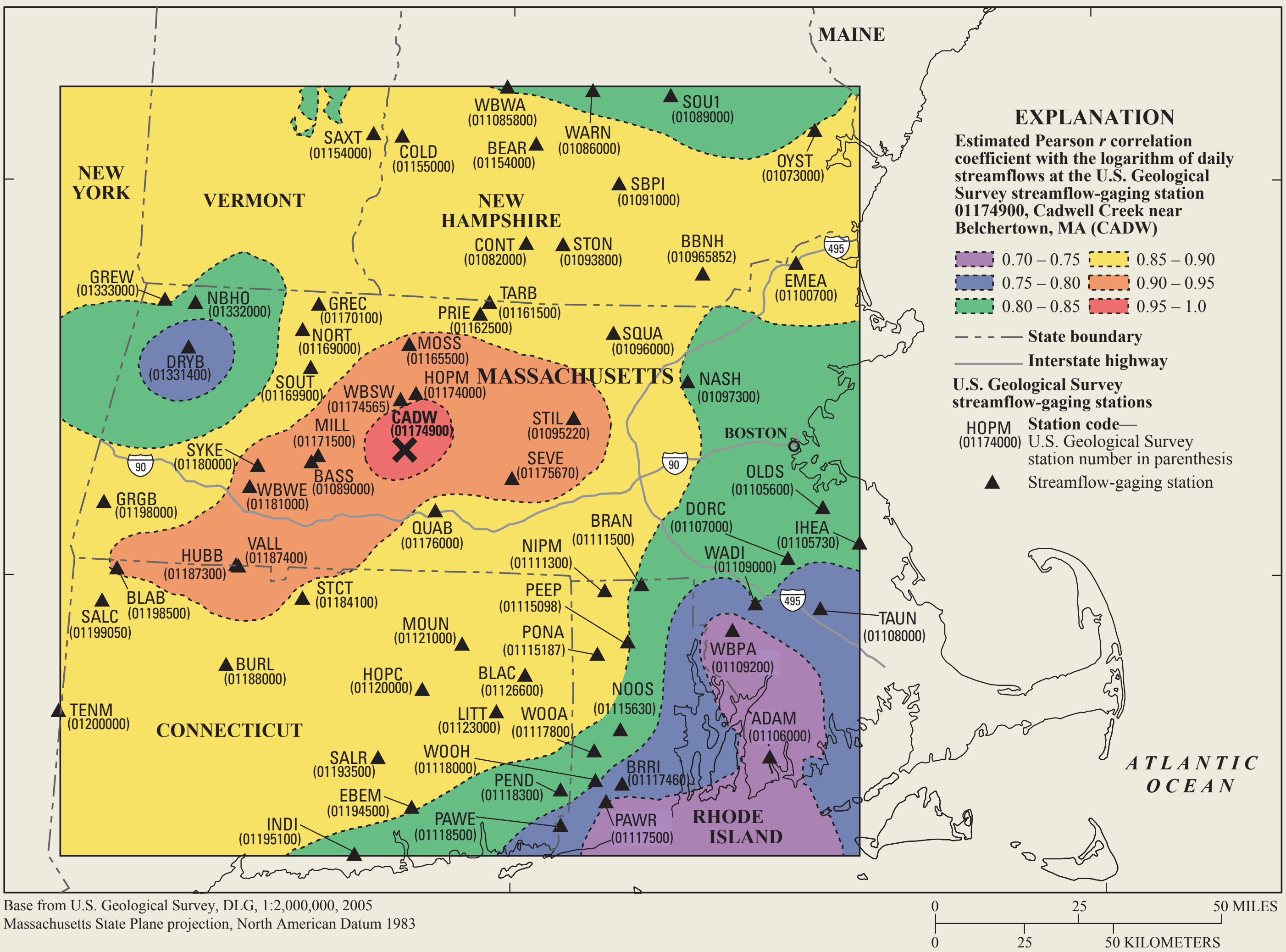
Prepared in cooperation with the
Massachusetts Department of Environmental Protection

The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged stream locations in Massachusetts



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005
Massachusetts State Plane projection, North American Datum 1983

Scientific Investigations Report 2009–5227

U.S. Department of the Interior
U.S. Geological Survey

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

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

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

Abbreviations

EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute, Inc.
MassDEP	Massachusetts Department of Environmental Protection
MassGIS	Massachusetts Geographic Information System
MA SYE	Massachusetts Sustainable-Yield Estimator
NPDES	National Pollutant Discharge Elimination System
FDC	Flow-duration curve
GIS	Geographic-information system
IHA	Indicators of Hydrologic Alteration
NAHAT	National Hydrologic Assessment Tool
N-S E	Nash-Sutcliffe efficiency
NPDES	National Pollutant Discharge Elimination System
PDF	Probability density function
STRMDEPL	STReaMflow DEPLetion by wells
WMA	Water Management Act

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Abstract

Federal, State and local water-resource managers require a variety of data and modeling tools to better understand water resources. The U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection, has developed a statewide, interactive decision-support tool to meet this need. The decision-support tool, referred to as the Massachusetts Sustainable-Yield Estimator (MA SYE) provides screening-level estimates of the sustainable yield of a basin, defined as the difference between the unregulated streamflow and some user-specified quantity of water that must remain in the stream to support such functions as recreational activities or aquatic habitat. The MA SYE tool was designed, in part, because the quantity of surface water available in a basin is a time-varying quantity subject to competing demands for water.

To compute sustainable yield, the MA SYE tool estimates a daily time series of unregulated, daily mean streamflow for a 44-year period of record spanning October 1, 1960, through September 30, 2004. Selected streamflow quantiles from an unregulated, daily flow-duration curve are estimated by solving six regression equations that are a function of physical and climate basin characteristics at an ungaged site on a stream of interest. Streamflow is then interpolated between the estimated quantiles to obtain a continuous daily flow-duration curve. A time series of unregulated daily streamflow subsequently is created by transferring the timing of the daily streamflow at a reference streamgage to the ungaged site by equating exceedence probabilities of contemporaneous flow at the two locations. One of 66 reference streamgages is selected by kriging, a geostatistical method, which is used to map the spatial relation among correlations between the time series of the logarithm of daily streamflows at each reference streamgage and the ungaged site. Estimated unregulated, daily mean streamflows show good agreement with observed unregulated, daily mean streamflow at 18 streamgages located across southern New England. Nash-Sutcliffe efficiency goodness-of-fit values are between 0.69 and 0.98, and percent root-mean-square-error values are between 19 and 283 percent.

The MA SYE tool provides an estimate of streamflow adjusted for current (2000–04) water withdrawals and discharges using a spatially referenced database of permitted groundwater and surface-water withdrawal and discharge volumes. For a user-selected basin, the database is queried to obtain the locations of water withdrawal or discharge volumes within the basin. Groundwater and surface-water withdrawals and discharges are subtracted and added, respectively, from the unregulated, daily streamflow at an ungaged site to obtain a streamflow time series that includes the effects of these withdrawals and discharges. Users also have the option of applying an analytical solution to the time-varying, groundwater withdrawal and discharge volumes that take into account the effects of the aquifer properties on the timing and magnitude of streamflow alteration.

For the MA SYE tool, it is assumed that groundwater and surface-water divides are coincident. For areas of southeastern Massachusetts and Cape Cod where this assumption is known to be violated, groundwater-flow models are used to estimate average monthly streamflows at fixed locations. The MA SYE tool can be applied only to basins with ranges of physical and climate basin characteristics that are within the range under which the regression equations were developed. For example, the MA SYE tool is valid for basins whose drainage areas are between approximately 4 and 294 square miles. There are several limitations to the quality and quantity of the spatially referenced database of groundwater and surface-water withdrawals and discharges. The adjusted streamflow values do not account for the effects on streamflow of climate change, septic-system discharge, impervious area, non-public water-supply withdrawals less than 100,000 gallons per day, and impounded surface-water bodies.

Introduction

The amount of surface water available for withdrawal in a basin is dependent upon several variables including, but not limited to, the total amount of water available (the unregulated streamflow at the outlet of the basin), the amount of water being withdrawn or discharged at a moment in time from the basin, the effects of those withdrawals or discharges on streamflow, the period of analysis, and the amount of water that may be needed to sustain aquatic habitat or support recreational uses. Surface-water availability also is dependent upon the effects of land cover (urbanization) and dams (both passive and actively managed dams) on streamflow, and the effects of climate change.

Safe versus Sustainable Yield

The term “safe yield” has historically been used to describe the amount of water available from a groundwater or surface-water source. Typically, the concept of safe yield implies that a single value represents the water available for withdrawal in a basin given some singular constraint, such as an engineering limitation or climate condition. In Massachusetts, legislation requires the Massachusetts Department of Environmental Protection (MassDEP) to regulate the permitting of water withdrawals greater than a 100,000 gallon-per-day threshold volume relative to the safe yield of a basin (Massachusetts Water Management Act, M.G.L. c. 21G). The exact regulatory definition of safe yield (from 310 CMR 36.00: The Water Management Act Regulations) is

> …the maximum dependable withdrawals that can be made continuously from a water source, including ground or surface water, during a period of years in which the probable driest period or period of greatest water deficiency is likely to occur; provided however, that such dependability is relative and is a function of storage and drought probability.

This definition is consistent with the historical interpretation of safe yield as a single value determined from a sole constraint on water availability; in the Massachusetts definition, that constraint is a period of severe drought. In recent years, attention has been given to other constraints that may affect the water availability in a basin, such as the preservation of the aquatic resources of the basin. Historically, this constraint has been a minimum-flow target that is constant over time. Poff and others (1997) state that the ecological-flow needs of a basin should reproduce the “natural-flow regime,” meaning that ecological-flow needs should reflect the magnitude, frequency, duration, timing, and rate of change that occurs naturally in streamflow. A single minimum-flow target would not be adequate to meet those needs; therefore, the sustainable yield of the basin, if constrained by ecological-flow needs, will not be a constant value.

To address the limitations of the safe-yield definition, recent literature has proposed that water availability is better expressed as a “sustainable yield” rather than a safe yield (Sophocleous, 2000; Alley and Leake, 2004; and Maimone, 2004). Sustainable yield is a measure of water availability that simultaneously considers the spatial and temporal availability of water (Maimone, 2004), as well as the complex interplay between the time varying and competing demands for water, such as human and ecological water needs (Alley and Leake, 2004). The concept of sustainable yield signifies the complexity and interdependence of some variables that affect water availability. To understand and quantify the sustainable yield of a basin, water managers and planners require flexible tools that address as many of these variables as possible and at the appropriate time scales.

Existing Tools to Estimate Streamflow and Assess Water Availability in Massachusetts

The calculation of sustainable yield and water availability in a basin require an estimate of unregulated, or baseline, streamflow conditions at the time scales appropriate to understanding the competing needs for water in a basin. For example, assessment tools used to understand ecological-flow needs typically require baseline streamflow values at the daily time scale (Black and others, 2005; The Nature Conservancy, 2005; Hendrickson and others, 2006). A variety of modeling tools have been used to estimate water availability in ungaged basins in Massachusetts; however, not all tools provide data on streamflow at the daily scale. These tools range from regression models that estimate annual or low-flow conditions at regional scales using a small set of explanatory characteristics of an ungaged basin (for example, Vogel and others, 1999 and Reis and Friesz, 2000) to calibrated, physically based models tailored to the conditions of individual Massachusetts Planning Basins (DeSimone and others, 2002; DeSimone, 2004; Zarriello and Ries, 2000; Barbaro and Zarriello, 2006; Barbaro, 2007).

In Massachusetts, quantile-based regression models were used to estimate selected unregulated low-flow streamflow statistics by relating the physical and climate characteristics of gaged basins to 13 low-flow streamflow statistics (Reis and Friesz, 2000). Reis and Friez (2000) related the median August streamflow value; the 7-day, 2-year and the 7-day, 10-year streamflow values; and streamflow quantiles at the 50-, 60-, 70-, 75-, 80-, 85-, 90-, 95-, 98-, and 99-percent exceedence probabilities (that is, the streamflow values exceeded 50, 60, 70, 75, 80, 85, 90, 95, 98, and 99 percent of the time, respectively) to the drainage area, mean basin slope, area of terrain underlain by stratified drift per unit of total stream length, and the location of the basin. These quantile-based regression equations are currently used in the Massachusetts StreamStats application (U.S. Geological Survey, 2009) to estimate unregulated low-flow streamflow statistics at ungaged sites.

Fennessey (1994) and Fennessey and Vogel (1990) used a parameter-based regression model to estimate daily streamflow quantiles at ungaged locations in the northeastern and mid-Atlantic United States, including Massachusetts. The parameter-based regression model, in which it is assumed that daily streamflow values can be represented by a particular continuous probability density function (PDF), provides a simple equation for approximating the structure of daily streamflow. The parameters of the PDF are regressed against readily measured physical and climate characteristics of gaged basins to estimate daily streamflow quantiles at an ungaged site. Fennessey (1994) found that the parameters of the generalized Pareto distribution were related to the drainage area, average annual precipitation, average annual snowfall, runoff-curve number (Soil Conservation Service, 1986), mean channel slope, and mean elevation of the basin (Fennessey, 1994). Whereas the Reis and Friesz (2000) regression equations estimate streamflow quantiles only at the 50-, 60-, 70-, 75-, 80-, 85-, 90-, 95-, 98-, and 99-percent exceedence probabilities, the parameter-based regression model can provide an estimate of a streamflow quantile at any exceedence probability, including the high-flow quantiles, which were not estimated by Ries and Friesz (2000).

In contrast to statistically based regression models that require only a few parameters to estimate streamflow, physically based basin models can be used to estimate streamflows at the monthly, daily, or sub-daily time scales. Basin models simulate specific hydrologic processes such as runoff generation, evapotranspiration, groundwater and surface-water interactions, and hydrologic responses to pumping and discharge stresses. In some cases, model uncertainty is explicitly considered (Walter and Leblanc, 2008). Such models are appropriate for detailed evaluation of the hydrologic effects of human stresses on streamflows, lake levels, and groundwater levels. Nonetheless, due to the substantial training, expertise, and time required to calibrate and use these physically based models, implementation of these models for a statewide, screening-level assessment of water availability is both cost and time prohibitive.

Mid-range in complexity between regression-based models and physically based models is the QPPQ method, introduced and named by Fennessey (1994) and also published by Hughes and Smakhtin (1996), Smakhtin (1999), Smakhtin and Masse (2000), and Mohamoud (2008). Fennessey (1994) paired the parameter-regression model with the use of a reference streamgage to estimate an unregulated, daily mean streamflow time series at an ungaged site. In this approach, daily streamflow quantiles at the ungaged site are estimated using the parameter-based regression model, which results in a continuous daily flow-duration curve (FDC) (the relation between exceedence probability and streamflow for each day of observed streamflow) at the ungaged site. The FDC is translated into a time series by use of a reference streamgage. As explained in Waldron and Archfield (2006), the observed time series of streamflow at the reference streamgage (Q) (fig. 1A) is used to construct an FDC (fig. 1B), which represents the probability of exceedence (P) for each unique streamflow value in the record. The assumption is then made that the probability of exceeding a flow at the reference streamgage is equivalent to the probability of exceeding a flow at the ungaged site (P) (fig. 1C). Lastly, by equating the exceedence probabilities at the ungaged site and reference streamgage, the dates of streamflow associated with each exceedence probability at the reference streamgage are transferred to the ungaged site to assemble a time series of streamflow at the ungaged site (Q) (fig. 1D).

The parameter-regression method coupled with the QPPQ method developed by Fennessey (1994) has been previously applied in the estimation of inflows to drinking-water reservoirs in Massachusetts (Waldron and Archfield, 2006). However, the parameter-regression equations in Fennessey (1994) cannot be used to estimate the FDC in an interactive, GIS-based application because the calculation of the runoff-curve number is not able to be automated. Archfield (2009) demonstrated several issues with the assumption that the generalized Pareto PDF can represent the structure of daily streamflow. Also, the selection criteria for the reference streamgage were not addressed in Fennessey (1994) or Waldron and Archfield (2006).

To provide estimates of the unregulated, daily mean streamflow and, ultimately, a tool to estimate screening-level values of sustainable yield for a basin in Massachusetts, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection, has developed a statewide, interactive decision-support tool termed the Massachusetts Sustainable-Yield-Estimator (MA SYE) tool. In addition to estimating screening-level values of sustainable yield for a basin, users of the MA SYE can compare the sustainable yield values to estimates of daily streamflow adjusted for current (2000–04) permitted water withdrawals and discharges in the basin of interest.

The MA SYE tool is a hindcasting tool that estimates unregulated, daily mean streamflow over a 44-year period from October 1, 1960, through September 30, 2004. Unregulated, daily mean streamflows are estimated using a quantile-based regression method similar to the equations in Ries and Friesz (2000) coupled with the QPPQ method (Fennessey, 1994; Hughes and Smakhtin, 1996; Smakhtin, 1999; Smakhtin and Masse, 2000; Mohamoud, 2008).

Supporting technical details on the development of the methods used by the MA SYE tool are provided in Archfield (2009). For the tool to compute sustainable yield, users provide flow targets specifying the quantity of water to remain in the stream to meet ecological flow, recreational flow, or some other need. Water withdrawals and discharges are used in the MA SYE tool to adjust unregulated daily mean streamflow. In this study, flows at streamgages in southern New England were related to readily available physical and climate basin characteristics to develop quantile-based regression models, and a criterion was developed to select the reference streamgage.

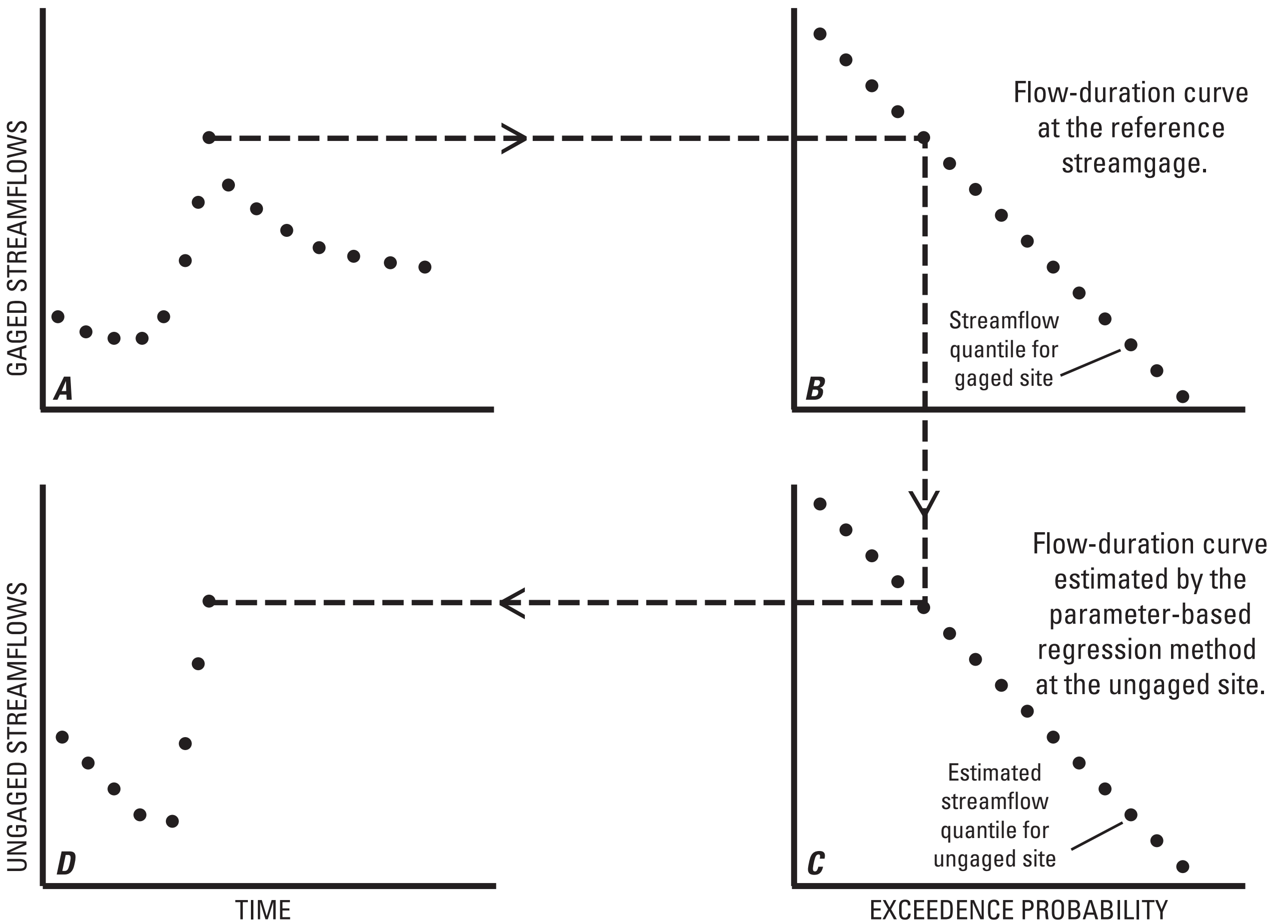


Figure 1. Translation of a flow-duration curve to a time series of estimated streamflow using the QPPQ method, showing (A) the observed time series, (B) flow-duration curve, (C) exceedence probability, and (D) estimated time series for the Massachusetts Sustainable-Yield Estimator tool. (Adapted from Fennessey, 1994, and Waldron and Archfield, 2006).

