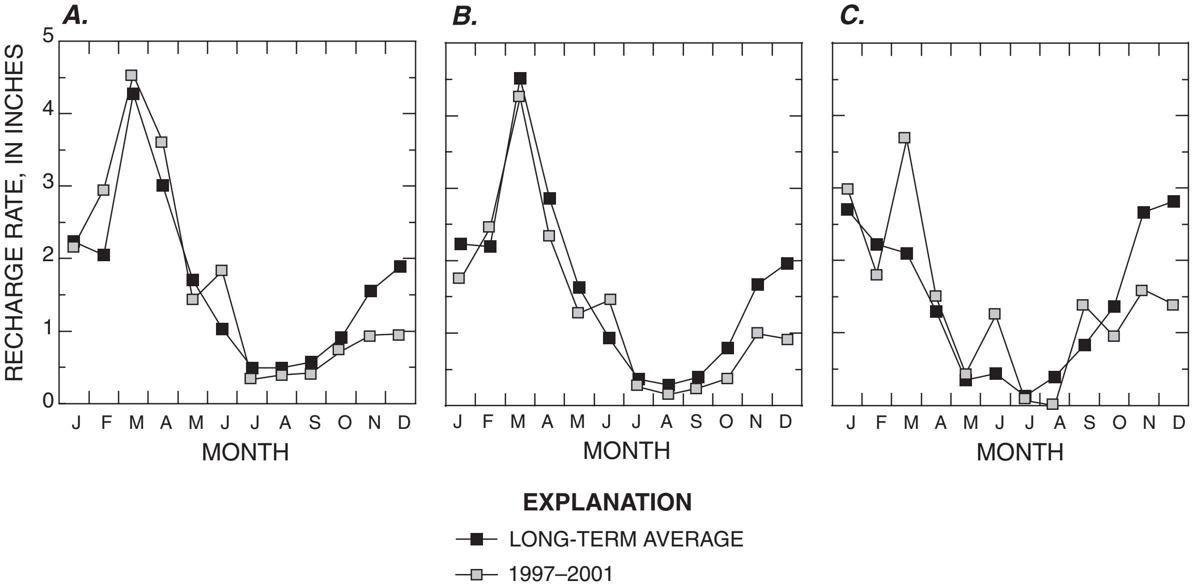
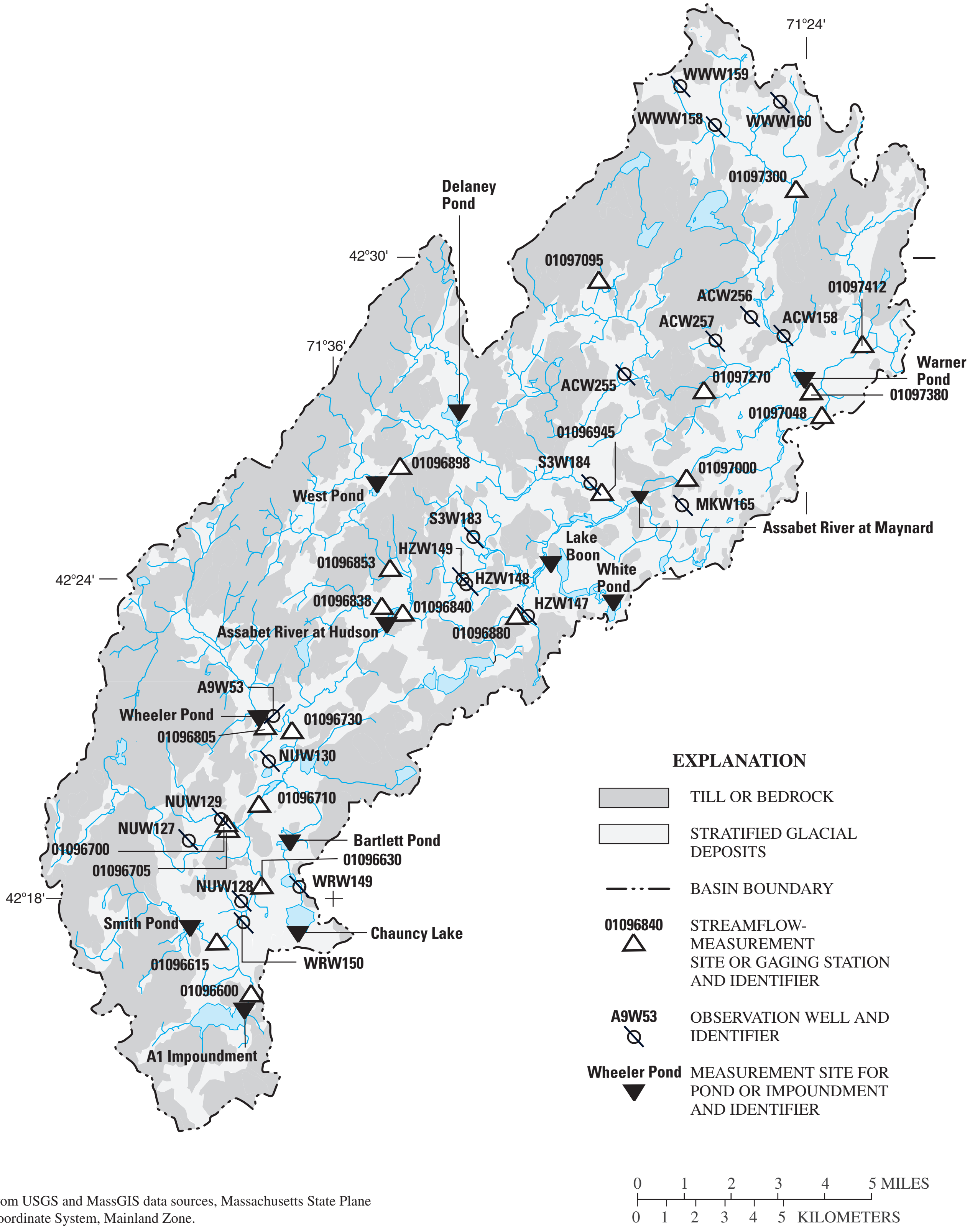


Figure 5. Monthly recharge rates estimated from *A*, streamflow records at the Assabet River streamflow-gaging station in Maynard; *B*, streamflow records at the Nashoba Brook streamflow-gaging station; and *C*, climate data from Bedford and West Medway weather stations, for long-term average conditions (period of record of data sources) and 1997–2001, Massachusetts.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 6. Streamflow-measurement sites, observation wells, and pond-measurement sites in the Assabet River Basin, eastern Massachusetts.

Table 3. Characteristics and water levels at observation wells and ponds in the Assabet River Basin, eastern Massachusetts.

[Site locations shown in figure 6. Wells are screened at bottom, with screened interval equal to 5 feet, unless otherwise indicated. **Latitude and longitude:** In degrees, minutes, and seconds. NGVD, National Geodetic Vertical Datum; -- not applicable or not known; ±, plus or minus]

Well identifier or pond name	Town	Latitude ° ′ ″	Longitude ° ′ ″	Well depth (feet below land surface)	Mean depth to water (feet below land surface)	Mean water-level elevation (feet above NGVD 29)		
						Water year 2000	Estimated, 1997–2001	
							Water level	90-percent confidence limits
				Observation wells				
A9W53	Berlin	42 21 27	071 37 25	20.3	12.84	227.84	230.09	±0.62
ACW255	Acton	42 27 51	071 28 33	47.7	23.85	195.72	196.19	±.24
ACW256	Acton	42 28 55	071 25 22	21.1	7.74	150.33	150.88	±.29
ACW257	Acton	42 28 29	071 26 16	19.8	11.46	157.84	159.78	±.76
HZW147	Hudson	42 23 20	071 31 00	27.6	19.75	181.89	182.57	±.22
HZW148	Hudson	42 23 56	071 32 33	18.0	10.72	200.43	201.48	±.28
HZW149	Hudson	42 24 01	071 32 38	19.5	12.08	191.37	192.18	±.30
MKW165	Maynard	42 25 24	071 27 06	18.7	7.31	194.53	195.55	±.36
NUW127	Northborough	42 19 07	071 39 32	21.7	6.78	296.96	298.44	±.43
NUW128	Northborough	42 17 59	071 38 13	52.6	23.82	272.60	273.40	±.23
NUW129	Northborough	42 19 32	071 38 44	17.5	8.19	285.37	285.97	±.34
NUW130[1]	Northborough	42 20 36	071 37 31	19.6	12.44	225.56	227.15	±.65
S3W183	Stow	42 24 49	071 32 23	30.5	12.22	193.29	194.01	±.26
S3W184	Stow	42 25 49	071 29 25	32.4	13.53	188.42	189.05	±.19
WRW149	Westborough	42 18 16	071 36 45	11.4	5.01	275.92	276.50	±.21
WRW150	Westborough	42 17 36	071 38 10	34.0	16.24	276.01	277.28	±.38
WWW158	Westford	43 32 31	071 26 16	16.4	11.62	188.22	189.74	±.57
WWW159	Westford	42 33 14	071 27 09	25.4	11.56	203.69	204.93	±.27
WWW160	Westford	42 32 57	071 24 37	25.5	13.90	207.08	207.80	±.05
				Ponds or impoundments				
A1 Impoundment[2]	Westborough	42 16 01	071 38 08	--	--	309.54	--	--
Assabet River[3]	Hudson	42 23 11	071 34 34	--	--	206.42	206.68	±.05
Assabet River	Maynard	42 25 29	071 28 10	--	--	176.12	176.45	±.12
Bartlett Pond[2]	Northborough	42 19 14	071 36 55	--	--	273.04	273.22	±.18
Chauncy Lake[2]	Westborough	42 17 26	071 36 47	--	--	280.44	280.81	±.18
Delaney Pond[4]	Stow	42 27 04	071 32 39	--	--	229.45	229.75	±.15
Lake Boon	Stow	42 24 21	071 31 23	--	--	186.60	--	--
Smith Pond[4]	Northborough	42 17 31	071 39 28	--	--	288.79	289.41	±.40
Warner Pond	Concord	42 27 32	071 23 51	--	--	120.29	--	--
West Pond[4]	Bolton	42 25 49	071 34 48	--	--	311.79	312.20	±.08
Wheeler Pond[4]	Berlin	42 21 27	071 37 47	--	--	224.25	224.88	±.31
White Pond	Stow	42 23 38	071 28 50	--	--	189.22	190.25	±.19

[1] Screened interval equal to 9.7 feet. Mean depth to water and mean water-level elevation for water year 2002 are averages of interpolated daily values.

[2] No data for June 2002.

[3] No data for April 2002.

[4] Missing data for winter 2002 because of ice.

Average water levels for 1997–2001 at observation wells in the basin were estimated by relating the measured monthly values to water levels at nearby long-term observation wells. Water levels at study sites initially were compared using scatterplots with same-day water levels at 17 long-term wells (table 4; only wells used are listed). Same-day water levels at long-term wells were interpolated between measured values, if necessary, by using the EXPAND procedure of SAS (SAS Institute, 1993). For each study site, one to six long-term wells were identified that correlated closely (R^2 values of linear regressions greater than 0.8) with the site. Relations between water levels at each study site and each long-term well were developed by using the Maintenance of Variance Extension, Type 1 (MOVE.1) method (Hirsch, 1982). The MOVE.1 equations were used to generate multiple estimates of mean annual and monthly water level during 1997–2001 for each study site, as described in DeSimone and others (2002); the associated mean square error of each relation (MSE) was used to combine the multiple estimates from each site into weighted average estimates of mean annual and monthly water level for 1997–2001 (table 3). The MSE also was used to calculate 90-percent confidence intervals for the estimates, as described in DeSimone and others (2002). Estimated annual average water levels for 1997–2001 at observation wells were about from 0.5 to 1.5 ft higher than the measured values for water year 2000 (table 3). Estimated average monthly water levels for 1997–2001 peaked earlier and higher than measured water levels, which is consistent with the trends shown at the long-term continuous-record monitoring well ACW 158 (fig. 7).

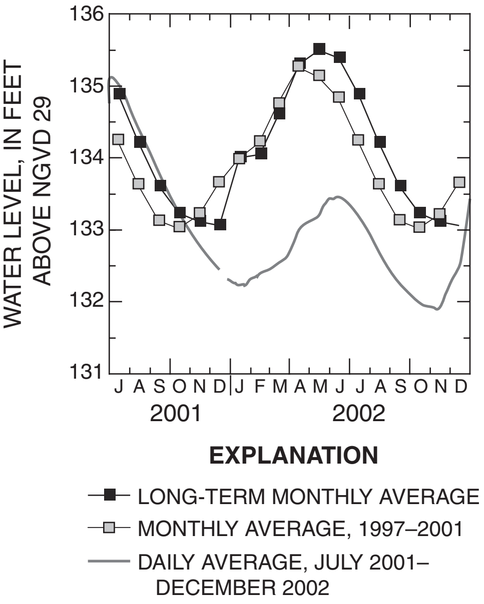


Figure 7. Monthly and daily average water levels at long-term observation well ACW158, Assabet River Basin, eastern Massachusetts.

Table 4. Characteristics and water levels at long-term observation wells near the Assabet River Basin, eastern Massachusetts.

[**Town:** See Socolow and others (2003) for additional location information. **Well-screen interval:** Wells screened in stratified glacial deposits, unless otherwise indicated. NGVD, National Geodetic Vertical Datum]

Well identifier	Town	Period of record	Well-screen interval (feet below land surface)	Mean depth to water (feet below land surface)	Mean water-level elevation (feet above NGVD 29)		
					Period of record	1997–2001	Water year 2002
ACW158	Acton	1965–present	32–34	18.94	134.06	134.24	132.73
CTW165	Concord	1965–present	65–67	41.52	157.74	158.48	155.40
CTW167	Concord	1965–present	22–25	7.38	127.62	127.21	124.82
DVW10	Dover	1965–present	52–54	33.37	126.63	126.59	126.54
FXW3	Foxborough	1965–present	30–32	19.12	270.88	271.02	270.03
HLW23	Haverhill	1960–present	[1]15	12.15	92.80	92.97	91.71
LTW104	Lexington	1965–present	19–21	53.37	177.40	177.73	177.81
NNW27	Norfolk	1965–present	16–18	6.10	153.90	154.41	153.28
NXW54	Northbridge	1984–present	10–12	4.23	365.77	365.37	365.40
SSW12[2]	Southborough	1990–present	18–20	6.95	443.05	442.63	440.18
SYW1[2]	Sterling	1947–present	[1]15	5.46	704.54	704.51	702.21
XMW78	Wilmington	1951–present	[1]12	7.94	87.06	86.91	86.16
WKW2	Wayland	1965–present	31–33	16.25	141.50	141.53	140.69

[1] Open-end well, cased to depth listed.

[2] Well screened in glacial till.

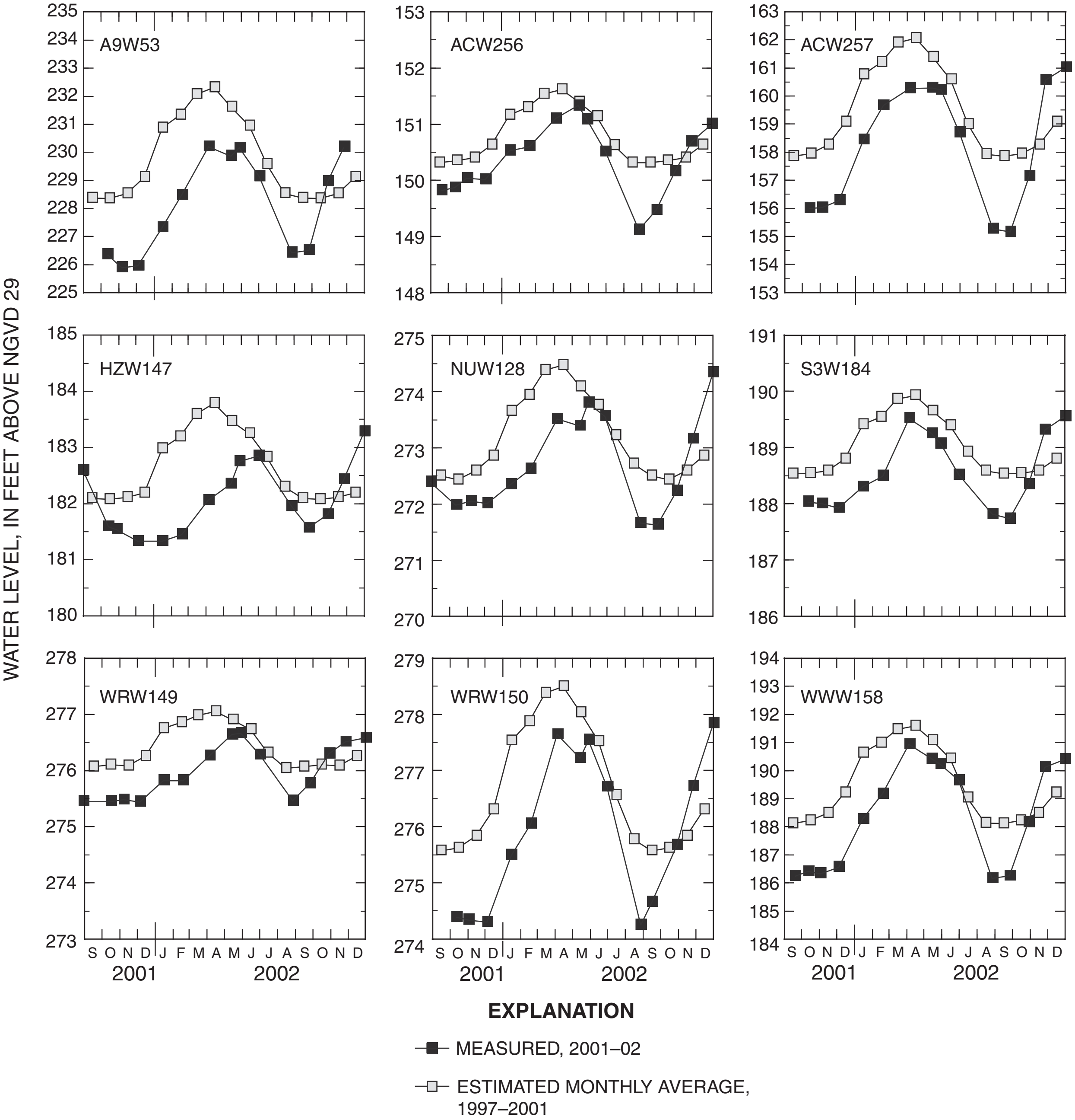


Figure 8. Measured water levels, September 2001 through December 2002, and estimated average monthly water levels, 1997–2001, at selected observation wells in the Assabet River Basin, eastern Massachusetts.

Surface Water

The Assabet River originates at a large flood-control dam and impoundment at its headwaters in Westborough (the A1 Impoundment), and is impounded by six other mill dams before joining the Sudbury River in Concord (fig. 1). Some of the impoundments, such as that upstream of the Ben Smith Dam in Maynard, extend for several miles. The total elevation change along the length of the river is about 200 ft and occurs mostly at the dams and near the headwaters of the river. Most major tributaries in the basin flow from northwest to southeast and include Hop, Cold Harbor, Howard, Stirrup, North, Danforth, Elizabeth, Fort Pond, and Nashoba Brooks (fig. 1). Flood-control or mill dams also are common along the major tributaries, creating reservoirs, lakes, or wetlands and in some cases affecting main stem flow. Examples include Millham Reservoir, Fort Meadow Reservoir, Lake Boon, Delaney Pond and surrounding wetlands, and the wetlands along Cold Harbor and Hop Brooks (fig. 1). Wetlands along small perennial and intermittent streams also are common throughout the basin.

Streamflow

Average flow in the Assabet River at the continuous streamflow-gaging station in Maynard (0109700), with a drainage area of about two-thirds of the basin (116 mi^2), is 188 ft^3/s (table 5). Average streamflow out of the basin is an estimated 287 ft^3/s (185 Mgal/d), as determined by the drainage-area ratio method and flow at the Maynard station. Average flow at the continuous streamflow-gaging station on Nashoba Brook (01097300), a major tributary to the Assabet River, is 20.2 ft^3/s (table 5). In addition to measurements at the two continuous streamflow-gaging stations in the basin, streamflow was measured at 6 partial-record sites on the main stem Assabet River and at 13 tributary sites at monthly intervals from May or June 2001 through December 2002 (fig. 6 and table 6; see Socolow and others, 2003, for measurement data). Streamflow measurements were made after several days of dry weather; therefore, they represented nonstorm streamflow. Nonstorm streamflow in tributaries is defined here as base flow minus any surface-water withdrawals; in the main stem Assabet River, it is base flow minus withdrawals plus wastewater discharges. Nonstorm streamflow excludes direct stream (stormwater) runoff, which occurs immediately after a precipitation event. Like water levels, streamflows in the basin during the measurement period were lower than average, as indicated by flows at streamflow-gaging stations in and near the basin (fig. 9 and table 5).

For streamflow-gaging stations in the basin, mean annual and monthly nonstorm streamflow for 1997–2001 was calculated directly from streamflow records by using the automated hydrograph-separation method, PART (Rutledge, 1993). For partial-record study sites, mean annual and monthly streamflow and nonstorm streamflow for 1997–2001 (Appendix 1) were estimated by using the MOVE.1 methods described previously for water levels. The MOVE.1 analysis was done on logarithms of flow, in the way that the method commonly is applied to streamflow (Bent, 1995, 1999; Ries and Friesz, 2000). Instantaneous streamflow at measurement sites was correlated with same-day mean daily streamflow at up to eight nearby long-term streamflow-gaging stations (table 5). Long-term stations were on largely unregulated streams and represent ranges of drainage areas and percentages of stratified glacial deposits in drainage areas that were similar to the study sites. Nonstorm streamflow, or base flow at long-term stations, was estimated by using PART. The comparison between streamflows at largely unregulated, long-term stations and at study sites assumes that flow components of nonstorm streamflow other than base flow at the study sites are of negligible quantity, or at least have insignificant effects on the temporal variation of flows. For main stem Assabet River sites where wastewater is a large and variable component of nonstorm streamflow, this assumption may introduce error, especially during low-flow months.

Mean annual flows for 1997–2001 at streamflow-gaging stations were similar to long-term average flows, and much higher than (about twice) flows in water year 2002 (table 5). Estimated mean annual nonstorm streamflow was about 70 to 80 percent of total flow at all stations except for the Old Swamp River station (01105600, 60 percent of total flow), which drains a small basin with extensive wetlands. Nonstorm streamflow at the Assabet River station (01097000), which would be expected to include most of the wastewater discharged to the river in the basin, was about 80 percent of total flow, one of the highest percentages of total flow.

Table 5. Drainage-area characteristics and mean annual flows at streamflow-gaging stations in and near the Assabet River Basin, eastern Massachusetts.

[**Period of record:** Extends from date shown to present. **Estimated nonstorm streamflow:** Estimated by using the automated hydrograph-separation method, PART (Rutledge, 1993). See Socolow and others (2003) for site locations. mi^2, square miles; ft^3/s, cubic foot per second; --, not determined]

Station number	Station name	Period of record	Drainage-area characteristics		Streamflow (ft^3/s)			Estimated nonstorm streamflow (ft^3/s)		
			Area (mi^2)	Area of stratified glacial deposits (percent)	Period of record	1997–2001	Water year 2002	Period of record	1997–2001	Water year 2002
01096000	Squannacook River near West Groton, MA	1950	63.7	27	112	108	53.3	82.6	80.6	41.4
01097000	Assabet River at Maynard, MA	1942	114.3	39	189	188	88.1	153	155	69.0
01097300	Nashoba Brook near Acton, MA	1964	12.2	61	20.2	16.9	10.6	15.6	13.0	8.5
01105730	Indian Head River at Hanover, MA	1967	30.3	71	62.6	65.3	39.1	45.3	46.5	30.1
01105600	Old Swamp River near South Weymouth, MA	1967	4.5	34	9.1	8.6	4.6	5.5	5.1	2.8
01109000	Wading River near Norton, MA	1926	43.3	59	73.1	76.2	37.0	61.1	63.3	30.7
01111300	Nipmuc River near Harrisville, RI	1965	15.9	28	30.4	28.4	13.2	22.0	20.9	10.5
01175670	Sevenmile River near Spencer, MA	1961	8.8	13	14.8	13.2	7.7	12.0	10.7	6.1

Wastewater in the Assabet River at Maynard station, which averaged 9.6 Mgal/d (14.9 ft^3/s) in 1997–2001, was about 8 percent of total flow annually. Some wastewater that discharges to the river during large storms from increased infiltration to sewers may be partitioned to the storm streamflow component of flow by PART. This component of flow would be difficult to quantify but probably was a small percentage of the total wastewater discharge. The effect of wastewater discharge on flows in the Assabet River is indicated by a significant upward trend with time in mean monthly nonstorm streamflow during the low-flow period. A Kendall rank correlation of monthly flow and year for the Assabet River showed significant relations for July, August, September, and October (*p*-values equal to 0.054, 0.034, 0.029, and 0.001, respectively). This trend was not apparent at other streamflow-gaging stations. Estimated mean monthly flows for 1997–2001 at partial-record sites (fig. 10), like the streamflow-gaging-station data and ground-water levels, were considerably higher than instantaneous measurements in the fall of 2001 and summer of 2002. Estimated mean monthly flows for 1997–2001 at partial-record sites peak sooner and higher than measurements in the spring of 2002, with the exception that high-flow measurements in early March 2002 were affected by heavy precipitation on March 1.

Nonstorm streamflows, calculated with PART or other hydrograph-separation methods for a basin, are estimates that incorporate simplifying assumptions about flow in the basin. Total flow is partitioned into storm and nonstorm components by applying an algorithm that is based on a simple model of streamflow recession that may not apply equally well to all seasons or various local conditions. The methods also may not be able to distinguish accurately between ground-water discharge and the slow drainage of water stored in impoundments or wetlands following a short-term or seasonal streamflow peak. Because of these and other considerations (DeSimone and others, 2002), streamflow components from PART and similar methods are considered to be more accurate for larger time intervals, such as years, than for shorter time intervals, such as months (Rutledge, 1993), and are always only estimates.

Table 6. Drainage-area characteristics and mean annual flows at streamflow-measurement sites in the Assabet River Basin, eastern Massachusetts.

[**Mean nonstorm streamflow, water year 2000:** Mean of 12 instantaneous monthly measurements for main stem sites and of 9–12 measurements for tributary sites. Site locations shown in figure 6. ft^3/s, cubic foot per second; mi^2, square mile; %, percent; --, not determined]

Station number	Station name	Drainage-area characteristics		Mean nonstorm streamflow, water year 2000 (ft^3/s)	Estimated mean annual flow, 1997–2001 (ft^3/s)					
					Streamflow			Nonstorm streamflow		
						90% confidence limits			90% confidence limits	
		Area (mi^2)	Area of sand and gravel (percent)		Flow	Lower	Upper	Flow	Lower	Upper
	Assabet River Main Stem									
01096600	Assabet River at Fisher Street near Westborough	6.7	24	3.4	--	--	--	--	--	--
01096630	Assabet River at School Street near Northborough	18.3	35	16.1	28.8	22.5	36.9	23.4	18.3	30.0
01096710	Assabet River at Allen Street at Northborough	29.5	34	26.6	49.0	35.0	68.7	41.7	29.8	58.5
01096730	Assabet River at Solomon Pond Mall near Marlborough	39.5	37	40.4	61.3	41.8	90.0	52.5	35.8	77.0
01096840	Assabet River at Route 85 at Hudson	63.9	35	51.5	96.4	79.4	117	81.5	67.1	98.9
01097000	Assabet River at Maynard (streamflow-gaging station)	116.0	39	[1]68.9	[2]188	--	--	[1]155	--	--
01097048	Assabet River at Pine Street at West Concord	119.3	41	101	205	174	240	169	144	199
	Tributaries to Assabet River									
01096615	Hop Brook at Indian Meadows near Northborough	7.7	25	7.4	14.8	10.8	20.2	11.1	8.1	15.1
01096700	Howard Brook at Northborough	2.7	29	2.1	4.1	2.3	7.4	2.9	1.6	5.2
01096705	Cold Harbor Brook at Northborough	6.8	28	5.8	12.2	7.3	20.6	8.6	5.1	14.4
01096805	North Brook near Berlin	15.5	22	15.1	18.0	12.0	26.8	13.4	9.0	20.0
01096838	Hog Brook below Tripp Pond at Hudson	3.0	31	1.5	4.0	3.0	5.3	3.0	2.3	4.0
01096853	Danforth Brook at Route 85 at Hudson	5.1	28	3.9	7.2	4.6	11.2	4.8	3.1	7.5
01096880	Fort Meadow Brook near Hudson	5.2	27	3.7	7.1	3.0	17.0	6.0	2.5	14.4
01096898	Great Brook at Route 117 near Bolton	4.5	27	2.9	6.9	4.4	10.8	4.7	3.0	7.4
01096945	Elizabeth Brook off White Pond Road near Stow	18.7	35	18.2	26.3	18.8	37.0	19.7	14.0	27.7
01097095	Unnamed Tributary Fort Pond Brook, Sargent Road near West Acton	2.2	0	1.5	4.1	2.3	7.2	2.3	1.3	4.0
01097270	Fort Pond Brook at River Road near South Acton	20.8	29	15.5	34.4	20.8	57.0	23.6	14.3	39.1
01097300	Nashoba Brook near Acton (streamflow-gaging station)	12.7	58	[1]8.5	[2]16.9	--	--	[1]13.0	--	--
01097380	Nashoba Brook at Commonwealth Avenue at West Concord	48.0	40	34.4	72.2	45.8	114	51.9	32.9	81.9
01097412	Spencer Brook at Barretts Mill Road near Concord	7.1	30	6.1	8.8	5.2	14.9	6.1	3.6	10.3

[1] Mean of monthly mean values, estimated from mean daily streamflow at streamflow-gaging station by using the automated hydrograph-separation method, PART (Rutledge, 1993, 1998).

[2] Mean of mean daily values at streamflow-gaging station.

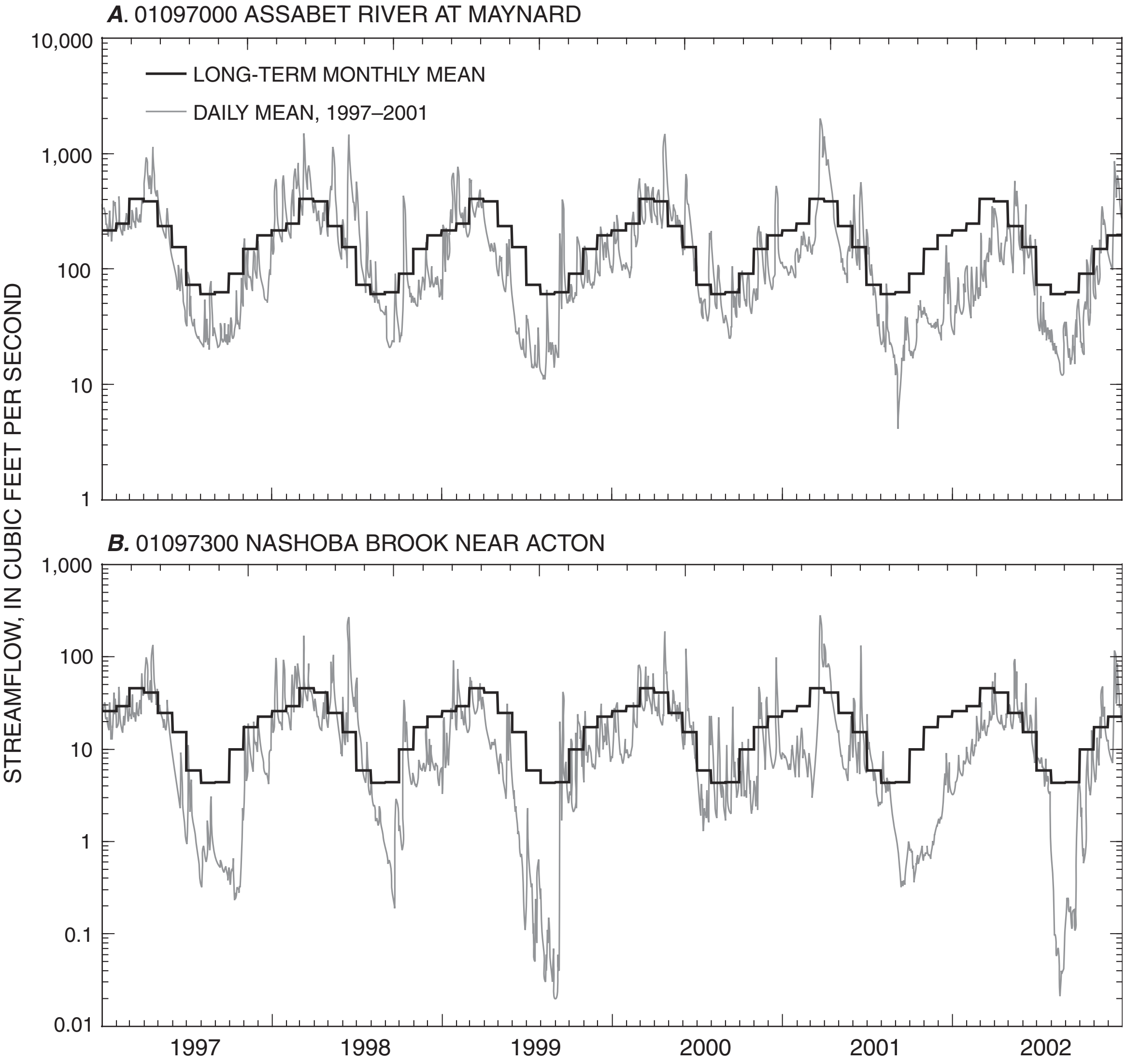


Figure 9. Monthly mean streamflow for long-term average conditions and daily mean streamflow, 1997–2001: *A*, Assabet River streamflow-gaging station at Maynard; *B*, Nashoba Brook streamflow-gaging station near Acton, Massachusetts.

Ponds and Wetlands

Ponds in the Assabet River Basin include instream ponds and impoundments, typically formed by mill or flood-control dams, and kettle lakes, depressions in the stratified glacial deposits that intersect the water table. Many kettle lakes also have surface-water inflows and outflows. Water levels were measured at about monthly intervals in 12 ponds and impoundments (fig. 6 and table 3). Water levels changed little in the river impoundments or ponds upstream of dams (instream ponds), such as Bartlett Pond and Lake Boon (fig. 11). In kettle lakes, such as Chauncy Lake and White Pond, water-level fluctuations were similar to those of ground water, although they were affected by ice conditions. Average annual water levels for 1997–2001 were estimated for ponds and impoundments by using the MOVE.1 methods (table 3), but these estimates may not be meaningful for ponds and impoundments where water levels are controlled predominantly by dams and outflow structures.

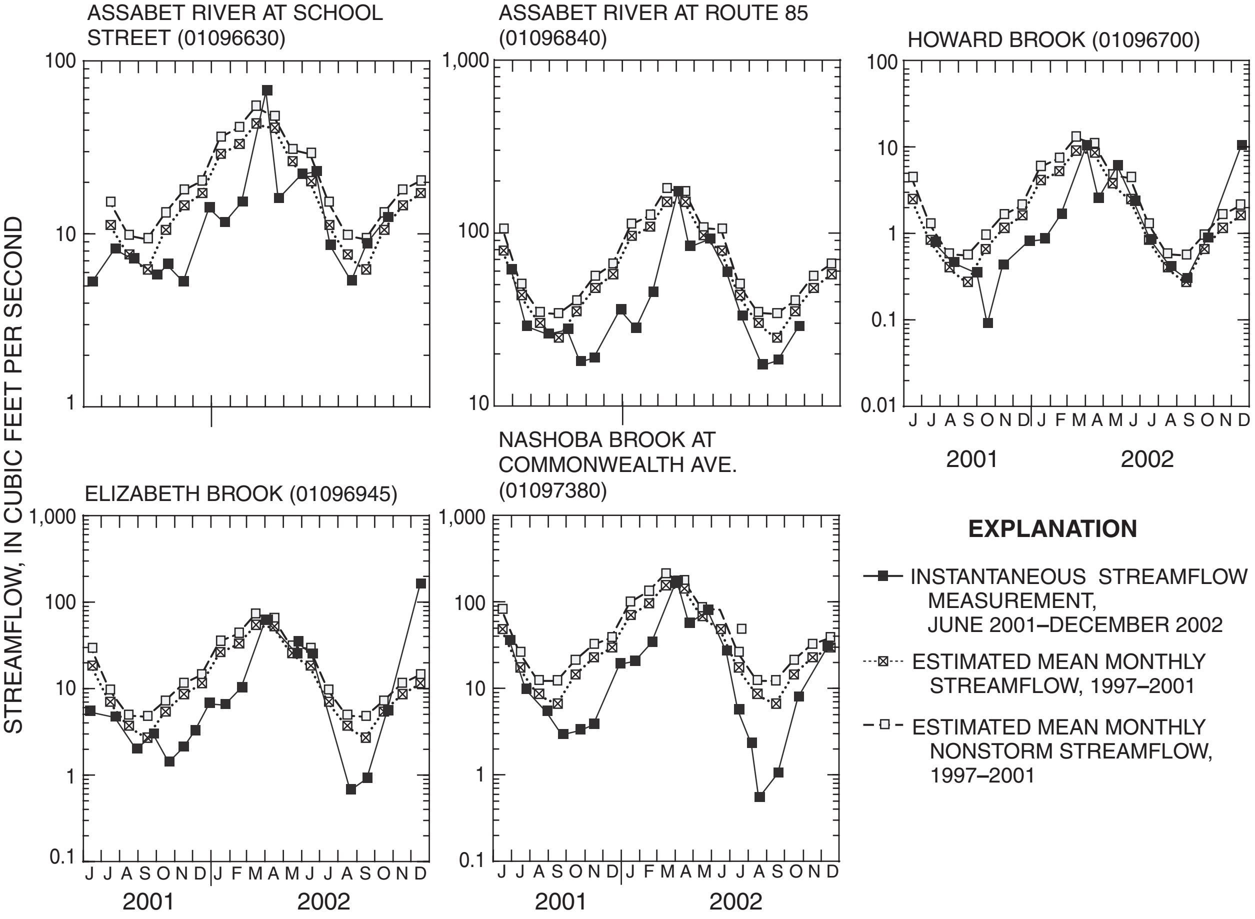


Figure 10. Instantaneous streamflow measurements, June 2001 through December 2002, and estimated mean monthly streamflow and nonstorm streamflow at selected flow-measurement sites in the Assabet River Basin, eastern Massachusetts.

Wetlands are common in the basin, covering 3 percent of the basin area in 1999. Wetlands include areas mapped as bogs, marshes, shrub swamps, and forested wetlands (fig. 1; MassGIS, 2001; 1:5,000 scale). Wetlands potentially have important but variable, and largely unknown, functions in surface- and ground-water-flow systems at the regional scale (Carter and Novitzki, 1988; Mitsch and Gosselink, 1993; Hunt and others, 1996; Cole and Brooks, 2000). Their interaction with surface and ground water varies with location in the landscape, connection with other surface waters, and subsurface soil and hydrogeologic conditions. Wetlands commonly are considered to store surface runoff and reduce flood peaks. Wetlands may receive ground-water inflow and drain to surface water; they may be isolated from the ground-water system; or when water levels in the wetland are above the surrounding water table, such as in a perched system, they may be sources of recharge to ground water. Evapotranspiration in riparian wetlands also may reduce streamflow in the summer (Motts and O’Brien, 1981). Wetlands in the Assabet River Basin, the majority of which are forested, are along all major tributaries and along the main stem river (fig. 1). Wetland areas that appear isolated in figure 1 are likely connected to the surface-water-flow system by small streams that in most cases that not apparent in the smaller scale (1:25,000) stream data. Because of their position low in the landscape and flow system, most wetlands in the basin probably are predominantly in areas of ground-water discharge (Motts and O’Brien, 1981).

