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Simulation of Reservoir Storage and Firm Yields of Three Surface-Water Supplies, Ipswich River Basin, Massachusetts

Water-Resources Investigations Report 02-4278

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

Cover photos: Low water levels following the 2002 spring drought in the Putnamville Reservoir (left) and Wenham Lake (right), Salem–Beverly Water Supply Board System.

Courtesy of: Richard Tomczyk, Ipswich River and Parker River Watersheds Team Leader, Massachusetts Executive Office of Environmental Affairs

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By PHILLIP J. ZARRIELLO

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MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION

Northborough, Massachusetts
2002

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
million gallons (Mgal)	133680	cubic feet
million gallons (Mgal)	3.0689	acre-feet
million gallons (Mgal)	3785.4	cubic meter
million gallons per day (Mgal/d)	1.54723	cubic feet per second
million gallons per year (Mgal/yr)	4.2362×10^{-3}	cubic feet per second
square mile (mi^2)	2.590	square kilometer

ABBREVIATIONS

HSPF	Hydrologic Simulation Program—FORTRAN
IFIM	Instream Flow Incremental Methodology
IRFRTG	Ipswich River Fisheries Restoration Task Group
MDEP	Massachusetts Department of Environmental Protection
MWRA	Massachusetts Water Resource Authority
SRIFIM	Saugus River Instream Flow Incremental Methodology

Simulation of Reservoir Storage and Firm Yields of Three Surface-Water Supplies, Ipswich River Basin, Massachusetts

By Phillip J. Zarriello

Abstract

A Hydrologic Simulation Program FORTRAN (HSPF) model previously developed for the Ipswich River Basin was modified to simulate the hydrologic response and firm yields of the water-supply systems of Lynn, Peabody, and Salem–Beverly. The updated model, expanded to include a portion of the Saugus River Basin that supplies water to Lynn, simulated reservoir system storage over a 35-year period (1961–95) under permitted withdrawals and hypothetical restrictions designed to maintain seasonally varied streamflow for aquatic habitat. A firm yield was calculated for each system and each withdrawal restriction by altering demands until the system failed. This is considered the maximum withdrawal rate that satisfies demands, but depletes reservoir storage.

Simulations indicate that, under the permitted withdrawals, Lynn and Salem–Beverly were able to meet demands and generally have their reservoir system recover to full capacity during most years; reservoir storage averaged 83 and 82 percent of capacity, respectively. The firm yields for the Lynn and Salem–Beverly systems were 11.4 and 12.2 million gallons per day (Mgal/d), respectively, or 8 and 21 percent more than average 1998–2000 demands, respectively. Under permitted withdrawals and average 1998–2000 demands, the Peabody system failed in all years; thus Peabody purchased water to meet demands. The firm yield for the Peabody system is 3.70 Mgal/d, or 37 percent less than the average 1998–2000 demand.

Simulations that limit withdrawals to levels recommended by the Ipswich River Fisheries Restoration Task Group (IRFRTG) indicate that under average 1998–2000 demands, reservoir storage was depleted in each of the three systems. Reservoir storage under average 1998–2000 demands and IRFRTG-recommended streamflow requirements averaged 15, 22, and 71 percent of capacity for the Lynn, Peabody, Salem–Beverly systems, respectively. The firm-yield estimates under the IRFRTG-recommended streamflow requirements were 6.02, 1.94, and 7.69 Mgal/d or 43, 64, and 34 percent less than the average 1998–2000 demands for the Lynn, Peabody, and Salem–Beverly systems, respectively. Simulations that limit withdrawals from the Saugus River to a less stringent set of restrictions (based on an Instream Flow Incremental Methodology study) than those previously simulated indicate that the firm yield of the Lynn system is about 31 percent less than the average 1998–2000 withdrawals (7.31 Mgal/d).

INTRODUCTION

The Commonwealth of Massachusetts requires water suppliers to calculate the maximum withdrawal rate that can be sustained under severe drought conditions to ensure that communities can meet current and future water-supply demands. This maximum withdrawal rate is referred to as the firm yield or safe yield of a supply system. The firm yield is calculated from a water budget and the storage characteristics of the supply system by an iterative process of increasing withdrawals until the system fails. A system is considered to have failed when the available storage of the system is first depleted. A surface-water-supply system can consist of one or more independent or interconnected reservoirs.

An important input variable in the firm-yield calculation is the contributing streamflow to the reservoir. Reservoirs that receive little streamflow will take longer to recover than reservoirs of the same size that receive large amounts of streamflow with similar water withdrawals. Surface-water inflows to supply reservoirs that obtain water from the Ipswich River Basin are not easily determined because the amount of water that can be obtained from the Ipswich River is regulated by the time of year, amount of streamflow, and by the capacity to pump water from the river. Furthermore, new operational procedures are being considered to maintain seasonally varied streamflow for aquatic ecosystem health. These constraints complicate the water budgets for the supply reservoirs and the firm-yield calculation for these systems.

The Hydrologic Simulation Program—FORTRAN (HSPF) model of the Ipswich River Basin previously developed by the U.S. Geological Survey (Zarriello and Ries, 2000) was identified as an appropriate method to calculate inflows and water budgets to the supply reservoirs under permitted withdrawals and hypothetical restrictions. The HSPF model can simulate reservoir storage under alternative withdrawal constraints from which a firm yield can be calculated. In 2002, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Protection (MDEP), undertook an investigation of three surface-water supplies that withdraw water from the Ipswich River Basin.

Purpose and Scope

This report describes the firm yield of three surface-water supply systems that obtain water from the Ipswich River Basin—Town of Lynn system, Town of Peabody system, and the Salem–Beverly Water Supply Board system (referred to hereafter as Lynn, Peabody and Salem–Beverly, respectively). The report describes each of these water-supply systems, their representation in the HSPF model, modifications of the existing model, and the reservoir storage and firm-yield simulated under (1) permitted withdrawals and (2) hypothetical restrictions. The hypothetical restrictions maintain seasonally varied streamflow and are more restrictive than the permitted withdrawals. All simulations were run for a 35-year period, from January 1961 through December 1995.

Acknowledgments

Richard Dawe, Superintendent of Water and Treatment and Supply, Town of Lynn; Peter Smyrnios, Superintendent of Water Treatment and Supply, Town of Peabody; and Richard Laramie and Ginger Hartman, of Camp Dresser, and McKee, Inc., consultants for the Salem–Beverly Water Supply Board, readily supplied information on operation and characteristics of the water-supply systems. Thomas Jobes, Aqua Terra Consultants, helped develop special-action features described in this report.

Study Area

The Ipswich River Basin in northeastern Massachusetts drains 155 mi^2 of the Atlantic coastal plain about 20 mi north of Boston (fig. 1). The river empties into the Atlantic Ocean near the southern end of Plum Island. The model area covers the 149 mi^2 above the Sylvania Dam; below the dam, the river is tidal and was not included in the model. Zarriello and Ries (2000) describe the physical and hydrologic characteristics of the basin, particularly as they relate to the development of the HSPF model. This report focuses on three surface-water supplies that obtain water from the Ipswich River Basin—two systems are operated by the towns of Lynn and Peabody, and one system is operated by the Salem–Beverly Supply Board.

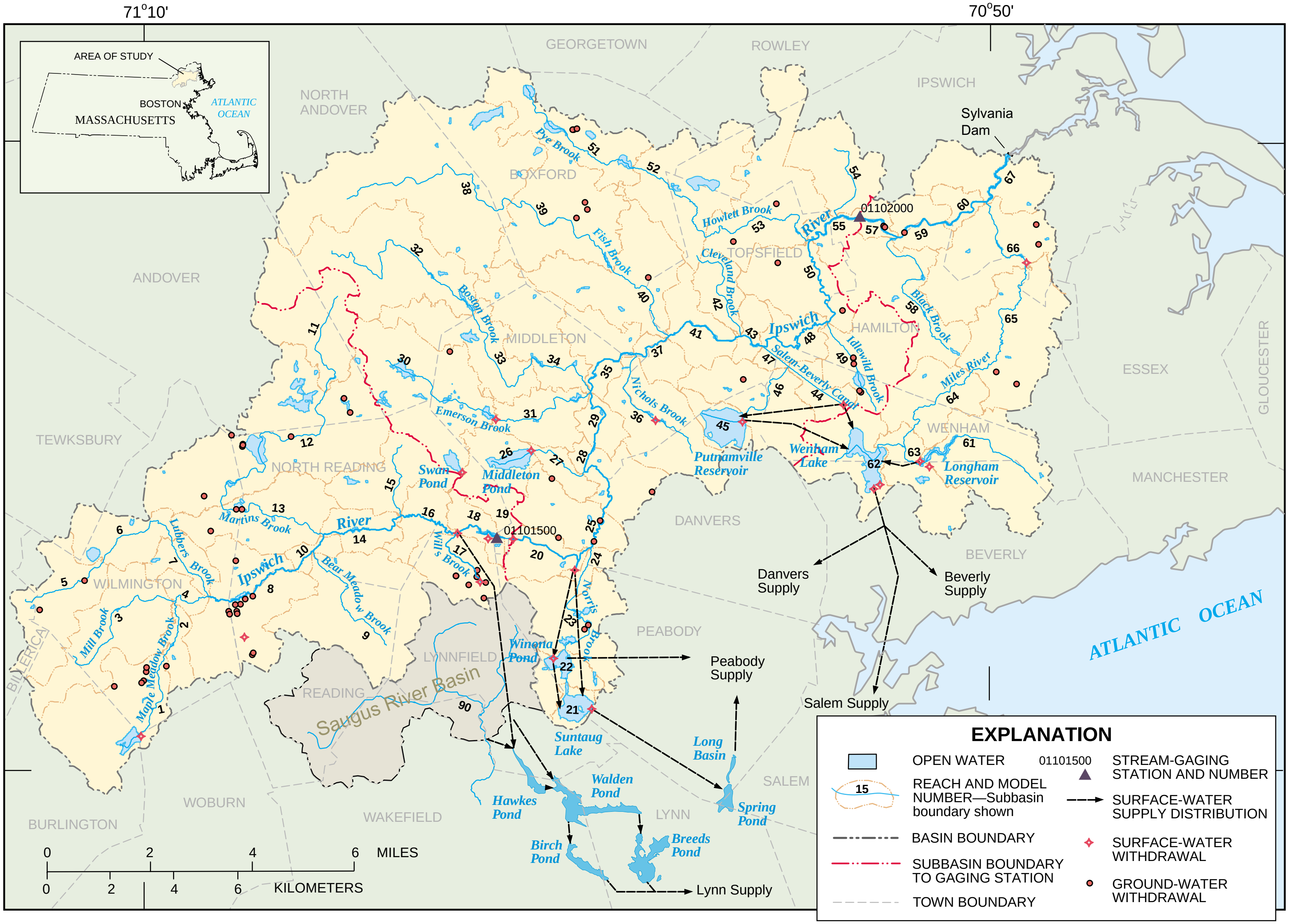

Figure 1. Principal geographic features, model reach numbers, and locations of the Lynn, Peabody and Salem–Beverly water-supply systems, Ipswich and Saugus River Basins, Massachusetts.

Lynn Water-Supply System

Lynn maintains four primary water-supply reservoirs—Hawkes Pond, Walden Pond, Birch Pond, and Breeds Pond (fig. 2), all of which are outside of the Ipswich River Basin (fig.1). Water is diverted seasonally when conditions allow from the Ipswich River to Walden Pond and in some cases to Hawkes Pond, and from the Saugus River to Hawkes Pond. An emergency connection is maintained from the Town of Peabody Suntaug Lake Reservoir to Walden Pond; however, this connection was not factored into the firm-yield analysis for the Lynn system. Water from Walden Pond can be gravity-fed to Birch Pond or pumped to Breeds Pond, then gravity-fed to the water-treatment facility. Under normal operations, water is pumped or gravity-fed through the reservoir-supply system to maintain optimal levels and water quality. Collectively, the four reservoirs and a small treated-water reservoir (low-service reservoir) have a usable storage capacity of about 3,940 Mgal. In addition to water obtained from the Ipswich and Saugus Rivers, Lynn can purchase water from the Massachusetts Water Resources Authority (MWRA).

Peabody Water-Supply System

Peabody maintains three primary supply reservoirs—Winona Pond, Suntaug Lake, and Spring Pond (fig. 3). Spring Pond is directly linked to two minor reservoirs—Long Basin and Fountain Pond. Spring Pond, Long Basin, and Fountain Pond are outside of the Ipswich River Basin. Water is pumped seasonally when conditions allow from the Ipswich River to Suntaug Lake, which then drains to Winona Pond or Fountain Pond. Two separate water-supply and treatment systems are operated by Peabody—(1) the Winona area system, and (2) the Coolidge area system. The Winona-system water is fed from Winona Pond and the Coolidge system water is fed through the Spring Pond reservoirs. A connection exists between the two systems. In addition, Peabody can purchase water from the MWRA. Since the two systems are interconnected, the firm-yield analysis can be calculated as a single system. The combined Peabody system has a usable storage capacity of about 1,230 Mgal.

Salem–Beverly Water-Supply System

The Salem–Beverly system supplies water to the towns of Salem, Beverly and occasionally Danvers. The Salem–Beverly system has three primary supply reservoirs—Longham Reservoir, Putnamville Reservoir, and Wenham Lake (fig. 4). All of the reservoirs and contributing drainage areas are within the Ipswich River Basin. Water from the Ipswich River is pumped from the Salem–Beverly Canal into Putnamville Reservoir or Wenham Lake (fig. 1). Water is gravity-fed into Wenham Lake from Longham and Putnamville Reservoirs, then pumped to a water-treatment facility. Combined, the Salem–Beverly system has a usable storage capacity of about 3,540 Mgal.

WATER WITHDRAWALS

The analysis of reservoir storage was initially made under average 1998–2000 demands for each system. Monthly demands (fig. 5) supplied to the MDEP as a requirement of the Drinking Water Program were disaggregated into daily values for model simulations. The same seasonal pattern of water demands was used when demands were increased or decreased to determine the system's firm yield. Demands reflect "raw" or "finished" water depending on whether water is lost during the treatment process. Raw water is simulated when water is consumptively used in the treatment process (for example, water used to flush filter beds is sent to waste). The total water demand in this case is the finished water plus the water used in the treatment process. If water is recycled during the treatment process (for example, water used to flush filter beds is returned to the reservoir), the finished water reflects the total demand.

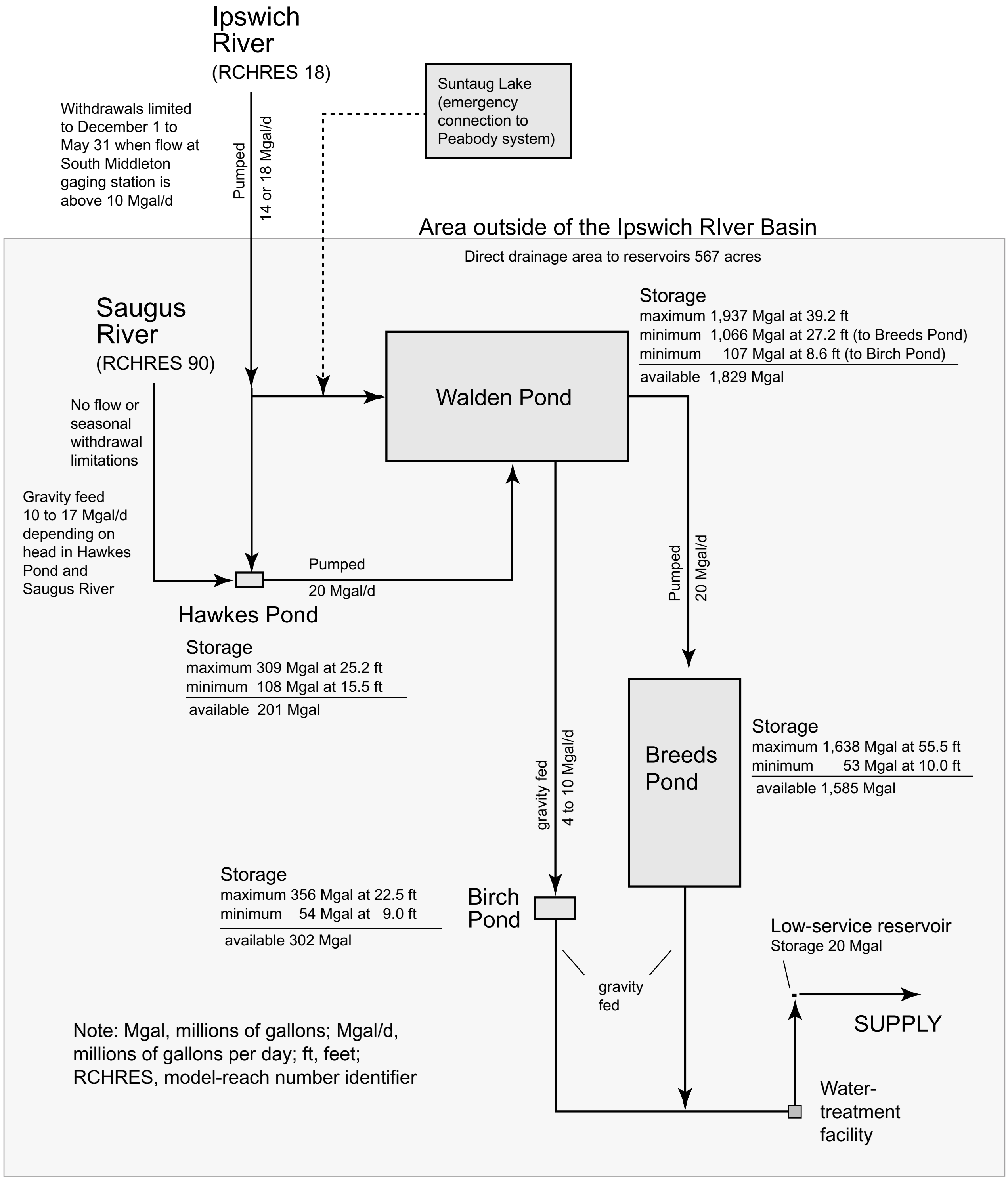

Figure 2. Water sources, storage reservoirs, and conveyance system for the Lynn water-supply system, Massachusetts.

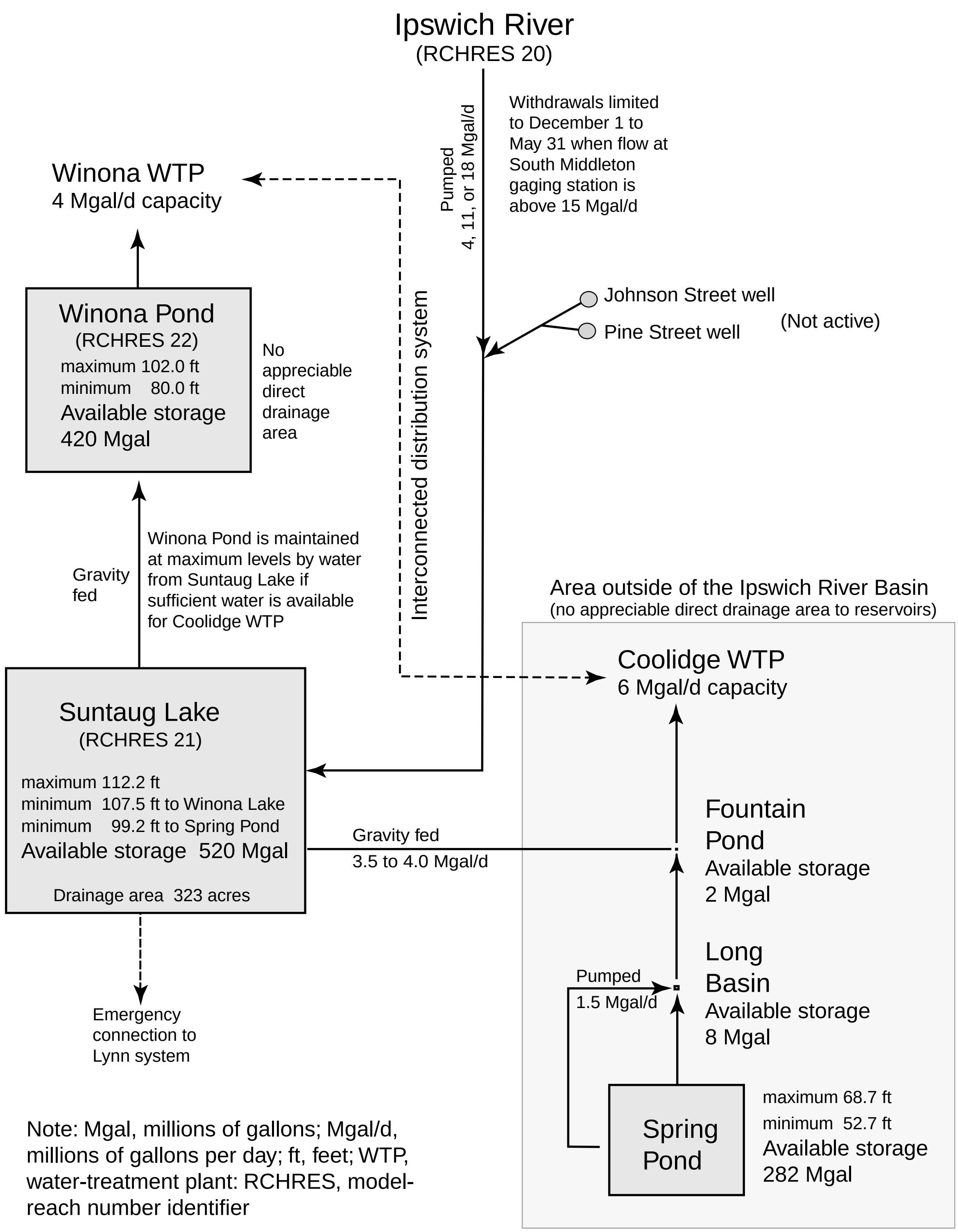

Figure 3. Water sources, storage reservoirs, and conveyance system for the Peabody water-supply system, Massachusetts.

