Prepared in cooperation with the
Massachusetts Department of Environmental Protection

Refinement and Evaluation of the Massachusetts Firm-Yield Estimator Model Version 2.0

Scientific Investigations Report 2011–5125

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

Cover. Top: Gatehouse at Flints (Sandy) Pond in Lincoln, Massachusetts. Bottom: Water entering Holden Pond #1 from Kendall Reservoir, Holden, Massachusetts. (Both photographs taken by Andy Massey)

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

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

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

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Abstract

The firm yield is the maximum average daily withdrawal that can be extracted from a reservoir without risk of failure during an extended drought period. Previously developed procedures for determining the firm yield of a reservoir were refined and applied to 38 reservoir systems in Massachusetts, including 25 single- and multiple-reservoir systems that were examined during previous studies and 13 additional reservoir systems. Changes to the firm-yield model include refinements to the simulation methods and input data, as well as the addition of several scenario-testing capabilities. The simulation procedure was adapted to run at a daily time step over a 44-year simulation period, and daily streamflow and meteorological data were compiled for all the reservoirs for input to the model.

Another change to the model-simulation methods is the adjustment of the scaling factor used in estimating groundwater contributions to the reservoir. The scaling factor is used to convert the daily groundwater-flow rate into a volume by multiplying the rate by the length of reservoir shoreline that is hydrologically connected to the aquifer. Previous firm-yield analyses used a constant scaling factor that was estimated from the reservoir surface area at full pool. The use of a constant scaling factor caused groundwater flows during periods when the reservoir stage was very low to be overestimated. The constant groundwater scaling factor used in previous analyses was replaced with a variable scaling factor that is based on daily reservoir stage. This change reduced instability in the groundwater-flow algorithms and produced more realistic groundwater-flow contributions during periods of low storage.

Uncertainty in the firm-yield model arises from many sources, including errors in input data. The sensitivity of the model to uncertainty in streamflow input data and uncertainty in the stage-storage relation was examined. A series of Monte Carlo simulations were performed on 22 reservoirs to assess the sensitivity of firm-yield estimates to errors in daily-streamflow input data. Results of the Monte Carlo simulations indicate that underestimation in the lowest stream inflows can cause firm yields to be underestimated by an average of 1 to 10 percent. Errors in the stage-storage relation can arise when the point density of bathymetric survey measurements is too low. Existing bathymetric surfaces were resampled using hypothetical transects of varying patterns and point densities in order to quantify the uncertainty in stage-storage relations. Reservoir-volume calculations and resulting firm yields were accurate to within 5 percent when point densities were greater than 20 points per acre of reservoir surface.

Methods for incorporating summer water-demand-reduction scenarios into the firm-yield model were developed as well as the ability to relax the no-fail reliability criterion. Although the original firm-yield model allowed monthly reservoir releases to be specified, there have been no previous studies examining the feasibility of controlled releases for downstream flows from Massachusetts reservoirs. Two controlled-release scenarios were tested—with and without a summer water-demand-reduction scenario—for a scenario with a no-fail criterion and a scenario that allows for a 1-percent failure rate over the entire simulation period. Based on these scenarios, about one-third of the reservoir systems were able to support the flow-release scenarios at their 2000–2004 usage rates. Reservoirs with higher storage ratios (reservoir storage capacity to mean annual streamflow) and lower demand ratios (mean annual water demand to annual firm yield) were capable of higher downstream release rates. For the purposes of this research, all reservoir systems were assumed to have structures which enable controlled releases, although this assumption may not be true for many of the reservoirs studied.

Introduction

The determination of available water for, and management of, public water supplies in Massachusetts drinking-water reservoirs has become increasingly complex as regulators try to provide adequate streamflows for ecological communities as well as increasing demands for drinking water. Controlled releases from reservoirs to satisfy ecological demands may impose further limits on the yield from a reservoir. A reservoir failure occurs when a reservoir is unable to provide sufficient water to meet demand. Reservoirs with high water demand relative to their firm yield are particularly at risk of failing during periods of drought. In order to ensure that reservoirs have sufficient water available even during extreme droughts, the Massachusetts Department of Environmental Protection (MassDEP) requires public water suppliers to estimate the firm yield of their reservoir systems.

The firm yield of a reservoir is defined as the maximum yield that can be delivered from a system without failure, even during a severe drought. To facilitate the calculation of a system's firm yield, MassDEP developed the Firm-Yield Estimator (FYE) guidance document (Massachusetts Department of Environmental Protection, 1996) and model (Massachusetts Department of Environmental Protection, 2000). The FYE model uses the water-balance equation to estimate reservoir storage over a period of time that includes the most extreme drought of record. The firm yield of a reservoir is calculated by solving the water-balance equation for each month of the simulation period with an initial yield of 0 million gallons per day (Mgal/d). If the reservoir storage is does not fully deplete during the simulation, yield is increased, and the water-balance equation is solved again. Iteration continues with increasing yield until a reservoir failure occurs. The firm yield is the maximum yield that can be used in the water-balance equation without causing the reservoir to fail during the simulation period. Waldron and Archfield (2006) calculated firm yields for 25 single- and multiple-reservoir systems in Massachusetts and examined the sensitivity of the FYE model to various model inputs. Archfield and Carlson (2006) further refined the FYE model by developing a procedure to estimate groundwater flows into and out of reservoir storage.

Growing demand for public water supply in Massachusetts may compete with ecosystem water needs, and there is increasing interest in ensuring that streams have adequate water to support aquatic communities. Reservoir impoundments can alter the natural streamflow patterns in reaches downstream of the dam. During periods when reservoir stage is lower than the spillway elevation, water cannot spill over the dam into the downstream reaches and can alter the characteristic pattern of high and low flows for that stream reach. These alterations to streamflow can be detrimental to downstream ecosystems and aquatic communities. Controlled releases from reservoir storage can be implemented to alleviate downstream ecosystem stress; however, these releases decrease reservoir storage. In some cases, meeting environmental streamflow needs during a severe drought may decrease reservoir yield enough that human needs cannot be met. Although the FYE model allows for user-specified monthly controlled releases, there have been no statewide applications of the model to examine the feasibility of implementing controlled releases in Massachusetts drinking-water reservoirs.

Water suppliers struggling to meet drinking-water demands or wishing to offset the effects of controlled flow releases may consider demand-management strategies such as outdoor summer water-use restrictions, or they may consider relaxing the no-fail reliability criterion of the reservoir, or a combination of these two strategies. Each strategy has advantages and disadvantages, and the appropriate solution may differ from one reservoir to another. Summer water-use restrictions limit non-essential water use during drought periods but may not conserve enough water to sustain use through long, multiyear droughts when winter and spring flows cannot replenish the reservoir. Relaxing the reliability requirement of a reservoir may provide a boost in yield, but reservoirs can run the risk of failure during very severe droughts. The MassDEP guidance document and original FYE model do not allow for user-specified reliability criteria or demand-management scenarios. For the current study, modifications to the FYE were developed to allow these options in order to assess the relative benefits of these operational strategies.

Purpose and Scope

The purpose of this report is to document the methods used to estimate firm yield for Massachusetts reservoirs and to examine the factors that affect the firm-yield estimates. The report describes several refinements to the existing firm-yield model, including simulation at a daily time step; refinement and validation of groundwater parameters; improved input data for streamflow, precipitation, and evaporation; and modification of the model to allow for demand-management scenarios and relaxed reliability criteria. Firm yields were calculated using the updated data and methodology for 25 reservoir systems previously studied as well as 13 reservoir systems that were not examined in previous firm-yield studies. The sensitivity of the model to bathymetric-map accuracy, drought severity, and uncertainty in input data was examined. Finally, the tradeoffs between controlled releases and demand-management scenarios were examined.

Refinements to the Existing Firm-Yield Estimator Model

The Massachusetts Department of Environmental Protection (MassDEP) guidance document details a procedure for calculating the firm yield of a reservoir in Massachusetts. To facilitate this calculation, the Firm-Yield Estimator (FYE) model (Massachusetts Department of Environmental Protection, 1996) was developed on the basis of this methodology. The FYE model defines the firm yield as the maximum yield at which a water-supply reservoir or system of reservoirs can operate without failure during the drought of record. Waldron and Archfield (2006) examined the sensitivity of the FYE model to various inputs required by the model and evaluated the model's overall procedure for estimating the firm yield for surface-water-dominated reservoirs in Massachusetts.

Archfield and Carlson (2006) expanded the methodology to include a set of equations used to estimate groundwater contributions to the reservoir water balance.

Because of the difficulty in obtaining daily values for all of the water-balance components, previous firm-yield analyses in Massachusetts have been performed using a monthly time step. Fennessey (1995) showed that firm yields estimated at a monthly time step are higher than yields estimated from data at a daily time step. The MassDEP guidance document specifies a regression-based correction factor that is used to adjust the firm yield for errors introduced by using a monthly time step instead of a daily time step. However, the applicability and validation of the correction factor remains unverified for Massachusetts reservoirs. New advances in daily streamflow estimation, however, have made it feasible to run the FYE model at a daily time step. Running the model at a daily time step eliminates the need for a correction factor.

With a daily time step and units of volume, the reservoir water-balance equation is:

$$S_i = Ar_i\left(P_i - E_i\right) + Aw_i Q_{st_i} - \alpha_i Q_y - Q_{rr_i} - Q_{sp_i} - Q_{ow_i} \pm Q_{gw_i} + S_{i-1} \quad (1)$$

where

i	= daily simulation time step;
S_i	= volume of water in usable storage for the current day, in million gallons;
Aw_i	= reservoir drainage area, in square miles;
Q_{sti}	= streamflow per unit drainage area, in miles[1];
Ar_i	= area of the reservoir surface, in square miles[1];
P_i	= precipitation, in miles[1];
E_i	= evaporation from the reservoir surface, in miles[1];
Q_{gwi}	= groundwater contributions or losses for the current day, in million gallons;
α_i	= peak-usage factor, dimensionless;
Q_y	= yield for the current day, in million gallons;
Q_{rri}	= controlled release, in million gallons;
Q_{spi}	= uncontrolled spill, in million gallons; and
Q_{owi}	= withdrawal from the reservoir by other users, in million gallons.

The firm yield is calculated by successively solving the water-balance equation over the period of record, starting at a full pool volume and increasing the yield at each repetition. The firm yield is the maximum yield volume that can be used without causing the reservoir volume to decrease to zero. For this study, firm yields were determined for 71 reservoirs—45 previously studied reservoirs and 26 new reservoirs—belonging to 38 reservoir systems (fig. 1; table 1). For the purposes of this study, a reservoir system refers to one or more reservoirs that are hydrologically connected. Firm yields for previously studied reservoir systems were re-estimated using the revised FYE-model methods and data. These revised firm yields supersede estimates of firm yield from Waldron and Archfield (2006) and Archfield and Carlson (2006). Previous estimates of firm yields are no longer considered valid.

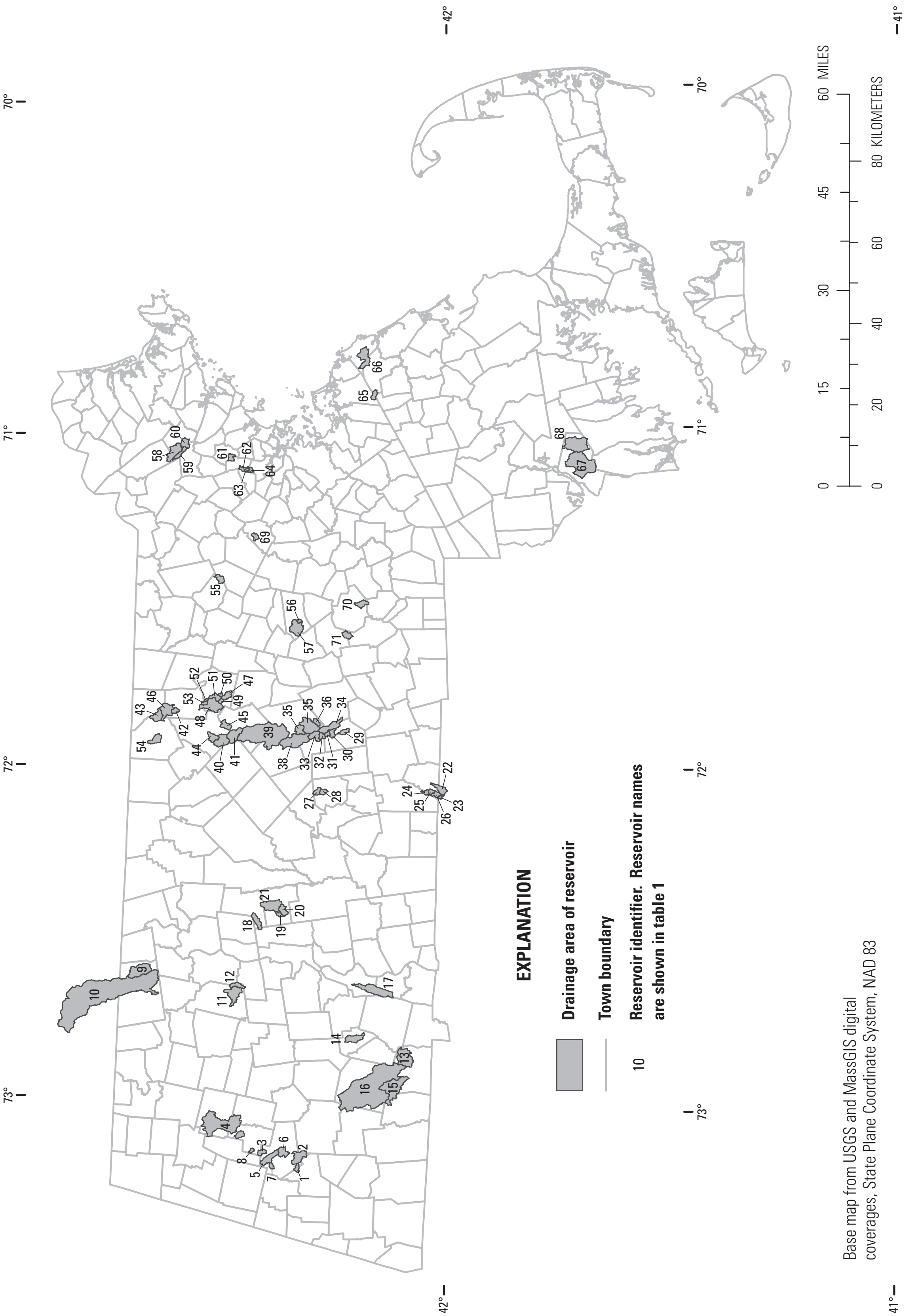
Reservoir-specific characteristics that affect model estimates of firm yield include the stage-storage relation, storage capacity, streamflows, direct precipitation, and evaporation from the reservoir surface. For reservoirs that are connected to an aquifer, the aquifer transmissivity and surficial geology underlying the reservoir also affect groundwater flows to and from the reservoir.

[1] Precipitation, streamflow, and evaporation are in units of length and, when multiplied by A_{ri}, become volumes (in cubic miles) that are converted to million gallons.

Bathymetry and Stage-Storage Relations

Bathymetric surveys were completed for 26 reservoirs that were not previously studied. Surveys were completed during the spring months of 2008 and 2009 when reservoirs were full or nearly full. Reservoir depths were determined with a narrow-beam echo sounder along transects across each reservoir. The location of each depth measurement was determined with a global positioning system (GPS). Reservoir-spillway elevations and intake elevations were provided by the public water supplier. In order to convert water depths to bottom elevations, the water depths were first adjusted to account for the reservoir stage on the day of the survey by adding the distance between the water surface and the spillway to each measurement. The reservoir bottom elevation was then calculated as the difference between the spillway elevation and the corrected depth measurements.

The GPS data were differentially corrected and imported into a geographic information system (GIS). Reservoir outlines were digitized from 1:5,000 digital orthoimagery (Office of Geographic and Environmental Information, 2005). Smoothed reservoir contours were generated from bottom elevations using a spatially interpolated grid in ArcINFO. A triangulated irregular network (TIN) model was generated using GPS position, bottom elevation, and the digitized reservoir shoreline. Reservoir volumes and surface areas were computed using the TIN surface model at 2-foot (ft) intervals. This method calculates the volume at each grid cell of the bottom-elevation map, making it more accurate than estimating volume from surface contours alone. Stage-storage relations developed from the bathymetric data were used to estimate reservoir surface area and reservoir stage based on reservoir-storage volumes at each daily time step during the simulation. Interpolation was used to estimate these quantities at volumes that fall between contour intervals. Stage-storage relations and bottom-elevation maps for reservoirs that were not previously studied by Waldron and Archfield (2006) are included in appendixes 1 and 2.



Base map from USGS and MassGIS digital coverages, State Plane Coordinate System, NAD 83

Figure 1. Locations of drainage areas for 71 drinking-water reservoirs in Massachusetts.

Table 1. Massachusetts drinking-water-supply systems and associated reservoirs included in this study.

[ID, identifier; SUASCO, Sudbury, Assabet, Concord; DPW, Department of Public Works]

Water supplier	Reservoir name	Reservoir ID	Drainage basin
Amherst Water Department	Atkins Reservoir	18	Connecticut
	Hill Reservoir	21	Connecticut
	Hawley Reservoir	19	Connecticut
	Amethyst Brook Intake	20	Connecticut
Ashburnham/Winchendon Joint Water Board	Upper Naukeag Lake	54	Millers
Concord Water Department	Nagog Pond	55	SUASCO
Danvers Water Department	Emerson Brook Pond	58	Ipswich
	Middleton Pond	60	Ipswich
	Swan Pond	59	Ipswich
Fall River Water Department	North Watuppa Reservoir	67	Narragansett Bay
	Copicut Reservoir	68	Buzzards Bay
Fitchburg Water Department	Bickford Pond	41	Chicopee
	Mare Meadow Reservoir	40	Chicopee
	Meetinghouse Reservoir	44	Nashua
	Wachusett Lake	45	Nashua
	Scott Reservoir	42	Nashua
	Fitchburg Reservoir	43	Nashua
	Lovell Reservoir	46	Nashua
Greenfield Water Department	Green River	10	Deerfield
	Leyden Glen Reservoir	9	Deerfield
Hingham/Hull (Aquarian Water Company)	Accord Pond	65	Boston Harbor
Hinsdale Water Department	Belmont Reservoir	8	Housatonic
Lee Water Department	Schoolhouse Reservoir	2	Housatonic
	Upper (Leahey) Reservoir	1	Housatonic
Leicester (Cherry Valley and Rochdale Water)	Henshaw Pond	29	French
Leominster DPW–Water Division	Distributing Reservoir	51	Nashua
	Morse Reservoir	50	Nashua
	Haynes Reservoir	49	Nashua
	Simonds Pond	52	Nashua
	Goodfellow Pond	53	Nashua
	Notown Reservoir	48	Nashua
	Fall Brook Reservoir	47	Nashua
Lincoln Water Department	Flints Pond (Sandy Pond)	69	Charles
Marlborough DPW–Water and Sewer Division	Millham Reservoir	57	SUASCO
	Williams Lake	56	SUASCO
Milford Water Company	Echo Lake	70	Charles

Table 1. Massachusetts drinking-water-supply systems and associated reservoirs included in this study.—Continued

[ID, identifier; SUASCO, Sudbury, Assabet, Concord; DPW, Department of Public Works]

Water supplier	Reservoir name	Reservoir ID	Drainage basin
North Brookfield Water Department	Doane Pond	28	Chicopee
	Horse Pond	27	Chicopee
Pittsfield Water Department	Ashley Lake/Lower Ashley Intake	3	Housatonic
	Farnham Reservoir	7	Housatonic
	Sandwash Reservoir	6	Housatonic
	Upper Sackett Reservoir	5	Housatonic
	Cleveland Reservoir	4	Housatonic
Scituate Water Department	Tack Factory Pond	66	South Coastal
Southbridge Water Department	Hatchet Pond	23	Quinebaug
	Hatchet Brook Reservoir #3	24	Quinebaug
	Hatchet Brook Reservoir #4	25	Quinebaug
	Hatchet Brook Reservoir #5	26	Quinebaug
	Cohasse Brook Reservoir	22	Quinebaug
Springfield Water Department	Borden Brook Reservoir	15	Westfield
	Cobble Mountain Reservoir	16	Westfield
South Deerfield Water Supply District	Roaring Brook Reservoir	11	Connecticut
	Whately Reservoir	12	Connecticut
Wakefield Water Department	Crystal Lake	61	North Coastal
Westborough Water Department	Sandra Pond	71	SUASCO
Westfield Water Department	Granville Reservoir	13	Westfield
	Montgomery Reservoir	14	Westfield
West Springfield Water Department	Bearhole Reservoir	17	Westfield
Winchester Water Department	Middle Reservoir	63	Mystic
	North Reservoir	62	Mystic
	South Reservoir	64	Mystic
Worcester Water Department	Holden Reservoir #1	35	Blackstone
	Holden Reservoir #2	36	Blackstone
	Kettle Brook Reservoir #1	30	Blackstone
	Kettle Brook Reservoir #2	36	Blackstone
	Kettle Brook Reservoir #3	32	Blackstone
	Kettle Brook Reservoir #4	33	Blackstone
	Lynde Brook Reservoir	34	Blackstone
	Kendall Reservoir	37	Nashua
	Pine Hill Reservoir	38	Nashua
	Quinapoxet Reservoir	39	Nashua

Surface-Water Inflows

Surface-water inflow volumes are generally orders of magnitude larger than the volumes of climatic water-balance components or groundwater contributions, making them one of the most important inputs in the determination of the firm yield. A recently developed method makes it possible to estimate daily streamflows for most locations in Massachusetts. The Sustainable Yield Estimator (SYE) (Archfield, 2010) application was used to estimate daily streamflow for all the reservoirs in this study. The SYE uses a regression-based method to develop a daily-flow-duration curve for an ungaged stream for the period of October 1, 1960 to September 30, 2004. The flow-duration curve is then transformed into a daily time series by equating the quantiles of the ungaged flow-duration curve to a flow-duration curve of a gaged index stream during the same time period. This method is similar to the method of streamflow estimation used in previous Massachusetts firm-yield studies (Waldron and Archfield, 2006) and the MassDEP FYE guidance document; however, the SYE tool employs new regression techniques and more robust index-streamflow-selection methods. For single-reservoir systems, basin characteristics used in the SYE regression equations were calculated for the entire reservoir watershed, excluding the reservoir area (table 2). For reservoirs in series along a stream, the areas of all upstream reservoir watersheds were excluded from the calculation of downstream reservoir basin characteristics.