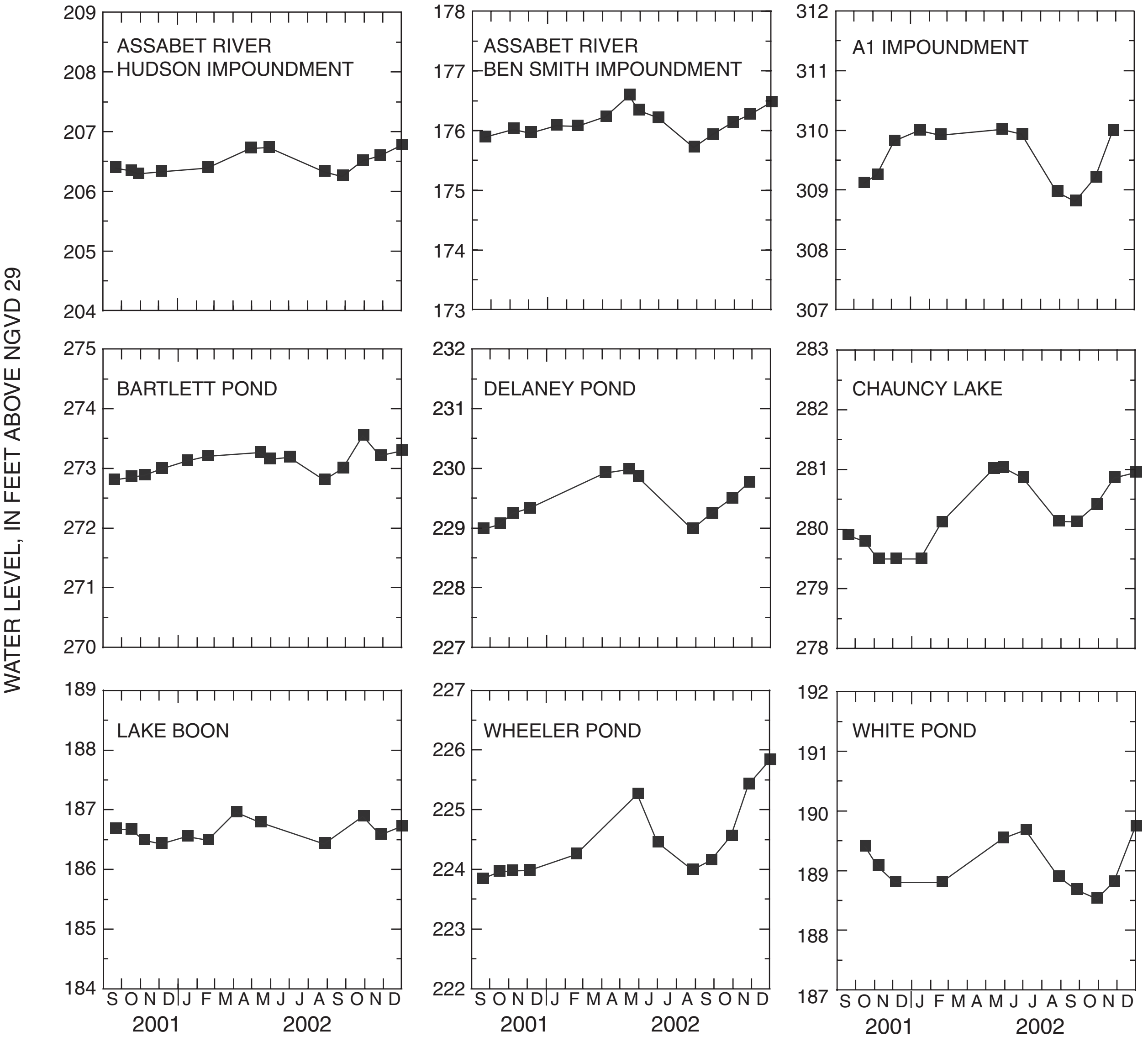


Figure 11. Measured water levels, September 2001 through December 2002, at selected ponds and impoundments in the Assabet River Basin, eastern Massachusetts.

Water Use and Management

Information on water use and management was collected to quantify inflows and outflows of water from the ground- and surface-water-flow systems in the basin. Water withdrawals for public supply, agricultural, and other uses are outflows from the aquifers and streams. After use, most of the water that is withdrawn for these purposes is returned to ground or surface water as wastewater. Water imported for public supply from sources outside of the basin represents an inflow when it is discharged to ground or surface water after use. Some water is used consumptively; this water is a net outflow in areas of private water supply and waste disposal. In publicly supplied areas, consumptive use is not a separate outflow from ground- or surface-water-flow systems, but is included in the imbalance between water withdrawals and wastewater return flows. Finally, infiltration of ground water into sewers is an outflow from the ground-water-flow system. When this water is discharged to streams as part of the treated wastewater from a municipal facility, it becomes an inflow to surface water. Inflows and outflows to the ground- and surface-water-flow systems from water use and management are shown schematically in figure 12. Overall, water use and management in the Assabet River Basin result in a net import of water, primarily as wastewater, and a net transfer of water from ground-water to surface-water-flow systems.

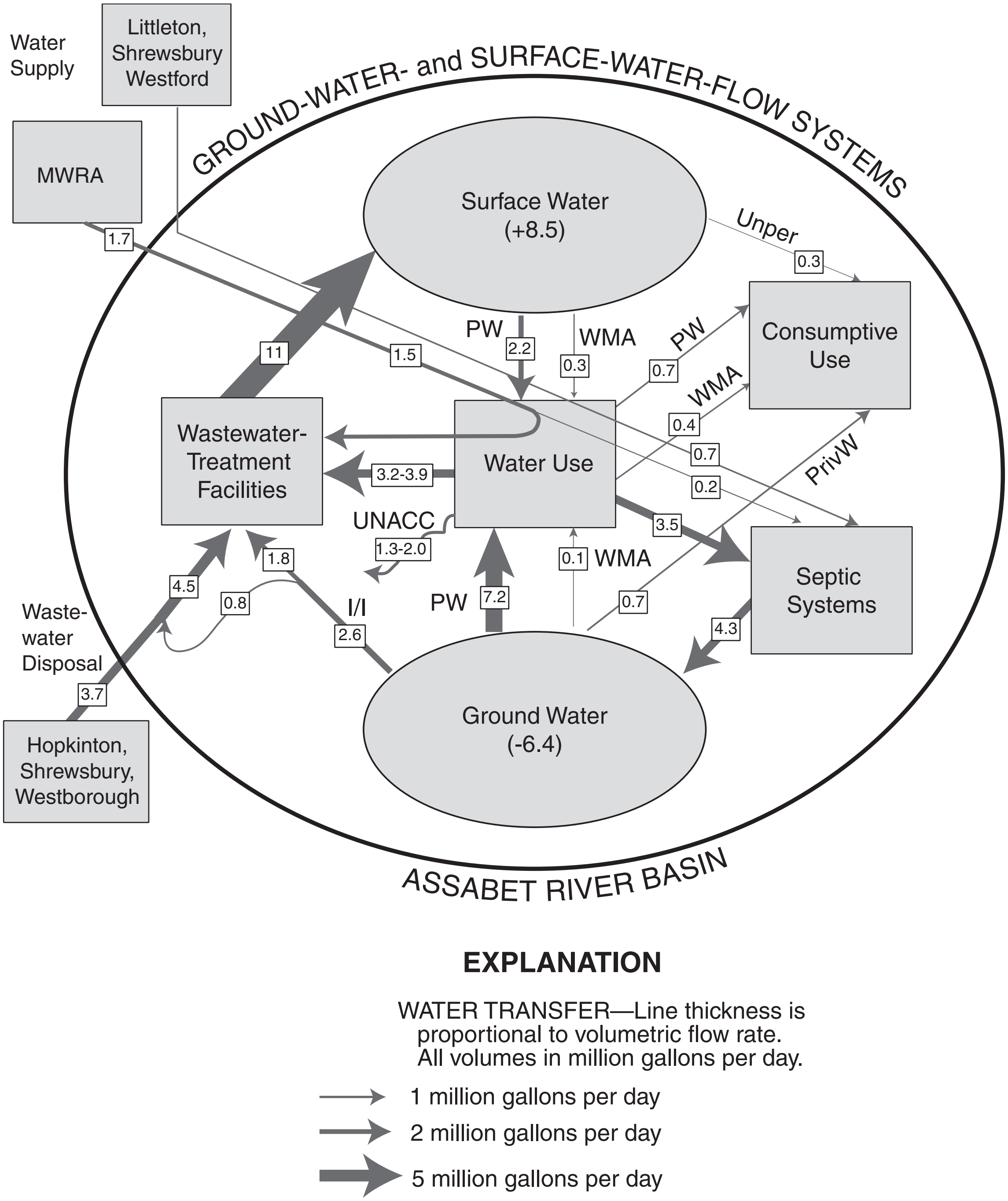


Figure 12. Water use and return flows in the Assabet River Basin in eastern Massachusetts. Water withdrawals and discharges are average annual rates for 1997–2001; consumptive-use, septic-system return flow, and unaccounted-for water are annual averages for 2000. I/I, infiltration to sewers; MWRA, Massachusetts Water Resources Authority; PrivW, private-water consumptive use; PW, public-water withdrawal or consumptive use; UNACC, unaccounted-for water; Unper, unpermitted agricultural and golf-course consumptive use; WMA, nonmunicipal permitted withdrawal or consumptive use. Positive (+) and negative (-) values are net gains and losses, respectively, from surface water and ground water.

Water Supply and Consumptive Use

Public-water systems (municipal or publicly owned systems) supply most water users in 12 of the 20 towns in the Assabet River Basin (table 7), serving about 80 percent of the basin population and about half of its area (fig. 13). Most publicly supplied water is obtained from within the basin, primarily from wells but also from several reservoirs (table 8 and fig. 14). Several towns that are only partly within the basin have water sources in the adjacent Blackstone, Concord, Nashua, or Sudbury River Basins as well as in the Assabet River Basin (table 9). The Massachusetts Water Resources Authority (MWRA) also supplies water to Marlborough, Northborough, and Clinton from sources in central Massachusetts.

Public-supply withdrawals from sources in the basin averaged 9.4 Mgal/d in 1997–2001 (table 8). Most (77 percent) public-supply withdrawals were from ground water (fig. 12), and ground-water withdrawals for public supply were nearly all (98 percent) from stratified glacial deposits. During the study period, total withdrawals by public-water systems in most towns in the basin were at or near their current permitted limits under the Massachusetts Water Management Act (WMA; table 9). Withdrawals were greatest in May, June, and July (fig. 15). Withdrawals likely were greater in these months because of outdoor water use, which is partly or wholly consumptive. This seasonal pattern also is apparent in per capita water-use rates in early summer, which average 30 percent greater than rates in November through March.

Imported water for public-supply use from MWRA for Marlborough and Northborough averaged about 1.7 Mgal/d in 1997–2001 (fig. 12). Water imported from MWRA for the small area of Clinton in the basin is not considered in this study, because it is disposed of outside of the Assabet River Basin. The estimate for Marlborough includes an apportionment, based on town area in and out of the basin, of the total amount of MWRA water supplied to Marlborough. The estimate for Marlborough may be higher than is typical because nearly all of Northborough's water was supplied by MWRA in 2001, which was a temporary arrangement. Most of the MWRA imported water is delivered to wastewater-treatment facilities after use (fig. 12). Little information is available on volumes of water imported (or exported) from sources in adjacent basins through the public-supply water-distribution systems of the individual towns (table 9). However, the volumes of imported or exported water are likely to be small, except in Shrewsbury, a densely populated town in which all water used in the basin in 1997–2001 originated in the adjacent Blackstone River Basin.

In the eight towns in the basin without public-water systems (table 7), private water companies or domestic wells supply water to residential, industrial, and other users. Nonmunicipal drinking-water sources are entirely from ground water, and include wells in bedrock and stratified glacial deposits. Data on locations and withdrawal rates for these sources are limited; however, comparison of public-water and sewer systems (fig. 13) indicates that areas without public water are not sewered. Consequently, water withdrawn through private water systems and wells is returned to the aquifers through on-site disposal, except for water that is used consumptively.

Consumptive use by publicly and privately supplied users was estimated from an analysis of seasonal water use in 11 publicly supplied towns (all publicly supplied towns except Clinton, for which no water-use data were collected; table 7) and land-use data. For this study, consumptive use is defined as the component of a water-supply withdrawal that is removed permanently from the ground- or surface-water system, through evaporation or other processes. Consumptive use was assumed to result from irrigation or other water use during the high-use months of spring, summer, and fall. Consumptive use (volumetric rates) in each month from April through October for each town was calculated as the difference between withdrawals in the month and the mean withdrawal rate in the low-use winter months of November through March. Months were identified as low- or high-use months based on the seasonal patterns of public-supply withdrawals in 1997–2001 (fig. 15). Areal rates were calculated by applying volumetric rates for each town to the developed land uses in publicly supplied areas in the towns, which were identified as areas of residential, commercial, industrial, and urban public land use within the extent of public-water systems. Monthly areal rates of consumptive water use ranged from 0.4 in/yr in April to 2.59 in/yr in July; the mean annual rate was 0.92 in/yr. These rates were applied to developed land-use areas in privately supplied towns to estimate a mean annual consumptive use for privately supplied parts of the basin of 0.72 Mgal/d. This volume is a net outflow from the ground-water system in privately supplied, developed areas (fig. 16). Consumptive use in publicly supplied parts of the basin was estimated similarly at 0.71 Mgal/d.

This volume is not a separate outflow from the ground- or surface-water systems in publicly supplied areas, as mentioned previously, because it is included in the difference between public-water withdrawals and municipal wastewater discharges. This approach to estimating consumptive use does not take into account any differences in population density or land use between publicly and privately supplied areas; therefore, consumptive use in privately supplied areas (which are likely to be less densely populated) may be over- or underestimated. This approach also does not quantify variation in rates of consumptive use among land uses.

Withdrawals by several large industrial, agricultural, and golf-course users averaged 0.43 Mgal/d in 1997–2001 (table 8). These consist of withdrawals greater than 100,000 gal/d that are permitted under the WMA. The nonmunicipal WMA withdrawals are mostly from surface-water sources, including the Assabet River, tributary streams, and ponds; wells in stratified glacial deposits and bedrock also are used (fig. 12). Seasonally, these withdrawals peak in mid- to late summer, because of increased irrigation by agricultural and golf-course users. Industrial uses usually are constant throughout the year.

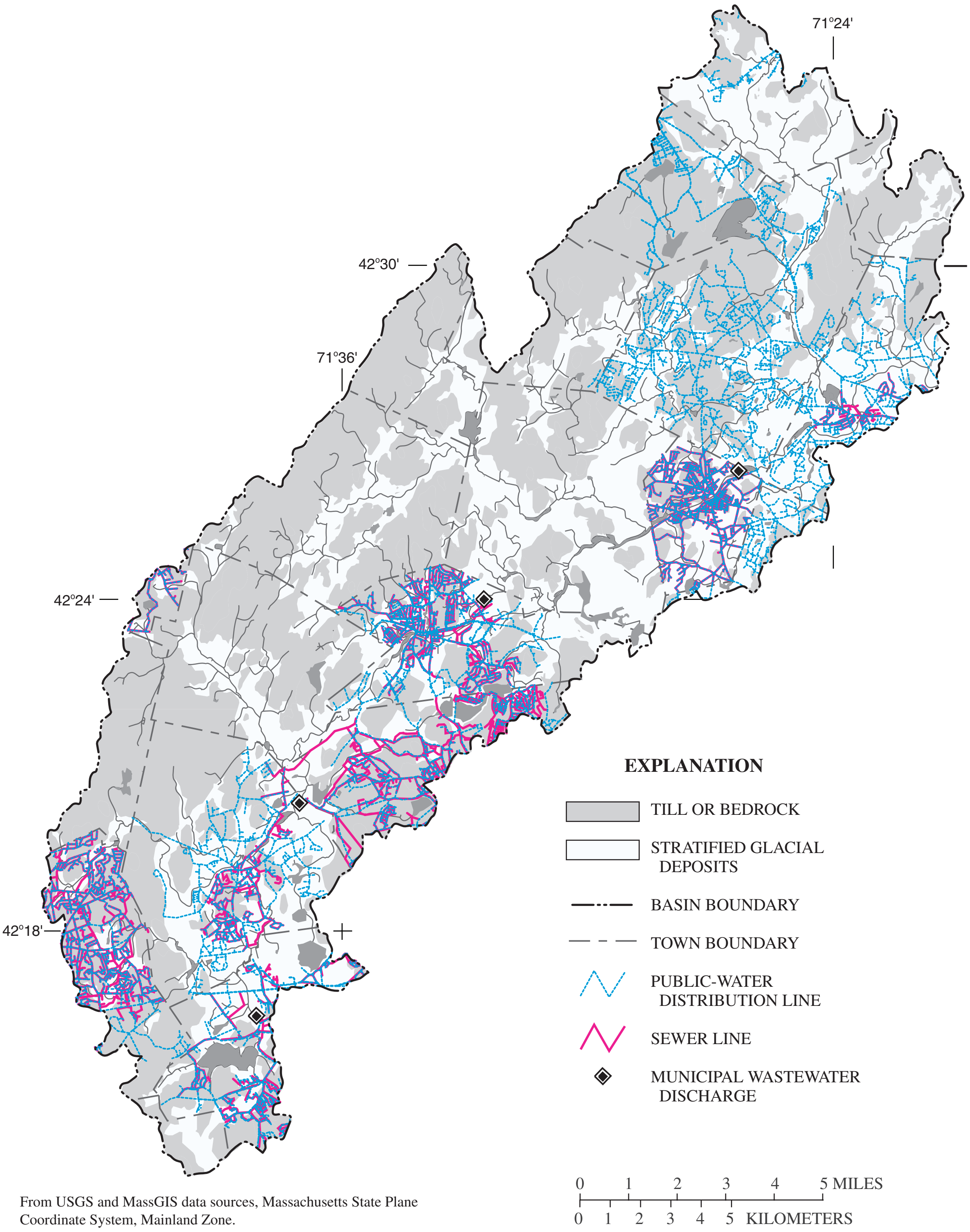
Table 7. Population on public water and sewer and per capita water use in the Assabet River Basin, eastern Massachusetts, 2000.

[**Total population:** From U.S. Census Bureau, 2003. **Population on public water and sewer:** From U.S. Census Bureau, 2003, and town water departments. **Estimated residential water use:** From 2000 public water-supply statistical reports from towns to the Massachusetts Department of Environmental Protection. **Estimated per capita use in summer:** Average use in May, June, and July. **Estimated per capita use in winter:** Average use from December through March. gal/person/d, gallons per person per day; Mgal/d, million gallons per day; --, not determined]

Town	Proportion of town in basin (percent)	Total population	Population on public water and sewer (percent)		Estimated public-supply residential water use (Mgal/d)	Estimated per capita use (gal/person/d)		
			Water	Sewer		Annual	Summer	Winter
Acton	100	20,331	94	0	1.39	73	82	68
Berlin	100	2,380	0	0	0	--	--	--
Bolton	72	4,148	0	0	0	--	--	--
Boxborough	66	4,868	0	0	0	--	--	--
Boylston	24	4,008	[1]0	0	0	--	--	--
Carlisle	29	4,717	0	0	0	--	--	--
Clinton	15	13,435	100	100	0	--	--	--
Concord	36	15,537	95	38	1.20	82	98	68
Grafton	7	14,894	[1]0	[1]0	0	--	--	--
Harvard	22	5,981	[1]0	0	0	--	--	--
Hudson	94	18,113	94	82	1.21	71	80	66
Littleton	42	8,184	80	0	[2].48	73	80	58
Marlborough	43	36,255	99	92	2.29	64	73	57
Maynard	100	10,433	100	95	.57	55	56	53
Northborough	94	14,013	85	20	.67	56	66	50
Shrewsbury	37	31,640	97	85	2.51	82	97	74
Stow	100	5,902	0	0	0	--	--	--
Sudbury	9	16,841	[1]100	0	1.19	71	110	76
Westborough	41	17,997	95	85	1.22	71	68	58
Westford	24	20,754	75	0	1.35	87	94	47
Average	--	--	--	--	--	73	82	61

[1] Value applies to area of town in basin.

[2] Includes use reported as semiresidential.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 13. Public-water and sewer systems in the Assabet River Basin, eastern Massachusetts.

Table 8. Permitted water-supply withdrawals and wastewater discharges in the Assabet River Basin, eastern Massachusetts.

[**Identifier:** See figure 14 for locations. **Source type:** GWSG, ground water, stratfied glacial deposits; GWB, ground water, bedrock; SW, surface water. **Subbasin:** MS, Main stem; Head, Headwaters. **Maximum permitted withdrawal rate:** Data from B.R. Bouck, Massachusetts Department of Environmental Protection, written commun., 2003; rates for industrial, agricultural, and golf-course sources are mean annual rates. No., number; Mgal/d, million gallons per day; --, not applicable or not known]

Identifier	Source name	Subbasin	Source type	Well depth (feet)	Mean annual withdrawal or discharge rate, 1997–2001 (Mgal/d)	Maximum permitted withdrawal rate (Mgal/d)
Public-Supply Withdrawals						
AN-01G	Acton Whitcomb Well	Fort Pond Brook	GWSG	35	0.12	0.35
AN-02G	Acton Conant Well	Nashoba Brook	GWSG	34	.14	.47
AN-03G	Acton Lawsbrook Well	Fort Pond Brook	GWSG	53	.16	.15
AN-04G	Acton Christofferson Well	Fort Pond Brook	GWSG	40	.19	.40
AN-05G	Acton Assabet Well No. 1	Assabet MS Lower	GWSG	68	.30	.50
AN-06G	Acton Assabet Well No. 2	Assabet MS Lower	GWSG	59	.36	.50
AN-07G	Acton Clapp Well	Fort Pond Brook	GWSG	36	.07	.35
AN-08G	Acton Scribner Well	Fort Pond Brook	GWSG	29	.10	.15
AN-09G	Acton Marshall Well	Nashoba Brook	GWSG	31	.03	.30
AN-10G	Acton Kennedy Wells No. 1–4	Nashoba Brook	GWSG	35	.37	.54
AN-11G	Acton Conant II Wells No. 1–5	Nashoba Brook	GWSG	28	.09	.43
CN-01S	Concord Nagog Pond	Nashoba Brook	SW	--	.30	--
CN-01G	Concord Second Division Well	Assabet MS Lower	GWSG	80	.58	.85
HD-01S	Hudson Gates Pond Reservoir	Assabet MS Middle	SW	--	.16	--
HD-01G	Hudson Rimkus Well	Assabet MS Middle	GWSG	60	.00	--
HD-02G	Hudson Kane Well	Fort Meadow Brook	GWSG	64	.16	.50
HD-03G	Hudson Chestnut Street Well No. 1	Fort Meadow Brook	GWSG	48	.61	.75
HD-04G	Hudson Chestnut Street Well No. 2	Fort Meadow Brook	GWSG	56	.69	1.01
HD-05G	Hudson Chestnut Street Well No. 3	Assabet MS Middle	GWSG	47	.43	1.01
ML-01S	Marlborough Millham Reservoir	Assabet MS Middle	SW	--	1.55	--
ML-02S	Marlborough Lake Williams Reservoir	Assabet MS Middle	SW	--	[1]--	--
MN-01S	Maynard White Pond	Assabet MS Middle	SW	--	.23	--
MN-01G	Maynard Old Marlborough Road Well Nos. 1 and 2	Taylor Brook	GWSG	46,49	.30	.58
MN-02G	Maynard Old Marlborough Road Well No. 3	Taylor Brook	GWSG	44	.14	.29
MN-03G	Maynard Great Road Well No. 4	Taylor Brook	GWSG	73	.12	.38
MN-04G	Maynard Rockland Avenue Wells Nos. 2, 3, and 5	Fort Pond Brook	GWB	355–470	.16	1.13
NB-01G	Northborough Brigham Street Well	Assabet MS Upper	GWSG	60	.34	.45
NB-02G	Northborough Lyman Street Well	Stirrup Brook	GWSG	57	.00	--
NB-03G	Northborough Crawford Street Well	Cold Harbor and Howard Brooks	GWSG	52	.32	.44
NB-04G	Northborough Howard Street Well	Cold Harbor and Howard Brooks	GWSG	41	.13	.29

Table 8. Permitted water-supply withdrawals and wastewater discharges in the Assabet River Basin, eastern Massachusetts.—Continued

[**Identifier:** See figure 14 for locations. **Source type:** GWSG, ground water, stratfied glacial deposits; GWB, ground water, bedrock; SW, surface water. **Subbasin:** MS, Main stem; Head, Headwaters. **Maximum permitted withdrawal rate:** Data from B.R. Bouck, Massachusetts Department of Environmental Protection, written commun., 2003; rates for industrial, agricultural, and golf-course sources are mean annual rates. No., number; Mgal/d, million gallons per day;

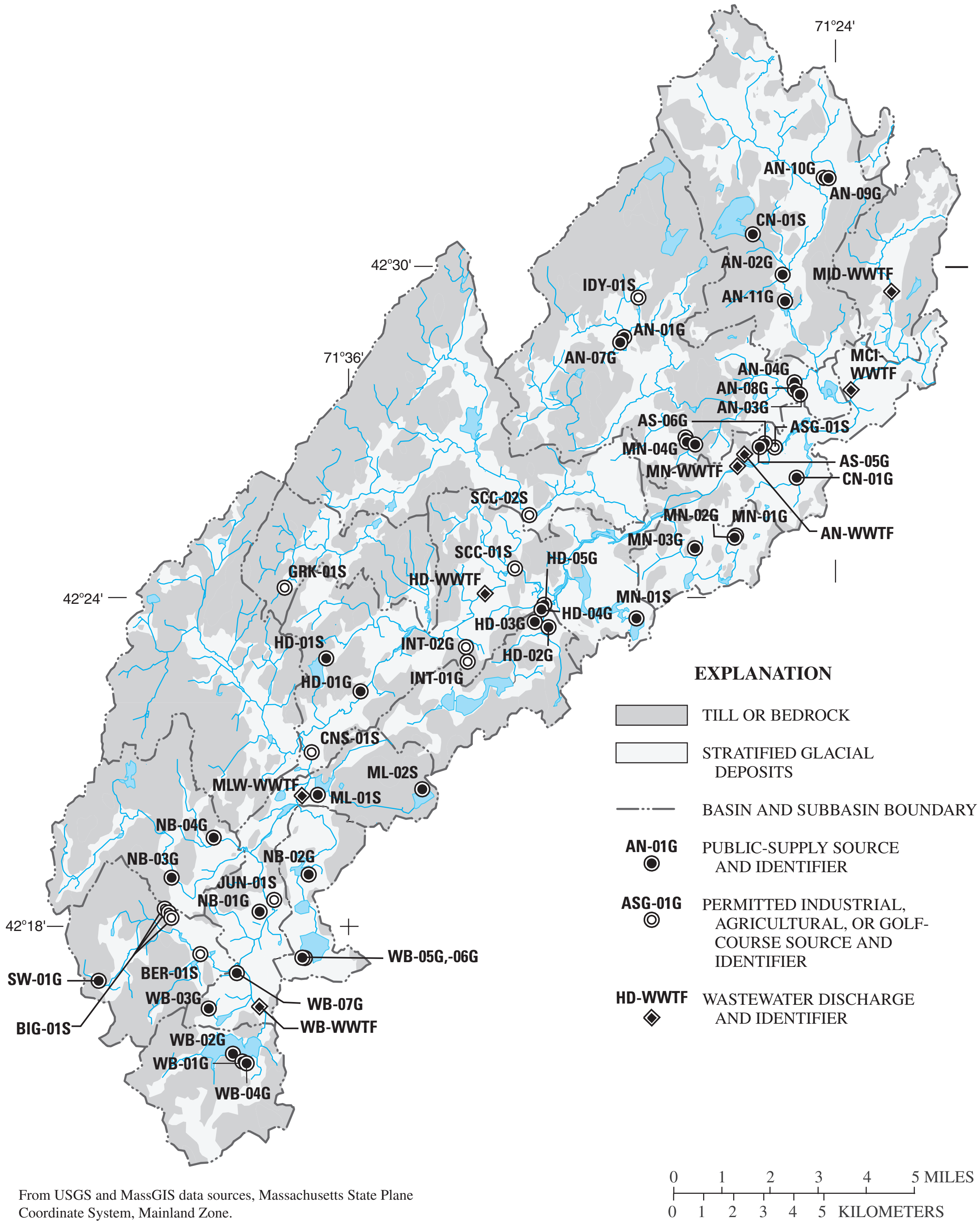
Identifier	Source name	Subbasin	Source type	Well depth (feet)	Mean annual withdrawal or discharge rate, 1997–2001 (Mgal/d)	Maximum permitted withdrawal rate (Mgal/d)
Public-Supply Withdrawals—Continued						
SW-01G	Shrewsbury South Street Well No. 1	Hop Brook	GWSG	38	0.00	0.20
WB-01G	Westborough Andrews Well No. 1	Assabet MS Head	GWSG	60	.28	.66
WB-02G	Westborough Andrews Well No. 2	Assabet MS Head	GWSG	34	.27	.35
WB-03G	Westborough Otis Street Well	Assabet MS Upper	GWSG	46	.29	.84
WB-04G	Westborough Wilkinson Well	Assabet MS Head	GWSB	53	.12	.36
WB-05G	Westborough Chauncy Lake Well No. 1	Stirrup Brook	GWSG	32	.01	.60
WB-06G	Westborough Chauncy Lake Well No. 2	Stirrup Brook	GWSG	36	.26	.79
WB-07G	Westborough Indian Meadows Well	Assabet MS Upper	GWSG	42	.00	1.13
Industrial, Agricultural, and Golf-Course Withdrawals						
ASG-01S	Assabet Sand and Gravel	Assabet MS Lower	SW	--	0.14	0.14
BER-01S	Berberian Farms	Hop Brook	SW	--	.02	.03
BIG-01S[2]	Bigelow Nurseries	Hop Brook	GWSG, SW	--	.10	.10
CNS-01S	Concrete Services	Assabet MS Middle	SW	--	--	.34
GRK-01S	Great Oak Farm	Danforth Brook	SW	--	.01	.04
IDY-01S	Idylwilde Farms	Fort Pond Brook	SW	--	.01	.01
INT-01G	Intel Hudson Plant Well No. D-1	Assabet MS Middle	GWB	356	.01	[3].35
INT-02G	Intel Hudson Plant Well No. D-2	Assabet MS Middle	GWB	300	.00	[3].35
JUN-01S	Juniper Farms Country Club	Assabet MS Upper	SW	--	.06	.08
SCC-01S	Stow Country Club Assabet River	Assabet MS Middle	SW	--	.04	[4].08
SCC-02S	Stow Country Club Wheeler Pond	Elizabeth Brook	SW	--	.05	[4].08
Wastewater Discharges						
AN-WWTF	Acton Adams Street Facility	Assabet MS Lower	GW	--	0.00	0.25
HD-WWTF	Hudson Wastewater-Treatment Facility	Assabet MS Middle	SW	--	2.30	2.65
MCI-WWTF	MCI Concord	Assabet MS Lower	SW	--	.25	.25
MLW-WWTF	Marlborough Westerly Wastewater-Treatment Facility	Assabet MS Upper	SW	--	2.07	2.89
MN-WWTF	Maynard Wastewater-Treatment Facility	Assabet MS Lower	SW	--	1.09	1.45
MID-WWTF	Middlesex School	Spencer Brook	SW	--	.02	.05
WB-WWTF	Westborough Regional Wastewater-Treatment Facility	Assabet MS Upper	SW	--	5.27	7.68

[1] Withdrawals are pumped to ML-01S.

[2] Includes two wells and a reservoir.

[3] Maximum permitted withdrawal rate is combined rate for INT-01G and INT-02G.

[4] Maximum permitted withdrawal rate is combined rate for SCC-01S, SCC-02S, and two other sources that were unused in 1997–2001.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 14. Permitted water-supply withdrawals and wastewater discharges in the Assabet River Basin, eastern Massachusetts

Table 9. Existing (1997–2001) and permitted withdrawals for municipal public-water systems in the Assabet, Sudbury, and Concord River Basins, eastern Massachusetts.

[**Basin location of public-water sources:** A, Assabet; S, Sudbury, C, Concord. **Maximum permitted withdrawals:** From Duane LeVangie, Massachusetts Department of Environmental Protection, written commun., 2002; rates are system-average annual rates permitted under the Massachusetts Water Management Act for withdrawals in the Assabet, Concord, and Sudbury River Basins. Mgal/d, million gallons per day]

Town	Basin location of public-water sources	Total mean annual withdrawals for public supply (Mgal/d)	Maximum permitted withdrawals (Mgal/d)
Acton	A	1.93	1.94
Concord	A,S,C	2.33	2.91
Hudson	A,S	2.57	2.95
Marlborough	A	1.55	1.77
Maynard	A	.96	1.09
Northborough	A	.79	.79
Shrewsbury	A	.00	.26
Westborough	A,S	2.51	3.11

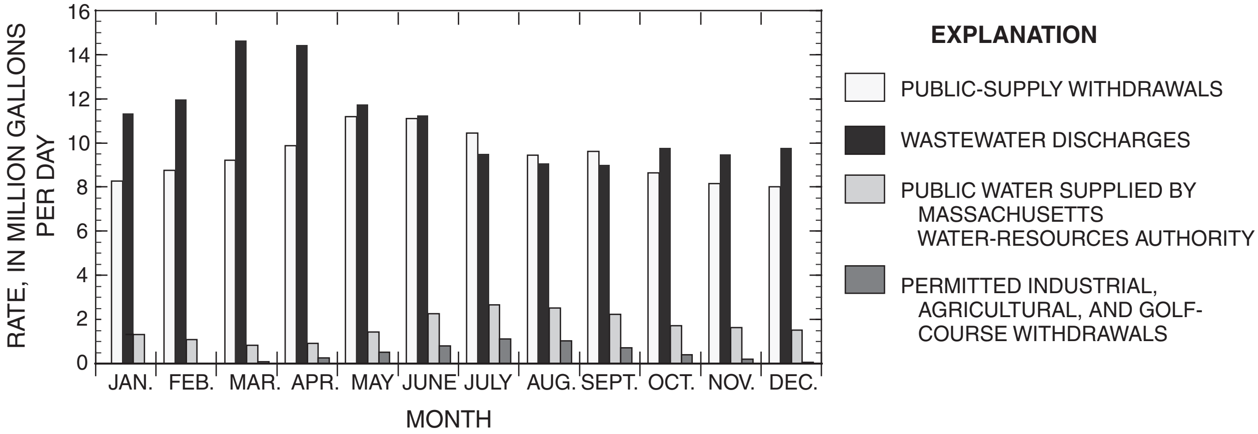
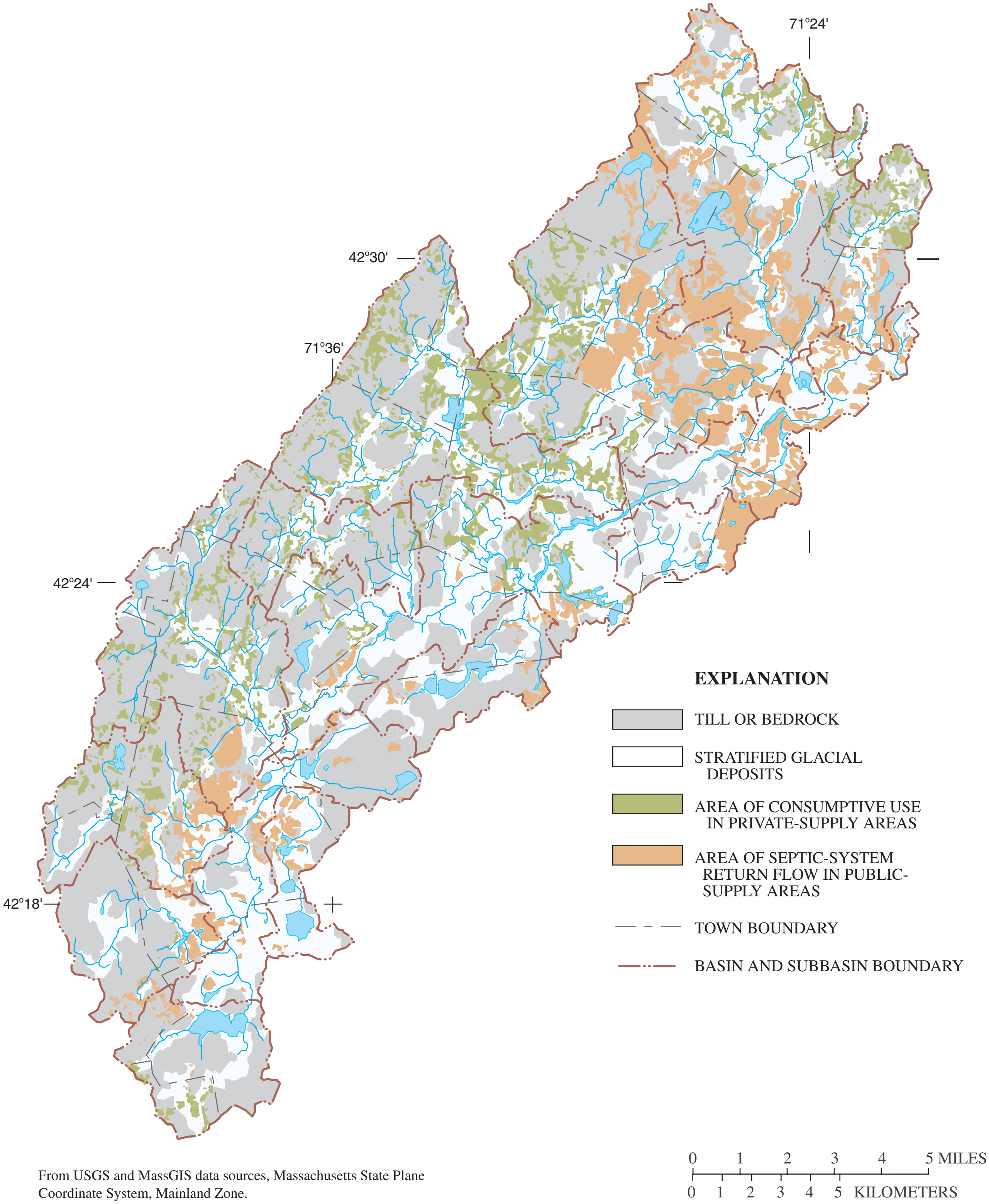


Figure 15. Monthly average permitted withdrawals, wastewater discharges, and imported water for public supply, 1997–2001, in the Assabet River Basin, eastern Massachusetts.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 16. Areas of private-water supply with consumptive water use and areas of public-water supply with septic-system return flow in the Assabet River Basin, eastern Massachusetts.