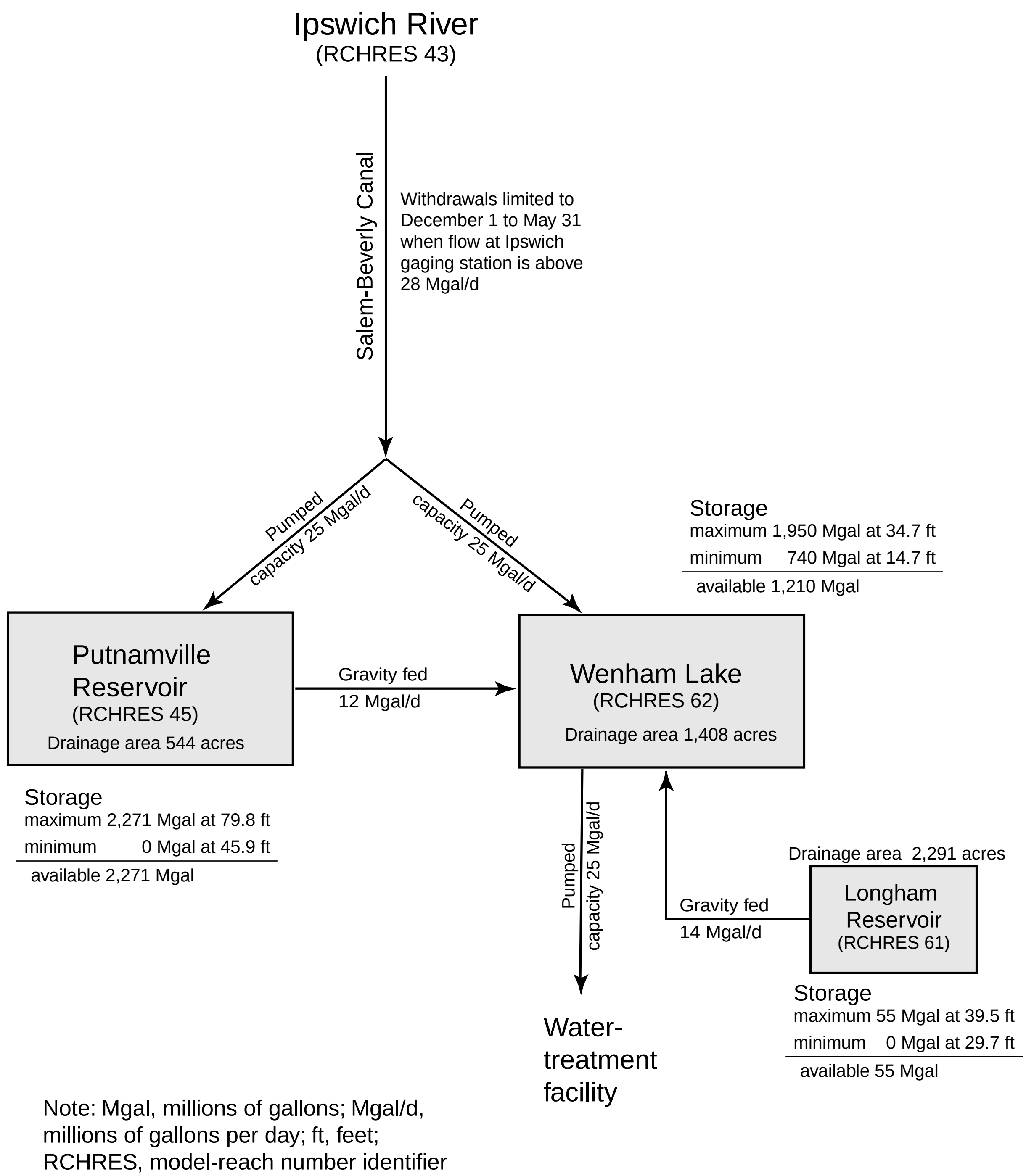

Figure 4. Water sources, storage reservoirs, and conveyance system for the Salem–Beverly water-supply system, Massachusetts.

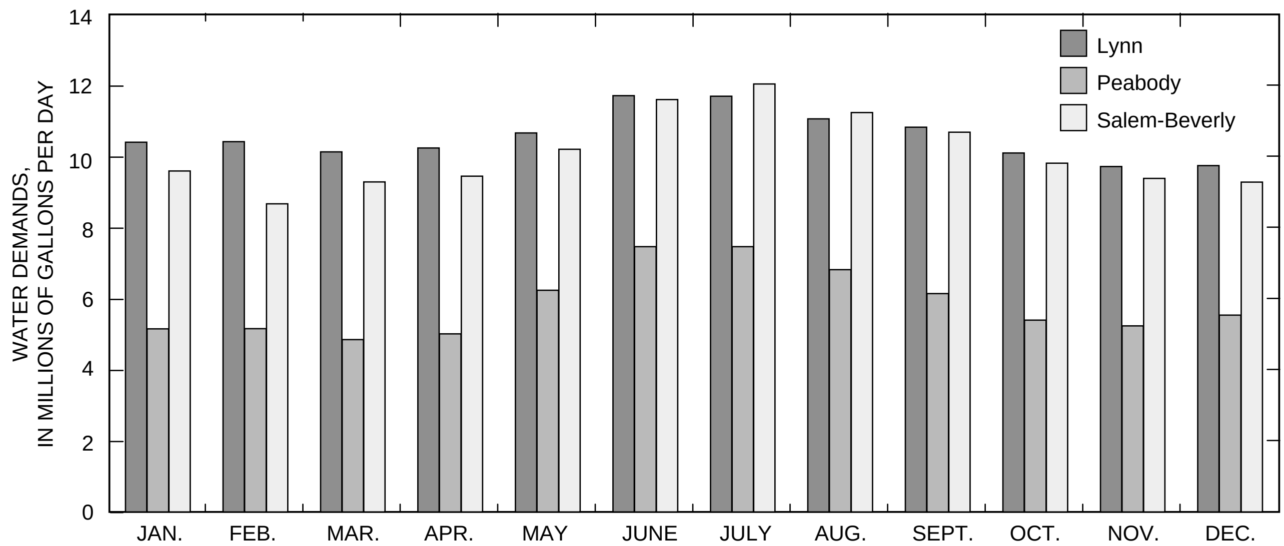

Figure 5. Monthly water demands from the Lynn, Peabody and Salem–Beverly water-supply systems, 1998–2000.

Water demands from the Lynn system are met primarily through withdrawals from the Saugus and Ipswich Rivers and a minor amount, which averaged 3.1 percent of the total 1998–2000 demand, purchased from the MWRA. Annual demands from the Lynn system averaged 3,855 Mgal/yr or about 10.6 Mgal/d (table 1); peak use during the summer was about 2 Mgal/d (about 20 percent) greater than winter use. Water demands from the Peabody system are met through withdrawals from the Ipswich River and water purchased from the MWRA. Annual demands from the Peabody system averaged 2,145 Mgal/yr or about 5.9 Mgal/d; peak use during the summer was about 2 Mgal/d (about 50 percent) greater than winter use. Peabody purchased about 10 percent of their water from the MWRA during 1998–2000, on average, but the percentage of purchased water ranged from zero to nearly 30 percent of the monthly demand. Water demands from the Salem–Beverly system are met through withdrawals from the Ipswich River and by direct drainage to the supply reservoirs. Annual demands from the Salem–Beverly system averaged 3,692 Mgal/yr or about 10.1 Mgal/d; peak use during the summer was about 3 Mgal/d (40 percent) greater than winter use.

WATER-WITHDRAWAL RESTRICTIONS

The amounts of water that can be supplied to each of three systems from the Ipswich River and Saugus River Basins are regulated by the Commonwealth of Massachusetts. Furthermore, new operation procedures are being considered to maintain seasonally varied streamflow for aquatic ecosystem health. These restrictions, described below, provide the limitations imposed in the HSPF model on the surface-water withdrawals in order to analyze reservoir storage and firm yield of each system. The firm-yield analysis included average 1989–95 ground water withdrawals in the model. These withdrawals deplete water that would have been available to each of these systems.

Table 1. Monthly water demands for Lynn, Peabody and Salem–Beverly supply systems, Massachusetts, 1998–2000

[Source: Massachusetts Department of Environmental Protection, Drinking Water Program, public water-supply annual statistical report. Mgal, millions of gallons; Mgal/d, millions of gallons per day]

Month	Total monthly demand, in Mgal				Mgal/d average
	1998	1999	2000	Average	
Lynn					
January	339	323	306	323	10.4
February	300	284	292	292	10.4
March	333	310	300	314	10.1
April	319	314	289	307	10.2
May	348	335	309	331	10.7
June	345	382	327	351	11.7
July	382	362	344	363	11.7
August	352	342	335	343	11.1
September	348	308	318	325	10.8
October	327	298	314	313	10.1
November	306	276	292	292	9.7
December	307	289	310	302	9.7
Total	4,006	3,823	3,735	3,855	10.6
Peabody					
January	155	177	147	160	5.2
February	140	150	143	144	5.2
March	139	162	150	150	4.8
April	140	162	149	150	5.0
May	189	207	184	193	6.2
June	180	289	203	224	7.5
July	231	246	217	231	7.5
August	208	225	201	211	6.8
September	185	183	185	184	6.1
October	153	177	172	167	5.4
November	139	168	164	157	5.2
December	152	183	180	172	5.5
Total	2,011	2,329	2,095	2,145	5.9

Month	Total monthly demand, in Mgal				Mgal/d average
	1998	1999	2000	Average	
Salem–Beverly					
January	302	287	303	297	9.6
February	262	258	207	243	8.7
March	283	282	299	288	9.3
April	278	280	292	283	9.4
May	319	322	309	316	10.2
June	314	404	327	348	11.6
July	384	384	352	373	12.0
August	343	369	333	348	11.2
September	319	320	323	321	10.7
October	307	299	308	304	9.8
November	279	278	288	282	9.4
December	278	286	299	288	9.3
Total	3,667	3,768	3,640	3,692	10.1

Permitted Withdrawals

The MDEP currently (2002) permits Lynn, Peabody, and Salem–Beverly to withdraw water from the Ipswich River between December 1 and May 31 when a minimum flow threshold in the river is met. The minimum flow thresholds are indexed to the two-USGS streamflow-gaging stations on the Ipswich River (fig. 1), referred to as the South Middleton station (01101500) and the Ipswich station (01102000). Lynn and Peabody can withdraw water during the 6-month window only when discharge at the South Middleton station is above 10 Mgal/d (15 ft^3/s) and 15 Mgal/d (23 ft^3/s), respectively. The Lynn intake is above the gaging station so flows at the gaging station reflect withdrawals made by Lynn. Peabody, however, withdraws water below the South Middleton station; therefore, Peabody's withdrawals must be subtracted from the streamflow at South Middleton to determine whether the flow criteria are met. Salem–Beverly can withdraw water during the 6-month window when streamflow at the Ipswich station, which is downstream of the Salem–Beverly Canal, is above 28 Mgal/d (43 ft^3/s). For any system to meet the flow criteria, streamflow has to be equal to or greater than the sum of the flow requirement and the rate at which water is withdrawn from the river. At a minimum, this value would equal the streamflow requirement plus the lowest pumping rate.

In addition to the streamflow-threshold restrictions, MDEP limits withdrawals to an annual maximum volume. Lynn is permitted to obtain a maximum annual volume of 956 Mgal from the Ipswich River and 3,259 Mgal from the Saugus River. Withdrawals from the Saugus River are not restricted to specific times of the year or flow thresholds, however. In addition to their registered permitted withdrawals, Lynn can withdraw an additional 120 Mgal/yr from either the Ipswich or Saugus Rivers. Preliminary model simulations indicated that streamflow is limiting in the Saugus River, therefore the additional permitted annual amount was applied to withdrawals from the Ipswich River (total annual limit 1,076 Mgal). Peabody is permitted to obtain a maximum annual volume of 1,500 Mgal/yr from the Ipswich River. In addition, Peabody is also restricted to an annual withdrawal of 1,631 Mgal/yr from the Ipswich River and the direct drainage to its reservoirs. The additional 131 Mgal/yr limit from the direct-drainage contribution was not considered in the model because water managers have no practical way of determining this contribution and the contributing drainage area is relatively small (596 acres). Salem–Beverly is permitted to obtain a maximum annual volume of 4,128 Mgal (registered permit of 3,716 Mgal/yr plus an additional permitted withdrawal of 412 Mgal/yr). Current restrictions are summarized in table 2.

Hypothetical Restrictions

Maintaining a sufficient and varied seasonal flow is a concern for restoring Ipswich River fisheries. The Ipswich River Fisheries Restoration Task Group (IRFRTG) identified four seasonal flow objectives to maintain a healthy aquatic ecosystem (Ipswich River Fisheries Restoration Task Group, written commun., 2002) listed in table 3.

The recommended flows are presented in cubic feet per second per square mile ($ft^3/s/mi^2$); the drainage areas to the river reaches at the withdrawal intakes are about 43.8, 45.6, and 100 mi^2 for Lynn, Peabody, and Salem–Beverly, respectively. These are the drainage areas to the downstream end of the model reach closest to where water is withdrawn (table 3). The model reach drainage area was used for the fisheries' recommended

Table 2. Criteria for permitted withdrawals from the Ipswich River, Massachusetts, by the Massachusetts Department of Environmental Protection

Supplier	Permitted withdrawal period	Streamflow threshold			Annual maximum (Mgal)
		Station	Million gallons per day	Cubic feet per second	
Lynn	December 1 through May 31	South Middleton	10	15	1,076
Peabody	December 1 through May 31	South Middleton	15	23	1,500
Salem–Beverly	December 1 through May 31	Ipswich	28	43	4,128

Table 3. Seasonal streamflow requirements recommended for fisheries protection by the Ipswich River Fisheries Restoration Task Group, Massachusetts

[**Recommended flow:** Ipswich River Fisheries current status and restoration approach, draft, April 16, 2002. **Lynn:** Identification number of the model reach on the Ipswich River where withdrawals are made. ft^3/s, cubic feet per second, $ft^3/s/mi^2$, cubic feet per second per square mile]

Time of year	Recommended flow ($ft^3/s/mi^2$)	Flow at the Ipswich River reach closest to the supply intake, in ft^3/s		
		Lynn (RCHRES 18)	Peabody (RCHRES 20)	Salem–Beverly (RCHRES 43)
June–October	0.49	21	22	49
November–February	1.0	44	46	100
March–April	2.5	110	115	250
May	1.5	66	69	150

flow requirement (instead of the drainage area to the intake, which may vary slightly from this area) because the flow criteria apply to the drainage area at the point where flow is simulated. These fisheries-recommended streamflows are more restrictive than the withdrawals currently permitted; simulations made using these flow requirements are referred to as hypothetical restrictions.

The hypothetical restrictions in flow per unit area recommended for the Ipswich River Basin were also applied to withdrawals from the Saugus River for the Lynn water supply (referred to as hypothetical restrictions—IRFRTG). These restrictions limit withdrawals to times when flows are above 5.2 ft^3/s from June through October, 11 ft^3/s from November through February, 26 ft^3/s in March and April, and 16 ft^3/s in May. In addition to the above restrictions, withdrawals from the Saugus River were also limited to a second set of streamflow requirements (referred to as hypothetical restrictions—SRIFIM) on the basis of a recent Instream Flow Incremental Methodology (IFIM) study by Gomez and Sullivan (2002). The flow recommendations from this study limit withdrawals from the Saugus River to times when flows are above 3.1 ft^3/s from June through September, 6.1 ft^3/s from October through February, 12 ft^3/s in March and April, and 10 ft^3/s in May, or 0.29, 0.57, 1.14, and 0.95 $ft^3/s/mi^2$, respectively. These limits required maintaining 37 to 54 percent less flow annually (an average 44 percent less) than the flow requirements recommended by the IRFRTG. Withdrawals from the Ipswich River were kept the same in both simulations.

MODEL DESCRIPTION

A HSPF precipitation-runoff model (Bicknell and others, 1997) was previously developed and calibrated for the Ipswich River Basin (Zarriello and Ries, 2000). The model is constructed as a series of one-line records that specify instructions to the various model modules, referred to as the User Control Input (uci). Some modules represent watershed processes such as runoff or infiltration of precipitation on pervious areas and other modules are needed for data management. For example, time-series data required for running the model is read through the EXT SOURCE block from the Water Data Management (WDM) system. The WDM file is organized by data set number (DSN) and attribute information, which contains all time-series data read into the model or written by the model during simulations.

The HSPF model consists of Hydrological Response Units (HRUs) that are representative of hydrologically similar land use and surficial materials. The HRUs are connected to river-reservoir reaches (RCHRES) that represent the hydrologic network of the basin. The Ipswich River Basin model was represented by 15 pervious area HRUs (PERLNDs) and two impervious area HRUs (IMPLNDs). Surface flow from IMPLNDs and surface and subsurface flow from PERLNDs is directed into 67 RCHRESs to represent the drainage network of the Ipswich River Basin. The basic Ipswich River Basin model is described by Zarriello and Ries (2000), and the modifications made to the model for simulating inflow to surface-water supplies under permitted withdrawals and hypothetical restrictions are described below. All simulations were conducted with a 1-hour time step and the centroid precipitation data.

Model Fit to High Flows

The HSPF model fit to observed streamflow in the Ipswich River Basin was described by Zarriello and Ries (2000) for the 1989–93 calibration period; however, that report focused primarily on the simulation of low flows. The model fit was reexamined during this study to evaluate its fit to high flows, which can affect the amount and timing of withdrawals. Model fit, in general, is described by the relation of simulated flows to observed flows.

Winter snow buildup and melt was identified as a possible cause of simulation error by Zarriello and Ries (2000). Snow buildup and melt variables in the model were adjusted to improve the model fit as part of this study. The values tested, while improving simulated snowmelt at times, typically resulted in poorer simulation results at other times; thus, further adjustments did not yield overall improvements in the model. Simulation error from snow buildup and melt was likely caused by the use of regional climatic data to represent local conditions. Hence, further adjustments to the model were not made.

Model-fit statistics of daily discharge presented in the previous report (Zarriello and Reis, 2000) are reproduced here along with the newly computed statistics for high flows during the 1989–93 periods. High flows were defined from flow-duration curves of observed discharges at the South Middleton and Ipswich gaging stations. High-flow discharges were defined by the 10- and 2-percent chance of exceedance on the flow-duration curve. Discharges at these exceedance intervals are equal to 155 and 308 ft^3/s at the South Middleton gaging station, and 447 and 899 ft^3/s at the Ipswich gaging station, respectively. The model-fit statistics (table 4) indicate that the high flows are simulated with a level of accuracy comparable to that for the simulated daily flows (all flows).

Modifications to the HSPF Model

The three surface-water supply systems have multiple reservoirs and complex operational rules for withdrawing water from supply sources and transferring water between reservoirs. The simulation of the complex operational dynamics of each of the multi-reservoir systems was beyond the scope of this study and furthermore, this type of simulation would needlessly complicate the model for undertaking a firm-yield analysis. The general approach was to combine the characteristics of the multi-reservoir system into a single reservoir for each of the three surface-water supplies. HSPF special actions were developed for each system. Special actions evaluated the reservoir storage deficit, determined whether criteria for withdrawing water from its source or sources could be satisfied, and when these criteria were met, withdrew water from the respective source within the physical constraints of each system. Modifications to the existing model included structural modifications and additional special actions.

Structural Modifications

The simplified representation of the reservoir systems and inclusion of portions of the system outside of the Ipswich River Basin required structural changes to the existing model. Water suppliers provided data on the maximum and minimum storage capacity and their respective water elevations for individual reservoirs in their system (figs. 2–4). The collective storage-surface area characteristics (FTABLE) of each system's individual reservoirs were defined by a single RCHRES. The maximum storage of the combined reservoir was defined as the sum of the storage capacities of the individual reservoirs. Reservoir storage was assumed to decline linearly over the range in stage from the maximum to the minimum capacity of individual reservoirs, unless otherwise noted. An individual reservoir went "off line" in the combined reservoir when the change in stage was greater than the change in stage between the individual reservoir's minimum and maximum storage. This approach, in effect, linked the individual reservoirs to a common elevation referenced to their maximum capacity in the combined reservoir. Reference to a reservoir, unless otherwise noted, refers to the combined reservoir used to represent the multi-reservoir systems.

The surface areas of the combined reservoirs for each system were developed in a similar manner. The surface areas of individual reservoirs were obtained from a MassGIS (http://www.state.ma.us/mgis) 1:25,000-scale coverage of hydrography; the areas were summed and the sum was assumed to represent the combined reservoir at full capacity. The surface area of an individual reservoir was assumed to vary

Table 4. Summary of high-flow model-fit statistics at the South Middleton and Ipswich gaging stations for Hydrologic Simulation Program— FORTRAN (HSPF) simulations made with the centroid and Reading precipitation data, Ipswich River Basin, Massachusetts, 1989–93

[**10-percent exceedance probability:** Discharges equal to or greater than 155 ft^3/s at the South Middleton gaging station, 447 ft^3/s at the Ipswich gaging station. **2-percent exceedance probability:** Discharges equal to or greater than 308 ft^3/s at the South Middleton gaging station, 899 ft^3/s at the Ipswich gaging station. RMSE, root mean square error; ft^3/s, cubic feet per second; <, less than; %, percent]

Model-fit statistic	All daily flows		10-Percent exceedance probability		2-Percent exceedance probability	
	Centroid	Reading	Centroid	Reading	Centroid	Reading
South Middleton gaging station						
Number of days	1,826	1,826	120	120	21	21
Correlation coefficient	.92	.92	.91	.90	.95	.93
Coefficient of model-fit efficiency	.85	.84	.66	.75	.89	.66
Standard error (ft^3/s)	.60	1.1	5.2	4.5	9.0	12
RMSE (ft^3/s)	94	100	66	57	42	72
Percent time simulated value <10% error	23	24	28	23	76	29
Percent time simulated value <25% error	51	49	62	69	100	95
Median percent error	-.40	5.6	-16	-16	-0.7	-13
Minimum percent error	-82	+89	-63	-48	-13	-25
Maximum percent error	1,588	2,122	86	79	61	17
Ipswich gaging station						
Number of days	1,826	1,826	120	120	21	21
Correlation coefficient	.94	.89	.93	.91	.93	.91
Coefficient of model-fit efficiency	.88	.79	.81	.72	.60	.18
Standard error (ft^3/s)	1.6	1.8	14	18	63	74
RMSE (ft^3/s)	51	54	181	223	332	474
Percent time simulated value <10% error	24	26	36	33	71	19
Percent time simulated value <25% error	56	58	61	80	81	71
Median percent error	-4.2	1.8	-14	-12	-4.5	-18
Minimum percent error	-88	-86	-47	-50	-31	-42
Maximum percent error (ft^3/s)	369	628	59	63	9.6	-3.3

linearly from its minimum and maximum values, unless otherwise noted. The surface area of the combined reservoir for a given change in stage was set equal to the sum of the surface areas of the individual reservoirs for each stage.

Withdrawals from each reservoir were averaged from the monthly 1998–2000 demands reported to MDEP, which may include water purchased from outside the basin. This water was included in the reservoir withdrawals because it reflects the pattern of monthly consumptive use and because water budgets could be calculated on the basis of actual use. Previously specified withdrawals from the Ipswich River for these supplies (read into the model through the EXT SOURCE block) were deleted and replaced by the average 1998–2000 withdrawals. All other withdrawals remained the same as previously simulated; these were primarily based on 1989–93 withdrawals.

The modified HSPF uci file for simulations under permitted withdrawals was named Ips-FYPR.uci and was given a scenario-identification attribute (IDSCEN) value of “FirmYPR.” The uci file for simulations under hypothetical restrictions was named “Ips-FYHR.uci” and was assigned an IDSCEN value of “FirmYHR.” Model input and output data sets associated with simulations for the firm-yield analysis are summarized in table 5. Specific modifications for each of the water-supply systems are described below.

Table 5. Time-series data associated with the firm-yield analysis simulations that are input to and output from the Hydrologic Simulation Program—FORTRAN (HSPF) model (EXT SOURCES and TARGETS) through the watershed data-management (WDM) system

[**Output DSN: Permitted:** Permitted withdrawal scenario. **Hypothetical:** Hypothetical withdrawal scenario. DSN, data set number in WDM file; TSTYPE and IDCONS, identification attributes in the WDM data set; RCHRES, model reach number; I/O, indicates data input to (I) or output from the model (O); ft^3/s, cubic feet per second; Mgal, millions of gallons]

Output DSN		I/O	Description	Supply system	TSTYPE	IDCONS	RCHRES	Units
Permitted	Hypo-thetical							
191	191	I	Average 1998–2000 water demands	Lynn	SWDL	SWDL	90	ft^3/s
192	192	I		Peabody	SWDL	SWDL	21	ft^3/s
193	193	I		Salem–Beverly	SWDL	SWDL	45	ft^3/s
830	831	O	Water withdrawn from Ipswich River	Lynn	VOL	RIV_VOL	18	ft^3/s
832	833	O		Peabody	VOL	RIV_VOL	20	ft^3/s
834	835	O		Salem–Beverly	VOL	RIV_VOL	43	ft^3/s
836	837	O	Water withdrawn from Saugus River	Lynn	VOL	RIV_VOL	90	ft^3/s
820	821	O	Reservoir storage	Lynn	VOL	RES_VOL	91	Mgal
822	823	O		Peabody	VOL	RES_VOL	21	Mgal
824	825	O		Salem–Beverly	VOL	RES_VOL	45	Mgal
801	802	O	Reservoir evaporation loss	Lynn	VOLE	RES_EVAP	91	Mgal
803	804	O		Peabody	VOLE	RES_EVAP	21	Mgal
805	806	O		Salem–Beverly	VOLE	RES_EVAP	45	Mgal
807	808	O	Precipitation on reservoir surface	Lynn	VOLP	RES_PREC	91	Mgal
809	810	O		Peabody	VOLP	RES_PREC	21	Mgal
811	812	O		Salem–Beverly	VOLP	RES_PREC	45	Mgal

Lynn

Storage and surface area of Hawkes Pond, Walden Pond, Breeds Pond, Birch Pond, and the low-service reservoir (all of which are outside the Ipswich River Basin) were combined into a new model reach (RCHRES 91) with an estimated combined available storage of 3,937 Mgal (12,082 acre-ft). The surface area at minimum capacity was assumed negligible; the combined surface area at full capacity was estimated at 3,430 acres. Relations among stage, storage, surface area, and discharge for this reach are defined in FTABLE 91. The area of direct drainage to the four main storage reservoirs is 566.6 acres and is mostly forest overlying coarse-grained permeable material. This drainage area was added to RCHRES 91 as PERLND 1, which most closely represents this type of land cover and surficial material.