Precipitation and Evaporation

Records of daily precipitation and temperature were obtained from 226 National Climatic Data Center (NCDC) climate stations in and around Massachusetts (fig. 2). There were 157 stations with daily precipitation records ranging from 1 to 44 years during the simulation period. Stations had varying amounts of missing data throughout the record, and no station had a complete daily record for the entire 44 years. In order to obtain a complete daily precipitation record at each reservoir, inverse-squared distance weighted interpolation of gaged precipitation stations was used. Although this method can result in an underestimation of precipitation variability, this method has been shown to perform as well or better than using data from the nearest precipitation station to estimate daily precipitation (Kruizinga and Yperlaan, 1978). For each day of the simulation period, inverse-squared distance interpolation was performed using the three nearest gaged stations within 15 miles (mi) that had recorded precipitation data for that day. Because each meteorological station had records of differing lengths, the set of stations used in the daily interpolation of precipitation may have varied from day to day for a given FYE reservoir site.

The interpolated daily precipitation was cross-validated using observed data from 31 long-term precipitation gages. Gages with over 40 years of data were chosen for validation, as well as two gages in the western part of Massachusetts where gages with 40-year records were not available. For each validation gage, inverse-squared distance weighted interpolation of the surrounding gages was used to produce a time series of daily precipitation for the gaged location. The estimated daily precipitation at each gaged station was then compared to the observed data, and the Nash Sutcliffe Efficiency (NSE) was calculated (Nash and Sutcliffe, 1970). The NSE is a commonly used indicator to assess the fit of a hydrologic model. An NSE value of 1 indicates a perfect fit between observed and modeled values. An NSE of 0 means that the modeled data has the same amount of error as just using the mean of the observed data. A negative NSE indicates that the mean of the observed data provides a better estimate than the modeled data. The NSE for the 31 validation gages ranged from -0.16 to 0.87 with a median of 0.68 (table 3). Only one site, located at the Worcester Regional Airport, had a NSE of less than zero. This site is located in a sparsely gaged area. Only one other gage falls within 5 mi of the Worcester site, and that gage has data from only October 1960 to November 1962. The second nearest gage to the Worcester site is 9.8 mi away. An analysis of the interpolated time series for the Worcester site shows that NSE calculated from October 1960 to November 1962 is 0.58, whereas the NSE for the remaining period is -0.23, indicating that interpolation results may be more unreliable when gaged sites are farther than 5 mi away. Other validation sites that performed poorly are located in areas of the State that are not densely gaged, indicating that estimated daily precipitation may be less accurate for reservoirs in sparsely gaged areas of Massachusetts.

Daily precipitation time series were validated using observed precipitation at two reservoirs. Daily precipitation measurements were available for Atkins Reservoir for March 1, 1994 to September 30, 2004, and for Echo Lake for October 1, 1960 to September 30, 1967. The interpolated precipitation time series showed good agreement with observed precipitation for both Atkins Reservoir and Echo Lake, with NSEs of 0.94 and 0.75, respectively (table 3).

Evaporation from lakes depends on meteorological factors as well as physical characteristics of the lake, but is generally equivalent to estimates of potential evapotranspiration. Daily evaporation from each reservoir was estimated using Hargreaves' equation for potential evapotranspiration (Hargreaves and Samni, 1982). This is a temperature-based method requiring daily average temperatures and daily temperature ranges. Daily minimum and maximum temperatures were interpolated from the NCDC gaged climate stations. There were 94 climate stations with daily minimum and maximum temperature records for periods ranging from 1 to 44 years during the simulation period. Temperatures were interpolated using inverse-squared distance for each reservoir in the same manner as for precipitation.

Table 2. Reservoir basin characteristics and index streamgages in Massachusetts used in the Sustainable Yield Estimator.

[mi², square miles; ft, feet; in, inches; °C, degrees Celsius; SYE, Sustainable Yield Estimator; DPW, Department of Public Works; X- and Y-coordinates in

Water supplier	Reservoir name	Drainage area, excluding surface area (mi²)	Mean basin elevation (ft)	Average annual precipitation (in)	Percentage of basin that is open water
Amherst Water Department	Atkins Reservoir	1.72	735.28	48.18	0.18
	Hill Reservoir	4.05	1,052.11	49.01	0.00
	Hawley Reservoir	1.50	877.33	48.58	0.07
	Amethyst Brook Intake	0.63	641.52	48.17	0.00
Ashburnham/Winchendon Joint Water Board	Upper Naukeag Lake	1.37	1,197.61	49.15	0.25
Concord Water Department	Nagog Pond	0.77	255.53	46.46	0.75
Danvers Water Department	Emerson Brook Pond	3.26	118.93	46.56	2.88
	Middleton Pond	1.32	118.73	46.81	14.21
	Swan Pond	1.19	127.79	46.63	1.94
Fall River Water Department	North Watuppa Reservoir	8.47	167.87	48.95	1.87
	Copicut Reservoir	5.66	193.97	49.14	0.02
Fitchburg Water Department	Bickford Pond	3.03	1,226.32	49.90	0.11
	Mare Meadow Reservoir	2.64	1,165.12	48.81	0.05
	Meetinghouse Reservoir	1.32	1,124.74	48.79	0.00
	Wachusett Lake	1.32	1,155.20	50.08	13.64
	Scott Reservoir	0.73	1,006.59	48.81	0.07
	Fitchburg Reservoir	1.90	1,161.41	49.36	0.16
	Lovell Reservoir	3.20	1,012.32	48.99	0.17
Greenfield Water Department	Green River	52.06	1,239.88	51.06	0.55
	Leyden Glen Reservoir	5.16	950.26	49.52	0.10
Hingham/Hull (Aquarian Water Company)	Accord Pond	0.79	161.96	46.75	0.62
Hinsdale Water Department	Belmont Reservoir	0.37	1,899.15	49.92	4.57
Lee Water Department	Schoolhouse Reservoir	2.94	1,889.41	53.39	1.60
	Upper (Leahey) Reservoir	0.63	1,808.39	51.21	0.00
Leicester (Cherry Valley and Rochdale Water)	Henshaw Pond	0.88	865.80	48.92	6.20
Leominster DPW–Water Division	Distributing Reservoir	1.14	810.73	49.56	0.00
	Morse Reservoir	0.28	802.11	49.65	0.00
	Haynes Reservoir	0.34	889.48	50.09	0.00
	Simonds Pond	0.18	806.71	49.11	0.00
	Goodfellow Pond	0.41	776.33	48.99	0.20
	Notown Reservoir	3.96	853.66	49.43	0.00
	Fall Brook Reservoir	1.21	814.81	49.98	0.18
Lincoln Water Department	Flints Pond (Sandy Pond)	0.55	267.40	46.99	0.01
Marlborough DPW–Water and Sewer Division	Millham Reservoir	3.40	367.12	47.95	0.23
	Williams Lake	0.26	459.58	47.90	7.02

Massachusetts State Plane meters; Elevation determined from the U.S. Geological Survey 30-meter National Elevation Dataset]

X-coordinate of the basin outlet	Y-coordinate of the basin outlet	Average maximum monthly temperature (°C)	Percentage of basin that is wetland	Percentage of basin that is underlain by sand and gravel	X-coordinate of the basin centroid	Y-coordinate of the basin centroid	SYE selected index-gage station number	SYE selected index-gage station name
118777	908834	13.81	1.48	8.83	120426	909179	01174565	West Branch Swift River near Shutesbury, Mass.
122433	903927	13.29	7.74	14.17	124269	905494	01174900	Cadwell Creek near Belchertown, Mass.
122301	903193	13.49	1.68	8.63	123102	902723	01174901	Cadwell Creek near Belchertown, Mass.
121496	903761	14.03	1.18	30.51	122101	903622	01174902	Cadwell Creek near Belchertown, Mass.
164340	934333	13.04	5.92	0.00	165210	934113	01161500	Tarbell Brook near Winchendon, Mass.
205467	917705	15.06	2.03	7.67	204811	918242	01097300	Nashoba Brook near Acton, Mass.
238199	928219	14.97	21.55	2.17	236141	929547	01100700	East Meadow River near Haverhill, Mass.
239406	927213	14.98	16.30	5.23	238221	926859	01100701	East Meadow River near Haverhill, Mass.
237151	926546	14.95	21.33	1.81	235723	928121	01100702	East Meadow River near Haverhill, Mass.
231755	825696	14.97	10.01	22.23	233089	829278	01106000	Adamsville Brook at Adamsville, R.I.
238117	827911	14.96	15.38	12.46	237949	830452	01106001	Adamsville Brook at Adamsville, R.I.
164479	914888	12.79	7.04	0.00	166284	914773	01095220	Stillwater River near Sterling, Mass.
164177	916252	12.98	10.05	0.20	164906	917830	01095221	Stillwater River near Sterling, Mass.
166748	920465	13.18	6.83	0.00	165767	920066	01095222	Stillwater River near Sterling, Mass.
168481	918229	12.93	2.93	31.48	168711	916854	01095223	Stillwater River near Sterling, Mass.
173121	929106	13.57	0.93	0.00	172300	929338	01096000	Squannacook River near West Groton, Mass.
171935	932770	13.16	3.16	0.87	171006	933726	01096001	Squannacook River near West Groton, Mass.
173661	929522	13.50	3.25	0.43	172349	931483	01096002	Squannacook River near West Groton, Mass.
108115	933534	12.60	1.56	3.46	102185	947478	01170100	Green River near Colrain, Mass.
108452	935080	13.16	2.01	0.00	108237	938076	01170101	Green River near Colrain, Mass.
250453	880610	14.97	9.09	41.52	250131	880232	01105600	Old Swamp River near South Weymouth, Mass.
64426	910317	11.44	2.07	0.00	63828	910493	01174566	West Branch Swift River near Shutesbury, Mass.
60722	900541	11.37	9.91	0.00	62276	898907	01174567	West Branch Swift River near Shutesbury, Mass.
58665	898849	11.61	1.42	0.00	59529	899287	01174568	West Branch Swift River near Shutesbury, Mass.
167375	886553	13.54	10.39	2.31	167098	887692	01175670	Sevenmile River near Spencer, Mass.
176425	919701	13.97	1.80	11.01	175631	919403	01095224	Stillwater River near Sterling, Mass.
176232	918736	14.26	0.00	11.80	176215	918123	01095225	Stillwater River near Sterling, Mass.
175076	918327	13.78	2.76	2.11	174682	918051	01095226	Stillwater River near Sterling, Mass.
175060	921964	13.98	0.91	0.00	174887	921729	01095227	Stillwater River near Sterling, Mass.
174545	921838	13.97	5.28	30.40	174160	922081	01095228	Stillwater River near Sterling, Mass.
173915	921424	13.85	7.39	5.25	173605	920156	01095229	Stillwater River near Sterling, Mass.
176961	916339	14.12	5.14	0.00	176023	916544	01095230	Stillwater River near Sterling, Mass.
215274	908829	15.04	10.62	5.41	215247	909592	01097301	Nashoba Brook near Acton, Mass.
190750	899448	14.76	9.40	12.95	192695	899418	01095231	Stillwater River near Sterling, Mass.
194093	898424	14.62	1.36	0.00	194406	898748	01097302	Nashoba Brook near Acton, Mass.

Table 2. Reservoir basin characteristics and index streamgages in Massachusetts used in the Sustainable Yield Estimator.—Continued

[mi², square miles; ft, feet; in, inches; °C, degrees Celsius; SYE, Sustainable Yield Estimator; DPW, Department of Public Works; X- and Y-coordinates in

Water supplier	Reservoir name	Drainage area, excluding surface area (mi²)	Mean basin elevation (ft)	Average annual precipitation (in)	Percentage of basin that is open water
Milford Water Company	Echo Lake	1.26	434.41	48.04	0.00
North Brookfield Water Department	Doane Pond	0.75	971.14	48.56	1.45
	Horse Pond	0.79	1,008.25	48.58	0.25
Pittsfield Water Department	Ashley Lake/Lower Ashley Intake	2.43	1,876.28	51.47	0.01
	Farnham Reservoir	2.93	1,871.90	52.10	3.30
	Sandwash Reservoir	1.67	1,956.55	53.44	0.83
	Upper Sackett Reservoir	0.86	1,793.27	50.80	0.00
	Cleveland Reservoir	13.74	1,900.26	52.30	0.05
Scituate Water Department	Main Reservoir	3.50	91.99	49.42	0.85
Southbridge Water Department	Hatchet Pond	0.18	909.38	51.55	4.88
	Hatchet Brook Reservoir #3	0.58	769.80	51.10	0.00
	Hatchet Brook Reservoir #4	0.54	767.57	51.41	0.04
	Hatchet Brook Reservoir #5	0.88	876.36	51.60	0.31
	Cohasse Brook Reservoir	1.76	783.94	51.61	0.00
Springfield Water Department	Borden Brook Reservoir	7.64	156.94	53.83	0.95
	Cobble Mountain Reservoir	35.88	179.39	54.74	1.03
South Deerfield Water Supply District	Roaring Brook Reservoir	3.97	847.42	49.32	0.00
	Whately Reservoir	1.22	690.84	47.68	0.29
Wakefield Water Department	Crystal Lake	0.74	144.64	47.83	0.00
Westborough Water Department	Sandra Pond	1.10	512.74	48.13	0.67
Westfield Water Department	Granville Reservoir	5.14	169.87	51.79	0.01
	Montgomery Reservoir	2.47	169.42	51.64	0.92
West Springfield Water Department	Bearhole Reservoir	5.51	156.94	47.83	9.65
Winchester Water Department	Middle Reservoir	0.22	188.78	47.89	0.00
	North Reservoir	0.53	181.41	47.91	0.63
	South Reservoir	0.35	196.31	47.85	0.00
Worcester Water Department	Holden Reservoir #1	4.31	988.16	49.10	0.26
	Holden Reservoir #2	0.66	870.25	48.89	10.78
	Kettle Brook Reservoir #1	1.05	997.81	49.09	0.19
	Kettle Brook Reservoir #2	0.46	1,056.53	49.21	9.47
	Kettle Brook Reservoir #3	0.68	1,102.12	49.32	0.00
	Kettle Brook Reservoir #4	1.65	1,155.72	49.32	0.03
	Lynde Brook Reservoir	2.99	955.96	48.90	0.90
	Kendall Reservoir	1.42	962.25	49.11	0.00
	Pine Hill Reservoir	6.20	1,051.33	48.91	1.65
	Quinapoxet Reservoir	19.23	978.06	49.24	1.16

Massachusetts State Plane meters; Elevation determined from the U.S. Geological Survey 30-meter National Elevation Dataset]

X-coordinate of the basin outlet	Y-coordinate of the basin outlet	Average maximum monthly temperature (°C)	Percentage of basin that is wetland	Percentage of basin that is underlain by sand and gravel	X-coordinate of the basin centroid	Y-coordinate of the basin centroid	SYE selected index-gage station number	SYE selected index-gage station name
199336	882420	14.89	7.43	0.00	198632	883339	01111500	Branch River at Forestdale, R.I.
152832	892890	13.37	6.03	0.00	152294	892837	01175671	Sevenmile River near Spencer, Mass.
152716	893521	13.26	9.44	0.00	152338	894330	01175672	Sevenmile River near Spencer, Mass.
61112	907556	11.49	7.71	0.00	63253	904598	01174569	West Branch Swift River near Shutesbury, Mass.
59624	905955	11.40	12.11	0.00	60066	905596	01174570	West Branch Swift River near Shutesbury, Mass.
62375	903170	11.26	17.66	0.00	63447	902808	01174571	West Branch Swift River near Shutesbury, Mass.
62981	908976	11.67	5.35	0.00	63448	907981	01174572	West Branch Swift River near Shutesbury, Mass.
67217	914454	11.40	11.65	2.15	67782	913389	01331400	Dry Brook near Adams, Mass.
261649	882089	14.90	19.31	8.34	259381	882706	01105731	Indian Head River at Hanover, Mass.
151250	864151	13.60	0.13	0.00	150964	863976	01126600	Blackwell Brook near Brooklyn, Conn.
152645	867506	13.96	1.11	1.60	152153	867618	01126601	Blackwell Brook near Brooklyn, Conn.
152344	866907	13.87	3.18	1.17	152234	866210	01126602	Blackwell Brook near Brooklyn, Conn.
151867	866016	13.67	4.57	1.42	151592	864861	01126603	Blackwell Brook near Brooklyn, Conn.
154253	866456	13.92	4.32	0.00	152957	863965	01126604	Blackwell Brook near Brooklyn, Conn.
81048	876485	12.78	6.82	1.94	79241	875630	01187300	Hubbard River near West Hartland, Conn.
84932	875556	12.90	5.31	2.00	79243	881286	01187400	Valley Brook near West Hartland, Conn.
104207	913954	13.57	3.48	3.30	102484	914911	01169900	South River near Conway, Mass.
105145	913574	13.91	1.40	0.00	104560	914117	01169901	South River near Conway, Mass.
235056	916292	14.88	4.44	14.16	234734	915498	01097303	Nashoba Brook near Acton, Mass.
191280	888045	14.59	5.81	21.87	190928	886932	01111501	Branch River at Forestdale, R.I.
87851	871847	13.65	0.93	4.68	86724	872716	01187401	Valley Brook near West Hartland, Conn.
91646	883065	13.30	8.82	6.54	91509	885160	01174573	West Branch Swift River near Shutesbury, Mass.
102251	875730	15.08	5.77	26.76	103356	879967	01171800	Bassett Brook near North Hampton, Mass.
231596	911210	14.84	2.84	0.00	231654	911686	01097304	Nashoba Brook near Acton, Mass.
231403	912841	14.85	2.99	8.29	231998	912548	01097305	Nashoba Brook near Acton, Mass.
231434	910191	14.86	2.13	0.00	231549	910787	01097306	Nashoba Brook near Acton, Mass.
169341	895131	13.32	3.82	5.85	168502	896269	01175673	Sevenmile River near Spencer, Mass.
169817	894051	13.70	1.15	6.58	169470	894531	01175674	Sevenmile River near Spencer, Mass.
167666	889650	13.21	5.77	0.00	166741	890617	01175675	Sevenmile River near Spencer, Mass.
167001	891321	13.08	2.72	0.00	166530	891878	01175676	Sevenmile River near Spencer, Mass.
166337	892458	13.00	8.00	0.00	166039	893177	01175677	Sevenmile River near Spencer, Mass.
165489	893916	12.92	10.67	0.00	166060	894897	01175678	Sevenmile River near Spencer, Mass.
169080	888876	13.39	8.28	0.00	168367	890969	01175679	Sevenmile River near Spencer, Mass.
167957	899596	13.43	2.22	5.65	167553	898601	01095232	Stillwater River near Sterling, Mass.
166626	900134	13.09	8.44	0.00	164905	899773	01095233	Stillwater River near Sterling, Mass.
168780	904242	13.33	9.26	9.04	166454	907298	01095234	Stillwater River near Sterling, Mass.