Purpose and Scope

This report represents the release and documentation of the MA SYE tool, which is used to determine streamflow at ungaged sites in Massachusetts. The data and methods used to develop the tool are documented, as well as the functionality and limitations.

Estimation of Unregulated, Daily Mean Streamflow

Unregulated, daily mean streamflow values are estimated for a period of 16,071 days (44 years from October 1, 1960, through September 30, 2004) using the MA SYE tool. Unregulated, daily mean streamflow values are used in the MA SYE tool to provide the baseline streamflow conditions from which user-specified flow targets are subtracted to determine sustainable-yield values for the basin. The MA SYE tool is used to estimate unregulated, daily streamflow with a two-step process that expands on the works of Fennessey (1994), Hughes and Smakhtin (1996), Smakhtin (1999), Smakhtin and Masse (2000), Ries and Friesz (2000), and Mohamoud (2008). First, the MA SYE tool is used to estimate a continuous daily FDC, which is based on 16,071 streamflow quantiles (one value for each day in the study period). The estimated streamflows are then transformed to a time series of daily streamflow using the QPPQ method (fig. 1) (Fennessey, 1994; Hughes and Smakhtin, 1996; Smakhtin, 1999; Smakhtin and Masse, 2000; Mohamoud, 2008).

Estimation of a Continuous Flow-Duration Curve at Ungaged Sites

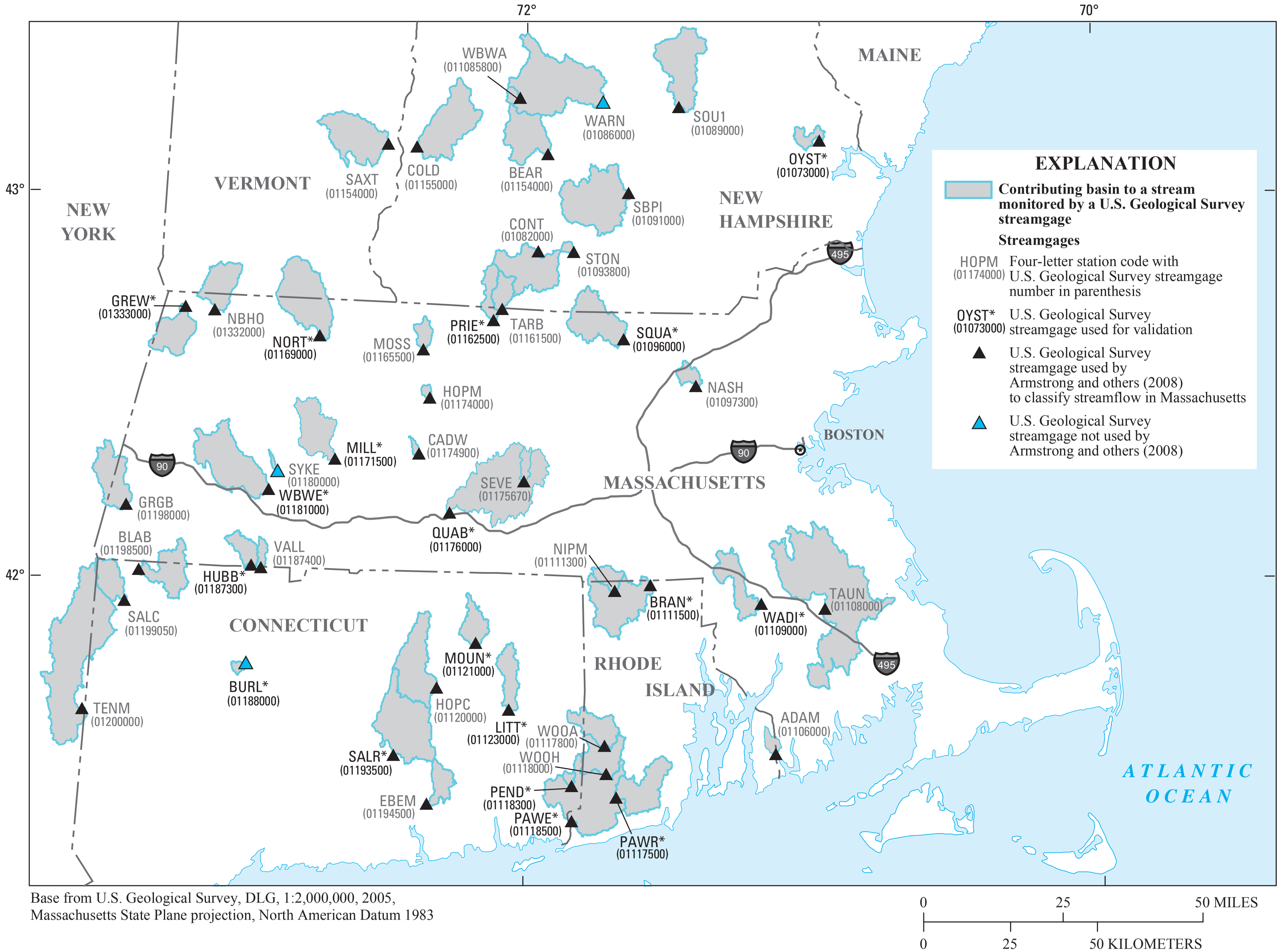
Quantile-based regression is used to estimate streamflow quantiles for six exceedence probabilities. An additional 11 streamflow quantiles are estimated by solving a regression equation that uses another estimated streamflow quantile as the explanatory variable. The remaining 16,054 streamflow quantiles are determined by log-linear interpolation to obtain a continuous daily FDC with 16,071 streamflow quantiles.

Although Reis and Friesz (2000) also used quantile-based regression equations, new quantile-based regression equations were developed because of the availability of recent high-resolution data sets, as well as additional streamflow data, all published since 2000. Furthermore, Reis and Friesz (2000) developed regression equations only for low-flow streamflow quantiles. The parameter-based regression equations used by Fennessey (1994) were not considered for use in estimating the FDC because of the challenges in determining an appropriate PDF to represent daily streamflow (Archfield, 2009).

Streamgages, Flow-Duration-Curve Statistics, and Basin Characteristics

Armstrong and others (2008) identified 85 USGS streamgages that monitor the least-regulated streams/stream reaches in southern New England. A subset of 47 streamgages and contributing basins were used to estimate the FDC at an ungaged site (fig. 2). The 47 streamgages were selected because the observed streamflow record contained greater than 20 years of values, including records from the drought of the 1960s (table 1, at end of report). This drought encompassed Massachusetts and is generally considered the drought of record. Armstrong and others (2008) provide a detailed description of the geologic, hydrologic, and climatic conditions in the study area, as well as information on water use, land cover, and the presence of dams within the study basins. Daily, continuous streamflow observations at the 47 streamgages were recorded for 20 to 86 years. Additional information on the locations, streamgage names and numbers, and periods of record can be found in Armstrong and others (2008).

To develop the quantile-based regression equations, the dependent variable, the streamflow quantiles, and the independent variables, which are the physical and climate basin characteristics, were quantified for each of the 47 streamgages. To compute the streamflow quantiles, the observed daily streamflows were ranked and an exceedence probability was computed for each corresponding ranked streamflow using the Weibull plotting position (Stedinger and others, 1993). Streamflow quantiles were estimated at the following: the 0.01, 0.05, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.85, 0.9, 0.95, and 0.99 exceedence probabilities (table 2, at end of report). The 15 streamflow quantiles include 8 quantiles also estimated by Ries and Friesz (2000) and 7 quantiles that represent high flows, which correspond to streamflows at low exceedence probabilities. Streamflow quantiles at the 0.00062 and 0.999938 exceedence probabilities also were estimated from the observed streamflow data (table 2, at end of report). The 0.00062 and 0.999938 exceedence probabilities are those for the largest and smallest streamflow quantiles calculated using the Weibull plotting position for a record containing 16,071 streamflow observations. The streamflow values are estimated with the MA SYE tool to provide upper and lower bounds on the estimated daily streamflows. The streamflows at the 0.00062 and 0.999938 exceedence probabilities were estimated for only 26 streamgages because a streamflow record of at least 16,071 daily observations is required to estimate these quantiles. Streamflow quantiles at each of the 17 exceedence probabilities were estimated from their observed streamflow records using the non-parametric quantile estimators presented in equations 2a and 2b of Vogel and Fennessey (1994).



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005, Massachusetts State Plane projection, North American Datum 1983

Figure 2. Locations of contributing basins to 47 stream reaches monitored by U.S. Geological Survey streamgages with greater than 20 years of observed, daily mean streamflow data including streamflow during the drought of the 1960s, in Connecticut, Massachusetts, New Hampshire, New York, Vermont, and Rhode Island, generally considered to be the southern New England study area.

This study tested 22 physical and climate basin characteristics (table 3) for use as explanatory (independent) variables. Armstrong and others (2008) provide the basin characteristics for 44 of the 47 streamgages, as well as details about the source and resolution of the characteristics. Physical and climate basin characteristics for the three streamgages not reported in Armstrong and others (2008) are given in table 3. Location variables also were tested as explanatory variables because they are considered substitutes for spatially varying characteristics that could not be readily obtained.

Regression against Basin Characteristics

Streamflow values at the 0.000062, 0.01, 0.05, 0.2, 0.4, and 0.8 exceedence probabilities (table 2) were regressed against the 22 basin characteristics listed in table 3. Regression equations were developed using weighted least-squares and ordinary least-squares regression (table 4). When weighted least-squares regression was used, regression weights were applied to the dependent variables and were computed as a function of the number of days of observed streamflow on which the estimated streamflow statistic was based. Two sets of regression equations were initially developed; one set of equations resulted from the use of the ordinary least-squares method and one set of equations resulted from the use of the weighted least-squares regression method. The final regression equations developed for streamflow quantiles at the 0.2, 0.4, and 0.8 exceedence probabilities used the ordinary least-squares regression equations because substantial reduction in prediction errors were observed over the weighted least-squares regression equations at these streamflow quantiles. Furthermore, streamflow quantiles used as the dependent variables in the regression equations were estimated using at least 20 years (7,300 days) of daily observations, making it unlikely that the record length affected the estimates of these quantiles.

Natural-log transformations of the dependent variables (streamflow quantiles at selected exceedence probabilities) and explanatory variables (physical and climate basin characteristics) were conducted to effectively linearize the relations between the variables. Because the regression equations were developed in logarithmic space, the form of the regression equation is

$$Y = exp^{\beta 0} X_1^{\beta 1} X_2^{\beta 2} \ldots X_n^{\beta n} exp^{BCF} , \qquad (1)$$

where

- Y is the dependent variable (the streamflow quantiles),
- X_n is the independent variables (either a basin characteristic or another estimated streamflow quantile),
- β_n is the regression estimated coefficient for explanatory variable X_n,
- β_0 is the regression-estimated constant term,
- *exp* is the base of the natural logarithm and,
- BCF is the bias correlation factor.

Bias correction factors were estimated using the Smearing Estimator (Duan, 1983) to remove bias in the regression estimates of the streamflow quantiles. Zero values in the regression variables were present in less than 2 percent of the basin characteristics. A streamgage with a zero value for a particular characteristic was not used to test the significance of that basin characteristic. Streamflow quantile values were all greater than zero.

The statistical software package Minitab was used to develop the regression equations. Stepwise regression was used to narrow the 22 basin characteristics to a smaller pool of potentially significant basin characteristics. All regression coefficients in the regression equations were significantly different from zero at the 0.05 significance level (table 4). Residuals (observed minus regression-estimated streamflow values) (plotted in log space) were generally homoscedastic and effectively normally distributed with greater than 75-percent confidence. Sites that greatly affected the fit of the regression models were removed from the final equations. These were sites such that their inclusion substantially reduced model fit. Variables in the final equations had variance-inflation factors of less than 2.5, meaning the correlations between the independent variables are minimal. Regression-coefficient values and other diagnostics are shown in table 4.

Daily streamflows are complex, and physical and climate processes affect portions of the FDC differently; different variables are related to different streamflow quantiles. For example, the percent of terrain underlain by sand and gravel deposits can affect low streamflow values; however, high streamflow values are not related to this variable (table 4). Percent of basin that is open water is used to estimate streamflow for the 40-percent exceedence probability and is negatively correlated with streamflow (table 4). Percent of basin that is wetlands is used to estimate streamflow for the 1-percent exceedence probability and is negatively correlated with streamflow (table 4). Average annual precipitation is used to estimate streamflow for the 1-, 5-, 20-, and 40-percent exceedence probabilities and is positively correlated with streamflow (table 4). Average maximum monthly temperature is used to estimate streamflow for the 80-percent exceedence probability and is negatively correlated with streamflow (table 4). Percent of basin of underlain by sand and gravel deposits was found to have a significant effect on the regression equation used to estimate streamflow at the 40- and 80-percent exceedence probabilities and is positively correlated with streamflow (table 4). Statewide maps of these characteristics are presented in appendix 1.

Table 3. Basin, climate, and land-use characteristics at five U.S. Geological Survey streamgages, tested for use in the Massachusetts Sustainable-Yield Estimator tool.

[These streamgages are not listed in table 3 of Armstrong and others (2008). Sources of the characteristics can be found in Armstrong and others (2008). Elevation characteristics are determined from the U.S. Geological Survey 30-meter National Elevation Dataset.]

Streamgage number	**01086000**	**01107000**	**01109200**	**01180000**	**01188000**
Streamgage name	**Warner River at Davisville, NH**	**Dorchester Brook near Brockton, MA**	**West Branch Palmer River near Rehoboth, MA**	**Sykes Brook at Knightville, MA**	**Burlington Brook near Burlington, CT**
Streamgage code	**WARN**	**DORC**	**WBPA**	**SYKE**	**BURL**
Basin, climate, and land-use characteristics and values					
Drainage area, in square miles	145.99	4.84	4.59	1.69	4.1
Mean basin elevation, in feet	938.42	192.23	143.65	1,099.28	923.19
Maximum basin elevation, in feet	2,689.4	279.37	253.26	1,319.29	1,170.39
Minimum basin elevation, in feet	391.55	114.93	101.97	645.37	759.55
Percent of basin with elevation above 500 feet	92.13	0	0	100	100
Elevation at the outlet of the station, in feet	403.33	126.97	108.1	645.37	778.02
Slope, in percent rise	12.7	2.53	1.75	13.96	5.82
Percent of basin that is underlain by sand and gravel deposits	4.23	22.45	65.79	0	33.03
X-coordinate at the station, in Massachusetts State Plane meters	181124.86	235931.22	220378.27	86990.6	78034.81
Y-coordinate at the station, in Massachusetts State Plane meters	1000085.97	867990.31	847719.56	894290.31	838067.81
X-coordinate at the center of the basin, in Massachusetts State Plane meters	166775.22	234694.48	219306.68	86033.68	76027.35
Y-coordinate at the center of the basin, in Massachusetts State Plane meters	1005190.34	871472.62	849452.99	896583.21	837132.47
Average annual precipitation, in inches	47.07	48.46	48.8	51.58	53.37
Average maximum temperature, in degrees Fahrenheit	13.05	15.25	15.19	13.34	13.86
Average minimum temperature, in degrees Fahrenheit	1.36	4.32	4.67	0.98	1.93
Percent of basin that is underlain by sand and gravel deposits	4.61	14.38	17.73	9.72	1.08
Percent of basin that is open water	1.99	0.21	0.37	1.07	0.05
Percent of basin that is forested	83.88	35.27	74.99	85.44	65.92
Percent of basin that is underlain by hydrologic soils group A	10.2	11.96	24.42	0	14.56
Percent of basin that is underlain by hydrologic soils group B	6.17	8.32	7.98	1.81	20.55
Percent of basin that is underlain by hydrologic soils group C	77.6	61.98	36.61	89.97	37.28
Percent of basin that is underlain by hydrologic soils group D	3.79	15.36	30.61	7.05	26.34

Table 4. Number of streamgages, regression method, explanatory variables, estimated regression coefficients, and regression diagnostics for streamflows at six exceedence probabilities used to estimate the daily, period-of-record flow-duration curve with the Massachusetts Sustainable-Yield-Estimator tool.

[**, characteristic not included in regression equation; †, Bias correction factor computed from Duan (1983), WLS, weighted-least squares; OLS, ordinary-least squares]

Exceedance probability	0.000	0.01	0.05	0.2	0.4	0.8
General regression information						
Number of streamgages used to develop regression equation	26	46	46	45	45	46
Regression method	WLS	WLS	WLS	OLS	OLS	OLS
Standard deviation of model error, reported on log space	0.058	0.018	0.012	0.075	0.102	0.261
Coefficient of determination, asjusted for the number of predictor variables, R-squared (adj)	90.7	98.9	99.5	99.6	99.3	96.5
Characteristics in the regression equation and coefficient value						
Constant term	1.786	-33.705	-24.866	5.066	20.203	49.726
Drainage area	0.820	0.938	0.978	0.994	1.031	1.048
Mean basin elevation	0.451	**	**	**	**	**
Average annual precipitation	**	2.539	2.129	0.949	0.750	**
Percent of basin that is open water	**	**	**	**	-0.028	**
Percent of basin that is wetlands	**	-0.091	**	**	**	**
Percent of basin that is underlain by sand and gravel deposits	**	**	**	**	0.036	0.151
Average maximum monthly temperature	**	**	**	**	**	-2.367
X-location of the basin outlet	**	**	**	0.085	0.108	**
Y-location of the basin outlet	**	**	1.345	**	**	**
Y-location of the basin centroid	**	1.942	**	-0.641	-1.769	-3.297
Bias correlation factor†	1.030	1.010	1.002	1.003	1.004	1.031

Regression against Streamflow Quantiles

Originally, 11 additional streamflow quantiles were regressed against physical and climate basin characteristics; however, because the regression equations were developed independently for streamflow quantiles at each of the exceedence probabilities, there was no constraint to ensure that estimated streamflows decreased with increasing exceedence probability. Thus the inherent structure of the data that ensures streamflow quantiles decrease with increasing exceedence probability is not preserved—a physical impossibility. To enforce physical consistency, 11 streamflow quantiles were recursively regressed against another estimated streamflow quantile. The process was done by first regressing one of the six streamflow quantiles estimated using basin characteristics against another quantile. This established an equation relating one quantile to another. The equations were then used to recursively estimate streamflow quantiles at 11 additional exceedence probabilities. For example, the streamflow quantile at the 80-percent exceedence probability is obtained by solving a quantile-based regression equation that is a function of basin characteristics. However, the streamflow quantile at the 85-percent exceedence probability is obtained using the relation between the streamflow quantiles at the 80- and 85-percent exceedence probabilities. Only the estimated streamflow at the 80-percent exceedence probability is needed to estimate the streamflow at the 85-percent exceedence probability. Subsequent streamflow quantiles are estimated from the relation between one quantile and another (table 5). After streamflow quantiles at the 17 exceedence probabilities are solved, streamflow is log-linearly interpolated between these quantiles to obtain a continuous, daily FDC.