Withdrawals by small and large agricultural and golf-course users in the Assabet River Basin are generally considered to be entirely consumptive (Barbara Kickham, Massachusetts Department of Environmental Protection, written commun., 2003). Data on water withdrawals by the large, permitted agricultural users were used to estimate consumptive use by the small, unpermitted users in privately supplied areas. Small agricultural users were identified as areas mapped in 1999 land-use data as nurseries and cropland. Mean annual consumptive use for nursery (0.04 mi^2) and cropland (3.2 mi^2) areas in the basin were estimated at 0.02 and 0.24 Mgal/d, respectively. Consumptive use by unpermitted golf-course withdrawals was estimated from application rates listed in the MADEP golf course water-use policy (Massachusetts Department of Environmental Protection, 2000) and the irrigated area of four unpermitted golf courses in the basin (Barbara Kickham, Massachusetts Department of Environmental Protection, written commun., 2003). Water use for agriculture and golf courses is seasonal, with maximum use in summer. Monthly mean rates of cropland use were estimated at 0.96 Mgal/d in June, July, and August; rates for nurseries ranged from 0.02 Mgal/d in November to 0.07 Mgal/d in July; and unpermitted golf-course withdrawals ranged from 0.008 Mgal/d in April to 0.22 Mgal/d in June, July, and August. Mean annual consumptive use by unpermitted golf courses in the basin was estimated at 0.08 Mgal/d. The unpermitted withdrawals may be from either surface water or ground water, but are shown as surface-water withdrawals in figure 12.

Wastewater Discharge and Return Flow

Municipal water-treatment facilities in Westborough, Marlborough, Hudson, and Maynard discharge treated wastewater into the Assabet River (fig. 14). These facilities treat wastewater from about 50 percent of the basin population, in eight towns. Additionally, wastewater from the MCI Concord prison facility is discharged to the Assabet River, and wastewater from Middlesex School in Carlisle is discharged to Spencer Brook (table 8). Total wastewater discharges averaged 11.0 Mgal/d in 1997–2001. Discharges from the four municipal facilities included water withdrawn from sources in and out of the basin: wastewater from Shrewsbury that originated from sources in the Blackstone River Basin is treated and discharged at the Westborough facility, and wastewater that was imported from MWRA is discharged at the Marlborough facility. The Marlborough facility also treats and discharges wastewater from Northborough (about 15 percent of total flows), but this water originated at sources in the Assabet River Basin. Seasonally, wastewater discharges are greatest in February, March, and April (fig. 15). Soils are saturated and the water table is high, so that infiltration of ground water to sewers is greatest during these months.

Wastewater from unsewered areas is returned to the ground-water-flow system through on-site septic systems. Areas receiving septic-system return flow as a net inflow to the ground-water system were identified as areas of developed land use within public-water systems that were beyond the extent of existing sewer systems (fig. 13). The rates and spatial distribution of septic-system return flow from residential water use was estimated from per capita water use, land use, and population data. Population densities per residential land-use type (multi-family residential, and high-, medium-, and low-density residential) were estimated from multiple regression of total population by town and area of each land-use type. Population densities determined by the regression were adjusted so that total population for each town equalled census data for year 2000. Septic-system return flow rates for residential areas were calculated by using the adjusted population densities and an average rate of nonconsumptive per capita water use for publicly supplied towns, about 60 gal/person/d (winter water-use rate; table 7). Return flow rates from water use in commercial, industrial, and urban public land-use areas were calculated from data on the number of employees per town per Standard Industrial Classification (SIC) Code for 2000 (Massachusetts Division of Employment and Training, 2003) and typical values of water use per employee per SIC code (Horn, 2000). Total commercial, industrial, and urban public water use was estimated for each town, and then apportioned to the study area by using the percentage of town area in the basin. Septic-system return flow rates thus calculated for land-use categories averaged 1.2 in/yr for low-density residential, 4.8 in/yr for medium-density residential, 10 in/yr for high-density residential, 33 in/yr for multi-family residential, and 13 in/yr for commercial, industrial, and urban public land use; the rates were assumed to be constant throughout the year. Summed across the entire study area, septic-system return flow was 4.34 Mgal/d, about 20 percent of which originated from water-supply sources outside of the basin (fig. 12).

Finally, infiltration to sewers is an outflow from the ground-water-flow system that can be estimated with information from the Wastewater Management Plans of towns in the Assabet Consortium. Infiltration to sewers was reported, as fractions of total wastewater flows, at 27 percent for Hudson, 32 percent for Marlborough, 26 percent for Maynard, 37 percent for Northborough, and 17 percent for Westborough and Shrewsbury (Camp, Dresser and McKee, 2002; Dufresne-Henry, 2001; Earth Tech, 2001e, 2002d; Fay, Spoffard, & Thorndike, 2001a). Rates vary seasonally, with maximum rates of infiltration in the spring, when the water table is high. Typical values in spring were reported at 35 to 45 percent of total wastewater flows. Applying these rates to 1997–2001 flows, and estimating infiltration for small areas of sewers in the study area in Concord and Clinton, infiltration to sewers in the basin was about 2.6 Mgal/d (fig. 12), or about 25 percent of average annual discharges from the municipal wastewater-treatment facilities.

Simulation of Ground-Water Flow

Ground-water levels and flow in the Assabet River Basin were simulated with the three-dimensional, finite-difference ground-water-flow modeling code, MODFLOW-2000 (Harbaugh and others, 2000). Steady-state and transient models were developed. The models were used to simulate water levels and flows in till and bedrock uplands and in stratified glacial deposits, but data were available to calibrate the model only in the stratified glacial deposits. The models were used to simulate average flow conditions from 1997 to 2001.

Steady-State Numerical Model

The steady-state numerical model simulated average annual conditions in the basin. Development of separate steady-state and transient models simplified model development and allowed for a two-step calibration approach, in which model-calculated average annual water levels and nonstorm streamflows first were matched to observed values with the steady-state model. The steady-state model also was useful for calculating average annual water balances and for evaluating the effects of alternative model practices on average annual nonstorm streamflows.

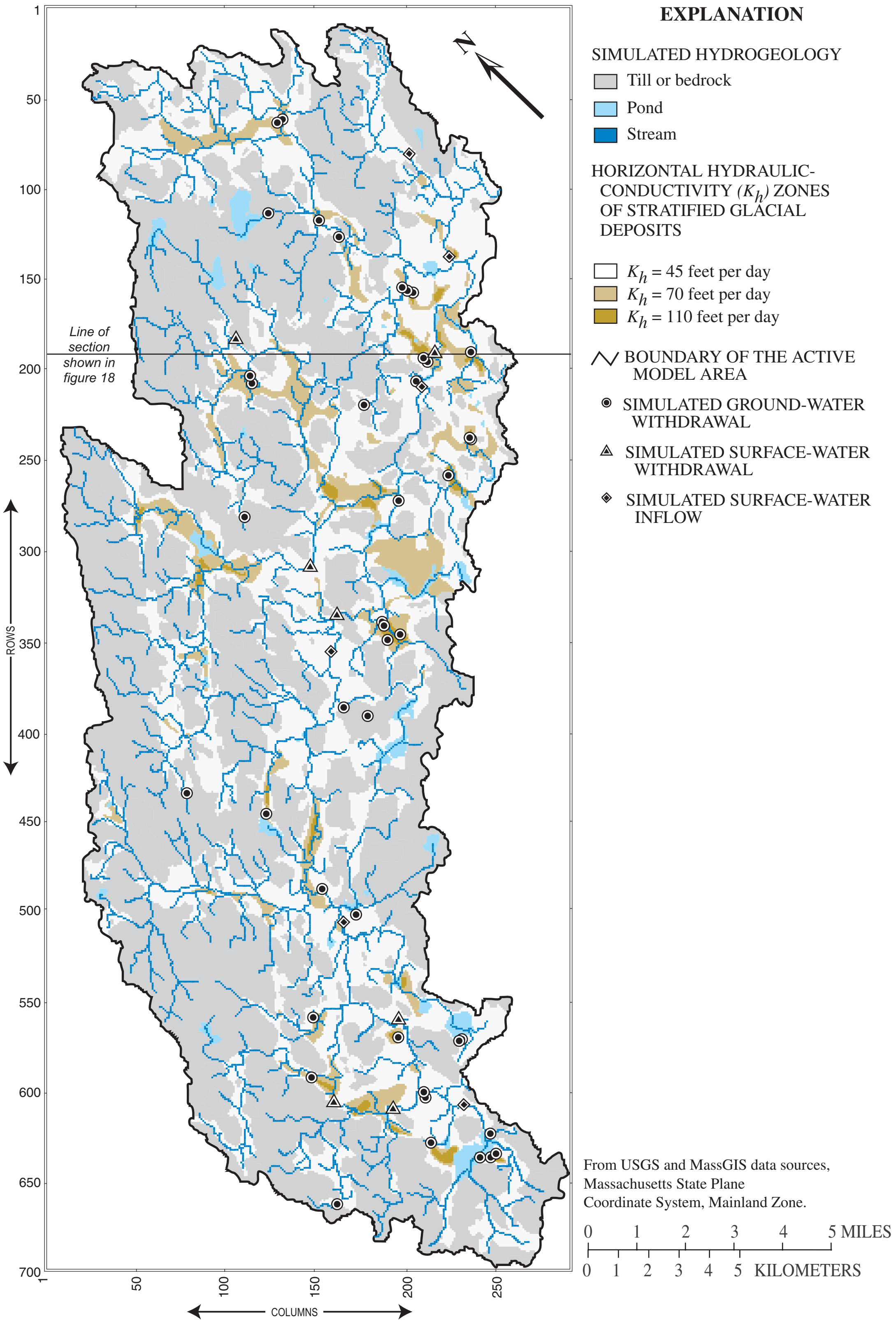
Spatial Discretization

The basin area was discretized into a grid of 700 rows and 290 columns of cells with uniform horizontal dimensions of 200 ft (fig. 17). The grid was rotated northeast at an angle of 45 degrees relative to north. Areas outside the basin boundary were inactive in the model. The vertical discretization consisted of two layers of variable thickness (fig. 18). The top of the upper layer (layer 1) was set equal to the land-surface elevation, which was interpolated from 30-meter digital-elevation-model data (Elassal and Caruso, 1983). The bottom of layer 1 was set equal to the top of the bedrock and till surface in the areas of stratified glacial deposits, except where stratified glacial deposits were less than 10 ft. In these areas, the bottom of layer 1 was set at 10 ft below land surface. In upland areas, the bottom of layer 1 was set uniformly at 12 ft below land surface, consistent with typical till thicknesses in the basin, as described previously. The bottom of the lower layer (layer 2) was set at a constant elevation of 200 ft below NGVD 29.

Boundary Conditions

The horizontal boundaries of the active model area were defined as a no-flow boundary that coincides with the boundary of the Assabet River Basin (fig. 17). In most areas, the basin boundary is in relatively low-permeability till and bedrock uplands. The use of the surface-water boundary to delineate a no-flow boundary was based on the assumption that ground- and surface-water divides coincide. This assumption was reasonable for the stratified glacial deposits and for shallow flow paths in the uplands and underlying bedrock, because of the rolling topography, distribution of permeable stratified glacial deposits in the lowlands, and close connection between surface and ground water in the basin. Where pumping wells are close to divides in stratified glacial deposits (for example, near Chauncy Lake in Westborough or near the confluence with the Sudbury River in Concord), surface- and ground-water divides may deviate locally. These deviations, however, are likely to be small. Fracture systems in bedrock also may result in flow across basin boundaries along deep flow paths; however, little data were available on these flow systems at a regional scale for use in the model simulation.

Both model layers were simulated by using a fixed-transmissivity approach. For layer 2, this approach is equivalent to simulating a confined aquifer and conforms to a conceptual model of flow in bedrock where the water table is in the surficial layer. Simulating layer 1, which represents the till and stratified glacial deposits, with the fixed-transmissivity approach also is reasonable in areas of thick stratified glacial deposits, where changes in saturated thickness from the seasonally fluctuating water table are small relative to total saturated thickness. In till areas and areas of thin stratified glacial deposits, water-table fluctuations may represent significant fractions of the total saturated thickness. In these areas, transmissivity may be underestimated during periods of high water levels and overestimated during periods of low water levels with this approach. The fixed-transmissivity approach was necessary, however, because numerical instabilities resulting from the fluctuating water table in the steeply sloping, thinly saturated stratified glacial deposits near the upland boundaries prevented model convergence when a variable transmissivity was simulated.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 17. Model area, grid, hydraulic-conductivity zones, and simulated ponds, streams, water withdrawals, and surface-water inflows for ground-water-flow models of the Assabet River Basin, eastern Massachusetts.

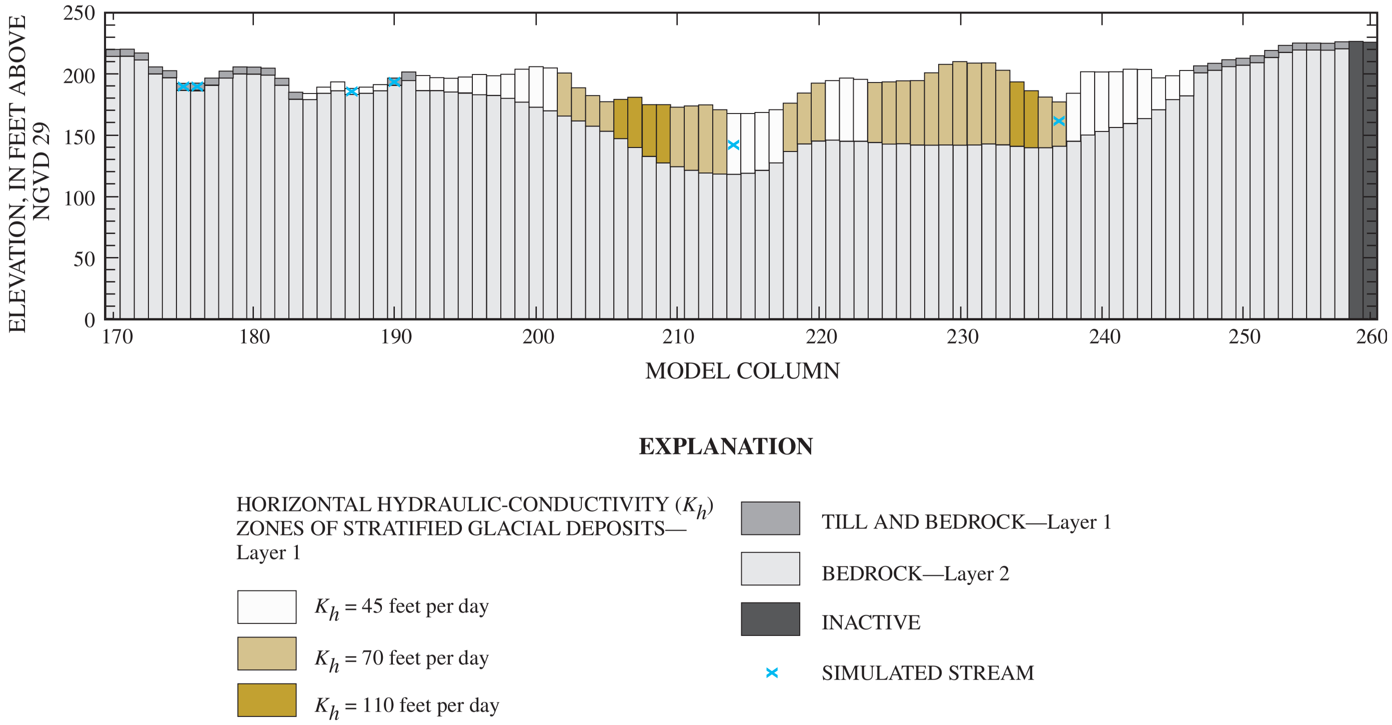


Figure 18. Vertical discretization for ground-water-flow models of the Assabet River Basin, eastern Massachusetts. Part of model row 191 is shown. Section line is shown in figure 17.

Streams were simulated as head-dependent flow boundaries with a version of the Stream Package (Prudic, 1989) that is compatible with MODFLOW-2000. This package simulates hydraulic interaction between the aquifer and adjoining streams and routes water between adjacent simulated stream reaches. Water may flow either into or out of the simulated aquifer. Flow, or leakage, is calculated by multiplying the specified streambed conductance by the difference between the stream stage and the water level in the underlying aquifer. Simulated streams may go dry when stream leakage to the aquifer exceeds inflows from upstream reaches.

Simulated streams included perennial and intermittent streams delineated in the available 1:25,000 scale hydrographic data (MassGIS, 2001). Nearly all streams in the data were simulated, including mapped stream channels in wetlands. Streams reaches (10,460 model cells) were grouped into 692 stream segments. This dense stream network (fig. 17) was simulated because of the strong control that streams, acting as ground-water discharge areas, exert on ground-water levels and flow directions in the basin. Stream-stage elevations were determined by using geographic information system (GIS) software to interpolate between 3-meter topographic contours (MassGIS, 2001) along simulated streams. Interpolated stream-stage elevations at dams were adjusted manually using information from topographic maps, surveyed river profiles for flood-insurance studies (U.S. Department of Housing and Urban Development, 1978, 1979a–f, 1981, 1982a–c, 1988a–c, 1999), dam-safety inspection reports, and as-built plans for flood-control structures (William Saloma, Massachusetts Department of Conservation and Recreation, written commun., 2002). Streambed elevations ranged from 1 to 4 ft below stream stage, depending on the size of the stream as represented by the Strahler stream order (Gordon and others, 1992).

Stresses

Recharge and Evapotranspiration

A number of processes and water fluxes were simulated with the MODFLOW-2000 recharge matrix. These processes included aquifer recharge from precipitation, evapotranspiration of ground water in wetlands, septic-system return flow, consumptive use in privately supplied areas, consumptive use by unpermitted agriculture, and infiltration of ground water to sewers. The Recharge package was used to apply all recharge fluxes to the active model area as specified fluxes to the upper model layer. The Evapotranspiration Package of MODFLOW-2000 also was used to simulate water flux.

Precipitation recharge rates were specified separately for stratified glacial deposits, till and bedrock upland areas, and kettle ponds. Precipitation recharge rates for stratified glacial deposits and upland areas were determined from literature sources, analysis of streamflow records, and a water-balance analysis of climate data, as described previously, and were adjusted during model calibration within a range of reasonable values. Final recharge rates for the calibrated model were 28.2 in/yr for stratified glacial deposits, 22.5 in/yr for till and bedrock uplands, and 1.8 in/yr for kettle ponds. The recharge rate for kettle ponds equaled the difference between mean monthly precipitation and PET, where PET was determined by an estimate of the Penman method, as described previously, averaged over the annual cycle.

Wetlands and ponds drained by streams (fig. 1) were simulated as areas of no recharge or net loss from the ground-water-flow system. These features were treated as areas of ground-water discharge, where, on average, water levels were equal to or less than the surrounding water table (Carter and Novitzki, 1988). Soils that are saturated during most of the year and low-permeability sediments likely result in no net recharge of water to aquifers from precipitation in most wetlands in the basin, under natural conditions. Precipitation onto saturated wetlands and ponds drained by streams becomes direct stream runoff and does not result in ground-water recharge or constitute a component of the base flow that is simulated by the ground-water-flow models. Therefore, ground water discharging to wetlands and instream ponds was subject to evapotranspiration and (or) ran off as streamflow. This conceptual model of the role of wetlands in the hydrologic system is consistent with several studies of wetlands in the New England valley-fill aquifer setting (Motts and O'Brien, 1981). Zero recharge was specified in the Recharge Package for wetlands in uplands. These wetlands are likely to dry out during the growing season (May through October), when evapotranspiration is greatest, or may be perched and not well connected to the regional flow system. Evapotranspiration loss rates were specified for wetlands in areas of stratified glacial deposits and for impoundments and instream ponds, based on estimated monthly Penman PET rates. For areas of open water (ponds and impounded reaches of streams), where water availability is not limited, the loss rate was equal to the estimated mean annual PET rate, 42.1 in/yr. For wetlands, a loss rate equal to the growing-season PET rate, 29.4 in/yr, was specified in the Recharge Package.

Evapotranspiration (ET) of ground water from areas not mapped as wetlands was simulated with the Evapotranspiration Package. This package simulates evapotranspiration as a water loss at a rate that varies linearly from a specified maximum, when and where the water table is at (or above) land surface, to zero at a specified depth (extinction depth). The package was activated only for areas of stratified glacial deposits (fig. 17); it was expected that simulated water levels in uplands likely would not be accurate enough to appropriately simulate ground-water ET with the Evapotranspiration Package in upland areas. The specified maximum ground-water evapotranspiration rate was equal to the estimated Penman growing-season PET rate, 29.4 in/yr. Extinction depths varied among subbasins from 2 to 6 ft. Smaller values for extinction depth were used in upland tributaries, where water levels in stratified glacial deposits were more influenced by higher water levels in adjacent uplands and model discretization effects. Larger values were used in main stem Assabet River subbasins and other areas, where stratified glacial deposits are more extensive.

Septic-system return flow, consumptive use in privately supplied areas, consumptive use by unpermitted agricultural uses, and infiltration of ground water to sewers were simulated with gain or loss rates equal to the mean annual rates that were determined, as described previously, from water-use, land-use, population, and other data. Septic-system return flow was simulated in areas of publicly supplied water use and on-site disposal (fig. 16). Rates varied among land-use categories and towns, averaging 1.2 in/yr for low-density residential (11.5 mi^2 or about 8,000 model cells), 4.8 in/yr for medium-density residential (5.8 mi^2 or about 4000 model cells), 10 in/yr for high-density residential (0.1 mi^2 or about 70 model cells), 33 in/yr for multifamily residential (0.5 mi^2 or about 350 model cells), and 13 in/yr for commercial, industrial, and urban public land use (3.1 mi^2 or about 2,200 model cells), as described previously. Consumptive use in areas of privately supplied water use (fig. 16) was simulated as a loss rate of 0.92 in/yr. Consumptive use by unpermitted agriculture was simulated as loss rates of 1.2 in/yr for areas mapped as cropland (about 2,200 model cells) and 10.6 in/yr for areas mapped as nurseries (about 30 model cells); note that these areas, especially nurseries, were limited in extent. Finally, infiltration of ground water to sewers was simulated as a loss rate that averaged 4.4 in/yr. The rate varied among towns, based on their reported rates of infiltration, from 2.5 to 6.1 in/yr. The loss rate for infiltration to sewers was applied to model cells based on the locations of existing sewer lines (fig. 13).

Water Withdrawals and Discharges

Water withdrawals from wells and reservoirs for public supply and withdrawals from wells, ponds, and streams for permitted agricultural, industrial, and golf-course uses (fig. 17 and table 8) were simulated with the Well Package of MODFLOW-2000. Wells screened in stratified glacial deposits and pond sources were simulated in layer 1, and bedrock wells were simulated in layer 2. Flow rates in the steady-state model (table 10) were equal to mean annual withdrawal rates for 1997–2001 for most sources (tables 8 and 10). For sources in Maynard, the total mean annual withdrawal rate for the system in 1997–2001 was distributed among sources proportionately to the withdrawals of the sources in 2001. In July 2000, withdrawals began from new bedrock wells (MN-04G); withdrawals from Maynard's surface-water source, White Pond (MN-01S), ended in this year. The 2001 distribution of withdrawals in Maynard was used in the model as the best representation of the current distribution of withdrawals among Maynard sources. Permitted sources that were not used in 1997–2001 (table 8) were not included in the model simulation, unless needed for model scenarios. Water use by unpermitted golf courses also was simulated with the Well Package (table 10 and fig. 17). These withdrawals may be from ground or surface water, but they were simulated with the Well Package for simplicity. Wastewater discharges to the Assabet River and Spencer Brook (table 8) were simulated as specified inflows at the beginning of stream reaches in the Stream Package.

Hydraulic Properties

Hydraulic properties required for the steady-state simulations were horizontal and vertical hydraulic conductivities and streambed conductances. Horizontal hydraulic conductivities (*Kh*) for stratified glacial deposits, till, and bedrock were determined from literature sources, aquifer-test data from public-supply wells, and lithologic logs from wells and boreholes, and were modified slightly during model calibration within a range of reasonable values. Horizontal hydraulic conductivity of the stratified glacial deposits was specified in three zones, coincident with the transmissivity zones described previously (fig. 3), at 45, 70, and 110 ft/d (fig. 17). Vertical hydraulic conductivities (*Kv*) were specified ratios of *Kh*:*Kv* of 20:1 for low- and medium-conductivity zones, and 10:1 for high-conductivity zones. These values are lower for fine-grained deposits and higher for coarse-grained deposits than values reported previously and were chosen to represent the expected heterogeneous character of sediments within the hydraulic conductivity zones. Horizontal and vertical hydraulic conductivities of till were specified at 10 and 0.1 ft/d, respectively. Horizontal and vertical hydraulic conductivities of bedrock were specified at 0.01 ft/d for most of the model area. An area near the bedrock public-supply wells in Maynard was simulated as a high-conductivity zone, at 14 ft/d, based on a local-scale model and contributing-area study of that wellfield (Lyford and others, 2003).

Model areas used to simulate ponds were assigned horizontal and vertical hydraulic conductivity values of 10,000 ft/d. Simulating ponds as active model cells allowed pond levels to change as stresses changed in the aquifer. The large hydraulic conductivity value effectively simulates the lack of resistance to flow through the ponds, and results in little or no water-level change across adjacent pond cells and realistic flow patterns in the aquifer surrounding the ponds.

Streambed conductances were determined from literature sources and assumed stream geometries and calculated as (Prudic, 1989):

$$C_{SB} = \frac{K_{SB} \bullet L_S \bullet W_S}{T_{SB}}, \qquad (2)$$

where

C_{SB} is streambed conductance, in ft^2/d;
K_{SB} is vertical hydraulic conductivity of the streambed, in ft/d;
L_S is stream length, in ft;
W_S is stream width, in ft; and
T_{SB} is streambed thickness, in ft.

Generally, streambed thickness and vertical hydraulic conductivity are variable and mostly unknown. Values of 1 ft and 1 ft/d for T_{SB} and K_{SB}, respectively, were assumed, resulting in specified streambed conductance values ranging from 1,000 to 3,000 ft^2/d for small to large streams. These values of K_{SB} are consistent with typical values of from 1 to 2 ft/d for streams in the glaciated northeastern United States (Rosenshein, 1968; DeLima, 1991; Prince and others, 1988; Dysart and Rheaume, 1999).

Table 10. Simulated water withdrawals and discharges in calibrated models (1997–2001) and in scenario 2 for permitted withdrawals and wastewater discharges and unpermitted golf-course withdrawals in the Assabet River Basin, eastern Massachusetts.

[**Identifier:** See table 8 for additional identification information; site locations shown in figure 14; identifiers ending in "G" and "S" denote ground-water and surface-water sources, respectively. **Simulated withdrawal or discharge rate:** Parentheses denote discharges. **Average summer withdrawal or discharge rate:** Average of monthly average June, July, and August rates. Mgal/d, million gallons per day]

Identifier	Model location			Simulated withdrawal or discharge rate (Mgal/d)			
				1997–2001		Scenario 2	
	Layer	Row	Column	Annual	Summer	Annual	Summer
Assabet River Main Stem Headwaters Subbasin							
WB-01G	1	636	245	0.28	0.33	0.29	0.33
WB-02G	1	636	239	.27	.28	.27	.28
WB-04G	1	634	248	.12	.10	.12	.10
Westborough Country Club	1	623	245	.005	.01	.005	.01
Assabet River Main Stem Upper Subbasin							
ML-01S	1	502	171	1.55	1.34	1.77	1.54
NB-01G	1	570	194	.34	.35	.34	.35
WB-03G	1	628	212	.29	.32	.29	.32
WB-07G	1	603	209	.00	.00	.59	.63
JUN-01S	1	561	194	.06	.16	.08	.19
MLW-WWTF	1	506	164	(2.07)	(1.95)	(2.89)	(2.72)
WB-WWTF	1	607	230	(5.27)	(4.63)	(7.68)	(6.75)
Indian Meadows Golf Course	1	600	208	.005	.01	.005	.01
Assabet River Main Stem Middle Subbasin							
HD-01S	1	446	121	0.16	0.30	0.18	0.35
HD-05G	1	340	185	.43	.44	.50	.51
ASG-01S	1	193	213	.14	.20	.14	.21
CNS-01S	1	488	152	.00	.00	.34	.34
INT-01G	2	392	177	.01	.01	.18	.18
INT-02G	2	387	164	.00	.00	.18	.18
SCC-01S	1	337	159	.05	.12	.05	.12
HD-WWTF	1	356	157	(2.30)	(2.08)	(2.65)	(2.40)
Butternut Farm Golf Club	1	273	194	.009	.02	.009	.02
Assabet River Main Stem Lower Subbasin							
AN-05G	1	196	210	0.30	0.32	0.31	0.32
AN-06G	1	194	208	.36	.41	.37	.41
CN-01G	1	191	234	.58	.54	.63	.58
AN-WWTF	1	207	204	.00	.00	.25	.18
MCI-WWTF	1	138	222	(.25)	(.26)	(.25)	(.26)
MN-WWTF	1	210	207	(1.09)	(1.01)	(1.45)	(1.34)
Hop Brook Subbasin							
SW-01G	1	662	160	0.00	0.00	0.26	0.32
BER-01S	1	611	188	.02	.07	.03	.10
BIG-01S	1	607	158	.10	.26	.10	.26
Cold Harbor and Howard Brook Subbasins							
NB-03G	1	592	146	0.32	0.30	0.32	0.30
NB-04G	1	559	147	.13	.14	.13	.14

Table 10. Simulated water withdrawals and discharges in calibrated models (1997–2001) and in scenario 2 for permitted withdrawals and wastewater discharges and unpermitted golf-course withdrawals in the Assabet River Basin, eastern Massachusetts.—Continued

[**Identifier:** See table 8 for additional identification information; site locations shown in figure 14; identifiers ending in "G" and "S" denote ground-water and surface-water sources, respectively. **Simulated withdrawal or discharge rate:** Parentheses denote discharges. **Average summer withdrawal or discharge rate:** Average of monthly average June, July, and August rates. Mgal/d, million gallons per day]

Identifier	Model location			Simulated withdrawal or discharge rate (Mgal/d)			
				1997–2001		Scenario 2	
	Layer	Row	Column	Annual	Summer	Annual	Summer
				Stirrup Brook Subbasins			
WB-05G	1	572	228	0.01	0.01	0.01	0.01
WB-06G	1	571	229	.26	.28	.27	.28
				Danforth Brook Subbasin			
GRK-01G	1	435	77	0.01	0.02	0.04	0.09
				Fort Meadow Brook Subbasin			
HD-02G	1	347	195	0.16	0.23	0.18	0.27
HD-03G	1	350	188	.61	.67	.69	.74
HD-04G	1	342	186	.69	.71	.79	.82
				Elizabeth Brook Subbasin			
SCC-02S	1	310	144	0.04	0.11	0.04	0.11
				Taylor Brook Subbasin			
MN-01G	1	239	234	0.27	0.30	0.30	0.34
MN-02G	1	238	233	.13	.12	.14	.13
MN-03G	1	259	222	.11	.17	.12	.20
				Fort Pond Subbasin			
AN-01G	1	204	112	0.12	0.11	0.12	0.11
AN-03G	1	158	202	.16	.17	.14	.15
AN-04G	1	155	196	.19	.22	.19	.22
AN-07G	1	208	113	.07	.13	.07	.14
AN-08G	1	157	199	.10	.11	.10	.11
MN-04G	2	220	175	.46	.51	.52	.57
IDY-01S	1	183	102	.01	.03	.01	.03
Wedgewood Pines Country Club	1	282	109	.06	.17	.06	.17
				Nashoba Brook Subbasin			
AN-02G	1	118	150	0.12	0.20	0.15	0.20
AN-09G	1	62	130	.03	.04	.03	.04
AN-10G	1	64	127	.37	.37	.38	.37
AN-11G	1	127	161	.09	.09	.09	.10
CN-01S	1	114	122	.30	.73	.32	.79
				Spencer Brook Subbasin			
MID-WWTF	1	81	200	(0.02)	(0.01)	(0.05)	(0.03)

Model Calibration

The steady-state model was calibrated by varying model input parameters—recharge, evapotranspiration, and hydraulic conductivity—within ranges of reasonable values to obtain as close a match as possible between simulated and observed ground-water levels and streamflows. Alternative models of aquifer geometry also were tested. Observed values consisted of the mean annual ground-water levels and streamflows estimated for 1997–2001 at 20 observation wells, 2 kettle ponds (Chauncy Lake and White Pond), 2 streamflow-gaging stations, and 18 partial-record flow-measurement sites (tables 11 and 12). Trial-and-error methods were used primarily in model calibration. However, using flows at partial-record sites and streamflow-gaging stations as observations, an inverse modeling code that is incorporated into MODFLOW-2000 (Hill, 1998; Hill and others, 2000) also was used to investigate the distribution of recharge between uplands and stratified glacial deposits. The final steady-state model incorporates parameters, particularly recharge rates, that were modified during calibration of the transient model.

Calculated water levels for observation wells and kettle ponds for the calibrated steady-state model are shown in table 11 and figure 19*A*. The mean absolute difference between observed and model-calculated ground-water levels (mean absolute water-level residual) was 3.67 ft; this value is less than 1 percent of the total ground-water-level change across the simulated water table in stratified glacial deposits (500 ft) and in the entire active model area (632 ft). The mean difference between observed and model-calculated water levels (mean water level residual) was 0.39 ft, indicating that water levels were neither consistently over- or underestimated to a large degree. In some cases, relatively large differences between observed and model-calculated water levels occurred at observation wells near boundaries between stratified glacial deposits and uplands, where model discretization effects likely were to be significant. For example, the water level at well WWW159 was overestimated substantially (table 11). In other cases, large differences between observed and model-calculated water levels may have resulted from variability in the hydraulic properties that was not included in the model. For example, the water level at well A9W53 was underestimated substantially (table 11). The lithologic log indicated that stratified glacial deposits at this well were silt, clay, and very fine sand, probably with a horizontal hydraulic conductivity significantly less than 45 ft/d, the value used to simulate stratified glacial deposits in this area (for example, BSC test site, table 1). Hydraulic conductivity could have been adjusted in this area, based on information from the lithologic log. It was decided, however, that in the absence of a conceptual framework for small-scale spatial variability in hydraulic properties in the basin, this and similar adjustments were unwarranted, because they would be applied inconsistently throughout the model area. Hydraulic properties were modified in a small area along the northern edge of the A1 impoundment (fig. 1) to simulate the effects of low permeability bottom sediments in the impoundment.

Model-calculated water levels at instream ponds and impoundments were nearly all within 1 ft of observed values (table 11). Water levels at these ponds and impoundments were not used for model calibration, however, because the observed values were used in many cases to set the elevations of simulated stream segments in the ponds. Also, the water level in instream ponds and impoundments is controlled primarily by the elevation of the outlet structure and the surface-water storage capacity, which are not well simulated by the ground-water-flow model.

Water levels at observation wells were sensitive to changes in hydraulic properties of stratified glacial deposits. Increasing or decreasing hydraulic conductivities of stratified glacial deposits by a factor of 2 increased the degree to which water levels were, on average, under- or overestimated, respectively, resulting in mean water level residuals of -1.15 and +1.85, respectively, although the mean absolute water-level residual changed little (3.84 and 3.96, respectively). Water levels at observation wells also were influenced, to a much lesser extent, by the hydraulic conductivity of the till uplands in layer 1. For example, decreasing the hydraulic conductivity of the till by a factor of 10 resulted in a mean water level residual of +0.41 and a mean absolute water level residual of 3.75. Changes in recharge rates also affected the match between observed and model-calculated water levels at observation wells. Increasing or decreasing recharge rates in stratified glacial deposits and till by 30 percent increased the degree to which water levels were, on average, over- or underestimated, respectively, resulting in mean water level residuals of +1.62 and -1.30, respectively. Water levels at observation wells were not sensitive to bedrock hydraulic properties. Increasing or decreasing the hydraulic conductivity of layer 2 by an order of magnitude resulted in simulated water levels at observation wells that essentially were unchanged (differed by less than 0.1 percent) relative to the calibrated model. Finally, water levels at observation wells were sensitive to specified stage elevations in adjacent streams. During model calibration, stream-stage elevations, particularly along the main stem Assabet River, were reviewed, and in some cases modified, based on 10-ft contour data in USGS topographic maps that predated the 3-m contour data initially used to define stream elevations.

The model-calculated water table (fig. 20) is consistent with the conceptual model of flow in the basin. Water-table contours are spaced closely in uplands, and mimic topography. In stratified glacial deposits, the water-table is relatively flat. Water-table contours decrease in the downstream direction in tributary valleys and along the Assabet River, and bend at large streams, indicating ground-water discharge to these streams.

Table 11. Steady-state model-calculated average annual water levels and observed water levels at observation wells and ponds in the Assabet River Basin, eastern Massachusetts.

[Site locations shown in figure 6. **Observed water level:** Estimated for 1997–2001 from measurements made during 2001–02, as described in text. NGVD, National Geodetic Vertical Datum; ±, plus or minus; -- not determined]

Well identifier or pond name	Model location			Average annual water level			
	Layer	Row	Column	Model calculated (feet above NGVD 29)	Observed (feet above NGVD 29)		Difference (model calculated minus observed, in feet)
					Water level	90-percent confidence limits	
				Observation wells			
A9W53	1	492	136	221.33	230.09	±0.62	-8.76
ACW158	1	145	193	128.98	134.24	--	-5.26
ACW255	1	214	140	196.75	196.19	±.24	+.55
ACW256	1	140	167	153.33	150.88	±.29	+2.45
ACW257	1	164	163	168.44	159.78	±.76	+8.65
HZW147	1	350	198	190.79	182.57	±.22	+8.22
HZW148	1	362	160	197.33	201.48	±.28	-4.15
HZW149	1	361	157	195.12	192.18	±.30	+2.94
MKW165	1	243	216	199.81	195.55	±.36	+4.26
NUW127	1	576	152	297.91	298.44	±.43	-.49
NUW128	1	579	198	272.72	273.40	±.23	-.68
NUW129	1	554	157	284.59	285.97	±.34	-1.39
NUW130	1	512	153	226.24	227.15	±.65	-.91
S3W183	1	340	145	199.69	194.01	±.26	+5.68
S3W184	1	271	170	186.22	189.05	±.19	-2.83
WRW149	1	550	215	274.96	276.50	±.21	-1.54
WRW150	1	587	207	273.36	277.28	±.38	-3.92
WWW158	1	77	76	189.52	189.74	±.57	-.22
WWW159	1	76	47	216.86	204.93	±.27	+11.93
WWW160	1	42	93	203.95	207.80	±.05	-3.85
				Ponds or impoundments			
A1 Impoundment	1	622	242	310.19	[1]310.00	--	--
Assabet River at Hudson	1	410	145	204.22	206.68	±0.05	--
Assabet River at Maynard	1	258	196	176.96	176.45	±.12	--
Bartlett Pond	1	533	191	272.47	273.22	±.18	--
Chauncy Lake[2]	1	569	233	280.64	280.81	±.18	-0.16
Delaney Pond	1	296	90	230.52	229.75	±.15	--
Lake Boon	1	318	187	186.86	[3]186.60	--	--
Smith Pond	1	611	188	290.17	289.41	±.40	--
Warner Pond	1	146	218	119.95	[3]120.2	--	--
West Pond	1	358	85	312.21	312.20	±.08	--
Wheeler Pond	1	499	130	224.85	224.88	±.31	--
White Pond[2]	1	309	226	188.28	190.25	±.19	-1.97

[1] Elevation of dam intake.