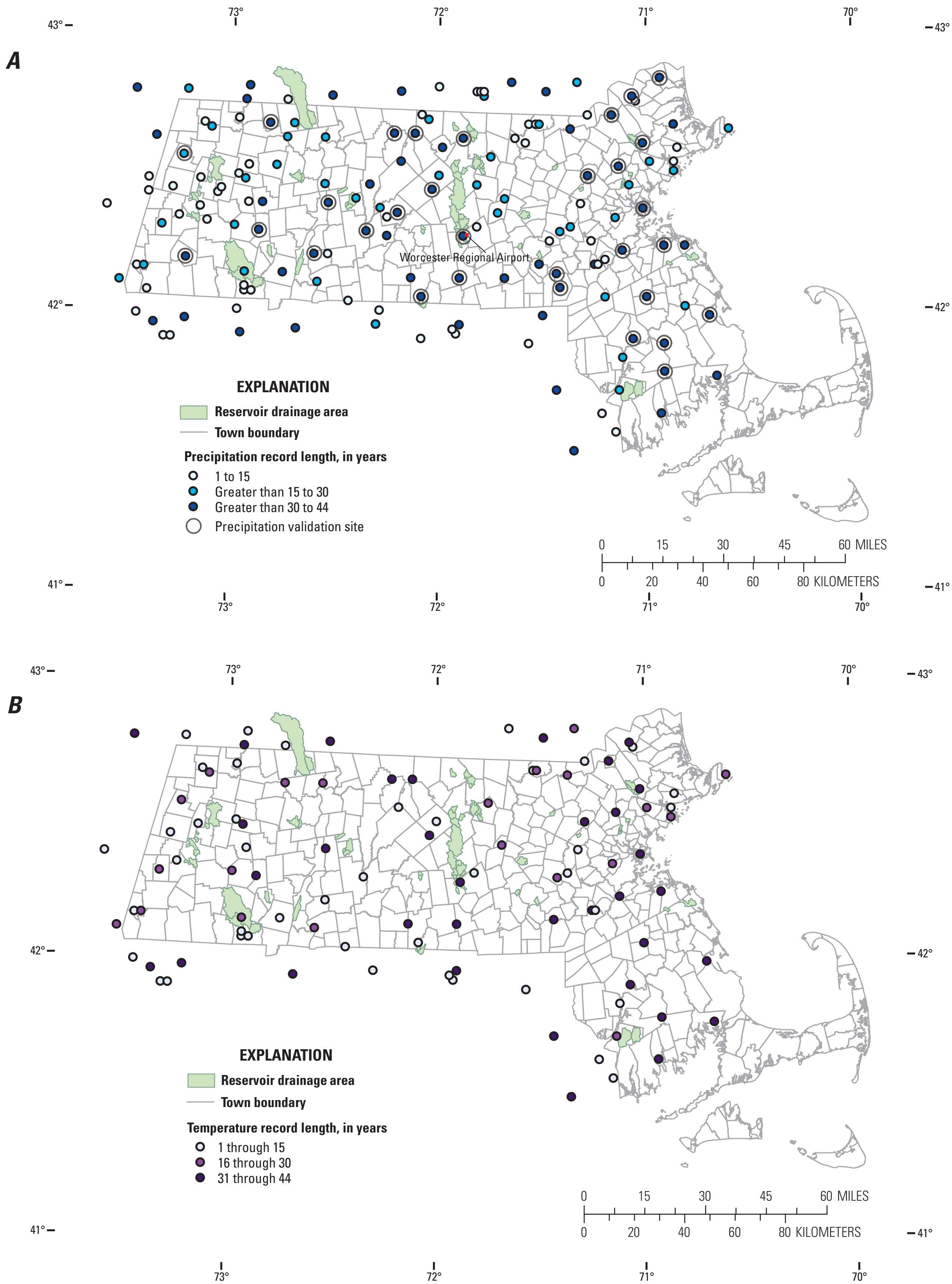


Figure 2. Location of reservoirs and record length at *A*, precipitation stations and validations sites, and *B*, meteorological stations in Massachusetts and vicinity.

Table 3. Nash-Sutcliffe Efficiency of daily precipitation at 33 gaged validation sites in Massachusetts.

[NCDC COOP ID, National Climatic Data Center Cooperative Station identifier; --, no data]

Precipitation-gage location	NCDC COOP ID	Nash-Sutcliffe Efficiency
Amherst	190120	0.67
Ashburnham	190190	0.52
Barre Falls Dam	190408	0.81
Bedford	190535	0.53
Belchertown	190562	0.86
Birch Hill Dam	190666	0.84
East Milton/Blue Hill	190736	0.49
Logan Airport, Boston	190770	0.66
Brockton	190860	0.51
Buffumville Lake, Charlton	190998	0.77
Franklin	192997	0.84
Hardwick	193401	0.84
Haverhill	193505	0.60
Heath	193549	0.73
Hingham	193624	0.70
Holyoke	193702	0.57
Knightville Dam, Huntington	193985	0.75
Lanesboro	194075	0.65
Lawrence	194105	0.36
Middleboro	194711	0.70
Middleton	194744	0.79
Newburyport	195285	0.42
Plymouth/Kingston	196486	0.69
Reading	196783	0.68
Rochester	196938	0.67
Southbridge	197627	0.87
Taunton	198367	0.37
Tully Lake, Royalston	198573	0.83
West Medway	199316	0.81
West Otis	199371	0.65
Worcester Regional Airport	199923	-0.16
Atkins Reservoir, Amherst	--	0.94
Echo Lake, Concord	--	0.75

Groundwater Contributions

Where a reservoir is in contact with an aquifer, groundwater may flow into or out of the reservoir depending on aquifer water table and reservoir stage. When reservoir stage falls because water is being used to meet demand, the decrease in stage will cause water from the aquifer to flow into the reservoir until the reservoir stage and aquifer water table regain equilibrium. In contrast, when reservoir stage rises, water from the reservoir may flow into the aquifer. During an extended drawdown period, groundwater inflows can potentially provide enough additional water to the reservoir storage to maintain a yield that would otherwise lead to failure.

Rorabaugh (1964) developed an analytical solution to the groundwater-flow equation for the case of one-dimensional flow in a finite-width aquifer bounded by a stream. Archfield and Carlson (2006) adapted these equations to estimate the groundwater contribution to reservoir storage due to time-varying changes in reservoir stage and applied the equations in the FYE model. When reservoir stage changes from one time step to the next, groundwater contributions are estimated as a flow rate per unit length (Archfield and Carlson, 2006, equations 3, 4, and 5). The flow rate is then multiplied by a scaling factor, L, which is the estimated length of reservoir shoreline in contact with the aquifer, in order to determine the total volume of groundwater flow per day. In the analysis by Archfield and Carlson (2006), L was parameterized as a constant, calculated as the perimeter in contact with sand and gravel for a reservoir at full pool. In reality, a reservoir may be in contact with an aquifer along any part of its bottom surface area, not just the perimeter, and the area that is in contact with the aquifer will decrease as the reservoir storage volume is depleted. Reservoirs at very low storage levels have a much smaller surface area that could be interacting with the aquifer and thus, the scaling parameter should vary with this surface area.

Parameterizing L as a constant results in overestimation of groundwater contributions during extreme reservoir drawdown periods when reservoir storage is low. Archfield and Carlson (2006) found that the overestimation of groundwater flows at low reservoir-storage levels led to numerical instabilities in the groundwater-flow equations, making groundwater-flow estimates for some reservoirs impossible. In order to better characterize groundwater contributions for this study, the scaling parameter L was allowed to vary on the basis of the reservoir stage. At full pool, L was defined in the same manner as in Archfield and Carlson (2006), as the length of the perimeter that intersected sand and gravel deposits. This was determined in a GIS by intersecting the full-pool contour line with a digital data layer of sand and gravel deposits (Office of Geographic and Environmental Information, 2004). In order to estimate the value of L when the reservoir stage was lower than full pool, the surface area of the reservoir at each contour interval was overlaid on the digital data layer of sand and gravel deposits. The value of L at each contour was estimated by decreasing the value of L at full pool in proportion to the decrease in the area which intersected sand and gravel at that contour level.

Applications of the Firm-Yield Estimator Model

Firm yields were determined for 38 reservoir systems in Massachusetts. Of these, 23 were single-reservoir systems, and 15 were multiple-reservoir systems. Reservoirs whose firm yield had been previously determined were re-evaluated using updated methods and data. Previous firm-yield studies in Massachusetts (Waldron and Archfield, 2006; and Archfield and Carlson, 2006) used a monthly time step, which can cause an overestimation of the firm yield (Fennessey, 1995). The inclusion of daily streamflows and meteorological data as well as a refined method for estimating groundwater flows in this study resulted in firm-yield estimates that differ from those found in Waldron and Archfield (2006).

Firm-yield estimates for both single- and multiple-reservoir systems are shown in table 4. Water-use data from Annual Statistical Reports provided by MassDEP for the years 2000 to 2004 indicate that 32 out of the 38 reservoir systems are currently operating below their firm yield or marginally at their firm yield. Because year-to-year usage in a system can vary, systems in which average usage was within 10 percent of the firm yield may be operating within the firm yield in some years but above the firm yield in other years. These reservoirs were listed as marginally operating within the firm yield.

Application of the Firm-Yield Estimator Model to a Single-Reservoir System

Single-reservoir systems consist of one reservoir that does not receive water from any other reservoir. Inflows to a single-reservoir system consist of streamflow into the reservoir from the surrounding watershed, precipitation that falls directly on the reservoir surface, and groundwater inflows. Outflows from a single-reservoir system are evapotranspiration, groundwater outflows, water withdrawals for public water supply or other uses, and releases from the reservoir for downstream flow requirements. Firm yields for a single-reservoir system are computed by successively solving the water-balance equation for the reservoir over the 44-year simulation period, increasing the yield each time by a minimum of 0.001 million gallons (Mgal). The highest yield that can be used without the reservoir failing for one day is the firm yield.

Echo Lake in Hopkinton, Massachusetts, currently augments the amount of available water in the reservoir by a diversion from the Charles River (not shown in fig. 1) approximately 2.5 mi below the Echo Lake Dam, at the crossing of Dilla Street in Milford, Mass. Water from the river at this point can be pumped back into the reservoir. The maximum pumping rate for the diversion is 3 million gallons per day (Mgal/d), and pumping primarily occurs during March through May (Metcalf and Eddy, 1997). In order to simulate this unique situation, streamflow for the length of the Charles River from the diversion point up to the Echo Lake Dam was estimated using SYE. The FYE model was modified for this reservoir only, such that a maximum of 3 Mgal/d of streamflow from the Charles River and from Echo Lake spillage during the previous simulated time step was added back into Echo Lake storage at the end of each simulation time step during the months of March through May. Including the Charles River diversion in the simulation of Echo Lake increased the firm yield by 35 percent, from 0.83 Mgal/d without the diversion to 1.12 Mgal/d including the diversion. A previously estimated firm yield for this lake, calculated using a reservoir capacity of 384 Mgal obtained from historical documents and without the Charles River skimming, is 0.56 Mgal/d (Metcalf and Eddy, 1997). The current study used a reservoir capacity of 461.6 Mgal based on volume estimates from current bathymetric measurements of the reservoir.

Main Reservoir in Scituate is simulated as a single-reservoir system, although water is actually transported from Main Reservoir to Old Oaken Bucket Pond by way of First Herring Brook (not shown in fig. 1) before being pumped to the water-treatment facility. Because of excessive aquatic-plant growth, bathymetric measurements could not be made in Old Oaken Bucket Pond. Because the stage-storage relation could not be determined for this reservoir, the firm yield could not be estimated. On the basis of the relative sizes of these two reservoirs, most of the available water for this system comes from Main Reservoir. Because storage in Old Oaken Bucket Pond was not considered for this analysis, the firm yield for this system represents a conservative estimate.

Application of the Firm-Yield Estimator Model to a Multiple-Reservoir System

Of the 71 reservoirs included in this study, 48 are in reservoir systems in which multiple reservoirs are hydrologically connected. Reservoirs may be configured in a variety of ways and can transfer water either through uncontrolled spills from an upstream reservoir that is at full pool into a river or open channel that transports water by gravity into a downstream reservoir, or by pumping water from one reservoir to another. Reservoir-configuration diagrams for newly surveyed reservoirs in this study are included in appendix 3. Configurations for previously studied reservoir systems are included in Archfield and Waldron (2006). Because individual reservoirs in a system have different storage capacities, they will not necessarily deplete and refill at the same rates. The optimal firm yield for a multiple-reservoir system depends on the time-varying withdrawal operations of each individual reservoir in the system. Estimating the optimal firm yield for a multiple-reservoir system requires complex optimization methods which are beyond the scope of this study. However, an approximation of a multiple-reservoir-system firm yield can be made by assuming that all reservoirs are operating at their individual maximum yield.

Table 4. Firm-yield estimates and 2000–2004 water usage for 38 reservoir systems in Massachusetts.

[Actual average annual usage refers to the period 2000–2004. Reservoirs with usage that was within 10 percent of the firm yield are considered marginally meeting their firm yield; Mgal/d, million gallons per day; DPW, Department of Public Works]

Water supplier	Reservoir system	Firm yield, no releases (Mgal/d)	Actual average annual usage (Mgal/d)	Operating at less than firm yield?
Amherst Water Department	Atkins Reservoir	1.16	0.83	Yes
Ashburnham/Winchendon	Upper Naukeag Lake	1.72	1.06	Yes
Concord Water Department	Nagog Pond	0.86	0.09	Yes
Fall River Water Department	North Watuppa system	18.20	12.89	Yes
Fitchburg Water Department	Lovell Reservoir system	2.77	0.18	Yes
Fitchburg Water Department	Meetinghouse system	5.61	2.71	Yes
Fitchburg Water Department	Wachusett Lake	1.08	0.35	Yes
Greenfield Water Department	Leyden Glen Reservoir	0.69	0.57	Yes
Hingham/Hull (Aquarian Water Company)	Accord Pond	0.66	0.59	Yes
Lee Water Department	Schoolhouse Reservoir	0.84	0.51	Yes
Leicester (Cherry Valley and Rochdale Water)	Henshaw Pond	0.35	0.26	Yes
Lincoln Water Department	Flints Pond	0.59	0.38	Yes
Marlborough DPW–Water and Sewer Division	Millham system	1.83	1.40	Yes
North Brookfield Water Department	Doane Pond system	0.71	0.42	Yes
Pittsfield Water Department	Ashley Lake	1.37	0.21	Yes
Pittsfield Water Department	Cleveland Reservoir	9.18	7.96	Yes
Pittsfield Water Department	Farnham Reservoir system	2.51	2.23	Yes
Pittsfield Water Department	Upper Sackett Reservoir	0.50	0.08	Yes
South Deerfield Water Supply District	Whately system	1.07	0.68	Yes
Southbridge Water Department	Hatchet Brook system	2.78	1.69	Yes
Springfield Water Department	Cobble Mountain system	42.70	36.57	Yes
Wakefield Water Department	Crystal Lake	0.40	0.28	Yes
West Springfield Water Department	Bearhole Reservoir	1.40	0.73	Yes
Westborough Water Department	Sandra Pond	0.80	0.67	Yes
Westfield Water Department	Granville Reservoir	3.03	2.47	Yes
Westfield Water Department	Montgomery Reservoir	1.13	0.00	Yes
Amherst Water Department	Centennial system	0.87	0.83	Marginally
Lee Water Department	Upper (Leahey) Reservoir	0.59	0.54	Marginally
Leominster DPW–Water Division	Fall Brook Reservoir	0.84	0.88	Marginally
Leominster DPW–Water Division	Simonds Pond system	2.26	2.32	Marginally
Scituate Water Department	Main Reservoir	0.63	0.61	Marginally
Winchester Water Department	South Reservoir system	1.01	1.10	Marginally
Danvers Water Department	Middleton Pond system	2.79	3.09	No
Greenfield Water Department	Green River	0.42	0.52	No
Hinsdale Water Department	Belmont Reservoir	0.12	0.15	No
Leominster DPW–Water Division	Distributing Reservoir system	0.58	0.87	No
Milford Water Company	Echo Lake	[1]1.12	1.40	No
Worcester Water Department	Holden Pond system	17.15	23.87	No

[1] Firm yield for Echo Lake includes water from the Charles River diversion.

The algorithm for calculating the firm yield of a multiple-reservoir system depends on its configuration and the method of water transport between reservoirs (fig. 3). For two reservoirs connected by either a river or open channel, water released from the upstream reservoir in order to meet demand, as well as any uncontrolled spills and controlled releases from the reservoir, is transported to the downstream reservoir. For two reservoirs that transport water through pumping, only the volume of water that is pumped from the first reservoir is added as a water input to the second reservoir, and uncontrolled spills and controlled releases are lost from the system. The firm-yield model first estimates the firm yield of the uppermost reservoir, which does not receive water from any other reservoirs, in the same manner as a single-reservoir system. The spillage volume, Q_{spi} and the yield volume, Q_{yi} are calculated for each simulation day and saved by the model. After the simulation for the first reservoir is finished, the model begins the simulation for the second reservoir and includes the inputs from the previous reservoir in the water balance. If the reservoirs are connected by pumping, the daily-yield volume from the previous reservoir is added as an additional inflow into the water-balance equation of the second reservoir. For reservoirs connected by gravity, the daily-yield volume, Q_{yi}, and the daily uncontrolled spill volume, Q_{spi}, are added as additional inflows into the water balance of the second reservoir. The maximum pump capacity may be set by the user. If the usage exceeds the pump capacity on a given day, only the maximum pump-capacity volume is transferred to the second reservoir, and the excess water remains in storage in the first reservoir. For systems with more than two reservoirs, firm yields of reservoirs that contribute water to any other reservoir are estimated before the receiving reservoir. The system firm yield is the firm yield calculated at the terminal reservoir after accounting for inflows from other reservoirs in the system.

The FYE is most appropriate for estimating yields of relatively simple multiple-reservoir configurations and reservoir operations. Because the model calculates the yield of each reservoir in the system sequentially, reservoir configurations in which water is routed through a reservoir more than once cannot be handled by the FYE. Only one reservoir system in the study had a configuration that could not be adequately modeled by the FYE. The Worcester system consists of 10 individual reservoirs with Holden Reservoir #1 as the terminal reservoir. Water is pumped into Holden Reservoir #1 from Lynde Brook Reservoir and gravity-fed by Kendall Reservoir. Water from Holden Reservoir #1 may be pumped either directly to the filtration plant or into Holden Reservoir #2 for storage, then back into Holden Reservoir #1. Because Holden Reservoir #1 both receives water from and releases water to Holden Reservoir #2, it cannot be modeled by the sequential algorithm used in the FYE. In order to estimate the firm yield for this system, Holden Reservoirs #1 and #2 were modeled as one reservoir with the combined reservoir characteristics of both individual reservoirs. Because of the operational complexities of this system, the firm yield estimated by the FYE may be less certain than in simpler reservoir systems.

