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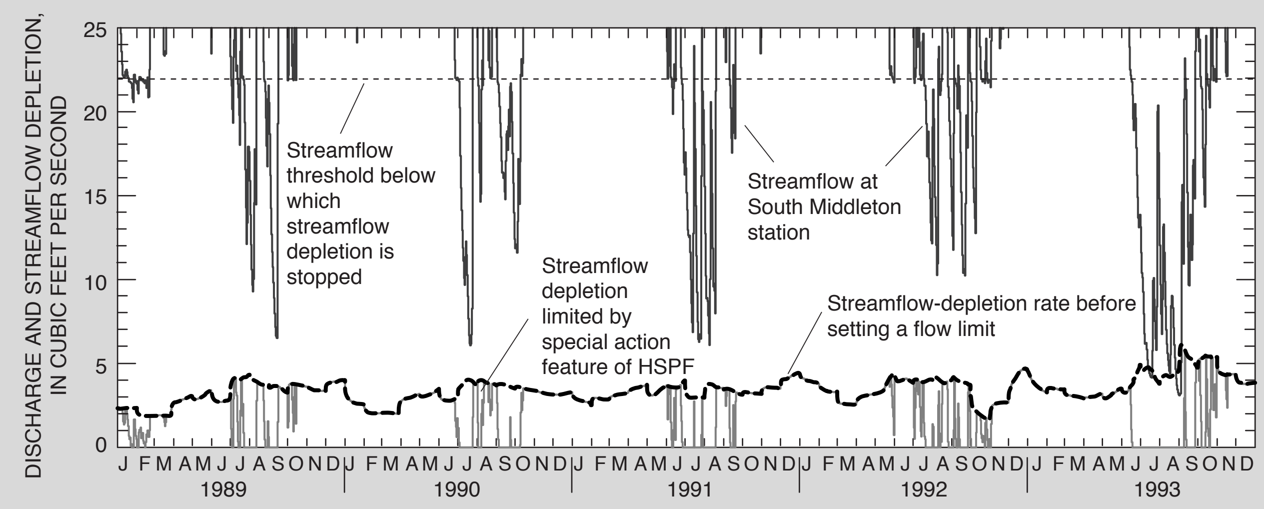
Open-File Report 01-483



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By PHILLIP J. ZARRIELLO

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Northborough, Massachusetts
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Effects of Water-Management Alternatives on Streamflow in the Ipswich River Basin, Massachusetts

By Phillip J. Zarriello

Abstract

Management alternatives that could help mitigate the effects of water withdrawals on streamflow in the Ipswich River Basin were evaluated by simulation with a calibrated Hydrologic Simulation Program—Fortran (HSPF) model. The effects of management alternatives on streamflow were simulated for a 35-year period (1961–95). Most alternatives examined increased low flows compared to the base simulation of average 1989 93 withdrawals. Only the simulation of no septic-effluent inflow, and the simulation of a 20 percent increase in withdrawals, further lowered flows or caused the river to stop flowing for longer periods of time than the simulation of average 1989–93 withdrawals. Simulations of reduced seasonal withdrawals by 20 percent, and by 50 percent, resulted in a modest increase in low flow in a critical habitat reach (model reach 8 near the Reading town well field); log-Pearson Type III analysis of simulated daily-mean flow indicated that under these reduced withdrawals, model reach 8 would stop flowing for a period of seven consecutive days about every other year, whereas under average 1989–93 withdrawals this reach would stop flowing for a seven consecutive day period almost every year. Simulations of no seasonal withdrawals, and simulations that stopped streamflow depletion when flow in model reach 19 was below 22 cubic feet per second, indicated flow would be maintained in model reach 8 at all times. Simulations indicated wastewater-return flows would augment low flow in proportion to the rate of return flow. Simulations of a 1.5 million gallons per day return flow rate indicated model reach 8 would stop flowing for a period of seven consecutive days about once every 5 years; simulated return flow rates of 1.1 million gallons per day indicated that model reach 8 would stop flowing for a period of seven consecutive days about every other year. Simulation of reduced seasonal withdrawals, combined with no septic effluent return flow, indicated only a slight increase in low flow compared to low flows simulated under average 1989–93 withdrawals. Simulation of reduced seasonal withdrawal, combined with 2.6 million gallons per day wastewater-return flows, provided more flow in model reach 8 than that simulated under no withdrawals.