Estimation of Streamflow Time Series by use of a Reference Streamgage

The MA SYE tool transforms the daily mean FDC at an ungaged site to a time series of daily mean streamflow using the QPPQ method (Fennessey, 1994; Hughes and Smakhtin, 1996; Smakhtin, 1999; Smakhtin and Masse, 2000; Mohamoud, 2008). The QPPQ method uses a reference streamgage to assign a date to each streamflow quantile along the estimated FDC by relating the exceedence probabilities at the ungaged site to the reference streamgage (fig. 1).

Table 5. Number of streamgages, regression method, explanatory variables, estimated regression parameters, and regression diagnostics for streamflows at 11 exceedence probabilities used to estimate the daily period-of-record flow-duration curve for the Massachusetts Sustainable-Yield-Estimator tool.

[†, Bias correction factor computed from Duan (1983), WLS, weighted-least squares; QX, streamflow value at the X divided by 100 exceedence probability]

Exceedance probability	Number of streamgages used to develop regression equation	Regression method	Standard deviation of model error, reported on log space	Coefficient of determination, asjusted for the number of predictor variables, R-squared (adjusted)	Value of constant term in the regression equation	Value of regression coefficient estimated for the explanatory variable	Explanatory variable	Bias correlation factor†
0.1	47	WLS	0.006	99.9	0.228	0.993	Streamflows at the Q15 estimated from the observed values	1.003
0.15	47	WLS	0.006	99.9	0.229	0.988	Observed streamflows at the Q20	1.003
0.3	47	WLS	0.006	99.9	0.345	0.986	Observed streamflows at the Q40	1.004
0.5	46	WLS	0.004	99.9	-0.335	1.011	Observed streamflows at the Q40	0.100
0.6	47	WLS	0.006	99.9	-0.367	1.01	Observed streamflows at the Q50	0.999
0.7	46	WLS	0.010	99.8	-0.463	1.02	Observed streamflows at the Q60	0.998
0.85	45	WLS	0.007	99.9	-0.346	1.03	Observed streamflows at the Q80	0.999
0.9	46	WLS	0.010	99.8	-0.386	1.04	Observed streamflows at the Q85	1.002
0.95	46	WLS	0.015	99.6	-0.492	1.06	Observed streamflows at the Q90	1.002
0.99	46	WLS	0.022	99.1	-0.665	1.05	Observed streamflows at the Q95	1.024
0.100	25	WLS	0.120	90.3	-1.525	1.204	Observed streamflows at the Q99	1.026

Reference Streamgages

The MA SYE tool selects a reference streamgage from 1 of 66 reference streamgages across southern New England (table 1; fig. 3). The reference streamgages include the 61 streamgages used by Armstrong and others (2008) to hydrologically classify Massachusetts streams and 5 additional streamgages that are also considered unregulated by Armstrong and others (2008), which enhanced the number of reference streamgages.

The QPPQ method requires that the reference streamgage and ungaged site have daily streamflow records for the time period of interest. Therefore, all reference streamgages in the MA SYE also must have records of 16,071 daily streamflows spanning October 1, 1960 through September 30, 2004. Therefore, the records for 50 of the 66 reference streamgages were extended using the MOVE.3 technique (Vogel and Stedinger, 1985) to ensure all reference streamgages had a period of streamflow record from October 1, 1960, through September 20, 2004. It is important to note that the streamflow values at the reference streamgage are not used in the QPPQ method; only the date and exceedence probabilities at the reference streamgage are used. Record extension for these streamgages followed the approach detailed in Armstrong and others (2008). Information on the record extension for 46 of the 50 reference streamgages is located in Armstrong and others (2008); record-extension information for the additional 4 reference streamgages is listed in table 6 of this report.

Selection of a Reference Streamgage

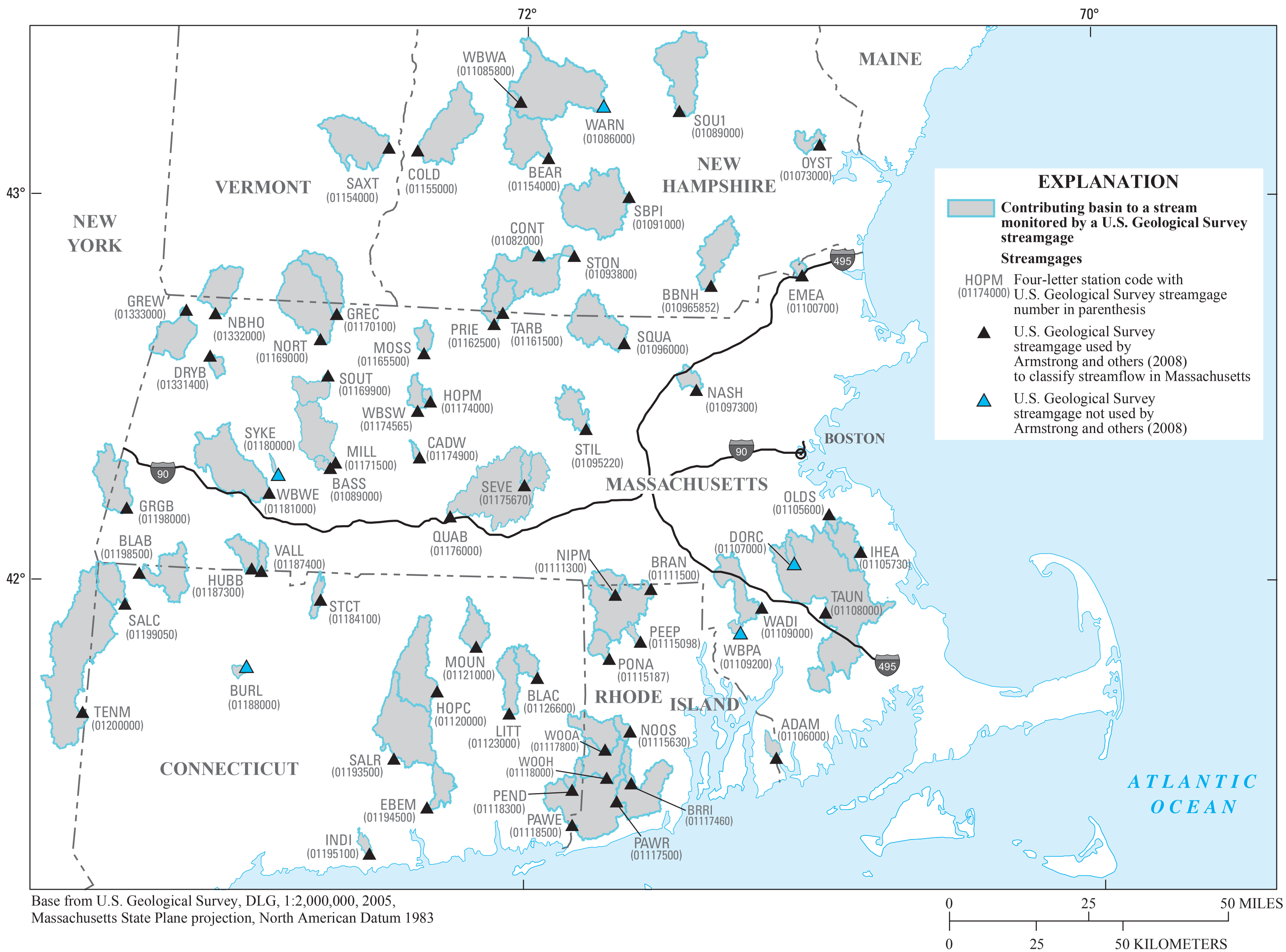
For the QPPQ method, it is assumed that the date of a particular streamflow being exceeded at the ungaged site is the same as at the reference streamgage. For example, if the streamflow on October 1, 1974, is exceeded 95 percent of the time at the reference streamgage, the streamflow exceeded 95 percent of the time at the ungaged site also occurred on October 1, 1974. By extension to other streamflow quantiles, for the QPPQ method it is assumed that the high-flow, mid-range flow, and low-flow events occur on the same day at both the reference streamgage and the ungaged site. Therefore, the ideal reference streamgage would be the one with the most streamflows correlated to those at the ungaged site. The MA SYE tool quantifies the correlation between the timing of the streamflows at 66 reference streamgages and those at the ungaged site by use of the Pearson *r* correlation coefficient (Helsel and Hirsch, 1992). The assumption of equivalent exceedence probabilities occurring on the same day is more likely to hold for two sites that have a value of Pearson *r* correlation coefficient close to one, which means the high-flow, mid-range flow, and low-flow events occur on exactly the same day at both the reference streamgage and the ungaged site.

Although the Pearson *r* correlation coefficient value is easily computed for two gaged sites, the Pearson *r* correlation coefficient value cannot be directly measured for streamflows at a gaged and ungaged site. For this reason, the MA

Table 6. Description of MOVE.3 (Vogel and Stedinger, 1985) record extension for four U.S. Geological Survey reference streamgages in the New England study area.

[These four reference streamgages were not used in Armstrong and others (2008). MOVE.3, Maintenance of Varience Extension, type-3]

Streamgage number	Streamgage name	Streamgage(s) used for MOVE.3 record extension	Correlation coefficient	Period of extension
01086000	Warner River near Davisville, NH	Soucook River near Concord, NH (01089000)	0.95	1979–1987
		Soucook River at Pembroke Road near Concord, NH (01089100)	0.97	1988–2001
		Squannacook River near West Groton, MA (01096000)	0.92	1987–1988
01180000	Sykes Brook at Knightville, MA	West Branch Westfield River 01181000)	0.97	1975–2004
01107000	Dorchester Brook near Brockton, MA	Wading River near Norton, MA (01109000)	0.93	1960–1962, 1974–2004
01109200	West Branch Palmer River near Rehoboth, MA	Pendleton Hill Brook near Clarks Falls, CT (01118300)	0.90	1960–1962, 1974–2004



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005,
Massachusetts State Plane projection, North American Datum 1983

Figure 3. Locations of contributing basins to 66 stream reaches monitored by U.S. Geological Survey streamgages, used as reference sites to estimate unregulated, mean streamflow with the Massachusetts Sustainable-Yield-Estimator tool, southern New England study area.

SYE estimates the correlation between the natural log of the streamflows at the ungaged site and each potential reference streamgage to select the reference streamgage for which logarithms of the daily streamflow are estimated to have the highest correlation with the logarithms of the daily streamflows at the ungaged site.

Time-series correlations between the ungaged site and each reference streamgage were obtained through kriging (Isaaks and Srivastava, 1989), a geostatistical method. For a given reference streamgage, the Pearson *r* correlation coefficient value was computed from the logarithms of the observed, concurrent daily streamflows at the given reference streamgage and each of the other reference streamgages used by the MA SYE tool. A spherical variogram model (Isaaks and Srivastava, 1989) was then developed for each reference streamgage to quantify the relation between the distances between each pair of reference streamgages and the differences in the Pearson *r* correlation coefficient values between each pair of reference streamgages. Each variogram model quantifies the Pearson *r* correlation-coefficient value for any ungaged site in relation to a reference streamgage. The reference streamgage with the highest Pearson *r* correlation coefficient value in relation to the ungaged site is selected for use with the QPPQ method. The MA SYE tool requires only the Massachusetts State-Plane coordinates of the ungaged site in order to select the reference streamgage. The variogram models can be used to create prediction maps of the Pearson *r* correlation coefficient value for each reference streamgage, which show the correlation between a reference streamgage and any ungaged site in Massachusetts (fig. 4). For the CADW 01174900 streamgage (fig. 4A), the areas with the higher estimated correlations form an ellipsoid with the major axis trending in the southwest-northeast direction; however, for the STIL 01095220 streamgage (fig. 4B), correlations appear to decrease radially with distance. Archfield (2009) provides a detailed explanation and validation of the variogram models.

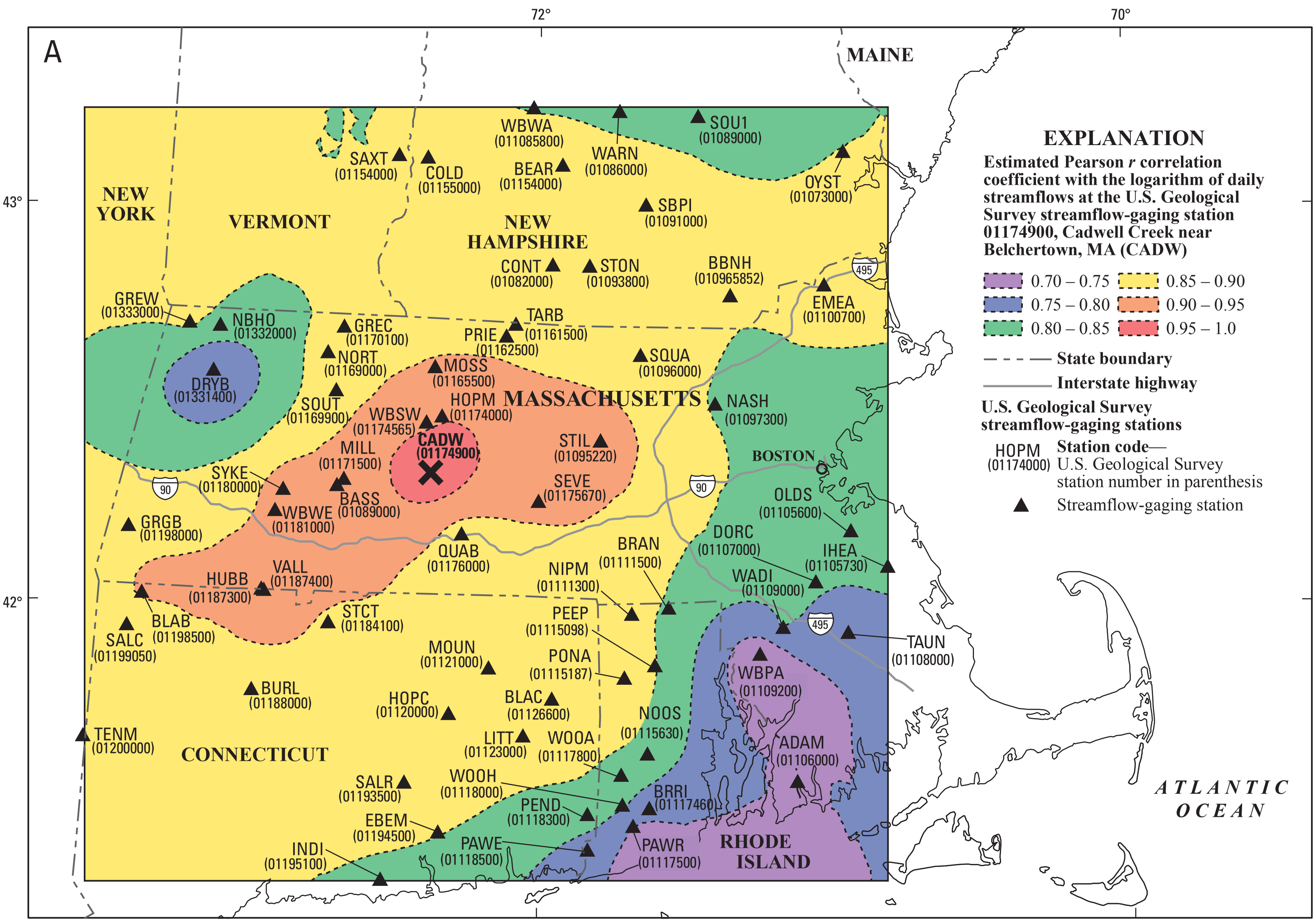
Comparison of Observed and Estimated Streamflows

A time series of unregulated, daily mean streamflow at an ungaged site is assembled in the following steps: (1) solve the regression equations, (2) interpolate between the regression-estimated streamflow quantiles to obtain a daily FDC at the ungaged site, (3) select the reference streamgage, and (4) apply the QPPQ method. To evaluate the MA SYE tool for use in estimating daily, unregulated streamflows at an ungaged site, a validation procedure was used at 18 streamgages because observed streamflow for the period-of-record of interest (October 1, 1960, to September 30, 2004) was available for these streamgages (fig. 2 and table 1). For each of the 18 streamgages, the FDC regression equations were re-developed independent of the streamgage, and the selection of the reference streamgage did not include the streamgage used in the kriging procedure. In effect, this validation experiment evaluates the estimates of streamflow at a streamgage that was not used in the development of the MA SYE tool. The 18 streamgages used in the cross-validation are representative of the distribution of basin characteristics at the 47 streamgages used to develop the continuous, daily FDC (fig. 5).

Observed and estimated streamflows were then compared for goodness of fit at each of the removed streamgages, and a Nash-Sutcliffe (NS) efficiency value (Nash and Sutcliffe, 1970) and percent root-mean-square-error (RMSE) values were computed for each of the 18 streamgages using the natural-log values of the observed and estimated daily streamflows. NS values ranged from 0.98 to 0.69, with a median value of 0.86 (fig. 6); percent RMSE values ranged from 19 to 284 percent, with a median value of 55 percent (fig. 6). Observed and estimated annual, monthly, and daily mean streamflows for streamgages with the best and worst agreement over the full 44-year period show good agreement and relatively unbiased results (fig. 7). However, the highest and lowest daily mean streamflows appear to show a “hook” feature (fig. 7E and 7F). The hook feature is likely an artifact of the log-linear interpolation among the 17 regression-estimated streamflows. Observed and estimated FDCs, when examined at the highest and lowest streamflows, show that the assumption of a log-linear relation between streamflow quantiles at the highest and lowest streamflows may not be appropriate (fig. 8). Nevertheless, these flows represent only the 160 days of highest flow and the 160 days of lowest flow; the other 15,751 streamflows were estimated reasonably by the MA SYE tool.