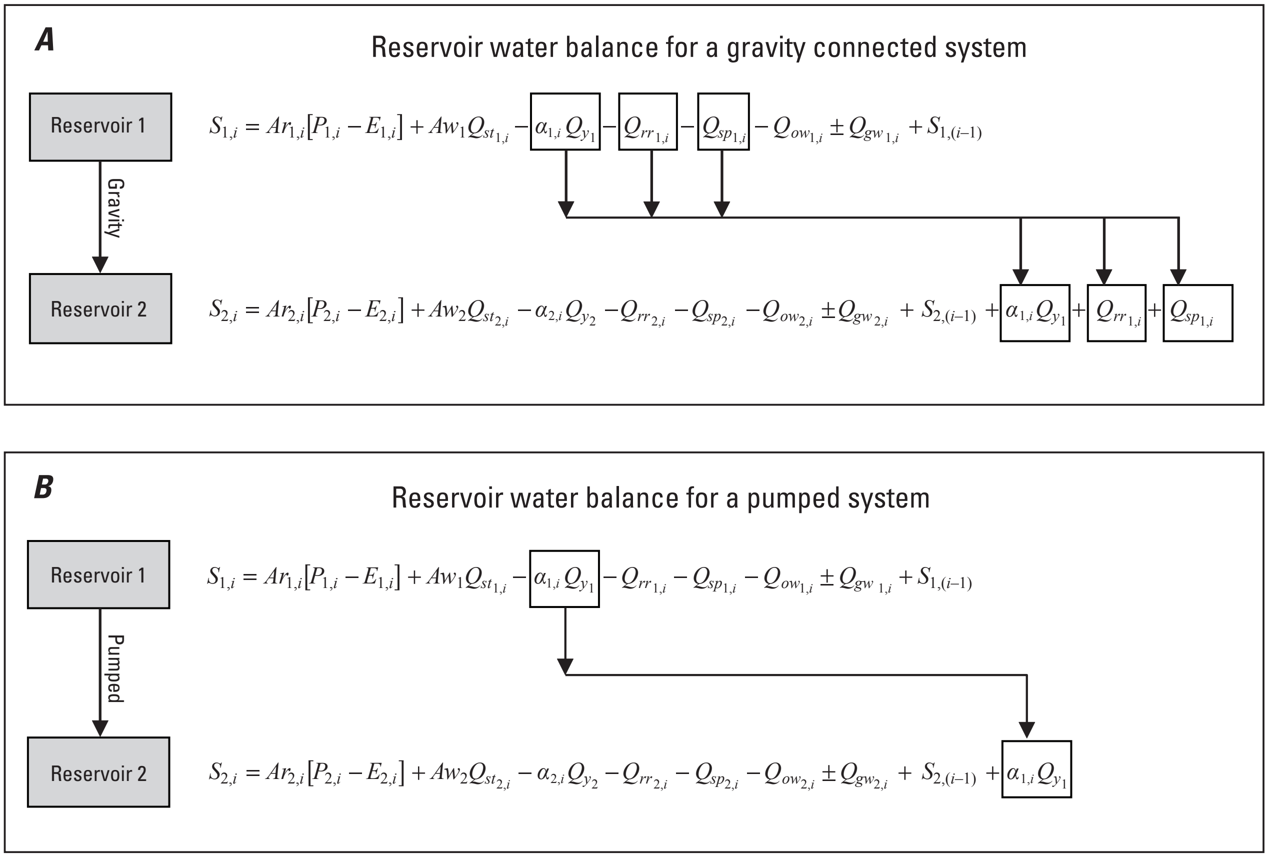
Firm-Yield Estimate Uncertainty and Sensitivity to Model Inputs

Uncertainty in firm yields determined using the FYE comes from many sources, including uncertainty in input data—such as daily streamflow, evaporation, precipitation, and stage-storage relations—and uncertainty associated with the estimation of groundwater-flow contributions. For reservoir systems that are operating at or near their estimated firm yield, the uncertainty associated with the firm-yield estimates could result in reservoirs exceeding their true firm yield. If the firm-yield estimate is higher than the true value of the firm yield, reservoirs risk failing if they are operating near their firm-yield estimate.

An analytical method to examine the effects of the combined uncertainty from all of the input data errors has not been determined for the FYE; however, the sensitivity of the model to individual sources of uncertainty can be examined. Daily streamflow volumes are generally many times greater than groundwater contributions and direct precipitation or evaporation from the reservoir surface. Therefore, relative uncertainties in the daily streamflow time series have the potential to contribute the greatest amount of uncertainty in the water balance equation and the resulting firm-yield estimate. The storage capacity of the reservoir is also important in estimating the firm yield. Reservoir volume and stage/storage relations are calculated from bathymetric-survey data. There is little guidance available regarding the number of bathymetric-data points needed to accurately assess reservoir capacity and the manner in which errors in this calculation might affect the firm-yield estimates. A final source of uncertainty in the firm-yield estimates comes from the equations used to estimate groundwater contributions to the water balance. These equations have not been extensively tested for use in reservoir simulation models, and parameter estimates for these equations are uncertain.

Sensitivity of Firm-Yield Estimates to Errors in Daily Streamflow

In order to investigate the potential sensitivity of the FYE to input streamflow errors, a series of Monte Carlo simulations were performed in which the daily-streamflow inputs were perturbed by a random-error term during the calculation of the firm yield for a particular reservoir. The range of firm-yield estimates obtained after many simulations is representative of the amount of uncertainty that can be expected in the firm yield due to errors in the input streamflow time series.



EXPLANATION

- i **= daily simulation time step**
- S_i **= volume of water in usable storage for the current day, in million gallons**
- Ar_i **= area of the reservoir surface, in square miles**
- P_i **= precipitation, in miles**
- E_i **= evaporation from the reservoir surface, in miles**
- Aw_i **= reservoir drainage area, in square miles**
- Q_{st_i} **= streamflow per unit drainage area, in miles**
- α_i **= peak-usage factor, dimensionless**
- Q_{y_i} **= yield for the current day, in million gallons**
- Q_{rr_i} **= controlled release, in million gallons**
- Q_{sp_i} **= uncontrolled spill, in million gallons**
- Q_{ow_i} **= withdrawal from the reservoir by other users, in million gallons**
- Q_{gw_i} **= groundwater contributions or losses for the current day, in million gallons**

Subscripts 1 and 2 identify the reservoirs

Figure 3. Water balances for a system of reservoirs in which *A*, water is transported by gravity and *B*, water is pumped from Reservoir 1 to Reservoir 2.

In order for the result of a Monte Carlo sensitivity analysis to be meaningful, the errors added to the streamflow in the simulations must accurately characterize the uncertainty in the input data. Uncertainty associated with SYE streamflow estimates is an area of ongoing research and is beyond the scope of this project (Archfield and others, 2010). However, as a first attempt at characterizing the uncertainty associated with FYE streamflow inputs, the structure of the randomly generated Monte Carlo error terms was based on the relative errors from a SYE cross-validation dataset. SYE-generated daily streamflows were computed for 18 U.S. Geological Survey (USGS) gaged sites and compared to the observed streamflow values (Archfield and others, 2010). The percent difference between the SYE predicted daily flows and the observed flows from these 18 sites was calculated for each day as

$$PD = (Q_{est} - Q_{obs})/Q_{est}, \quad (2)$$

where

PD is the percent difference between the SYE predicted streamflow and observed streamflow,

Q_{obs} is the observed streamflow, and

Q_{est} is the estimated streamflow.

For each of the gages, the exceedence probability of each of the daily flows also was calculated. For each exceedence probability, the mean percent difference between observed and estimated flows across all 18 gaged sites was calculated as well as the standard deviation of the percent differences.

Figure 4 shows that for streamflows with exceedence probabilities up to about 0.6, the mean percent difference between observed and predicted is near zero, and the standard deviation of the percent differences is fairly constant, indicating that flows in this range are relatively unbiased but contain some amount of random error. For low streamflows with higher exceedence probabilities, the mean percent difference between observed and predicted deviates from zero, and the mean standard deviation of the differences increases, indicating a potential bias and greater uncertainty in the low daily streamflows. Since low flows generally occur during drought periods, underprediction of streamflows during these times could lead to underprediction of the firm-yield estimate.

In order to construct a random-error term for inclusion in the Monte Carlo simulations, the percent difference between observed and predicted daily streamflows was assumed to be normally distributed. The mean and standard deviation of the sample distribution for the percent difference between observed and predicted flows were estimated from figure 4. For simulated flows with exceedence probabilities less than 0.6, the error term was generated from a Gaussian distribution with a mean of zero and a standard deviation of 0.3. In order to capture the greater uncertainty in the low flows, simulated streamflows with exceedence probabilities greater than 0.95 were generated from a Gaussian distribution with a mean of -0.75 and a standard deviation of 1. Streamflows with exceedence probabilities of 0.6 to 0.95 were generated from a Gaussian distribution with a mean of -0.25 and a standard deviation of 0.5. Although the percent differences between observed and predicted streamflows are large at higher exceedence probabilities, the percent difference represents a very small volume of water, because flows at the 0.95 exceedence probability and above are generally very low for the stream gages in the cross-validation dataset. Random percent errors generated for each day of the simulation were applied to the daily streamflows as

$$Q^{*} = Q_{est} - (Err_{i} * Q_{est}) \quad (3)$$

where

Q^{*} is the daily streamflow modified by random error term,

Q_{est} is the daily-streamflow volume estimated by the SYE, and

Err_{i} is the randomly generated error term.

Monte Carlo simulations with 500 repetitions were run for 22 reservoirs in the study, and the distribution of the resulting firm yields for each reservoir is shown in table 5. Firm yields generated by the Monte Carlo simulations in the selected reservoir were somewhat higher than the original firm-yield estimates. This is due to the underprediction bias in the lowest streamflows. When this bias is corrected in the Monte Carlo simulations, firm yields increase. The mean firm yield generated by the Monte Carlo simulations ranged from 0.6 to 10.6 percent higher than original firm-yield estimates across all 22 reservoirs, indicating that firm yields computed by the model are potentially underestimated by this amount and therefore represent a conservative estimate of the firm yield (table 5).

The mean percent change in firm yield was used to compare the sensitivity behaviors of different reservoirs. Mean percent change in firm yield was calculated as the percent difference between the initial firm-yield estimate and the mean firm-yield estimate generated by the Monte Carlo simulation. The mean percent changes in firm yields were highest in reservoirs with low storage ratios, defined as the reservoir capacity divided by the mean annual streamflow. This indicates that these low-storage reservoirs are more sensitive to errors in the streamflow input data than reservoirs with high storage ratios (fig. 5).

It is important to note that because the sample distribution used to generate the random errors in the Monte Carlo simulations was based on the average behavior at 18 gaged sites, it may not accurately characterize the errors in streamflow input data at all FYE reservoirs. The errors in the streamflows for any particular reservoir may have more or less bias or variability than the average relative errors at the gaged sites and, therefore, would have a different range of firm-yield estimates. In addition, this method does not account for autocorrelation of the daily relative errors in streamflows. Further study regarding uncertainty in the SYE tool is needed for a more precise sensitivity analysis of the effects of streamflow input data on the firm yield.

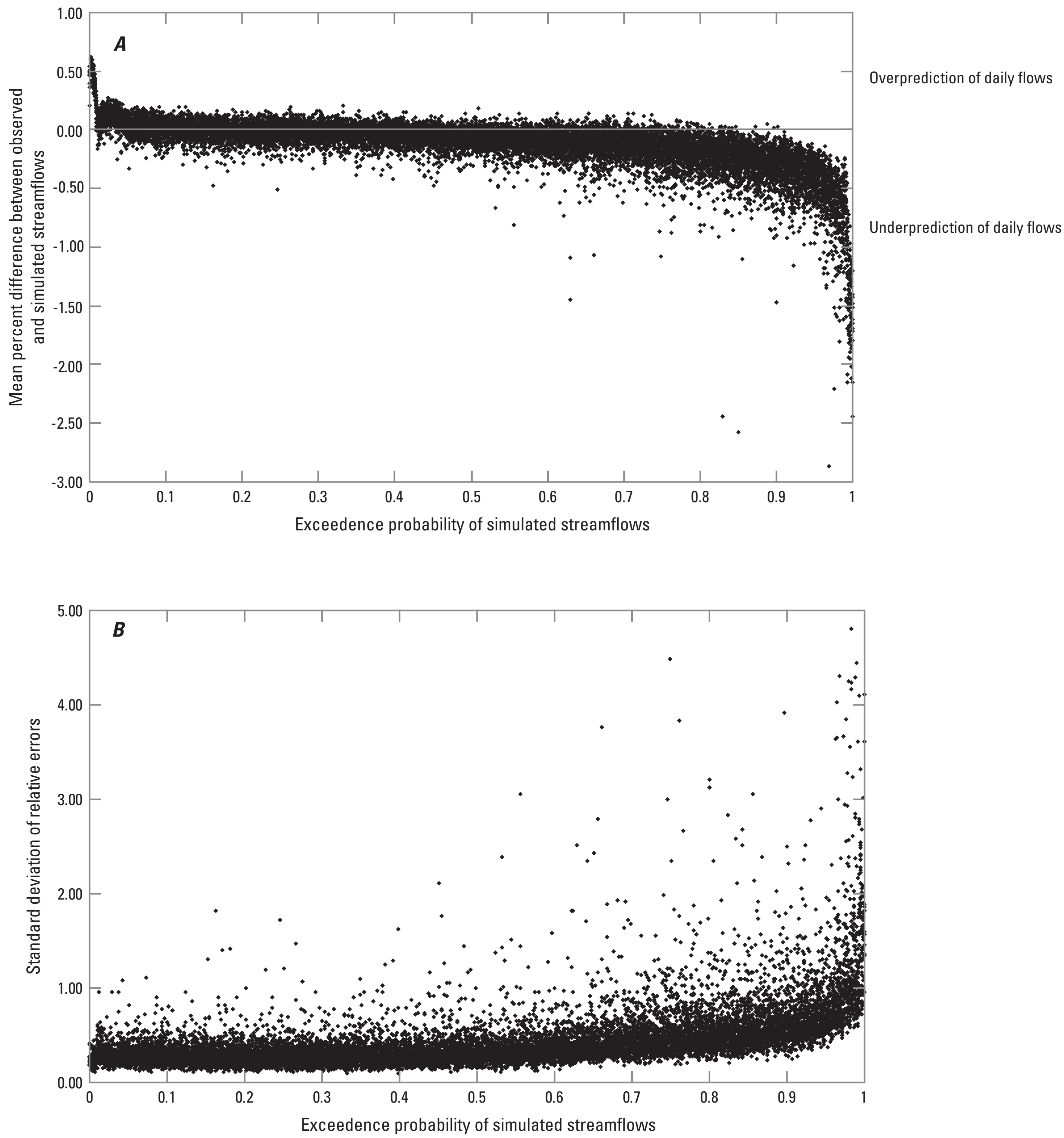


Figure 4. *A*, Mean percent difference and *B*, standard deviation of the percent difference of daily streamflows generated by the Sustainable Yield Estimator at 18 U.S. Geological Survey gaged sites in Massachusetts.

Table 5. Distribution of firm yields resulting from 500 Monte Carlo simulations at selected reservoirs in Massachusetts.

[Mgal/d, million gallons per day]

Reservoir name	Firm-yield estimate (Mgal/d)	Mean firm-yield estimate from Monte Carlo simulations (Mgal/d)	Standard deviation of Monte Carlo firm-yield estimates	Highest Monte Carlo firm-yield estimate (Mgal/d)	Lowest Monte Carlo firm-yield estimate (Mgal/d)
Ashley Lake	1.37	1.42	0.02	1.47	1.36
Atkins Reservoir	1.16	1.28	0.02	1.33	1.23
Belmont Reservoir	0.12	0.12	0.00	0.13	0.12
Bickford Reservoir	1.91	1.96	0.02	2.01	1.91
Cleveland Reservoir	9.18	9.56	0.10	9.86	9.24
Cohasse Reservoir	1.16	1.19	0.02	1.24	1.13
Copicut Reservoir	7.30	7.41	0.05	7.56	7.25
Emerson Brook Reservoir	1.22	1.27	0.02	1.32	1.23
Fall Brook Reservoir	0.84	0.86	0.01	0.89	0.82
Farnham Reservoir	1.62	1.69	0.02	1.74	1.63
Fitchburg Reservoir	1.22	1.24	0.01	1.27	1.20
Flints Pond	0.59	0.59	0.00	0.61	0.58
Granville Reservoir	3.03	3.32	0.13	3.59	3.07
Hatchet Pond	0.21	0.21	0.00	0.22	0.21
Henshaw Pond	0.35	0.37	0.01	0.38	0.35
Horse Pond	0.50	0.51	0.01	0.53	0.49
Leyden Glen Reservoir	0.69	0.75	0.01	0.79	0.71
Quinapoxet Reservoir	4.21	4.46	0.03	4.57	4.38
Sandwash Reservoir	0.89	0.93	0.01	0.97	0.89
Schoolhouse Reservoir	0.84	0.91	0.01	0.94	0.88
Upper Sackett Reservoir	0.50	0.51	0.01	0.53	0.48
Wachusett Lake	1.08	1.10	0.02	1.15	1.06

Sensitivity of the Firm-Yield Model to Bathymetric-Map Accuracy

Water-depth measurements of a reservoir are necessary to determine the maximum storage capacity of the reservoir and the relation between reservoir stage and storage. Reservoir-depth measurements are interpolated using a GIS to create a continuous bathymetric map from which lake volume can be determined. Because the firm yield of a reservoir is dependent upon the storage capacity, it is important that the number of water-depth measurements collected is adequate to characterize this input variable to the FYE model.

Bathymetric measurements are generally made along parallel or gridded straight-line transects of the lake. The spacing of transect intervals is important because the density of water-depth measurements affects the accuracy of the computer-generated bathymetric maps and computed storage capacity. Although it is beneficial to have as many measurement points as possible, very high density transect intervals may be prohibitively time consuming and expensive to obtain, especially for large reservoirs. However, if the spacing of measurement transects is too wide and point density too low, important physiographical features may be missed, causing errors in the resulting bathymetric-contour maps and storage calculations. Wilson and Richards (2006) show that lake capacity computed from bathymetric surveys decreases as transect-interval spacing increases. Storage capacity calculated from 400- and 800-ft transect intervals differed by 15.6 and 36.8 percent, respectively, from storage capacity calculated using 50-ft transect intervals.

The effect of water-depth measurement density on reservoir capacity and firm-yield estimation was examined using three reservoirs which represent typical reservoir sizes and shapes in Massachusetts. Upper Sackett Reservoir, located in Pittsfield, Mass., is the smallest of the three reservoirs, with an area of 19 acres and a gently sloping “U”-shaped lake-bottom topography. Cohasse Reservoir in Southbridge, Mass., is a long, narrow valley impoundment with a surface area of

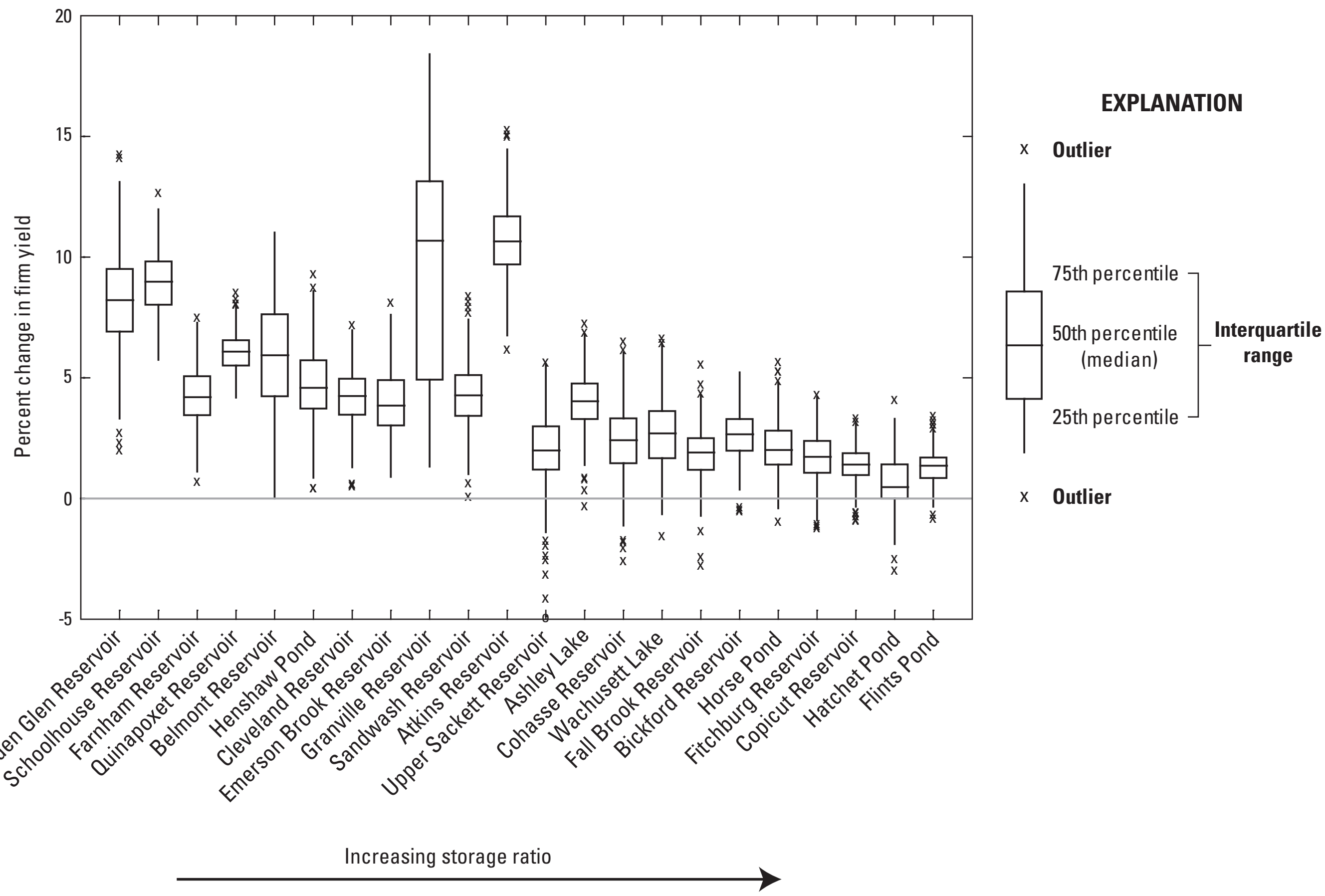


Figure 5. Percent change in firm yield of selected reservoirs in Massachusetts after accounting for potential errors in daily streamflow in 500 Monte Carlo simulations.