Lynn obtains water from the Saugus and Ipswich Rivers. Withdrawals from the Ipswich River are taken from RCHRES 18 through the second exit gate. The first exit gate is used for a minor diversion by the Thomson Country Club and a third exit gate (added for the firm-yield analysis) is used for downstream channel routing. The Saugus River was not included in the HSPF model developed by Zarriello and Ries (2000). Therefore, a surrogate measure of its flow, needed to limit the amount of water withdrawn for supply, was made by summing flow in the Ipswich River Basin model at RCHRESs 3, 9, and 11. The drainage area above the Lynn's water-supply diversion on the Saugus River (10.63 mi^2) is nearly the same as the combined drainage area of RCHRESs 3, 9, and 11 (10.84 mi^2). In addition, the drainage area characteristics of the Saugus River at this point are similar to the combined drainage characteristics of RCHRESs 3, 9, and 11, particularly the percentage of sand and gravel (each is about 18 percent). Thus, summing the flows in these reaches is believed to be a reasonable estimate of Saugus River flow at Lynn's water-supply intake. The flows in RCHRESs 3, 9, and 11 were copied into a new target reach (RCHRES 90), which was assigned a location attribute (IDLOCN) value of ‘RCH90’ and a constituent attribute (IDCONS) value of ‘RIV_FLOW.’ The model reach representing the simplified reservoir (RCHRES 91) was also assigned an IDLOCN value of RCH90. This allows the user to point to the same reach segment on the display map to obtain simulated flow for the Saugus River or storage in the Lynn reservoir within GenScn, a graphical user interface developed for the HSPF model (Kittle and others, 1998).

Peabody

Storage and surface area of Suntaug Lake, Winona Pond, Spring Pond and two minor reservoirs (Long Basin and Fountain Pond) were combined into an existing model reach representing Suntaug Lake (RCHRES 21). Winona Pond, which was previously represented in the model as RCHRES 22, was deleted from the uci files. The combined available storage of these reservoirs was estimated at 1,250 Mgal (3,880 acre-ft) with a surface area of 328 acres at full capacity. Direct drainage to RCHRES 21 (596 acres) remained unchanged because drainage area to the other supply reservoirs is negligible. The surface area at the minimum capacity was assumed to be equal to half the surface area at the full capacity (Peter Smyrnios, oral commun., April 9, 2002). The FTABLE of RCHRES 21 was modified to reflect the combined characteristics of the Peabody reservoirs. Except for the direct drainage to Suntaug Lake, Peabody reservoirs obtain water from the Ipswich River at RCHRES 20 through the first exit gate.

Salem–Beverly

Storage and surface area of Longham Reservoir and Wenham Lake were combined into an existing model reach representing Putnamville Reservoir (RCHRES 45). Longham Reservoir (RCHRES 61) and Wenham Lake (RCHRES 62) were deleted from the uci files. The drainage areas to RCHRES 61 and 62 were added to the respective HRUs drainage areas in RCHRES 45 (total drainage area 4,257 acres). Stage-storage-surface area curves were available for Wenham Lake and Putnamville Reservoir; FTABLE relations were developed on the basis of these curves. Salem–Beverly obtains water from direct drainage to its supply reservoirs and the Salem–Beverly Canal, which connects to the Ipswich River at RCHRES 43 (fig. 1). Diversions from the Ipswich River were made at RCHRES 43 through the first exit gate.

Special Actions

The special actions feature of the HSPF model provides programmed instructions to the model. This feature extends the power and flexibility of the model to simulate conditions that are not available in the main model modules. Special actions developed for the firm-yield analysis control the time and rate water was obtained from its source according to permitted withdrawals or hypothetical restrictions, flow conditions, reservoir storage, and limitations of the infrastructure. The many user-defined variables (UVNAMEs) and variable quantities (UVQUANs) specified to develop special actions for the firm yield analysis are summarized in table 6. Specific instructions developed for each supply system are described below.

Lynn

Lynn’s water-supply demands were first satisfied by withdrawals from the Saugus River (RCHRES 90). Demands that could not be met from the Saugus River were made through withdrawals from the Ipswich River (RCHRES 18) according to the following rules:

1. Withdrawals ceased when the maximum storage capacity of the reservoir (3,937 Mgal) is satisfied.
2. Withdrawals from the Ipswich River were limited to two pumping rates—22 and 28 ft^3/s (14 and 18 Mgal/d, respectively). The rate was determined by the flow available in the Ipswich River and reservoir-storage deficit.
3. Withdrawals from the Saugus River (gravity-fed) were limited by pipe size and the head difference between the Saugus River and Hawkes Pond. The head difference for the purposes of this analysis was considered to depend on the combined reservoir stage rather than the stage of the Saugus River. The upper withdrawal limit, 26 ft^3/s (17 Mgal/d), was reached when the reservoir storage was low (below 80 percent of capacity). The lower withdrawal limit, 15 ft^3/s (10 Mgal/d), was reached when the reservoir storage was high (above 95 percent of capacity). Withdrawals were scaled linearly between these upper and lower limits.

Table 6. Special-action variables and quantities used to simulate inflows to surface-water supply reservoirs in the Hydrologic Simulation Program—FORTRAN (HSPF) model of the Ipswich River Basin, Massachusetts

[acre-ft, acre feet; acre-ft/hr, acre feet per hour; ft^3/s, cubic feet per second; --, none]

Description	UVQUAN	Operation type	Units	UVNAME
Current month	month	MON	--	--
Lynn				
Flow available in Saugus River	qsaugr	COPY 3	ft^3/s	--
	qsr_af	COPY 3	acre-ft/hr	--
Current storage in reservoir	lynsto	RCHRES 91	acre-ft	--
Flow Ipswich River at intake RCHRES 18	qrch18	RCHRES 18	ft^3/s	--
Flow Ipswich River South Middleton gaging station (RCHRES 19)	qrch19	RCHRES 19	ft^3/s	--
Flow factor Saugus River	mxqfac	GLOBAL	--	--
Storage factor Lynn reservoir	mxsfac	GLOBAL	--	MXSFAC
Amount needed to fill reservoir	lyndem	GLOBAL	acre-ft	LYNDEM
	ldem_q	GLOBAL	ft^3/s	LYNDEM
Total annual diversion Saugus River	lynsau	GLOBAL	acre-ft	LYNSAU
Total annual diversion Ipswich River	lynips	GLOBAL	acre-ft	LYNIPS
Current Saugus River diversion	lysdiv	GLOBAL	acre-ft	LYSDIV
Diversion from Saugus River	lsdivq	GLOBAL	ft^3/s	LYSDIV
Current Ipswich River diversion	lyidiv	GLOBAL	ft^3/s	LYIDIV
	lyi_af	GLOBAL	acre-ft/hr	LYIDIV
Peabody				
Current storage in reservoir	peasto	GLOBAL	acre-ft	--
Flow Ipswich River at intake RCHRES 20	qrch20	RCHRES 20	ft^3/s	--
Amount needed to fill reservoir	peadem	GLOBAL	acre-ft	PEADEM
	pdem_q	GLOBAL	ft^3/s	PEADEM
Total annual diversion Ipswich River	peaips	GLOBAL	acre-ft	PEAIPS
Current Ipswich River diversion	peadiv	GLOBAL	ft^3/s	PEADIV
	pea_af	GLOBAL	acre-ft/hr	PEADIV
Salem–Beverly				
Flow Ipswich River at RCHRES 43	qrch43	GLOBAL	ft^3/s	--
Flow Salem-Beverly canal (RCHRES 47) at Ipswich River	qrch47	GLOBAL	ft^3/s	--
Flow Ipswich River at Ipswich gaging station (RCHRES 56)	qrch56	RCHRES 56	ft^3/s	--
Current storage in reservoir	salsto	RCHRES 45	acre-ft	--
Amount needed to fill reservoir	saldem	GLOBAL	acre-ft	SALDEM
Amount needed to fill reservoir	sdem_q	GLOBAL	ft^3/s	SALDEM
Total annual diversion Ipswich River	salips	GLOBAL	acre-ft	SALIPS
Current Ipswich River diversion	saldiv	GLOBAL	ft^3/s	SALDIV
Current Ipswich River diversion	sal_af	GLOBAL	acre-ft/hr	SALDIV
Flow in RCHRES 56 above minimum	savail	GLOBAL	ft^3/s	SAVAIL
Flow in Reaches 43 and 44	shypq	GLOBAL	ft^3/s	SHYPQ

4. Permitted withdrawals—Withdrawals from the Ipswich River were permitted between December 1 and May 31 when flow at RCHRES 19 (South Middleton gaging station), including withdrawals, was greater than 15 ft^3/s (10 Mgal/d). Withdrawals from the Ipswich River ceased when these conditions were not satisfied. No time or flow-triggered restrictions were imposed on withdrawals from the Saugus River.

   Annual permitted withdrawals were not to exceed 1,076 Mgal/yr from the Ipswich River and 3,259 Mgal/yr from the Saugus. Withdrawals cease when the maximum permitted withdrawal was reached during a calendar year.

5, Hypothetical restrictions—Withdrawals from the Ipswich River ceased when seasonal flows at RCHRES 18 (including withdrawals) were below 21 ft^3/s from June through October, 44 ft^3/s from November through February, 110 ft^3/s in March and April, and 66 ft^3/s in May.

   Saugus River withdrawals, limited on the basis of the Ipswich River Fisheries Restoration Task Group recommended flow requirements (hypothetical restrictions—IRFRTG), ceased when flows at RCHRES 90 (including withdrawals) were below 5.2 ft^3/s from June through October, 11 ft^3/s from November through February, 26 ft^3/s in March and April, and 16 ft^3/s in May. Saugus River withdrawals, limited on the basis of the IFIM-recommended flow requirements (hypothetical restrictions—SRIFIM), ceased when flows at RCHRES 90 were below 3.1 ft^3/s from June through October, 6.1 ft^3/s from November through February, 12 ft^3/s in March and April, and 10 ft^3/s in May.

   The maximum annual withdrawal limits of 1,076 Mgal/yr from the Ipswich River and 3,259 Mgal/yr from the Saugus were also applied to the hypothetical restrictions. The time window was increased by 1 month to allow withdrawals between November 1 through May 31 from the Ipswich River. Withdrawals from the Saugus River were only limited by streamflow requirements.

Examples of simulated withdrawals from the Ipswich and Saugus Rivers under permitted withdrawals and hypothetical restrictions (IRFRTG-recommended flows) during the 1989 calendar year are shown in figure 6*A* and *B*. The reservoir was assumed to start at full capacity, which may not have been true at the beginning of 1989. Under the permitted withdrawals, nearly all flow is diverted from the Saugus River during January and February and from mid June through December. Only during March through May, when flow was relatively high and the supply reservoir was at or near capacity, were diversions less than the flow in the river and, at times, diversions stopped completely because the reservoir was at capacity. While diversion from the Saugus can appreciably affect its flow, the magnitude of the diversions simulated under the permitted withdrawals may not reflect the actual operating practices. These simulations were intended only to evaluate the firm yield of the system under current restrictions.

Withdrawals from the Ipswich River during the 1989 calendar year were made only when criteria for allowing withdrawals were met and only when diversions from the Saugus River could not satisfy storage deficit. These conditions were met mostly during periods of low flow that were above the streamflow-withdrawal threshold; at high flows, demands were mostly satisfied by diversion from the Saugus River. Withdrawals stop and start frequently (as much as every hour) and appear as a solid, but when enlarged show the frequent stopping and starting pattern when flow in the Ipswich River was near the flow threshold (fig. 6*B*). These frequent on-and-off cycles or "painting" of the withdrawal curve occur during most periods when withdrawals are made from the Ipswich River, but this type of operation is not likely in practice.

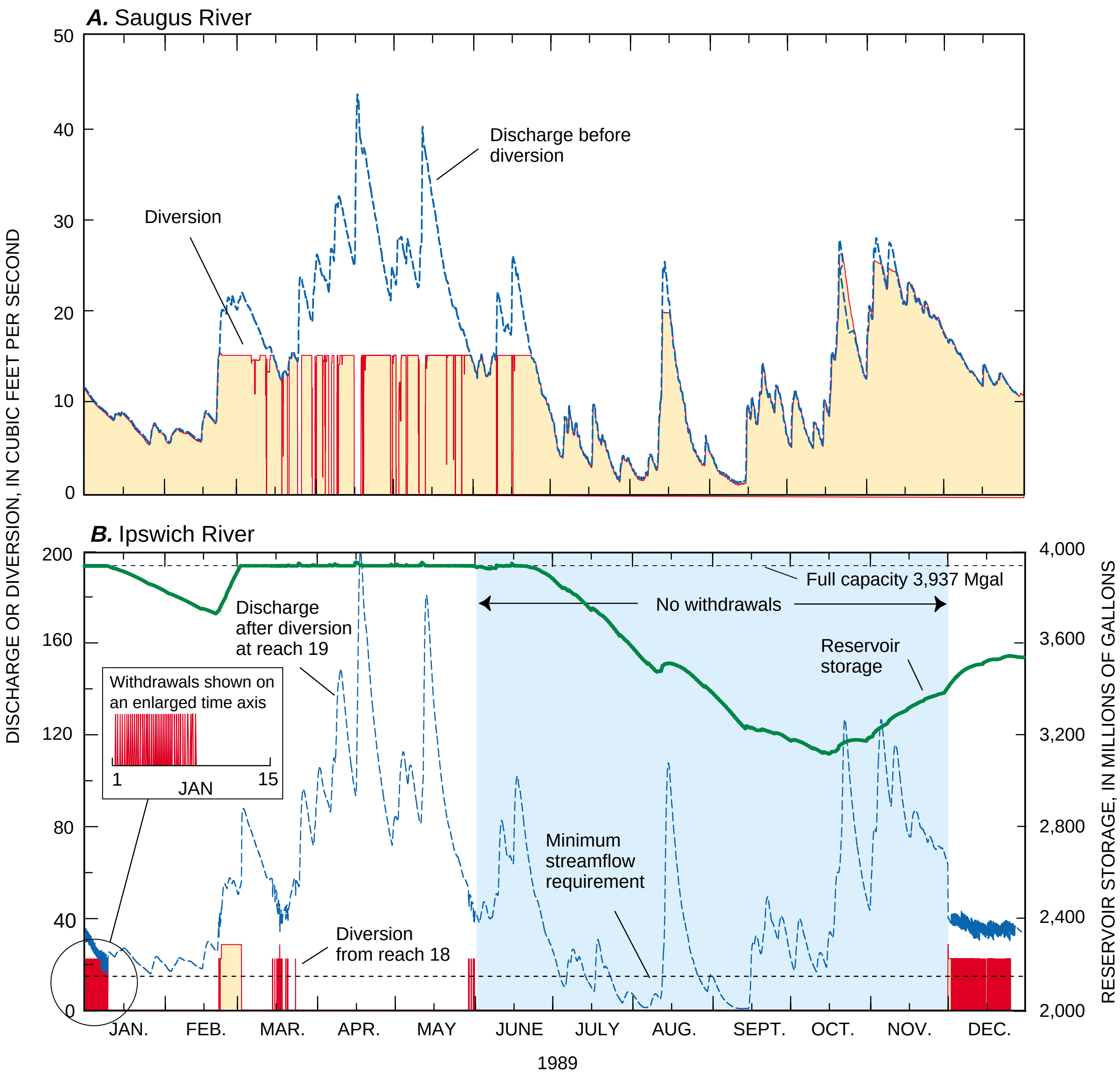

Figure 6. Example of withdrawals limited by the Hydrologic Simulation Program-FORTRAN special actions under permitted withdrawals from the (*A*) Saugus River and (*B*) Ipswich River for the Lynn water-supply system, Massachusetts, 1989.

Under hypothetical restrictions (fig. 7), diversions from the Saugus River ceased when flow in the river dropped below the minimum seasonal flow requirements. As a result, less flow was diverted from the Saugus River than under the permitted withdrawals; thus, the need for withdrawals from the Ipswich River increased, despite the more restrictive flow requirements.

Peabody

Peabody water-supply demands were satisfied from withdrawals from the Ipswich River (RCHRES 20) according to the following rules:

1. Withdrawals ceased when the maximum storage capacity of the reservoir (1,250 Mgal) was satisfied.
2. Withdrawals were limited to three pumping rates—6.2, 17, or 28 ft^3/s (4, 11, or 18 Mgal/d, respectively). The pumping rate was determined by the available flow in the Ipswich River and the reservoir storage deficit.
3. Permitted withdrawals—Withdrawals from the Ipswich River were permitted between December 1 and May 31 when flow at RCHRES 19, after subtracting withdrawals, was greater than 23 ft^3/s (15 Mgal/d). Withdrawals ceased when these conditions were not satisfied.

   Annual permitted withdrawals were not to exceed 1,500 Mgal/yr from the Ipswich River. Withdrawals from the Ipswich River ceased when the maximum permitted withdrawal was reached during a calendar year.
4. Hypothetical restrictions—Withdrawals from the Ipswich River ceased when the seasonal flows at RCHRES 20 (after subtracting withdrawals) were below 22 ft^3/s from June through October, 46 ft^3/s from November through February, 115 ft^3/s in March through April, and 69 ft^3/s in May.

   The maximum annual withdrawal limits under permitted withdrawals were also applied to the hypothetical restrictions. The time window was increased by 1 month to allow withdrawals between November 1 through May 31.

Examples of simulated withdrawals from the Ipswich River under permitted restrictions and hypothetical restrictions during the 1989 calendar year are shown in figure 8*A* and *B*. As was the case for Lynn, the reservoir was assumed to start at full capacity at the beginning of 1989. Under permitted restrictions, withdrawals from the Ipswich River were made between December 1 and May 31 when flow at the South Middleton gaging station was greater than 23 ft^3/s plus the withdrawal rate. Withdrawals were mostly at the high pumping rate, 18 Mgal/d (27 ft^3/s), but the lower pumping rates were used when the reservoir was near capacity or flow in the river was too low to sustain the higher pump rate. Under the hypothetical restrictions, withdrawals from the Ipswich River were made between December 1 and May 31 when streamflow was above the minimum seasonal flow target plus the pumping rate. As a result, the reservoir storage was depleted by the end of September.

Salem–Beverly

Salem–Beverly water-supply demands were satisfied from withdrawals from the Ipswich River (RCHRES 43) according to the following rules:

1, Withdrawals ceased when the maximum storage capacity of the reservoir (3,555 Mgal) was satisfied.

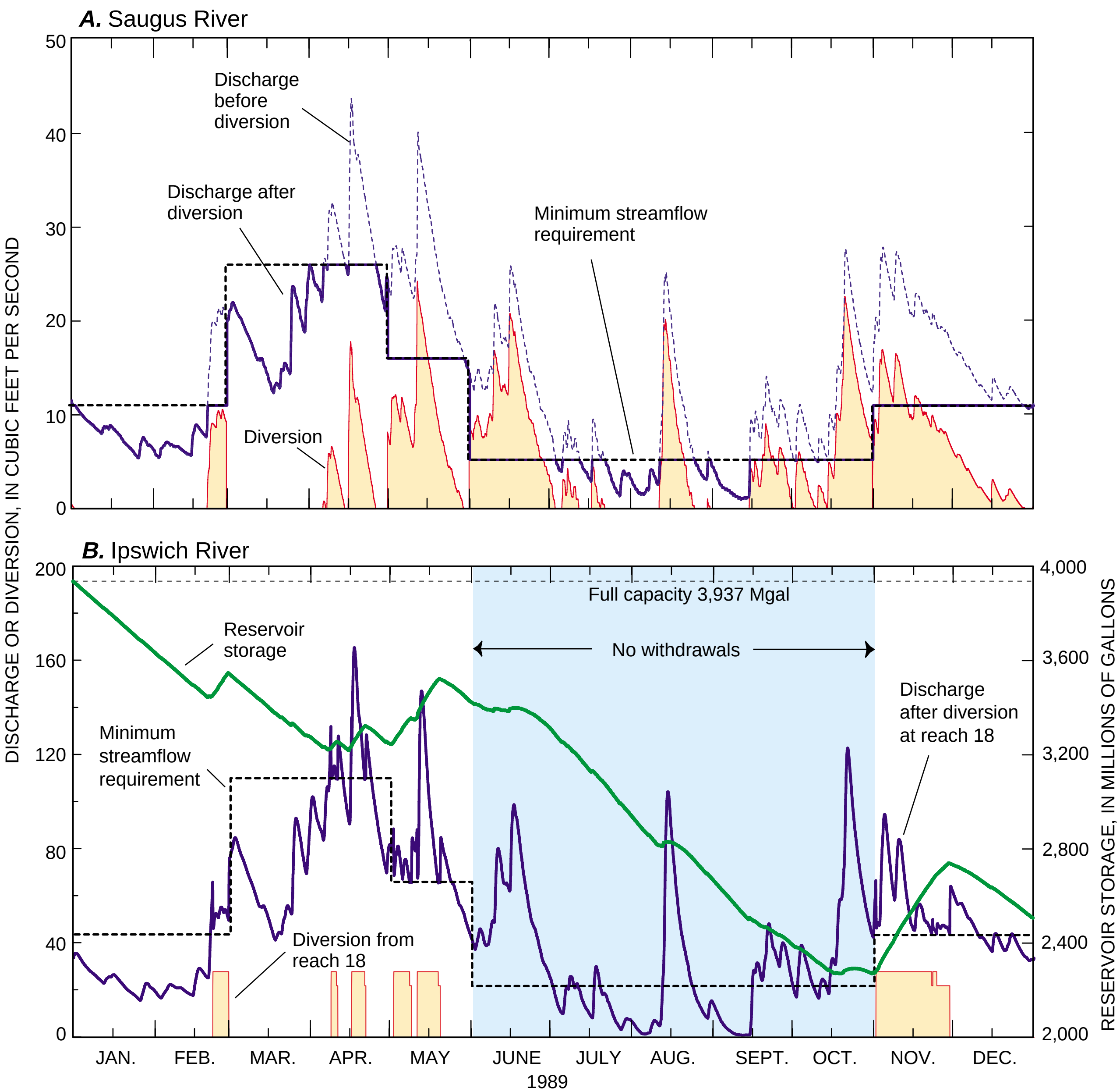

Figure 7. Example of withdrawals limited by the Hydrologic Simulation Program-FORTRAN special actions under hypothetical restrictions from the (*A*) Saugus River and (*B*) Ipswich River for the Lynn water-supply system, Massachusetts, 1989.

2. Withdrawals were limited to 39 or 77 ft^3/s (two pumps, each of which is capable of pumping 25 Mgal/d). The withdrawal rate was determined by the available flow in the Ipswich River and the reservoir storage deficit.