[2] Kettle pond, included in summary statistics comparing model-calculated and observed water levels.

[3] Average of water levels measured in water year 2002.

Table 12. Steady-state model-calculated average annual nonstorm streamflow and observed nonstorm streamflow at measurement sites in the Assabet River Basin, eastern Massachusetts.

[Site locations shown in figure 6. **Observed nonstorm streamflow:** Estimated for 1997–2001 from measurements made during 2001–02, as described in text. --, not determined]

Station number	Model location			Average annual nonstorm streamflow (cubic foot per second)				
	Layer	Row	Column	Model calculated	Observed			Difference (model calculated minus observed)
					Flow	90-percent confidence limits		
						Lower	Upper	
Assabet River								
01096630	1	565	199	27.5	23.4	18.3	30.0	+4.1
01096710	1	535	166	41.2	41.7	29.8	58.5	-.6
01096730	1	490	149	50.7	52.5	35.8	77.0	-1.8
01096840	1	398	147	85.2	81.5	67.1	98.9	+3.8
01097000	1	230	206	144	[1]155	--	--	-11.4
01097048	1	151	235	153	169	144	199	-16.5
Tributaries to Assabet River								
01096615	1	606	204	10.1	11.1	8.1	15.1	-1.0
01096700	1	554	160	3.4	2.9	1.6	5.2	+.5
01096705	1	556	163	8.3	8.6	5.1	14.4	-.3
01096805	1	499	137	22.0	13.4	9.0	20.0	+8.6
01096838	1	404	135	1.5	3.0	2.3	4.0	-1.5
01096853	1	386	123	5.8	4.8	3.1	7.5	+.9
01096880	1	354	193	4.3	6.0	2.5	14.4	-1.8
01096898	1	341	87	6.1	4.7	3.0	7.4	+1.4
01096945	1	271	179	25.9	19.7	14.0	27.7	+6.2
01097095	1	193	87	3.2	2.3	1.3	4.0	+.9
01097270	1	188	178	21.2	23.6	14.3	39.1	-2.5
01097300	1	83	146	15.0	[1]13.0	--	--	+2.0
01097380	1	145	222	50.9	51.9	32.9	81.9	-1.1
01097412	1	106	223	7.1	6.1	3.6	10.3	+1.0

[1] Mean of monthly mean values, estimated from mean daily streamflow at streamflow-gaging station by using the automated hydrograph-separation method, PART (Rutledge, 1993, 1998).

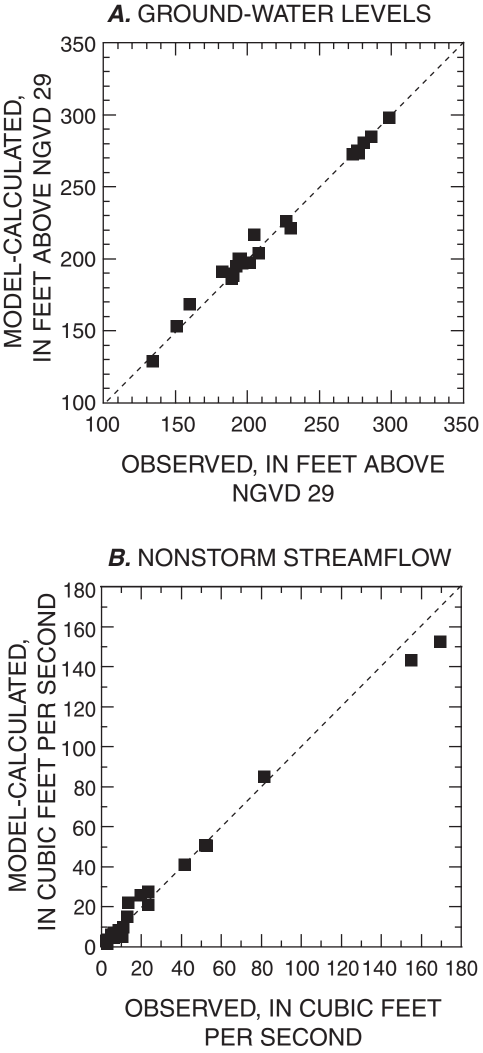
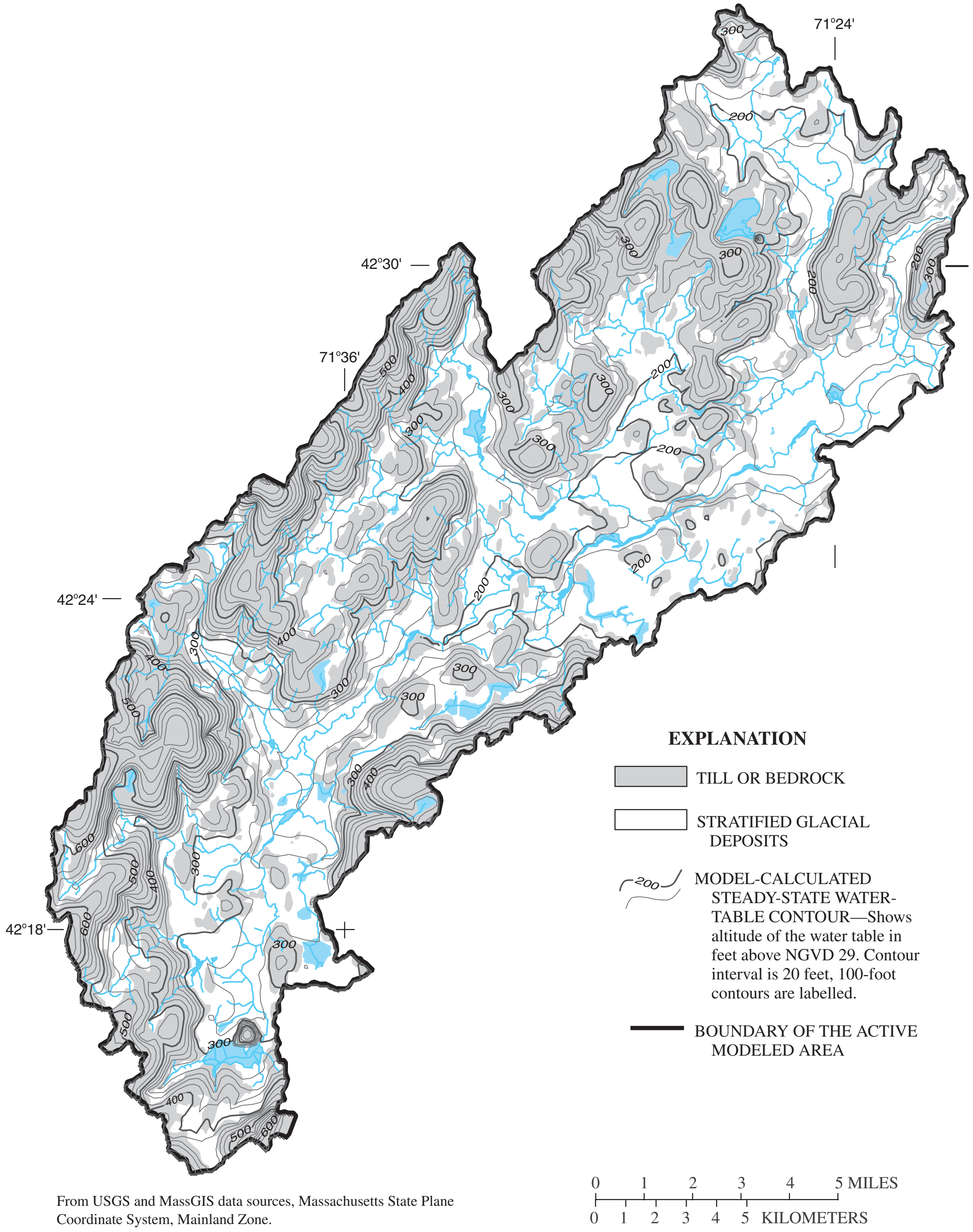


Figure 19. Relation between observed and model-calculated *A*, ground-water levels; and *B*, nonstorm streamflow for average conditions, 1997–2001, for the steady-state ground-water-flow model of the Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text. Line of equality between observed and model-calculated values is shown.

Calculated nonstorm streamflow at streamflow-gaging stations and partial-record measurement sites are shown in table 12 and figure 19*B*. Observed and model-calculated nonstorm streamflow differ by about -8 percent at the Assabet River at Maynard station (01097000) and by +13 percent at the Nashoba Brook station (01097300). Nonstorm streamflows at partial-record sites on the main stem Assabet differ by less than 20 percent, and flows at most partial-record sites on tributaries differ by about 30 percent or less; large differences (greater than 30 percent) generally were associated with sites on small streams with low flows. Overall, the mean absolute difference between model-calculated and observed nonstorm streamflow (mean absolute flow residual) was 3.4 ft^3/s, or 2 percent of the total range of observed flows. The mean difference between observed and model-calculated water levels (mean flow residual) was -0.55 ft^3/s.

Streamflows were sensitive to recharge rates, evapotranspiration rates, and the distribution of recharge between areas of stratified glacial deposits and uplands. Increasing or decreasing recharge rates in stratified glacial deposits and till by 30 percent resulted in flows at all sites being consistently over- or underestimated, with mean flow residuals of +11.6 and -12.5 ft^3/s, respectively; the mean absolute flow residuals were equal in magnitude to the mean flow residuals in both cases (all differences were in the same direction). Increasing or decreasing evapotranspirative loss rates in wetlands, instream ponds, impoundments, and nonwetland areas by 30 percent had smaller, inverse effects than changes in recharge rates, resulting in mean flow residuals of -3.1 and +2.1 ft^3/s, respectively. Finally, a uniform recharge rate for stratified glacial deposits and uplands, equal to the area-weighted average of the rates used in the calibrated model, resulted in flows being overestimated, with a mean flow residual of 2.2 ft^3/s, and a mean absolute flow residual of 3.2 ft^3/s.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 20. Model-calculated steady-state water table in the Assabet River Basin, eastern Massachusetts.

Model-Calculated Water Budgets and Flows

The average annual water budget for the ground-water-flow system in the Assabet River Basin, as calculated by the steady-state model, is given in table 13. Water budgets for individual subbasins are tabulated in Appendix 2. Most inflows (92 percent) were from precipitation recharge. Stream leakage to the aquifer, either from induced infiltration caused by pumping or from natural infiltration (for example, in areas of abrupt changes in aquifer permeability) was 6 percent of total flows. Septic-system return flow accounted for only 2 percent of total inflows. Outflows consisted mostly (71 percent) of ground-water discharge to streams, but evapotranspiration from wetlands (15 percent) and nonwetland areas (7 percent) also were significant outflows. Basinwide, water withdrawals from ground water were 5 percent of total flows. Other outflows, including infiltration to sewers and consumptive use in privately supplied areas, were about 1 percent or less of total flows.

The relative magnitudes of flow components in subbasins were similar to the basinwide budget. However, water withdrawals, septic-system return flow, and other fluxes caused by human activity (anthropogenic fluxes) varied among subbasins, from zero in the Elizabeth Brook subbasin, to relatively large fractions of total flows, as in the Assabet Main Stem Upper and Fort Meadow subbasins (fig. 21 and Appendix 2). Septic-system return flow was largest in basins where much of the population was served by public water and private disposal, such as the Fort Pond and Nashoba Brook subbasins.

Subbasins also can be compared in terms of the magnitude of withdrawals and other anthropogenic outflows relative to total model-calculated flows through the subbasin as a measure of the degree of alteration to the hydrologic system. Anthropogenic outflows exceeded 10 percent of total model-calculated flows through the subbasin, on an average annual basis, in four subbasins, including Taylor Brook, Fort Meadow Brook, Stirrup Brook, and the Assabet Main Stem Upper subbasin (fig. 22). Anthropogenic outflows also are relatively large percentages (5 to 10 percent) of total flows in the Assabet Main Stem Headwaters and Lower subbasins, and Hop Brook and Cold Harbor and Howard Brooks subbasins.

Finally, model-calculated ground-water discharge to streams can be combined with information about surface-water withdrawals and wastewater discharges, which are accounted for with the Well and Stream Routing Packages of the flow model, to describe the components of flow in the surface-water system (table 13). In the main stem Assabet subbasins, wastewater accounts for a variable percentage of total nonstorm streamflow (fig. 23). On an average annual basis, wastewater accounts for 23, 13, and 8 percent of nonstorm streamflow out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively (fig. 23). The wastewater component of flow decreases downstream, from a maximum of 60 percent immediately downstream of the Westborough Regional Wastewater Treatment Facility to 7.5 percent at the confluence with the Sudbury River (fig. 24). On an average annual basis, surface-water withdrawals are insignificant fractions of total nonstorm streamflow (table 13).

Table 13. Steady-state model-calculated average annual water budget for the Assabet River Basin, eastern Massachusetts.

[S1, Scenario 1; S2, Scenario 2; ET, evapotranspiration; Mgal/d, million gallons per day]

Hydrologic budget component	Rate of flow (Mgal/d)		
	1997—2001	S1	S2
Ground-water-flow system			
Inflow			
Recharge to stratified glacial deposits	77.4	77.4	77.4
Recharge to uplands	102.5	102.5	102.5
Recharge to kettle ponds	.06	.06	.06
Stream leakage to aquifer	10.9	8.4	11.7
Septic-system return flow	4.3	.0	3.0
Ground-water discharge of wastewater	.0	.0	.3
Total inflow	195.2	188.4	195.0
Outflow			
Ground-water discharge to streams	139.6	146.0	137.1
ET from wetlands and ponds	29.3	29.3	29.3
ET from nonwetland areas	13.0	13.2	12.7
Water-supply withdrawal[1]	9.9	.0	12.2
Consumptive use in privately supplied areas	.7	.0	.7
Consumptive use by unpermitted agriculture	.2	.0	.2
Infiltration to sewers	2.6	.0	2.9
Total outflow	195.3	188.5	195.2
Budget error (inflow minus outflow)	-0.1	-0.1	-0.2
Surface-water-flow system			
Inflow			
Net ground-water discharge[2]	129.0	137.5	125.8
Wastewater discharge	11.0	.0	15.0
Outflow			
Water-supply withdrawals	.3	.0	.4
Total nonstorm streamflow	139.7	137.5	140.4

[1] Includes withdrawals from ground water and surface water

[2] Equal to model-calculated ground-water discharge to streams minus stream leakage to aquifer plus surface-water withdrawals. Surface-water withdrawals are included because they are included in water withdrawals calculated by the model for the ground-water-flow system.

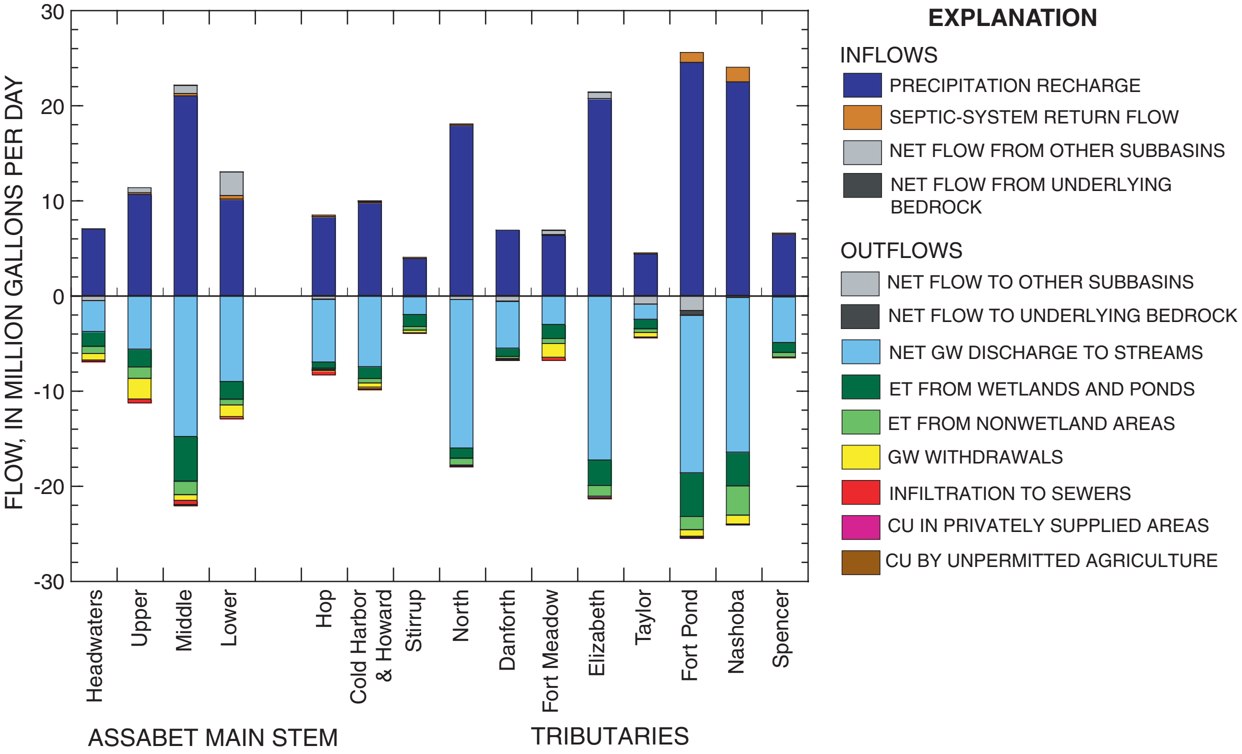


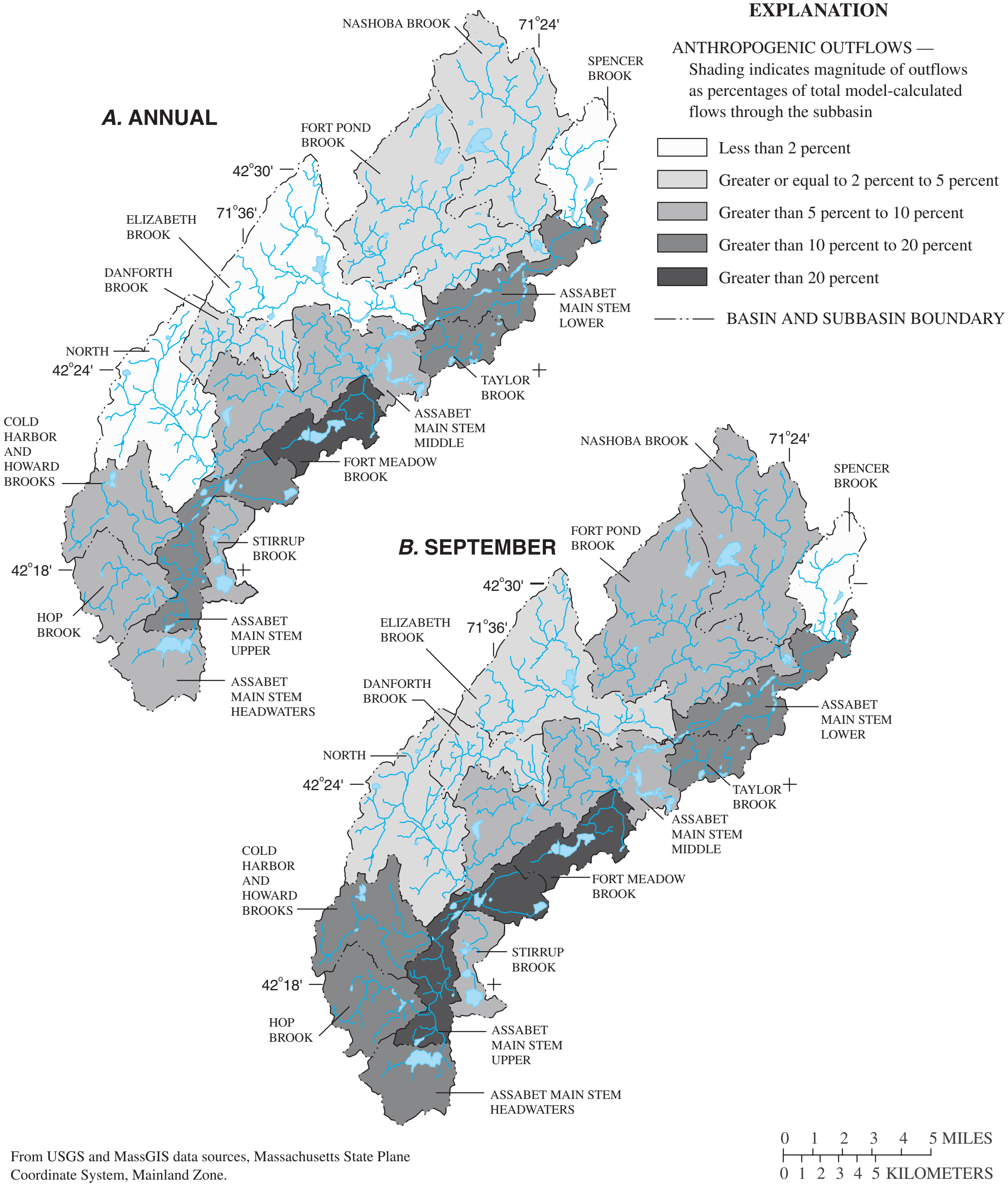
Figure 21. Model-calculated average annual inflows to and outflows from the surficial layer (layer 1) of the simulated ground-water-flow system in subbasins of the Assabet River Main Stem and tributary subbasins, 1997–2001, Assabet River Basin, eastern Massachusetts. Positive values are inflows and negative values are outflows. GW, ground water; ET, evapotranspiration; CU, consumptive use.

Transient Numerical Models

The transient models were developed to simulate the variations in hydrologic conditions, particularly the low-flow period, late summer, within an average annual cycle. The effects of water-management practices on hydrologic systems often are a concern during these months, because streamflow depletion and water-quality alterations have their greatest effects during low flows. Water demands also typically are greatest during the summer. The transient model is similar to the steady-state model in that the model grid, aquifer geometry, boundary conditions (other than specified flows), and hydraulic properties (with the addition of aquifer storage) are the same. Stresses, however, vary with time. The transient model was used to simulate dynamic equilibrium, or the condition in which there is no net change in storage over the annual cycle (Barlow and Dickerman, 2001).

Temporal Discretization and Initial Conditions

The annual hydrologic cycle was divided into 12 monthly stress periods that varied in length from 28 to 31 days. Within each monthly stress period, aquifer stresses and boundary flows were assumed to be uniform. Sixteen time steps of uniform length were used within each stress period. Ground-water levels from the calibrated steady-state model were specified as the initial conditions. Discrepancies between the initial water-level conditions (average annual conditions) and stresses specified during the first month of the transient model (January) were resolved by running the transient simulations for five repeated 1-year cycles. After five annual cycles, the effects of the initial conditions were eliminated, and change in storage was negligible over a 1-year cycle. The difference between flow into and out of storage was 0.15 percent of the total water budget in the last year of the 5-year simulation. This year was used as a representative annual cycle of change under dynamic-equilibrium conditions.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 22. Anthropogenic outflows relative to total model-calculated average *A*, annual; and *B*, September outflows from the simulated ground-water-flow system in subbasins of the Assabet River Basin, eastern Massachusetts.

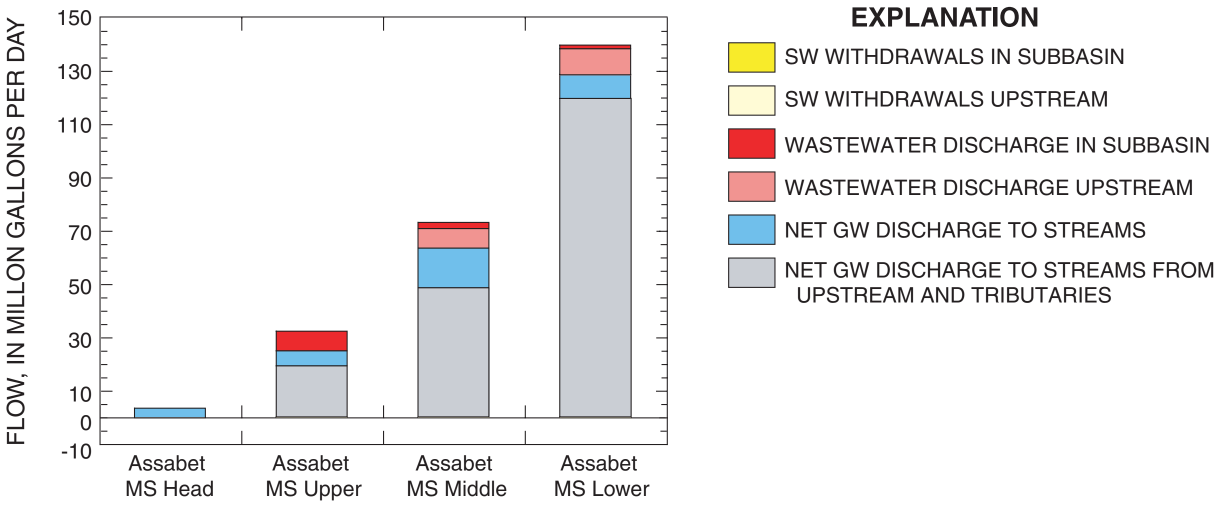


Figure 23. Model-calculated components of average annual nonstorm streamflow in subbasins of the of the Assabet River Main Stem (MS), 1997–2001, eastern Massachusetts. SW, surface water, GW, ground water. Surface-water withdrawals of 0.06, 0.05, and 0.14 million gallons per day from the Upper, Middle and Lower subbasins are too small to be apparent at this scale.

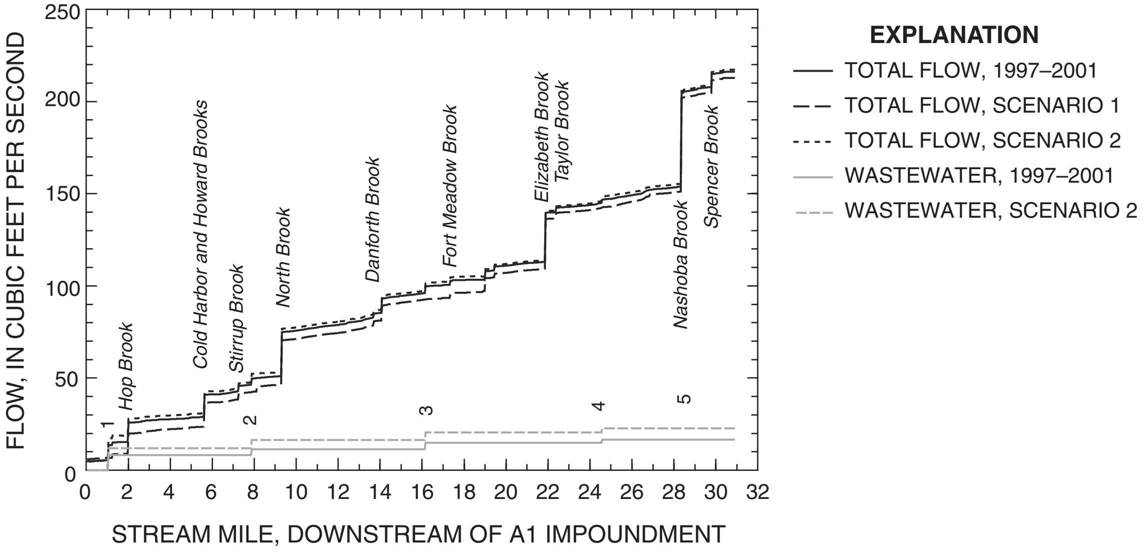


Figure 24. Model-calculated average annual total nonstorm streamflow and the component of flow that originated as wastewater, for existing conditions (1997–2001) and two hypothetical scenarios of altered withdrawals and discharges in the Assabet River Basin, eastern Massachusetts. Numbers show locations of wastewater-treatment facility (WWTF) discharges: 1, Westborough WWTF; 2, Marlborough WWTF; 3, Hudson WWTF; 4, Maynard WWTF; 5, MCI Concord WWTF.

Boundary Conditions and Stresses

Boundary conditions, including the no-flow boundary that delineated the active model area and the head-dependent flow boundaries that simulated streams, were the same in the transient model as in the steady-state model. Stream stages did not vary with time, but remained the same throughout the transient simulation and equal to those used for the steady-state model simulation. Specified flows in the Stream Package for wastewater discharges (simulated specified inflows) were set equal to the average monthly flow rates for 1997–2001 (Appendix 3).

Average monthly recharge rates were based on basin-wide rates determined from streamflow records and a water-balance analysis (fig. 5), and on the distribution of recharge in stratified glacial deposits and uplands that was used in the steady-state model. Recharge rates were modified during model calibration. Average monthly rates of evaporative loss of ground water from open water and wetlands (Recharge Package) and nonwetland areas (Evapotranspiration Package) in stratified glacial deposits were set equal to the monthly average PET rate (fig. 25) in growing-season months only (May to October) for wetlands and nonwetland areas and in each month of the annual cycle for areas of open water. Average monthly recharge rates for kettle ponds were set equal to the difference between mean monthly precipitation and PET, and ranged from -3.9 in/month in July to 2.9 in/month in March.

Public-water supply withdrawals, other larger permitted withdrawals, and discharges from wastewater-treatment facilities were set equal to average monthly volumes for 1997–2001, except for Maynard public-supply wells, as described previously (Appendix 3). Rates of septic-system return flow were constant throughout the annual cycle and equaled the rate used in the steady-state model (0.08 in/month). This rate was not varied because it represented the nonconsumptive component of water use, excluding the additional use in spring, summer, and fall that is primarily for irrigation and other consumptive purposes. Consumptive use in privately supplied areas was simulated by loss rates in the April through October that ranged from 0.03 in/month in April to 0.22 in/month in July, determined from the analysis of public-water use rates described previously. Consumptive use by unpermitted agriculture was simulated by loss rates of 0.4 in/month in June, July, and August for cropland and from 0.09 to 3.3 in/month in April through November for nurseries; these rates were similar to reported rates by permitted users. Finally, infiltration to sewers was simulated by loss rates that varied from 0.2 in/month in September to 0.6 in/month in March and April, based on the average annual infiltration rate and the seasonal distribution of wastewater discharges.

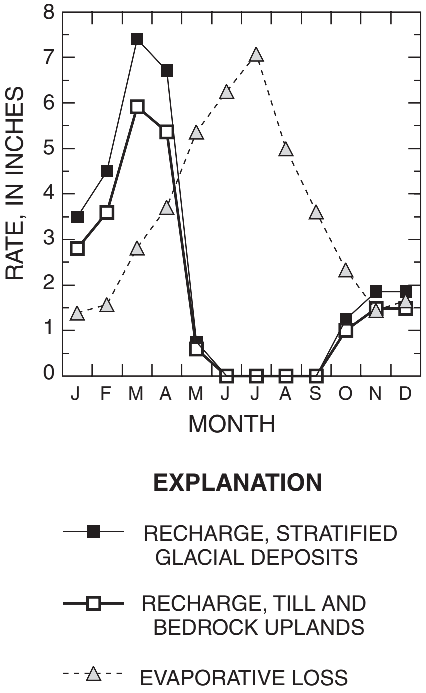


Figure 25. Monthly average recharge rates and rates of evaporative loss of ground water for the transient ground-water-flow model of the the Assabet River Basin, eastern Massachusetts.

Hydraulic Properties

The storage properties of each simulated hydrogeologic unit were characterized by a constant storage term that was specified in the model as specific storage (L^{-1}). For each model layer, specific storage was specified as an array of values equal to the storage term divided by layer thickness. For stratified glacial deposits in layer 1, the storage term represented specific yield and was set equal to 0.18. For till-covered uplands in layer 1, the storage term also conceptually represented specific yield. However, a storage term for till-covered uplands in layer 1, 2.5×10^{-6}, was used in the final calibrated model that was considerably lower than the expected specific yield of these deposits, based on literature sources. This approach was used to compensate for the inability of the model to simulate the complete dewatering of upland cells in layer 1. This inability, a consequence of using the fixed-transmissivity approach, would result in unrealistically large water exchanges with storage during times in the annual cycle when the water level in layer 1 was below the layer bottom. In the transient simulations, as in the actual ground-water systems, water-level fluctuations in the till-covered uplands were large, tens of feet in many areas; therefore, it is likely that the till deposits in these settings dry out to the extent that they no longer transmit water for some period of the year (Randall and others, 1988). For bedrock in layer 2, the storage term represents a confined storage coefficient and was specified as 2.0×10^{-7}, which is consistent with literature sources. A storage term of 1.0 was used for areas simulated as ponds.

Model Calibration

The transient model was calibrated primarily by varying the monthly recharge rates, evapotranspiration, and storage properties within ranges of reasonable values to obtain a close match between simulated and observed monthly streamflows and water levels. Observed values were the mean monthly water levels and flows estimated for 1997–2001 at the same long-term and study sites as used in the steady-state model (tables 11 and 12). Alternative models of aquifer geometry and hydraulic properties also were tested that varied layer thickness and hydraulic conductivity for layer 1 in uplands and varied the minimum thicknesses for layer 1 in stratified glacial deposits. An alternative distribution and routing of recharge in uplands also was tested to simulate the recharge of unchanneled runoff from uplands. In this test, recharge in uplands was reduced by about 30 percent and the volumetric difference was applied as an enhanced recharge to the upland edge of stratified glacial deposits. Finally, model runs were completed in which the storage properties of thin stratified glacial deposits were reduced to approximate the effects of model cells in these areas going dry.

Average monthly recharge rates used in the calibrated transient model are shown in figure 25. Precipitation recharge rates in the model generally were higher in winter and spring than basinwide rates estimated from streamflow and climate records (fig. 5) and lower than estimated basinwide rates in summer. In some months, the recharge rates used in the transient model exceeded the average monthly precipitation rate. This result is reasonable because the precipitation recharge rate, particularly to stratified glacial deposits, includes several processes that were not directly simulated in the model, including recharge of snowmelt, recharge of unchanneled surface runoff from uplands, and possibly recharge at the edges of saturated wetland areas.

Model-calculated water-level fluctuations generally corresponded well with the observed timing of seasonal high and low water levels (fig. 26). In most cases, however, the amplitude of observed water-level fluctuations was overestimated, in many cases by several feet. The average difference between model-calculated and observed water-level fluctuations was 2.71 ft. One possible explanation for this difference is that water-level fluctuations in the uplands affected model-calculated water levels in the stratified glacial deposits. Model-calculated water levels in the simulated till deposits of the uplands, especially in areas of higher elevations, fluctuated by tens of feet and probably overestimated actual water-level fluctuations in these deposits. Spatial heterogeneity in the storage properties of the stratified glacial deposits, which was not simulated, is another likely factor in the overestimation of water-level fluctuations at some observation wells. The specified storage term of 0.18, used basinwide for stratified glacial deposits, probably was too low for deposits in the vicinity of some observation wells. For example, wells ACW255, HZW147, and S3W184 were screened in medium or coarse to very coarse sand, deposits for which a higher storage term probably would be appropriate. In contrast, wells A9W53 and WRW150, where water-level fluctuations were better matched, were screened in silt, very fine sand, and clay and in poorly sorted, silty fine to very coarse sand, respectively. Water-levels fluctuations in simulated ponds generally were underestimated. This result probably was a consequence of the constant elevation specified for stage in stream cells within the pond. In actuality, pond levels, even in instream ponds with dams or control structures, fluctuate in response to seasonal water-level changes and runoff events (fig. 11).

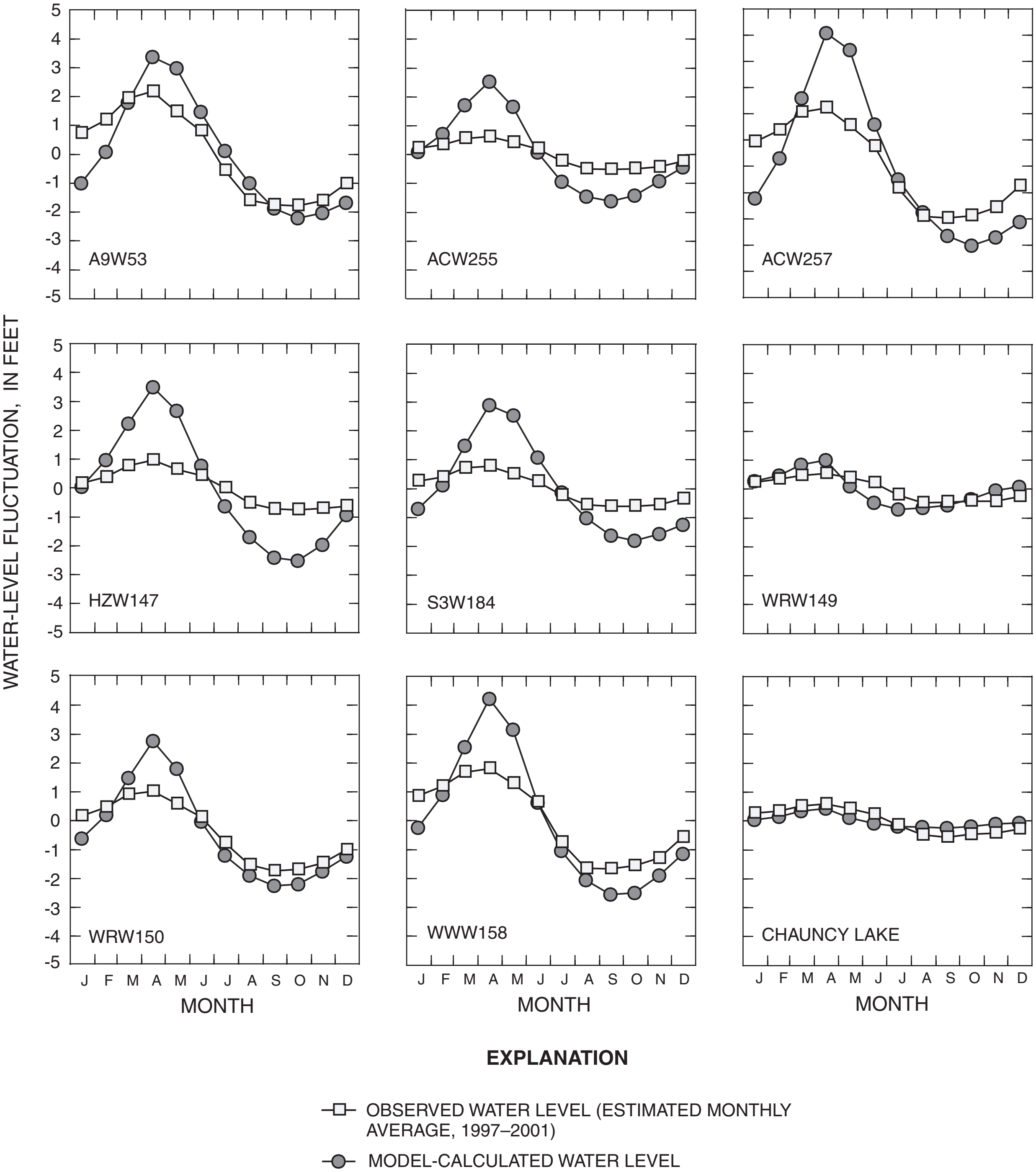


Figure 26. Model-calculated and observed water-level fluctuations during the average annual cycle for selected observation wells and ponds in the Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text. Fluctuations are shown relative to the average annual water levels.