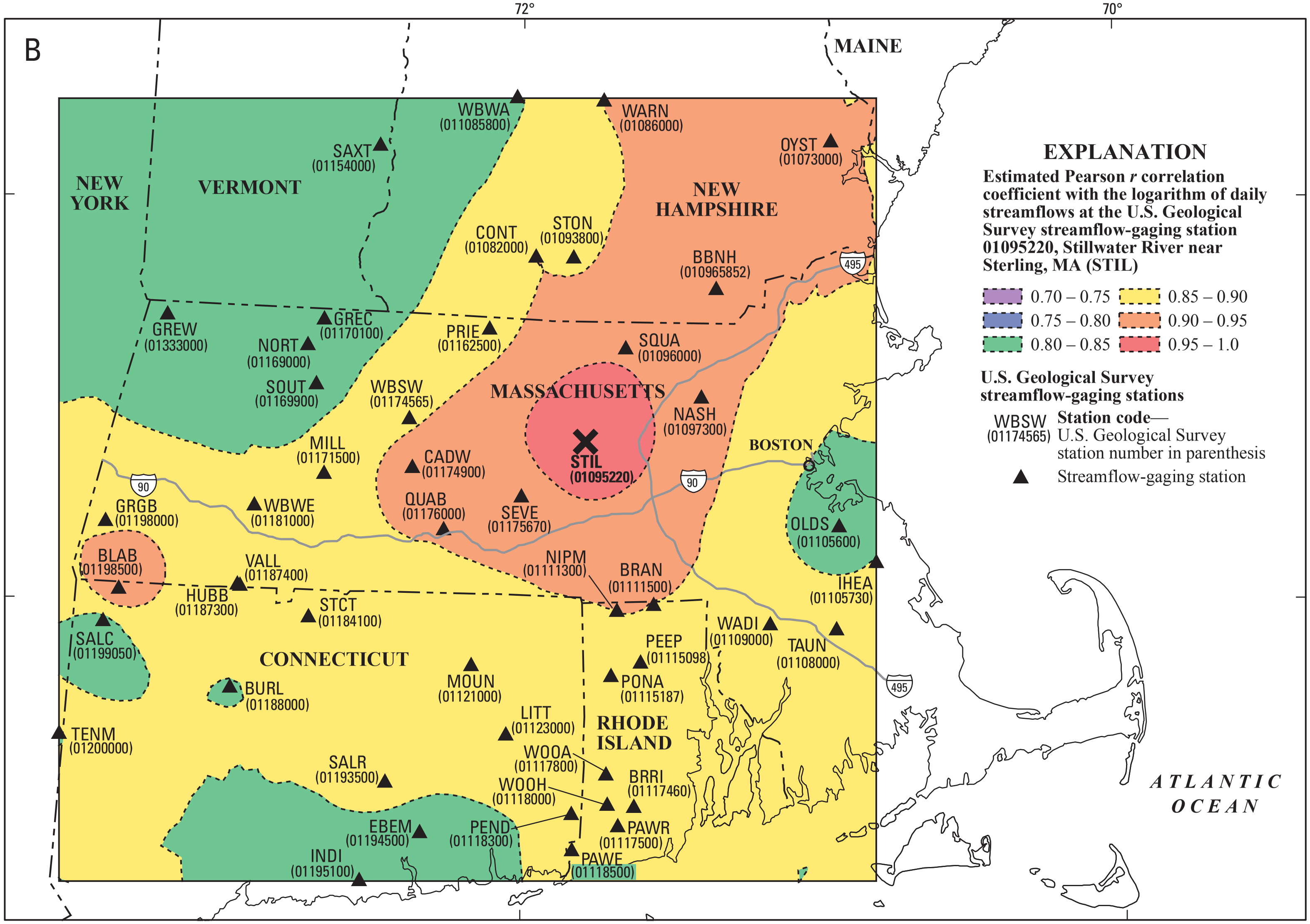
A comparison of observed and estimated hydrographs for streamgages with the best (01187300, Hubbard River near West Harland, CT (HUBB)) and worst (01188000, Burlington Brook near Burlington, CT (BURL)) agreement over the period October 1, 1960, through September 30, 1962—the period of time at the start of the worst drought of record—show good agreement in both real and log space (fig. 9A and 9B). Differences between the observed and estimated daily mean streamflow shown for the 18 streamgages are likely to be typical of the differences one could expect when using the MA SYE tool because the range of basin characteristics for the 18 streamgages used in the cross-validation experiment are nearly identical to the range of these characteristics at the 47 streamgages from which the regression equations were developed (fig. 5).

Streamflow estimates at 29 streamgages used in the development of the MA SYE quantile-based regressions overlapped with those for the streamgages used by Ries and Friesz (2000) (table 1 identifies these 29 streamgages). The estimated streamflow quantiles from the MA SYE tool were compared with the observed streamflow quantiles and the Massachusetts StreamStats-estimated streamflow quantiles estimated at the 0.50, 0.60, 0.70, 0.80, 0.85, 0.9, 0.95, and 0.99 exceedence probabilities by Ries and Friesz (2000) and used in the Massachusetts StreamStats equations. Before making the comparison at each streamgage, the streamgage was were removed from the MA SYE equations, and the regression coefficients were re-estimated. This ensured that the MA SYE-estimated streamflow quantile was not affected by the inclusion of this



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005
Massachusetts State Plane projection, North American Datum 1983

Figure 4. Estimated Pearson *r* correlations with the logarithm of daily streamflows at the U.S. Geological Survey streamgages (A) 01174900, Cadwell Creek near Belchertown, MA (CADW), and (B) 01095220, Stillwater River near Sterling, MA (STIL).



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005
Massachusetts State Plane projection, North American Datum 1983

Figure 4. Estimated Pearson *r* correlations with the logarithm of daily streamflows at the U.S. Geological Survey streamgages (A) 01174900, Cadwell Creek near Belchertown, MA (CADW), and (B) 01095220, Stillwater River near Sterling, MA (STIL).—Continued

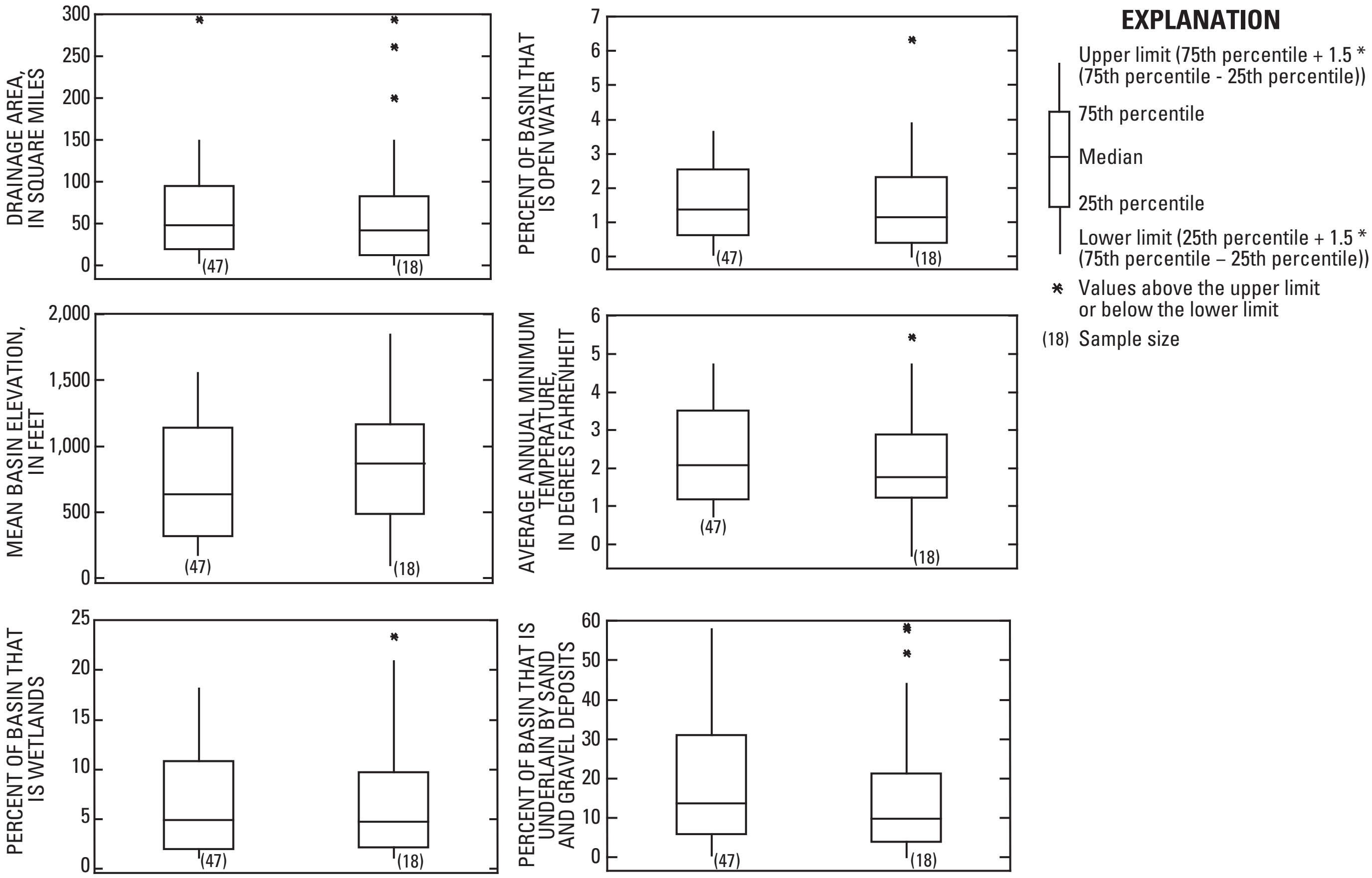


Figure 5. Distribution of basin characteristics used in six regression equations to estimate unregulated, daily mean streamflow at selected streamflow quantiles and range of characteristics used to validate the estimated mean, daily streamflows computed by the Massachusetts Sustainable-Yield Estimator (MA SYE) tool.

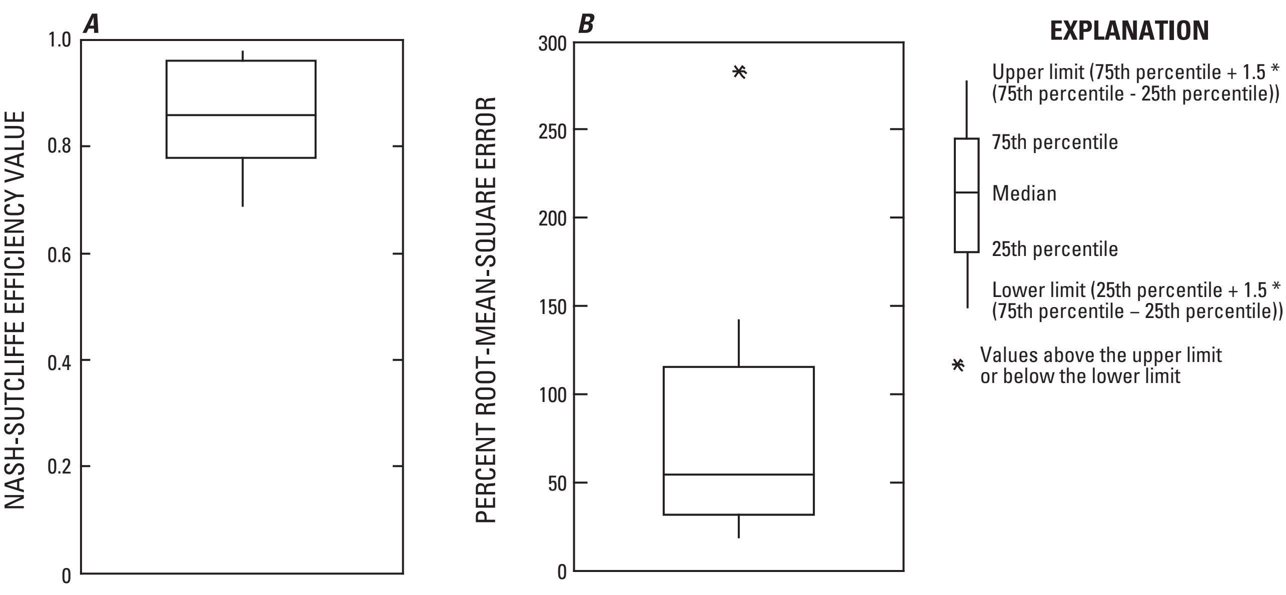


Figure 6. Distribution of goodness-of-fit statistics, (A) Nash-Sutcliffe efficiency values and (B) percent root-mean-square error, computed from observed and estimate mean, daily streamflow values at 18 U.S. Geological Survey streamgages.

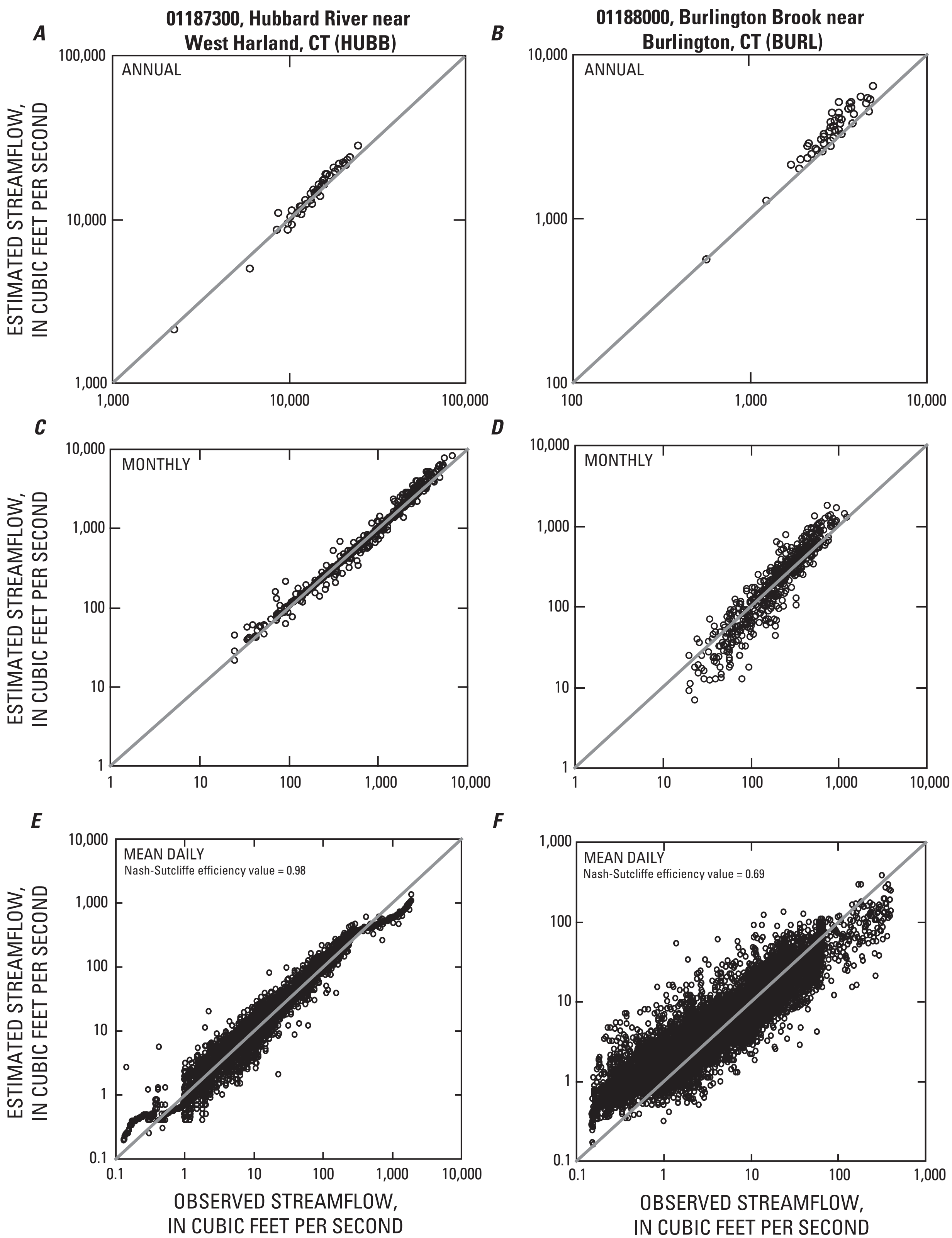


Figure 7. Observed and estimated (A-B) annual, (C-D) monthly, and (E-F) daily mean streamflows for U.S. Geological Survey streamgages 01187300, Hubbard River near West Harland, CT (HUBB) and 01188000, Burlington Brook near Burlington, CT (BURL), southern New England study area, 1960–2004.

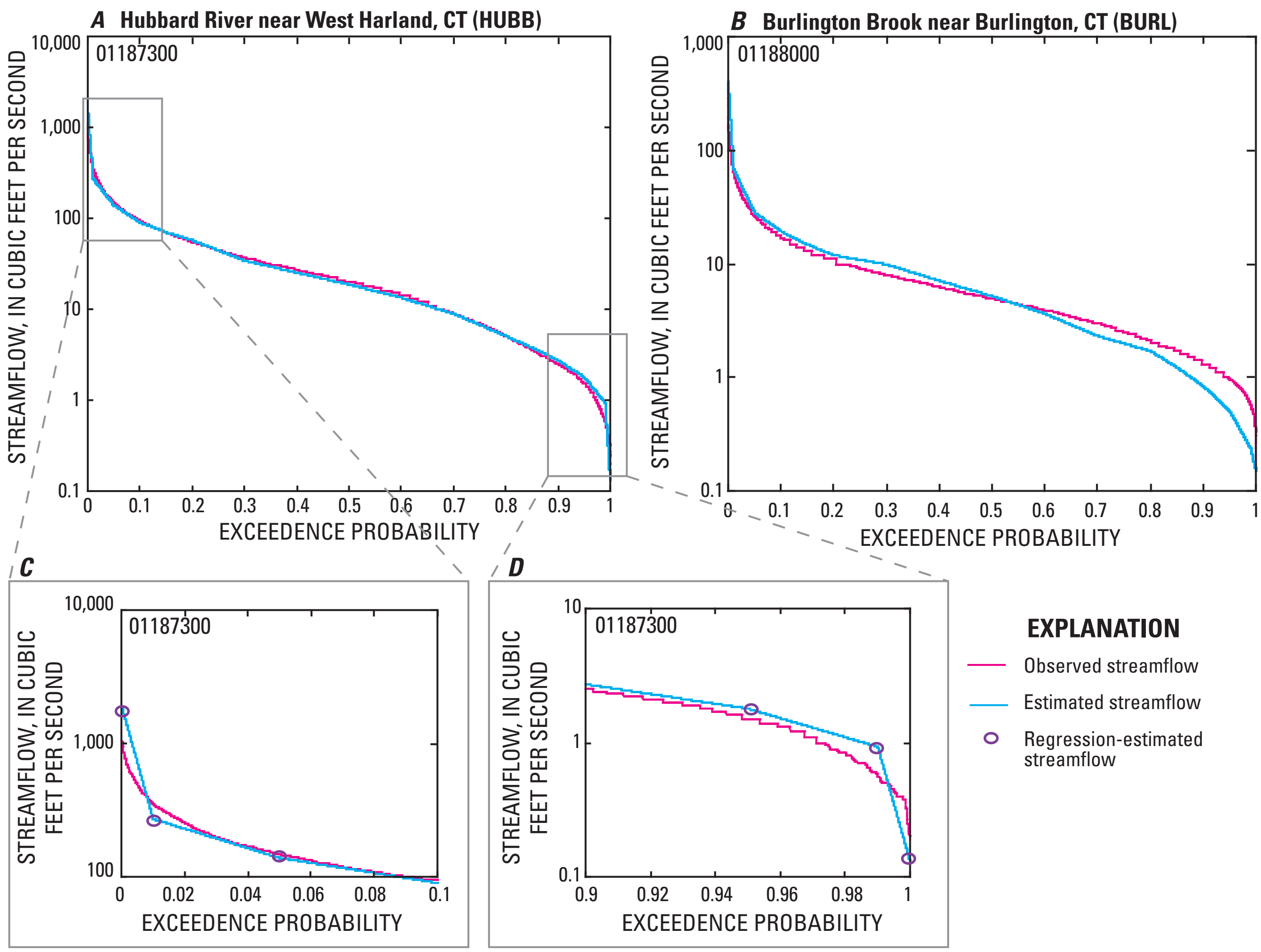


Figure 8. Observed and estimated streamflow quantiles by exceedence probability for U.S. Geological Survey streamgages (A, C, and D) 01187300, Hubbard River near West Harland, CT (HUBB) and (B) 01188000, Burlington Brook near Burlington, CT (BURL), southern New England study area.

streamgage in the development of the equation. However, it was not possible to perform this operation on the equations developed by Ries and Friesz (2000); therefore, a rigorous comparison of the MA SYE and Massachusetts StreamStats could not be conducted. In all cases evaluated, however, the MA SYE-estimated streamflow quantiles were consistent with the observed streamflow quantiles and the streamflow quantiles estimated by the Massachusetts StreamStats equations (Ries and Friesz, 2000) (fig. 10). Furthermore, all MA SYE-estimated streamflow values at each of the 29 streamgages fell within the 90-percent confidence intervals reported by Ries and Friesz (2000).

Uncertainty of Estimated Streamflows

The uncertainty associated with estimated time series of unregulated, daily mean flow at an ungaged site involves three major components: (1) estimation of the FDC at the ungaged site, (2) choice of a reference streamgage based on maps of cross-correlations among flow records of existing gaged sites, and (3) transfer of daily streamflows from the reference streamgage to the ungaged site using the QPPQ method and its inherent assumptions. Each of these major components adds unique uncertainty to the estimated streamflows at the ungaged site, in addition to the measurement error associated with the observed streamflows used to develop the regression equations and the selection and use of the reference streamgage.