3. Permitted withdrawals—Withdrawals from the Ipswich River were permitted between December 1 and May 31 when flow at RCHRES 56 (Ipswich gaging station), including withdrawals, was greater than 43 ft^3/s (28 Mgal/d). Withdrawals ceased when these conditions were not satisfied.

Annual permitted withdrawals were not to exceed 4,128 Mgal/yr from the Ipswich River. Withdrawals ceased when the maximum volume was reached during a calendar year.

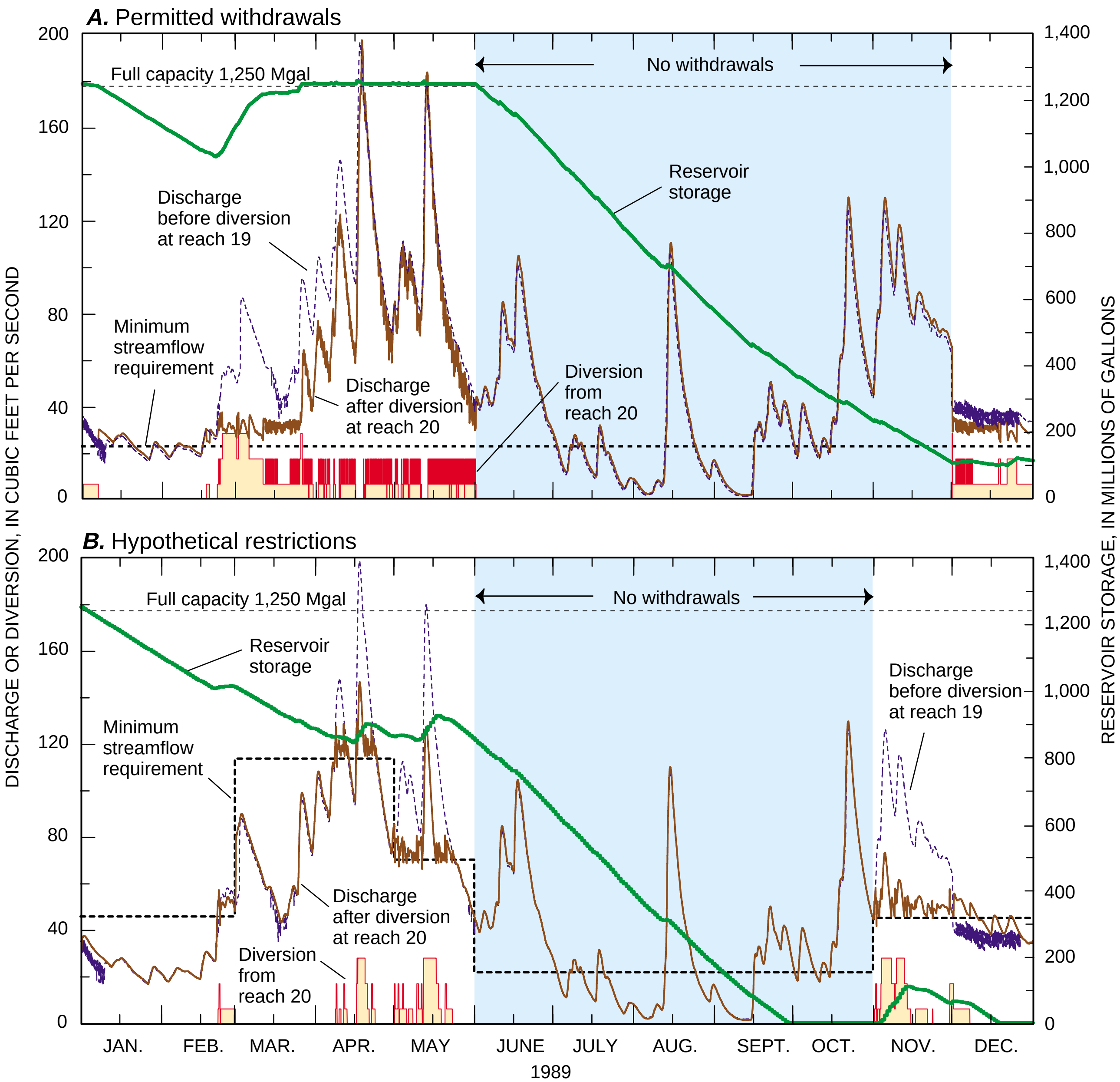

Figure 8. Example of withdrawals limited by the Hydrologic Simulation Program—FORTRAN special actions under (*A*) permitted withdrawals and (*B*) hypothetical restrictions for the Peabody water-supply system from the Ipswich River, Massachusetts, 1989.

4. Hypothetical restrictions—Withdrawals from the Ipswich River ceased when the sum of flows in RCHRES 43 and 47 (including withdrawals) was below 49 ft^3/s from June through October, 100 ft^3/s from November through February, 250 ft^3/s in March and April, and 150 ft^3/s in May. The flows in RCHRES 43 and 47 were summed to represent total flow in the river at the point of withdrawal (flow in the Ipswich River plus the contributing drainage area to the Salem–Beverly canal).

The maximum annual withdrawal limits under permitted withdrawals were also applied to the hypothetical restrictions. The time window was increased by 1 month to allow withdrawals between November 1 through May 31.

Examples of withdrawals from the Ipswich River under permitted withdrawals and hypothetical restrictions during the 1989 calendar year are shown in figure 9*A* and *B*. As in the previous examples, the reservoir was assumed to start at full capacity at the beginning of 1989. Under permitted restrictions, withdrawals were made from the Ipswich River between December 1 and May 31 when flow at the Ipswich gaging station was greater than 43 ft^3/s plus the pumping rate. Withdrawals were mostly at the low pumping rate, 25 Mgal/d (39 ft^3/s), because the reservoir was near capacity at the time when discharge in the Ipswich River could have sustained the higher pumping rate (50 Mgal/d). Diversions from the Ipswich River indicate frequent on-and off cycles (which appear as solid black areas on the diversion curve).

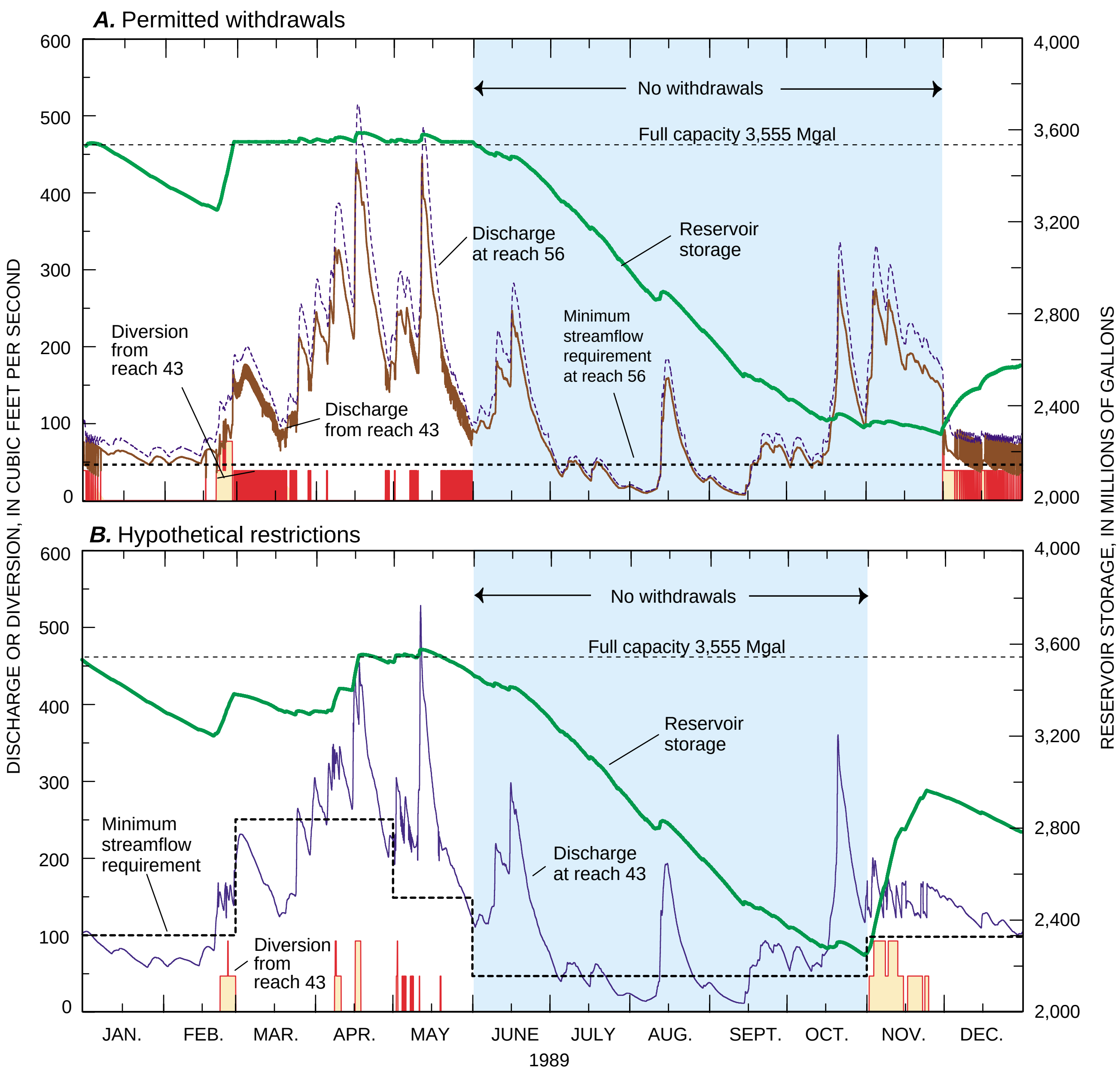

Figure 9. Example of withdrawals limited by the Hydrologic Simulation Program—FORTRAN special actions under (*A*) permitted withdrawals and (*B*) hypothetical restrictions for the Salem–Beverly water-supply system from the Ipswich River, Massachusetts, 1989.

These on-and off cycles were initially caused by reservoir being near capacity (January through May), but when withdrawals resumed in December, the on-and-off cycles were caused by streamflow being near the permitted threshold. The on-and-off diversions are reflected in the discharge hydrograph at the Ipswich station (reach 56).

Under hypothetical restrictions, withdrawals are allowed between December 1 and May 31 when streamflow was above the minimum seasonal flow target plus the withdrawal rate. Withdrawals from the Ipswich River under the hypothetical restrictions occurred more often at the higher pumping rate than under the permitted withdrawals because of the greater need to satisfy the reservoir-storage deficit.

SIMULATED RESERVOIR STORAGE AND FIRM YIELD

Simulations were run for a 35-year period (1961–95) under permitted withdrawals and hypothetical restrictions from the Ipswich River and average 1998–2000 demands from the Lynn, Peabody and Salem–Beverly systems. For the Lynn system, hypothetical restrictions also included limiting withdrawals from the Saugus River by (1) IRFRTG-recommended streamflow requirements and (2) an IFIM study streamflow requirements. Reservoir storage, withdrawals, and river discharge at the point of withdrawal were simulated for each system. Simulations were made at an hourly time step; however, storage and flow characteristics are reported for daily, monthly or yearly averages. Water budgets were calculated annually over the simulation period. These budgets included the total water withdrawn from the Ipswich River (and from the Saugus River for Lynn) and change in storage and evaporation loss from each supply system. Other withdrawals, including streamflow depletion by groundwater pumping, which also affect streamflow, were held at the average for 1989–93 conditions as described by Zarriello and Ries (2000).

For supply systems that did not fail during the simulation period, a firm yield was calculated by incrementally increasing average 1998–2000 withdrawals until the reservoir storage was nearly depleted. For reservoir systems that failed during the simulation period, a firm yield was calculated by incrementally decreasing the average 1998–2000 withdrawals until the reservoir was nearly depleted. Withdrawal rates were changed (up or down) by adjusting the multiplier (MFACT) in the EXT SOURCE block of the uci file, which is where withdrawal rates are read into the model. The firm yield reported was the withdrawal rate that maintained the least storage in the reservoir, but satisfied demands. Further changes in the MFACT (made at two significant digits to the right of the decimal) would result in depleted storage.

Firm-yield estimates are affected by upstream withdrawals. Therefore, the Peabody-system firm yield was determined by setting the Lynn withdrawal to its firm-yield withdrawal rate and the Salem–Beverly-system firm yield was determined by setting the Lynn and Peabody withdrawals to their respective firm-yield withdrawal rates. All other withdrawals were maintained at the same rate.

Lynn—Permitted Withdrawals

Simulation results for permitted withdrawals indicate that the Lynn reservoir maintained storage and was able to refill to capacity during most years except for the droughts of the 1960s and 1980s under average 1998–2000 demands (averaged 10.6 Mgal/d). The reservoir system did not to refill to capacity from 1965 to 1969 (fig. 10*A*) and reached its minimum storage on January 7, 1967, when storage dropped to 22 percent of capacity (885 Mgal). The reservoir system did not refill to capacity during 1980–82, and in 1977 and 1989 recovery was short by a small amount (fig. 10*A*). During the 1980s drought, the reservoir storage reached a minimum of 38 percent of capacity (1,560 Mgal) in mid-November of 1981.

Annual reservoir storage under the permitted withdrawals averaged 3,264 Mgal or about 83 percent of capacity. The average monthly reservoir storage (fig. 11 and table 7) was at a minimum in November (averaged 67 percent of capacity) and at a maximum in May (averaged 96 percent of capacity). The average monthly reservoir storage was at a minimum at the end of the period of restricted withdrawals from the Ipswich River and at a maximum at the end of the period when withdrawals can be taken from the Ipswich River. The reservoir-storage duration curve (fig. 10*B*) indicates that the reservoir was at or near capacity 50 percent of the time, greater than 60 percent of capacity about 90 percent of the time, and greater than 30 percent of capacity about 99 percent of the time.

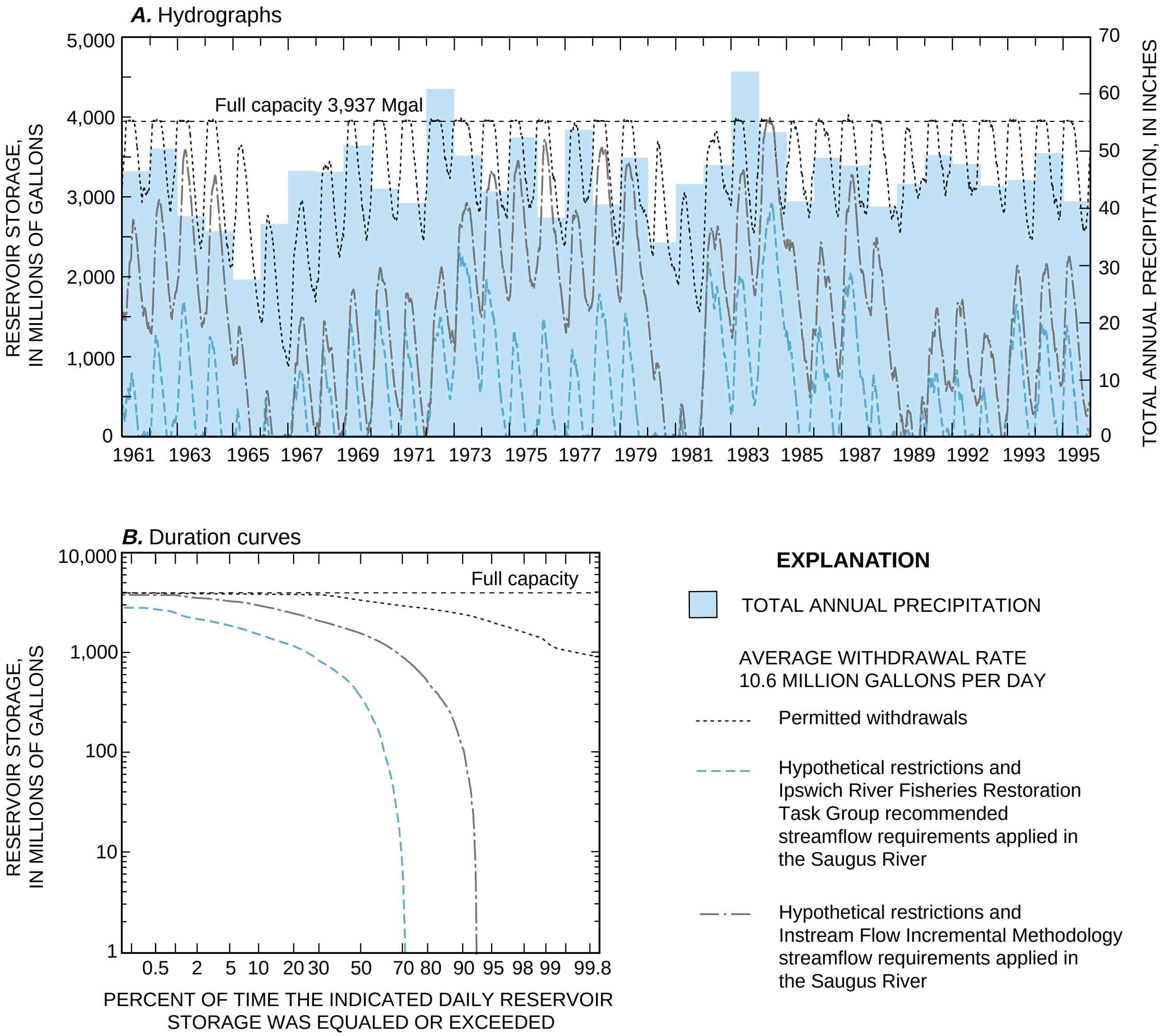

Figure 10. Daily reservoir storage simulated at the average 1998–2000 demands under permitted and hypothetical restrictions, Lynn water-supply system, Massachusetts, 1961–95; (*A*) hydrographs and (*B*) duration curves.

Lynn withdrew water from the Ipswich River about 15 percent of the time under permitted restrictions (fig. 12). Withdrawals, when they occurred, are mostly at the maximum pumping rate of 18 Mgal/d (28 ft^3/s); the lower pumping rate (14 Mgal/d) was used infrequently. Average annual withdrawals from the Ipswich River ranged from 0.43 to 4.56 ft^3/s and averaged 3.95 ft^3/s during 1961–95. During the 6 months when withdrawals from the Ipswich River were permitted, withdrawals averaged 7.94 ft^3/s. Average annual withdrawals from the Ipswich River reached 92 percent of the allowed annual limit (1,076 Mgal/yr); this limit was reached in 23 of the 35 years during 1961–95.

Permitted withdrawals from the Saugus River were restricted to an annual limit, but withdrawals were also limited by available flow and the need to replenish reservoir storage. Average annual withdrawals from the

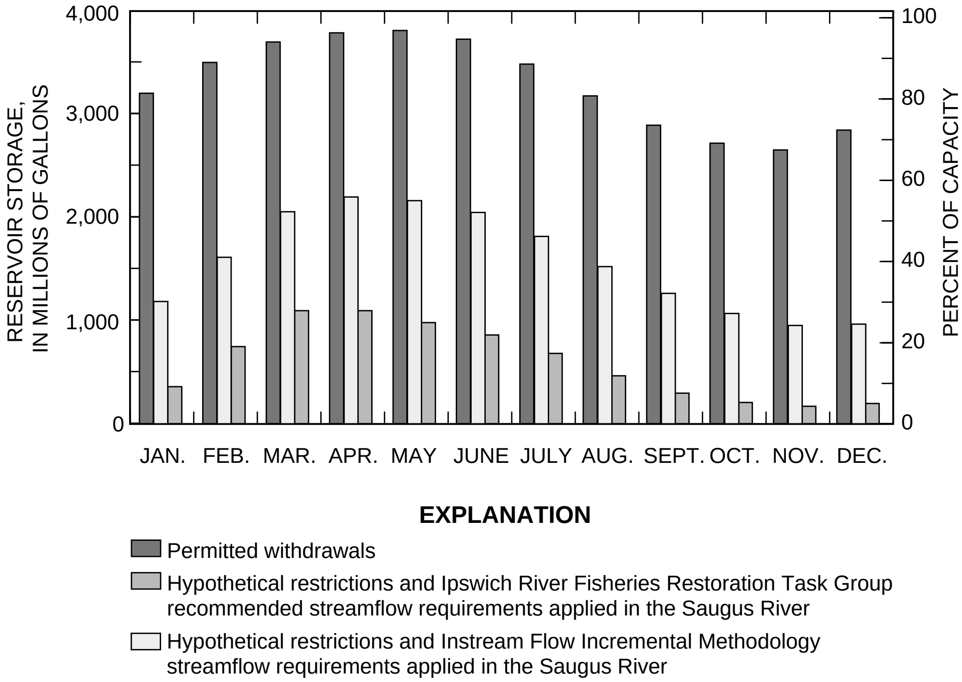

Figure 11. Average monthly reservoir storage simulated at average 1998–2000 demands (10.6 million gallons per day) under permitted withdrawals and hypothetical restrictions, Lynn water-supply system, Massachusetts, 1961–95.

Saugus River ranged from 8.01 to 13.80 ft^3/s and averaged 10.79 ft^3/s. Average annual withdrawals from the Saugus River were about 2.7 times greater than the average annual withdrawals from the Ipswich River. About 5 percent of the time, no water was diverted from the Saugus River because the reservoir was at or near capacity. Diversions from the Saugus were at the maximum rate (26 ft^3/s) about 10 percent of the time, indicating low reservoir levels and a flow in the Saugus River equal to or greater than 26 ft^3/s. Diversions from the Saugus River between the upper and lower head-driven withdrawal rates (15 to 26 ft^3/s) indicate that the reservoir storage was high or that Saugus River flow was at least 15 ft^3/s; diversions at these rates occurred between 5 and 50 percent of the time. Diversions less than 15 ft^3/s indicate that either the Saugus River flow was less than the demand or the reservoir was near capacity; diversions less than 15 ft^3/s occurred about 50 percent of the time. Average annual withdrawals from the Saugus River reached 78 percent of the allowed annual limit (3,259 Mgal/yr); this limit was reached in 3 of the 35 years during 1961–95.

Streamflow-duration curves for the Ipswich River at the Lynn intake indicate only slightly less flow below the 50-percent exceedance interval than simulations with no withdrawals (fig. 13*A*). Streamflow-duration curves for the Saugus River at the Lynn diversion, however, indicate that permitted withdrawals appreciably affect streamflow (fig. 13*B*). Without diversion, a minimum flow of 0.5 ft^3/s could be expected. Under permitted withdrawals, flow could be diverted to the extent that little or no flow is left in the Saugus River about 60 percent of the time.

The volume of direct precipitation on the reservoir was distributed relatively evenly throughout the year, averaging 555 Mgal/yr during 1961–95, or about 14 percent of the average annual demand (fig. 14). Direct precipitation on the reservoir was typically least in October when the reservoir storage was low and the corresponding footprint of the reservoir system was small. The estimated direct evaporation loss from the reservoir system varied from an average of 105 Mgal in July to 2.7 Mgal in January and averaged 450 Mgal annually. Annual evaporation from the reservoir was about 19 percent less than direct precipitation on the reservoir.