As with water levels, the timing of seasonal fluctuations in flow between model-calculated and estimated (observed) nonstorm streamflows for streamflow-gaging stations and partial-record sites were well matched (figs. 27 and 28, Appendix 1). The amplitudes of fluctuations also were reasonably well matched at most sites. Differences between model-calculated and estimated monthly nonstorm flows (monthly flow residuals) averaged 0.06 ft^3/s, or 16 percent of estimated monthly flows overall, which indicates that monthly flows were not consistently over-or underestimated to a large extent. The absolute monthly flow residuals at all sites averaged 6.4 ft^3/s, or 39 percent of estimated monthly nonstorm flows overall. The average of monthly flow residuals for all sites is an indicator of the overall model fit; monthly flow residuals varied considerably among sites and months (standard deviation of all monthly flow residuals equal to 55 percent of estimated nonstorm flows). Large flow residuals, as percentages of estimated flows, may result because of error in the calibration data, because estimated flows are low, or for other reasons as discussed in the following paragraphs and in the “Model Limitations” section.

At the Assabet River streamflow-gaging station in Maynard, seasonally high nonstorm flows were slightly underestimated (by 10 to 20 percent, January through May) by model-calculated flows. Seasonally low flows (August through December) were overestimated by 20 to 60 percent (fig. 27*A*). Similarly, nonstorm flows at the Nashoba Brook streamflow-gaging station were overestimated during the seasonal low-flow period (fig. 27*B*). Absolute monthly flow residuals at the Assabet River and Nashoba Brook stations averaged 23 and 46 percent, respectively, of estimated flows. In all months at both stations (except July at the Nashoba station), the model-calculated flows are less than the monthly mean of measured streamflow, as expected for the component of flow that is calculated by the ground-water-flow model, which excludes direct runoff. Differences between model-calculated and estimated nonstorm flows at the streamflow-gaging stations may have resulted from several sources of error, including an insufficient characterization of the heterogeneity or magnitude of aquifer storage properties, or of time-varying fluxes such as recharge or evapotranspiration. The inability of the model to simulate changes in transmissivity and the drying out of cells

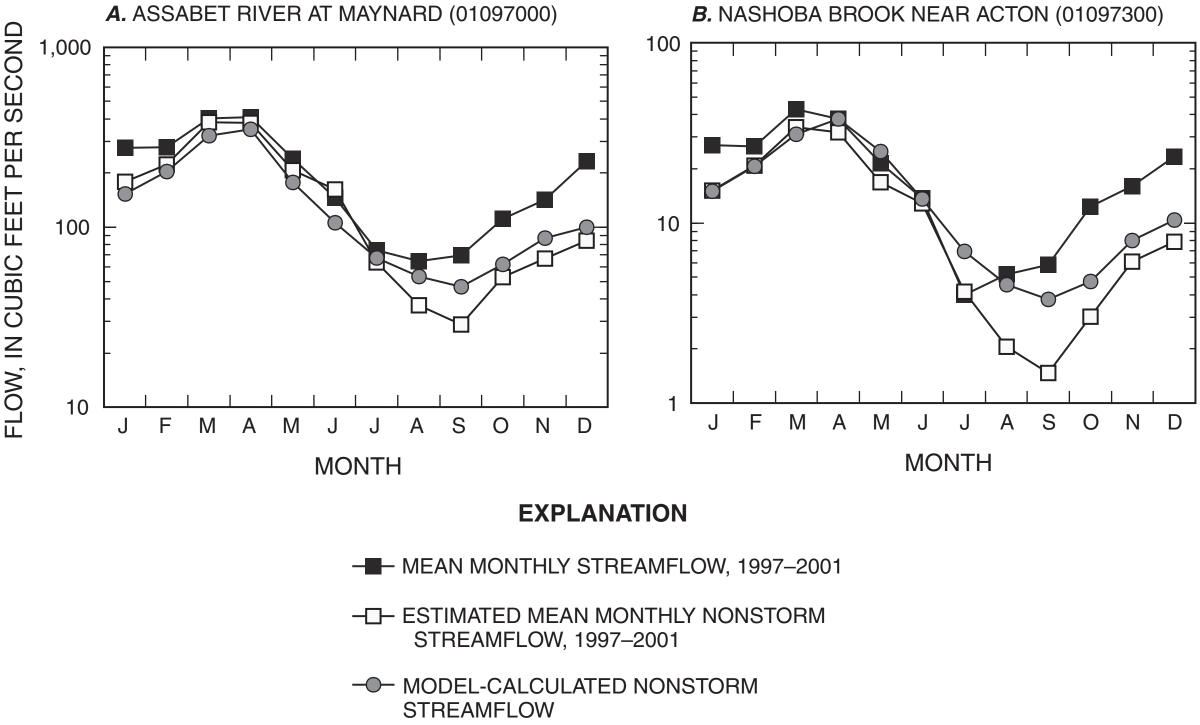


Figure 27. Model-calculated and observed mean monthly nonstorm streamflow at the *A*, Assabet River at Maynard; and *B*, Nashoba Brook near Acton streamflow-gaging stations on the Assabet River, Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text.

in thinly saturated areas—changes that accompany seasonal water-table fluctuations—also may have contributed to differences between model-calculated and estimated nonstorm flows. Efforts to compensate for these drawbacks of the fixed-transmissivity approach, by using alternative model geometries, such as previously described, did not greatly change the model-calculated fluctuations in flow at the streamflow-gaging stations. Also, the estimated mean monthly nonstorm streamflows at the stations, which are used as calibration data for the transient model, contain sources of error, as described previously. Moreover, estimated mean monthly nonstorm streamflow for August to December of 1997–2001 were unusually low, relative to long-term values, ranging from 40 to 60 percent lower than period-of- record values for the Assabet River station and from 50 to 70 percent lower for the Nashoba Brook station. Long-term storage effects, resulting from the near-drought conditions in 1999 and 2001 (fig. 4), that were not simulated in the model also may have affected low estimated nonstorm streamflows for 1997–2001.

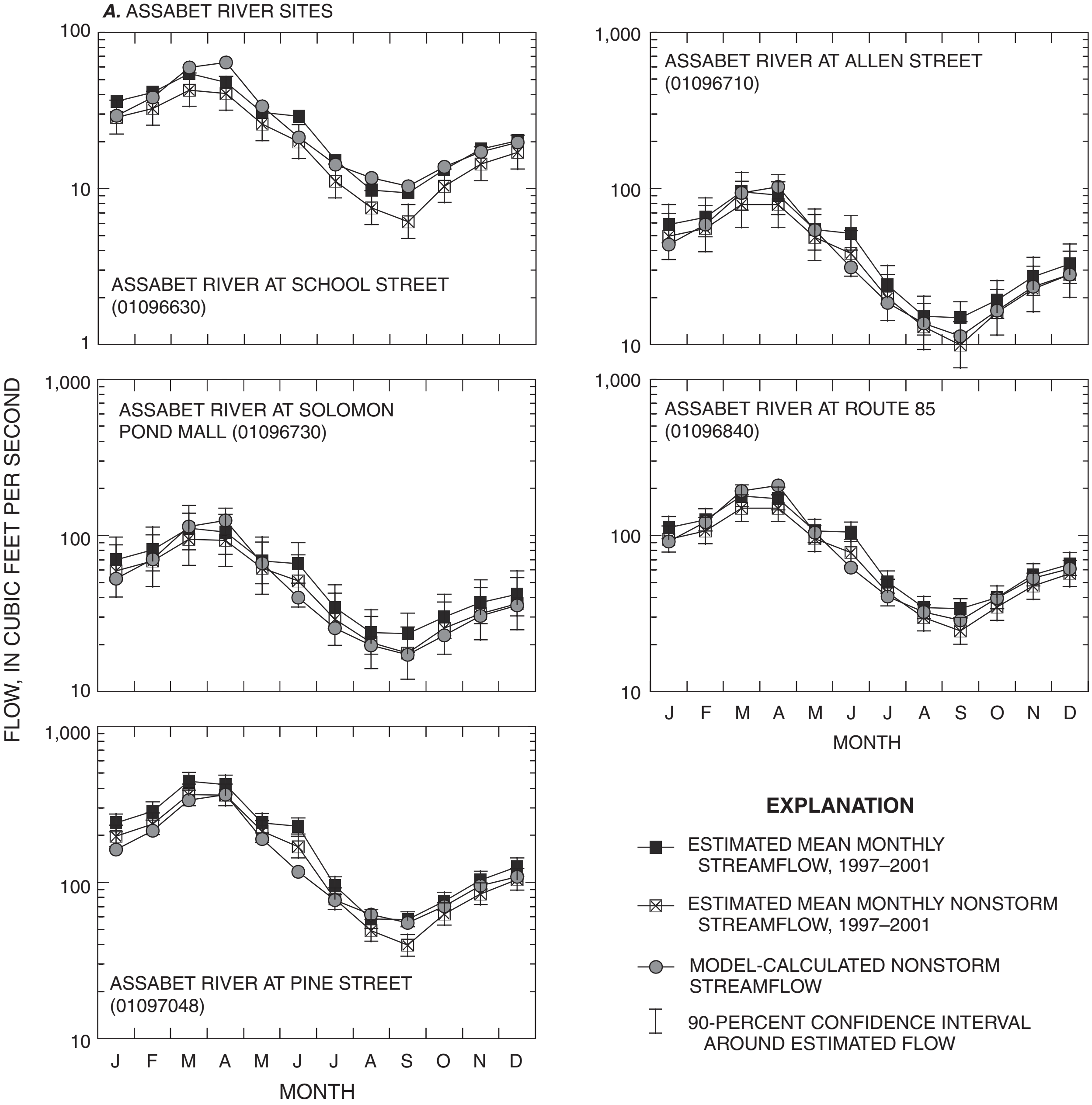


Figure 28. Model-calculated and observed mean nonstorm streamflow at flow-measurement sites on the *A*, Assabet River; and *B*, tributaries, Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text.

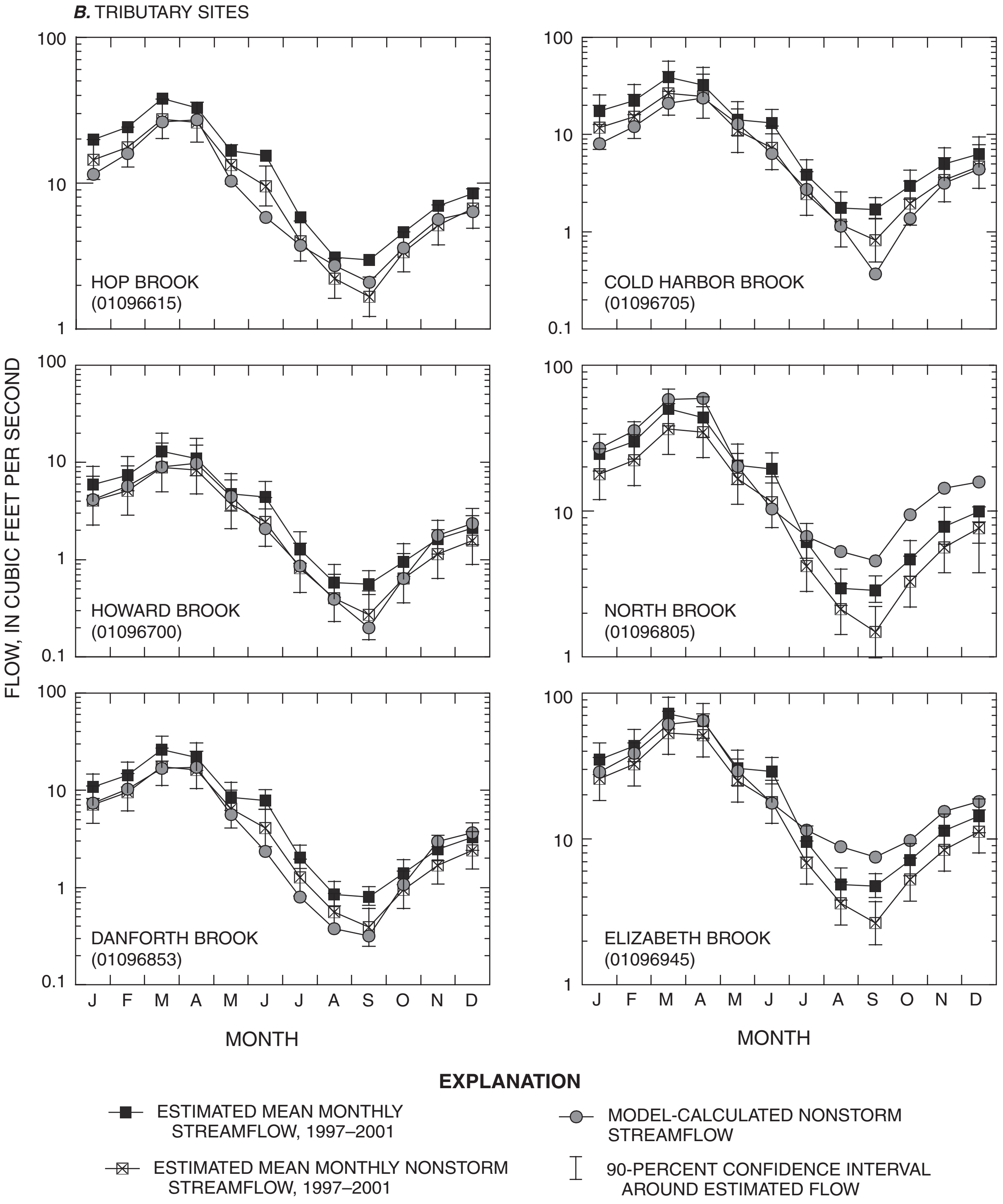


Figure 28—Continued. Model-calculated and observed mean monthly nonstorm streamflow at flow-measurement sites on the *A*, Assabet River; and *B*, tributaries, Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text.

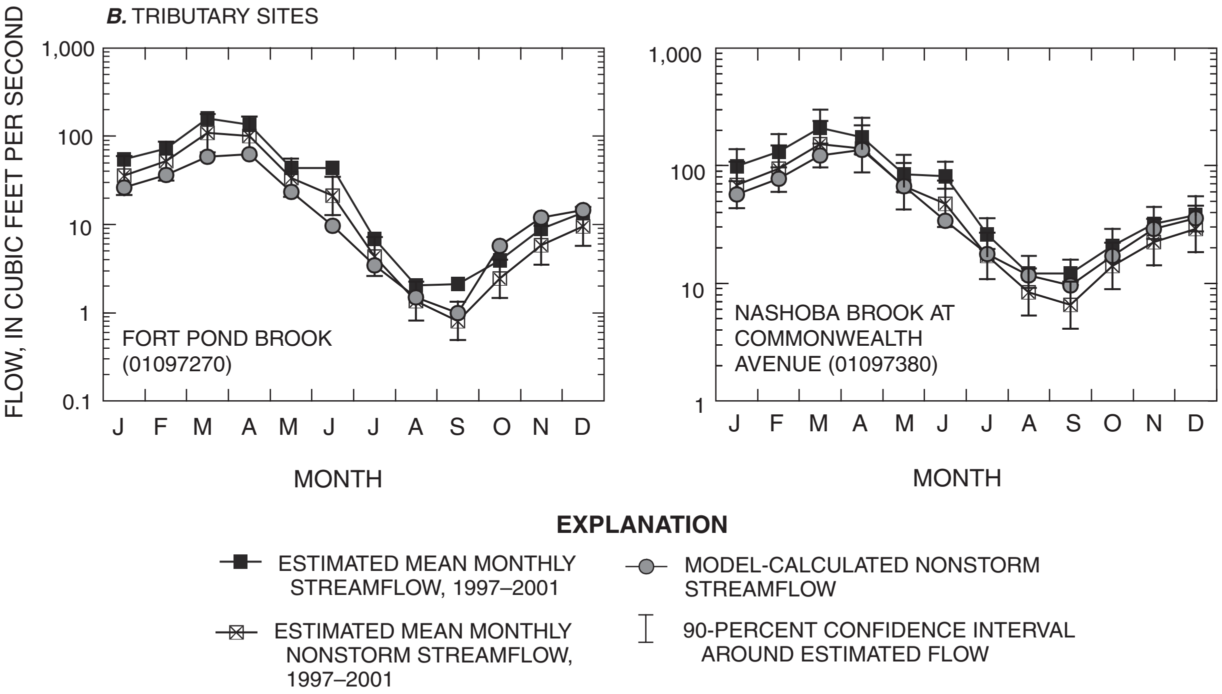


Figure 28—Continued. Model-calculated and observed mean monthly nonstorm streamflow at flow-measurement sites on the *A*, Assabet River; and *B*, tributaries, Assabet River Basin, eastern Massachusetts. Observed values are estimates for 1997–2001 from measurements made in 2001–02 as described in the text.

At partial-record flow measurement sites, model-calculated mean monthly flows were, in most cases, within 90-percent confidence intervals of estimated nonstorm streamflows in most months (fig. 28*B*). At two tributary sites (North Brook, 01096805, and Elizabeth Brook, 01096945), estimated nonstorm streamflows in low-flow months were overestimated significantly. These differences may have resulted for similar reasons, as discussed previously, for low flows at the streamflow-gaging stations. Estimated flows at the tributary partial-record sites contain additional sources of error, however, because they are based on correlation with long-term stations and on much less data than estimates for the Assabet River and Nashoba Brook stations. Low flows estimated at partial-record sites may be particularly affected by error. In some cases, measured flows during the study period at tributary sites were approximately zero or less than could be measured, and these values were not included in the correlation of study-site flows with long-term stations. Consequently, the low-flow conditions were not well characterized at these sites.

Monthly average nonstorm streamflows and water levels calculated with the transient model were not sensitive to changes in hydraulic conductivity. Increasing or decreasing the hydraulic conductivity (*Kh* and *Kv*) of stratified glacial deposits by a factor of 2 had little effect on model-calculated nonstorm streamflows (figs. 29*A*, *B*). Absolute monthly flow residuals with these changes were similar to those produced by the calibrated model (table 14). Increasing or decreasing the hydraulic conductivity of the till and bedrock uplands (layer 1) by a factor of 2 similarly had little effect on model-calculated nonstorm streamflows (figs. 29*C*, *D* and table 14). These changes in hydraulic conductivity of stratified glacial deposits or till also had little effect on model-calculated water-level fluctuations during the annual cycle. The average difference between observed (estimated values for 1997–2001) and model-calculated annual water-level fluctuations (water-level fluctuation residual) changed by 10 percent or less, relative to the calibrated model (table 14).

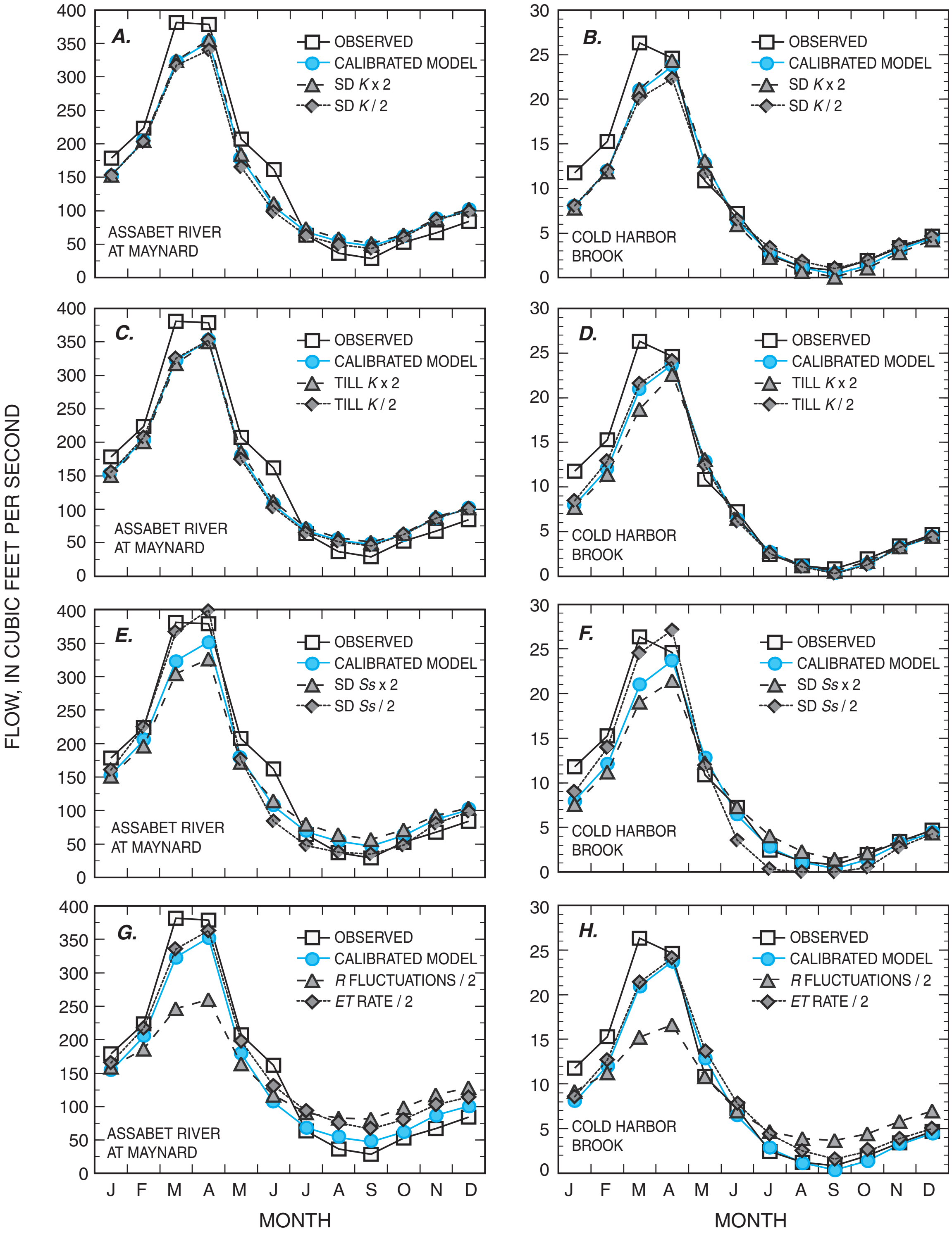


Figure 29. Observed and model-calculated monthly nonstorm streamflow for the calibrated transient model and for several alternative model parameters at the Assabet River at Maynard and a selected tributary site in the Assabet River Basin, eastern Massachusetts. Horizontal and vertical hydraulic conductivity (*K*) of stratified glacial deposits (SD) multiplied and divided by 2 for the *A*, Assabet River at Maynard and *B*, Cold Harbor Brook; horizontal and vertical hydraulic conductivity of till multiplied and divided by 2 for the *C*, Assabet River at Maynard and *D*, Cold Harbor Brook; storage property (*Ss*) of stratified glacial deposits increased and decreased by 50 percent for the *E*, Assabet River at Maynard and *F*, Cold Harbor Brook; recharge (*R*) fluctuations during the annual cycle and evapotranspiration (*ET*) rate in wetlands and non-wetland areas decreased by 50 percent for the *G*, Assabet River at Maynard and *H*, Cold Harbor Brook.

Table 14. Water-level-fluctuation residuals and mean absolute-flow residuals for the calibrated transient model and model runs that use alternative model parameters, Assabet River Basin, eastern Massachusetts.

[**Alternative model parameters:** *Kh*, horizontal hydraulic conductivity, in feet per day; *Kv*, vertical hydraulic conductivity, in feet per day, *Ss*, storage property, dimensionless. **Water-level fluctuation residual:** Mean difference between observed and model-calculated water-level fluctuation during the annual cycle. **Mean absolute flow residual:** Mean difference between observed and model-calculated average monthly nonstorm streamflows. **Average low-flow period:** July, August, and September. ET, evapotranspiration; NA, not applicable; --, not listed]

Model run	Alternative model parameters	Water-level fluctuation residual (feet)	Mean absolute flow residual (percent)					
			All sites		Assabet River station		Nashoba Brook station	
			Annual	Low-flow period	Annual	Low-flow period	Annual	Low-flow period
Calibrated model	NA; see text for values	2.71	39	54	23	39	46	116
Multiply hydraulic conductivity of stratified glacial deposits by 2	*Kh*, 220, 140, 90 *Kv*, 22, 7, 4.5	2.65	44	66	26	50	55	140
Divide hydraulic conductivity of stratified glacial deposits by 2	*Kh*, 55, 35, 22.5 *Kv*, 5.5, 1.8, 1.1	2.85	38	50	21	28	35	79
Multiply hydraulic conductivity of till by 2	*Kh*, 20 *Kv*, 0.2	2.71	42	67	26	49	51	132
Divide hydraulic conductivity of till by 2	*Kh*, 5 *Kv*, 0.05	2.72	41	54	22	33	44	106
Increase storage property of stratified glacial deposits by 50 percent	*Ss*, 0.27	1.28	52	95	33	67	74	202
Decrease storage property of stratified glacial deposits by 50 percent	*Ss*, 0.09	6.10	41	49	15	16	22	16
Decrease fluctuations in monthly recharge during the annual cycle by 50 percent	--	.68	107	257	59	116	100	254
Decrease monthly ET rates from wetlands, water bodies, and nonwetland areas by 50 percent	--	2.24	64	130	39	94	117	312

Monthly average nonstorm streamflows and water levels calculated with the transient model were sensitive to changes in storage properties. Increasing the specified storage property (specific yield) of stratified glacial deposits (SD *Ss*) by 50 percent reduced the average water-level fluctuation residual to 1.28 ft, about half that of the calibrated transient model, thereby improving the fit between observed and model-calculated water-level fluctuations (table 14). This increase in SD *Ss*, however, resulted in a worse fit of model-calculated to observed monthly nonstorm streamflows (figs. 29*E, F*), especially during the low-flow period. During July, August, and September, the difference between observed and model-calculated nonstorm streamflows (in percent) at the Assabet River and Nashoba Brook streamflow-gaging stations more than doubled when SD *Ss* was increased, relative to the calibrated model (table 14). This pattern also was evident at most flow-calibration sites, where average observed flows for July, August, and September were overestimated by 52 percent with the calibrated model and by 95 percent when SD *Ss* was increased by 50 percent. Similar, though inverse, results were obtained when SD *Ss* was decreased by 50 percent. Decreasing SD *Ss* resulted in good matches between high and low flows at the streamflow-gaging stations on the Assabet River (fig. 29*E*) and Nashoba Brook, where absolute monthly flow residuals were reduced relative to the calibrated model (table 14). Decreasing SD *Ss*, however, did not result in a better match between observed and model-calculated nonstorm streamflows at many tributaries, for example, at Cold Harbor Brook (fig. 29*F*). Additionally, water-level fluctuations were overestimated greatly with the decreased SD *Ss,* with the mean water-level fluctuation residual equal to 6.10 ft.

Monthly average nonstorm streamflows and water levels calculated with the transient model also were sensitive to changes in the distribution of recharge during the annual cycle. The distribution of recharge during the annual cycle could be changed in several ways. As an example, the fluctuation of monthly recharge rates around the mean annual rate was reduced proportionately by 50 percent (a factor of 2). With this change, which resulted in a mean water-level-fluctuation residual equal to 0.68 ft, the match between observed and model-calculated water-level fluctuations was improved greatly. However, the fluctuations in mean monthly nonstorm streamflows also were decreased greatly, such that the match between observed and model-calculated flows was much worse, especially during the low-flow period (table 14). For July, August, and September, absolute monthly flow residuals with reduced fluctuation of recharge averaged 116 percent of observed flows for the Assabet River streamflow-gaging station, 254 percent for the Nashoba Brook station, and 257 percent for all flow-calibration sites.

Finally, changes in the ET rate specified for wetlands, water bodies, and nonwetland areas also affected model-calculated nonstorm streamflows and water-level fluctuations. Decreasing the specified ET rates by 50 percent resulted in less fluctuations in water levels than simulated by the calibrated model (table 14). Model-calculated monthly nonstorm streamflows were higher than in the calibrated model, especially in the summer. This resulted in a worse fit between observed and model-calculated monthly nonstorm streamflows at many sites (figs. 29*G, H* and table 14).

The model runs with alternative values for storage properties and monthly recharge rates illustrate how the calibrated transient model balanced the need to match the observed monthly nonstorm streamflows and annual water-level fluctuations. In evaluating these model results, however, it is important to consider that the observed data used in model calibration were estimates that included several potential sources of error. Also, the inability of the ground-water-flow model to simulate unsaturated-zone and surface-water processes may contribute to differences between model-calculated and observed water-levels and streamflows, as discussed in the “Model Limitations” section.

Model-Calculated Water Budgets and Flows

Average water budgets for March and September, the high- and low-flow months of the simulated annual cycle, were calculated for the Assabet River Basin (table 15) and for its subbasins (fig. 30; subbasins shown in fig. 1). The detailed water budgets for the subbasins are tabulated in Appendix 2. During March, inflows to the ground-water-flow system were nearly all from precipitation recharge; outflows were about equally to storage and ground-water discharge to streams. During September, inflows to the ground-water-flow system were nearly all from storage, and outflows were about equal to evapotranspiration (from wetlands and nonwetland areas) and ground-water discharge to streams.

Anthropogenic outflows and inflows were larger percentages of total flows through the ground-water system or of streamflows in September than annually or in March, primarily because flows were lower overall in September. Basinwide, anthropogenic outflows equalled 9 percent of total flows through the ground-water system for water-supply withdrawals, 1.5 percent for infiltration to sewers, and less than 1 percent for other outflows in September; the inflow of septic-system return flow was 4 percent of total flows. Among subbasins, water withdrawals varied from 20 to 25 percent of total flows in the Assabet Upper Main Stem and Fort Meadow Brook subbasins to zero in basins with private supply. ET also varied among subbasins, depending to a large extent on the areal distribution of wetlands. The transient model also indicates that anthropogenic flows are large percentages of total model-calculated flows during low-flow periods in the same subbasins as on an average annual basis (figs. 22*B* and 30*B*). Anthropogenic outflows account for more than 20 percent of total model-calculated flows in September in the Fort Meadow and Assabet Main Stem Upper subbasins.

Table 15. Transient model-calculated average March and September water budgets for the Assabet River Basin, eastern Massachusetts.

[S1, Scenario 1; S2, Scenario 2; ET, evapotranspiration; Mgal/d, million gallons per day]

Hydrologic budget component	Rate of flow (Mgal/d)					
	1997–2001		S1		S2	
	March	September	March	September	March	September
Ground-water-flow system						
Inflow						
Recharge to stratified glacial deposits	247.4	0	247.4	0	247.4	0
Recharge to uplands	327.2	0	327.2	0	327.2	0
Recharge to kettle ponds	1.1	.06	1.1	.06	1.1	.06
Storage	.5	93.2	.0	90.3	.7	95.1
Stream leakage to aquifer	11.5	13.4	7.7	11.7	12.2	14.3
Septic-system return flow	4.3	4.3	0	0	3.0	3.0
Ground-water discharge of wastewater	0	0	0	0	.3	.3
Total inflow	592.0	111.6	583.4	102.1	591.9	112.8
Outflow						
Storage	260.9	.6	258.8	.4	261.6	.6
Ground-water discharge to streams	308.5	49.0	315.5	53.0	304.8	47.8
ET from wetlands and ponds	7.6	39.4	7.6	39.4	7.6	39.4
ET from nonwetland areas	0	9.7	0	9.9	0	9.4
Water-supply withdrawal[1]	9.3	10.5	0	0	11.4	13.0
Consumptive use in privately supplied areas	0	1.2	0	0	0	1.2
Consumptive use by unpermitted agriculture	0	.04	0	0	0	.04
Infiltration to sewers	4.2	1.7	0	0	4.7	1.9
Total outflow	590.8	112.1	581.9	102.7	590.1	113.3
Budget error (inflow minus outflow)	1.2	.5	1.5	.6	1.8	.5
Surface-water-flow system						
Inflow						
Net ground-water discharge[2]	297.1	36.1	307.8	41.3	292.7	34.1
Wastewater discharge	14.6	9.0	0	0	20.0	12.2
Outflow						
Water-supply withdrawals	.08	.5	0	0	.08	.6
Total nonstorm streamflow	311.7	45.1	307.8	41.3	312.6	45.7

[1] Includes withdrawals from ground water and surface water.

[2] Equal to model-calculated ground-water discharge to streams minus stream leakage to aquifer plus surface-water withdrawals. Surface-water withdrawals are included because they are included in water withdrawals calculated by the model for the ground-water-flow system.

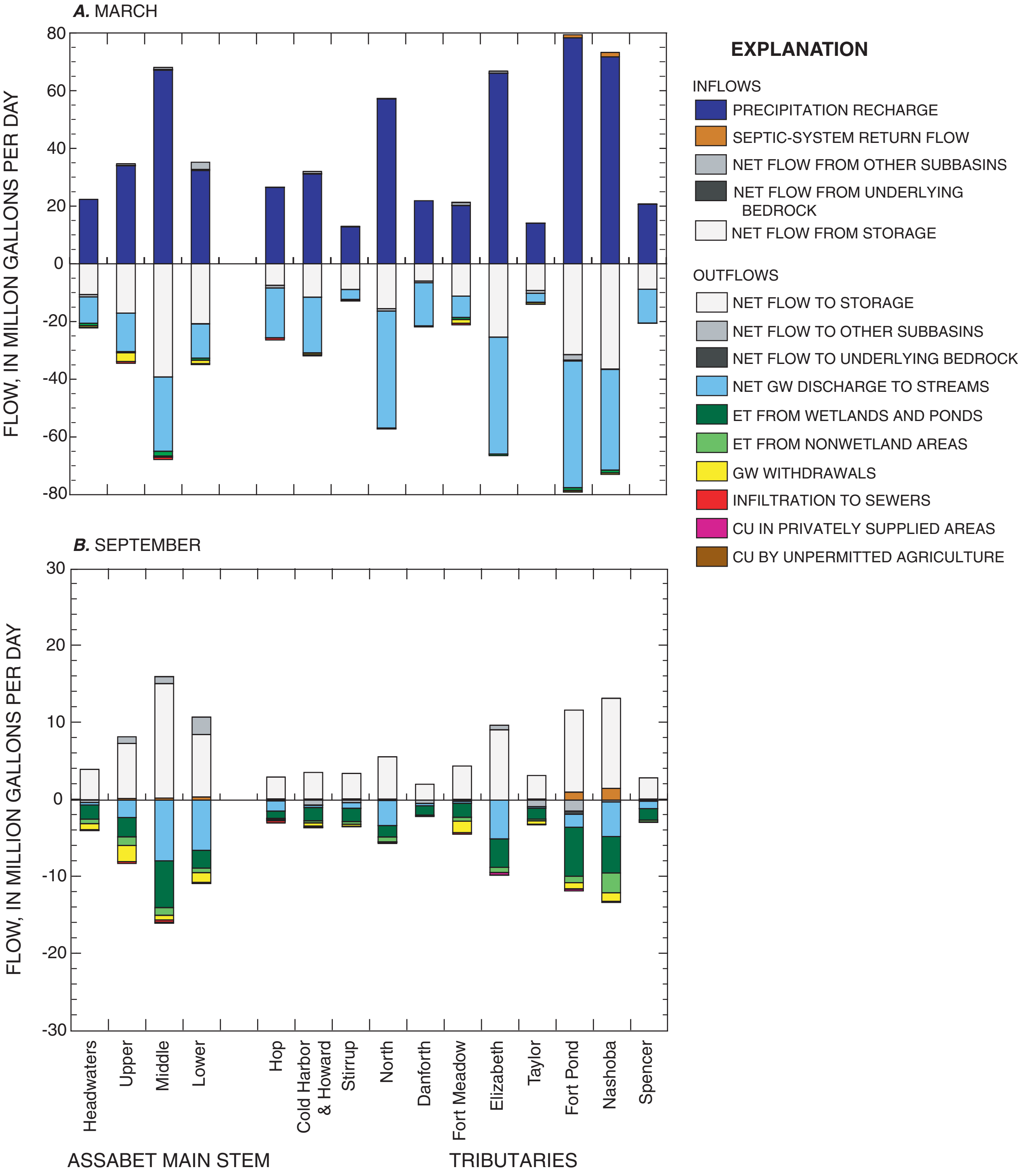


Figure 30. Model-calculated average *A*, March; and *B*, September inflows to and outflows from the surficial layer (layer 1) of the simulated ground-water-flow system in subbasins of the Assabet River Main Stem and tributary subbasins, 1997–2001, Assabet River Basin, eastern Massachusetts. Positive values are inflows and negatives values are outflows. GW, ground water; ET, evapotranspiration; CU, consumptive use.

Anthropogenic inflows and outflows to the surface-water-flow system (wastewater discharges and surface-water withdrawals) also accounted for larger fractions of total nonstorm streamflow in the main stem Assabet subbasins in September (fig. 31*B*) than annually or in March (figs. 23 and 31*A*). In September, wastewater accounted for on average 55, 32, and 20 percent of model-calculated nonstorm streamflow out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively, which is at least twice the fraction of flow that is wastewater on an annual average basis. At its maximum, immediately downstream of the Westborough Regional Wastewater Treatment Facility (stream mile 1.04, fig. 32), wastewater accounted for 93 percent of average September model-calculated nonstorm streamflow in the Assabet River. In March, when overall flows were much higher, wastewater accounted for only 14, 8, and 5 percent of nonstorm streamflow out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively (fig. 31*A*). Surface-water withdrawals, although larger percentages of total flows in September than annually, remained insignificant fractions of total model-calculated nonstorm streamflow in the main stem Assabet River (fig. 31*B*).

Model-calculated nonstorm streamflows at selected sites, when converted to cubic feet per second per square mile, can be compared to minimum streamflow requirements for habitat protection (fig. 33). Minimum streamflow requirements to maintain aquatic habitat recently were investigated for sites in Massachusetts, including six sites in the Assabet River Basin (Armstrong and others, 2004; Parker and others, 2004; table 16). Median values of 0.21 and 0.18 $ft^3/s/mi^2$ were determined for the low-flow period (R2Cross and wetted-perimeter methods, fig. 33), and a median value of 0.87 $ft^3/s/mi^2$ was determined for the high-flow period (R2Cross method) at 10 riffle sites in the Assabet and adjacent Charles River Basins; these values also bracketed the interquartile range of mean monthly flows for July, August, and September at several nearby streamflow-gaging stations with relatively unaltered flow (Parker and others, 2004). The minimum streamflow requirements determined with these two methods represent flows needed to provide a minimum water depth and velocity in the stream channel to maintain a healthy habitat for fluvial fish (Armstrong and others, 2001; Parker and others, 2004).