A rigorous uncertainty analysis would incorporate the uncertainty introduced by each of these sources of error in an integrated fashion that would result in prediction intervals that enclose the estimated unregulated, daily mean streamflows within a stated degree of confidence. If the MA SYE tool were based on a single modeling approach, such as the multivariate regression used in Ries and Friesz (2000), or a physically based model, one could employ standard methods

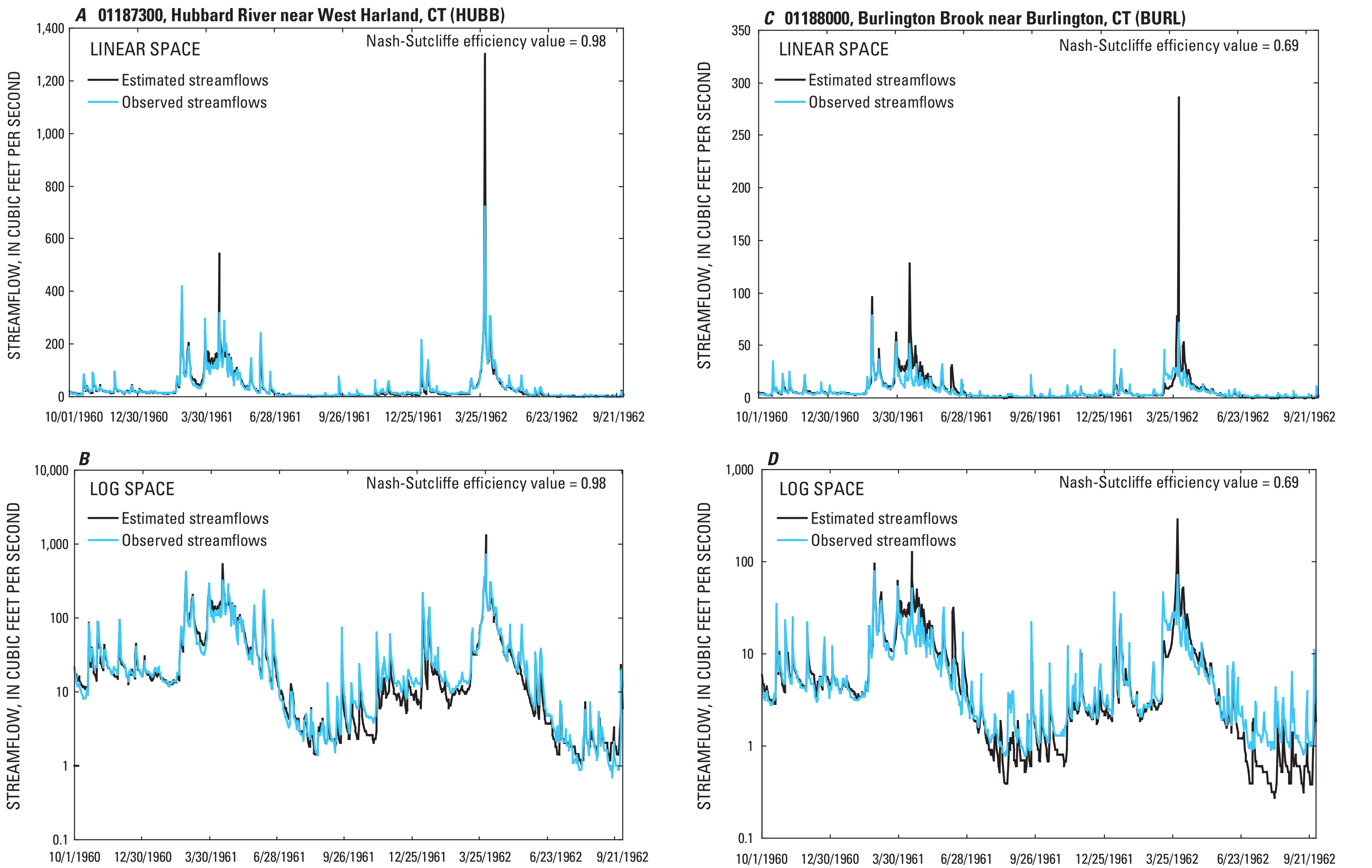


Figure 9. Observed and estimated streamflows for U.S. Geological Survey streamgages (A-B) 01187300, Hubbard River near West Harland, CT (HUBB) and (C-D) 01188000, Burlington Brook near Burlington, CT (BURL) showing the best (A-B) and worst (C-D) agreement between unregulated observed and estimated mean, daily streamflow, in linear space and log space, southern New England study area, 1960–62.

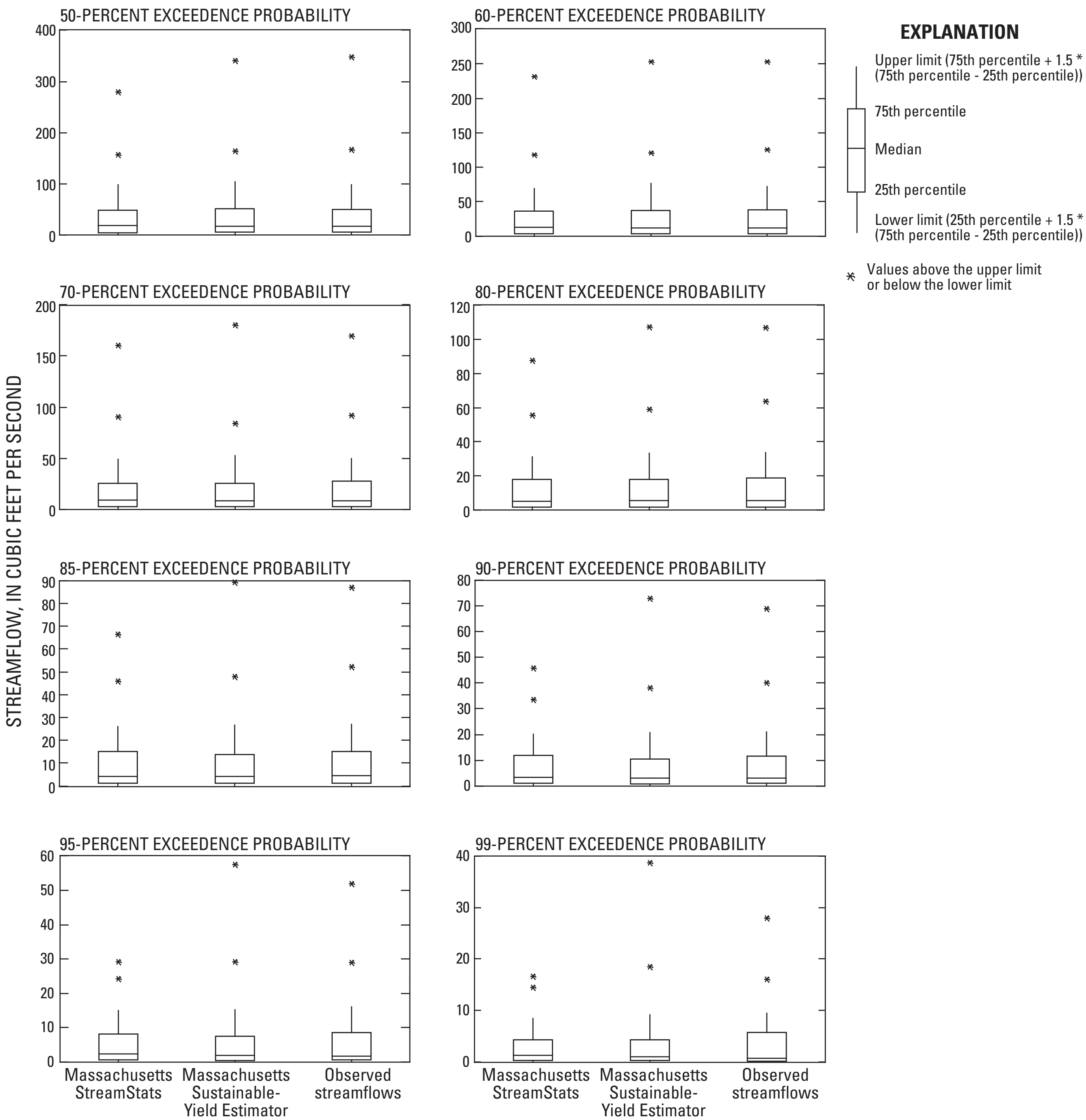


Figure 10. Distribution of observed streamflow and streamflow estimated by the Massachusetts StreamStats and Massachusetts Sustainable-Yield-Estimator tool for eight exceedence probabilities at 29 U.S. Geological Survey streamgages in Massachusetts.

of uncertainty analysis for such model predictions. However, the estimated streamflows used in the MA SYE tool are derived from a variety of complex modeling steps so the standard methods of uncertainty analysis do not provide meaningful prediction intervals. Identifying the true uncertainty is unusually challenging given the interaction of the major MA SYE components. For example, employing the widely used method termed "generalized likelihood uncertainty estimation" (GLUE) (see Stedinger and others, 2008) does not suffice for this problem because GLUE applies only to physically based models, and there are many more sources of error in addition to the model parameter errors accounted for in a GLUE methodology. The actual uncertainty of the MA SYE-estimated streamflows is unknown and remains an area for future research.

To address the issue of uncertainty in this report, the conditions under which one can be expected to obtain the type of goodness-of-fit values reported (fig. 6) are documented. Because the goodness-of-fit values are based on rigorous cross-validation experiments, they represent the range of uncertainty that one can expect in future applications of the MA SYE tool at ungaged sites. For example, figure 6 demonstrates the use of cross-validation experiments, and shows that the use of the estimated time series of daily streamflows that resulted from the goodness-of-fit test generated NS efficiency values in the range of 0.69 to 0.98 with a median value of approximately 0.86. In other words, the range of uncertainty expected from future applications of the MA SYE at ungaged sites will vary across the spectrum of estimated daily streamflows as illustrated by the distribution NS efficiency values reported in figure 6 and time-series plots depicted in figure 9.

In a particular application of the MA SYE tool, the question will arise as to what would be the expected value of the NS efficiency value at an ungaged site. Multivariate ordinary least squares regression was employed to develop a predictive model for values of NS efficiency as a function of the information that would be available to the user of the MA SYE. The two key factors which drive our overall ability to transfer information from a reference streamgage to an ungaged site are the degree of correlation, ρ, between the natural logarithms of the daily streamflows at each site and the variability of the streamflows at the ungaged site. Here the variability of the daily streamflows is measured using the standard deviation of the natural logarithms of the daily streamflows denoted as σ_y. Note that for a lognormal variable x, its coefficient of variation depends only on σ_y where y=ln(x).

Because the efficiency values for reasonable models cannot exceed unity, logit, probit and complementary log-log models (see McCullagh and Nelder, 1983; and Agresti, 1990) were fit to the efficiency values, and all the models restricted predicted values of efficiency to be less than unity. Of the three candidate transformations, the probit model produced the most favorable results in terms of overall goodness-of-fit. A probit model was developed using multivariate ordinary least squares regression to fit the model

$$\Phi^{-1}(E) = \beta_0 + \beta_1 \rho + \beta_2 \sigma_y , \qquad (2)$$

where

$\Phi^{-1}(E)$ is the inverse of a standard normal distribution evaluated at NS efficiency, E,
β_0 is the regression-estimated constant term,
ρ is the correlation between the natural logarithms of the daily streamflows at each site,
β_1 is the regression estimated coefficient for ρ,
σ_y is the standard deviation of the natural logarithms of the daily streamflows, and
β_2 is the regression estimated coefficient for σ_y.

The resulting model, inverted to obtain an estimate of NS efficiency is

$$E = \Phi[-14.388 + 14.033\rho + 1.9722\sigma_y] , \qquad (3)$$

where now $\Phi(\,)$ is the cumulative distribution function for a standard normal random variable. The t-ratios of the model parameters β_0 , β_1, β_2 are -3.08, 3.02 and 3.89, respectively, leading to p-values of 0.008, 0.009 and 0.001, respectively. The model has an adjusted R^2 value equal to 48.4 with model residuals which are extremely well approximated by a normal distribution. A comparison of the values of NS efficiency estimated from the cross-validation experiments and those estimated using equation (3) is shown in figure 11.

The regression model shown in equation (3) documents how average values of goodness of fit vary with both ρ and

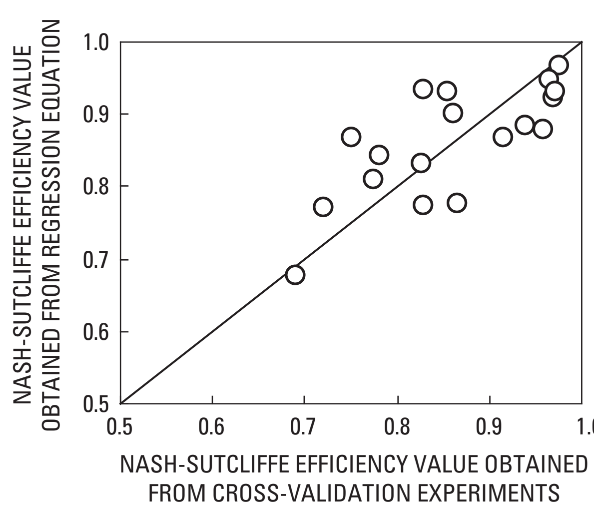


Figure 11. Nash-Sutcliffe efficiency values obtained from the cross-validation experiments in relation to values obtained from regression equations to estimate uncertainty in the daily unregulated streamflows estimated by the Massachusetts Sustainable-Yield-Estimator tool.

σ_y. In general, one expects the NS efficiency value to increase as the correlation between the reference streamgage and the ungaged site increases because that correlation reflects the overall similarity between the two sites. One also expects values of NS efficiency to increase for ungaged sites which have greater overall flow variability because the FDC regression equations have greater predictive capability in such cases. The greater predictive capability associated with the FDC regression equations relate to the recursive nature of the regressions. As σ_y increases, the quantiles of the FDC show greater correlation with each other, which results in recursive regressions with higher explanatory power. An open question remains as to what conditions would lead the QPPQ method to yield higher values of NS efficiency. Further research is needed to better understand these issues.

The t-ratios associated with ρ and σ_y reflect the fact that σ_y explains somewhat more of the overall variability in values of NS efficiency than ρ. The effect attributable to ρ could be caused largely by the choice of a reference streamgage, whereas the effects due to σ_y are due largely to the transfer of streamflow using the QPPQ method and the estimation of the FDC at the ungaged site using regression methods. Thus the regression in equation (3) seems to indicate that more accurate streamflow estimates will likely result from improvements in all three of the major steps associated with the SYE methodology.

Streamflow Adjusted for Groundwater and Surface-Water Withdrawals and Discharges

The MA SYE tool can modify estimates of unregulated, daily mean streamflow at an ungaged site on the basis of permitted groundwater and surface-water withdrawal and discharge locations contained within the basin of interest. For a user-selected basin, groundwater and surface-water withdrawals and discharges are subtracted and added, respectively, from the unregulated, daily streamflow to obtain a time series of daily streamflow at an ungaged site that has been adjusted by the reported 2000 through 2004 withdrawal and discharge volumes. Users also have the option to apply an analytical solution to time-varying groundwater withdrawals and discharges that incorporate the effects of the aquifer properties on the timing and magnitude of streamflow alteration.

Reported Groundwater and Surface-Water Withdrawals and Discharges

A statewide, spatially referenced database of groundwater and surface-water withdrawals and groundwater discharges from 2000 through 2004 was provided by the Massachusetts Geographic Information System (MassGIS) and MassDEP (Christian Jacques, Massachusetts Geographic Information System, written commun., 2007; Thomas Lamonte and Kari Winfield, Massachusetts Department of Environmental Protection, written commun., 2008). The U. S. Environmental Protection Agency (USEPA) provided the National Pollutant Discharge Elimination System (NPDES) surface-water discharge locations and volumes for 2000 through 2004, which are also included in the statewide database.

The database of withdrawals and discharges contains 6,581 locations of groundwater and surface-water withdrawals and discharges in Massachusetts (fig. 12 and table 7), covering four major categories: (1) groundwater and surface-water public-water-supply withdrawals, including community, non-community, and transient facilities using less than 100,000 gallons per day; (2) groundwater and surface-water withdrawals greater than 100,000 gallons per day use as regulated by the Massachusetts Water Management Act (M.G.L. c. 21G), including public and non-public water suppliers (examples of the latter include golf courses and agricultural, commercial, and industrial facilities supplying water for non-human consumption); (3) groundwater pollutant discharges greater than 10,000 gallons per day as regulated by MassDEP (M.G.L. 310 CMR 5), including discharges of sanitary sewer, industrial non-contact cooling waters, Laundromat and carwash waters, and water used in groundwater-treatment systems; and (4) NPDES surface-water discharges as regulated by the USEPA.

Volumes of withdrawal and discharge are available for public-water-supply withdrawals, groundwater discharges, and NPDES surface-water discharges. Public- and non-public water-supply withdrawals greater than 100,000 gallons per day (withdrawals regulated by the WMA) are managed as a withdrawal system, and therefore, withdrawal volumes are reported as the sum of all sources within a withdrawal system, not by individual withdrawal source. Some withdrawal systems are comprised of only public-water-supply withdrawals, in which case, source volumes are also available; however, some withdrawal systems are a combination of public- and non-public-water-supply withdrawals (some withdrawal volumes are available by withdrawal source) and some are only non-public-water-supply withdrawals (no withdrawal volumes are available by withdrawal source). For withdrawal systems that contain both public- and non-public-water-supply withdrawal locations, the source-level withdrawals are subtracted from the total reported withdrawal volume for the system, and the remaining system withdrawal volumes are divided equally among the non-public-water-supply withdrawals to obtain source volumes for each withdrawal location in the system. For withdrawal systems that contain only non-public-water-supply withdrawal locations, the system withdrawal volumes are divided equally among the non-public-water-supply withdrawals to obtain source volumes for each withdrawal location in the system.