Table 7. Average monthly and minimum daily reservoir storage simulated at average 1998–2000 demands (10.6 million gallons per day) under permitted withdrawals and hypothetical restrictions, Lynn water-supply system, Massachusetts, 1961–95

[IFIM, Instream Flow Incremental Methodology; IRFRTG, Ipswich River Fisheries Restoration Task Group; Mgal, millions of gallons]

Month	Reservoir storage under permitted withdrawals				Reservoir storage under hypothetical restrictions							
					With IRFRTG-recommended streamflow requirements applied to the Ipswich and Saugus Rivers withdrawals				With IFIM streamflow requirements applied to the Saugus River withdrawals and IRFRTG applied to Ipswich River withdrawals			
	Average monthly (Mgal)	Percent of capacity	Minimum daily (Mgal)	Percent of capacity	Average monthly (Mgal)	Percent of capacity	Number of days dry	Percent of time dry	Average monthly (Mgal)	Percent of capacity	Number of days dry	Percent of time dry
January	3,176	81	885	22	356	9.0	225	21	1,187	30	74	6.8
February	3,472	88	1,160	29	740	19	104	11	1,615	41	30	3.0
March	3,668	93	1,800	46	1,086	28	46	4.2	2,057	52	0	.0
April	3,756	95	2,340	59	1,086	28	69	6.6	2,200	56	0	.0
May	3,779	96	2,540	65	971	25	136	13	2,166	55	26	2.4
June	3,696	94	2,280	58	852	22	152	14	2,049	52	60	5.7
July	3,457	88	1,920	49	676	17	275	25	1,819	46	66	6.1
August	3,151	80	1,560	40	460	12	390	36	1,525	39	121	11
September	2,869	73	1,310	33	292	7.4	608	58	1,266	32	150	14
October	2,696	68	1,100	28	204	5.2	656	60	1,069	27	169	16
November	2,631	67	1,030	26	166	4.2	557	53	953	24	126	12
December	2,822	72	903	23	193	4.9	466	43	968	25	84	7.7
Average	3,263	83	1,569	40	590	15	[1]3,684	29	1,573	40	[1]906	7.1

[1]Total number of dry days.

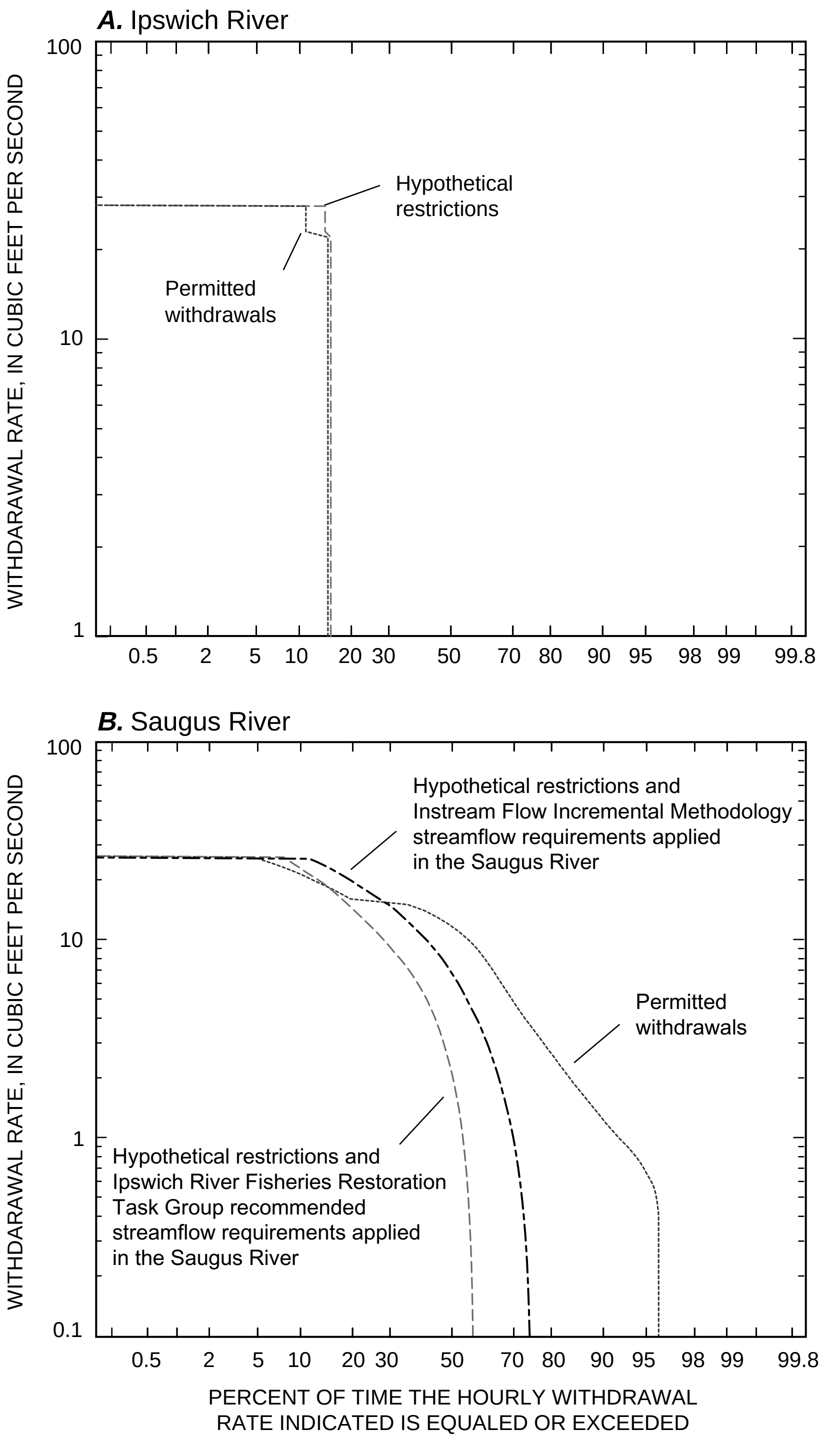

Figure 12. Withdrawal-duration curves simulated from the (*A*) Ipswich River (model reach 18), and (*B*) Saugus River (model reach 90), under permitted and hypothetical restrictions and average 1998–2000 demands (10.6 million gallons per day), for the Lynn water-supply system, Massachusetts, 1961–95.

The change in reservoir surface area that results relative to the change in storage introduces some model error because the contributing drainage to the reservoir area does not increase by an proportional amount to the decrease in surface area of the reservoir. If precipitation falling within the footprint of the reservoir system at full capacity is assumed to contribute direct precipitation regardless of the reservoir stage, then direct precipitation accounts for 704 Mgal/yr, on average, or about 18 percent of the average annual water demand. Direct precipitation on the reservoir system with a constant surface area was 27 percent larger than that simulated under permitted withdrawals. While this difference seems large, the error introduced in the firm-yield analysis is considered small because direct precipitation when the reservoir is prone to fail is likely small. Alternatively, simulating the reservoir with a fixed surface area would introduce error in the evaporation loss, which is likely a more critical component of the water budget when the reservoir is prone to fail. Therefore, simulating the reservoir with a variable surface area provides a more conservative firm-yield estimate than simulating the reservoir with a fixed surface area. Firm-yield analysis indicated that, under the permitted restrictions, Lynn could increase average annual 1998–2000 withdrawals by about 8 percent, to an average daily withdrawal of 11.4 Mgal/d (4,163 Mgal/yr). Reservoir storage simulated with an 8-percent increase in withdrawals resulted in a minimum daily average of 17 Mgal on January 7, 1967, or about 0.4 percent of full capacity (fig. 15).

Total withdrawals in January averaged 321 Mgal, which is nearly equal to the average annual withdrawal rate.

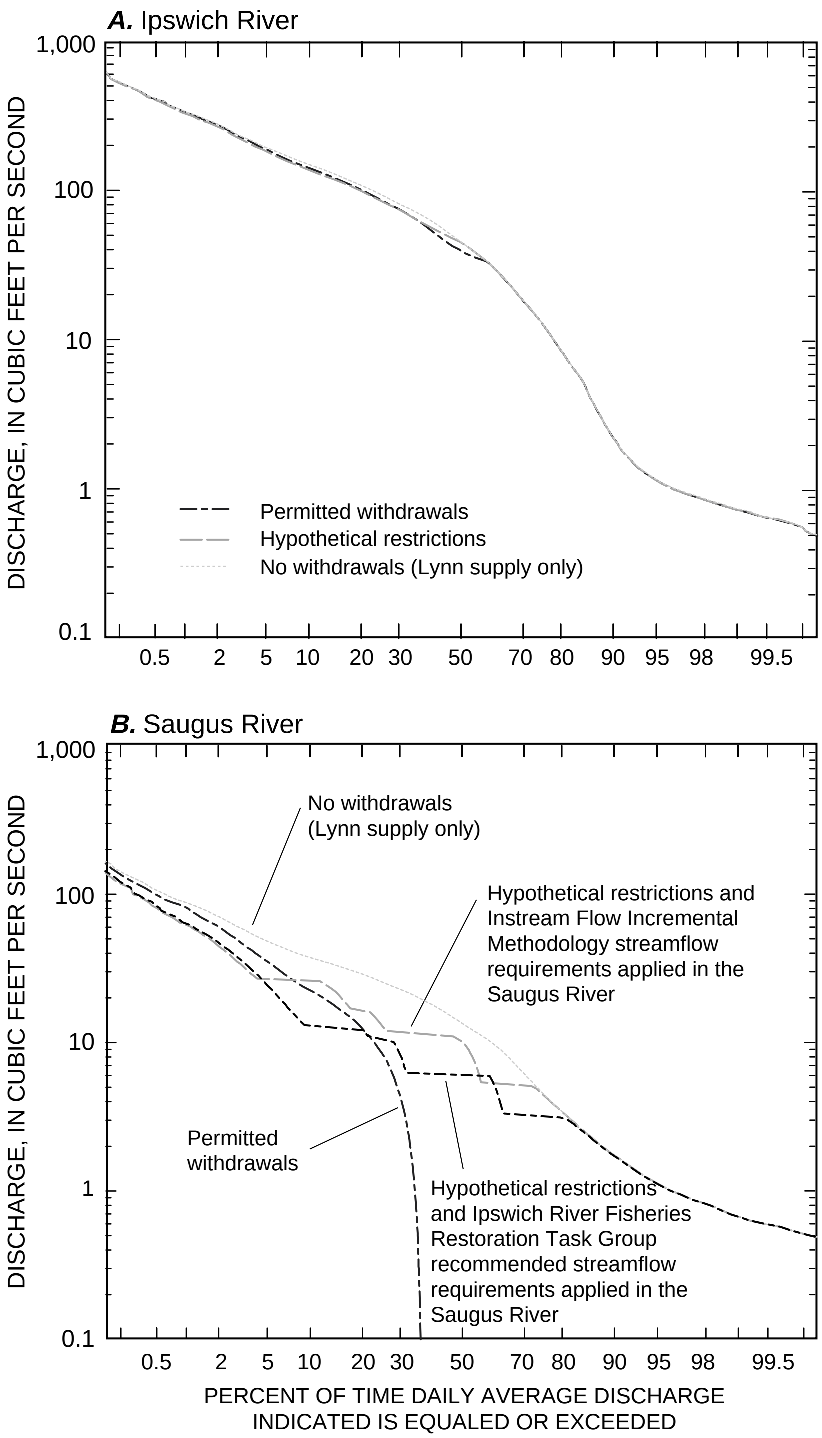

Figure 13. Daily streamflow-duration curves simulated with no withdrawals and at 1998–2000 demands (10.6 million gallons per day) under permitted withdrawals and hypothetical restrictions at the intake locations on the (*A*) Ipswich River (model reach 18) and (*B*) Saugus River (model reach 90), Lynn water-supply system, Massachusetts, 1961–95.

Interestingly, the reservoir did not fail during the summer when water demands are greatest and inflows are typically least. Annual reservoir storage at the firm-yield withdrawal rate averaged 73 percent of capacity and was at a minimum of 28 percent in 1967. During the drought of the early 1980s, reservoir storage was at a minimum of 644 Mgal or about 16 percent of capacity on November 16, 1981.

Lynn—Hypothetical Restrictions—IRFRTG

Simulation results for the IRFRTG streamflow requirements applied to both the Ipswich and Saugus Rivers indicate that the Lynn reservoir storage was depleted during most years and the system did not completely refill during any year under average 1998–2000 demands (fig. 10*A*). Storage was maintained only during years of above-normal precipitation (1972–74 and 1982–84).

The annual reservoir storage under hypothetical restrictions averaged 590 Mgal or about 15 percent of capacity. Reservoir storage was depleted during most of 1965, 1966, 1980, 1981, and 1989, and averaged only 36 Mgal during these years. Storage in 1980 averaged only 2.5 Mgal. Average monthly storage was at a minimum in November, which averaged 4.2 percent of capacity, and at its maximum in March, which averaged 28 percent of capacity (fig. 11, table 7). During 1961–95 the daily reservoir storage was depleted 60 and 53 percent of the time in the months of October and November, respectively. Reservoir storage was depleted least often during the months of March and April, 4.2 and 6.6 percent of the time, respectively (table 7). The storage-duration curve (fig. 10*B*) indicates that the reservoir

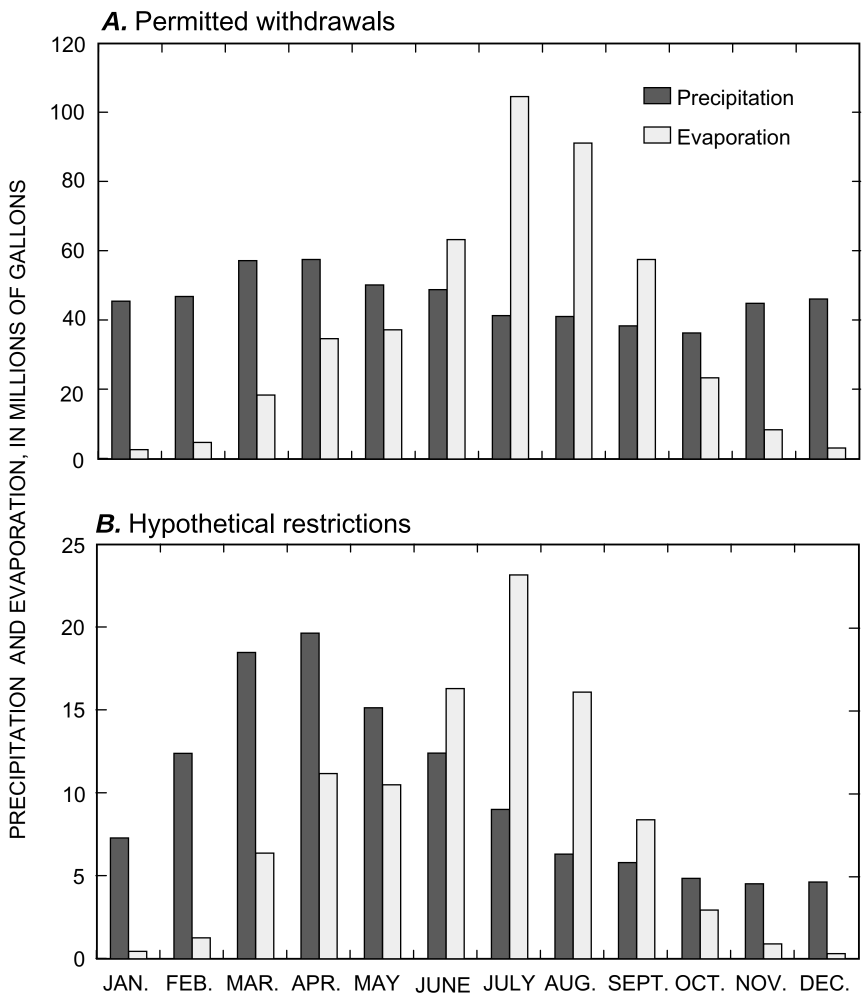

Figure 14. Average monthly volume of direct precipitation to and evaporation loss simulated at average 1998–2000 demands (10.6 million gallons per day) under (*A*) permitted withdrawals and (*B*) hypothetical restrictions, Lynn water-supply reservoir system, Massachusetts, 1961–95.

system failed about 30 percent of the time; the reservoir system was less than 10 percent of capacity 50 percent of the time and was above 56 percent of capacity only 5 percent of the time. The average monthly reservoir storage under hypothetical restrictions ranged between 6.3 and 30 percent of the reservoir storage for similar months under the permitted withdrawals.

Lynn withdrew water from the Ipswich River at about the same frequency (about 15 percent of the time) under hypothetical restrictions as under permitted withdrawals (fig. 12*A*). Withdrawals, when they occurred, were mostly at the maximum pumping rate of 18 Mgal/d (28 ft^3/s); pumping at the lower rate (14 Mgal/d) was used slightly less frequently under hypothetical restrictions than under the permitted withdrawals. Average annual withdrawals from the Ipswich River ranged from 0.90 to 4.56 ft^3/s with an average withdrawal of 4.28 ft^3/s. The average annual withdrawal from the Ipswich River under hypothetical restrictions was about 8 percent greater than under permitted withdrawals because more water is needed from the Ipswich River to compensate for greater restrictions on withdrawals from the Saugus River. During the 7 months when withdrawals were permitted from the

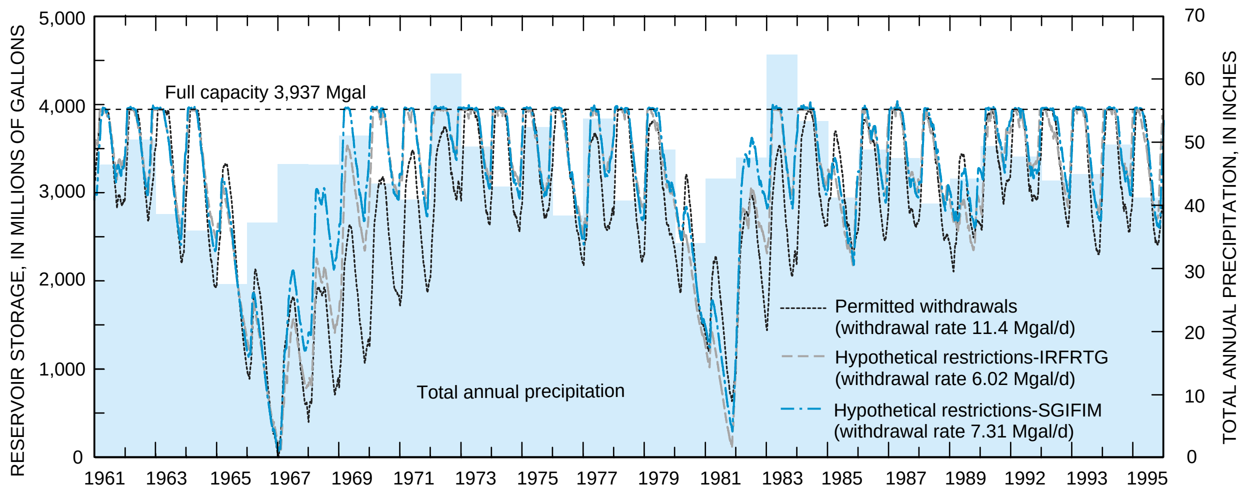

Figure 15. Daily reservoir storage simulated at firm-yield withdrawal rates in million gallons per day (Mgal/d) under permitted withdrawals and hypothetical restrictions, Lynn water-supply system, Massachusetts, 1961–95.

Ipswich River, withdrawals averaged 7.51 ft^3/s. Annual withdrawals from the Ipswich River, on average, reached 99 percent of the allowed annual limit (1,076 Mgal/yr); this limit was reached in 30 of 35 years during 1961–95. This result is up slightly from simulations under permitted withdrawals (withdrawals averaged 92 percent of the permitted limit), and indicates that, under hypothetical restrictions, Lynn must maximize its use of the Ipswich River to make up for decreases in withdrawals from the Saugus River. This result also indicates that the permitted annual withdrawal limits from the Ipswich River can result in further restrictions than that allowed by the hypothetical streamflow restrictions.

Withdrawals from the Saugus River of more than 1 ft^3/s occur about 50 percent of the time under hypothetical restrictions (fig. 12*B*). Average annual withdrawals from the Saugus River ranged from 1.12 to 13.4 ft^3/s and averaged 6.75 ft^3/s. Average annual withdrawals from the Saugus River were about 1.6 times greater than the average annual withdrawals from the Ipswich River. Average annual withdrawals from the Saugus River are about 37 percent less under hypothetical restrictions than under the permitted withdrawals; the minimum annual withdrawal (when streamflow conditions are less favorable for withdrawals) was about 86 percent less under hypothetical restrictions than under the permitted restrictions. Annual withdrawals from the Saugus River, on average, were 49 percent of the allowed annual limit (3,259 Mgal/yr); this limit was not exceeded during 1961–95. This result indicates that withdrawals from the Saugus River are limited by the hypothetical streamflow restrictions and not by the annual withdrawal limit.

Flow-duration curves indicate that withdrawals from the Ipswich River under the hypothetical restrictions have a minor effect on streamflow (fig. 13*A*). Saugus River streamflow was maintained under hypothetical restrictions so that flows with a 75-percent chance of exceedance or more (low flows) are the same as flows simulated without withdrawals (fig. 13*B*). Flows that have less than a 10-percent chance of exceedance (high flows) were somewhat lower than the flows simulated without withdrawals or under permitted restrictions. Note that the no-withdrawal curve shown in figure 13*A* refers only to withdrawals for the Lynn water supply (ground-water withdrawals are still active).

The volume of direct precipitation on the reservoir system under hypothetical restrictions was between 10 and 32 percent of the direct precipitation under the permitted withdrawals. The decrease in volume of direct precipitation under hypothetical restrictions is consistent with the decrease in reservoir surface area relative to the surface area under permitted withdrawals. Direct precipitation on the reservoir averaged 120 Mgal annually or about 12 percent of the average annual demands. Average monthly inflow from direct precipitation was more variable under hypothetical restrictions than under permitted withdrawals (fig. 14) because of the larger variations in the surface area under hypothetical restrictions. Direct precipitation on the reservoir with a constant surface area was 5.8 times larger than that simulated under variable surface area. Direct evaporation loss from the reservoir under hypothetical restrictions follows the same seasonal pattern as under permitted withdrawals, but at a rate that was 74 to 90 percent less because of the decreased surface area. Evaporation loss from the reservoir under hypothetical restrictions averaged 98 Mgal annually or about 78 percent less than under the permitted withdrawals. Annual evaporation from the reservoir is about 18 percent less than direct precipitation on the reservoir.

Firm-yield analysis indicated that under the hypothetical restrictions and the IRFRTG-recommended flow restrictions in the Saugus River, Lynn would need to decrease its average annual 1998–2000 withdrawals by about 43 percent to 6.02 Mgal/d (2,197 Mgal/yr). Lynn would have to purchase 4.58 Mgal/d, on average, to meet its 10.6 Mgal/d average 1998–2000 demands. A 43-percent decrease in annual withdrawals resulted in a minimum daily average reservoir storage of 74 Mgal on February 2, 1967, or about 1.9 percent of full capacity (fig. 15). A 42-percent decrease in withdrawals resulted in depleted storage for 15 days in January 1967. The firm yield under hypothetical restrictions was 5.28 Mgal/d less (about half) than the firm yield under permitted restrictions (11.4 Mgal/d). Reservoir storage at the firm-yield withdrawal rate under hypothetical restrictions averaged 79 percent of capacity annually during 1961–95; the minimum average annual storage was 21 percent of capacity in 1981. During the drought of the early 1980s, the minimum daily reservoir storage was 116 Mgal or about 2.9 percent of capacity on November 16, 1981.

Lynn—Hypothetical Restrictions—SRIFIM

Simulation results with IFIM streamflow requirements in the Saugus River under average 1998–2000 demands indicate that the Lynn reservoir storage was less than the storage under permitted withdrawals, but more than the storage under the IRFRTG hypothetical requirements (fig. 10). Similar to hypothetical restrictions under IRFRTG flow requirements, the reservoir did not completely refill during most years under average 1998–2000 demands and IFIM flow restrictions (fig. 10*A*).