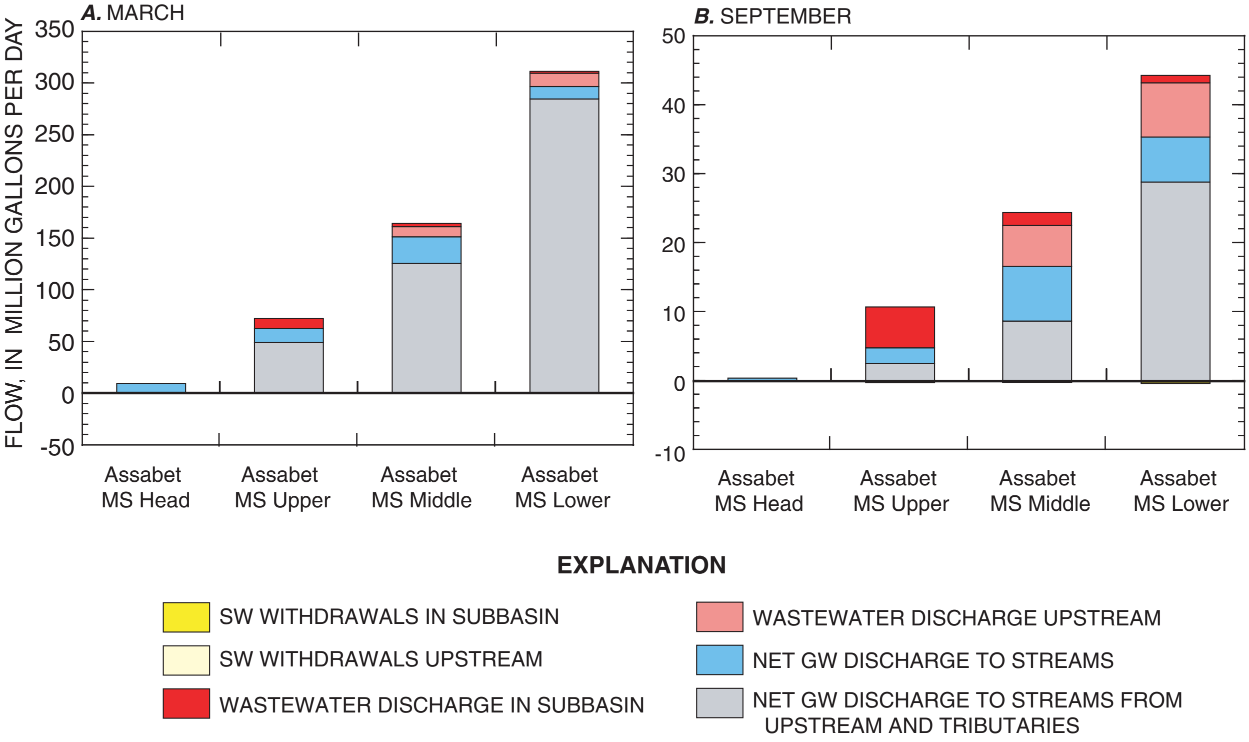


Figure 31. Model-calculated components of average *A*, March; and *B*, September nonstorm streamflow in subbasins of the Assabet River Main Stem (MS), eastern Massachusetts. SW, surface water; GW, ground water. Surface-water withdrawals in September of 0.12, 0.12, and 0.16 million gallons per day from the Upper, Middle, and Lower subbasins, respectively, are too small to be apparent at this scale.

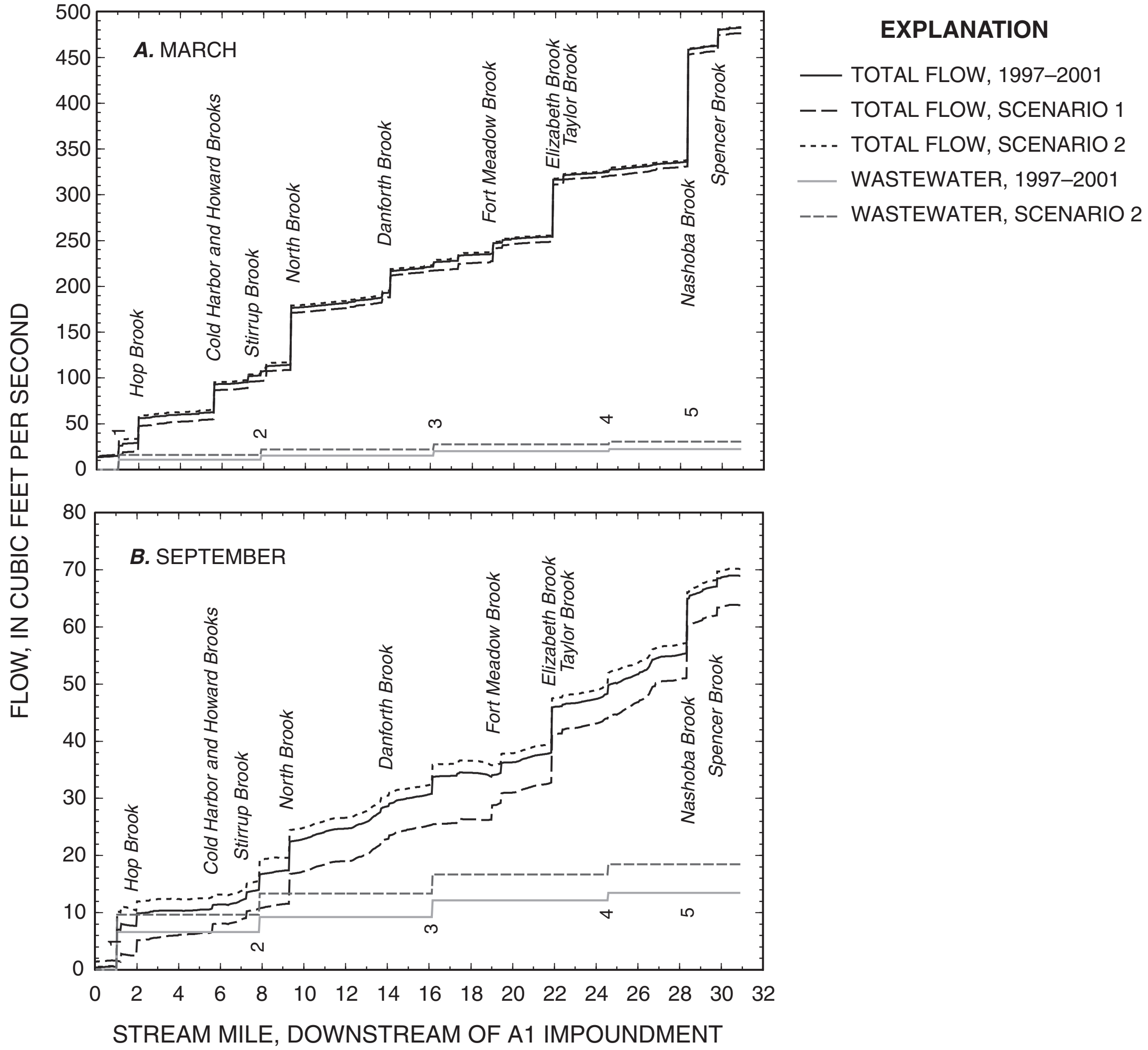


Figure 32. Model-calculated average *A*, March and *B*, September total nonstorm streamflow and the component of streamflow that originated as wastewater, for existing conditions (1997–2001) and two hypothetical scenarios of altered withdrawals and discharges in the Assabet River Basin, eastern Massachusetts. Numbers show locations of wastewater-treatment facility (WWTF) discharges: 1, Westborough WWTF; 2, Marlborough WWTF; 3, Hudson WWTF; 4, Maynard WWTF; 5, MCI Concord WWTF.

Model-calculated mean monthly nonstorm streamflows under existing conditions in September (in most cases the lowest-flow month of the annual cycle) at the outlets of about half the tributary subbasins were above the median minimum streamflow requirements for low flows for Assabet and Charles River Basin sites (0.18 or 0.21 ft^3/s/mi^2; fig. 33; Parker and others, 2004). Model-calculated mean September nonstorm streamflow for Cold Harbor and Howard, Danforth, Fort Meadow, Taylor, and Fort Pond Brook subbasins were lower than the low-flow minimum streamflow requirement; these include subbasins where withdrawals and other flow alterations were 10 to 25 percent of total flows. At five of the six sites in the Assabet River Basin where minimum streamflow requirements were determined, model-calculated mean September nonstorm streamflow was above or near the minimum streamflow requirements for low-flow conditions (table 16).

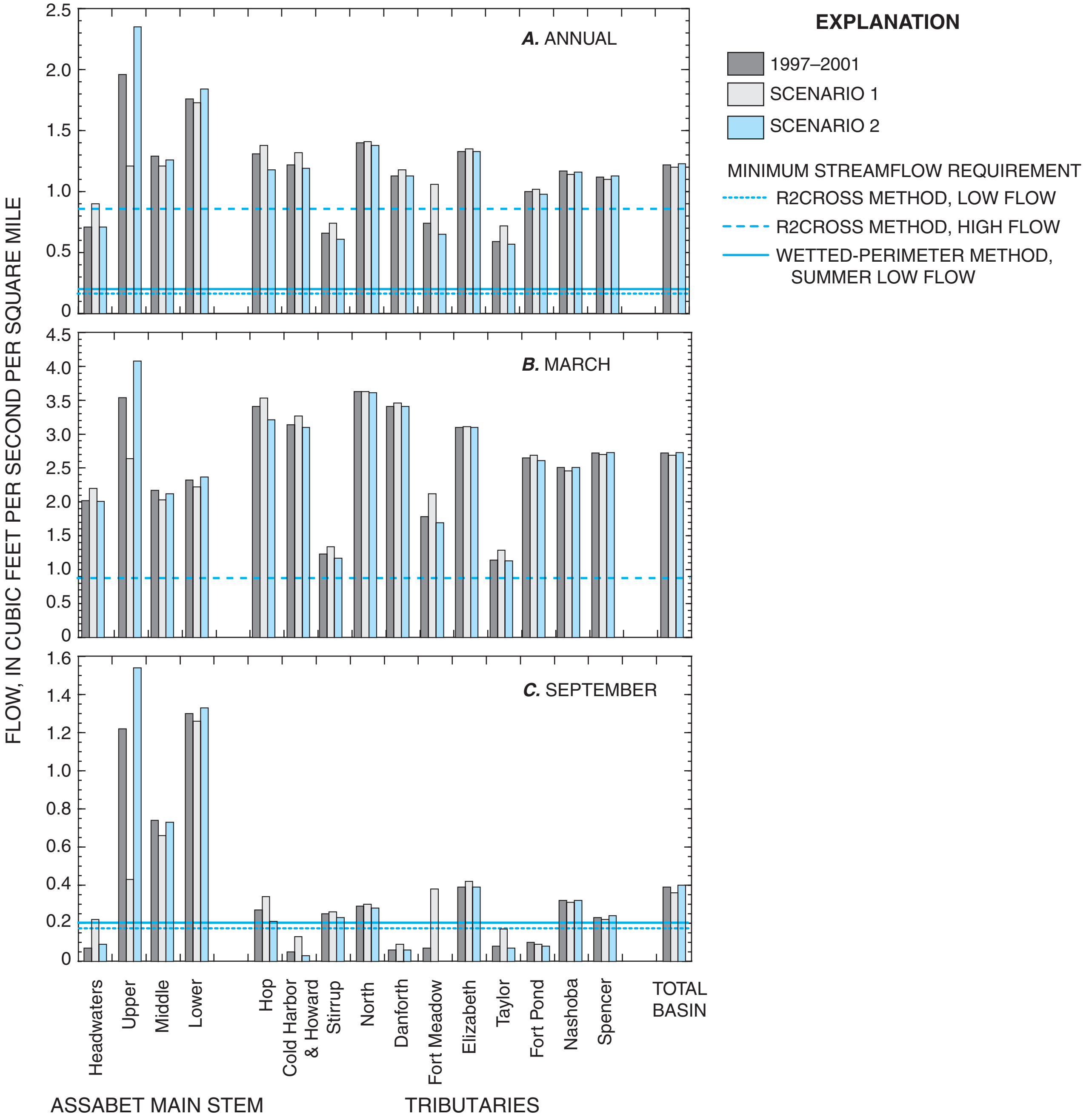


Figure 33. Model-calculated average *A*, annual; *B*, March; and *C*, September nonstorm streamflow from subbasins of the Assabet River Main Stem, eastern Massachusetts, and tributaries for comparison with minimum streamflow requirements for the protection of aquatic habitat. Minimum streamflow requirements from Parker and others (2004).

Table 16. Model-calculated mean monthly nonstorm streamflows for August and September at sites for comparison with minimum streamflow requirements for habitat protection, Assabet River Basin, eastern Massachusetts.

[**Minimum streamflow requirement for habitat protection**: from G.W. Parker, U.S. Geological Survey, written commun., 2004. ft^3/s/mi^2, cubic foot per second per square mile; mi^2, square mile]

Station number	Station name	Drainage area (mi^2)	Minimum streamflow requirement for habitat protection (ft^3/s/mi^2)			Model-calculated non-storm streamflow (ft^3/s/mi^2)								
			R2Cross method		Wetted-perimeter method	1997–2001			Scenario 1			Scenario 2		
			High flow	Low flow		Annual	March	September	Annual	March	September	Annual	March	September
01096015	Assabet River, Fisher Street, Westborough	6.8	1.01	0.07	0.05	0.75	2.11	0.08	0.94	2.29	0.23	0.74	2.10	0.09
01096701	Cold Harbor Brook, Cherry Street, Northborough[1]	5.1	.69	.05	.26	1.36	3.24	.21	1.43	3.35	.26	1.35	3.23	.20
01096853	Danforth Brook, Route 85, Hudson	5.1	2.13	.30	.51	1.12	3.29	.06	1.14	3.30	.07	1.12	3.28	.06
01096877	Fort Meadow Brook, Shay Street, Hudson	5.0	1.51	.45	.35	.89	1.65	.36	.98	1.76	.43	.85	1.61	.33
01096945	Elizabeth Brook off White Pond Road, Stow	18.7	.55	.34	.18	1.38	3.26	.40	1.41	3.27	.43	1.38	3.26	.40
01097380	Nashoba Brook,Commonwealth Avenue, West Concord[2]	48.0	.14	.10	.11	1.06	2.54	.20	1.06	2.54	.19	1.05	2.53	.19

[1] Minimum streamflow requirement based on hydraulic model for one stream-channel cross section only.

[2] Stream channel at riffle site was a constructed channel.

Several factors complicate the comparison of model-calculated flows with minimum streamflow requirements. Model-calculated flows may under- or overestimate actual average monthly flows at measurement sites. For example, model calibration data indicated that mean monthly flows during the low-flow period were overestimated by the model at sites in Elizabeth and North Brooks; estimated flow values were equal to 0.24 and 0.17 $ft^3/s/mi^2$, respectively, at partial-record measurement sites (Appendix 2), as compared to model-calculated values of 0.39 and 0.29 $ft^3/s/mi^2$. Also, the median minimum streamflow requirements are based on site-specific values that are variable. For example, minimum streamflow requirements for low-flow conditions determined with the R2Cross method varied from 0.05 to 0.45 $ft^3/s/mi^2$ for the six sites in the Assabet River Basin (table 16). This variability may result partly from differences in stream-channel materials, flow alterations in the basin, or other sources. Therefore, minimum flows to maintain fluvial habitat may vary naturally among subbasins, and along stream reaches within subbasins. Model-calculated flows are monthly averages of nonstorm flow. A mean September model-calculated flow that is at or near the minimum streamflow requirement may represent mean daily flows that are below the minimum streamflow requirement about half the time. Conversely, stormwater flows augment mean daily flows during some of this time. Finally, application of minimum streamflow requirements, such as determined by methods like these, for comparison with measured or model-calculated flows or for regulatory purposes would take into account the natural variability within a month and between years (Armstrong and others, 2004)

Model Limitations

The steady-state and transient flow models of the Assabet River Basin provide a regional-scale simulation of ground-water flow in the stratified glacial aquifers in the study area. As with all mathematical models of natural systems, the simplifications and assumptions incorporated into the models cause limitations in their appropriate uses and to the interpretations of simulation results.

The ground-water-flow models simulate flows and water levels in surface-water features only to the extent that they represent discharge areas or boundaries for the ground-water system. Flows in simulated streams, therefore, do not include the direct runoff component of streamflow, but represent only the component of flow that originated as ground-water discharge (base flow), plus any augmentations resulting from wastewater discharge. Although delineation of storm flow and base flow conceptually is simple, runoff and the response of the hydrologic system to precipitation events are complicated and variable, such that in practice distinguishing between storm runoff and base flow is difficult. The simulated surface-water features represent a simplified version of the surface-water-flow system. The models do not simulate the hydraulics of the surface-water system, such as storage provided by impoundments and wetlands. Although these effects are in many cases short-term, they may affect the monthly average flows simulated by the ground-water-flow models. Another simplification of the surface-water system is the use of a fixed value, representing average conditions, for stream stage; this approach may lead to inaccuracies in flow rates between aquifers and streams, particularly during periods of high flow or around impoundments. Finally, wetlands are simulated in a simple way that may not adequately describe their roles and the variability in their function in the hydrologic system. For example, the seasonal effect of wetlands on streamflows, as areas of water loss through evapotranspiration during the growing season, is simulated. The role of wetlands as drains during high-flow months, however, is probably not adequately simulated, because only mapped stream channels are simulated as areas in wetlands where ground-water can discharge to the surface-water system. More information about the regional-scale function of wetlands in hydrologic systems like the Assabet River Basin, and alternative approaches for simulating them, are needed in order to more accurately simulate the role of wetlands in the basin.

Ground-water flow through till and bedrock also is simplified greatly in the Assabet River Basin models. Ground water in fractured bedrock can have a widely variable area of recharge and discharge. Water withdrawals from bedrock aquifers can be simulated, and their effects on hydrologic fluxes, including streamflows, in the basin can be determined in a general way. However, the simulated locations of contributing areas for bedrock withdrawals may differ from actual contributing areas if flow patterns in the bedrock differ substantially from near-surface flow patterns. The models can be modified, however, to incorporate site-specific information about flow patterns and contributing areas for specific withdrawals, as was done for the existing models (Lyford and others, 2003) for the Maynard bedrock supply wells.

Unsaturated-zone processes are not simulated in the ground-water-flow model. Storage and flow in the unsaturated zone affect the timing of ground-water recharge and affect ground-water-level fluctuations. Lack of detailed knowledge about unsaturated-zone processes and the inability to account for them in the model may affect the calibration results. These effects probably are more significant for transient model results than for steady-state results, because unsaturated-zone processes would be expected to influence the timing of recharge.

Temporal and spatial scales also limit model use and accuracy. Hydrologic processes and hydraulic stresses were represented in the transient models as monthly averages. Simulation results are monthly average ground-water levels and flows. The models were not intended to be used to simulate changes at time scales, such as daily values, which substantially may exceed or fall below monthly average values. Spatial data available at the regional scale also limit model accuracy. For example, horizontal and vertical variations in hydraulic properties at the scale of subbasins or depositional packages were not simulated because of a lack of available data. The spatial resolution of the simulation results was limited by the area of the 200×200-ft grid cell. Water withdrawals, discharges, and streamflow and water-level observations were averaged within grid cells, and their exact locations were approximated by the centers of the cells in which these fluxes occurred.

Evaluation of Ground-Water-Management Alternatives

The ground-water-flow models developed in this study can be used to evaluate the response of the ground-water-flow system, and consequent effects on streamflow, that result from changes in water-management practices or hydrologic conditions in the Assabet River Basin. Increased water withdrawals or discharges, alternative pumping schedules for existing withdrawals, land disposal of treated wastewater, sewering, or stormwater recharge are examples of water-management practices that may be simulated. Altered hydrologic conditions that could be simulated include drought conditions or conditions of altered recharge that may result, for example, from land-use changes.

Two approaches were used to investigate alternative water-management practices in the Assabet River Basin. Both approaches use the transient flow model. First, the flow model was used to determine the effects of increased withdrawals and discharges in several hypothetical scenarios. These scenarios represented possible changes in water use in the basin or water-management practices that could mitigate potential adverse effects of increased water withdrawals and (or) wastewater discharges. Second, the flow model was used in conjunction with optimization techniques. This approach was used to quantify possible increases in streamflow that could be obtained by optimizing water withdrawals in an area of the basin where demands on water resources are high. Both hypothetical scenarios and optimization analyses were defined through consultation with the TAC.

Simulation of Altered Withdrawals and Discharges

Three scenarios of altered withdrawals and discharges were tested. In the first scenario (S1), water flows and stresses associated with human management of the hydrologic system were eliminated. In the second scenario (S2), water withdrawals and discharges were increased to rates currently allowed by State and Federal permits. In a third set of scenarios (S3A–D), wastewater discharge at hypothetical ground-water discharge sites was simulated. Results of the scenarios were evaluated with respect to changes in model-calculated nonstorm streamflow relative to existing (1997–2001) conditions.

Simulation of No Water Management

In S1, water withdrawals and wastewater discharges were set to zero. Recharge rates representing septic-system return flow, consumptive use in privately supplied areas, consumptive use by unpermitted agriculture, and infiltration to sewers also were set to zero. All other stresses and properties, including recharge from precipitation and evapotranspiration of ground water, remained the same as were used in the calibrated transient model. Detailed water budgets for the entire Assabet River Basin and subbasins for S1 are provided in table 15 and Appendix 2.

On an average annual basis, model-calculated nonstorm streamflows in tributaries and at the outlet of the Assabet Main Stem Headwaters subbasin were greater in most cases in S1 than under simulated existing (1997–2001) conditions (table 17). Increases relative to model-calculated 1997–2001 flows ranged from 2 percent, in the Elizabeth Brook subbasin, to 44 percent, in the Fort Meadow Brook subbasin. In most subbasins, increases in model-calculated flows resulted from a combination of decreased withdrawals and decreased infiltration to sewers, the relative importance of which varied among subbasins (fig. 34). Decreased withdrawals contributed most to the increases in model-calculated streamflows in the Assabet Main Stem Headwaters, Cold Harbor and Howard Brooks, Stirrup Brook, Fort Meadow Brook, and Taylor Brook subbasins. In the Hop Brook and Danforth Brook subbasins, decreased infiltration to sewers contributed most to increases in model-calculated streamflows. Decreases in withdrawals and infiltration to sewers were offset in many subbasins by decreases in septic-system return flow (fig. 34), which was an inflow to the aquifer and augmented streamflow under simulated existing conditions. In the Fort Pond Brook and Nashoba Brook subbasins, with primarily public water supply and private disposal, decreases in septic-system return flow were nearly equal or greater than decreases in withdrawals or other outflows, such that model-calculated streamflows in these subbasins were less or about the same in S1 than under simulated existing conditions. In Elizabeth Brook, where private water supply and disposal serve most of the population, the small streamflow increase resulted mostly from decreased consumptive use (fig. 34). In the North and Spencer Brook subbasins, with no public-water withdrawals but with public and private disposal, decreases in consumptive use and septic-system return flow balanced such that streamflow changes were small. In a few subbasins, there also were relatively large changes in flows to or from adjacent subbasins that resulted from the elimination of large withdrawals near subbasin boundaries in S1 (fig. 34).

Along the main stem Assabet River downstream of the Headwaters subbasin (and downstream of the Westborough Wastewater Treatment Facility), model-calculated flows were less in S1 than under simulated existing conditions (fig. 24 and table 17). At outlets of the Assabet River Main Stem subbasins, flow reductions ranged from 2 to 3 percent on an annual average basis, and resulted primarily from the elimination of wastewater discharges to the river. These reductions in wastewater discharge, which augment flow in the river under existing conditions, were offset partly by decreases in water withdrawals and infiltration to sewers, which deplete flow under existing conditions, and increased flow from tributaries.

Changes in mean monthly model-calculated flows in S1 relative to simulated existing conditions varied during the annual cycle and among subbasins, depending on the variable monthly rates of withdrawals, infiltration to sewers, and other flows and on the response time of streamflow to these changes. Changes generally were smaller fractions of total model-calculated nonstorm streamflow during March, when overall flows through the hydrologic system were high, and changes were larger fractions of total streamflow during September, during the low-flow period (table 17 and fig. 32). In March, increases in model-calculated nonstorm streamflow in tributaries ranged from less than 1 to about 20 percent. In September, increases ranged from 4 to more than 100 percent. In the Main Stem Assabet River, proportional decreases in streamflow in S1 relative to existing conditions were greatest downstream of the Westborough Wastewater Treatment Facility, resulting in decreases of more than 60 percent, and were least, about 7 percent, at the confluence with the Sudbury River (fig. 32).

Table 17. Model-calculated nonstorm streamflow from subbasins in the Assabet River Basin, eastern Massachusetts, for existing conditions (1997–2001) and two scenarios of altered water-management practices.

Subbasin	Model-calculated nonstorm streamflow (cubic foot per second)								
	1997–2001			Scenario 1			Scenario 2		
	Annual	March	September	Annual	March	September	Annual	March	September
Assabet River									
Main Stem Headwaters	5.06	14.33	0.53	6.37	15.57	1.58	5.04	14.24	0.62
Main Stem Upper	50.12	113.0	16.89	45.52	107.57	11.04	52.56	116.27	19.44
Main Stem Middle	113.01	254.38	37.97	109.16	248.72	32.69	113.92	255.59	39.56
Main Stem Lower	216.17	482.13	68.94	212.87	476.26	63.81	217.21	483.57	70.79
Tributaries to Assabet River									
Hop Brook	10.28	26.73	2.15	10.84	27.71	2.65	9.24	25.20	1.66
Cold Harbor and Howard Brooks	11.65	29.96	.49	12.65	31.20	1.27	11.34	29.60	.25
Stirrup Brook	2.86	5.37	1.10	3.21	5.81	1.13	2.63	5.08	.99
North Brook	23.93	62.20	5.01	24.08	62.18	5.18	23.67	61.81	4.83
Danforth Brook	7.79	23.45	.45	8.10	23.80	.59	7.75	23.41	.44
Fort Meadow Brook	4.73	11.43	.43	6.79	13.62	2.46	4.20	10.83	.01
Elizabeth Brook	26.51	61.85	7.83	26.96	62.15	8.33	26.51	61.85	7.83
Taylor Brook	2.47	4.80	.33	3.04	5.44	.71	2.41	4.74	.30
Fort Pond Brook	50.92	122.34	9.56	50.87	122.21	9.23	50.34	121.69	9.14
Nashoba Brook	25.24	54.32	6.96	24.70	53.09	6.80	25.17	54.27	6.90
Spencer Brook	7.31	17.77	1.50	7.19	17.62	1.45	7.36	17.84	1.56

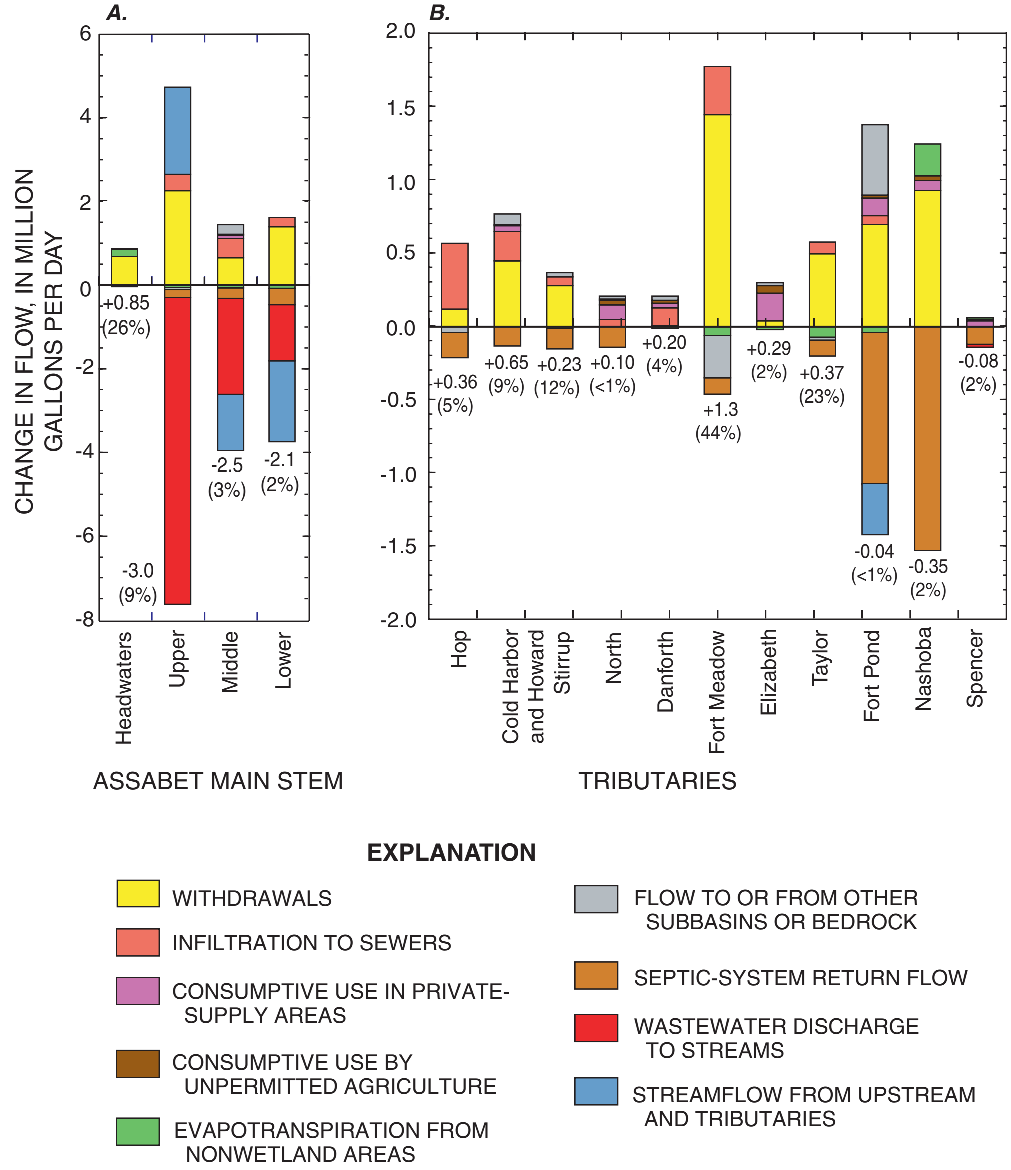


Figure 34. Model-calculated changes, relative to simulated 1997–2001 conditions, in average annual inflows to and outflows from the surficial layer (layer 1) of the simulated ground-water-flow system in subbasins of the *A*, Assabet River Main Stem; and *B*, tributary subbasins, in a hypothetical scenario of no water management (scenario 1) in the Assabet River Basin, eastern Massachusetts. Numbers are net changes in model-calculated non-storm streamflow relative to existing conditions, in million gallons per day and percent (%); <, value is less than value shown.

Simulation of Increased Withdrawals and Discharges

In S2, withdrawal rates for municipal and nonmunicipal sources/users were increased to system-wide average annual rates permitted under the WMA (tables 9 and 10). Rate increases were distributed among months and among individual sources in proportion to existing (1997–2001) pumping rates (Appendix 3). For municipal sources, if this resulted in rates greater than permitted rates for an individual source ("Zone II" approved rates, B.R. Bouck, Massachusetts Department of Environmental Protection, oral commun., 2002), the withdrawal rate at the source was set to its approved rate, and rates at other sources in the hydrologic system were increased. The WMA permit for Westborough applies to sources in the Assabet and Sudbury River Basins. However, it was considered reasonable to simulate all of the available increase in system-wide withdrawals from Assabet sources, because a new source for Westborough in the basin (WB-07G or the Indian Meadows Well) had the capacity to provide most of the additional withdrawals. Withdrawals in excess of 1997–2001 rates for Westborough were taken from WB-07G until its Zone II approved rate was reached.

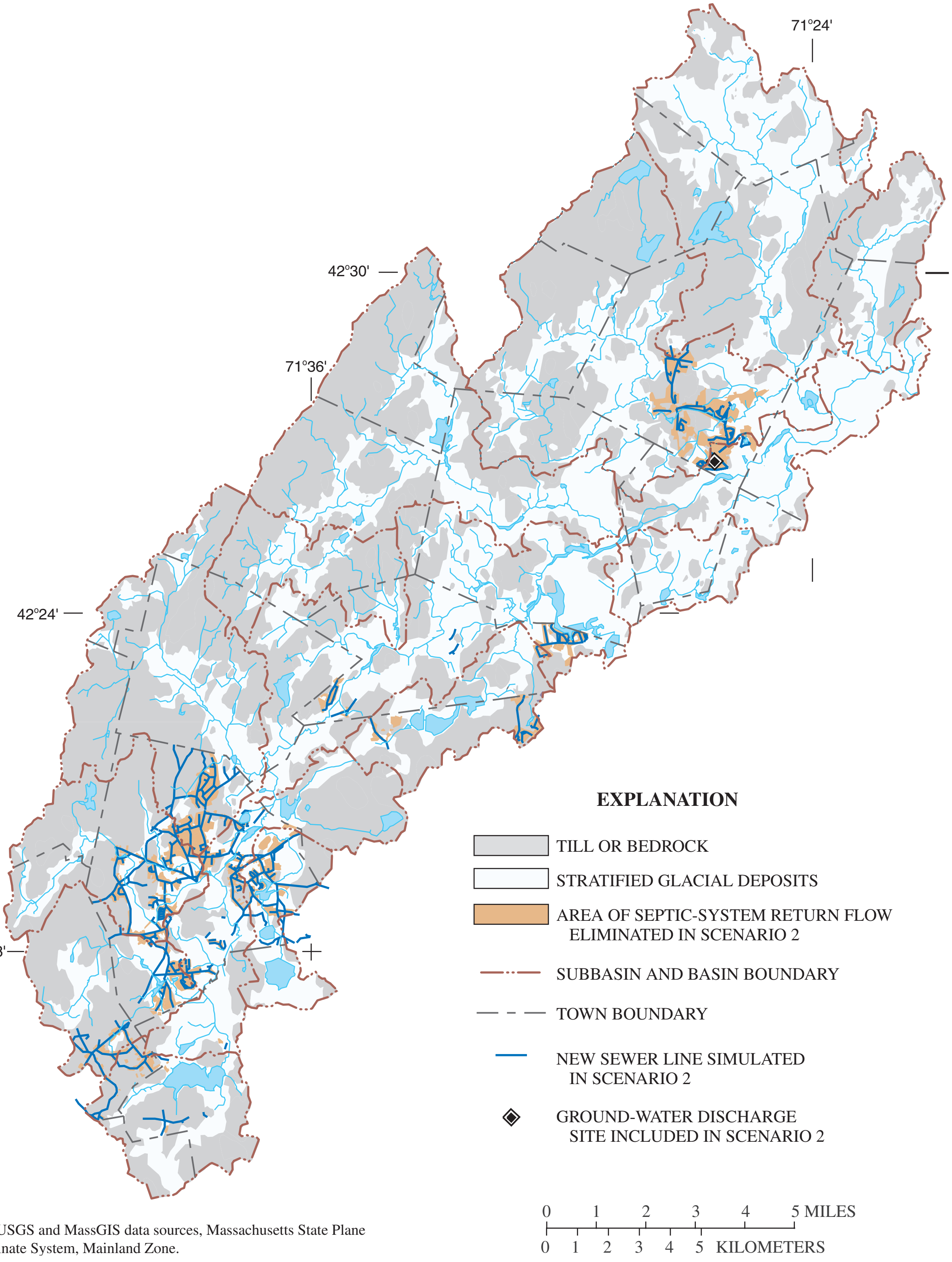
Wastewater discharges at municipal and nonmunicipal treatment facilities were increased in S2 to rates permitted under the National Pollution Discharge Elimination System (NPDES; table 10), on an average annual basis. Rate increases for wastewater discharges were distributed among months in proportion to existing discharge rates, as was done for water withdrawals (Appendix 3). The increase in wastewater discharge, 3.0 Mgal/d, exceeded the increase in water-supply withdrawals, 2.3 Mgal/d, in the basin. This result was considered reasonable because increased wastewater discharges could result from the increased imports into the basin or from increased delivery of wastewater from within the basin (from newly sewered areas) to the treatment facilities.

The extension of existing sewered areas also were simulated in S2. New sewers were simulated in areas identified in the Wastewater Management Plans of towns in the Assabet Consortium. These areas included nearly all of the developed areas of Northborough that were not sewered under existing conditions, and small areas of Hudson, Maynard, Marlborough, and Westborough (fig. 35). Sewers also were simulated in an area in southwest Acton where sewers were installed after 2001 (Woodward and Curran, 2002; fig. 35). Ground-water discharge of wastewater from the new treatment facility in Acton, the Adams Street facility, was simulated with the Well Package at the permitted rate of 0.25 Mgal/d. Infiltration to sewers was simulated with the Recharge Package by using loss rates that varied by town and were set equal to 50 percent of the rates used for existing sewers. The average rate for all towns was used for the Acton sewers. Septic-system return flow in areas of new sewers was eliminated (fig. 35).

Aquifer stresses and properties other than withdrawals and discharges for permitted users and infiltration to sewers were the same as those used in the calibrated transient model representing existing conditions. Consumptive use in privately supplied areas, consumptive use by unpermitted agriculture and golf courses, and septic-system return flow in unsewered areas were not changed in S2. Detailed water budgets for the entire Assabet River Basin and subbasins for S2 are provided in Appendix 2.

On an average annual basis, model-calculated nonstorm streamflows in nearly all tributaries in S2 were less than under simulated existing conditions (table 17). Decreases relative to model-calculated 1997–2001 flows ranged from less than 1 percent, in the Danforth and Nashoba Brook subbasins, to about 10 percent, in the Hop and Fort Meadow Brook subbasins. Model-calculated flows did not change in the Elizabeth Brook subbasin, where withdrawals and other fluxes did not change. Flows increased in the Spencer Brook subbasin because of increased wastewater discharge from the Middlesex School. In Hop, Fort Meadow, and Taylor Brook subbasins, increased withdrawals accounted for most of the decrease in streamflow (the large increase in flow to adjacent subbasins in Hop Brook resulted from increased withdrawals at a source outside the subbasin boundary), but decreased septic-system return flow accounted for most of the decreased streamflow in other subbasins (fig. 36). As in S1, changes in monthly model-calculated nonstorm streamflows were largest relative to 1997–2001 flows in September during the low-flow period, when decreases in model-calculated flows ranged from about 1 to 98 percent (table 17).

In the Assabet River Main Stem subbasins other than the Headwaters subbasin, model-calculated nonstorm streamflows increased relative to 1997–2001 flows (fig. 24 and table 17). The increases were about 5 percent in the Upper subbasin and less than 1 percent in the Middle and Lower subbasins, on an average annual basis, and resulted from the net effects of increased wastewater discharge, increased withdrawals, and decreased inflow from tributaries. Consequently, the percentage of streamflow that originated as wastewater increased relative to simulated existing conditions. In March, wastewater accounted for 19, 11, and 6 percent of model-calculated flow out of the Upper, Middle, and Lower subbasins, respectively, increases of several percentage points relative to simulated 1997–2001 flows (figs. 32*A* and 37*A*). In September, wastewater accounted for 69, 42, and 27 percent of model-calculated flow from the three subbasins, or increases of about 10 percentage points (figs. 32*B* and 37*B*).



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 35. Changes in sewer lines and areas of septic-system return flow simulated in a hypothetical scenario of increased withdrawals and discharges (scenario 2) in the Assabet River Basin, eastern Massachusetts.