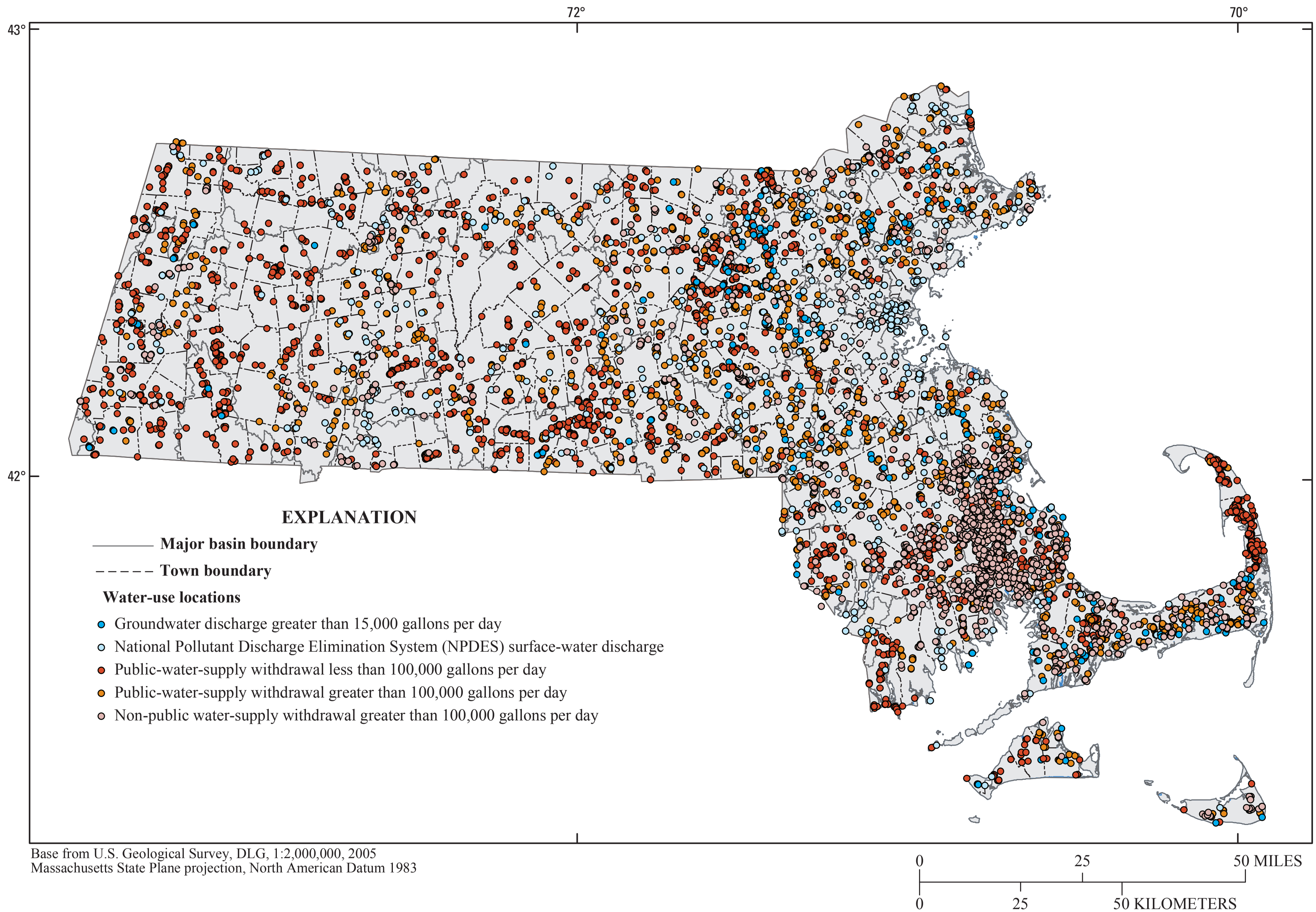


Figure 12. Locations of groundwater and surface-water withdrawals and discharges in Massachusetts used by the Massachusetts Sustainable-Yield-Estimator tool to adjust the unregulated, daily mean streamflow.

Table 7. Water-use type, number of sites, reporting units and statistics, and time and spatial resolution of water withdrawal and discharge sites in the statewide water-use database used with the Massachusetts Sustainable-Yield-Estimator tool to adjust daily, unregulated streamflow at ungaged sites in Massachusetts.

[*, volumes are reported for either the source of the water or as a sum of volumes from aggregated withdrawal sources]

Water-use type	Number of sites in statewide database	Reporting units	Reported statistic	Time resolution of reported data	Resolution of reported data*
Public-water-supply withdrawal less than 100,000 gallons per day	2,361	Million gallons per year	Annual total	Annual data	Withdrawal volumes reported for water source
Public-water-supply withdrawal greater than 100,000 gallons per day	1,420	Million gallons per year	Annual total	Annual data	Withdrawal volumes reported for water source
Non-public water-supply withdrawal greater than 100,000 gallons per day	715	Million gallons per day	Daily volume	Annual data	Withdrawal volumes reported as sum of volumes from aggregated withdrawal sources
Non-public water-supply withdrawal greater than 100,000 gallons per day used for cranberry production	1,028	Area cultivated, in square miles	Acres	Annual data	Withdrawal volumes reported as sum of volumes from aggregated withdrawal sources
Ground-water discharge greater than 10,000 gallons per day	204	Gallons per day	Maximum daily discharge	Monthly data	Withdrawal volumes reported for water source
National Pollutant Discharge Elimination System (NPDES) surface-water discharge	854	Million gallons per day or gallons per day	Annual average, 30-day average, monthly average, daily average, rolling average, weekly average	Monthly data	Withdrawal volumes reported for water source

Disaggregation of Withdrawal and Discharge Volumes

The MA SYE tool adjusts the unregulated, daily mean streamflow using the permitted groundwater and surface-water withdrawals in the statewide database; however, the resolution and quality of the reported data are not uniform (table 7), and daily withdrawal and discharge volumes are not reported. Therefore, withdrawal and discharge volumes must first be disaggregated to daily values before the unregulated, daily mean streamflow can be adjusted. In the MA SYE tool, data reported in the spatially referenced database can be overridden and replaced by more detailed information or by hypothetical withdrawal and discharge volumes.

Groundwater and surface-water discharge volumes are recorded monthly in the statewide database. To obtain daily discharge values, the monthly volumes are divided by the number of days in each respective month, which results in constant daily discharge values over each month.

Groundwater and surface-water withdrawals are reported annually in the statewide database. Annual volumes are disaggregated to monthly values using one of three monthly withdrawal patterns. For non-public-water-supply withdrawals, volumes are disaggregated from annual to monthly values using a constant monthly withdrawal pattern. Daily volumes are computed by dividing the monthly volumes by the number of days in each respective month. For public-water-supply withdrawals, separate monthly withdrawal patterns are used for groundwater and surface-water withdrawals. These patterns were computed using a sample of towns across Massachusetts that had source-level electronically available monthly volumes (table 8). Selected towns had either all groundwater (25 towns) or all surface-water (6 towns) withdrawal volumes for the periods shown in table 8. Monthly volumes for a town were divided by the total annual withdrawal volume to obtain the fraction of annual water withdrawal from the groundwater or surface-water sources in each month. For towns with groundwater withdrawals, average monthly fractions vary between the summer and winter months (fig. 13A). For towns with surface-water withdrawals, average monthly fractions do not vary substantially, even in the summer months (fig. 13B). The demand curves used in the MA SYE tool are the median values of the monthly demand fractions in each month (fig. 13). After disaggregating withdrawal volumes to monthly volumes using one of the three characteristic demand patterns, the MA SYE computes daily water-use values from the monthly values by dividing the monthly volumes by the number of days in each respective month.

Use of the STRMDEPL Program

Several assumptions are made about the withdrawal and discharge volumes when using the MA SYE tool, including a steady-state condition between a groundwater withdrawal or discharge and streamflow. For the steady-state condition,

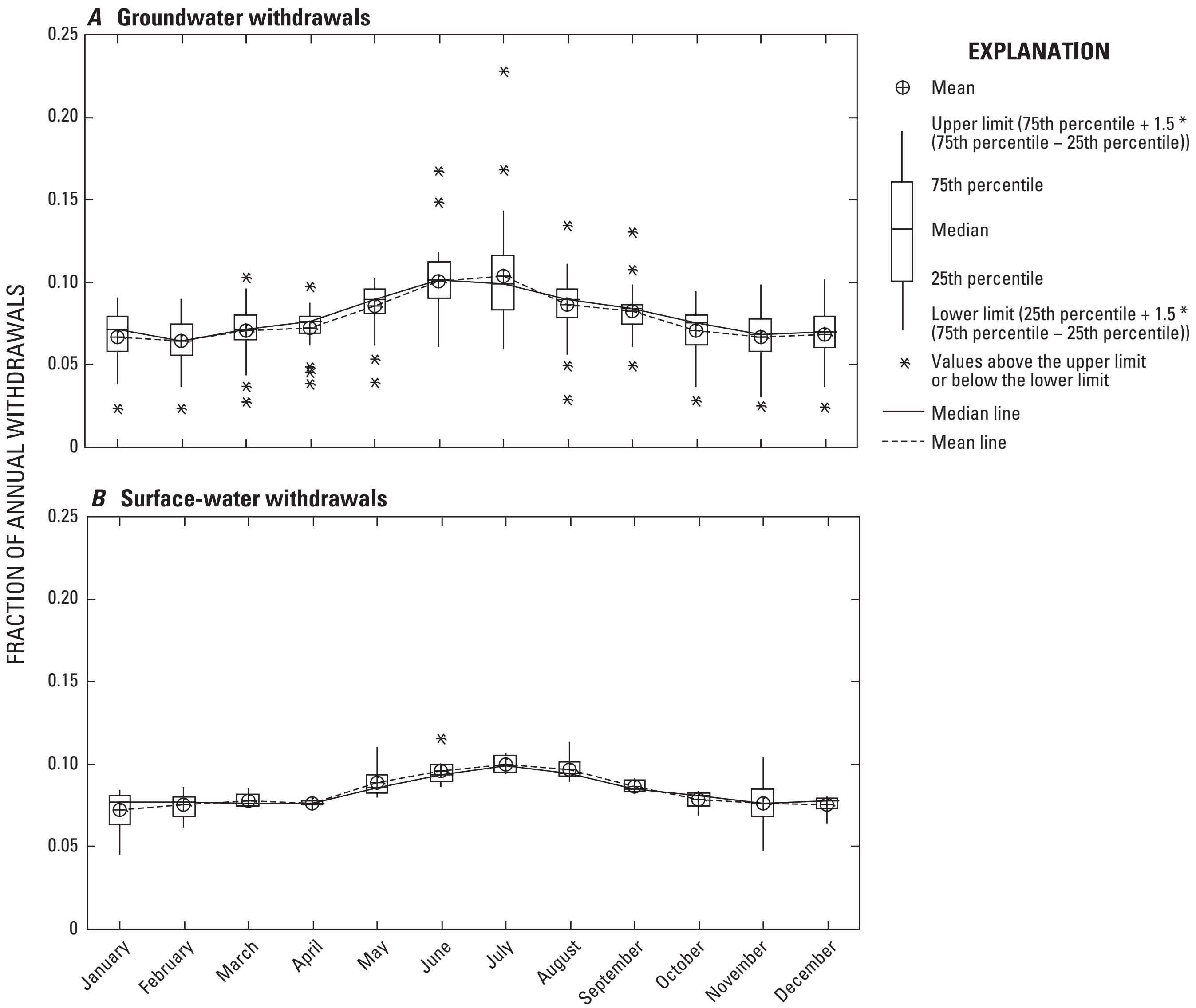


Figure 13. Distribution of the monthly fraction of the total annual withdrawal volumes for (A) groundwater and (B) surface-water public-water-supply withdrawals in Massachusetts.

Table 8. Source of water withdrawals, towns, and years of monthly data used to determine characteristic demand curves for public water supply groundwater and surface–water withdrawals in Massachusetts.

Source of water withdrawal	Town	Years of monthly data
Surface water	Ashburnham	1993–2000
	Gardner	1993–2000
	Lynnfield	1994–1999
	Wakefield	1994–1999
	Winchendon	1996–2003
	Worcester	1996–2001
Groundwater	Acton	2000–2004
	Auburn	1996–2001
	Bellingham	1996–2001
	Blackstone	1996–2003
	Boylston	1996–2001
	Byfield	1993–2001
	Douglas	1996–2001
	Georgetown	1990–2001
	Grafton	1996–2001
	Hopedale	1996–2001
	Hopkinton	1996–1999
	Mendon	1996–2001
	Millbury	1996–2001
	Millville	1996–2001
	Natick	1996–2003
	North Attleboro	1996–2001
	Northbridge	1996–2001
	Rowley	1995–2000
	Shrewsbury	1996–2001
	Sutton	1996–2001
	Templeton	1993–2000
	Upton	1996–2001
	Uxbridge	1993–1998
	Whitinsville	1998–2001
	Wrentham	1996–2001

it is assumed that there are no time-lag effects of groundwater withdrawals or discharges on streamflow. For some groundwater withdrawal and discharge locations, this may be a reasonable assumption; however, for other groundwater withdrawal and discharge locations this assumption may not hold.

To account for time-lag effects, users have the option of applying the program STMDEPL (Barlow, 2000) to account for the effects of the aquifer on streamflow depletion or augmentation. The STMDEPL program requires three parameters: (1) the transmissivity of the aquifer, T, in units of square length per time, (2) the storativity of the aquifer, S, a dimensionless quantity, and (3) the distance between the withdrawal or discharge location and the nearest surface-water body within the same basin, in length units. As input to the STRMDEPL program, the transmissivity (T) and storativity (S) are combined and entered as a single parameter, known as diffusivity (S/T).

For the purposes of the MA SYE, it was not practical to assign diffusivity values to each of the 4,250 groundwater withdrawal and discharge locations because of the time and effort involved, and because, for many locations, the diffusivity value is unknown. Furthermore, time-lag effects are likely to be negligible for groundwater withdrawals and discharges located in close proximity to a surface-water body; therefore, populating diffusivity values for these locations would not be useful. To understand the relation between proximity and time-lag effects on streamflow, a simple sensitivity experiment using STRMDEPL was performed. STRMDEPL was used to simulate the streamflow depletion for a broad range of diffusivities and distances between a hypothetical groundwater-withdrawal location and the nearest surface-water body (fig. 14). For distances less than 250 feet, streamflow depletion is about equal to the withdrawal rate from the well, and the time-lag effects of the withdrawal on streamflow are negligible (fig. 14).

Diffusivity values are not available in the statewide database, but distances between groundwater withdrawal and discharge locations and the nearest surface-water body are provided in the MA SYE tool. Approximately one-half of the groundwater withdrawal and discharge locations in the statewide database are within 250 feet of the nearest surface-water body. The ArcHydro raindrop tool (Maidment, 2002) was used to identify the nearest surface-water body (stream or lake) within the contributing basin. The raindrop tool traces the surface path of a drop of water on the landscape to the receiving surface-water body. Once the nearest surface-water body was identified, the perpendicular distance between the withdrawal or discharge location and the surface-water body was computed. Distances between groundwater discharge or withdrawal sources and the nearest surface-water body have been pre-calculated for 3,029 locations, and these distances are stored in the spatially referenced database.

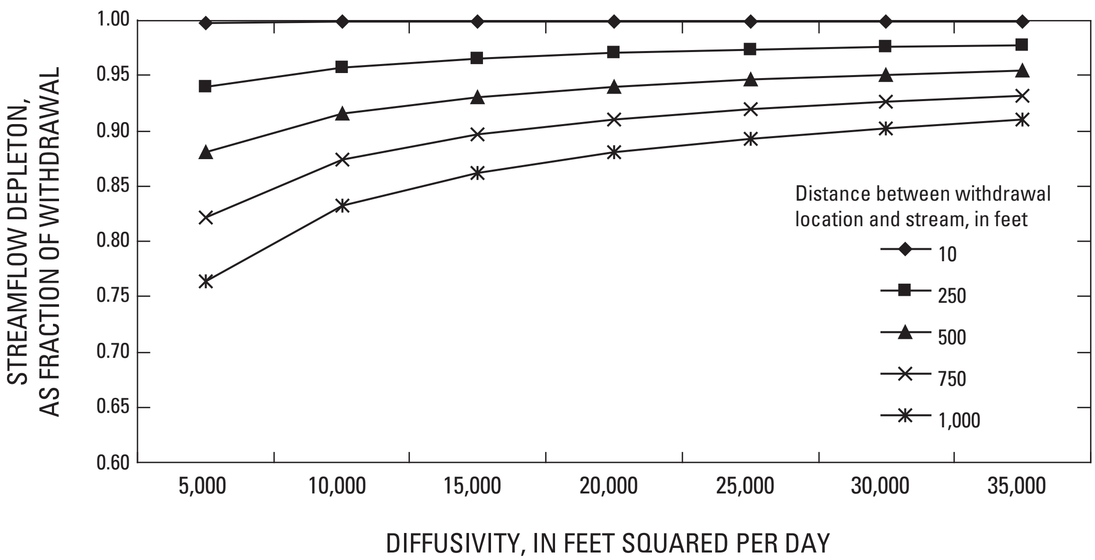


Figure 14. Streamflow depletion estimated by the STRMDEPL program for a range of diffusivity values and distances between a hypothetical withdrawal location and stream (STRMDEPL program from Barlow, 2000).

Estimation of Streamflow when Groundwater and Surface-Water Divides are not Coincident

It is assumed when using the MA SYE tool that the contributing basin to the user-selected stream location has coincident groundwater and surface-water divides. This assumption is true for a large portion of Massachusetts; however, for many areas in southeastern Massachusetts, groundwater and surface-water divides differ. For these areas, existing, calibrated groundwater-flow models (Masterson and others, 2009; Walter and others, 2004; Walter and Whelan, 2004) were used to simulate average monthly streamflows at fixed locations near the mouths of major streams (fig. 15). For each fixed location, withdrawals and discharges in the groundwater-flow model were removed to simulate unregulated, average monthly streamflow. A second set of average monthly streamflows also was simulated using present day (as specified in the respective reports) withdrawal and discharge volumes. In the MA SYE tool, users can select from one of the fixed stream locations in these areas for calculation of sustainable yield. Results are served to the user through the MA SYE tool user interface, as described in the MA SYE user's manual located at *http://pubs.usgs.gov/sir/2009/5227/*.

Calculation of Sustainable Yields Using the Massachusetts Sustainable-Yield Estimator (MA SYE) Tool

The MA SYE tool provides estimates of unregulated, daily mean streamflow and adjusted daily streamflows for groundwater and surface-water withdrawals and discharges. Users can quickly and easily compute the screening-level values of sustainable yield by specifying time-varying flow targets (the quantities of water to be left in the stream). The flow targets can be entered as monthly user-specified values in cubic feet per second, cubic feet per second per mile, or daily percentage of the unregulated streamflows to remain in the stream. These flow targets are then subtracted from the unregulated, daily streamflow to provide an estimate of the sustainable yield for the contributing basin at the location on the stream of interest. Calculations are based not only on user-specified flow targets but also on a user-specified time period between 1960 and 2004.

Users can also adjust the unregulated, daily mean streamflow by subtracting and adding the reported groundwater and surface-water withdrawal and discharge volumes, respectively. The user can adjust each selected year of unregulated, daily mean streamflow by the withdrawal and discharge volumes

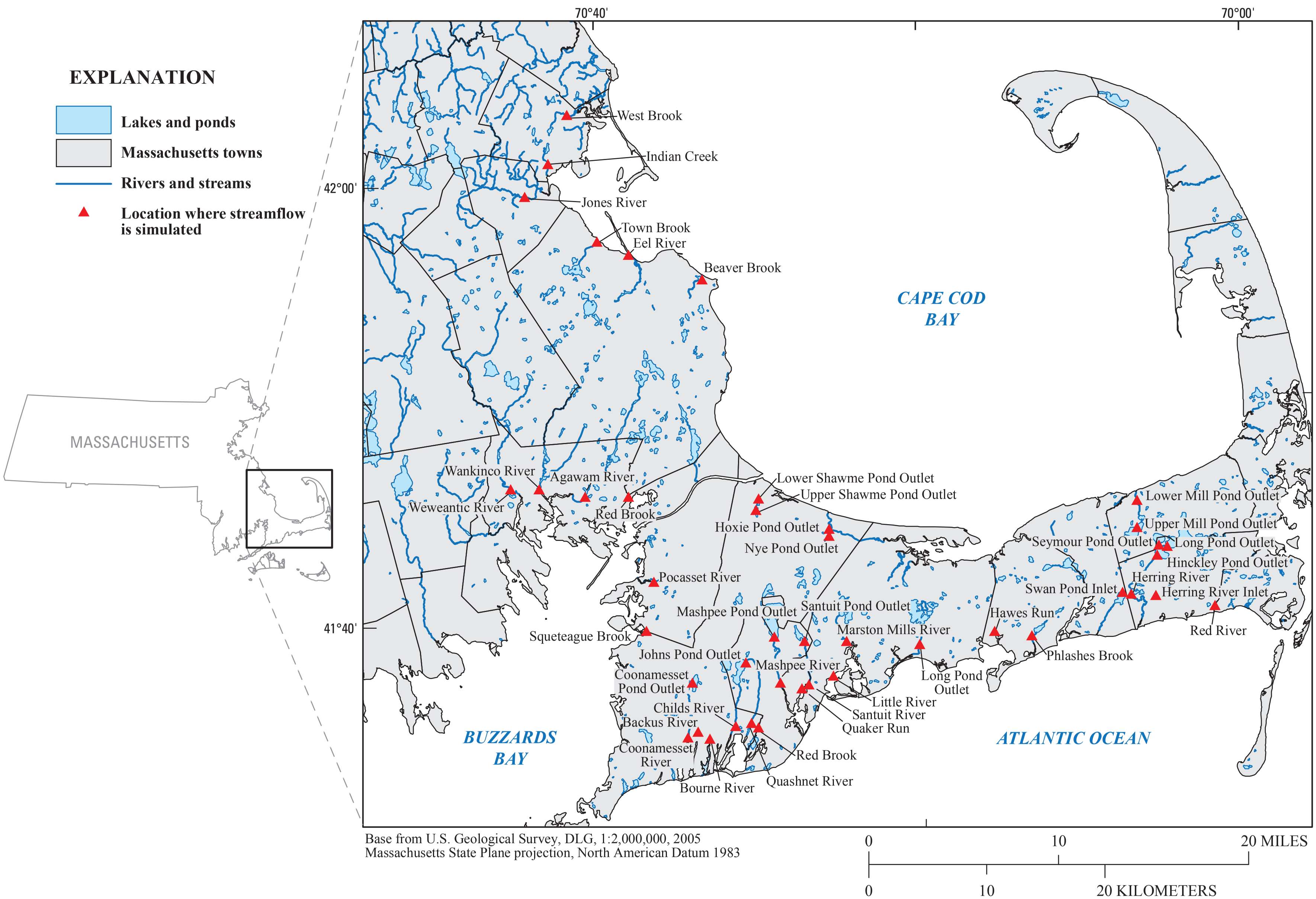


Figure 15. Locations in Massachusetts near the mouths of major streams for which unregulated and regulated streamflows were simulated using a groundwater-flow model because groundwater and surface-water divides are not coincident.

reported for a particular year from 2000 through 2004 or by an average year. Results of the unregulated and adjusted streamflows, as well as the user-specified flow targets, are summarized on a two-page report that graphically displays the unregulated and adjusted streamflows along with the flow targets for the user-specified time period. Average, monthly unregulated streamflow values are calculated and compared to the flow targets. General information about the calculation of the unregulated and adjusted streamflows also is provided in the summary report, such as the physical and climate basin characteristics, reference streamgage used to compute the unregulated streamflows, and the number of withdrawal and discharge locations in the basin.