56 acres and a steeply sloping "V"-shaped lake bottom. South Reservoir in Winchester, Mass., is the largest of the three reservoirs with an area of 72 acres and a relatively flat lake bottom. The area-to-perimeter ratios of Cohasse Reservoir, South Reservoir, and Upper Sackett Reservoir were 154.9, 183.0, and 202.6, respectively. Lake depths ranged from 45 to 53 ft, and surveys from all three reservoirs included high water-depth measurement densities. Original transect spacing for these three lakes ranged from 15 to 50 meters (m) and always included at least one complete shoreline-perimeter transect (table 6).

Survey measurements were interpolated using the TOPOGRID command in ARC/INFO (Environmental Systems Research Institute, Inc., 1994) to create bathymetric surfaces for each reservoir. Reservoir storage capacity was computed using the Volume tool in the 3D Analyst toolbox (Environmental Systems Research Institute, Inc., 1994). For the purposes of this uncertainty analysis, this bathymetric surface was assumed to be the true lake bottom from which water depths at points along hypothetical transects of varying spacings and patterns using a GIS were measured. Hypothetical transect lines were applied in three patterns: parallel lines across the width of the lake, perpendicular gridded lines across the width and length of the lake, and gridded lines with an additional perimeter transect (fig. 6). Each transect pattern was applied using five different transect spacings: 15, 30, 60, 90, and 120 m, respectively. Points were placed every 5 m along each transect and overlaid on top of the reference bathymetric surface from which the depth was obtained. Water depths along the hypothetical transects were used to create a new bathymetric surface using the same method as for the original transect measurements, in addition to calculating reservoir storage capacity and stage-storage relations. The reservoir capacity and stage-storage data were entered into the FYE, and the firm yield was calculated for each transect pattern. The storage volume and firm yield estimated from the different transect patterns were then

Table 6. Reservoir capacity and firm yield for selected reservoirs in Massachusetts calculated using various transect patterns and sampling-point densities.

[m, meters; pts/acre, points per acre; Mgal, million gallons; Mgal/d, million gallons per day; --, no data]

Transect pattern	Transect width (m)	Cohasse Reservoir			Upper Sackett Reservoir			South Reservoir		
		Bathymetric sampling point density (pts/acre)	Usable storage capacity (Mgal)	Firm yield (Mgal/d)	Bathymetric sampling point density (pts/acre)	Usable storage capacity (Mgal)	Firm yield (Mgal/d)	Bathymetric sampling point density (pts/acre)	Usable storage capacity (Mgal)	Firm yield (Mgal/d)
Actual survey measurements	--	**71.33**	**369.99**	**1.16**	**127.19**	**162.73**	**0.51**	**58.05**	**411.29**	**0.44**
Parallel transects only	15	21.98	366.22	1.15	25.49	159.68	0.51	25.30	395.60	0.43
	30	11.07	359.95	1.14	12.64	157.70	0.50	12.67	377.58	0.42
	60	5.65	346.51	1.12	6.32	149.46	0.49	6.42	334.24	0.39
	90	3.77	325.45	1.09	4.23	134.65	0.46	4.44	288.37	0.35
	120	2.88	290.51	1.04	3.19	119.26	0.44	2.86	199.71	0.27
Gridded transects	15	94.25	369.68	1.16	50.58	160.37	0.51	50.41	400.40	0.43
	30	24.10	364.98	1.15	24.99	159.68	0.51	25.34	391.69	0.43
	60	12.38	358.61	1.14	12.64	155.80	0.50	12.77	357.40	0.40
	90	7.96	346.89	1.13	8.36	147.76	0.49	8.55	332.53	0.39
	120	6.48	336.95	1.11	6.77	140.85	0.47	6.30	295.97	0.36
Gridded transects with added perimeter transect	15	107.43	369.23	1.16	62.67	160.93	0.51	63.80	402.62	0.44
	30	37.28	364.78	1.15	37.09	160.63	0.51	38.73	398.39	0.43
	60	25.56	358.55	1.14	24.74	159.46	0.51	26.16	383.19	0.42
	90	21.14	352.32	1.13	20.46	156.91	0.50	21.95	375.06	0.42
	120	19.65	345.16	1.12	18.87	152.58	0.49	19.70	364.54	0.41

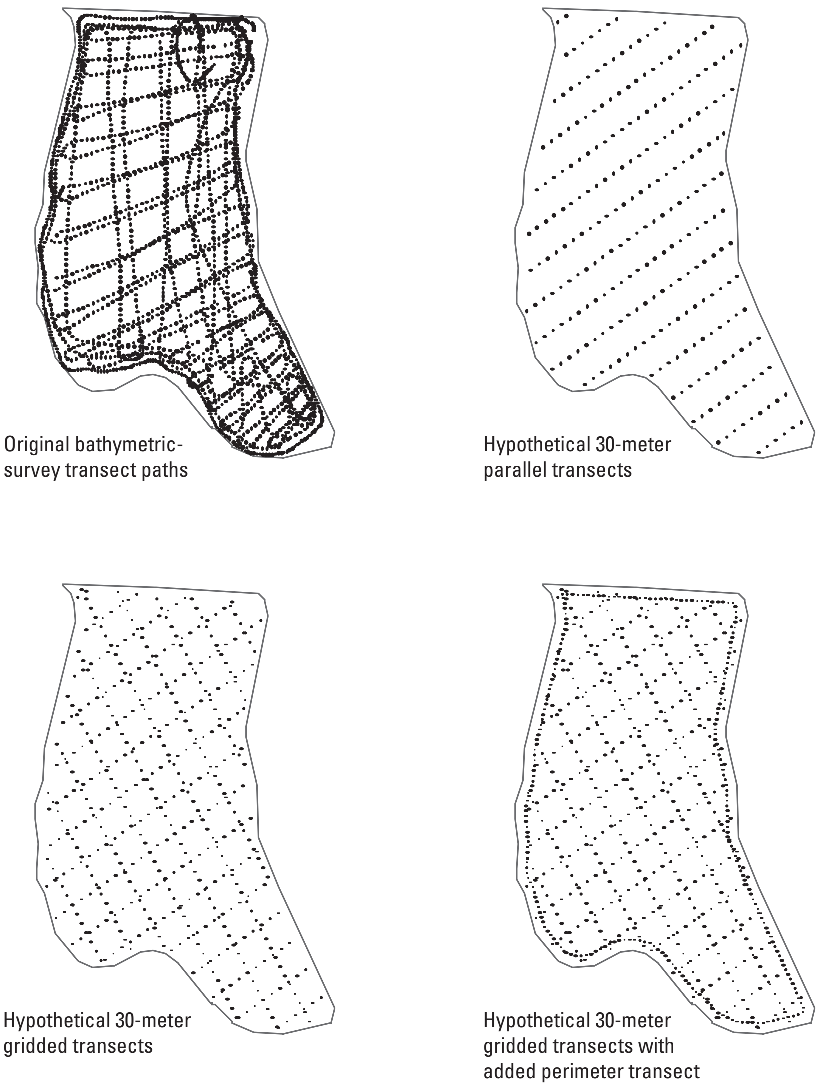


Figure 6. Original and hypothetical 30-meter transect spacing for Upper Sackett Reservoir in Pittsfield, Massachusetts.

compared to the volume and firm yield estimated from original transect measurements (table 6).

Errors in estimated reservoir volume and firm yield were smallest for Cohasse Reservoir, which is long and narrow, and were largest in South Reservoir, which has a sprawling, flat-bottomed lake form, indicating that reservoir shape may play a role in bathymetric accuracy. In general, parallel transects spaced farther than 15 m apart did a poor job of characterizing the bathymetry. Gridded transects performed better: in Cohasse and Upper Sackett Reservoirs, gridded transects spaced 60-m apart or less produced results with minimal (less than 5 percent) error rates in volume and firm yield. Gridded transects spaced 30 m or less apart in South Reservoir also produced minimal error rates. Adding a perimeter transect to gridded transects did not result in an appreciable improvement in volume or firm-yield accuracy in Cohasse Reservoir; however, in Upper Sackett and South Reservoirs, which have rounder reservoir shapes and lower perimeter-to-area ratios, the addition of a perimeter transect improved the volume and firm-yield estimates by roughly 50 percent. The percent changes in reservoir storage capacity and firm yield for selected reservoirs are shown in figure 7.

For each hypothetical transect-pattern scenario, the average spatial density of measurement points was calculated as the number of measurement points divided by the reservoir surface area. Measurement densities fewer than 10 measurements per acre resulted in unreliable bathymetric maps with volume errors between 6 and 51 percent and yield-estimate errors between 3 and 40 percent. Errors in volume and firm-yield estimates were less than 5 percent when point densities were above more than 20 points per acre.

It is important to note that errors in bathymetric maps and calculations can also arise as a result of the methods employed during GIS processing. The type of interpolation method used, grid-cell size, and degree of smoothing can all affect the resulting bathymetric-map calculations and resulting firm yield. Bathymetry calculations may be more or less sensitive to the density of depth measurements when analyzed using different GIS techniques than those used here.

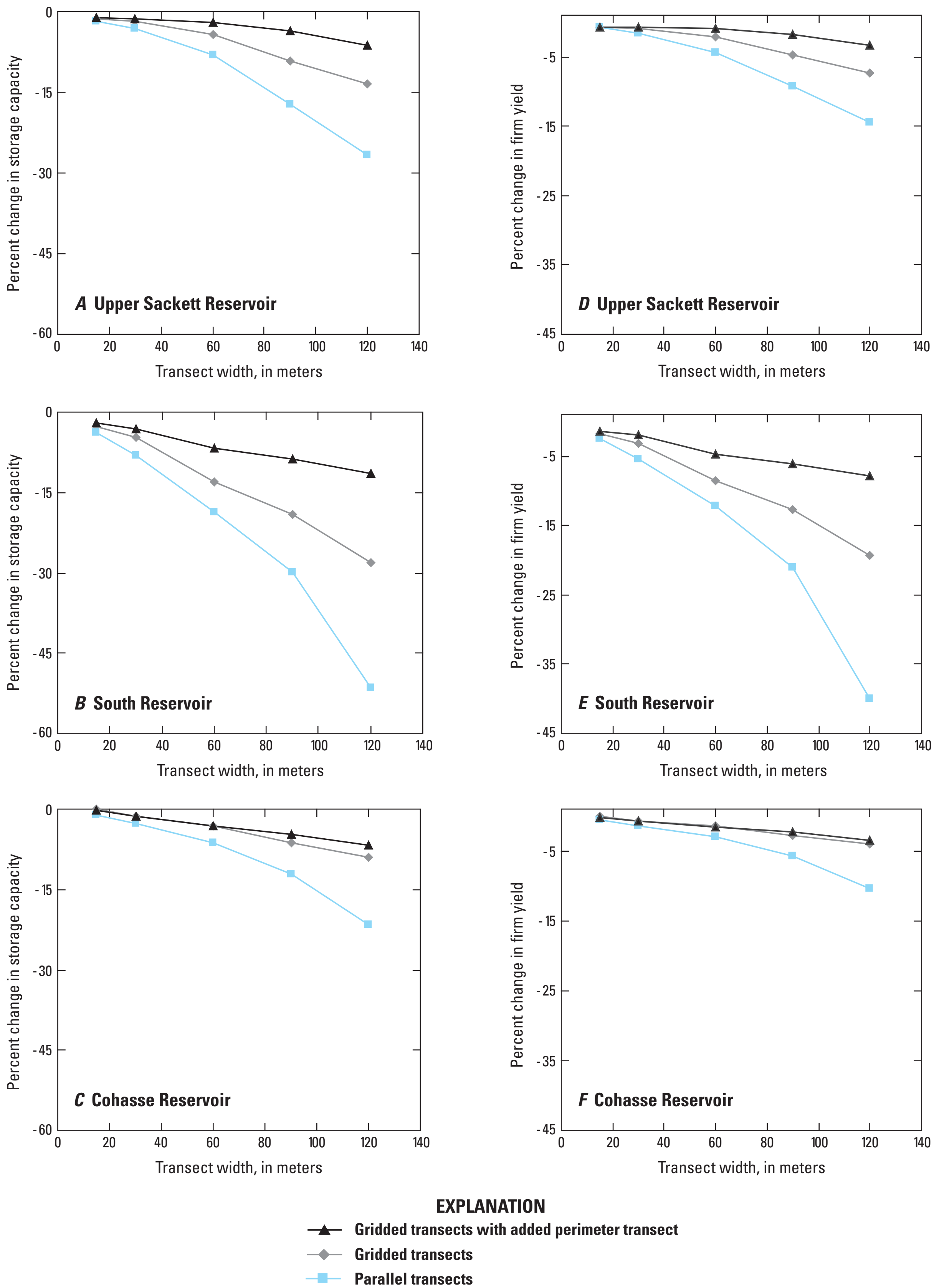


Figure 7. *A–C*, Percent change in reservoir storage capacity and *D–F*, firm yield, resulting from transect spacings and patterns for three study reservoirs in Massachusetts.

Validation of Groundwater Parameters

Reservoir-aquifer geometry in the FYE is parameterized by (1) the length of shoreline in contact with sand and gravel, (2) the distance from the reservoir shoreline to the aquifer boundary, and (3) the transmissivity of the aquifer (Archfield and Carlson, 2006). The first two of these parameters are estimated by intersecting reservoir-shoreline locations with maps of sand and gravel deposits (Office of Geographic and Environmental Information, 2004). The calculated perimeter length is highly sensitive to the spatial scale of the lake-boundary map layer, and little guidance is available regarding proper map scale for estimating this parameter. Transmissivity values are based on published USGS hydrologic atlases, which lack numerical and geographical precision and are unavailable for some areas of Massachusetts.

Archfield and Carlson (2006) show that the FYE model is most sensitive to the transmissivity of the aquifer and length of shoreline in contact with sand and gravel. Groundwater flows into and out of the reservoir are highest during periods when reservoir stage is changing, so inaccuracies in these calculations due to parameter estimation will be most pronounced during periods of extreme reservoir storage changes. In the case where either of these two groundwater parameters is overestimated, the FYE will overestimate groundwater flows entering the reservoir during drought periods. This would cause the simulated reservoir stages to be too high and could lead to an overestimation of firm yield.

An attempt was made to use observational data to calibrate estimates of groundwater parameters. The FYE model was modified to accept observed water-use withdrawal rates in place of the yield in the water-balance equation and also to output daily reservoir stage. Simulated reservoir stage was then compared to observed reservoir stage. If other model-input time series such as streamflow, precipitation, and water-use withdrawal volumes, are known with certainty, groundwater parameters can be calibrated by minimizing discrepancies between observed and simulated reservoir stage. The requisite observational data for a rigorous validation of groundwater parameters were not available for any of the reservoirs in the study; however a limited amount of observational data was available from water suppliers for Nagog Pond in Acton, Mass., and Atkins Reservoir in Amherst, Mass.

Observational data for Atkins Reservoir include daily precipitation, daily withdrawal volumes, and daily reservoir stage for March 1994 to September 2004. The FYE was run for this time period using observational precipitation and water-use rates. The simulation period includes several reservoir critical periods in which the reservoir stage decreases from full pool to a local minimum, then fully refills. The most severe drawdown period occurred on October 12, 2002, when the reservoir dropped to roughly 44 percent of its total capacity. Comparison of observed and simulated reservoir stages shows that reservoir stage was overestimated during these severe critical periods (fig. 8). Other deviations in the shape of the simulated stage when compared to the observed stage, such as the delayed reservoir recovery in several of the drawdown periods, are most likely caused by errors in daily streamflow, precipitation, or evaporation input time series. The consistent bias in estimating the peak drawdown stage, however, may be caused by inaccuracies in groundwater parameters.

Because the firm yield is determined from the lowest reservoir stage during a severe drawdown period, it is important that the model can accurately predict the magnitude of a drawdown. Errors in simulated reservoir stage at nearly full-pool volumes or in the timing of the simulated drawdown period or recovery period are less important in estimating the firm-yield value. Transmissivity and parameter *L* were adjusted in order to minimize bias in the simulation during the major drawdown periods. Agreement between observed and simulated reservoir stages during the major drawdown periods improved by decreasing transmissivity and parameter *L* by 30 to 50 percent of their original values (fig. 8). However, errors in the shape of the simulated daily reservoir stage remain due to errors in the streamflow, precipitation, and evaporation time series. Because of errors in the other input data series, the values for transmissivity and parameter *L* could not be calibrated with a high degree of precision, but the results of the simulations indicate that initial estimates of transmissivity and perimeter length in contact with the aquifer may have been too high. Despite a lack of precision in these variables, the inclusion of groundwater contributions did improve the agreement between observed and simulated reservoir stages compared to a simulation using only streamflow and climate inputs to the system.

Atkins Reservoir is almost fully surrounded by sand and gravel deposits; however, surficial-geology maps show that only a small portion of the area of Nagog Pond intersects with sand and gravel deposits. In addition, estimated transmissivity values for this area are low, indicating a relatively limited groundwater influence in this reservoir. Available data for Nagog Pond include once-monthly reservoir stage observations and total monthly water-use withdrawal volumes for the period of February 1975 to September 1984. Monthly withdrawal data were disaggregated into daily withdrawals by dividing the monthly total by the number of days in each month. These daily values were used in place of the yield term in the modified FYE model, and simulated stages were compared to observed reservoir stages. Drawdown periods are less severe in the observed record for Nagog Pond than for Atkins Reservoir. The lowest reservoir stage occurred in November 1980, when reservoir storage was at 62 percent of maximum capacity.

Comparison of the simulated reservoir stage with the observed reservoir stage shows a slight underestimation of reservoir stage during drawdown periods (fig. 9). There is also an overall negative bias in the last half of the simulation, from about 1980 to 1984. A consistent deviation of modeled reservoir stage from measured stage, such as that seen here, is most likely caused by errors in the streamflow, precipitation, or evaporation input data and not errors in groundwater parameters. Nagog Pond has fewer nearby climate stations than other reservoirs in the study, making the meteorological

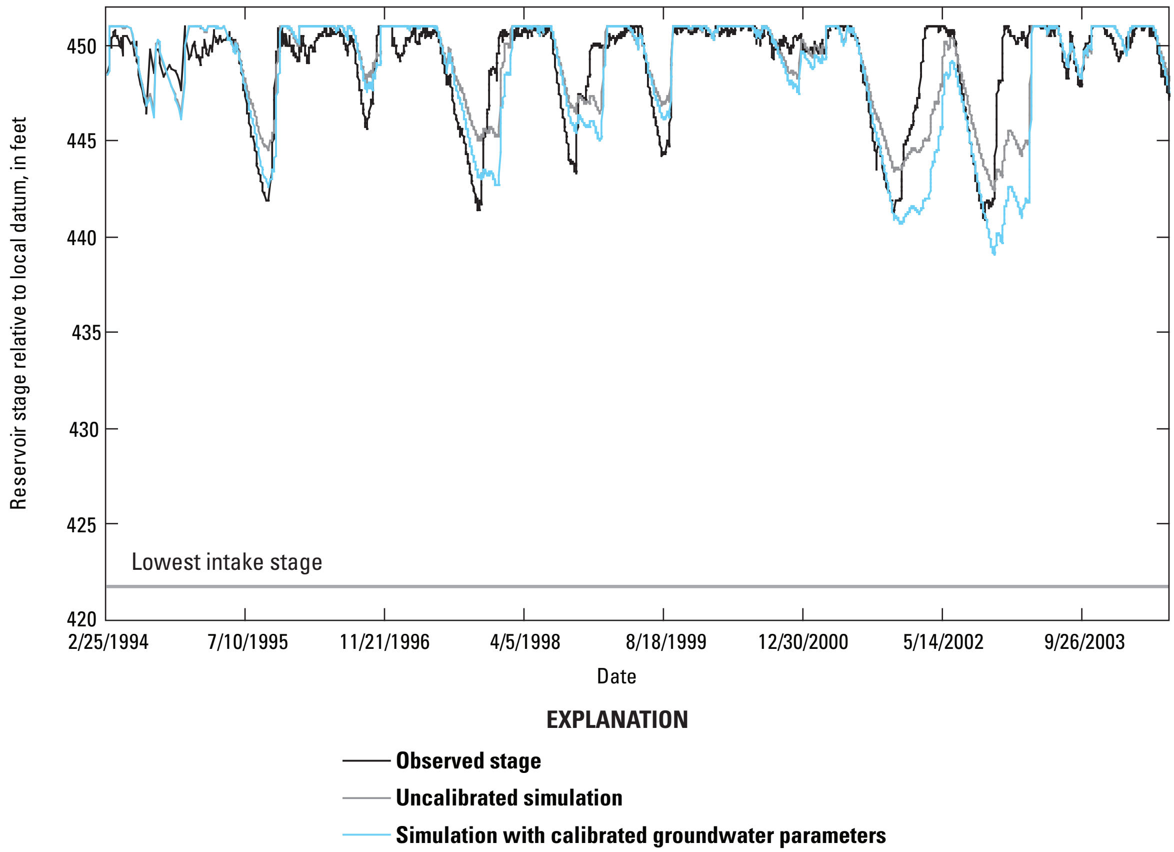


Figure 8. Daily simulated and observed reservoir stage for Atkins Reservoir in Amherst, Massachusetts.

input data more uncertain for this reservoir. Increasing the groundwater parameters for transmissivity and *L* by as much as 300 percent resulted in only minor effects on the simulated stage of this reservoir (fig. 9); parameter adjustments greater than this are unrealistic based on geologic maps of the area. In this case, it is most likely that errors in the prediction of daily reservoir stage during droughts are due to errors in other input data, and a calibration of the groundwater parameters for this reservoir cannot be determined.