Annual reservoir storage under the SRIFIM restrictions averaged 1,573 Mgal or about 40 percent of capacity. Storage was depleted in 8 of 35 years (1965–68, 1980–81, 1989, 1992) and the minimum daily storage was 10 percent of capacity or less in about half the years during 1961–95. The daily reservoir storage was depleted about 66 percent of the time in 1966 and 1981, about 40 percent of the time in 1965, and about 35 percent of the time in 1980. The average monthly reservoir storage (fig. 11 and table 7) was at a minimum in October through December (averaged about 25 percent of capacity) and at a maximum in April and May (averaged 55 percent of capacity). The duration curve of the daily mean reservoir storage (fig. 10*B*) indicated that the reservoir was near capacity 5 percent of the time but the storage was depleted about 7 percent of the time.

Lynn withdrawals from the Ipswich River for these simulations are the same as the withdrawals under the hypothetical restrictions with IRFRTG-recommended streamflow requirements for the Saugus River. This indicates that, even with the less stringent streamflow requirements for the Saugus River, the model still attempts to satisfy the storage deficit by diverting as much water as possible from the Ipswich River under the IRFRTG-recommended streamflow limitations. Saugus River annual average diversions ranged from 3.66 to 13.8 ft^3/s and averaged 9.62 ft^3/s. Average annual withdrawals from the Saugus River were about 2.2 times greater than the average annual withdrawals from the Ipswich River. Annual diversions from the Saugus River ranged from 27 to 100 percent of the allowed annual limit. The maximum allowed diversion from the Saugus River occurred once in 1972, and the minimum annual diversion occurred during 1965 and 1980. The annual diversion averaged 70 percent of total annual allowed withdrawal limit.

Streamflow-duration curves for the Ipswich River at the Lynn intake were similar for IRFRTG- and SRIFIM-withdrawal restrictions. Streamflow-duration curves for the Saugus River at the Lynn diversion indicate that withdrawals based on the SRIFIM restrictions maintained low flows (that is, streamflow with greater than a 80-percent exceedance level are unchanged from simulations with no withdrawals). In contrast, streamflow in the Saugus River at the Lynn intake under the

SRIFIM restrictions was about half the streamflow under the IRFRTG restrictions between the 5 and 70 percent exceedance interval (fig. 13*B*).

The volume of direct precipitation on the reservoir averaged 253 Mgal/yr during 1961–95, or about 6 percent of the average annual demand (fig. 14). The estimated direct evaporation loss from the reservoir system varies from an average of 52.0 Mgal in July to 0.90 Mgal in January and averaged 218 Mgal annually. Annual evaporation from the reservoir is about 14 percent less than the direct precipitation to the reservoir.

Firm-yield analysis indicated that, under the SRIFIM hypothetical restrictions, Lynn would need to decrease its average annual 1998–2000 withdrawals by about 31 percent to 7.31 Mgal/d (2,670 Mgal/yr). Lynn would have to purchase 3.29 Mgal/d, on average, to meet its 10.6 Mgal/d average 1998–2000 demands. A 31-percent decrease in annual withdrawals resulted in a minimum daily average reservoir storage of 81 Mgal on December 13, 1966, or about 2 percent of full capacity (fig. 15). A 30-percent decrease in withdrawals resulted in depleted storage for 4 days in December 1966. The firm yield under the SGIFIM hypothetical restrictions was 4.09 Mgal/d less (about 36 percent less) than the firm yield under permitted restrictions (11.4 Mgal/d) and 1.29 Mgal/d more (about 21 percent more) than the firm yield under the IRFRTG hypothetical restrictions (6.02 Mgal/d). Reservoir storage at the firm-yield withdrawal rate under SRIFIM hypothetical restrictions averaged 81 percent of capacity annually during 1961–95; the minimum average annual storage was 26 percent of capacity in 1966. During the drought of the early 1980s, the minimum daily reservoir storage was 304 Mgal or about 7.7 percent of capacity on November 16, 1981.

Peabody—Permitted Withdrawals

Simulation results indicate that the Peabody reservoir storage was depleted each year during 1961–95 under the permitted withdrawals and average 1998–2000 demands (fig. 16*A*). The reservoir system did not refill to capacity most years except for brief periods in 1982 and 1986; during these years, the reservoir filled to capacity for about two weeks following periods of above-normal precipitation. The reservoir storage recovered to 80-percent capacity or more (averaged 86 percent of capacity) for most years except 1965, 1966, 1980, 1981, 1985, and 1989. During 1966, 1981, and 1985, the reservoir system refilled to less than half capacity.

Annual reservoir storage under the permitted restrictions averaged 403 Mgal or about 32 percent of capacity. Reservoir storage was at a monthly minimum from October through December, and averaged slightly less than 1 percent of capacity (storage was often depleted), and was at a maximum during April at 80 percent of capacity (fig. 17 and table 8). Daily average reservoir storage was depleted about 30 percent of the time, below 25 percent of capacity about 50 percent of the time, and below 80 percent of capacity about 90 percent of the time (fig. 16*B*).

Peabody was able to withdraw water from the Ipswich River under permitted withdrawals about 25 percent of the time (fig. 18). Withdrawals, when they occurred, were mostly at the maximum pumping rate of 18 Mgal/d (28 ft^3/s); the lower rates (11 and 4 Mgal/d) were used infrequently. Average annual withdrawals from the Ipswich River ranged from 4.88 to 6.36 ft^3/s and averaged 6.27 ft^3/s. During the 6 months when withdrawals were permitted, the monthly withdrawals averaged 12.7 ft^3/s. Annual withdrawals, on average, were 99 percent of the allowed annual limit (1,500 Mgal/yr); annual withdrawal limits were reached in all years except 1966 and 1980–81. Streamflow-duration curves (fig. 19) for RCHRES 20 indicate that simulated flow was slightly less under permitted restrictions than flow without withdrawals below the 60-percent-exceedance interval. Withdrawals for Lynn and Peabody were both stopped under the no-withdrawal scenario (ground-water withdrawals still applied); stopping withdrawals for Peabody only would have had even less effect on streamflow.

Average monthly precipitation on the Peabody reservoir ranged from a low of 1.09 Mgal in November to 32.0 Mgal in April in response to changes in reservoir surface area (fig. 20). Average annual direct precipitation was 187 Mgal during 1961–95 or about 9 percent of the average annual demands. Estimated evaporation loss from the reservoir varied widely from summer to winter and averaged 176 Mgal annually or about 6 percent less than direct precipitation. Average monthly evaporation from the reservoir was greatest during July (46 Mgal) and lowest during December (0.09 Mgal).

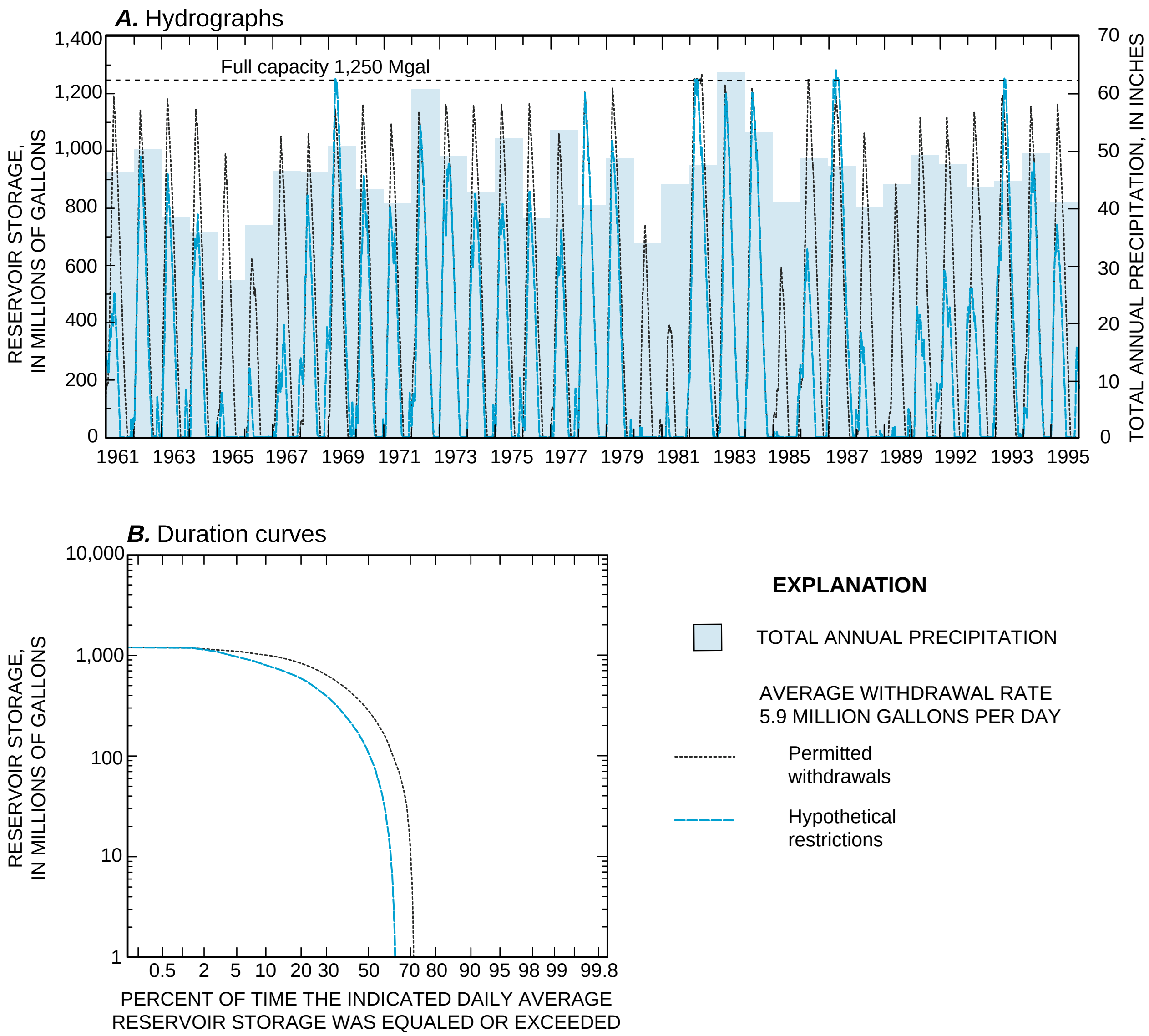

Figure 16. Daily reservoir storage simulated at average 1998–2000 demands under permitted withdrawals and hypothetical restrictions, Peabody water-supply system, Massachusetts, 1961–95; (*A*) hydrographs and (*B*) duration curves.

Firm-yield analysis indicated that, under the permitted withdrawals, Peabody would have to decrease average annual 1998–2000 withdrawals by about 37 percent to 3.70 Mgal/d (1,351 Mgal/yr). Peabody would need to purchase 2.2 Mgal/d, on average, to meet demands. A 37-percent decrease in withdrawals resulted in a minimum daily storage of 13.3 Mgal on November 30, 1981, or about 1.1 percent of capacity (fig. 21). This decrease in demand is consistent with the amount of water purchased by Peabody from the MWRA during 1998–2000, which made up nearly 30 percent of Peabody's total demand in the late summer of 1999. Total withdrawals in December averaged 172 Mgal, which was slightly below the average annual withdrawal rate (179 Mgal/yr). Reservoir storage at the firm-yield withdrawal rate averaged 23 percent of capacity annually and average annual storage was at a minimum of 11 percent in 1981. During the drought of the 1960s, daily reservoir storage was at a minimum of 91 Mgal or about 7 percent of capacity on December 25, 1966.

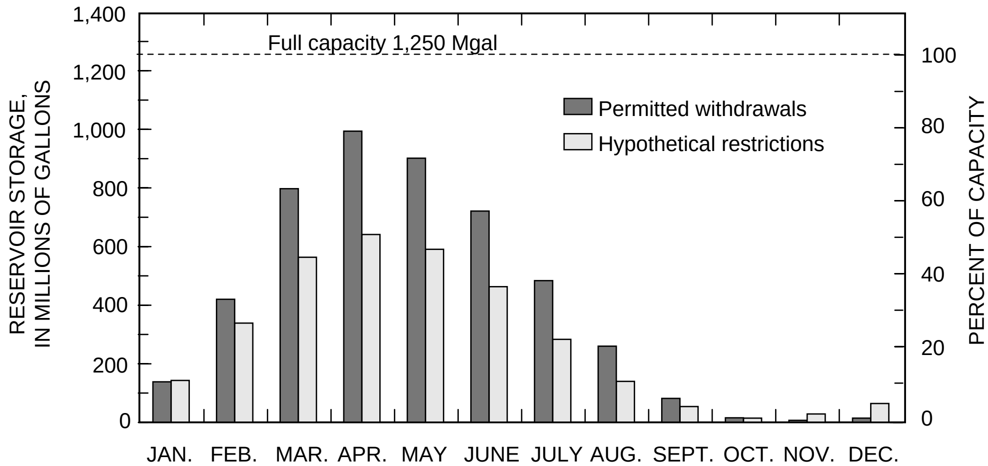

Figure 17. Average monthly reservoir storage simulated at average 1998–2000 demands (5.9 million gallons per day) under permitted withdrawals and hypothetical restrictions, Peabody water-supply system, Massachusetts, 1961–95.

Table 8. Average monthly and minimum daily reservoir storage simulated at 1998–2000 demands (5.9 million gallons per day) under permitted withdrawals and hypothetical restrictions for the Peabody, Massachusetts, water-supply system, 1961–95

Month	Reservoir storage under permitted withdrawals				Reservoir storage under hypothetical withdrawal restrictions			
	Average (Mgal)	Percent of full capacity	Number of days dry	Percent of time dry	Average (Mgal)	Percent of full capacity	Number of days dry	Percent of time dry
January	138	11	167	15	142	11	251	23
February	420	34	69	7.0	338	27	111	11
March	797	64	14	1.3	563	45	78	7.2
April	994	80	0	.0	641	51	99	9.4
May	902	72	0	.0	590	47	159	15
June	721	58	0	.0	463	37	227	22
July	483	39	45	4.1	283	23	321	30
August	260	21	95	8.8	139	11	549	51
September	81.2	6.5	327	31	53.3	4.3	716	68
October	14.8	1.2	947	87	13.7	1.1	925	85
November	6.1	.5	1,019	97	27.9	2.2	642	61
December	13.7	1.1	933	86	63.8	5.1	598	55
Average	403	32	301	28	277	22	390	36

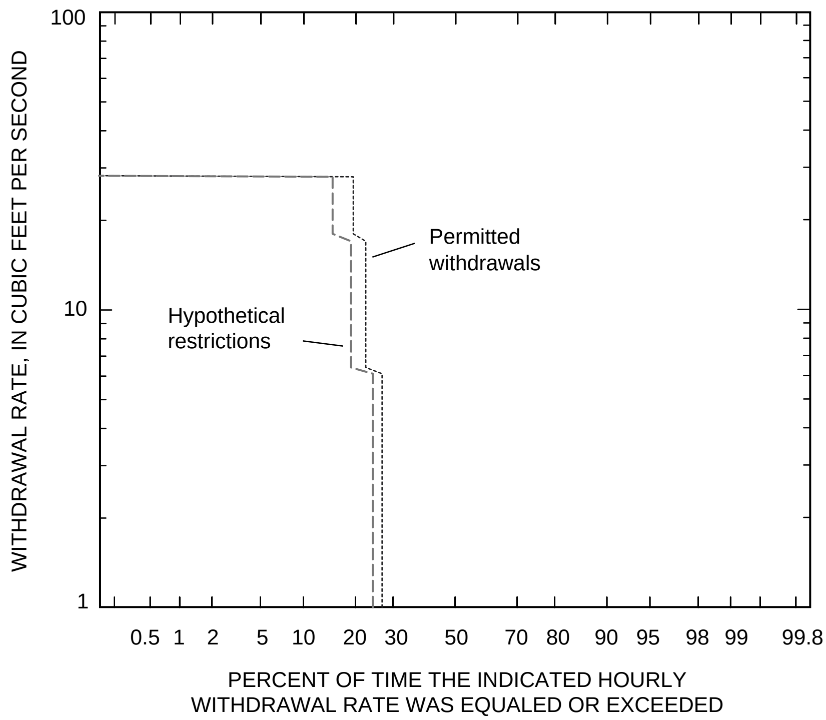

Figure 18. Withdrawal-duration curves from the Ipswich River (model reach 20) simulated at average 1998–2000 demands (5.9 million gallons per day) under permitted withdrawals and hypothetical restrictions, Peabody water-supply system, Massachusetts, 1961–95.

Peabody—Hypothetical Restrictions

Simulation results indicate that, under the hypothetical restrictions and average 1998–2000 demands (5.9 Mgal/d), Peabody's reservoir storage was depleted each year during 1961–95 (fig 16*A*). The reservoir did not refill to capacity most years except for brief periods in 1969, 1982, 1987, and 1993; during these years, the reservoir filled to capacity for only 8 to 42 days following periods of above-normal precipitation. On average, the reservoir filled to 60-percent capacity, and in 14 of 35 years, filled to less than half its capacity.

Annual reservoir storage under the hypothetical restrictions averaged 277 Mgal or about 22 percent of capacity. Reservoir storage was depleted, or nearly depleted, each year during October and November, which averaged slightly less than 2 percent of capacity. Average monthly storage in December increased slightly (5.1 percent of capacity) compared to the average December storage under permitted withdrawals (1.1 percent of capacity) because of the expanded time window within which withdrawals were allowed. Average monthly storage was greatest in April, at 51 percent of capacity, but was about 36 percent less than average April storage under permitted withdrawals (fig. 17 and table 8). Daily reservoir storage was depleted about 5 percent more often than under the permitted withdrawals, below 25 percent of capacity about 70 percent of the time, and below 80 percent of capacity about 95 percent of the time (fig. 16*B*).

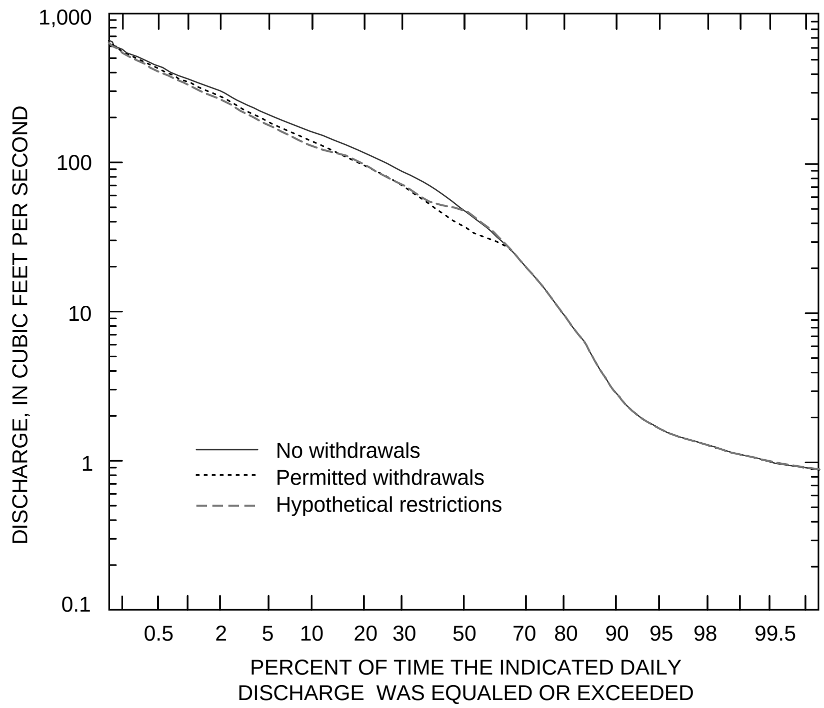

Figure 19. Daily average streamflow-duration curves simulated with no withdrawals and at average 1998–2000 demands (5.9 million gallons per day) under permitted withdrawals, and hypothetical restrictions at the intake location on the Ipswich River (model reach 20), Peabody water-supply system, Massachusetts, 1961–95.

Peabody withdrew water from the Ipswich River slightly less frequently under hypothetical restrictions than under permitted withdrawals (fig. 18). Average annual withdrawals from the Ipswich River ranged from 0.82 to 6.36 ft^3/s and averaged 5.27 ft^3/s during 1961–95. During the 7 months when withdrawals were permitted, monthly withdrawals averaged 9.21 ft^3/s. Annual withdrawals, on average, reached 83 percent of the allowed limit (1,500 Mgal/yr); annual limits were reached in 22 of 35 years. The fact that annual withdrawal limits were not reached during dry years indicates that withdrawals during these years were flow-limited. Ipswich River streamflow (fig. 19) under hypothetical restrictions is only slightly lower at the 50-percent exceedance interval than under permitted withdrawals.

Average monthly precipitation on the Peabody reservoir ranged from a low of 2.13 Mgal in October to 25.0 Mgal in April (fig. 20) mainly because of large variation in the reservoir surface area. Direct precipitation averaged 150 Mgal/yr during 1961–95 or about 7 percent of the average annual demands. Simulated annual evaporation averaged 118 Mgal or about 21 percent less than the direct annual precipitation, but varied widely from summer to winter. If a constant reservoir surface area at full capacity is assumed, direct precipitation averaged 402 Mgal/yr or about 19 percent of average demands. Direct precipitation on the reservoir with a constant surface area was about 2.7 times larger than simulated with a variable surface area.

Firm-yield analysis indicated that, under the hypothetical restrictions, Peabody would have to decrease average annual 1998–2000 withdrawals by about 67 percent to 1.94 Mgal/d (708 Mgal/yr). Peabody would need to purchase 3.96 Mgal/d, on average, to meet demands. Simulation of a 67-percent decrease in withdrawals resulted in a minimum daily reservoir storage of 15 Mgal on November 15, 1981, or about 1.2 percent of capacity (fig. 21). The firm yield under hypothetical restrictions was 1.76 Mgal/d, about half the withdrawal rate that could be sustained under permitted withdrawals. Annual reservoir storage at the firm-yield withdrawal rate averaged 25 percent of capacity and was at a minimum average annual

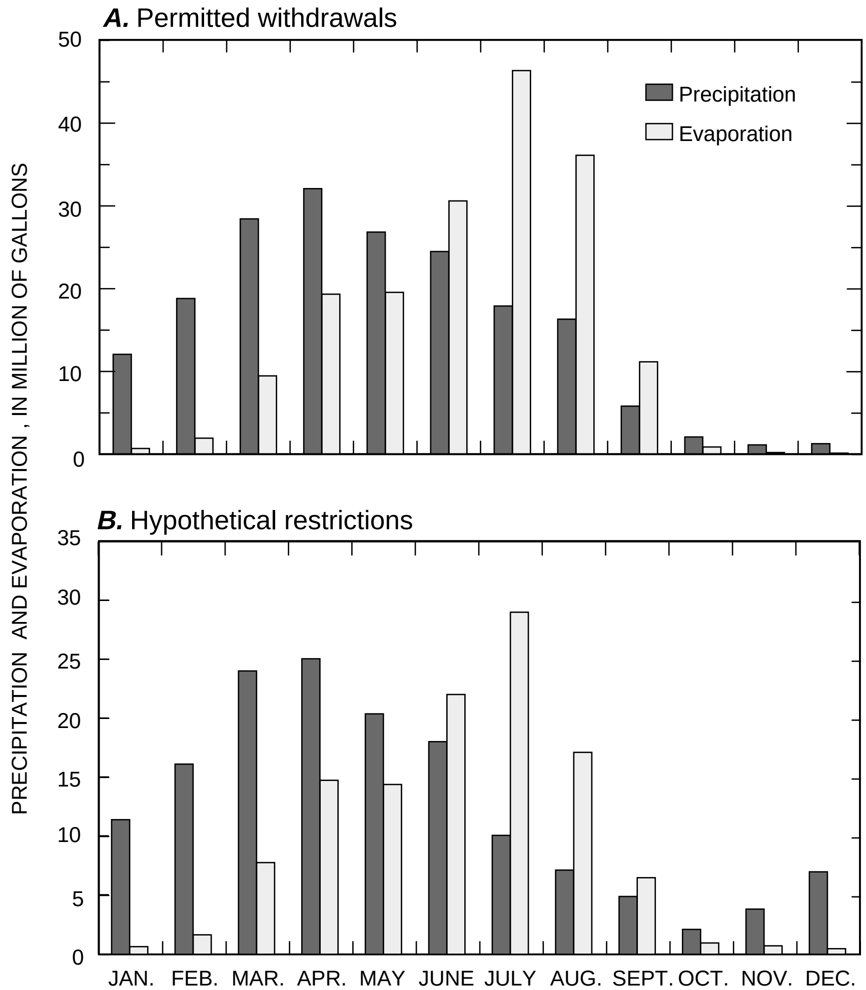

Figure 20. Average monthly volume of direct precipitation and evaporation simulated at average 1998–2000 demands (5.9 million gallons per day) under (*A*) permitted withdrawals and (*B*) hypothetical restrictions from the Peabody water-supply reservoir system, Massachusetts, 1961–95.

capacity of 7 percent in 1981. During the drought of the 1960s, reservoir storage was at a minimum of 211 Mgal or about 17 percent of capacity on January 6, 1967.