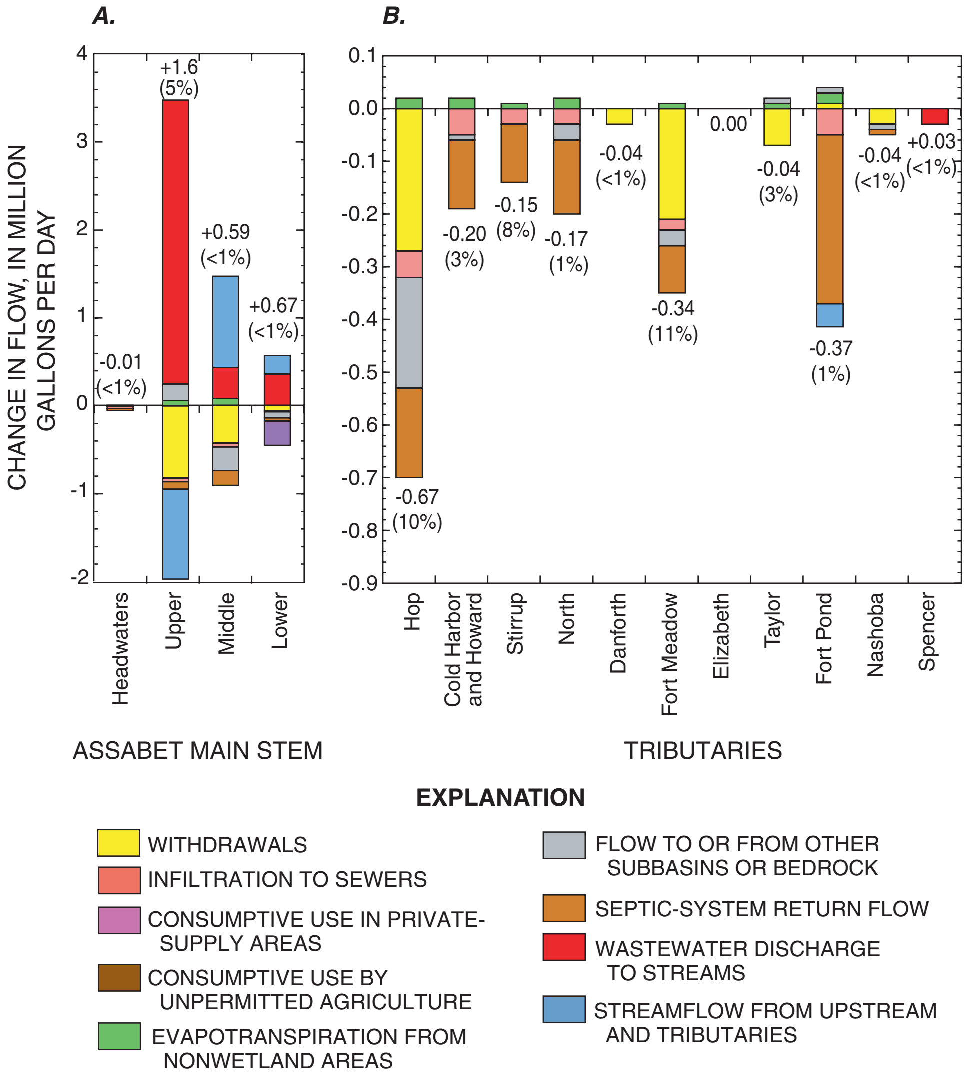


Figure 36. Model-calculated changes, relative to simulated 1997–2001 conditions, in average annual inflows to and outflows from the surficial layer (layer 1) of the simulated ground-water-flow system in subbasins of the *A*, Assabet River Main Stem; and *B*, tributary subbasins, in a hypothetical scenario of increased withdrawals and discharges (scenario 2) in the Assabet River Basin, eastern Massachusetts. Numbers are net changes in model-calculated nonstorm streamflow relative to existing conditions, in million gallons per day and percent (%); <, value is less than value shown.

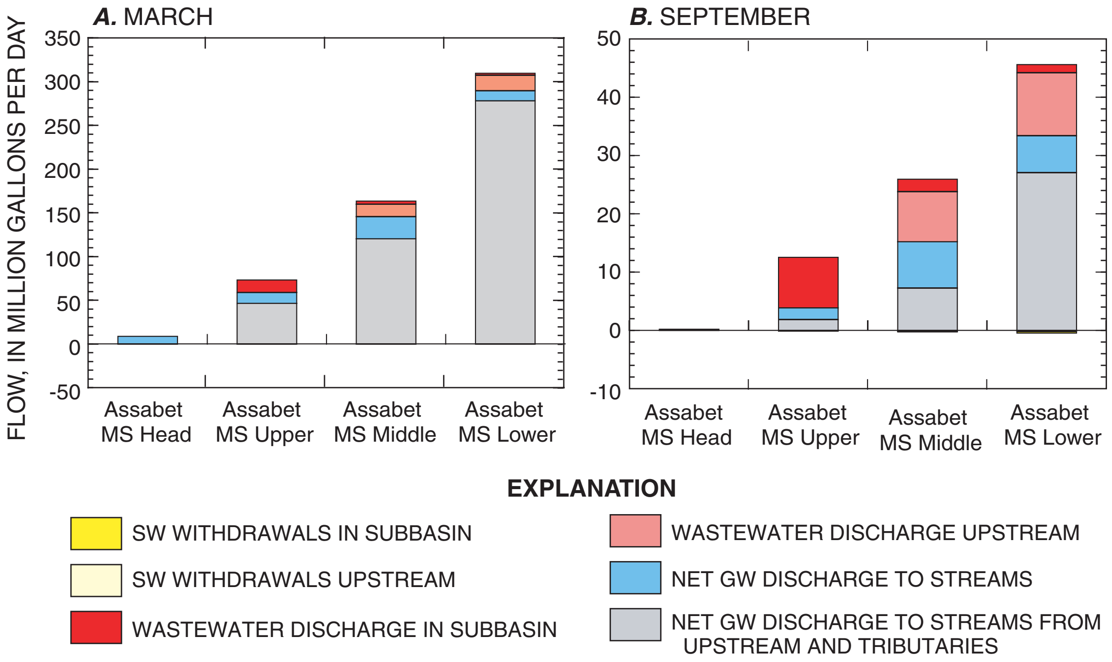


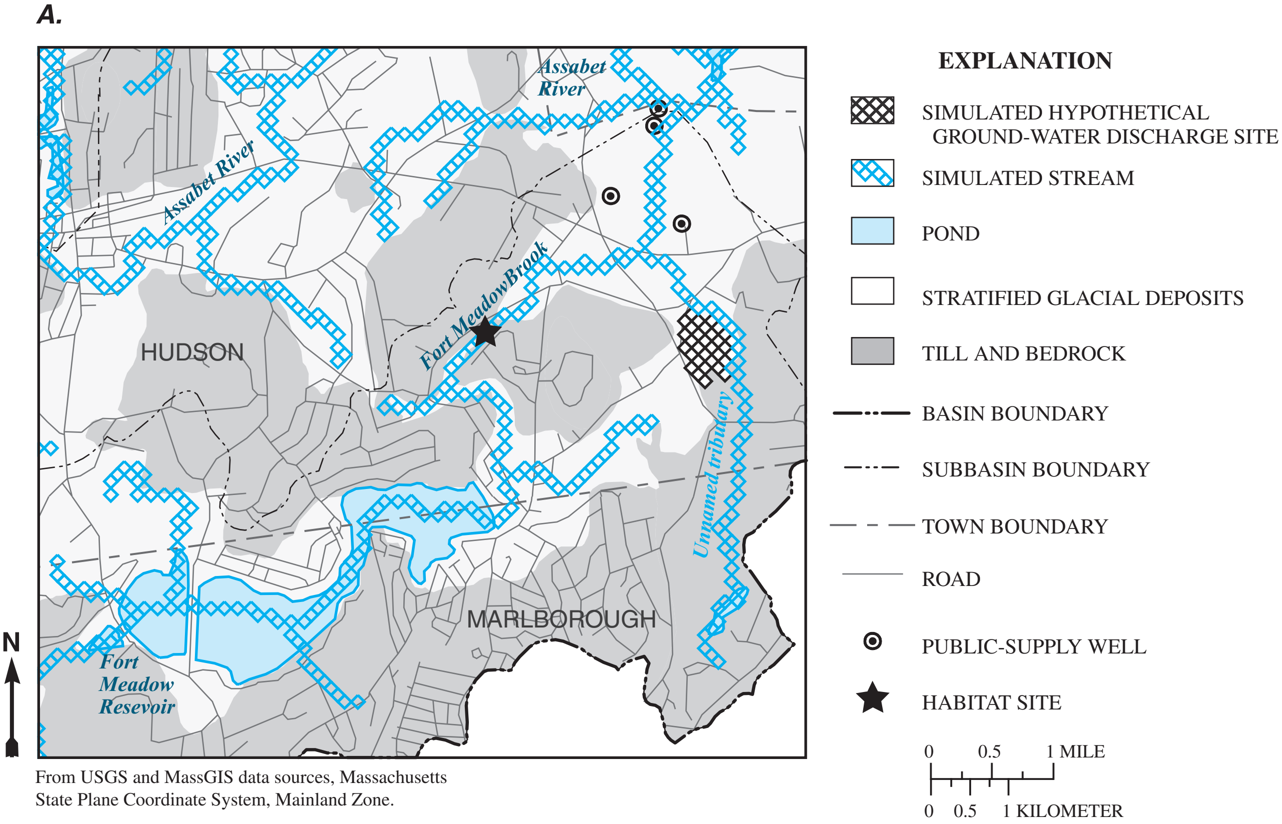
Figure 37. Model-calculated components of average *A*, March; and *B*, September nonstorm streamflow in subbasins of the Assabet River Main Stem (MS), in a hypothetical scenario of increased withdrawals and discharges (scenario 2) in the Assabet River Basin, eastern Massachusetts. SW, surface water; GW, ground water. Surface-water withdrawals in September of 0.15, 0.12, and 0.17 million gallons per day from the Upper, Middle, and Lower subbasins, respectively, are too small to be apparent at this scale.

In many subbasins, evapotranspiration from nonwetland areas decreased, contributing to a small increase in model-calculated nonstorm streamflow (Appendix 2). This process was simulated with the Evapotranspiration Package, and its rate varied with water levels. Therefore, lowered water levels resulting from increased withdrawals and decreased septic-system return flow in S2 were accompanied by less ET from nonwetland areas. Reduced ET from a wetland represents a change in its hydrologic budget that could be accompanied by other changes in the wetland, for example, in its vegetation. Because ET from wetland areas was simulated as a fixed loss rate, the effects of altered withdrawals and return flow on this process were not simulated in S2 or in S1.

Simulation of Ground-Water Discharge of Wastewater

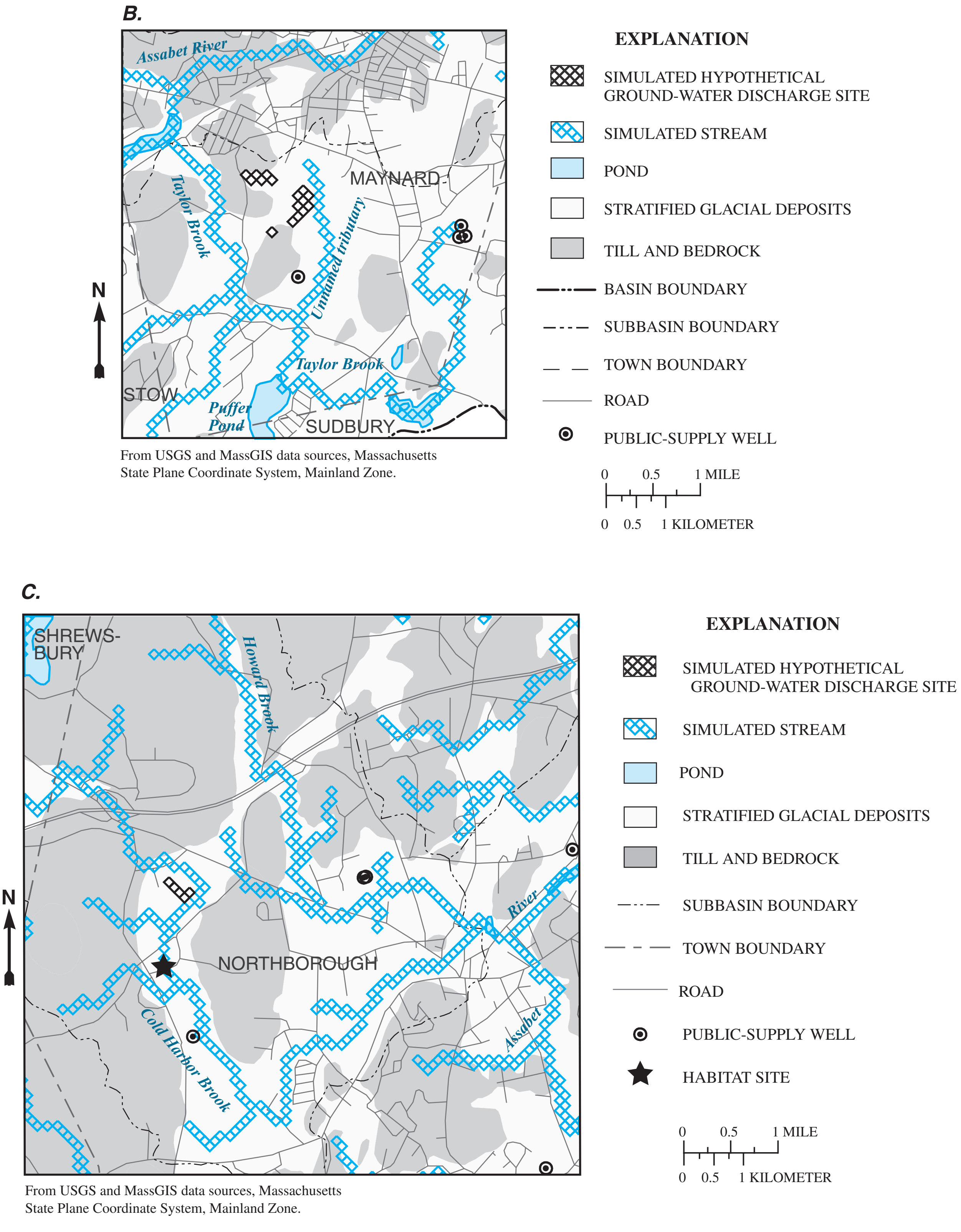
Wastewater recharge to the ground-water flow system was simulated for four hypothetical ground-water discharge sites in the basin in S3A–D (fig. 38 and table 18). The four sites were chosen in consultation with the TAC from among those identified in the Wastewater Management Plans of the Assabet Consortium towns. The sites were chosen in subbasins with relatively large water withdrawals, in areas of stratified glacial deposits, and, where possible, upstream of a site where minimum streamflow requirements for habitat protection were investigated (Parker and others, 2004); they included several identified as most feasible for discharge in the Wastewater Management Plans. A site in Northborough in the Cold Harbor and Howard Brooks subbasin was included because of its location near the headwaters of a small tributary and upstream of a habitat site, although its size and other considerations made it less favorable than other sites (Fay, Spoffard, and Thorndike, 2002a).

Wastewater discharge at the sites was simulated with the Well Package of MODFLOW-2000. Flow rates were selected by using available data and analysis in the Wastewater Management Plans. Rates ranged from 0.31 to 1.5 Mgal/d (table 18). The simulated discharge was distributed over multiple model cells at each site (table 18 and figs. 38*A*–*D*) within the land parcel identified in the Wastewater Management Plan. For sites in Hudson (site A) and Westborough (site D), model cells for discharge were identified by using areas delineated in GIS as viable for ground-water discharge based on soils, wetland areas, and other considerations (Stacy Rogers and John Himlan, Earth Tech, written commun., 2003). For the site in Northborough (site C), an area for discharge was delineated in GIS within the appropriate parcel that was outside of a 100-ft buffer around wetland areas (parcel data, David Kane, Town of Northborough, written commun., 2003; wetland data, MassGIS, 2001). For the site in Maynard (site B), no digital spatial data were available. Model cells for discharge were approximately within the identified parcels and outside of a 100-ft buffer around wetlands.



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

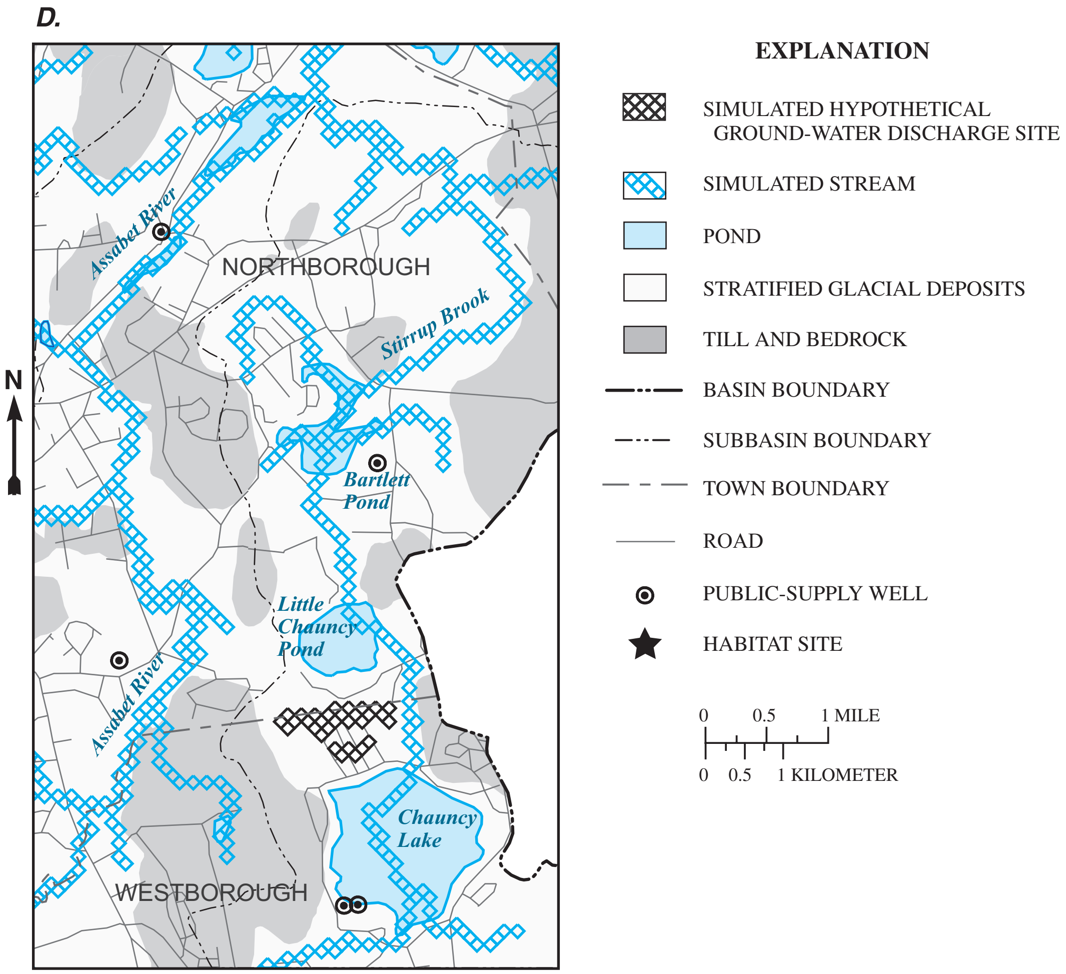
Figure 38. Hypothetical ground-water discharge sites for wastewater used in simulations (scenarios 3A–D) in the Assabet River Basin, eastern Massachusetts: *A*, Fort Meadow Brook subbasin in Hudson (S3A); *B*, Taylor Brook subbasin in Maynard (S3B); *C*, Cold Harbor and Howard Brooks subbasin in Northborough (S3C); and *D*, Stirrup Brook subbasin in Westborough (S3D).



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 38—Continued. Hypothetical ground-water discharge sites for wastewater used in simulations (scenarios 3A–D) in the Assabet River Basin, eastern Massachusetts: *A*, Fort Meadow Brook subbasin in Hudson (S3A); *B*, Taylor Brook subbasin in Maynard (S3B); *C*, Cold Harbor and Howard Brooks subbasin in Northborough (S3C); and *D*, Stirrup Brook subbasin in Westborough (S3D).



From USGS and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 38—Continued. Hypothetical ground-water discharge sites for wastewater used in simulations (scenarios 3A–D) in the Assabet River Basin, eastern Massachusetts: *A*, Fort Meadow Brook subbasin in Hudson (S3A); *B*, Taylor Brook subbasin in Maynard (S3B); *C*, Cold Harbor and Howard Brooks subbasin in Northborough (S3C); and *D*, Stirrup Brook subbasin in Westborough (S3D).

Table 18. Hypothetical ground-water discharge sites for wastewater used in simulations in the Assabet River Basin, eastern Massachusetts.

[**Site:** Shown in figures 38*A*–*D*. **Site name:** As given in Wastewater Management Plans for towns, see text for references. Mgal/d, million gallons per day; #, number]

Site	Subbasin	Town	Site name or number	Simulated discharge rate (Mgal/d)	Number of model cells
A	Fort Meadow Brook	Hudson	Kane Property #11 and #11A	0.75	32
B	Taylor Brook	Maynard	Great Road #5	.75	16
C	Cold Harbor Brook	Northborough	#76	.31	5
D	Stirrup Brook	Westborough	Westborough State Hospital #27	1.5	31

Hypothetical Discharge Site in the Fort Meadow Brook Subbasin

Simulated wastewater discharge of 0.75 Mgal/d at site A in Hudson (fig. 38*A*) resulted in increases in model-calculated nonstorm streamflow in Fort Meadow Brook, its tributary, and in the Assabet River, relative to existing conditions. Small increases in flow (0.1 to 0.2 ft^3/s or about 0.1 Mgal/d) began downstream of the Fort Meadow Reservoir (stream mile 3.1, figs. 38*A* and 39*A*). Most of the model-calculated flow increase, however, was downstream of the unnamed tributary (joining Fort Meadow Brook at stream mile 4.9; fig. 38*A*) along which the hypothetical discharge site is located. At its confluence with the Assabet River, average annual model-calculated flow in Fort Meadow Brook increased by 1.05 ft^3/s (0.68 Mgal/d, or 22 percent of 1997–2001 flow) relative to existing conditions. These accounted for nearly all of the increase in total model-calculated flow in the Assabet River (1.09 ft^3/s or 0.70 Mgal/d) in S3A, which was realized at the confluence of the Assabet River and the outlet from Lake Boon, or about 0.5 stream mile downstream of Fort Meadow Brook (fig. 38*A*). The increase in total model-calculated nonstorm streamflow (0.70 Mgal/d) was slightly less than the simulated discharge (0.75 Mgal/d), because model-calculated ground-water ET from nonwetland areas also increased, by 0.05 Mgal/d, as a result of increased water levels.

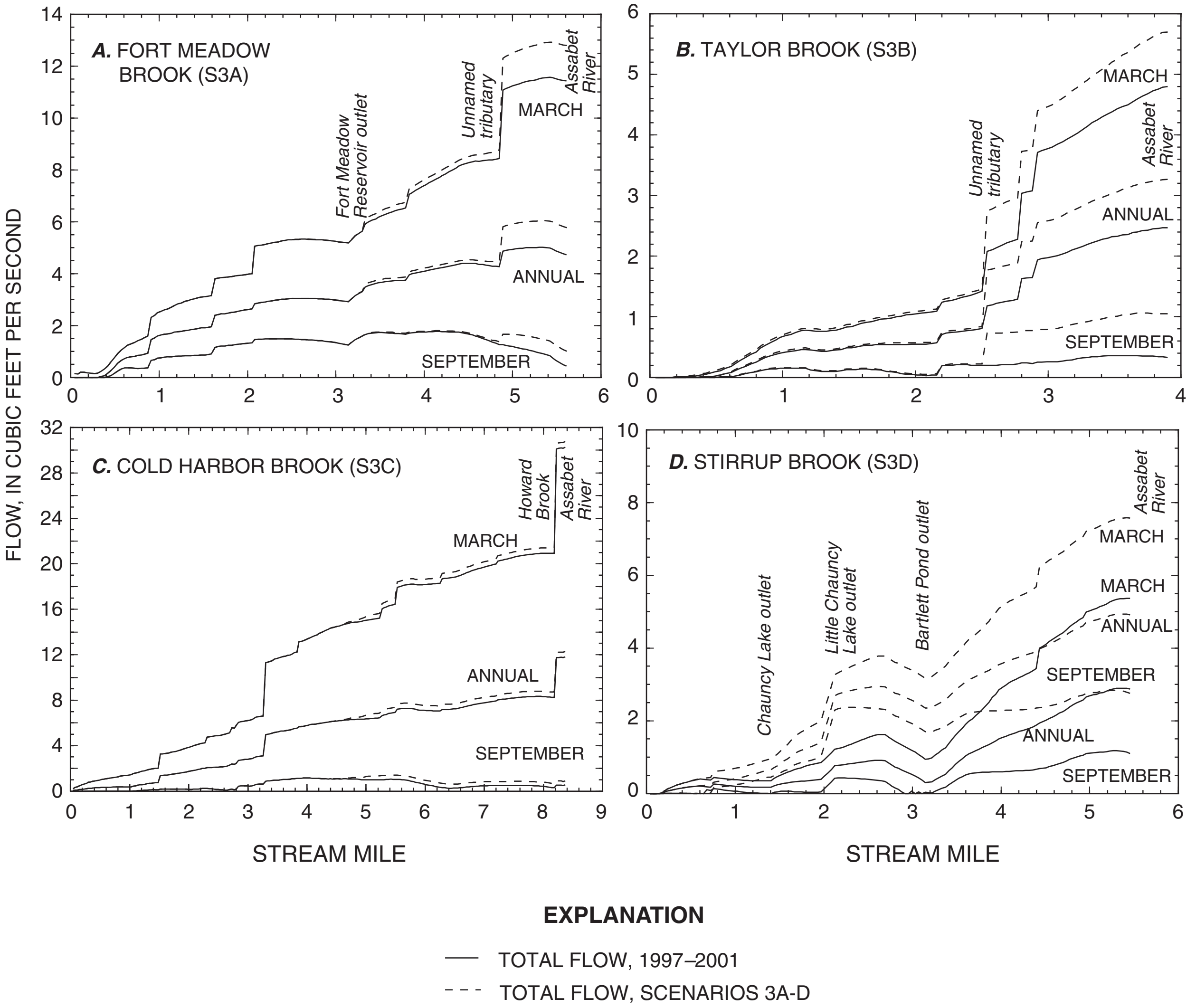


Figure 39. Model-calculated average annual, March, and September nonstorm streamflow in tributaries to the Assabet River for existing conditions (1997–2001) and scenarios (S3A–D) of hypothetical ground-water discharge of wastewater at four sites in the Assabet River Basin, eastern Massachusetts: *A*, Fort Meadow Brook (S3A); *B*, Taylor Brook (S3B); *C*, Cold Harbor Brook (S3C); and *D*, Stirrup Brook (S3D).

Seasonally, model-calculated nonstorm streamflows in S3A increased more during high-flow periods than during low-flow periods, although the wastewater discharge rate was constant. Model-calculated flow in Fort Meadow Brook at its confluence with the Assabet River increased by 1.37 ft^3/s (0.89 Mgal/d, or 12 percent of 1997–2001 flow) in March and by 0.58 ft^3/s (0.38 Mgal/d, or 130 percent of 1997–2001 flow) in September (fig. 39*A*); corresponding increases were 1.46 ft^3/s (0.94 Mgal/d) and 0.62 ft^3/s (0.41 Mgal/d) for total flow in the Assabet River. The seasonal variation was caused by ground-water storage effects and by increased model-calculated ground-water ET, which was simulated in warm-weather months. Changes in ground-water ET ranged from 0.04 Mgal/d in October to 0.13 Mgal/d in June. The remainder of the seasonal variation in model-calculated flows resulted from changes in flows to and from storage. In September, the flow augmentation more than doubled model-calculated nonstorm streamflow out of the subbasin for 1997–2001, increasing flow from 0.07 to 0.16 $ft^3/s/mi^2$. This subbasin yield in S3A in September was about half the model-calculated yield under the scenario of no anthropogenic water management (S1). During other low-flow months, June through October, model-calculated flow out of the basin increased from 40 to 90 percent. At a site where minimum streamflow requirements for aquatic habitat were investigated (Parker and others, 2004), however, flow increases in S3A were small (0.05 ft^3/s or 0.01 $ft^3/s/mi^2$), because the habitat site on Fort Meadow Brook was upstream of the confluence with the tributary along which the hypothetical ground-water discharge site was located.

Hypothetical Discharge Site in the Taylor Brook Subbasin

At site B in Maynard (fig. 38*B*), simulated wastewater discharge of 0.75 Mgal/d resulted in increases in model-calculated nonstorm streamflow in Taylor Brook, its tributary, and in the Assabet River, relative to existing conditions. Most of the increase in model-calculated flow was downstream of the unnamed tributary (joining Taylor Brook at stream mile 2.5; fig. 38*B*) along which the hypothetical discharge site was located. At its confluence with the Assabet River, model-calculated flow in Taylor Brook increased by 0.79 ft^3/s (0.51 Mgal/d, or 32 percent of 1997–2001 flow), on an average annual basis. Model-calculated flow in the Assabet River increased by 0.82 ft^3/s (0.55 Mgal/d) downstream of the impoundment near the Maynard/Acton town line (fig. 1; not shown on fig. 38*B*), about 2.3 stream miles downstream from Taylor Brook; increases downstream of the confluence of Taylor Brook with the Assabet River resulted from underflow of ground water, which discharged directly to the Assabet River, out of the subbasin. Increases in model-calculated ground-water ET, which averaged 0.20 Mgal/d annually and ranged from 0.13 Mgal/d in October to 0.54 Mgal/d in July, accounted for the difference between the wastewater discharge and the increase in average annual streamflow. Increases in model-calculated streamflows relative to existing streamflows varied seasonally, but less than those in S3A. The relatively large increases in ground-water ET in S3B in warm-weather months were balanced by changes in storage. Increases in monthly average model-calculated nonstorm streamflow were 0.90 ft^3/s (0.58 Mgal/d, or 19 percent of 1997–2001 flow) in March and 0.71 ft^3/s (0.46 Mgal/d, or 210 percent of 1997–2001 flow) in September in Taylor Brook (fig. 38*B*), and increases were 0.93 ft^3/s (0.60 Mgal/d) in March and 0.74 ft^3/s (0.48 Mgal/d) in September in the Assabet River downstream of the Powdermill Impoundment. As with the scenario of wastewater discharge in the Fort Meadow Brook subbasin in S3A, discharge at the hypothetical site in the Taylor Brook subbasin substantially increased model-calculated low flows out of the subbasin, relative to existing conditions. Model-calculated nonstorm September streamflow in Taylor Brook, downstream of stream mile 2.4, about tripled, relative to existing conditions, and yield from the subbasin increased from 0.08 to 0.25 $ft^3/s/mi^2$; this flow was greater than the model-calculated flow in S1, with all anthropogenic withdrawals and discharges removed.

Hypothetical Discharge Site in the Cold Harbor and Howard Brooks Subbasins

Simulated wastewater discharge of 0.31 Mgal/d at site C in Northborough (fig. 38C) resulted in increases in model-calculated nonstorm streamflow in Cold Harbor Brook and the Assabet River, relative to existing conditions. The increase in model-calculated flow began at about stream mile 4.5 (fig. 39*C*), adjacent to the discharge site, and continued for about 1 mi farther downstream, where a maximum increase of 0.46 ft^3/s (0.30 Mgal, or 4 percent of 1997–2001 flow) was attained on an average annual basis. Model-calculated streamflow in the Assabet River also increased by 0.46 ft^3/s, downstream of its confluence with Cold Harbor and Howard Brooks, indicating that none of the simulated wastewater discharge left the Cold Harbor and Howard Brooks subbasin through ground-water underflow. Ground-water ET increased only slightly, by 0.01 Mgal/d, averaged annually. Monthly average model-calculated nonstorm streamflow in Cold Harbor Brook was augmented by about 0.46 ft^3/s from January through June (March shown in fig. 39*C*). Increases in warm-weather months, during which ground-water ET increased by 0.02 to 0.1 Mgal/d, ranged from 0.36 to 0.43 ft^3/s (0.24 to 0.28 Mgal/d). Changes in storage were small, probably because the discharge site is close to the stream and in an area where the stratified glacial deposits are thin. Although smaller than changes in S3A and S3B, the flow augmentations in S3C more than doubled model-calculated nonstorm streamflow out of the Cold Harbor and Howard Brook subbasin in low-flow months, relative to simulated existing conditions, increasing subbasin yield from 0.05 to 0.13 $ft^3/s/mi^2$ in September. At the habitat site along Cold Harbor Brook (fig. 38*C*), yield increased from 0.21 to 0.28 $ft^3/s/mi^2$ in September, higher than the yield in S1 (0.26 $ft^3/s/mi^2$, table 17), in which all anthropogenic withdrawals and discharges were removed. The yield in S3C at the habitat site also was higher than the minimum streamflow requirements determined at the site (Parker and others, 2004; table 16).

Hypothetical Discharge Site in the Stirrup Brook Subbasin

Simulated wastewater discharge of 1.5 Mgal/d at site 3D in Westborough (fig. 38*D*) resulted in increases in model-calculated nonstorm streamflow in Stirrup Brook and the Assabet River, relative to existing conditions. Model-calculated flow in Stirrup Brook was augmented from the outlet of Chauncy Lake to the confluence of Stirrup Brook with the Assabet River, with increases complete by the outlet from Bartlett Pond (fig. 39*D*). On an average annual basis, model-calculated flow in Stirrup Brook increased by a maximum of 2.04 ft^3/s (1.32 Mgal/d, or 70 percent of 1997–2001 flow; fig. 39*D*). In the Assabet River, flow increased slightly (0.10 ft^3/s or less) upstream of Stirrup Brook, but most of the 2.15 ft^3/s (1.39 Mgal/d) increase in model-calculated flow resulted from inflow from Stirrup Brook and was downstream of the confluence. Ground-water ET also increased, by 0.11 Mgal/d, averaged annually. Seasonally, changes in ET were smaller than changes to or from storage, which were more than 0.5 Mgal/d in some months. In September, model-calculated nonstorm streamflow in Stirrup Brook was augmented by about 1.67 ft^3/s (1.08 Mgal/d), more than doubling model-calculated flow for existing conditions or for S1, in which all anthropogenic withdrawals and discharges were removed. Yield from the subbasin increased from 0.25 $ft^3/s/mi^2$ (existing conditions) to 0.63 $ft^3/s/mi^2$. It appears, therefore, that the simulated discharge in the Stirrup Brook subbasin would result in streamflows that are higher than would exist without any water management.

Summary of Scenarios of Ground-Water Discharge of Wastewater

The scenarios of hypothetical ground-water discharges indicate that, during the low-flow period in the four subbasins, streamflows would increase substantially in stream reaches downstream of the discharge sites. The flow increases, however, would not be as large as the constant discharge rate because of storage effects and increased ground-water ET in low-flow months. The effect of storage on streamflow augmentations that results from added inflows to the ground-water system was similar to results for the Upper Charles River Basin in eastern Massachusetts, in which a constant increased areal recharge was simulated (DeSimone and others, 2002). The importance of altered ground-water ET varied among subbasins, and changes in ground-water ET would be better quantified with local-scale models that would more accurately simulate water-level changes near a discharge site than does a regional-scale model. Also, as in S1 and S2, the effects of changes in ET in wetlands that may accompany the altered hydrologic system near the discharge sites were not included in S3A–D, because wetland ET was simulated in the model as a fixed-rate loss that does not vary with changing water levels. The scenarios of hypothetical ground-water discharge (S3A–D) also indicated that streamflows in the Assabet River would increase, but in most cases the changes were small, 1 percent or less, relative to total streamflow. In S3D, a relatively large discharge (1.5 Mgal/d) was simulated near the headwaters of the basin. In this scenario, model-calculated September nonstorm streamflow in the Assabet River increased by 10 percent at the outlet of the Main Stem Upper subbasin and by 4 percent at the outlet of the Main Stem Middle subbasin, relative to simulated existing conditions. Consequently, because direct wastewater discharges to the river did not change in S3D, the wastewater fraction of model-calculated nonstorm streamflow decreased from 55 to 50 percent, at the outlet of the Main Stem Upper subbasin, and from 32 to 31 percent, at the outlet of the Main Stem Middle subbasin. These and other changes in the wastewater fraction of nonstorm streamflow assume that ground water discharged to the river, originating as wastewater recharged to ground water at the hypothetical disposal sites, was similar in quality to background ground-water discharge. The changes in S3D at the outlet of the Assabet Main Stem Upper and Middle subbasins were the largest changes in model-calculated flow in the Assabet River in the scenarios of hypothetical ground-water discharge. Under scenarios in which ground-water recharge of wastewater was accompanied by reductions in direct discharge of wastewater to the Assabet River, the wastewater fraction of nonstorm streamflow in the river would decrease relative to simulated changes in S3A–D.

Simulation-Optimization of Withdrawals, Discharge, and Streamflow Depletion

Municipal water-supply systems typically manage withdrawals from multiple wells that are in different tributary subbasins or along the Assabet River. Several towns also have identified one or more possible ground-water discharge sites for wastewater. Because the effects of specific withdrawals and discharges on streamflow vary temporally and spatially, these anthropogenic fluxes may be managed to minimize their potential adverse effect on streamflow in specific basins, which may be more stressed than others, or during particular times of year. Simulation-optimization methods were applied in the upper part of the Assabet River Basin to investigate water-management practices to meet such goals. In this area of the basin (Assabet Main Stem Upper subbasin and upstream areas), water withdrawals and wastewater discharges are high relative to total flows (fig. 23 and 31), and streamflow depletion in tributaries and along the main stem river adversely affects water quality. The analysis was applied to public-supply withdrawals and a hypothetical ground-water discharge in Westborough. Specifically, the analysis addressed the following question: can streamflow depletion in the Assabet River and its tributaries in this area of the basin be reduced relative to current conditions while also maintaining current public-supply withdrawals for Westborough?

Methods

The simulation-optimization approach relies on the ground-water-flow model to simulate the hydrologic response of the stream-aquifer system to applied stresses, such as water withdrawals and discharges. Optimization methods then are used to answer specific management questions about the applied stresses and hydrologic responses. The questions are formulated mathematically into a management model that consists of a set of equations and has three components: an objective function, decision variables, and constraints (Ahlfeld and Mulligan, 2000). The objective function represents the goal of the management process and is some quantity (a stress or response) that is maximized or minimized. The decision variables are the quantities to be determined, for example, withdrawal rates at supply wells. The constraints set limits (for example, maximum withdrawal rates) on the values of decision variables in the solution. More information about simulation-optimization methods for ground-water-resource management can be found in Ahlfeld and Mulligan (2000), Barlow and Dickerman (2001), and Eggleston (2004). An optimization software package, LINDO (Shrage, 1997), was used to solve the management problems posed in this study.

The management model is linked to the ground-water-flow model through a matrix of response coefficients (Gorelick and others, 1993; Ahlfeld and Mulligan, 2000). Response coefficients quantify the relation between an applied stress and the response of the hydrologic system to the stress at a specific observation point. Streamflow depletion is the response quantified in this study; stresses include pumping at supply wells and ground-water discharge. Response coefficients are calculated as:

$$R_{i,j,ts,tr} = \frac{Qsd_{i,j,ts,tr}}{Qw_{i,ts}}, \qquad (3)$$

where

$R_{i,j,ts,tr}$ is response coefficient at observation point *j* during month *tr* caused by a stress at well or discharge site *i* during month *ts* (dimensionless);

$Qsd_{i,j,ts,tr}$ is streamflow depletion at observation point *j* during month *tr* caused by a stress at well or discharge site *i* during month *ts* (ft^3/d); and

$Qw_{i,ts}$ is stress at well or discharge site *i* during month *ts* (ft^3/d).