Groundwater is an important component of the water balance for many reservoirs in Massachusetts. The ability to accurately estimate groundwater flows in and out of these reservoirs is necessary for an accurate firm-yield estimate. Archfield and Carlson (2006) show that changes in the groundwater parameters *L* and *T* of 80 percent can lead to 10- to 40-percent changes in the firm yield.. Further study is needed in order to validate these parameters, improve methods for their estimation, and improve the numerical methods with which they are incorporated in the model. In particular, accurate time series for observed streamflow and precipitation are needed so that comparisons of observed and simulated reservoir stages are not confounded by errors in the estimation of these inputs.

Effect of Drought Severity on Firm-Yield Estimates

A system's firm yield depends largely on the severity of the drought used in its estimation. The FYE calculates firm yield by increasing reservoir yield in the water-balance equation throughout the simulation period, until the reservoir fails. A firm yield calculated using a very severe or extended drought will be lower than a yield calculated using a milder, shorter drought. For most reservoirs in Massachusetts, the multiple-year drought of the mid-1960s was the most severe drought on record; however, other severe droughts occurred

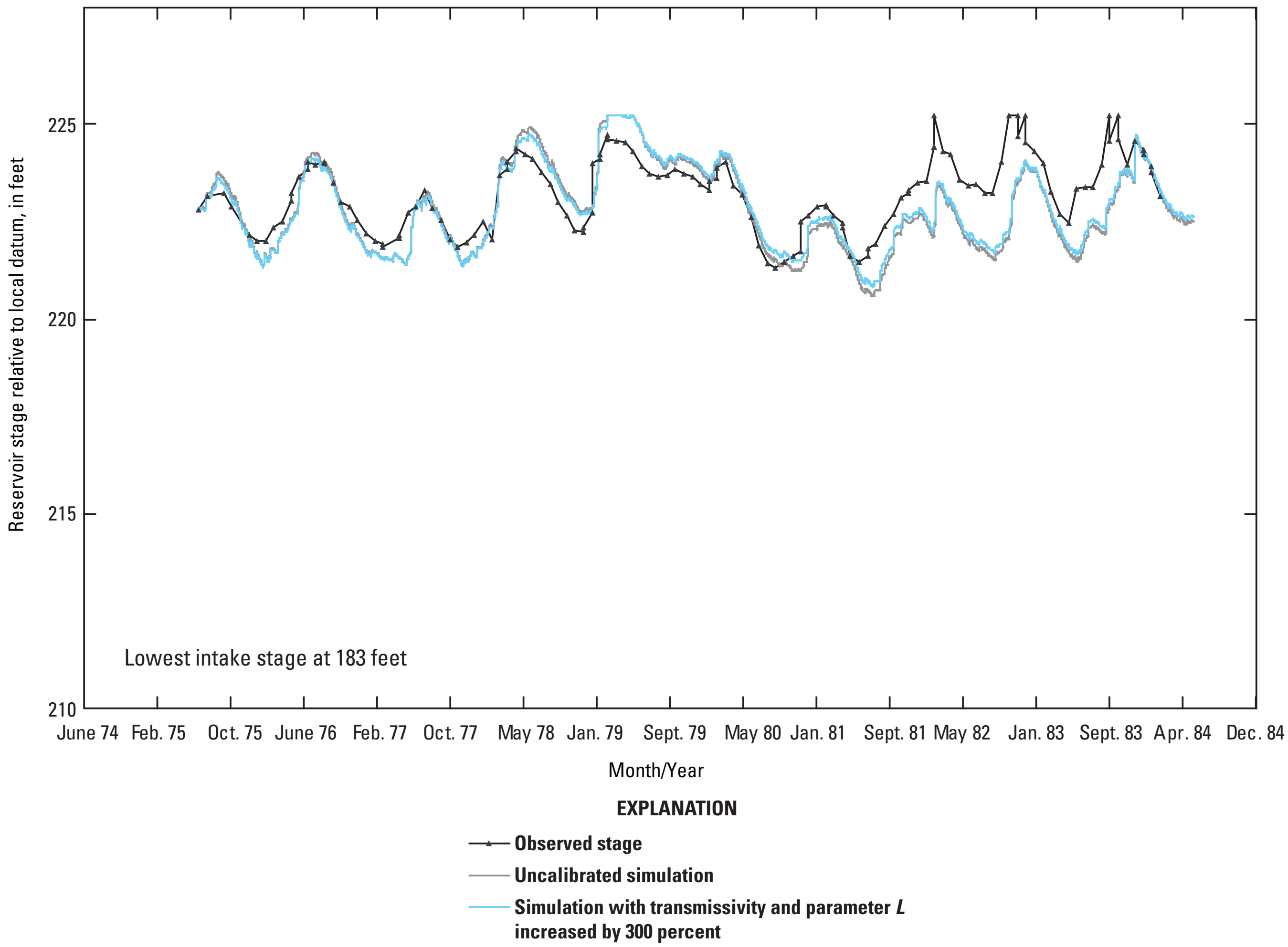


Figure 9. Daily simulated and observed reservoir stage for Nagog Pond in Concord, Massachusetts.

during the 1980s and in 2002. Differences in the firm yields determined from the droughts in the historical record and the behavior of reservoirs under different drought conditions have not been evaluated in Massachusetts.

Drought periods can be defined in terms of either a prolonged period of below-average precipitation (meteorological drought) or streamflow (hydrologic drought). Hydrologic-drought periods may differ slightly from meteorological-drought periods because of evaporation and groundwater storage. Because the firm yield is more sensitive to streamflow than to direct precipitation, hydrologic drought is considered in this analysis.

Hydrologic droughts can be characterized in terms of their duration and intensity. The 3-month moving streamflow average was calculated from the daily streamflow record and compared to the average seasonal streamflow from the entire long-term streamflow record. Seasonal flow periods were defined as: spring (March through May), summer (June through August), autumn (September through November), and winter (December through February). The drought duration was defined as the number of consecutive months for which the 3-month moving average is less than the average seasonal flow. Drought intensity was calculated as the percent difference between the magnitude of the 3-month moving average streamflow and the average seasonal streamflow over the duration of the drought, expressed as a percentage of average streamflow.

Using the daily streamflow record generated from the SYE, hydrologic droughts were characterized for reservoirs in Massachusetts. Analysis of droughts focused on the droughts in the 1960s, 1980s, and 2002, as these were the three most severe droughts for most Massachusetts reservoirs. The drought of the 1960s is notable for its extended length. Durations for this drought ranged from 20 to 69 months, with a median of 38 months (table 7, fig. 10). Average 3-month streamflows during this drought were 48 to 74 percent below average over the duration of the 1960s drought. Droughts in the 1980s and 2002 were shorter in duration but in some cases

Table 7. Firm yields and reliability of reservoirs in Massachusetts calculated using three major droughts in the historical record.

[Dates are in months and years from 1964 to 2002; Mgal/d, million gallons per day]

		1960s drought				1980s drought				
	Storage ratio	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Reliability (percent)
Accord Pond	0.60	20	47.9	0.67	Sep-66	22	54.8	0.66	Sep-81	100.0
Amythest Brook Intake	0.01	36	68.2	0.06	Nov-64	5	58.6	0.10	Sep-83	98.7
Ashley Lake	0.37	36	68.1	1.37	Feb-66	24	35.8	1.91	Feb-81	98.4
Atkins Reservoir	0.31	36	66.9	1.16	Oct-66	20	39.2	1.69	Oct-81	96.4
Bearhole Reservoir	0.04	47	58.8	1.40	Nov-64	8	72.8	1.84	Feb-81	98.4
Belmont Reservoir	0.17	36	73.6	0.12	Feb-66	23	39.1	0.16	Feb-81	98.7
Bickford Reservoir	0.59	36	66.2	1.91	Jan-66	17	41.6	2.73	Jan-81	98.4
Borden Brook Reservoir	0.70	37	57.8	6.34	Nov-66	11	39.0	8.88	Nov-81	96.6
Cleveland Reservoir	0.26	64	53.6	9.18	Feb-65	8	80.2	9.39	Feb-81	99.9
Cohasse Reservoir	0.40	69	57.2	1.16	Feb-66	12	37.4	1.73	Nov-85	97.0
Crystal Lake	0.49	47	65.5	0.40	Nov-66	11	59.3	0.68	Sep-85	97.2
Distributing Reservoir	0.01	36	67.2	0.15	Nov-64	5	54.8	0.23	Sep-83	98.1
Doane Pond	0.11	47	69.5	0.21	Feb-66	8	61.0	0.34	Nov-80	95.7
Echo Lake	0.79	38	66.7	0.83	Jan-67	11	46.4	1.33	Nov-85	97.3
Emerson Brook	0.26	38	62.3	1.22	Feb-66	15	59.1	1.59	Nov-85	98.5
Fall Brook Reservoir	0.57	36	68.2	0.84	Feb-66	17	43.0	1.31	Oct-81	97.1
Fitchburg Reservoir	0.70	48	69.3	1.22	Mar-67	15	61.7	1.97	Jan-86	96.7
Goodfellow Pond	0.04	36	67.4	0.07	Nov-64	17	41.9	0.10	Nov-80	99.2
Granville Reservoir	0.26	38	57.9	3.03	Feb-66	12	61.9	4.21	Feb-81	98.2
Hatchet Brook Reservoir #3	0.31	69	59.5	0.32	Feb-66	11	36.5	0.49	Feb-85	97.1
Hatchet Brook Reservoir #4	0.87	69	58.8	0.51	Dec-66	12	39.1	0.81	Nov-86	95.2
Hatchet Brook Reservoir #5	0.37	69	58.2	0.57	Feb-66	12	38.9	0.86	Nov-85	97.1
Hatchet Pond	1.55	69	63.2	0.21	Jan-67	14	33.5	0.35	Feb-89	94.1
Hawley Reservoir	0.01	36	67.1	0.17	Nov-64	21	40.2	0.31	Sep-80	98.4
Haynes Reservoir	0.69	36	70.6	0.26	Oct-66	23	29.8	0.44	Mar-89	96.6
Henshaw Pond	0.21	47	68.3	0.35	Feb-66	8	59.6	0.57	Feb-81	95.9
Hill Reservoir	0.01	36	64.9	0.65	Dec-64	18	42.5	0.97	Feb-81	98.4
Holden Reservoir #1	0.37	47	64.1	2.58	Nov-66	16	38.4	4.20	Nov-88	95.5
Holden Reservoir #2	0.70	47	68.9	0.47	Mar-67	16	44.2	0.78	Mar-89	96.2
Horse Pond	0.62	47	69.0	0.50	Jan-67	16	43.4	0.87	Mar-89	95.7
Kendall Reservoir	0.91	36	64.9	1.49	Nov-66	23	25.3	2.16	Nov-88	95.9
Kettle Brook Reservoir #1	0.03	47	68.4	0.12	Nov-64	12	48.2	0.22	Nov-84	96.6
Kettle Brook Reservoir #2	0.50	47	71.0	0.27	Jan-67	16	46.3	0.47	Mar-89	95.9
Kettle Brook Reservoir #3	0.42	47	69.6	0.38	Jan-67	16	44.3	0.65	Jan-89	96.0
Kettle Brook Reservoir #4	0.56	47	67.2	1.08	Jan-67	16	41.3	1.83	Jan-89	96.0
Leyden Glen Reservoir	0.02	58	57.1	0.69	Feb-65	14	11.7	0.71	Feb-81	99.9
Lovell Reservoir	0.23	47	71.7	1.16	Feb-66	15	61.3	1.80	Nov-85	98.0
Lynde Brook Reservoir	0.35	47	66.6	1.51	Feb-66	8	58.4	2.59	Feb-81	95.9
Main Reservoir	0.09	35	64.2	0.63	Dec-65	23	59.1	0.77	Oct-80	99.4

1980s drought			2002 drought								
Number of failure events	Average failure duration (days)	Average yield deficit during failure (Mgal/d)	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Reliability (percent)	Number of failure events	Average failure duration (days)	Average yield deficit during failure (Mgal/d)
0	0	0.0	13	49.8	0.75	Oct-02	99.2	14	10	9.2
17	12	0.6	22	55.3	0.10	Jan-02	98.8	13	15	0.8
13	20	35.2	23	54.7	1.81	Feb-03	99.0	4	39	74.8
20	29	36.5	22	54.9	1.49	Nov-02	98.0	11	29	32.7
19	14	14.4	17	54.2	1.81	Oct-02	98.6	14	16	16.5
8	27	3.3	25	55.7	0.16	Mar-02	98.7	7	30	3.7
13	20	69.3	20	49.2	2.49	Nov-02	98.9	10	17	49.0
16	34	246.3	12	47.0	8.70	Nov-02	97.0	15	33	228.9
2	6	30.3	10	34.8	12.87	Jan-02	94.3	51	18	155.2
15	32	52.3	10	40.5	1.45	Dec-02	99.0	4	41	56.3
16	28	17.6	10	58.3	0.65	Nov-02	97.6	12	32	19.6
14	22	2.8	20	49.5	0.21	Oct-02	98.7	12	17	1.9
30	23	4.9	20	56.7	0.27	Jan-02	98.9	7	26	4.1
11	40	58.8	20	54.6	1.17	Nov-02	98.2	9	32	37.2
7	35	40.1	12	57.5	1.72	Feb-02	97.7	12	31	37.7
13	36	40.9	20	50.5	1.13	Nov-02	98.3	13	21	19.3
9	58	95.7	22	53.7	1.94	Dec-02	97.0	5	96	160.3
13	10	0.8	20	50.3	0.10	Oct-02	99.2	13	10	0.8
11	26	78.4	12	47.1	4.53	Nov-02	97.7	13	28	95.7
18	26	11.2	10	56.9	0.40	Mar-02	99.1	4	35	12.0
29	26	23.2	10	41.9	0.71	Dec-02	97.0	21	23	17.3
16	29	23.7	10	41.5	0.72	Dec-02	99.0	4	41	28.2
23	41	14.9	10	59.6	0.31	Feb-03	96.4	11	52	17.3
22	12	1.8	22	54.6	0.28	Feb-02	98.8	16	12	1.6
19	29	9.2	20	52.9	0.38	Nov-02	98.1	14	22	5.9
32	21	7.9	20	55.3	0.49	Feb-02	98.2	11	27	9.2
22	12	5.2	22	52.2	0.91	Feb-02	98.8	17	12	4.5
18	40	125.4	20	51.4	3.48	Nov-02	97.9	7	49	131.3
10	61	42.5	20	56.1	0.69	Dec-02	97.4	6	70	43.6
23	30	22.5	20	56.1	0.74	Nov-02	97.5	16	25	16.1
19	35	71.2	20	48.5	1.86	Nov-02	98.6	9	25	41.0
21	26	4.2	20	55.5	0.15	Dec-01	99.3	7	17	1.8
10	65	26.4	20	58.1	0.39	Dec-02	97.8	3	119	39.9
12	54	29.7	20	56.7	0.53	Dec-02	97.9	3	114	51.0
9	72	114.2	20	54.4	1.54	Dec-02	97.8	3	1,173	152.4
1	3	2.6	10	40.8	1.19	Feb-02	98.5	20	12	16.0
7	47	64.2	12	60.3	1.82	Mar-02	97.8	8	44	61.1
16	42	85.3	20	53.8	2.14	Dec-02	97.9	6	56	95.9
5	18.4	7.4	4	57.6	1.06	Oct-02	95.4	33	22.2	18.6

Table 7. Firm yields and reliability of reservoirs in Massachusetts calculated using three major droughts in the historical record.—Continued

[Dates are in months and years from 1964 to 2002; Mgal/d, million gallons per day]

		1960s drought					1980s drought				
	Storage ratio	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Reliability (percent)
Mare Meadow Reservoir	1.36	36	67.4	2.68	Dec-66	23	26.9	3.70	Mar-89	97.1
Meetinghouse Reservoir	0.97	36	68.3	1.12	Dec-66	23	28.2	1.78	Mar-89	95.6
Middle Reservoir	1.15	47	70.0	0.15	Jan-67	14	39.2	0.28	Aug-89	96.4
Millham Reservoir	0.20	36	61.8	1.79	Nov-65	16	44.3	2.47	Feb-81	97.7
Montgomery Reservoir	0.18	38	59.6	1.13	Feb-66	8	69.2	1.35	Feb-81	99.0
Morse Reservoir	0.29	36	70.1	0.17	Feb-66	11	26.1	0.28	Feb-81	96.4
North Reservoir	0.98	47	66.9	0.39	Jan-67	14	36.4	0.65	Sep-89	96.4
Notown Reservoir	0.37	36	64.9	2.13	Feb-66	17	40.3	3.11	Feb-81	97.9
Pine Hill Reservoir	1.00	36	64.4	5.52	Nov-66	23	24.7	7.86	Mar-89	95.9
Quinapoxet Reservoir	0.13	36	60.2	4.21	Nov-64	16	42.2	4.88	Nov-80	99.8
Roaring Brook Dam	0.09	59	57.8	0.98	Dec-64	8	78.6	1.23	Nov-80	99.4
Sandra Pond	0.28	38	63.9	0.80	Dec-66	15	36.4	1.21	Nov-81	95.7
Sandwash Reservoir	0.28	36	69.6	0.89	Feb-66	24	36.8	1.31	Feb-81	97.6
Schoolhouse Reservoir	0.08	36	68.7	0.84	Dec-64	22	36.8	1.11	Feb-81	99.4
Scott Reservoir	0.47	48	70.8	0.40	Feb-66	15	63.5	0.61	Nov-85	97.5
Simonds Pond	0.17	36	72.4	0.07	Feb-65	11	28.9	0.08	Feb-81	99.0
Swan Pond	0.38	38	64.1	0.44	Nov-65	15	61.1	0.53	Nov-85	99.7
Upper (Leahey) Reservoir	0.97	36	72.3	0.59	Dec-66	23	36.0	0.88	Mar-89	97.1
Upper Naukeag Lake	1.43	46	73.1	1.72	Mar-67	9	21.1	2.71	Mar-89	91.7
Upper Sackett Reservoir	0.35	36	71.4	0.50	Sep-65	14	59.5	0.72	Sep-85	97.7
Wachusett Lake	0.55	36	66.3	1.08	Oct-66	23	27.2	1.69	Mar-89	96.6
Whately Reservoir	0.02	59	60.5	0.09	Nov-63	8	81.6	0.10	Oct-80	99.6