Salem–Beverly—Permitted Withdrawals

Simulation results indicate that, under the permitted withdrawals and average 1998–2000 demands (10.1 Mgal/d), the Salem–Beverly reservoir storage was maintained continuously during 1961–95 (fig. 22*A*). The reservoir was able to refill each year, even during the droughts of the 1960s and 1980s, albeit briefly.

Annual reservoir storage under the permitted restrictions and average 1998–2000 demands averaged 2,931 Mgal or about 82 percent of capacity (fig. 22*A*). The minimum annual average reservoir storage (2,310 Mgal) was 65 percent of capacity in 1980, which was only slightly less than the 1966 annual average storage (2,330 Mgal). The average monthly reservoir storage (fig. 23 and table 9) was at a minimum in November (averaged 57 percent of capacity) and at a maximum in April and May (averaged 100 percent of capacity or more). Daily average storage was near capacity 50 percent of the time, greater than 55 percent of capacity about 90 percent of the time, and greater than 42 percent of capacity about 99 percent of the time (fig. 22*B*).

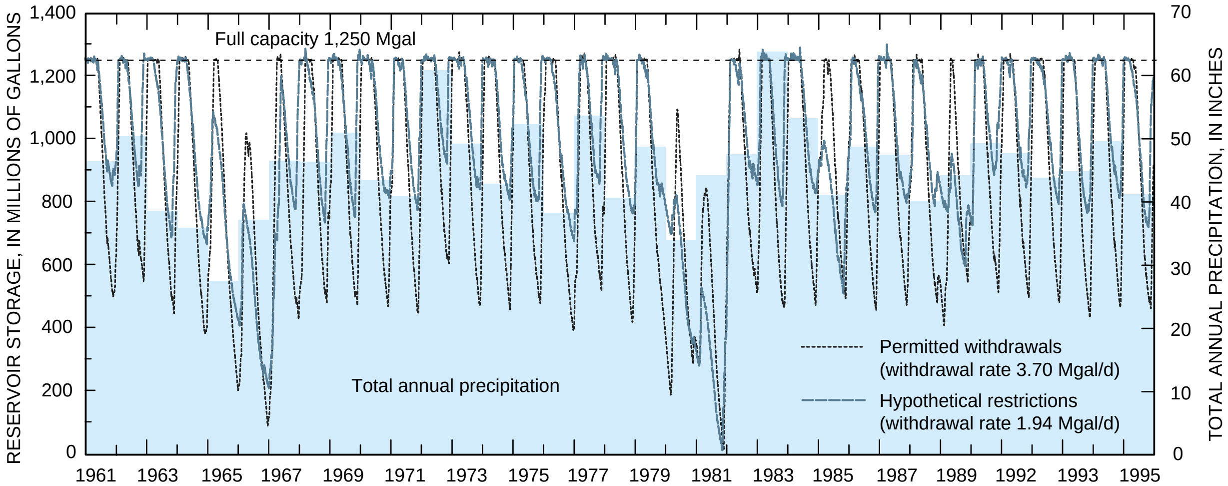

Figure 21. Daily reservoir storage simulated at firm-yield withdrawal rates in million gallons per day (Mgal/d) under permitted withdrawals and hypothetical restrictions, Peabody water-supply system, Massachusetts, 1961–95.

Salem–Beverly withdrew water from the Ipswich River about 15 percent of the time under permitted withdrawals (fig. 24); during this time withdrawals were split between the maximum pumping rate of 50 Mgal/d (77 ft^3/s) and the lower pumping rate of 25 Mgal/d (37 ft^3/s). Annual average withdrawals ranged from 2.21 to 15.4 ft^3/s and averaged 8.15 ft^3/s during 1961–95. During the 6 months when withdrawals were permitted, the average monthly withdrawal averaged 16.2 ft^3/s. Annual withdrawals, on average, were 47 percent of the allowed limit (4,128 Mgal/yr); the maximum annual withdrawal was 88 percent of the annual limit in 1981. Ipswich River streamflow, under permitted restrictions, is affected mostly between the 10- and 60-percent exceedance intervals as compared to no withdrawals (fig. 25).

Average monthly precipitation on the Salem–Beverly reservoir ranged from 40.9 Mgal in October to 60.3 Mgal in April (fig. 26). Direct precipitation averaged 603 Mgal/yr during 1961–95, which was about 16 percent of the average annual demand. Generally, direct precipitation was distributed more evenly throughout the year than the direct precipitation on the Lynn and Peabody reservoirs because the Salem–Beverly reservoir surface area fluctuated less. Estimated evaporation from the reservoir averaged 544 Mgal annually or about 10 percent less than direct precipitation, but evaporation varied widely from summer to winter. Evaporation, on average, was greatest during July (110 Mgal) and lowest during January (3.1 Mgal). Average July evaporation from the reservoir was about 2.5 times greater than the average direct precipitation for July.

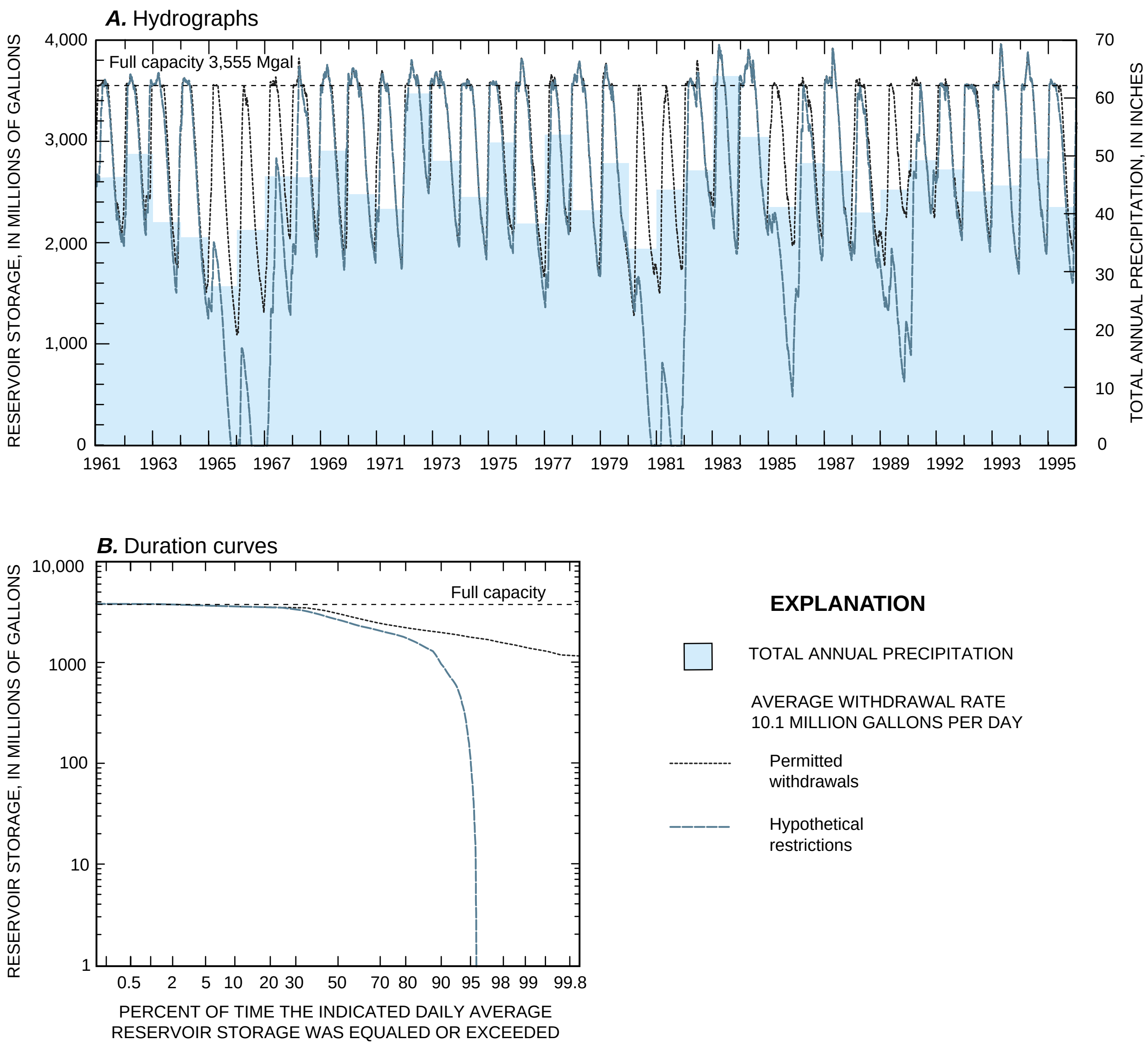

Figure 22. Daily reservoir storage simulated at average 1998–2000 demands under permitted withdrawals and hypothetical restrictions for the Salem–Beverly water-supply system, Massachusetts, 1961–95; (*A*) hydrographs and (*B*) duration curves.

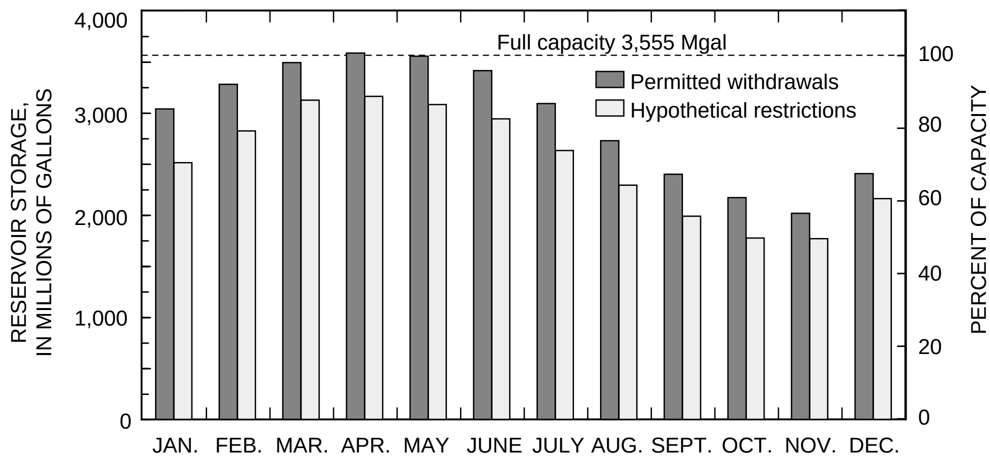

Figure 23. Average monthly reservoir storage simulated at average 1998–2000 demands (10.1 million gallons per day) under permitted withdrawals and hypothetical restrictions, Salem–Beverly water-supply system, Massachusetts, 1961–95.

Table 9. Average monthly and minimum daily reservoir storage simulated at average 1998–2000 demands (10.1 million gallons per day) under permitted withdrawals and hypothetical restrictions for the Salem–Beverly, Massachusetts, water-supply system, 1961–95

[Mgal, million gallons]

Month	Reservoir storage under permitted withdrawals				Reservoir storage under hypothetical withdrawal restrictions			
	Average (Mgal)	Percent of full capacity	Minimum daily (Mgal)	Percent of full capacity	Average (Mgal)	Percent of full capacity	Number of days dry	Percent of time dry
January	3,039	85	1,100	31	2,513	71	85	7.8
February	3,280	92	1,350	38	2,824	79	22	2.2
March	3,492	98	1,290	36	3,124	88	0	0
April	3,586	101	2,170	61	3,162	89	0	0
May	3,556	100	3,320	93	3,082	87	0	0
June	3,413	96	3,020	85	2,941	83	0	0
July	3,091	87	2,590	73	2,632	74	43	4.0
August	2,727	77	2,180	61	2,293	64	62	5.7
September	2,400	68	1,860	52	1,989	56	60	5.7
October	2,170	61	1,580	44	1,775	50	84	7.7
November	2,017	57	1,350	38	1,769	50	104	9.9
December	2,406	68	1,130	32	2,161	61	89	8.2
Average	2,931	82	1,912	54	2,522	71	46	4.3

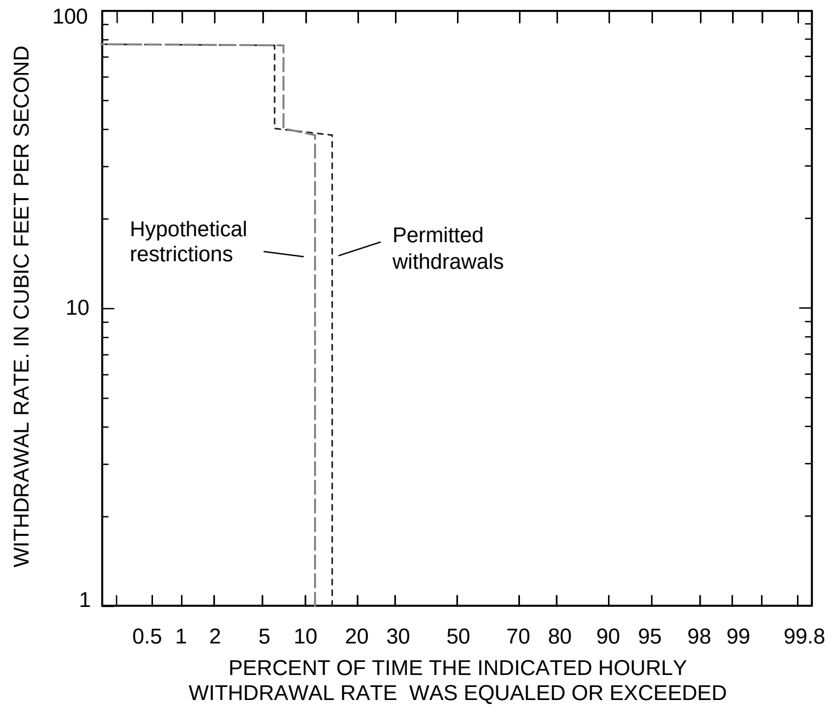

Figure 24. Withdrawal-duration curves from the Ipswich River (model reach 43) simulated at average 1998–2000 demands (10.1 million gallons per day) under permitted withdrawals and hypothetical restrictions, Salem–Beverly water-supply system, Massachusetts, 1961–95.

Firm-yield analysis indicates that, under permitted withdrawals, Salem–Beverly would be able to increase average annual 1998–2000 withdrawals by about 21 percent, to 12.2 Mgal/d (4,467 Mgal/yr). With a 21-percent increase in average 1998–2000 withdrawals, the minimum daily reservoir storage was 24 Mgal on December 24, 1966, or about 0.7 percent of capacity (fig. 27). Increasing average 1998–2000 withdrawals by 22 percent caused the storage to be depleted for 4 days in December 1966. December withdrawals averaged 297 Mgal, which is slightly less than the annual average withdrawal rate (308 Mgal). The reservoir did not fail during the summer when withdrawals were typically about 20 percent above the average annual withdrawal rate. Reservoir storage at the firm-yield withdrawal rate averaged 67 percent of capacity during 1961–95; the minimum annual capacity was 30 percent in 1981. During the drought of the early 1980s, daily reservoir storage was at a minimum of 82.9 Mgal or about 2.3 percent of capacity on November 30, 1981.

Salem–Beverly—Hypothetical Restrictions

Simulation results indicated that, under the hypothetical restrictions and average 1998–2000 demands, the Salem–Beverly reservoir storage was depleted during the drought years of the mid 1960s and early 1980s (fig. 22*A*). The reservoir did not fill to

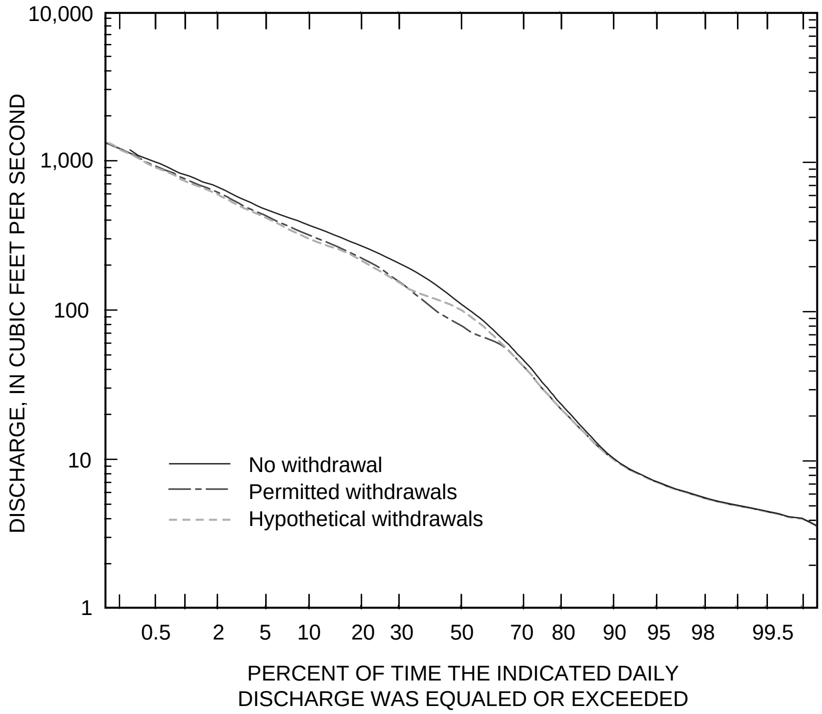

Figure 25. Daily streamflow-duration curves simulated with no withdrawals and at average 1998–2000 demands (10.1 million gallons per day) under permitted withdrawals and hypothetical restrictions at the Ipswich River (total flow at model reaches 43 and 47), Salem–Beverly water-supply system, Massachusetts, 1961–95.

capacity during these droughts and two other periods of below-normal precipitation in the mid and late 1980s. In general, however, the simulated reservoir storage under hypothetical restrictions closely matched the simulated storage under permitted withdrawals.

Reservoir storage under the hypothetical restrictions averaged 2,522 Mgal annually or about 71 percent of capacity. Average monthly reservoir storage was least in October and November, which averaged about 50 percent of capacity, and greatest in April, which averaged 89 percent of capacity (fig. 23 and table 9). Average storage in March and May was nearly equal to the average storage in April. Daily reservoir storage under hypothetical restrictions was similar to the daily storage under permitted restrictions until the 80-percent exceedance interval (fig. 22*B*). At the 90-percent exceedance level daily storage drops sharply; this drop reflects the occasional periods when storage was depleted (about 5 percent of the time). The reservoir storage was depleted occasionally in all months except March through June (table 8); storage was most often depleted in November (about 9.9 percent of the time).

Salem–Beverly withdrew water from the Ipswich River at a slightly lower rate under hypothetical restrictions than under permitted withdrawals (fig. 24). Annual withdrawals from the Ipswich River ranged from 0.42 to 14.9 ft^3/s and averaged 7.31 ft^3/s during 1961–95. Monthly withdrawals averaged 13.9 ft^3/s during the 7 months when withdrawals were allowed. Annual withdrawals, on average, were 42 percent of the allowed limit (4,128 Mgal/yr); annual limits were not reached during 1961–95. The annual maximum withdrawal was 3,515 Mgal in 1977 or about 85 percent of the allowed limit. Ipswich River streamflow is affected slightly less around the 50-percent exceedance interval under hypothetical restrictions than under permitted withdrawals (fig. 25).

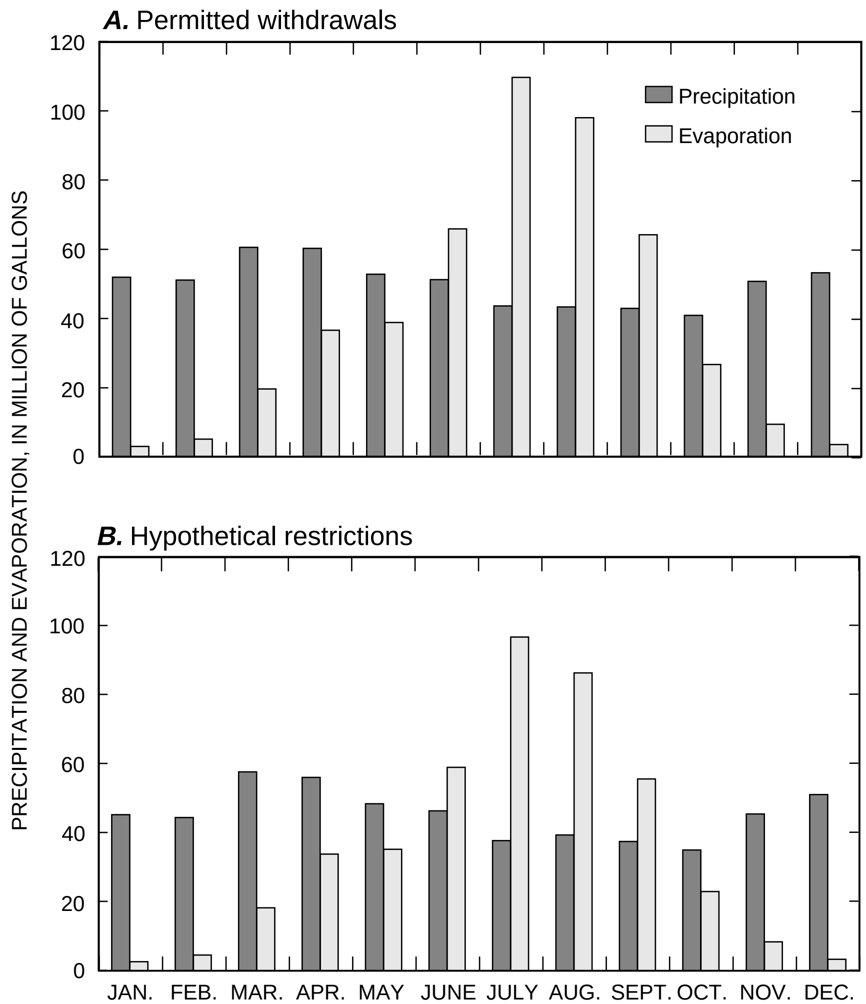

Figure 26. Average monthly volume of direct precipitation and evaporation simulated at average 1998–2000 demands (10.1 million gallons per day) under (*A*) permitted withdrawals and (*B*) hypothetical restrictions from the Salem–Beverly water-supply reservoir system, Massachusetts, 1961–95.

Average monthly precipitation on the Salem–Beverly reservoir ranged from 35 Mgal in October to 58 Mgal in March (fig. 26). Direct precipitation averaged 544 Mgal/yr or about 15 percent of the average annual demands. Simulated evaporation from the reservoir averaged 426 Mgal annually or about 22 percent less than the direct precipitation. If the reservoir surface area is assumed constant at full capacity, direct precipitation averaged 700 Mgal/yr, or about 19 percent of the average annual water demand. Direct precipitation on the reservoir system with a constant surface area was 16 percent larger than simulated under permitted withdrawals and 29 percent larger than simulated under hypothetical restrictions.