The response-matrix approach assumes a linear relation between aquifer stresses and hydrologic responses. This assumption allows multiple responses to be added or subtracted through superposition. Linearity is assumed with respect to the magnitude and the timing of the stress, such that response coefficients are assumed equal for all stresses or times of application in the annual cycle. When nonlinear responses to a stress occurs, for example, when a stream goes dry or a stress is close to a flow boundary, the linearity assumption may be a source of error (Eggleston, 2004). These errors, however, appear to be small in most cases (Barlow, 1997; Barlow and Dickerman, 2001; Eggleston, 2004). The fixed-transmissivity approach for the flow model used in this study eliminated one potential source of error from nonlinearity, the nonlinear response of the water table to changes in stress.

Simulation-Optimization of Withdrawals and Discharges in Westborough

Water was withdrawn for municipal supply in Westborough in 1997–2001 from six wells, and a new well was permitted recently (table 10 and fig. 14). The wells are in the Assabet Main Stem Headwaters (WB-01G, WB-02G, and WB-04G), Assabet Main Stem Upper (WB-03G, WB-07G), and Stirrup Brook (WB05, WB06) subbasins. A hypothetical ground-water discharge site for wastewater in the Stirrup Brook subbasin (GWD-D) also has been identified (Fay, Spoffard, and Thorndike, 2002a); this site was simulated in scenario S3D (table 18 and fig. 38*D*). The seven pumping wells and one discharge site are the stress sites included in the optimization analysis.

Response Coefficients

Response coefficients for stress sites in the study were determined by using the calibrated transient flow model, which simulates existing conditions (1997–2001). The response coefficients for the pumping wells and discharge site were obtained from model runs (one run per well or discharge site) in which flux rates were increased by 0.5 Mgal/d (wells) or 1.5 Mgal/d (discharge site) for 1 month. Response coefficients initially were determined for streamflow observation points at the outlets from the four Assabet subbasins and from three tributary subbasins—Hop Brook, Cold Harbor and Howard, and Stirrup Brooks (fig. 1). Streamflow responses at the Assabet Main Stem Middle and Lower subbasins were nearly the same as responses at the Main Stem Upper subbasin; therefore, streamflow responses at the Middle and Lower subbasins observation points are not reported and were not included in the optimization analysis. Streamflow depletions at the outlet of the Cold Harbor and Howard Brooks subbasin, which were unchanged by increased pumping or discharge at the Westborough sites, also were omitted. Response coefficients used in the analysis are given in table 19.

Table 19. Hydrologic response coefficients for the public-supply wells and a hypothetical ground-water-discharge site in the upper Assabet River Basin, eastern Massachusetts

[Response coefficients represent change in streamflow per unit withdrawal (1 cubic foot per second) for 1 month of pumping at supply wells, dimensionless. **Observation sites:** Streamflow outlets of the Assabet Main Stem Headwaters (Abt Head), Assabet Main Stem Upper (Abt Upper), Hop Brook (Hop) and Stirrup Brook (Stirrup) subbasins. **Months:** Month 1 is the month in which pumping occurs. --, no hydrologic response at observation point from pumping at supply well]

Supply well	Observation site	Months												Average annual streamflow response
		1	2	3	4	5	6	7	8	9	10	11	12	
WR-01G	Abt Head	-0.083	-0.083	-0.094	-0.094	-0.090	-0.086	-0.082	-0.078	-0.078	-0.078	-0.075	-0.072	-0.992
	Abt Upper	-.087	-.087	-.091	-.091	-.087	-.087	-.082	-.078	-.078	-.078	-.074	-.074	-.992
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	--	--	--	--	--	--	--	--	--	--	--	--	--
WR-02G	Abt Head	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.997
	Abt Upper	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.083	-.997
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	--	--	--	--	--	--	--	--	--	--	--	--	--
WR-03G	Abt Head	--	--	--	--	--	--	--	--	--	--	--	--	--
	Abt Upper	-.442	-.142	-.092	-.032	-.021	-.021	-.034	-.037	-.032	-.030	-.027	-.023	-.932
	Hop	-.008	-.010	-.009	-.008	-.006	-.005	-.026	-.031	-.022	-.020	-.014	-.010	-.129
	Stirrup	--	--	--	--	--	--	--	--	--	--	--	--	--
WR-04G	Abt Head	-.130	-.141	-.107	-.089	-.078	-.071	-.067	-.062	-.061	-.061	-.058	-.055	-.980
	Abt Upper	-.144	-.144	-.104	-.086	-.076	-.072	-.067	-.061	-.058	-.058	-.058	-.054	-.980
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	--	--	--	--	--	--	--	--	--	--	--	--	--
WR-05G	Abt Head	--	--	--	--	--	--	--	--	--	--	--	--	--
	Abt Upper	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.055	-.659
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.051	-.632
WR-06G	Abt Head	--	--	--	--	--	--	--	--	--	--	--	--	--
	Abt Upper	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.056	-.673
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.052	-.649
WR-07G	Abt Head	--	--	--	--	--	--	--	--	--	--	--	--	--
	Abt Upper	-.389	-.233	-.095	-.056	-.036	-.025	-.016	-.012	-.012	-.011	-.009	-.008	-.902
	Hop	-.135	-.098	-.042	-.022	-.013	-.009	-.006	-.006	-.005	-.004	-.005	-.003	-.349
	Stirrup	--	--	--	--	--	--	--	--	--	--	--	--	--
GWD-D	Abt Head	--	--	--	--	--	--	--	--	--	--	--	--	--
	Abt Upper	.077	.077	.077	.077	.077	.077	.077	.077	.077	.077	.077	.077	.925
	Hop	--	--	--	--	--	--	--	--	--	--	--	--	--
	Stirrup	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073	.880

The linearity assumption was tested by comparing transient model runs in which the stress rate was increased in March (high-flow month) and September (low-flow month), and by comparing model runs in which the stress rate for pumping wells was 25 and 100 percent of the Zone II approved rates for the wells; the latter runs used conditions of no water management (S1 conditions). These tests were made using wells WB-02G, WB-03G, and WB-07G. Differences between response coefficients from simulations in which the stress was applied in March and September at individual stress sites indicated that the linearity assumption generally was valid for the analysis. In most cases, response coefficients differed by more than 10 percent only when they were less than 0.005, that is, during months and at locations where the hydrologic response was less than 0.5 percent of the applied stress. In a few cases, larger differences were caused by the nonlinear response of ET from nonwetland areas to the applied stresses.

Increased pumping or discharge at stress sites resulted in changes in ET from nonwetland areas and in changes in simulated discharge to streams. ET changed because this flux, simulated with the Evapotranspiration Package of MODFLOW-2000, varies with the depth of the simulated water level below land surface. The ET response is nonlinear, because ET occurs only in some months of the annual cycle, and its magnitude is linear with respect to the stress only when the simulated water level is between land surface and the specified extinction depth. To calculate monthly response coefficients for streamflow, the steady-state model first was used to determine the average annual change in ET, as a percentage of the applied stress (steady-state ET response coefficient). Monthly response coefficients for streamflow then were determined with the transient model. The monthly response coefficients then were adjusted to ensure a mass balance between withdrawals and the resulting streamflow depletions and ET changes (Barlow, 1997; Eggleston, 2004). The monthly response coefficients were scaled so that they summed to one minus the steady-state ET response coefficient (that is, equalled the steady-state streamflow depletion). This was done for locations sufficiently downstream of the stress site (pumping well or discharge site) where all depletion effects accumulated. At some locations, such as the Hop Brook observation point, the steady-state streamflow depletion and ET changes were less than the corresponding increased stress, because additional depletions were downstream of the observation point. In these cases, monthly response coefficients were scaled to the steady-state streamflow depletion. With this approach for scaling the streamflow response coefficients, the change in ET was assumed equal in all months of the annual cycle, and its nonlinearity was approximated as a linear response. This approach was reasonable because, for most stress sites, the ET response was a small fraction of the total hydrologic response (steady-state ET response coefficients were less than 0.1, or 10 percent of the applied stress). For two wells (WR-05G and WR-06G), the steady-state ET response was about 30 percent of the applied stress, indicating that temporal variations in the ET response probably were significant. However, response coefficients at these wells, which were adjacent to Chauncy Lake, were affected by lake storage, such that temporal variations in streamflow depletion, if any, were not well quantified.

Several of the pumping wells were adjacent to the A1 Impoundment or to Chauncy Lake. Response coefficients for streamflow depletion downstream of these lakes (Assabet Headwaters and Stirrup Brook observation points) resulting from 1 month of pumping were nearly uniform in all subsequent months of the annual cycle. This most likely resulted from the large storage capacity of the lakes, which dampens the effect of changes in upstream pumping on streamflow. A withdrawal of 0.5 Mgal/d, capturing water infiltrated from the lake or ground water that would discharge to it, would change the water level in the A1 Impoundment or Chauncy Lake by 0.1 in. or less. This change was insufficient to alter the dynamics of simulated flow out of the lakes, which were controlled by total inflows, lake storage capacity, and in the model simulation, by specified stream elevations that correspond to the flow-control structure or other lake outlet. In actuality, the effect of withdrawals adjacent to the lakes on downstream streamflow may vary temporally to some extent. However, a more detailed representation of the lakes, including the hydraulics of their storage and outflows, than that which can be obtained with the ground-water-flow model would be needed to quantify this variability. Response coefficients were set equal in each month of the annual cycle for three wells adjacent to the A1 Impoundment or Chauncy Lake where no consistent temporal variation was seen (WR-02G, WR-05G, and WR-06G). For two wells near the A1 impoundment (WR-01G and WR-04G), response coefficients were indicative of the slight temporal variation apparent in modeling results (table 19).

Response coefficients for the ground-water discharge site also were calculated as uniform throughout the annual cycle, scaled to one minus the steady-state ET response (table 19). This approach was used because the ground-water discharge at the hypothetical site was simulated at a constant rate. Under dynamic equilibrium, the effect of a constant discharge on streamflow is constant throughout the annual cycle, except for the monthly variation in ET. The monthly variation in ET was not simulated because the ET effect is small, relative to the discharge (table 19), and because of the possible inaccuracies in results produced by the regional-scale model, as described for ground-water-discharge scenarios (S3A–D).

Finally, the response coefficients for nearly all wells and locations were small (less than 0.03 or 3 percent of the applied stress) more than 12 months after the pumping month. These small response coefficients are affected strongly by numerical errors in simulation results, such as round-off errors. Therefore, response coefficients for only the first 12 months were used. Their sum was scaled up to the steady-state streamflow-depletion response (one minus the steady-state ET response). This approach was not used for the response to pumping at WR-03G at the Hop Brook observation point. Response to pumping at this well at Hop Brook peaked in the ninth month after the pumping month, and continued for several months thereafter. Because the transient flow model simulates dynamic equilibrium, response coefficients for months 13-22 could be added to coefficients for months 1-10 to obtain the final response coefficients for this observation point and stress site.

Management-Model Application

The goal of the management model was to maximize ground-water discharge to streams in the Westborough area, while maintaining public-supply withdrawals for the town at or above existing (1997–2001) levels. Streamflow depletion is of greatest concern for water-quality, habitat, and other considerations during the warm weather, low-flow months. The objective function, therefore, was formulated to minimize streamflow depletion during the July, August, and September. Several formulations were made: (1) to minimize streamflow depletion during July, August, and September at the Assabet Main Stem Upper subbasin observation point, the downstream location where all effects from Westborough withdrawals accumulated; (2) to minimize streamflow depletion during July, August, and September at the Assabet Main Stem Headwaters subbasin observation point, upstream of the Westborough Wastewater Treatment Facility, where wastewater constitutes the greatest percentage of flow in the Assabet River, and at the Assabet Main Stem Upper subbasin observation point; and (3) to minimize streamflow depletion during July, August, and September at both observation points along the Assabet Main Stem and at observation points at the outlets of Hop and Stirrup Brooks. Solutions to these three objective functions were found with (OPT-1, OPT-2, and OPT-3) and without (OPT-4, OPT-5, and OPT-6) discharge at the hypothetical ground-water-discharge site.

Constraints on withdrawal rates at wells were applied: (1) to limit monthly average withdrawals at individual wells to the Zone II approved pumping rates; (2) to ensure that the sum of withdrawals at all sources in each month equaled or exceeded monthly average total withdrawals for Westborough for 1997–2001; and (3) to limit the sum of withdrawals at all sources in each month to the system-wide average annual withdrawal permitted to Westborough under the WMA. When the ground-water-discharge site was included, constraints were applied to limit the monthly average discharge rate to 1.5 Mgal/d in all months of the year. Constraints also were placed on streamflow depletion at the four observation points. Monthly average nonstorm streamflow was constrained in each month of the annual cycle to be greater or equal to the lesser of (1) the minimum streamflow requirement recommended by the U.S. Fish and Wildlife Service, 0.5 $ft^3/s/mi^2$ (Aquatic Base Flow or ABF; U.S. Fish and Wildlife Service, 1981), or (2) the simulated monthly average nonstorm streamflow for 1997–2001 conditions. Decision variables were monthly average pumping rates at the seven supply wells and, when included, the monthly average rate of ground-water discharge. All other hydrologic flows, including wastewater discharge to streams, septic-system return flow, and infiltration to sewers, were the same as in 1997–2001 conditions.

Small increases in streamflow in low-flow months (July through October) were obtained at the main stem Assabet River sites in solutions to all three management models without ground-water discharge (OPT1-3). The increases were about 0.4 to 0.5 ft^3/s at the Headwaters subbasin observation point, and about 0.6 to 0.7 ft^3/s at the Upper subbasin observation point, relative to 1997–2001 conditions (table 20). Although small in magnitude, this increase about doubled model-calculated flow at the Assabet Headwaters site in September relative to simulated existing conditions. Flow increases at the Assabet Main Stem Upper subbasin observation point were slightly more in OPT-1 (when depletion at the Main Stem Upper site only was minimized) than in OPT-2 (when depletion at both Assabet River sites was minimized) or in OPT-3 (when depletion at Assabet River sites and Hop and Stirrup Brook sites was minimized). In Hop Brook, streamflow in low-flow months increased slightly, by less than 0.05 ft^3/s. The streamflow increases were offset by streamflow decreases in high-flow months at the Assabet River Main Stem Upper and Hop Brook sites. Flows simulated at the Stirrup Brook site were the same as 1997–2001 flows.

Pumping rates in the solutions to OPT1-3 (fig. 40*A*–*C*) were similar in that (1) wells near ponds (WB-01G, WB-02G, WB-05G, and WB-06G) were pumped at high rates in the summer and (2) wells near streams (WB-03G and WB-07G) were pumped at high rates in the winter, spring, and fall. System-wide total withdrawals equalled average withdrawals during each month of 1997–2001, the minimum allowed. These patterns contrast with the average distribution of pumping among sources in 1997–2001, in which the proportions contributed by most sources to total system-wide withdrawals were similar most months of the year (fig. 40*G*). The inclusion of WB-07G in the management model (WB-07G was not active in 1997–2001) also is probably the reason why low flows in Hop Brook in OPT1-3 were similar to 1997–2001 flows. Withdrawals at WB-07G, which is adjacent to Hop Brook and the Assabet River, immediately affect streamflow (table 19), relative to withdrawals at other wells, which either are more distant from the river (WB-03G) or adjacent to and buffered by ponds (fig. 15). Solutions to the management model take advantage of the variable response of this well and other wells on streamflow, maximizing withdrawals at WB-07G until constrained by the Zone II approved limit of the well, or by the minimum allowed streamflow depletion at Hop Brook. The streamflow-depletion constraint at Hop Brook results in 1997–2001 flows in low-flow months in this tributary. In many cases in the solutions to OPT1-3, withdrawal rates at individual sources were at Zone II approved rates or were zero. These extreme changes in pumping rates may be unrealistic for some supply wells, such that the streamflow increases that result under solutions to OPT1-3 probably represent upper limits on flow augmentations that could be realized by management of existing sources, within the limitations of model error and assumptions. Also, although the pumping rates determined in OPT1-3 resulted in quantitatively the optimal solution to the objective functions that were posed, alternative pumping schemes may have yielded similar solutions in terms of minimized streamflow depletion. For example, multiple combinations of pumping at closely located wells, such as WB-01G, WB-02G, and WB-04G, may yield similar depletions in streamflow downstream of the wells.

Table 20. Model-calculated average monthly nonstorm streamflow, 1997–2001, and changes in monthly average nonstorm streamflow determined by solutions to management models in the upper Assabet River Basin, eastern Massachusetts.

[Nonstorm streamflows determined at streamflow-observation sites at the outlets of Assabet Main Stem Headwaters (Assabet Head), Assabet Main Stem Upper (Assabet Upper), Hop Brook, and Stirrup Brook Subbasins. Subbasin locations shown in figure 1. ft^3/s, cubic foot per second]

Month	Simulated monthly average nonstorm streamflow, 1997-2001 (ft^3/s)				Change in monthly average nonstorm streamflow (ft^3/s)											
					OPT-1				OPT-2				OPT-3			
	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook
January	5.01	52.12	11.75	2.69	0.30	-0.59	-0.45	0.00	0.37	-0.56	-0.49	0.00	0.32	-0.58	-0.46	0.00
February	7.81	69.80	16.25	3.61	.34	-.65	-.46	.00	.42	-.64	-.41	.00	.36	-.59	-.45	.00
March	14.33	113.00	26.73	5.37	.32	-.21	-.25	.00	.40	-.02	-.21	.00	.34	-.14	-.23	.00
April	16.40	124.00	27.72	6.70	.32	-.27	-.09	.00	.37	-.03	-.08	.00	.35	-.23	-.08	.00
May	7.86	65.85	10.71	4.64	.35	-.23	-.03	.00	.39	-.13	-.02	.00	.38	-.20	-.02	.00
June	3.53	39.59	5.99	2.54	.37	.32	.00	.00	.43	-.14	.00	.00	.40	.19	.00	.00
July	1.70	24.98	3.84	1.59	.39	.57	.02	.00	.46	.48	.01	.00	.42	.55	.02	.00
August	1.03	19.44	2.79	1.22	.40	.71	.03	.00	.47	.67	.01	.00	.43	.71	.02	.00
September	.53	16.89	2.15	1.10	.40	.76	.02	.00	.43	.74	.00	.00	.39	.73	.02	.00
October	.96	22.45	3.69	1.28	.35	.69	.00	.00	.38	.71	.00	.00	.34	.67	.00	.00
November	1.72	30.07	5.77	1.77	.30	-.07	-.28	.00	.35	-.03	-.28	.00	.30	-.07	-.28	.00
December	2.55	35.27	6.59	2.07	.27	-.49	-.44	.00	.33	-.46	-.47	.00	.29	-.48	-.45	.00

Month	Simulated monthly average nonstorm streamflow, 1997-2001 (ft^3/s)				Change in monthly average nonstorm streamflow (ft^3/s)											
					OPT-4				OPT-5				OPT-6			
	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook	Assabet Head	Assabet Upper	Hop Brook	Stirrup Brook
January	5.01	52.12	11.75	2.69	0.99	1.81	-0.43	1.61	1.02	1.81	-0.43	1.59	0.99	1.81	-0.45	1.64
February	7.81	69.80	16.25	3.61	1.00	1.70	-.44	1.61	1.02	1.71	-.44	1.59	1.00	1.71	-.46	1.64
March	14.33	113.00	26.73	5.37	.99	1.92	-.30	1.61	1.01	2.05	-.27	1.59	.99	2.18	-.25	1.64
April	16.40	124.00	27.72	6.70	.98	1.95	-.13	1.61	1.00	2.02	-.11	1.59	.98	2.10	-.09	1.64
May	7.86	65.85	10.71	4.64	.98	2.58	-.04	1.61	1.00	2.60	-.04	1.59	.98	2.10	-.03	1.64
June	3.53	39.59	5.99	2.54	.98	2.75	.00	1.61	1.00	2.76	.00	1.59	.98	2.64	.00	1.64
July	1.70	24.98	3.84	1.59	.99	2.94	.02	1.61	1.00	2.94	.02	1.59	.99	2.87	.02	1.64
August	1.03	19.44	2.79	1.22	.99	3.00	.03	1.61	1.01	3.00	.03	1.59	.99	3.02	.03	1.64
September	.53	16.89	2.15	1.10	.99	3.05	.03	1.61	1.01	3.05	.02	1.59	.99	3.07	.02	1.64
October	.96	22.45	3.69	1.28	.98	3.02	.00	1.61	1.02	2.92	.00	1.59	.98	3.04	.00	1.64
November	1.72	30.07	5.77	1.77	.98	2.33	-.25	1.61	1.02	2.31	-.26	1.59	.98	2.33	-.28	1.64
December	2.55	35.27	6.59	2.07	.99	1.95	-.40	1.61	1.03	1.94	-.40	1.59	.99	1.94	-.44	1.64

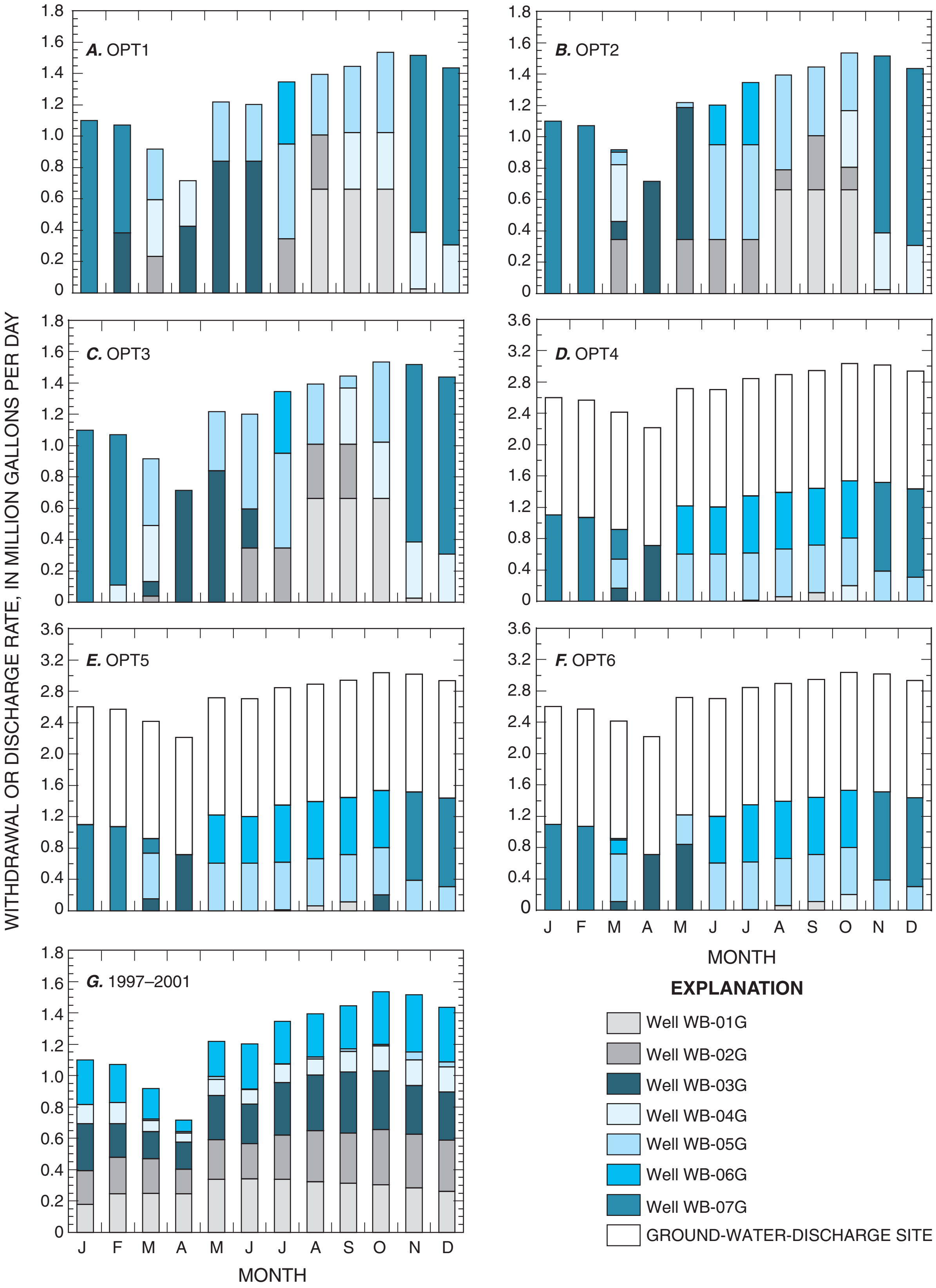


Figure 40. Monthly withdrawal and discharge rates for 1997–2001 and for the management-model applications (OPT1-6) for decreased streamflow depletion in the Assabet River and tributaries in low-flow months in the upper part of the Assabet River Basin, eastern Massachusetts: *A*, OPT1; *B*, OPT2; *C* OPT3; *D*, OPT4; *E*, OPT5; *F*, OPT6; and *G*, 1997–2001.

The effect of ET changes from increased pumping, as represented by response coefficients used in the optimization analysis, may be apparent in the results obtained for Stirrup Brook, WB-05G, and WB-06G (table 20). Wells in the Stirrup Brook subbasin were two of five wells upstream of lakes with response coefficients that were uniform or nearly uniform throughout the year. The ET response of the Stirrup Brook wells, however, was greater than that of other wells. Pumping at one of these wells, therefore, may have been preferred in the solution because it had less effect on downstream streamflow than pumping the same volume at another well, as defined by the scaled monthly response coefficients (table 19). This may explain why, in solutions to OPT1-3, one or the other of the two wells in the Stirrup Brook subbasin was pumped at or near its Zone II approved rate when other wells upstream of lakes were not pumping. As a result, pumping at WB-05G and WB-06G was maximized until the streamflow depletion constraint in Stirrup Brook, which limited depletion to the depletion occurring under 1997–2001 conditions in the low-flow months, was reached. Moreover, because the effects of pumping at WB-05G and WB-06G were the same in each month of the annual cycle, flow in low-flow months could not be augmented through decreased pumping (and, therefore, altered streamflow depletion) in high-flow months.

In solutions to management models with discharge at the hypothetical ground-water-discharge site (OPT4-6), streamflow increased in low-flow months at both Assabet River sites and in Stirrup Brook (table 20). The increases were about 1 ft^3/s at the Assabet Main Stem Headwaters subbasin observation point, about 3 ft^3/s at the Assabet Main Stem Upper subbasin observation point, and about 1.6 ft^3/s at the Stirrup Brook subbasin observation point, relative to 1997–2001 conditions (table 20). In all three solutions, ground-water discharge equalled the maximum allowable rate (1.5 Mgal/d of 2.3 ft^3/s). Systemwide, pumping was nearly entirely from WB-05G, WB-06G, and WB-07G (figs. 40*D–F*). Withdrawals at WB-05G and WB-06G, in the Stirrup Brook subbasin, were offset by the ground-water discharge, and these wells were pumped at or near Zone II approved rates in the summer, and at lesser rates in the spring and fall. Withdrawals at WB-07G, with immediate effects in the adjacent Assabet River, were at or near Zone II approved rates in the high-flow winter months. Increased pumping at the Stirrup Brook wells, relative to 1997–2001 and OPT1-3, made reduced pumping possible at wells in the Assabet Main Stem Headwaters subbasin, resulting in the flow increases from this subbasin. As in OPT1-3, Hop Brook low flows changed little in OPT4-6 (table 20), and system-wide total withdrawals equalled average withdrawals in 1997–2001.

The optimization analysis indicates that streamflow in the Assabet River in the upper part of the basin could be increased by management of existing water-supply sources for Westborough, but by small amounts. The calculated increases would reduce the average percentage of total nonstorm streamflow in the river that is wastewater at the outlet of the Assabet Main Stem Upper subbasin (between Westborough and Marlborough Wastewater Treatment Facilities) by about 0.3 percent annually, by about 0.1 percent in an average March, and by about 2 percent in an average September, relative to 1997–2001 conditions. With discharge to the ground-water system at a hypothetical ground-water-discharge facility in Westborough included, the analysis indicates that flows could be increased by much larger amounts. Resulting decreases in the average wastewater component of nonstorm streamflow at the outlet of the Assabet Main Stem Upper subbasin would be about 1 percent annually, 0.3 percent in an average March, and about 8 percent in an average September. These reductions assumed that wastewater discharge to the river from existing treatment facilities was maintained at 1997–2001 rates. The management practices used in the solutions to optimization problems may be unrealistic for some supply wells, but could be modified with more detailed information. General management principles were illustrated in which withdrawals at wells adjacent to streams are minimized in low-flow months, in favor of withdrawals at wells upstream of ponds or impoundments or at wells at greater distances from stream reaches where depletion is of concern. These principles also could be applied elsewhere in the basin.

Summary

Water-supply withdrawals and wastewater disposal in the Assabet River Basin in eastern Massachusetts alter the flow and water quality in the basin. Discharges of treated wastewater and streamflow depletion from ground-water withdrawals adversely affect water quality in the Assabet River, especially during low-flow months and in headwater areas. Streamflow depletion also contributes to loss of aquatic habitat in the tributaries of the river. Withdrawals and wastewater discharges are likely to increase, in response to rapid development in this area, where population increased by 15 percent on average, and by more than 30 percent in some towns, between 1990 and 2000. The purpose of the study described in this report, which was completed by the U.S. Geological Survey and the Massachusetts Department of Conservation and Recreation, was to determine the effects of the current and future withdrawals and discharges on water resources in the basin, and to evaluate the effects of water-management alternatives. Data were collected to better define water resources in the basin, numerical ground-water-flow models were developed and applied to simulate existing and future conditions and water-management alternatives in the basin, and a simulation-optimization approach was used to investigate the potential to reduce existing streamflow depletion.

Ground water occurs in three major units in the basin—stratified glacial deposits, glacial till, and bedrock. Most water withdrawals are from the stratified glacial deposits. These deposits are along tributary streams and the main stem Assabet River and are in close hydraulic connection with streams, ponds, and wetlands. The stratified glacial deposits typically are less than 75 ft thick, and average about 35 ft thick throughout the basin. Horizontal hydraulic conductivity of the stratified glacial deposits, as depth-weighted averages, ranged from about 50 to 110 ft/d, in three mapped transmissivity zones. Little data were available on other hydraulic properties of stratified glacial deposits, or hydraulic properties of till or bedrock in the basin, and these properties were estimated primarily from literature sources.

The Assabet River flows about 31 stream miles and drops about 200 ft in elevation through the basin. Seven dams impound the river, some of which back water up for several miles. Mean annual flow at a streamflow-gaging station in Maynard, MA, with a drainage area of about two-thirds of the basin, was 188 ft^3/s from 1942–2000. The nonstorm component of streamflow (ground-water discharge or base flow plus wastewater discharge) was estimated at 82 percent of total flow, using an automated hydrograph separation method. Wastewater at the streamflow-gaging station was about 8 percent of total flow in 1997–2001, on an average annual basis. Ponds in the Assabet River Basin include instream ponds, impoundments, and kettle lakes. Wetlands are common, covering 3 percent of basin area in 1999. The wetlands potentially play an important, but variable and largely unknown, role in the regional hydrologic system in the basin.

Streamflow records at the Assabet River streamflow-gaging station and at another long-term station in the basin on Nashoba Brook were used to estimate recharge rates in the basin, by using an automated hydrograph-displacement method. Estimated recharge rates from streamflow records were about 20 in/yr for long-term conditions for the 1997–2001 period. Using a water-balance method and climate data from nearby weather stations, estimated recharge rates were about 17 in/yr for long-term conditions for 1997–2001.

A detailed water budget for anthropogenic water flows in the basin was constructed with data from 1997–2001. Public-water supply served about 80 percent of the basin population and about half the basin area. Permitted water withdrawals averaged 9.9 Mgal/d. Most (95 percent) water withdrawals were for public supply and most (74 percent) were from ground-water sources. Water (2.4 Mgal/d) also was imported into the basin for public supply. Wastewater from about 50 percent of the basin population was treated at four facilities that discharge to the Assabet River. Wastewater discharges averaged 11 Mgal/d and included about 5.4 Mgal/d that originated from sources outside of the basin, such that the basin was a net importer of wastewater in 1997–2001. Wastewater disposal to groundwater through septic systems averaged 4.3 Mgal/d, and loss of ground water through infiltration to sewers averaged 2.6 Mgal/d. Consumptive use was estimated from seasonal patterns of water use in publicly supplied towns, and averaged 0.7 Mgal/d each in publicly and privately supplied areas.

Steady-state and transient ground-water-flow models were developed, by using MODFLOW-2000, that simulated flow in the stratified glacial deposits, glacial till, and underlying crystalline bedrock in the basin. Two layers were simulated with transmissivities that did not change with changing water levels. A detailed stream network, which included all perennial streams at the 1:25,000 scale, was simulated by using the Stream Package. A monthly time step was used to simulated the average annual cycle at dynamic equilibrium. The models were calibrated to 1997–2001 conditions of average annual (steady-state model) and monthly (transient model) water withdrawals and discharges, water levels, and nonstorm streamflow. Calibration data consisted of water levels and flows estimated for 1997–2001 at 20 observation wells, 2 kettle ponds, 2 continuous streamflow-gaging stations, and 18 partial-record flow-measurement sites. Water-level and flow estimates for 1997–2001 were made from monthly measurements during August 2001 to December 2002 by correlation of measurements with water levels and flows at nearby long-term observation sites and streamflow-gaging stations. Model parameters that were adjusted during calibration included recharge, hydraulic conductivity, storage properties, and evapotranspiration. The mean absolute water-level residual for the calibrated steady-state model was 3.67 ft, or less than 1 percent of the total relief of the simulated water table in the stratified glacial deposits or the entire model area. The mean water-level residual was 0.39 ft. The mean absolute flow residual for the calibrated steady-state model was 3.4 ft^3/s, or 2 percent of the total range of estimated flows for 1997–2001. For the calibrated transient model, the mean absolute monthly flow residuals averaged 39 percent of monthly nonstorm streamflows.

Total flow through the simulated hydrologic system averaged 195 Mgal/d annually. Precipitation recharge was the dominant inflow and was simulated with rates of 28.2 in/yr for stratified glacial deposits and 22.5 in/yr for glacial till. Septic-system return flow (4.3 Mgal/d) accounted for 2 percent of total inflows annually. Ground-water discharge to streams was the primary outflow, but evapotranspiration of ground water from wetlands and nonwetland areas, which were simulated as areas of net water loss, were important components of the hydrologic system. Water-supply withdrawals (9.9 Mgal/d) and infiltration to sewers (2.6 Mgal/d) averaged 5 and 1.3 percent of total outflows; other anthropogenic losses averaged less than 1 percent of total outflows annually. Anthropogenic outflows were larger components of the hydrologic system in low-flow months, averaging 12 percent of total outflows basinwide in September. Water budgets for individual tributary and main stem subbasins identified areas, such as Fort Meadow Brook and the Assabet Main Stem Headwaters subbasin, where anthropogenic flows were relatively large percentages (20 to 25 percent in September) of total outflows. Wastewater discharged to the Assabet River accounted for 23, 13, and 8 percent of total nonstorm streamflow (base flow plus wastewater discharge) out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively, on an annual average basis, and 55, 32, and 20 percent, respectively, in an average September.

Model-calculated, nonstorm streamflows at selected sites can be compared to minimum streamflows required for the protection of aquatic habitat, which recently (2004) were investigated at six sites in the basin. Model-calculated, September nonstorm streamflow at the outlets of about half the tributary subbasins fell between upper and lower minimum streamflow requirements determined for sites in the Assabet and adjacent Charles River Basins. Model-calculated September nonstorm streamflow for Cold Harbor and Howard, Danforth, Fort Meadow, and Fort Pond Brook subbasins were lower than the lower minimum streamflow requirement of about 0.2 $ft^3/s/mi^2$; these include subbasins where withdrawals and other flow alterations were 10 to 25 percent of total flows. The comparison of model-calculated flows with minimum-streamflow requirements is complicated, however, by model calibration error, variability in requirements among sites, and temporal scale issues.

Water-management alternatives were evaluated by simulating hypothetical scenarios of altered withdrawals and discharges. A scenario with no water management quantified tributary and main stem nonstorm streamflows that would result without withdrawals, discharges, septic-system return flow, or consumptive use. In this scenario, tributary flows increased in most subbasins by 2 to 44 percent relative to simulated 1997–2001 conditions. The increases resulted mostly from variable combinations of decreased withdrawals and decreased infiltration to sewers. In subbasins with public-water supply and private disposal, streamflows were nearly unchanged, because decreased withdrawals were offset by decreased septic-system return flow. Total nonstorm streamflow in the Assabet River decreased slightly in this scenario, by 2 to 3 percent annually, because gains in ground-water discharge were offset by the elimination of wastewater discharges.

A second scenario quantified the effects on nonstorm streamflow of increasing withdrawals and discharges to currently permitted levels. In this scenario, tributary flows decreased in most subbasins, by less than 1 to 10 percent relative to simulated 1997–2001 conditions. In the Assabet River, flows increased slightly (1 to 5 percent annually), and the percentage of wastewater in the river increased to 69, 42, and 27 percent of total nonstorm streamflow out of the Assabet Main Stem Upper, Middle, and Lower subbasins, respectively, in an average September.

A third set of scenarios quantified the effects of ground-water discharge of wastewater at four hypothetical sites in Hudson, Maynard, Northborough, and Westborough. Wastewater discharged at a constant rate that varied among sites from 0.3 to 1.5 Mgal/d increased simulated nonstorm streamflow in the tributary streams adjacent to the sites, and in downstream reaches of the Assabet River. In low-flow months, increases in tributary flows were less than the constant discharge rate because of storage effects and increased ground-water evapotranspiration. Average September flows, however, more than doubled in these scenarios relative to simulated 1997–2001 conditions in the tributaries adjacent to the discharge sites, Fort Meadow, Taylor, Cold Harbor, and Stirrup Brooks. Increases in Assabet River flows were small, with reductions in the wastewater component of flow in September of 5 percent or less; flows increased the most at the outlet of the Main Stem Upper subbasin in a scenario where a large volume of water was discharged near the headwaters of the river.

Simulation-optimization analysis also was used to evaluate water-management alternatives in the upper part of the basin to determine whether streamflow depletion could be reduced, relative to simulated 1997–2001 conditions, by management of monthly withdrawals, with and without ground-water discharge. Existing supply wells, one new well, and a hypothetical discharge site in Westborough were included in the analysis. Without ground-water discharge, simulated September nonstorm streamflow in the Assabet River about doubled at the outlet of the Main Stem Headwater subbasin, and increased by about 4 percent at the outlet of the Main Stem Upper subbasin. These increases were obtained by using sources upstream of lakes, which appeared to buffer the temporal effect of withdrawals, in low- and moderate-flow months and by using sources adjacent to streams, which immediately affected flows, in high-flow months. In optimization problems that included ground-water discharge, simulated flows increased substantially, with increases of 18 percent at the outlet of the Main Stem Upper subbasin and more than doubling flow in Stirrup Brook. The general principles illustrated in the simulation-optimization analysis could be applied in other areas of the basin where streamflow depletion is of concern.

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