1980s drought			2002 drought								
Number of failure events	Average failure duration (days)	Average yield deficit during failure (Mgal/d)	Drought length (months)	Drought intensity (percent below average streamflow)	Firm yield (Mgal/d)	Date of maximum storage depletion	Reliability (percent)	Number of failure events	Average failure duration (days)	Average yield deficit during failure (Mgal/d)
19	24	127.6	20	50.3	3.21	Dec-02	99.0	8	21	88.4
31	22.7	39.7	20	51.1	1.52	Nov-02	98.3	15	17.7	26.9
9	64.6	15.7	10	62.4	0.27	Dec-02	97.1	5	93.4	22.2
17	21.4	32.3	10	54.8	2.43	Nov-02	98.0	14	22.9	34.8
6	26.8	23.3	10	44.9	1.49	Feb-02	98.4	8	32.5	34.7
24	23.8	4.6	20	52.4	0.24	Nov-02	98.0	14	22.5	3.7
18	32.6	19.3	12	30.3	0.62	Dec-02	97.2	11	40.3	23.1
13	26.1	61.6	20	47.4	2.95	Nov-02	98.4	10	25.8	57.8
21	31.4	226.3	20	47.3	6.91	Nov-02	98.5	8	29.4	172.7
3	13.3	94.8	19	45.8	5.04	Nov-01	99.6	4	16.3	116.1
10	10.5	8.7	10	56.9	1.39	Dec-01	98.3	18	15.3	15.9
12	57.8	56.4	20	53.3	1.04	Dec-02	97.6	4	95.8	75.3
13	29.2	26.9	23	56.1	1.19	Nov-02	98.6	6	36.3	30.4
10	9.5	6.0	23	54.9	1.12	Feb-02	99.3	11	10.3	6.4
4	102.0	51.4	12	61.9	0.63	Dec-02	97.3	5	87.8	45.6
9	17.4	0.9	20	54.6	0.09	Feb-02	98.4	9	29.4	2.0
5	9.2	20.3	12	59.1	0.51	Nov-01	99.8	2	16.0	35.9
11	42.1	38.7	25	53.9	0.78	Dec-02	98.4	8	32.5	24.4
89	14.9	33.9	12	51.2	2.40	Feb-03	97.0	37	13.2	27.4
11	34.1	22.4	24	54.0	0.63	Oct-02	98.7	8	26.0	14.8
24	22.9	35.3	20	48.9	1.44	Nov-02	98.2	18	16.2	19.6
5	13.0	0.9	10	59.4	0.15	Nov-01	97.6	22	17.6	2.3

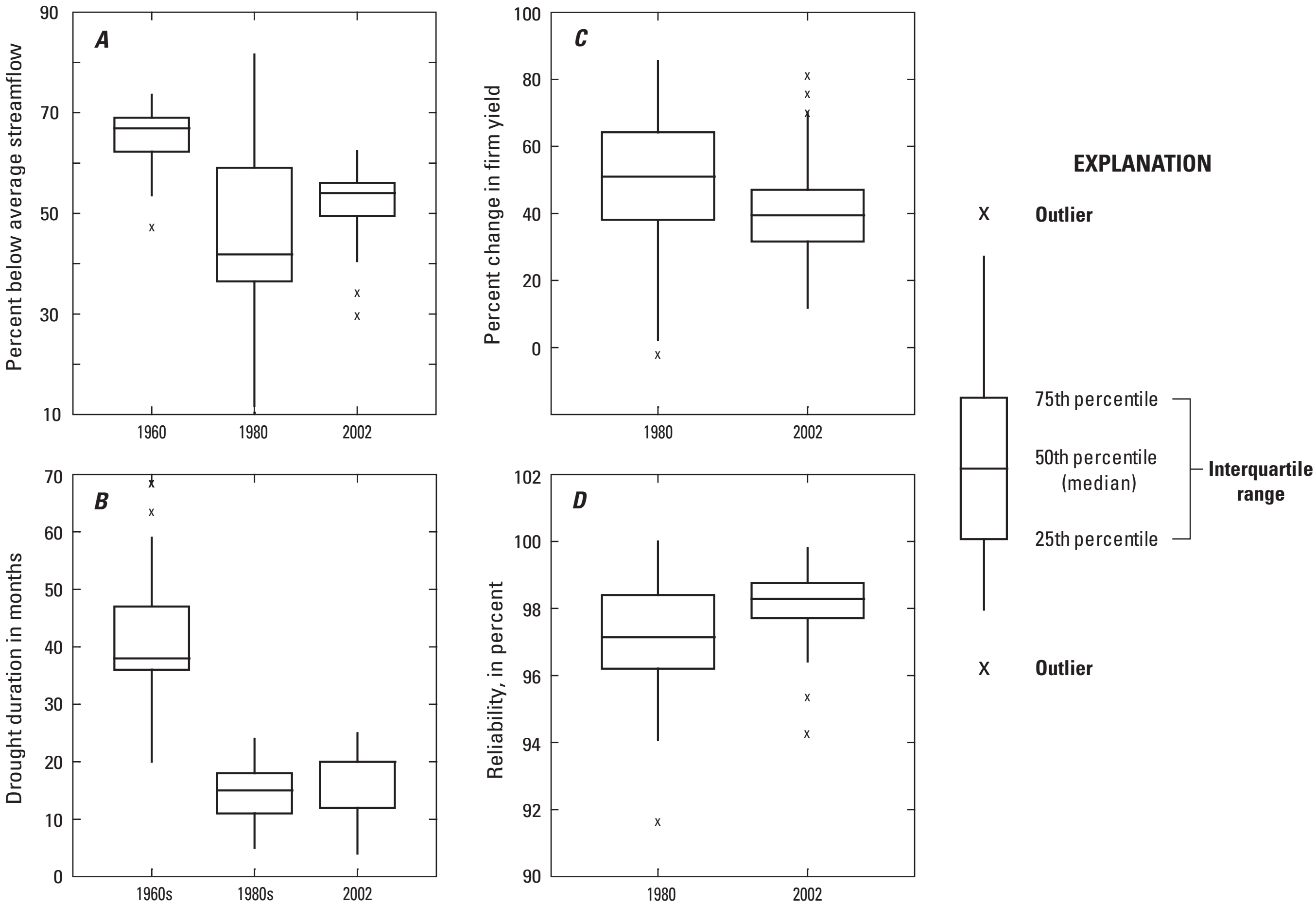


Figure 10. *A*, Percent below average streamflow and *B*, duration of droughts of the 1960s, 1980s, and 2002. *C*, Percent change in firm yield and *D*, reliability of firm yields when calculated with the droughts of the 1980s or 2002.

more intense during the drought period. Drought durations for both the 1980s and 2002 droughts ranged from 4 to 25 months. Reservoirs underwent a wide range of drought intensities in the 1980s with average streamflows 12 to 82 percent below normal levels. Some reservoirs underwent two separate droughts in the 1980s, one at the beginning of the decade and one at the end. For the purposes of this study, the most severe of the two 1980s droughts was used. Streamflows were -30 to 62 percent below average levels during the 2002 drought.

The sensitivity of reservoir firm yield to drought severity was examined by calculating the firm yield using three different drought periods: 1960s, 1980s and 2001–2002 droughts. In order to calculate the firm yield using a drought from the 1980s or 2002, the FYE model was modified to consider only failures during the drought in question when calculating the firm yield. Reservoir failures that occurred either before or after the drought being studied were ignored by the model, and the firm yield was incremented until a failure occurred during the drought in question. This method produces results identical to the results of a simulation performed with a truncated historical record, as long as the reservoir returns to full pool before the drought period of interest. Reservoirs that did not return to full pool from one drought to the next were removed from the analysis. All reservoirs were run as single-reservoir systems for the purpose of this analysis.

For most reservoirs, the drought of the 1960s was the most severe and resulted in the lowest firm-yield estimate. Accord Pond in Hingham, Mass., was the only exception. For this reservoir, the firm yield estimated for a drought in 1981 was slightly lower than the yield estimated for the 1960s drought. Overall, firm yields exceeded those during the 1960s drought by an average of 49 percent for the drought in the 1980s and 41 percent for the drought of 2001–2002. Individual reservoirs responded differently to these two droughts. Approximately three quarters of the reservoirs underwent more severe conditions during the 2001–2002 drought than in the drought of the 1980s, leading to lower firm-yield estimates for the 2001–2002 drought than for the 1980s drought.

Reservoirs operating at a firm yield computed for a less severe drought run the risk of failure should a more severe drought occur. The risk of failure for a particular reservoir can be characterized by the reservoir's reliability, resilience, and vulnerability. For each day of the simulated record, the reservoir state was classified as being either a failure or not. Reliability is the percentage of days in which the reservoir did not fail throughout the entire simulation. The reliability reflects the overall failure rate for the entire simulation period. For a given reliability, failures may occur in several long-duration events or many short-duration events. A failure event is the period of consecutive days a reservoir is in a failing state. The resilience of a reservoir and is defined as the average of the durations of all the failure events during the simulation. Reservoirs that recover quickly after a failure are more resilient and will have a shorter average failure duration. The magnitude of a failure is characterized by the yield deficit, which is the difference between the daily water demand and the daily amount that the reservoir is able to supply during a failure event.

In order to investigate the risk and magnitude of potential failures due to operating at a firm yield calculated for a drought other than the 1960s drought, the water-balance equation was solved using the estimated firm yields for the 1980s and 2002 droughts for each reservoir and allowing the reservoir to fail during other time periods in the simulation. These simulations were used to calculate reservoir reliability, average failure duration, and average yield deficit. Average reliabilities of reservoirs operating at the 1980s and 2002 firm yields were 97 and 98 percent, respectively (fig. 10). Average failure durations across reservoirs ranged from several days to several months. This information is useful for gaging the risk of failure should a drought more severe than any on record occur.

Effect of Controlled Releases and Demand Management on Firm Yield

Reservoirs that are managed solely to maintain storage and meet human water demand can affect downstream areas by depleting the amount of water available for ecological communities and disrupting natural streamflow patterns. When a river is impounded to create a drinking-water reservoir, water that would have flowed downstream is allocated to fill the reservoir or used to supply drinking water. During periods in which the reservoir is at full storage, any inflows that exceed water demand and natural reservoir outflows will spill to the downstream reach. During periods in which the reservoir water surface is below the spillway, downstream reaches will not receive any water.

Several recent studies have highlighted the effects of impoundments on Massachusetts streams and fish communities (Weiskel and others, 2010; Armstrong and others, 2010), and more consideration is being given to the environmental needs in the river reach downstream from a reservoir impoundment. One approach to mitigate the effects of impoundments on downstream reaches is to implement controlled releases from the reservoir into the stream either by manipulating spillway boards or through a release valve. Such releases would necessarily decrease the firm yield of a reservoir because they would increase the daily reservoir outflows, causing less water to be available for withdrawals. For reservoirs operating near their firm yield, meeting environmental flow requirements during a drought period could jeopardize the ability of the reservoir to meet drinking-water demands.

The effects of imposing instream-flow requirements may potentially be offset by implementing several management strategies. Water demand in Massachusetts typically peaks during summer months when water availability is the lowest. Reservoir storage may become depleted during these periods, leaving little or no water available for environmental flow releases. Demand-management scenarios such as nonessential summer water-use restrictions may help to lower water demand during these periods, allowing more water to be available for environmental flows. Another potential management strategy is to relax the definition of firm yield to allow reservoir operation at less than 100 percent reliability. Although this may put the reservoir at risk of occasional failure during severe droughts, this strategy may be feasible in towns that have emergency water sources or that can import water from other systems. Understanding the effects of management scenarios and controlled releases on firm yield is necessary for water-supply managers and regulators to evaluate the risks and tradeoffs between allocations of water for human versus environmental needs.

Controlled-Release Scenarios

The FYE can account for user-specified monthly release rates for downstream environmental flows. The choice of an appropriate controlled-release scenario for any particular reservoir in Massachusetts is an area of ongoing research. For illustrative purposes in this report, two hypothetical reservoir release scenarios were developed to test the effects of controlled releases on reservoir firm yield. For each month, a flow-duration curve was developed from the 44-year daily streamflow record. Monthly controlled releases for the two scenarios were set at the 10th- and 25th-percentile monthly flow volumes (appendix 4). For multiple-reservoir systems, reservoir releases were implemented at each reservoir in the system based on the respective streamflows estimated for each individual reservoir. Firm yields were calculated for each of the two controlled-release scenarios and compared with reported usage data from 2000 to 2004 (table 8). For the purposes of this study, all reservoirs were considered capable of releasing water downstream. This may not be possible in all systems because reservoirs may not have a release structure installed for this purpose.

Table 8. Water usage and firm yields for reservoir systems in Massachusetts under various controlled-release, demand-management,

[Mgal/d, million gallons per day; %, percent; DPW, Department of Public Works]

			Scenarios with no controlled releases			
Water supplier	**Reservoir system**	**Average annual usage 2000–2004 (Mgal/d)**	**Firm yield with no-fail criteria and no demand management (Mgal/d)**	**Firm yield with no-fail criteria and demand management (Mgal/d)**	**Firm yield with 1% failure criteria, no demand management (Mgal/d)**	**Firm yield with 1% failure criteria and demand management (Mgal/d)**
Amherst Water Department	Amethyst Brook Intake system	**0.83**	0.87	0.93	1.19	1.36
Amherst Water Department	Atkins Reservoir	**0.83**	1.16	1.23	1.25	1.40
Ashburnham/Winchendon	Upper Naukeag Lake	**1.06**	1.72	1.81	1.88	1.98
Concord Water Department	Nagog Pond	**0.09**	0.86	1.02	0.96	1.27
Danvers Water Department	Middleton Pond system	**3.09**	2.79	3.06	3.14	3.40
Fall River Water Department	North Watuppa system	**12.89**	18.20	19.05	20.01	20.69
Fitchburg Water Department	Lovell Reservoir system	**0.18**	2.77	2.89	3.20	3.43
Fitchburg Water Department	Meetinghouse system	**2.71**	5.61	6.33	6.30	6.63
Fitchburg Water Department	Wachusett Lake	**0.35**	1.08	1.18	1.24	1.36
Greenfield Water Department	Green River	**0.52**	0.42	0.42	1.49	1.49
Greenfield Water Department	Leyden Glen Reservoir	**0.57**	0.69	0.69	1.12	1.17
Hingham/Hull (Aquarian Water Company)	Accord Pond	**0.59**	0.66	0.77	0.75	0.87
Hinsdale Water Department	Belmont Reservoir	**0.15**	0.12	0.13	0.15	0.16
Lee Water Department	Schoolhouse Reservoir	**0.51**	0.84	0.89	1.14	1.23
Lee Water Department	Upper (Leahey) Reservoir	**0.54**	0.59	0.64	0.67	0.73
Leicester (Cherry Valley and Rochdale Water)	Henshaw Pond	**0.26**	0.35	0.36	0.43	0.46
Leominster DPW–Water Division	Distributing Reservoir system	**0.87**	0.58	0.66	0.66	0.78
Leominster DPW–Water Division	Fall Brook Reservoir	**0.88**	0.84	0.90	0.98	1.10
Leominster DPW–Water Division	Simonds Pond system	**2.32**	2.26	2.43	2.77	2.99
Lincoln Water Department	Flints Pond	**0.38**	0.59	0.64	0.68	0.73
Marlborough DPW–Water and Sewer Division	Millham system	**1.40**	1.83	1.99	2.15	2.32
Milford Water Company	Echo Lake	**1.40**	1.12	1.20	1.42	1.42
North Brookfield Water Department	Doane Pond system	**0.42**	0.71	0.74	0.80	0.86
Pittsfield Water Department	Ashley Lake	**0.21**	1.37	1.41	1.82	1.90
Pittsfield Water Department	Cleveland Reservoir	**7.96**	9.18	9.47	10.53	11.17
Pittsfield Water Department	Farnham system	**2.23**	2.51	2.66	2.98	3.21
Pittsfield Water Department	Upper Sackett Reservoir	**0.08**	0.50	0.55	0.58	0.64
Scituate Water Department	Main Reservoir	**0.61**	0.63	0.70	0.81	0.94
South Deerfield Water Supply District	Whately system	**0.68**	1.07	1.11	1.09	1.26
Southbridge Water Department	Hatchet Brook system	**1.69**	2.78	2.87	3.28	3.57
Springfield Water Department	Cobble Mountain system	**36.57**	42.70	45.14	45.42	48.83
Wakefield Water Department	Crystal Lake	**0.28**	0.40	0.44	0.47	0.51
West Springfield Water Department	Bearhole Reservoir	**0.73**	1.40	1.53	1.72	1.99
Westborough Water Department	Sandra Pond	**0.67**	0.80	0.86	0.89	0.95
Westfield Water Department	Granville Reservoir	**2.47**	3.03	3.18	3.66	3.95
Westfield Water Department	Montgomery Reservoir	**0.00**	1.13	1.17	1.35	1.43
Winchester Water Department	South Reservoir system	**1.10**	1.01	1.07	1.11	1.20
Worcester Water Department	Holden Pond system	**23.87**	17.15	17.64	18.87	20.38

and reliability scenarios.

Scenarios with 10th-percentile monthly flow releases				Scenarios with 25th-percentile monthly flow releases			
Firm yield with no-fail criteria and no demand management (Mgal/d)	Firm yield with no-fail criteria and demand management (Mgal/d)	Firm yield with 1% failure criteria, no demand management (Mgal/d)	Firm yield with 1% failure criteria and demand management (Mgal/d)	Firm yield with no-fail criteria and no demand management (Mgal/d)	Firm yield with no-fail criteria and demand management (Mgal/d)	Firm yield with 1% failure criteria, no demand management (Mgal/d)	Firm yield with 1% failure criteria and demand management (Mgal/d)
0.34	0.46	0.71	1.01	0.56	0.79	0.63	0.86
0.81	0.86	0.90	0.99	0.60	0.63	0.68	0.75
1.44	1.52	1.58	1.66	1.22	1.29	1.35	1.42
0.71	0.84	0.79	1.02	0.62	0.73	0.68	0.85
2.01	2.18	2.21	2.39	1.41	1.53	1.57	1.70
13.39	14.01	14.78	15.27	10.80	11.30	11.93	12.37
2.12	2.21	2.49	2.66	1.64	1.71	2.03	2.17
4.32	4.79	4.83	5.21	3.54	3.89	4.02	4.35
0.77	0.85	0.91	1.00	0.61	0.67	0.73	0.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.21	0.21	0.45	0.48	0.00	0.00	0.00	0.00
0.50	0.57	0.59	0.67	0.40	0.45	0.47	0.53
0.06	0.06	0.08	0.08	0.02	0.02	0.04	0.04
0.43	0.45	0.62	0.66	0.17	0.17	0.25	0.27
0.47	0.52	0.56	0.60	0.41	0.45	0.49	0.53
0.19	0.19	0.24	0.27	0.08	0.12	0.15	0.17
0.37	0.44	0.47	0.55	0.27	0.29	0.36	0.40
0.61	0.65	0.71	0.81	0.46	0.49	0.55	0.62
1.60	1.72	1.64	1.92	1.21	1.31	1.25	1.53
0.45	0.49	0.52	0.56	0.36	0.39	0.42	0.45
1.06	1.14	1.25	1.35	0.60	0.64	0.79	0.85
0.90	0.96	1.05	1.16	0.72	0.77	0.85	0.94
0.55	0.57	0.63	0.68	0.45	0.47	0.52	0.56
0.89	0.92	1.25	1.35	0.61	0.63	0.90	0.98
5.99	6.30	7.22	7.74	4.15	4.35	5.34	5.75
1.92	2.03	2.20	2.38	1.60	1.69	1.87	2.03
0.34	0.37	0.39	0.44	0.24	0.26	0.28	0.32
0.13	0.13	0.51	0.61	0.00	0.00	0.12	0.14
0.80	0.89	0.83	1.04	0.41	0.50	0.45	0.55
2.31	2.38	2.76	2.97	2.00	2.05	2.33	2.46
33.01	34.80	35.54	37.97	27.36	28.74	29.55	31.21
0.24	0.27	0.29	0.32	0.14	0.16	0.17	0.19
0.78	0.87	0.94	1.05	0.00	0.00	0.21	0.25
0.55	0.59	0.62	0.66	0.37	0.40	0.42	0.46
1.79	1.87	2.35	2.55	0.91	0.96	1.48	1.59
0.60	0.63	0.80	0.89	0.24	0.24	0.43	0.49
0.82	0.86	0.91	0.98	0.70	0.74	0.75	0.82
11.34	11.74	12.37	13.61	3.57	9.20	9.82	10.66

Controlled releases for the two scenarios lowered firm yields by an average of 35 percent for the 10th-percentile flow-release scenario and 55 percent for the 25th-percentile flow-release scenario. Of the 38 systems studied, 16 were able to meet or marginally meet their current (2000 to 2005) usage requirements while releasing monthly 10th-percentile flows, and 11 were able to meet or marginally meet their current usage while releasing 25th-percentile flows. Because year-to-year usage in a system can vary, systems in which average usage was within 10 percent of the firm yield of a particular scenario may be operating within the firm yield in some years but above the firm yield in other years. These reservoirs are listed as marginally operating within the firm yield (table 8).