Firm-yield analysis indicated that, under the hypothetical restrictions, Salem–Beverly would need to decrease average 1998–2000 withdrawals by about 24 percent to 7.69 Mgal/d (2,806 Mgal/yr). A 24-percent decrease in average 1998–2000 withdrawals resulted in a minimum daily reservoir storage of 8.0 Mgal on December 24, 1966, or about 0.2 percent of capacity (fig. 27). Decreasing average 1998–2000 withdrawals

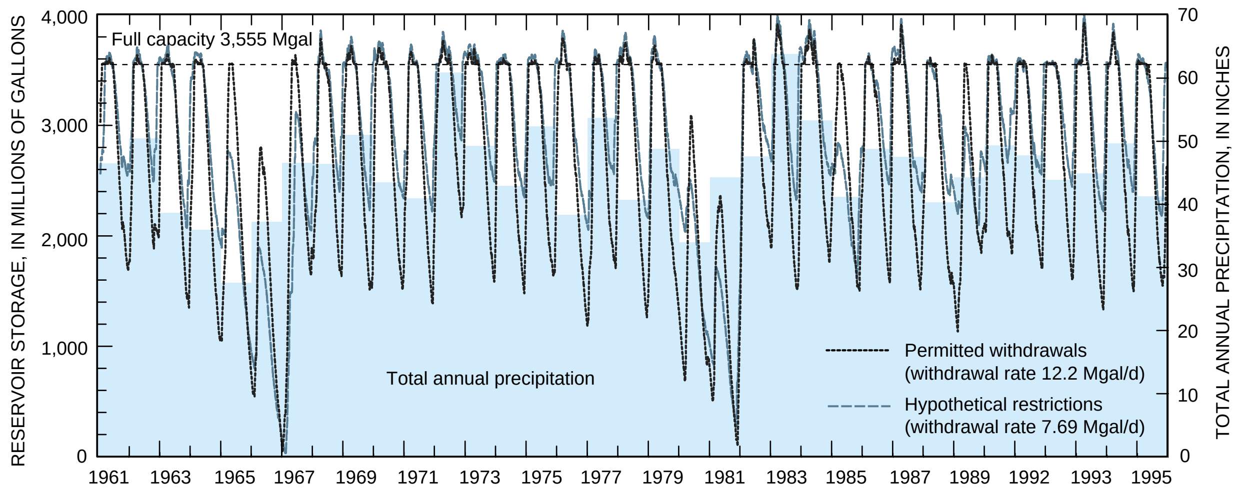

Figure 27. Daily reservoir storage simulated at firm-yield withdrawal rates in million gallons per day (Mgal/d) under permitted withdrawals and hypothetical restrictions, Salem–Beverly water-supply system, Massachusetts, 1961–95.

by 23 percent resulted in depleted storage for 32 days at the beginning of 1967. Salem–Beverly would have an average shortfall of 2.41 Mgal/d between average 1998–2000 demands and the firm-yield withdrawal rate under hypothetical restrictions. Reservoir storage at the firm-yield withdrawal rate averaged 73 percent of capacity annually and was at a minimum average capacity of 26 percent in 1981. During the drought of the early 1980s, reservoir storage was at a minimum of 259 Mgal or about 7.3 percent of capacity on November 16, 1981.

DISCUSSION OF SIMULATION RESULTS

The reservoir storage and firm-yield analysis indicates that reservoir storage was strongly tied to streamflow and the withdrawal restrictions placed upon it. Simulation results indicate that the firm-yield withdrawal rates for permitted withdrawals, relative to average 1998–2000 demands, could increase by 8 and 21 percent for Lynn and Salem–Beverly, respectively, and would need to decrease by 37 percent for Peabody (table 10) to maintain withdrawals within the firm-yield rate. Overall withdrawals from the Ipswich River by these suppliers could increase by 3 percent at the firm-yield withdrawal rate under the permitted withdrawals. Simulation results indicate that the firm-yield withdrawal rates under the Ipswich River hypothetical restrictions (and IRFRTG-recommended streamflow requirements applied in the Saugus River for the Lynn System) would be 43, 67 and 24 percent less than average 1998–2000 demands, for Lynn, Peabody, and Salem–Beverly respectively. Overall withdrawals from the Ipswich River by these suppliers would need to decrease by 41 percent to attain the firm-yield withdrawal rate. In order to meet demands, decreased withdrawals from the Ipswich River Basin (and Saugus River Basin for Lynn) would require importing water from other sources or imposing stringent conservation measures, or both. Simulation results under SRIFIM streamflow requirements applied in the Saugus River indicate that the firm-yield withdrawal rate for Lynn is about 31 percent less than the average 1998–2000 demands (7.31 Mgal/d).

These estimates are calculated as the maximum withdrawal rate that can be sustained without depleting reservoir storage. Refined stage-storage characteristics of the supply reservoirs could affect the firm yield calculated. Furthermore, water-supply managers may not be able to lower reservoirs to the minimum reported level because of engineering or water-quality constraints. For example, as reservoir levels approach the upper invert elevation of the intake, pumps may not operate properly because a vortex that entrains air could develop.

Simulation results produced two distinct types of response curves when transformed into dimensionless quantities of percent reservoir capacity against the

Table 10. Firm-yield estimates for three surface-water-supply systems under permitted withdrawals and hypothetical restrictions, Ipswich River Basin, Massachusetts

[Mgal, million gallons]

Supplier	Average 1998–2000 demands (Mgal/d)	Permitted		Hypothetical	
		Firm yield (Mgal/d)	Percent change from 1998–2000	Firm yield (Mgal/d)	Percent change from 1998–2000
Lynn	10.6	11.4	8.0	[1]6.02	-43
Lynn	10.6	--	--	[2]7.31	-31
Peabody	5.88	3.70	-37	1.94	-67
Salem–Beverly	10.1	12.2	21	7.69	-24
Total	26.6	27.3	3.0	[1]15.6	-41

[1]Applied Ipswich River Fisheries Restoration Task Group recommended streamflow requirements to the Saugus River withdrawals.
[2]Applied Instream Flow Incremental Methodology streamflow requirements to the Saugus River withdrawals.

percent of time the daily reservoir storage equals or exceeds a specified capacity (fig. 28). The response curves for Lynn under permitted withdrawals, and for Salem–Beverly under permitted withdrawals and hypothetical restrictions, are similar (convex shape). These systems, under permitted withdrawals, maintained at least 25 percent of capacity, and maintained at least 50 percent of their capacity 95 percent of the time. Under hypothetical restrictions, Salem–Beverly would be able to maintain 50 percent of the reservoir storage 80 percent of the time, but unless trigger conservation measures are implemented, the Salem–Beverly system storage would be depleted about 5 percent of the time.

Simulation results under 1998–2000 demands indicate that the reservoir storage for the Lynn system under hypothetical restrictions (IRFRTG-recommended streamflow requirements applied in the Saugus River) and Peabody system under permitted and hypothetical restrictions have similar response curves (concave shape). For these systems and conditions storage was 50 percent of capacity nearly 70 percent of the time or more and failed about 30 percent of the time or more; the reservoir systems would have less than 25 percent storage about 50 to 75 percent of the time. For the Lynn system under hypothetical restrictions and SRIFIM streamflow requirements applied in the Saugus River, the reservoir systems would have less than 25 percent storage about 30 percent of the time. Without imports of water, Peabody's reservoir storage would be expected to be below 50 percent of capacity about 70 percent of the time during 1965–95, as indicated by the simulation results under permitted withdrawals; thus, Peabody needs to obtain some water from other sources. For systems that can obtain water from other sources, the firm yield of the reservoir system would be added to the maximum amount of water that can be obtained from other sources to obtain the overall firm yield. The amount of water from other systems could be limited by infrastructure, permit agreements, firm-yield constraints of the other sources, or a combination of these factors.

Under firm-yield withdrawal rates, the reservoir storage nearly empties for each system for each set of withdrawal restrictions; thus, response curves are generally similar (fig. 29). Although the reservoir does not completely empty at the firm-yield withdrawal rate, the percent of time when the reservoir storage is at low capacity could be important in evaluating the systems' firm yields. For example, at the firm-yield withdrawal rates the Peabody reservoir is below 50 percent capacity about 25 percent of the time under permitted withdrawals, but storage is below 50 percent of capacity less than 10 percent of the time under hypothetical restrictions. Thus, the reservoir storage is at a greater capacity for a greater percentage of time under hypothetical restrictions than under permitted withdrawals. The additional reservoir storage under hypothetical restrictions compared to the permitted withdrawals at a given percentage of time provides more protection from droughts. Reservoir storage for each of the systems evaluated under hypothetical restrictions was generally greater than the reservoir storage under permitted restrictions above the 5-percent exceedance level because the firm-yield withdrawal rate was less under hypothetical restrictions than for permitted withdrawals.

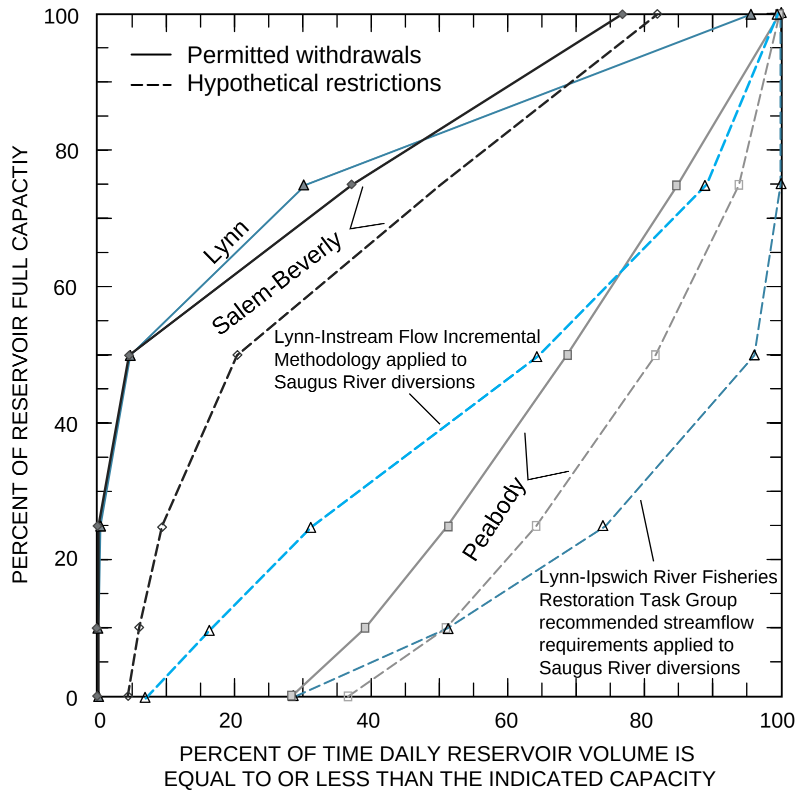

Figure 28. Percentage of time the daily reservoir storage equals or is less than the indicated capacity simulated for 1961–95 at average 1998–2000 demands under permitted withdrawals and hypothetical restrictions for three surface-water supplies in the Ipswich River Basin, Massachusetts.

Water-supply management practices commonly restrict water use as the reservoir storage drops to critical levels. These restrictions often begin as voluntary conservation practices at the first signs of reservoir storage falling below normal levels and could extend to water rationing if storage falls to very low levels. Imposing progressively restrictive water-use measures when reservoir storage reaches critical levels can help safeguard water supplies during droughts. Restrictions triggered by designated low levels of reservoir storage could increase the firm-yield of a system because storage would be maintained for longer periods if phased reductions in water use were imposed. The effects of further water-use restrictions on reservoir storage could be examined by the use of additional HSPF special actions that alter demands through storage-triggered reductions. Altered demands should be based on the expected changes in water use under phased restrictions. The percentage of time reservoir storage is at or below specified capacities at the average 1998–2000 withdrawal rates (fig. 28) provides an indication of the frequency at which these three suppliers would need to impose water-use restrictions under permitted withdrawals and hypothetical restrictions.

For example, water-use restrictions might be progressively triggered when reservoir storage drops below 75, 50 and 25 percent of capacity. Lynn, under permitted withdrawals, average 1998–2000 withdrawals, and no imports of water, could then be expected to issue first-stage restrictions about 30 percent of the time, 2d-stage restrictions about 5 percent of the time, and 3d-stage restrictions about 1 percent of the time. Lynn, under hypothetical restrictions, average 1998–2000 withdrawals, and no imports of water would be expected to have first-stage restrictions all the time, 2d-stage restrictions about 95 percent of the time, and 3d-stage restrictions about 75 percent of the time. Even with successive water-use restrictions, Lynn may not be able to prevent the reservoir system from failing under hypothetical restrictions and IRFRTG-recommended

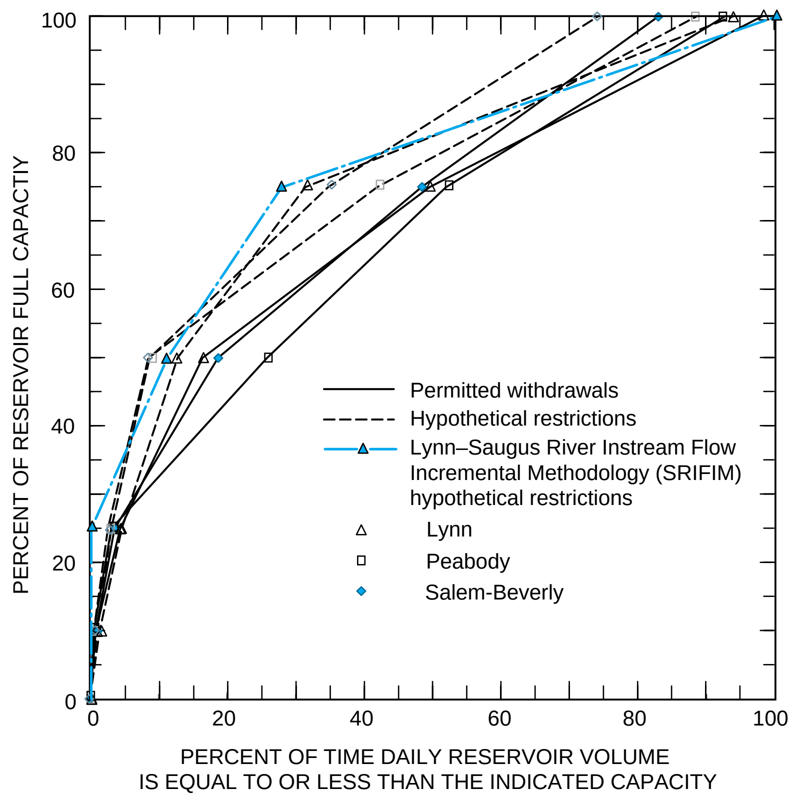

Figure 29. Percentage of time daily reservoir storage equals or is less than the specified capacity simulated for 1961–95 at firm-yield withdrawal rates under permitted withdrawals and hypothetical restrictions for three surface-water supplies in the Ipswich River Basin, Massachusetts.

streamflow requirements in the Saugus River. In general, supply systems and conditions that result in convex response curves would require fewer restrictions, for shorter periods of time, than supply systems and conditions that result in a concave response curve.

The firm-yield estimator model (Massachusetts Department of Environmental Protection, 1996) performs a screening analysis to determine the frequency and length of time over which a reservoir fails to refill to capacity. In cases where the reservoir fails to refill 1 month a year for 15 percent of the years in the screening period, the state recommends a bootstrap method to generate a synthetic precipitation and streamflow record for computing the monthly water budget for the reservoir. The bootstrap method randomly pieces together 2-year data sequences 500 times to generate a 1,000-year record from which a firm yield is calculated. The bootstrap procedure was recommended in the firm-yield guidance document because of the influence of starting conditions on the firm-yield estimate for large reservoir systems (what constitutes a large reservoir was not defined, however). Pretto and others (1997) state that a minimum simulation period of 500 years is needed to estimate the firm-yield of large reservoirs to prevent the influence of starting conditions in the firm-yield calculation.

The firm-yield estimates for the systems evaluated in this study were largely insensitive to the reservoir-storage starting condition. Starting conditions affect the reservoir firm-yield estimate only when the reservoir system fails to cycle through a period of partial depletion and full recovery before entering the period of failure. Each of the three systems was able to go through several cycles of seasonal low storage and full recovery before entering the critical drought period of the mid 1960s even if the initial storage was set to half capacity. The reservoir system did not go through a cycle of full recovery before the critical drought period only when the initial storage was set unreasonably low (typically less than 35 percent of capacity). For each firm-yield simulation for each reservoir system, the initial reservoir storage was set to the average January storage simulated at the firm-yield withdrawal rate. In all cases, the reservoir went through several cycles of seasonal low storage and recovery before the critical drought period that first depleted storage. Thus, for the reservoir system examined, a 500-year simulation was not necessary in order to prevent the influence of starting conditions on the firm-yield estimate.

SUMMARY

The firm yield of a surface-water supply is considered by the Commonwealth of Massachusetts to be the maximum withdrawal rate that can be sustained during a severe drought. To ensure that communities can meet current and future water-supply demands, the Commonwealth requires water suppliers to calculate a firm yield for their system. The firm-yield calculation requires information on inflows to water-supply reservoirs, but the volume of water supplied from the Ipswich River is not easily derived because withdrawals are regulated by the time of year and minimum streamflow requirements. The Hydrologic Simulation Program FORTRAN (HSPF) model previously developed for the Ipswich River Basin was modified to simulate the hydrologic response and firm yields of water-supply reservoirs under average 1998–2000 demands over a 35-year period (1961–95). The HSPF model was used to simulate inflows to the reservoir systems that could be made under permitted withdrawals and hypothetical restrictions, which are designed to maintain seasonally varied streamflow for aquatic habitat.

Three surface-water supply systems that withdraw water from the Ipswich River were examined for this study—Lynn, Peabody and Salem–Beverly. The Lynn system also withdrew water from the Saugus River. Annual water demands during 1998–2000 averaged 3,855 Mgal/d for Lynn, 2,145 Mgal/d for Peabody, and 3,692 Mgal for Salem–Beverly. Lynn and Peabody, on average, obtained about 3 and 10 percent of annual water supply from the Massachusetts Water Resource Authority (MWRA), respectively, during 1998–2000. Seasonally, summertime demands are about 20 to 50 percent higher than the winter demands.

Massachusetts Department of Environmental Protection (MDEP) permitted withdrawals allow these supply systems to obtain water from the Ipswich River between December 1 and May 31, when flows are above minimum thresholds. These thresholds are referenced to streamflow at U.S. Geological Survey (USGS) gaging stations at South Middleton and Ipswich. The minimum discharges allowed after withdrawals are 15 and 23 ft^3/s at the South Middleton gaging station for Lynn and Peabody, respectively, and 43 ft^3/s at the Ipswich gaging station for Salem–Beverly. Withdrawals by Lynn from the Saugus River, however, are not restricted by season or flow requirements. Withdrawals from the Ipswich and Saugus Rivers are restricted to a maximum annual volume.

Maintaining seasonally varied streamflow has been recommended for fisheries in the Ipswich River. The streamflow requirements recommended are expressed as a flow per unit drainage area and vary from 0.49 $ft^3/s/mi^2$ from June through October, 1.0 $ft^3/s/mi^2$ from November through February, 2.5 $ft^3/s/mi^2$ in March and April, and 1.5 $ft^3/s/mi^2$ in May. Maintaining these seasonal flows would require water suppliers to stop withdrawals when streamflow at the intake drops below these limits. For example, the drainage area at the Peabody intake is 46 mi^2; thus Peabody would stop pumping when streamflow (including withdrawals) drops below 115 ft^3/s during March and April. These recommended streamflows were simulated as hypothetical restrictions. The Lynn system was simulated by two sets of hypothetical restrictions on withdrawals from the Saugus River. The first set of hypothetical restrictions limited Saugus River withdrawals to the same streamflow criteria recommended by the Ipswich River Fisheries Restoration Task Group (IRFRTG); the second set of restrictions had less stringent streamflow requirements developed on the basis of the Saugus River Instream Flow Incremental Methodology (SRIFIM) study. SRIFIM streamflow requirements stopped withdrawals when flows were below 0.29 $ft^3/s/mi^2$ from June through

September, 0.57 $ft^3/s/mi^2$ from October through February, 1.14 $ft^3/s/mi^2$ in March and April, and 0.95 $ft^3/s/mi^2$ in May.

The HSPF model previously developed for the Ipswich River Basin was modified to include a simplified representation of multi-reservoir supplies as a single reservoir for each of the three surface-water supplies. Modifications also included HSPF special actions that evaluated the reservoir storage deficit, determined whether criteria for withdrawing water from its source or sources could be satisfied, and withdrew water when these conditions were met within the physical constraints of the system. Separate model-run files were developed for the permitted withdrawals and the hypothetical restrictions. Model simulations were made on an hourly time step for the 1961–95 period with average 1989–93 ground-water withdrawals and average 1998–2000 surface-water withdrawals. The average surface-water withdrawals were incrementally increased to determine the reservoir firm yield for systems that did not fail during 1961–95 under average 1998–2000 withdrawals, and were incrementally decreased to determine the reservoir firm yield for systems that failed during 1961–95 under average 1998–2000 withdrawals.

Simulation results indicated that, under the permitted withdrawals, Lynn and Salem–Beverly were able to meet demands and generally have their reservoir systems recover to full capacity during most years. The firm yields for the Lynn and Salem–Beverly systems were 11.4 Mgal/d (4,163 Mgal/yr) and 12.2 Mgal/d (4,467 Mgal/yr), respectively, which is an increase of 8 and 21 percent, respectively, from their average 1998–2000 withdrawals. At the firm-yield withdrawal rate, reservoir storage for these systems was typically depleted first in late 1966 or early 1967, which was at the end of the most severe drought on record. Simulations under the permitted withdrawals and average 1998–2000 surface-water demands indicated that reservoir storage averaged 83 and 82 percent of capacity for the Lynn and Salem–Beverly systems, respectively. Under permitted restrictions and average 1998–2000 demands, Peabody was not able meet demands and the reservoir system was not able to fully recover during most years. The firm yield for the Peabody system is 3.70 Mgal/d (1,351 Mgal/yr), which is 37 percent less than the average 1998–2000 withdrawals. Peabody purchased about 10 percent of its water from the MWRA, on average, during 1998–2000, but water obtained from the MWRA was as much as 30 percent of their total monthly demand during this period.

Simulations indicate that under the hypothetical restrictions and IRFRTG-recommended streamflow requirements applied in the Saugus River, and average 1998–2000 demands, none of the three water-supply systems could meet demands. Reservoir storage was depleted during most years except for periods of above-normal precipitation for the Lynn system, and in all years for the Peabody system. The Salem–Beverly system reservoir storage was depleted during the droughts of the mid-1960s and early 1980s. The reservoir storage was not able to recover to full capacity in all years for the Lynn system and in most years for the Peabody system, but the Salem–Beverly system recovered to full capacity in most years except during the drought years. Reservoir storage under hypothetical restrictions and average 1998–2000 demands averaged 15, 22, and 71 percent of capacity for the Lynn, Peabody, Salem–Beverly systems, respectively. The firm yield under the hypothetical restrictions was 43, 67, and 24 percent less than average 1998–2000 demands for the Lynn, Peabody, and Salem–Beverly systems, respectively. The firm yield under hypothetical restrictions is 6.02 Mgal/d (2,197 Mgal/yr) for Lynn (IRFRTG-recommended streamflow requirements applied in the Saugus River), 1.94 Mgal/d (708 Mgal/yr) for Peabody, and 7.69 Mgal/d (2,806 Mgal/yr) for Salem–Beverly. The firm yield, under hypothetical restrictions and the SRIFIM-recommended streamflow requirements applied in the Saugus River, was about 31 percent less than the average 1998–2000 demands for Lynn (7.31 Mgal/d). Firm-yield estimates do not include the effects of phased water-use restrictions, which could be simulated by additional HSPF special actions.

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