The MA SYE tool was designed as a desktop application that employs the Environmental Systems Research Institute, Inc. (ESRI) ArcMap GIS software (Environmental Systems Research Institute, Inc., 2009) coupled with Microsoft Excel and Access, commonly used and widely available spreadsheet and database programs, respectively. Available options are

- Select the period of analysis,
- Select an average or single year of withdrawal and discharge volumes to adjust the unregulated streamflow,
- Select a different reference streamgage,
- Edit withdrawal and discharge volumes for any water-use point within the basin,
- Apply STRMDEPL (Barlow, 2000) to a groundwater withdrawal or discharge volume,
- Add or edit aquifer properties used in the computation of streamflow depletion,
- Add a volume or percent of total withdrawals returned to the basin from septic-system discharge,
- Enter custom flow targets or choose from a predefined list of targets, and
- Export results to text files compatible with the Indicators of Hydrologic Alteration (IHA) (The Nature Conservancy, 2005) tool and the National Hydrologic Assessment Tool (NAHAT) (Hendrickson and others, 2006), which allow for the computation of over 151 streamflow statistics. Unregulated and adjusted streamflows can be readily output to these programs for a comparison of a wide variety of flow statistics.

Once a user selects the location on a stream of interest from the MA SYE GIS user interface, a spreadsheet template guides the user through the remaining functions of the MA SYE tool. All related files needed to use the MA SYE along with a complete user's manual with installation instructions for the MA SYE tool is available at *http://pubs.usgs.gov/sir/2009/5227/*.

Limitations

There are several limitations to the use of the MA SYE tool for estimating unregulated, daily mean streamflow time series. In particular, the use of the regression equations is limited to the range of basin characteristics used to develop the regression equations (fig. 5). The MA SYE tool provides warnings for all basin characteristics with values outside the range for which the regression equations were developed. Spatial correlation between streamflows could be accommodated through a generalized least-squares approach, but that is beyond the scope of this report. Prediction and confidence intervals associated with estimates of unregulated, daily mean streamflows could be used to make comparisons using existing methods to estimate unregulated streamflow at ungaged sites or to determine whether significant differences exist between estimated unregulated and regulated streamflows. The three components— (1) regression equations, (2) reference-streamgage selection criteria, and (3) the assumption of equivalent exceedence probabilities on the same day—all contribute to the uncertainty associated with MA SYE estimates of unregulated, daily mean streamflows; however, there does not currently exist a theoretical framework from which prediction or confidence intervals for the MA SYE-estimated daily streamflows can be derived. A lack of theoretical framework for error documentation also limits the understanding of, and ability to model, the unregulated, daily mean FDC.

Estimates of adjusted, daily mean streamflow have several important limitations. Adjusted streamflow estimates consider only withdrawal and discharge locations that are part of the statewide water-use database. Limitations of the quality and resolution of the statewide database affect the estimates of adjusted streamflow. The use of a constant daily withdrawal pattern for non-public-water-supply withdrawal volumes does not take into account the seasonal withdrawals, such as golf course watering, which will lead to underestimation of the effects of withdrawals during the summer low-flow period. The MA SYE tool addresses these data quality and resolution limitations by allowing the user to override reported withdrawal and discharge volumes in the statewide database and provide more detailed information.

A change in withdrawal or discharge volumes at one location may have an affect on withdrawal or discharge volumes at other locations in the basin. For example, an increase in a withdrawal volume at one location might result in increases in the discharge volume at other locations within the basin. Additionally, if monthly data are redistributed within a particular year, no warnings are provided if the new annual total dischage or withdrawal volume differs from the annual volume reported in the MA SYE water-use database.

Adjusted streamflow estimates do not account for the effects of impoundments; septic-system discharge; private domestic withdrawals; non-public-water-supply withdrawals of less than 100,000 gallons per day; and impervious area, which can affect streamflow. To address the limitation of septic-system discharge, the MA SYE allows the user to enter a percentage of total withdrawals that is returned to the basin or a volume that is added to the adjusted streamflow. Withdrawals from surface-water reservoirs are directly subtracted from the unregulated streamflows, and the storage effects of reservoirs are not included in the adjusted-streamflow estimates. Users have the option of removing surface-water reservoirs from the adjusted-streamflow calculations by choosing to ignore the withdrawal location, which entirely removes the effects of these withdrawals on the adjusted-streamflow values.

The MA SYE tool does not contain data on withdrawal and discharge volumes for locations outside of Massachusetts. Therefore, if a user-selected point on a stream has a contributing area outside of Massachusetts, the MA SYE tool warns the user that the adjusted streamflows will not include the withdrawal and discharge volumes located outside of Massachusetts. An updated version of STRMDEPL, termed “STMDEPL08” (Reeves, 2008) has been developed to address some of the simplifying assumptions in STRMDEPL; however STMDEPL08 has not been incorporated into the MA SYE tool.

The MA SYE tool is unable to estimate streamflow for locations on the main stems of the Connecticut and Merrimack Rivers because large portions of these drainage basins are outside of Massachusetts and the methods developed for the MA SYE tool do include streamgages or basin characteristics for the northern portions of these basins. Furthermore, basin characteristics for these basins cannot presently be summarized in a consistent manner and are outside the scope of the MA SYE tool. If a user clicks on the main stems of the Connecticut and Merrimack Rivers, the MA SYE tool delineates a drainage basin but displays a message that the MA SYE tool is unable to continue.

Summary

To quantify the sustainable yield of a basin—the unregulated, daily mean streamflow less some user-specified flow targets–at ungaged sites in Massachusetts, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection (MassDEP), developed the Massachusetts Sustainable-Yield-Estimator (MA SYE) tool. The MA SYE tool is designed to be a flexible, statewide, screening-level decision-support system to compute the sustainable yield of a basin and to evaluate the effects of water withdrawals and discharges on streamflow. The MA SYE tool estimates both the unregulated, daily mean streamflow and streamflow adjusted for water withdrawals and discharges within the basin for a user-selected location on a stream in Massachusetts.

The MA SYE tool estimates an unregulated, daily mean time series of streamflow for a 44-year period (October 1, 1960, through September 30, 2004) using statistically based methods. First, streamflow quantiles are calculated at six exceedence probabilities by regressing streamflow against readily measureable climate and physical basin characteristics. Next streamflow quantiles at 11 additional exceedence probabilities are solved by use of regression to quantify the structure of the streamflow quantiles. A continuous daily flow-duration curve (FDC) at the ungaged site is then obtained by log-linear interpolation among the 17 regression-estimated streamflow quantiles. Lastly, a reference streamgage is used to transform the FDC into daily mean streamflow. The reference streamgage is determined from the estimated correlation of the logarithms of the daily streamflows between the ungaged location and one of 66 potential reference streamgages.

The MA SYE tool estimates an adjusted daily mean time series of streamflow at ungaged sites from reported withdrawal and discharge volumes at locations within the basin. Withdrawal and discharge volumes used in the MA SYE tool are obtained from a spatially referenced statewide database of groundwater and surface-water withdrawals, groundwater discharges, and National Pollutant Discharge Elimination System (NPDES) surface-water discharges. For a user-selected basin, groundwater and surface-water withdrawal and discharge volumes are subtracted and added, respectively, from the unregulated, daily streamflow. Time-varying groundwater withdrawals and discharges can be optionally modified using an analytical program, STRMDEPL, which simulates the effects of the aquifer properties on the timing and magnitude of streamflow alteration.

For the MA SYE tool, it is necessary that groundwater and surface-water divides are coincident for the contributing basin; however, in southeastern Massachusetts and Cape Cod, groundwater-flow models have shown that the surface and subsurface divides differ. In the MA SYE tool, streamflows are obtained from existing groundwater-flow model simulations for these areas, which computed streamflows with and without inclusion of the groundwater and surface-water withdrawals in the model simulations. For the MA SYE tool, it is assumed that groundwater and surface-water divides are coincident for all other areas in Massachusetts.

The user interface of the MA SYE tool was designed as a desktop application that employs Environmental Systems Research Institute, Inc. ArcMap software, a geographic information system, coupled with Microsoft Excel and Access. On the basis of user-defined constraints such as existing water withdrawals and discharges in the basin and flow targets, the MA SYE tool estimates the sustainable yield of the basin by subtracting the flow targets from the unregulated, daily mean streamflow. The MA SYE tool supplies the user with graphical and numerical comparisons of the unregulated and adjusted streamflows relative to any user-specified flow targets. Users can compute the water availability in the basin for any number of water-management scenarios (by changing the withdrawal and discharge volumes, the time period of analysis, or flow targets). Results of each water-management scenario are summarized in a two-page report that displays the unregulated and adjusted streamflow hydrographs for the user-specified time

period and presents selected streamflow statistics calculated from these hydrographs in tabular format.

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Tables 1–2

Table 1. Summary of 66 U.S. Geological Survey streamgages, number of streamflow observations, and the periods of observed, mean daily streamflow record, New England study area.

[REG, used to develop regression equations; REF, used as a reference streamgage; VAL, used in validation of methods; SS, used in Massachusetts StreamStats (Ries and Friesz, 2000) comparison; ¥, site not used in Armstrong and others (2008) to classify streamflows in Massachusetts.]

Streamgage number	Streamgage name	Four-letter abbreviation for streamgage	Number of daily streamflow values	Period of observed streamflow record	Use of streamgage in analysis
01106000	Adamsville Brook at Adamsville, RI	ADAM	14,105	October 1, 1940–September 30, 1978; February 17, 1987–September 30, 1987	REG, REF
01171800	Bassett Brook near North Hampton, MA	BASS	4,352	November 1, 1962–September 30, 1974	REF, SS
010965852	Beaver Brook at North Pelham, NH	BBNH	7,234	October 1, 1986–July 24, 2006	REF
01084500	Beard Brook near Hillsboro, NH	BEAR	9,131	October 1, 1945–September 30, 1970	REG, REF
01198500	Blackberry River at Canaan, CT	BLAB	8,130	October 1, 1949–October 20, 1971	REG, REF
01126600	Blackwell Brook near Brooklyn, CT	BLAC	4,754	October 1, 1963–October 5, 1976	REF
01111500	Branch River at Forestdale, RI	BRAN	23,719	January 24, 1940–December 31, 2004	REG, REF, VAL
01117468	Beaver River near Usquepaug, RI	BRRI	11,556	December 4, 1974–July 24, 2006	REF
01188000¥	Burlington Brook near Burlington, CT	BURL	26,756	October 1, 1931–December 31, 2004	REG, REF, VAL
01174900	Cadwell Creek near Belchertown, MA	CADW	13,229	July 13, 1961–September 30, 1997	REG, REF, SS
01155000	Cold River at Drewsville, NH	COLD	13,979	June 23, 1940–September 30, 1978	REG, REF
01082000	Contocook River at Peterborough, NH	CONT	12,962	July 7, 1945–September 30, 1977; October 1, 2001–December 31, 2004	REG, REF
01107000¥	Dorchester Brook near Brockton, MA	DORC	4,360	October 24, 1962–September 30, 1974	REF, SS
01331400	Dry Brook near Adams, MA	DRYB	4,352	November 1, 1962–September 30, 1974	REF, SS
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	17,265	October 1, 1937–October 6, 1981; October 1, 2001–December 31, 2004	REG, REF
01100700	East Meadow River near Haverhill, MA	EMEA	4,355	October 29, 1962–September 30, 1974	REF, SS
01170100	Green River near Colrain, MA	GREC	14,177	October 1, 1967–July 24, 2006	REF, SS
01333000	Green River at Williamstown, MA	GREW	20,192	September 20, 1949–December 31, 2004	REG, REF, VAL, SS

Table 1. Summary of 66 U.S. Geological Survey streamgages, number of streamflow observations, and the periods of observed, mean daily streamflow record, New England study area.—Continued

[REG, used to develop regression equations; REF, used as a reference streamgage; VAL, used in validation of methods; SS, used in Massachusetts StreamStats (Ries and Friesz, 2000) comparison; ¥, site not used in Armstrong and others (2008) to classify streamflows in Massachusetts.]

Streamgage number	Streamgage name	Four-letter abbreviation for streamgage	Number of daily streamflow values	Period of observed streamflow record	Use of streamgage in analysis
01198000	Green River near Great Barrington, MA	GRGB	8,227	October 1, 1951–September 30, 1971; March 24, 1994–September 30, 1996	REG, REF, SS
01120000	Hop Brook near Columbia, CT	HOPC	14,250	October 1, 1932–October 6, 1971	REG, REF
01174000	Hop Brook near New Salem, MA	HOPM	12,735	November 19, 1947–September 30, 1982	REG, REF, SS
01187300	Hubbard River near West Hartland, CT	HUBB	16,587	August 4, 1959–December 31, 2004	REG, REF, VAL
01105730	Indian Head River at Hanover, MA	IHEA	14,625	July 8, 1966–July 24, 2006	REF, SS
01195100	Indian River near Clinton, CT	INDI	9,029	November 4, 1981–July 24, 2006	REF
01123000	Little River near Hanover, CT	LITT	19,451	October 1, 1951–December 31, 2004	REG, REF, VAL
01171500	Mill River at Northampton, MA	MILL	24,151	November 18, 1938–December 31, 2004	REG, REF, VAL, SS
01165500	Moss Brook at Wendell Depot, MA	MOSS	24,470	June 4, 1909–October 16, 1909; April 25, 1910–June 30, 1910; July 19, 1910–August 27, 1910; June 1, 1916–September 30, 1982	REG, REF, SS
01121000	Mount Hope River near Warrenville, CT	MOUN	23,468	October 1, 1940–December 31, 2004	REG, REF, VAL
01097300	Nashoba Brook near Acton, MA	NASH	15,135	July 26, 1963–December 31, 2004	REG, REF, SS
01332000	North Branch Hoosic River at North Adams, MA	NBHO	21,651	June 22, 1931–September 30, 1990	REG, REF, SS
01111300	Nipmuc River near Harrisville, RI	NIPM	14,185	March 1, 1964–September 30, 1991; October 1, 1993–December 31, 2004	REG, REF
01115630	Nooseneck River at Nooseneck, RI	NOOS	6,519	November 26, 1963–September 30, 1981	REF
01169000	North River at Shattuckville, MA	NORT	23,761	December 13, 1939–December 31, 2004	REG, REF, VAL, SS
01105600	Old Swamp River near South Weymouth, MA	OLDS	14,676	May 20, 1966–July 24, 2006	REF, SS
01073000	Oyster River near Durham, NH	OYST	25,585	December 15, 1934–December 31, 2004	REG, REF, VAL

Table 1. Summary of 66 U.S. Geological Survey streamgages, number of streamflow observations, and the periods of observed, mean daily streamflow record, New England study area.—Continued

[REG, used to develop regression equations; REF, used as a reference streamgage; VAL, used in validation of methods; SS, used in Massachusetts StreamStats (Ries and Friesz, 2000) comparison; ¥, site not used in Armstrong and others (2008) to classify streamflows in Massachusetts.]

Streamgage number	Streamgage name	Four-letter abbreviation for streamgage	Number of daily streamflow values	Period of observed streamflow record	Use of streamgage in analysis
01118500	Pawtucket River at Westerly, RI	PAWE	23,411	November 27, 1940–December 31, 2004	REG, REF, VAL
01117500	Pawcatuck River at Wood River Junction, RI	PAWR	23,401	December 7, 1940–December 31, 2004	REG, REF, VAL
01115098	Peeptoad Brook at Elmdale Road near Westerly, RI	PEEP	4,118	June 23, 1994–September 30, 2005	REF
01118300	Pendleton Hill Brook near Clarks Falls, CT	PEND	16,894	October 1, 1958–December 31, 2004	REG, REF, VAL
01115187	Ponaganset River at South Foster, RI	PONA	4,508	March 22, 1994–July 24, 2006	REF
01162500	Priest Brook near Winchendeon, MA	PRIE	31,677	May 25, 1916–September 30, 1917; July 18, 1918–August 31, 1935; October 1, 1936–December 31, 2004	REG, REF, VAL, SS
01176000	Quaboag River at West Brimfield, MA	QUAB	33,738	August 19, 1912–December 31, 2004	REG, REF, VAL, SS
01199050	Salmon Creek at Lime Rock, CT	SALC	15,798	October 1, 1961–December 31, 2004	REG, REF
01193500	Salmon River near East Hampton, CT	SALR	27,851	October 1, 1928–December 31, 2004	REG, REF, VAL
01154000	Saxtons River at Saxtons River, VT	SAXT	16,753	June 20, 1940–September 30, 1982; June 1, 2001–December 31, 2004	REG, REF
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	13,945	July 27, 1940–September 30, 1978	REG, REF
01175670	Sevenmile River near Spencer, MA	SEVE	16,102	December 1, 1960–December 31, 2004	REG, REF, SS
01089000	Soucook River near Concord, NH	SOU1	13,149	October 1, 1951–September 30, 1987	REG, REF
01169900	South River near Conway, MA	SOUT	13,880	January 1, 1967–December 31, 2004	REF, SS
01096000	Squannacook River near West Groton, MA	SQUA	20,181	October 1, 1949–December 31, 2004	REG, REF, VAL, SS
01184100	Stony Brook near West Suffield, CT	STCT	9,210	May 7, 1981–July 24, 2006	REF
01095220	Stillwater River near Sterling, MA	STIL	4,476	April 22, 1994–July 24, 2006	REF, SS

Table 1. Summary of 66 U.S. Geological Survey streamgages, number of streamflow observations, and the periods of observed, mean daily streamflow record, New England study area.—Continued

[REG, used to develop regression equations; REF, used as a reference streamgage; VAL, used in validation of methods; SS, used in Massachusetts StreamStats (Ries and Friesz, 2000) comparison; ¥, site not used in Armstrong and others (2008) to classify streamflows in Massachusetts.]