Summer Water-Demand Management

Outdoor summer water-use restrictions are often implemented by water-resources managers as a way to conserve water during drought periods. Water usage peaks during summer months due to outdoor water use, such as irrigation, residential-lawn watering, or filling of swimming pools. Outdoor summer water-use restrictions decrease the summer water demand and often go into effect when a reservoir falls below a certain level. Demand-reduction scenarios can be implemented in several stages as the reservoir falls to successively lower levels. The firm-yield-model code was altered to allow the user to specify a summer water-use-restriction scenario. This type of demand-management scenario can be specified by the user as a percentage by which to decrease demand during summer months (June–September) when the reservoir falls below a user-specified percentage of its total capacity. If reservoir storage falls below the percentage of total capacity specified in the demand-management scenario on any simulation day, and the simulation is in a summer month, the yield, Q_y, for that day is decreased by the percentage specified by the user. Simulation then continues as usual. When a multiple-reservoir system is simulated, the demand-management scenario is applied to all reservoirs in the system.

The amount of summer water-demand reductions that can be achieved by summer outdoor water restrictions is highly variable and depends on many factors such as climate, land use, and population density. Further study is needed to determine appropriate demand-reduction strategies for Massachusetts reservoirs. For illustrative purposes in this report, the effect of implementing one hypothetical demand-management scenario was examined for the reservoir systems in this study. The demand-management scenario specified

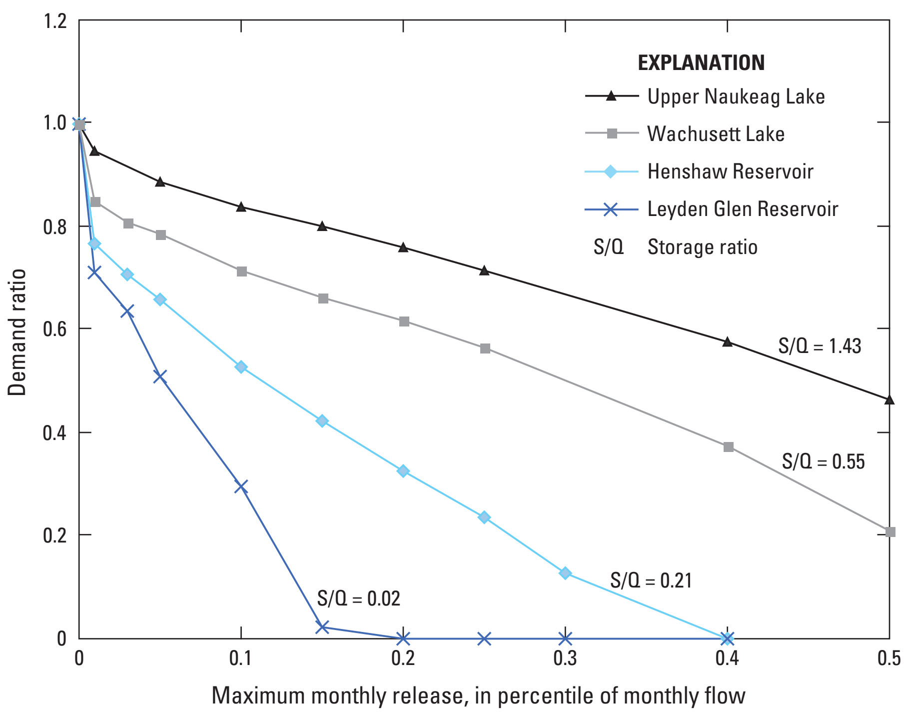


Figure 11. Maximum monthly releases as a percentile of long-term monthly flows that is possible at various demand ratios for four reservoirs of increasing storage ratio.

a 15-percent demand reduction when the reservoir fell to 60 percent of its maximum capacity, a 25-percent demand reduction when the reservoir fell to 40 percent of its maximum capacity, and a 35-percent demand reduction when the reservoir fell to 20 percent of its total capacity. Reducing summer demand in this way increased firm yields by an average of 7 percent. By implementing this demand-reduction scenario, two of the six systems that are currently operating above the estimated firm yield were able to marginally meet demand requirements. In addition, this demand scenario enabled one additional reservoir system to support 25th-percentile flow releases and four additional systems to support 10th-percentile flow releases (table 8).

The amount of water available for downstream flow releases depends on the water demands of the reservoir and the storage ratio. The demand ratio is defined as the annual average water demand divided by the firm yield of the reservoir. For a given controlled-release rate, the maximum demand ratio possible for a reservoir may be calculated by dividing the firm yield calculated with controlled releases by the firm yield without releases. Reservoirs that are operating at or near their firm yield will have demand ratios close to 1. These reservoirs have less water available for downstream flow releases because most of the available water in storage is being allocated to human use. Reservoirs with low storage ratios are also less able to support high levels of controlled releases. Reservoirs with low storage in relation to their average daily streamflow are more susceptible to variability in daily streamflow and have proportionally less water available in storage during even minor periods of low flow. The maximum controlled releases (as percentiles of long-term monthly flows) that are possible at various demand ratios for selected reservoirs with increasing storage capacity are shown in figure 11.

Reducing Reservoir Reliability Requirements

Reservoir reliability is set by the user by specifying the maximum number of days during the simulation when the reservoir is allowed to fail. Reliability is calculated as the percentage of days when the reservoir did not fail during the simulation. In order to run the FYE at a reliability of less than 100 percent, the model code was modified to allow the simulation to run through a failing state. When calculating the daily water balance, the model will first solve the water-balance equation without allocating for yield. If reservoir storage at this point is sufficiently high to fully satisfy daily demand, then the usage term is subtracted, and simulation continues as normal. If the usable storage at this point is not sufficient to satisfy daily demand, then all the available water in storage is allocated to yield, bringing available storage to zero. The reservoir is considered to be failing in this situation because the amount of water supplied by the reservoir is less than the full demand volume. After the full 44-year simulation is completed, the number of failure days is totaled. Yield is incrementally increased until the number of days of reservoir failures equals the amount specified by the user. The failures may occur in many short-duration events or a small number of long-duration events. The total number of failure events and the average duration of failure periods are reported for each reservoir simulation. In addition, the FYE also calculates and reports the average yield deficit. These failure statistics can help water managers gage the risks and potential costs of employing a strategy that includes relaxing the no-fail operating criterion of a reservoir. For multiple-reservoir systems, the reliability set by the user is applied to all reservoirs in the system.

In order to examine the effect of relaxing the no-fail criterion, simulations of the reservoir systems in this study were run using a 99-percent reliability criterion (fig. 12). This criterion allows for a total of 160 allowable failures during the 44-year simulation period. Relaxing the reliability criterion increased yields by an average of 25 percent. Under this scenario, estimated yields are sufficient to meet demand at all but three systems in the study. In addition, relaxing the reliability criterion enables two additional systems to support 25th-percentile flow releases and nine additional systems to support 10th-percentile flow releases; these systems could not otherwise support releases under the no-fail scenario.

Tradeoffs Between Demand Management, Controlled Releases, and Reliability

Implementing downstream release flows, implementing demand-management strategies, or operating the reservoir at a lower reliability all have risks and benefits associated with them. In determining the best possible strategy for any given reservoir system, a water manager may use any combination of these three strategies in order to maximize the reservoir yield at the lowest cost. Tradeoff curves can be constructed to examine the effect of different strategies on the firm yield. For a given reservoir, a family of tradeoff curves can be constructed showing the different combinations of controlled releases, reliability criteria, and demand-management strategies that can be used to achieve a target yield. Sample tradeoff curves for Upper Leahey Reservoir are shown in figure 13. On the basis of reported water usage for 2000–2004, Upper Leahey would be able to support only very minimal environmental flow releases without implementing some sort of demand-management strategy. In order to achieve controlled releases at the 10th percentile of monthly flows, a more severe outdoor summer water-use restriction scenario would need to be implemented than the one tested here.

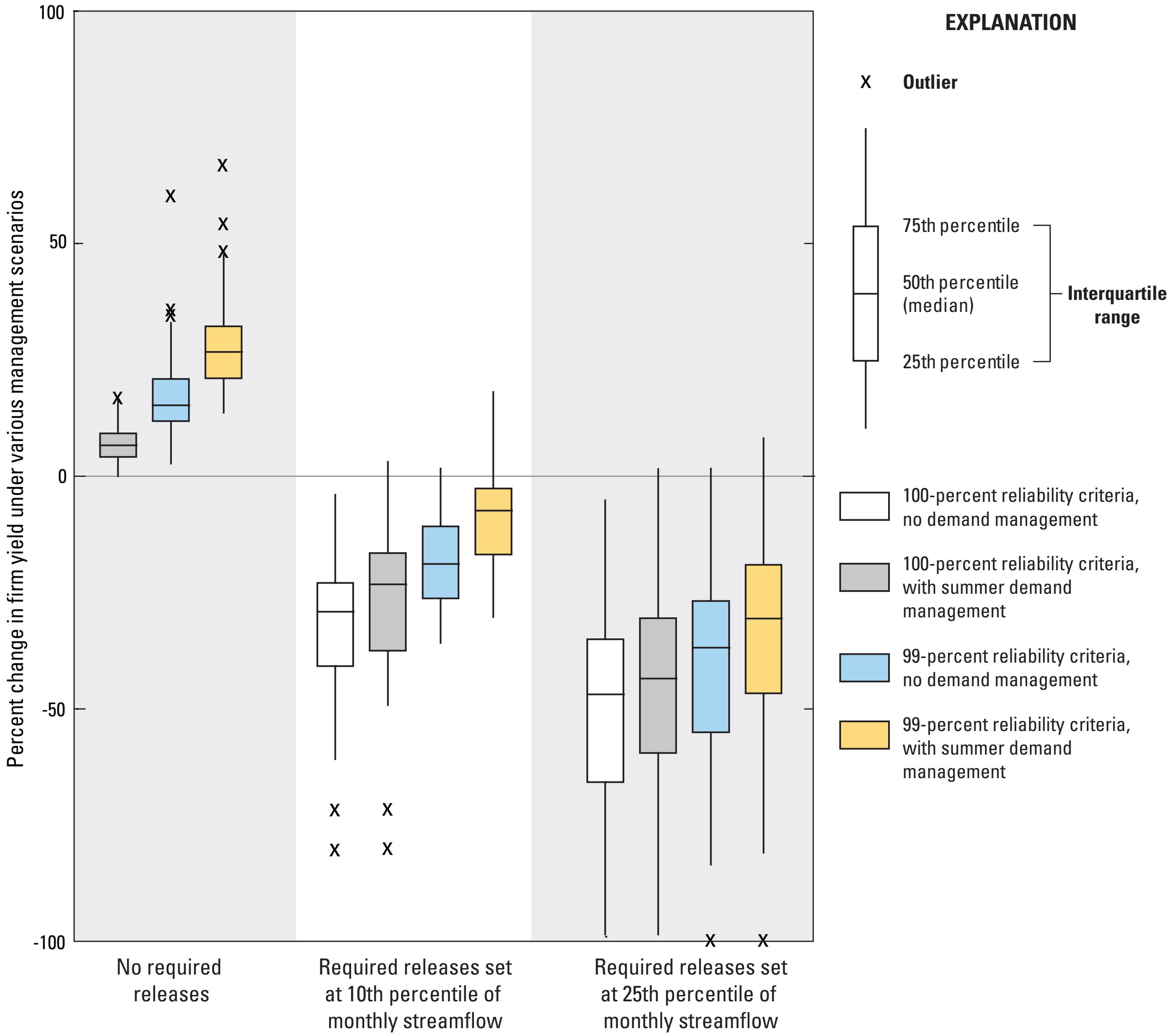


Figure 12. Percent changes of firm yield for Massachusetts reservoirs under various management scenarios.

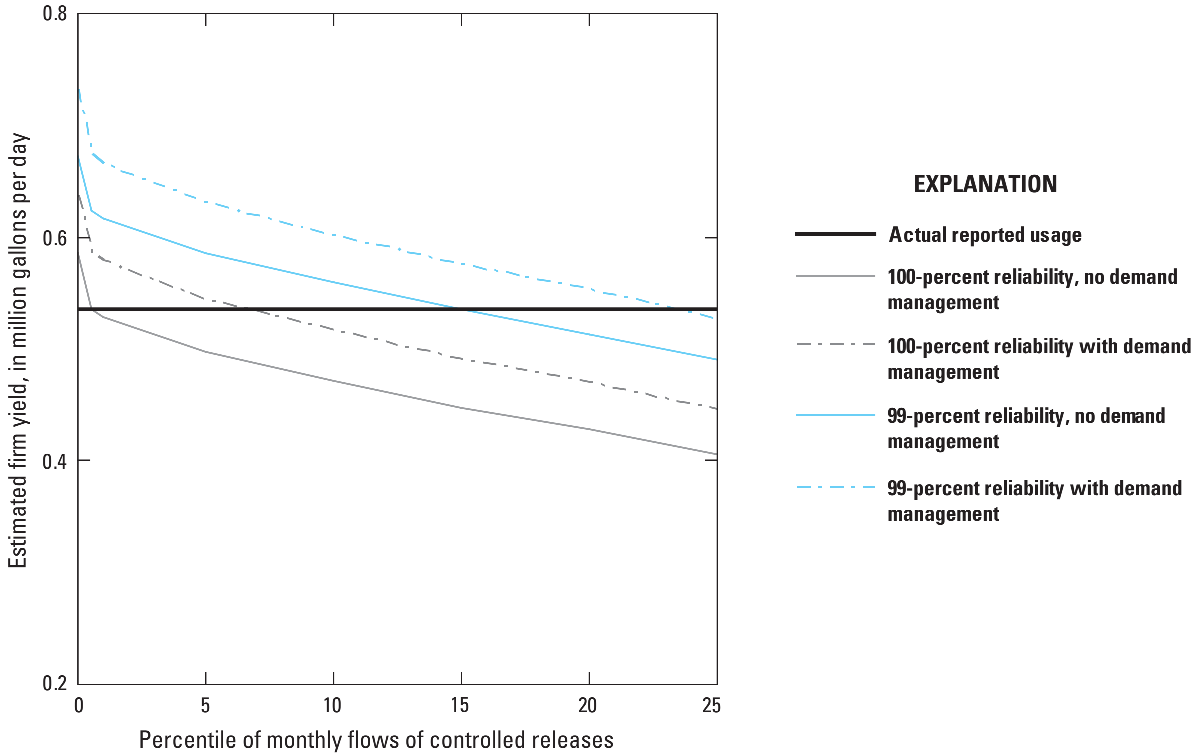


Figure 13. Tradeoff curves depicting the estimated yield in relation to controlled releases under various management scenarios for Upper Leahy Reservoir, in Lee, Massachusetts.

Summary and Conclusions

Procedures for determining the firm yield of a reservoir, which were previously developed, were further refined and implemented for 38 reservoir systems in Massachusetts, including 25 single- and multiple-reservoir systems that were examined in previous studies and 13 additional reservoir systems. Changes to the Firm-Yield Estimator (FYE) model include simulation of the 44-year historical record by daily time steps; the incorporation of daily input data for streamflow, precipitation, and evaporation; refinements to the groundwater simulation; and enhanced scenario-testing capabilities. This study documents the procedural refinements to the model, examines sources of uncertainty in the estimated firm yields, and demonstrates the use of the model to assess the feasibility of controlled releases under several example management scenarios. Because of these refinements, estimates of firm yield based on previous versions of the FYE are no longer considered valid.

Uncertainty in the FYE model comes from many sources, including errors in the input data for streamflow, precipitation, evaporation, and stage-storage relations. Reservoirs that overlie substantial sand and gravel deposits have additional uncertainty in firm-yield estimates because of uncertainty in estimating groundwater inflows and outflows to the reservoir. In addition, uncertainty in firm-yield estimates may arise from other factors, such as seepage or reservoir-operation details, that are not accounted for in the FYE. An analytical method to estimate overall uncertainty in the FYE model was not determined; however, the sensitivity of the model to errors in daily streamflow and stage-storage relations was examined. Because the lowest streamflows may be underestimated by the SYE, firm yields estimated by the FYE may be conservative. A Monte Carlo simulation showed that, on average, firm yields increased 1 to 10 percent after accounting for errors in daily streamflows. Errors in firm yields can also arise from errors in the stage-storage and volume calculations as a result of spatially imprecise bathymetric data. Experiments on three reservoirs showed that bathymetric data that are sampled too sparsely can result in an underestimation of reservoir volume and firm yield. Bathymetric surveys with measurement densities of less than 20 points per acre or transects spaced more than 30 to 60 meters apart resulted in underestimation of reservoir volume and firm-yield estimates by 5 percent or more.

Reservoirs in contact with sand and gravel may receive water flows from and may discharge to groundwater sources. In a previous study, equations were developed and implemented to estimate the magnitude of groundwater contributions to the reservoir water balance on the basis of changes in reservoir storage at each time step. The parameterization of these equations was refined in this study in order to allow the scaling factor to be adjusted on the basis of the changing reservoir stage. This eliminated instabilities in the groundwater-equation algorithm that arose during low-storage periods. Validation of the groundwater parameters at one reservoir indicated that parameter estimation from published maps is highly uncertain.

Firm yields estimated using the historical record are sensitive to the severity of droughts during the simulation periods. For this study, a 44-year historical record, which includes the most severe drought on record, was used for firm-yield estimation. Firm yields based on this drought may not be adequate to protect against failures should a more severe drought occur in the future. The sensitivity of firm yields to drought severity was examined by estimating firm yields based on three droughts during the simulation period. Firm yields based on droughts in the 1980s and 2002 exceeded those during the 1960s drought by an average of 49 and 41 percent, respectively; however, operating reservoirs at these yields led to average failure rates of 2 to 3 percent when applied over the entire simulation period.

Because of concern over water availability for ecological needs in Massachusetts streams, regulators may wish to examine the effects of regular releases from drinking-water reservoirs to enhance instream flow downstream from impoundments. An analysis of two controlled-release scenarios showed that reservoirs with a large storage ratio (reservoir capacity divided by mean streamflow) and low demand ratio (average annual water demand as a percentage of the annual firm yield) were able to support the highest levels of flow releases without sacrificing yield for human use. Roughly half the reservoir systems studied were able to support minimal monthly flow releases equal to the monthly 10th-percentile daily flow. Reservoirs can increase their daily yield by implementing summer water-use restrictions or by relaxing the no-fail criterion of the firm yield. One scenario involving hypothetical summer water-use restrictions and another involving a 1-percent failure criterion were tested. The scenario with summer water-use restrictions that was tested led to an average increase of 7 percent in the firm yield, which was generally not sufficient to enable controlled releases from a reservoir that was otherwise unable to support them. Relaxing the reservoir reliability to 99 percent led to an average increase of 25 percent in reservoir firm yield but also left the reservoir vulnerable to failures. Reservoir operators can weigh the relative risks and benefits of various management strategies using tradeoff curves and statistics for failure magnitude and duration.

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Appendix 1. Hypsographic Data

Tables of reservoir storage, surface area, stage, and length of reservoir perimeter in contact with sand and gravel for each reservoir included in this report that were not included in previous firm-yield reports are located on the CD–ROM in the folder titled HypsographicData.

CD–ROM

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Contents

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Appendix 2. Bathymetric Maps

Bathymetric maps of all reservoirs included in this report that were not included in previous firm-yield reports are located on the CD–ROM in the folder titled BathymetricMaps.

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Appendix 3. Reservoir-System Diagrams

Schematic diagrams of all reservoir systems included in this report that were not included in previous firm-yield reports are located on the CD–ROM in the folder titled SystemDiagrams.

CD–ROM

[In pocket]

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Kettle Brook Reservoir #1
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Scituate Water Department
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Concord Water Department
North Watuppa Reservoir
Fall River Water Department
Pine Hill Reservoir
Worcester Water Department
Quinapoxet Reservoir
Worcester Water Department
Sandra Pond
Westborough Water Department
Upper Naukeag Lake
Ashburnham/Winchendon Joint Water Board

Appendix 4. Monthly Percentile Streamflows

Tables of monthly 10th and 25th percentile reservoir inflows that were used for management scenarios in this report are located on the CD–ROM in the folder titled Monthly Flow Tables.

CD–ROM

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Tables

Monthly 10th Percentile of Streamflows Estimated Using the Sustainable Yield Estimator for Reservoirs in Massachusetts, 1960–2004

Monthly 25th Percentile of Streamflows Estimated Using the Sustainable Yield Estimator for Reservoirs in Massachusetts, 1960–2004

Prepared by the Pembroke Publishing Service Center.

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Levin and others—**Refinement and Evaluation of the Massachusetts Firm-Yield Estimator Model Version 2.0**—Scientific Investigations Report 2011–5125

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