Streamgage number	Streamgage name	Four-letter abbreviation for streamgage	Number of daily streamflow values	Period of observed streamflow record	Use of streamgage in analysis
01093800	Stony Brook tributary near Temple, NH	STON	15,129	May 1, 1963–September 30, 2004	REG, REF
01180000¥	Sykes Brook at Knightville, MA	SYKE	10,621	June 20, 1945–July 18, 1974	REG, REF, SS
01161500	Tarbell Brook near Winchendon, MA	TARB	24,572	May 29, 1916–September 6, 1983	REG, REF, SS
01108000	Taunton River near Bridgewater, MA	TAUN	21,160	October 1, 1929–April 23, 1976; April 19, 1985–May 31, 1988; October 1, 1996–December 31, 2004	REG, REF, SS
01200000	Ten Mile River, CT	TENM	25,820	October 1, 1930–April 4, 1988; April 12, 1988–Febraury 7, 1989; November 2, 1990–December 19, 1990; October 1, 1991–September 30, 1999; October 1, 2000–December 31, 2004	REG, REF
01187400	Valley Brook near West Hartland, CT	VALL	11,688	October 1, 1940–September 30, 1972	REG, REF
01109000	Wading River near Norton, MA	WADI	29,069	June 1, 1925–December 31, 2004	REG, REF, VAL, SS
01086000¥	Warner River at Davisville, NH	WARN	15,433	October 1, 1939–September 30, 1978; October 1, 2001–December 31, 2004	REG, REF
01109200¥	West Branch Palmer River near Rehoboth, MA	WBPA	4,357	October 27, 1962–September 30, 1974	REF, SS
01174565	West Branch Swift River near Shutesbury, MA	WBSW	4,529	November 8, 1983–September 30, 1985; April 1, 1995–September 30, 2005	REF, SS
01085800	West Branch Warner River near Bradford, NH	WBWA	15,473	May 22, 1962–September 30, 2004	REG, REF
01181000	West Branch Westfield at Huntington, MA	WBWE	25,325	September 1, 1935–December 31, 2004	REG, REF, VAL, SS
01117800	Wood River near Arcadia, RI	WOOA	14,589	January 23, 1964–September 30, 1981; October 1, 1982–December 31, 2004	REG, REF
01118000	Wood River Hope Valley, RI	WOOH	23,306	March 12, 1941–December 31, 2004	REG, REF

Table 2. Streamflow quantiles corresponding to 17 exceedence probabilities estimated from the observed period of record at 47 U.S. Geological Survey streamgages, New England study area.

[**, observed streamflow record does not contain enough observations to estimate; QX, streamflow value at the X divided by 100 exceedence probability]

USGS streamgage number	Streamgage name	Code	Estimated Q99.9938, in cubic feet per second	Estimated Q99, in cubic feet per second	Estimated Q95, in cubic feet per second	Estimated Q90, in cubic feet per second
01106000	Adamsville Brook at Adamsville, RI	ADAM	**	0.07	0.13	0.3
01084500	Beard Brook near Hillsboro, NH	BEAR	**	1.2	2.7	4.3
01198500	Blackberry River at Canaan, CT	BLAB	**	3.4	6.1	8.7
01111500	Branch River at Forestdale, RI	BRAN	2.6	13	20	26
01188000	Burlington Brook near Burlington, CT	BURL	0.17	0.65	1	1.3
01174900	Cadwell Creek near Belchertown, MA	CADW	**	0.11	0.21	0.34
01155000	Cold River at Drewsville, NH	COLD	**	4.7	7.3	9.9
01082000	Contocook River at Peterborough, NH	CONT	**	6	11	15
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	0.03	0.75	2	3.4
01333000	Green River at Williamstown, MA	GREW	3.3	4.9	8.1	11
01198000	Green River near Great Barrington, MA	GRGB	**	3.3	4.8	6.6
01120000	Hop Brook near Columbia, CT	HOPC	**	4.3	7.8	11
01174000	Hop Brook near New Salem, MA	HOPM	**	0.02	0.14	0.32
01187300	Hubbard River near West Hartland, CT	HUBB	0.19	0.59	1.5	2.5
01123000	Little River near Hanover, CT	LITT	3.4	4.9	7.2	9
01171500	Mill River at Northampton, MA	MILL	3.8	6.4	10	14
01165500	Moss Brook at Wendell Depot, MA	MOSS	0.3	0.7	1.2	1.7
01121000	Mount Hope River near Warrenville, CT	MOUN	0.2	1.2	2.6	4.1
01097300	Nashoba Brook near Acton, MA	NASH	**	0.14	0.6	1.2
01332000	North Branch Hoosic River at North Adams, MA	NBHO	3.2	5.7	8.5	11
01111300	Nipmuc River near Harrisville, RI	NIPM	**	0.39	1	1.7
01169000	North River at Shattuckville, MA	NORT	5.2	9.4	16	21
01073000	Oyster River near Durham, NH	OYST	0.02	0.54	0.85	1.2
01118500	Pawtucket River at Westerly, RI	PAWE	25	68	98	127
01117500	Pawcatuck River at Wood River Junction, RI	PAWR	15	28	40	50
01118300	Pendleton Hill Brook near Clarks Falls, CT	PEND	0.01	0.07	0.31	0.59
01162500	Priest Brook near Winchendeon, MA	PRIE	0.1	0.6	1.5	2.4
01176000	Quaboag River at West Brimfield, MA	QUAB	5	16	29	40
01199050	Salmon Creek at Lime Rock, CT	SALC	**	3.9	6.5	8.8
01193500	Salmon River near East Hampton, CT	SALR	1.1	6.8	13	19
01154000	Saxtons River at Saxtons River, VT	SAXT	2.4	4.8	7.7	11
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	**	4.5	8.3	12
01175670	Sevenmile River near Spencer, MA	SEVE	**	0.25	0.57	1.1
01089000	Soucook River near Concord, NH	SOU1	**	4	7.2	10
01096000	Squannacook River near West Groton, MA	SQUA	0.53	6.4	11	15
01093800	Stony Brook tributary near Temple, NH	STON	**	0.14	0.28	0.45
01180000	Sykes Brook at Knightville, MA	SYKE	**	0.07	0.12	0.17
01161500	Tarbell Brook near Winchendon, MA	TARB	0.15	1.1	2.3	3.3
01108000	Taunton River near Bridgewater, MA	TAUN	9	28	52	69
01200000	Ten Mile River, CT	TENM	7.2	15	26	36
01187400	Valley Brook near West Hartland, CT	VALL	**	0.3	0.5	0.8
01109000	Wading River near Norton, MA	WADI	0.38	2.4	4.6	6.8
01086000	Warner River at Davisville, NH	WARN	**	6.2	12	18
01085800	West Branch Warner River near Bradford, NH	WBWA	**	0.21	0.41	0.66
01181000	West Branch Westfield at Huntington, MA	WBWE	3.4	7.2	12	18
01117800	Wood River near Arcadia, RI	WOOA	**	7.7	12	15
01118000	Wood River Hope Valley, RI	WOOH	10	19	28	35

Table 2. Streamflow quantiles corresponding to 17 exceedence probabilities estimated from the observed period of record at 47 U.S. Geological Survey streamgages, New England study area.—Continued

[**, observed streamflow record does not contain enough observations to estimate; QX, streamflow value at the X divided by 100 exceedence probability]

USGS streamgage number	Streamgage name	Code	Estimated Q85, in cubic feet per second	Estimated Q80, in cubic feet per second	Estimated Q70, in cubic feet per second	Estimated Q60, in cubic feet per second
01106000	Adamsville Brook at Adamsville, RI	ADAM	0.64	1.2	3.3	6.4
01084500	Beard Brook near Hillsboro, NH	BEAR	6.2	8.6	17	27
01198500	Blackberry River at Canaan, CT	BLAB	11	14	21	30
01111500	Branch River at Forestdale, RI	BRAN	32	38	60	87
01188000	Burlington Brook near Burlington, CT	BURL	1.7	2	2.8	3.8
01174900	Cadwell Creek near Belchertown, MA	CADW	0.52	0.72	1.3	2.1
01155000	Cold River at Drewsville, NH	COLD	14	17	27	37
01082000	Contocook River at Peterborough, NH	CONT	19	23	36	50
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	5	6.9	12	20
01333000	Green River at Williamstown, MA	GREW	15	19	28	38
01198000	Green River near Great Barrington, MA	GRGB	9	12	20	32
01120000	Hop Brook near Columbia, CT	HOPC	15	21	36	52
01174000	Hop Brook near New Salem, MA	HOPM	0.58	0.81	1.6	2.5
01187300	Hubbard River near West Hartland, CT	HUBB	3.7	5.1	9	15
01123000	Little River near Hanover, CT	LITT	11	13	19	26
01171500	Mill River at Northampton, MA	MILL	17	21	30	42
01165500	Moss Brook at Wendell Depot, MA	MOSS	2.3	3	4.8	7.4
01121000	Mount Hope River near Warrenville, CT	MOUN	6	8.2	14	22
01097300	Nashoba Brook near Acton, MA	NASH	2	3	5.1	7.7
01332000	North Branch Hoosic River at North Adams, MA	NBHO	14	19	27	37
01111300	Nipmuc River near Harrisville, RI	NIPM	2.6	3.8	7.4	12
01169000	North River at Shattuckville, MA	NORT	27	34	50	70
01073000	Oyster River near Durham, NH	OYST	1.6	2.1	3.8	6.4
01118500	Pawtucket River at Westerly, RI	PAWE	155	182	248	338
01117500	Pawcatuck River at Wood River Junction, RI	PAWR	59	70	92	122
01118300	Pendleton Hill Brook near Clarks Falls, CT	PEND	0.92	1.3	2.5	4
01162500	Priest Brook near Winchendeon, MA	PRIE	3.6	5	8.4	12
01176000	Quaboag River at West Brimfield, MA	QUAB	52	64	92	126
01199050	Salmon Creek at Lime Rock, CT	SALC	11	14	19	25
01193500	Salmon River near East Hampton, CT	SALR	25	32	55	83
01154000	Saxtons River at Saxtons River, VT	SAXT	14	18	28	40
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	16	22	36	60
01175670	Sevenmile River near Spencer, MA	SEVE	1.8	2.6	4.3	6.6
01089000	Soucook River near Concord, NH	SOU1	13	17	28	43
01096000	Squannacook River near West Groton, MA	SQUA	18	22	32	47
01093800	Stony Brook tributary near Temple, NH	STON	0.66	0.9	1.6	2.5
01180000	Sykes Brook at Knightville, MA	SYKE	0.23	0.3	0.6	0.91
01161500	Tarbell Brook near Winchendon, MA	TARB	4.5	5.7	8.7	12
01108000	Taunton River near Bridgewater, MA	TAUN	87	107	170	253
01200000	Ten Mile River, CT	TENM	48	60	95	142
01187400	Valley Brook near West Hartland, CT	VALL	1	1.6	3	5
01109000	Wading River near Norton, MA	WADI	9.3	12	21	34
01086000	Warner River at Davisville, NH	WARN	24	32	52	78
01085800	West Branch Warner River near Bradford, NH	WBWA	0.92	1.3	2.3	3.6
01181000	West Branch Westfield at Huntington, MA	WBWE	24	31	48	72
01117800	Wood River near Arcadia, RI	WOOA	19	23	32	45
01118000	Wood River Hope Valley, RI	WOOH	41	49	67	92

Table 2. Streamflow quantiles corresponding to 17 exceedence probabilities estimated from the observed period of record at 47 U.S. Geological Survey streamgages, New England study area.—Continued

[**, observed streamflow record does not contain enough observations to estimate; QX, streamflow value at the X divided by 100 exceedence probability]

USGS streamgage number	Streamgage name	Code	Estimated Q50, in cubic feet per second	Estimated Q40, in cubic feet per second	Estimated Q30, in cubic feet per second	Estimated Q20, in cubic feet per second
01106000	Adamsville Brook at Adamsville, RI	ADAM	9.2	12	16	22
01084500	Beard Brook near Hillsboro, NH	BEAR	41	58	84	130
01198500	Blackberry River at Canaan, CT	BLAB	40	52	71	101
01111500	Branch River at Forestdale, RI	BRAN	119	156	196	256
01188000	Burlington Brook near Burlington, CT	BURL	5	6.3	8	11
01174900	Cadwell Creek near Belchertown, MA	CADW	3	4	5.2	7
01155000	Cold River at Drewsville, NH	COLD	52	71	105	165
01082000	Contocook River at Peterborough, NH	CONT	69	90	120	170
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	29	39	50	67
01333000	Green River at Williamstown, MA	GREW	50	66	87	121
01198000	Green River near Great Barrington, MA	GRGB	44	62	88	122
01120000	Hop Brook near Columbia, CT	HOPC	73	100	133	183
01174000	Hop Brook near New Salem, MA	HOPM	3.6	4.9	6.6	9.2
01187300	Hubbard River near West Hartland, CT	HUBB	20	27	37	55
01123000	Little River near Hanover, CT	LITT	36	47	60	80
01171500	Mill River at Northampton, MA	MILL	57	76	100	140
01165500	Moss Brook at Wendell Depot, MA	MOSS	10	14	20	30
01121000	Mount Hope River near Warrenville, CT	MOUN	31	42	56	75
01097300	Nashoba Brook near Acton, MA	NASH	11	16	22	31
01332000	North Branch Hoosic River at North Adams, MA	NBHO	48	64	87	125
01111300	Nipmuc River near Harrisville, RI	NIPM	18	25	34	45
01169000	North River at Shattuckville, MA	NORT	94	126	172	249
01073000	Oyster River near Durham, NH	OYST	9.8	14	19	29
01118500	Pawtucket River at Westerly, RI	PAWE	448	561	703	892
01117500	Pawcatuck River at Wood River Junction, RI	PAWR	155	192	237	296
01118300	Pendleton Hill Brook near Clarks Falls, CT	PEND	5.7	7.5	9.8	13
01162500	Priest Brook near Winchendeon, MA	PRIE	17	23	33	49
01176000	Quaboag River at West Brimfield, MA	QUAB	167	221	295	391
01199050	Salmon Creek at Lime Rock, CT	SALC	32	41	53	70
01193500	Salmon River near East Hampton, CT	SALR	116	156	204	273
01154000	Saxtons River at Saxtons River, VT	SAXT	56	76	109	164
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	88	120	163	240
01175670	Sevenmile River near Spencer, MA	SEVE	9.2	12	17	23
01089000	Soucook River near Concord, NH	SOU1	60	82	112	165
01096000	Squannacook River near West Groton, MA	SQUA	66	89	118	162
01093800	Stony Brook tributary near Temple, NH	STON	3.5	4.8	6.8	10
01180000	Sykes Brook at Knightville, MA	SYKE	1.3	1.8	2.6	3.8
01161500	Tarbell Brook near Winchendon, MA	TARB	17	22	30	43
01108000	Taunton River near Bridgewater, MA	TAUN	349	455	583	750
01200000	Ten Mile River, CT	TENM	195	260	343	463
01187400	Valley Brook near West Hartland, CT	VALL	7.2	9.6	13	19
01109000	Wading River near Norton, MA	WADI	50	68	89	117
01086000	Warner River at Davisville, NH	WARN	119	168	243	364
01085800	West Branch Warner River near Bradford, NH	WBWA	5	6.9	10	15
01181000	West Branch Westfield at Huntington, MA	WBWE	99	132	178	258
01117800	Wood River near Arcadia, RI	WOOA	58	74	92	115
01118000	Wood River Hope Valley, RI	WOOH	119	151	187	233

Table 2. Streamflow quantiles corresponding to 17 exceedence probabilities estimated from the observed period of record at 47 U.S. Geological Survey streamgages, New England study area.—Continued

[**, observed streamflow record does not contain enough observations to estimate; QX, streamflow value at the X divided by 100 exceedence probability]

USGS streamgage number	Streamgage name	Code	Estimated Q15, in cubic feet per second	Estimated Q10, in cubic feet per second	Estimated Q5, in cubic feet per second	Estimated Q1, in cubic feet per second	Estimated Q006, in cubic feet per second
01106000	Adamsville Brook at Adamsville, RI	ADAM	26	34	47	95	**
01084500	Beard Brook near Hillsboro, NH	BEAR	170	230	364	777	**
01198500	Blackberry River at Canaan, CT	BLAB	122	160	240	556	**
01111500	Branch River at Forestdale, RI	BRAN	304	377	514	951	3,870
01188000	Burlington Brook near Burlington, CT	BURL	13	17	26	61	477
01174900	Cadwell Creek near Belchertown, MA	CADW	8.6	11	17	40	**
01155000	Cold River at Drewsville, NH	COLD	215	293	447	933	**
01082000	Contocook River at Peterborough, NH	CONT	210	272	393	730	**
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	81	101	139	287	1,490
01333000	Green River at Williamstown, MA	GREW	146	187	271	525	2,100
01198000	Green River near Great Barrington, MA	GRGB	150	195	281	566	**
01120000	Hop Brook near Columbia, CT	HOPC	223	283	400	785	**
01174000	Hop Brook near New Salem, MA	HOPM	11	14	20	42	**
01187300	Hubbard River near West Hartland, CT	HUBB	70	94	148	350	1,310
01123000	Little River near Hanover, CT	LITT	93	115	167	360	1,870
01171500	Mill River at Northampton, MA	MILL	172	219	319	674	3,440
01165500	Moss Brook at Wendell Depot, MA	MOSS	37	48	69	140	786
01121000	Mount Hope River near Warrenville, CT	MOUN	90	113	165	355	2,250
01097300	Nashoba Brook near Acton, MA	NASH	38	49	66	121	**
01332000	North Branch Hoosic River at North Adams, MA	NBHO	160	220	348	753	4,080
01111300	Nipmuc River near Harrisville, RI	NIPM	53	67	98	200	**
01169000	North River at Shattuckville, MA	NORT	318	428	672	1,460	7,580
01073000	Oyster River near Durham, NH	OYST	36	47	70	138	681
01118500	Pawtucket River at Westerly, RI	PAWE	1,020	1,200	1,490	2,180	5,940
01117500	Pawcatuck River at Wood River Junction, RI	PAWR	340	395	487	702	1,780
01118300	Pendleton Hill Brook near Clarks Falls, CT	PEND	15	19	26	50	251
01162500	Priest Brook near Winchendeon, MA	PRIE	62	81	119	225	1,240
01176000	Quaboag River at West Brimfield, MA	QUAB	458	551	713	1,130	7,540
01199050	Salmon Creek at Lime Rock, CT	SALC	83	101	141	280	**
01193500	Salmon River near East Hampton, CT	SALR	324	402	568	1,150	8,230
01154000	Saxtons River at Saxtons River, VT	SAXT	215	290	450	954.6	3,340
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	305	403	600	1,150	**
01175670	Sevenmile River near Spencer, MA	SEVE	27	34	48	87	**
01089000	Soucook River near Concord, NH	SOU1	207	275	405	765	**
01096000	Squannacook River near West Groton, MA	SQUA	199	252	365	700	3,330
01093800	Stony Brook tributary near Temple, NH	STON	13	17	26	57	**
01180000	Sykes Brook at Knightville, MA	SYKE	4.7	6.2	9.3	19	**
01161500	Tarbell Brook near Winchendon, MA	TARB	54	70	103	185	1,390
01108000	Taunton River near Bridgewater, MA	TAUN	880	1,060	1,390	2,200	4,700
01200000	Ten Mile River, CT	TENM	550	681	941	1,800	10,200
01187400	Valley Brook near West Hartland, CT	VALL	24	30	51	109	**
01109000	Wading River near Norton, MA	WADI	137	168	223	360	1140
01086000	Warner River at Davisville, NH	WARN	457	590	866	1,620	**
01085800	West Branch Warner River near Bradford, NH	WBWA	20	27	47	109	**
01181000	West Branch Westfield at Huntington, MA	WBWE	328	440	675	1,530	9,800
01117800	Wood River near Arcadia, RI	WOOA	131	155	197	319	**
01118000	Wood River Hope Valley, RI	WOOH	265	314	401	650	2,040

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