INTRODUCTION

The Ipswich River Basin in northeastern Massachusetts supplies water to many communities in and near the basin. At times, insufficient flow caused in part by water withdrawals from the basin have affected the aquatic habitat and recreational use of the river. The Ipswich River Task Force, now known as the Ipswich River Watershed Management Council, was formed in 1996 in response to low-flow problems associated with water-supply withdrawals. The mission of the Council is to protect the ecological integrity of the river and to sustain the quality of an important drinking water supply. A comprehensive watershed management plan, rooted in sound scientific data and analysis, is integral to this mission.

The Hydrological Simulation Program—Fortran (HSPF) precipitation-runoff model developed and calibrated for the Ipswich River Basin by the U.S.

Geological Survey, in cooperation with Massachusetts Departments of Environmental Protection and Environmental Management (Zarriello and Ries, 2000), provides a quantitative tool for evaluating the streamflow response to various water management plans. In 2001, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Executive Office of Environmental Affairs (EOEA), began evaluating the effects of management alternatives on streamflow in the Ipswich River Basin by modifying the existing HSPF model of the basin.

Purpose and Scope

This report describes the effects of 11 hypothetical water-management alternatives on streamflow in the Ipswich River Basin, Massachusetts. Water-management alternatives include altering water-withdrawal rates, returning wastewater to the basin, stopping septic-effluent inflows, and combinding withdrawal and wastewater management alternatives. All management alternatives were evaluated with an existing HSPF model documented in Zarriello and Ries (2000). This report includes a brief discussion of the HSPF model, but focuses on the modifications that were made to the model to simulate the water-management alternatives. This report describes the simulation results for eleven management plans and compares these results to simulations of no withdrawals and to simulations of average withdrawals from January 1989 through December 1993. All simulations were run for the 35-year period from January 1961 through December, 1995.

Study Area

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 for the basin. This report focuses on the headwaters of the Ipswich River Basin above the South Middleton station.

Model Description

The Hydrological Simulation Program—Fortran (HSPF) precipitation-runoff model (Bricknell and others, 1997) was developed and calibrated for the Ipswich River Basin (Zarriello and Ries, 2000). The Ipswich River Basin HSPF model consists of 15 pervious (PERLND) and 2 impervious (IMPLND) hydrological response units (HRUs) that are generally similar in land use and surficial geologic deposits. Surface flow from IMPLNDs and surface and subsurface flow from PERLNDs is directed into 67 river reaches or reservoir segments (RCHRES) that represent the hydrologic network of the basin. The model was calibrated to flow data from the South Middleton and Ipswich streamgaging stations for the period 1989–93. Daily withdrawals were obtained or estimated from monthly records for each major pumped well in the basin for 1989–93 (or longer when available).

The analytical program STRMDEPL (Barlow, 2000) was used to calculate streamflow-depletion rates caused by each pumped well. This rate reflects the time-delayed response of streamflow depletion to changes in pumping; the time-delay response is a function of the distance of the well from the stream and the hydraulic properties of the aquifer. The surface-water withdrawals and streamflow-depletion rates caused by pumping individual wells were combined to obtain the total streamflow-depletion rate for each reach affected by withdrawals. In this study, new streamflow-depletion rates were computed that reflect the alternative withdrawal rate being simulated. The STRMDEPL extension (Zarriello and others, 2001) in GenScn, a graphic interface for running and analyzing HSPF model simulations (Kittle and others, 1998), was used to compute new combined streamflow-depletion rates for each reach where withdrawals were altered for the period that pump rate data were available (generally from January 1989 through December 1993). For other periods (generally from January 1961 through December 1988, and January 1994 through December 1995), the average monthly streamflow-depletion rates were calculated from the available streamflow-deletion data and transformed into a daily streamflow-depletion rate.

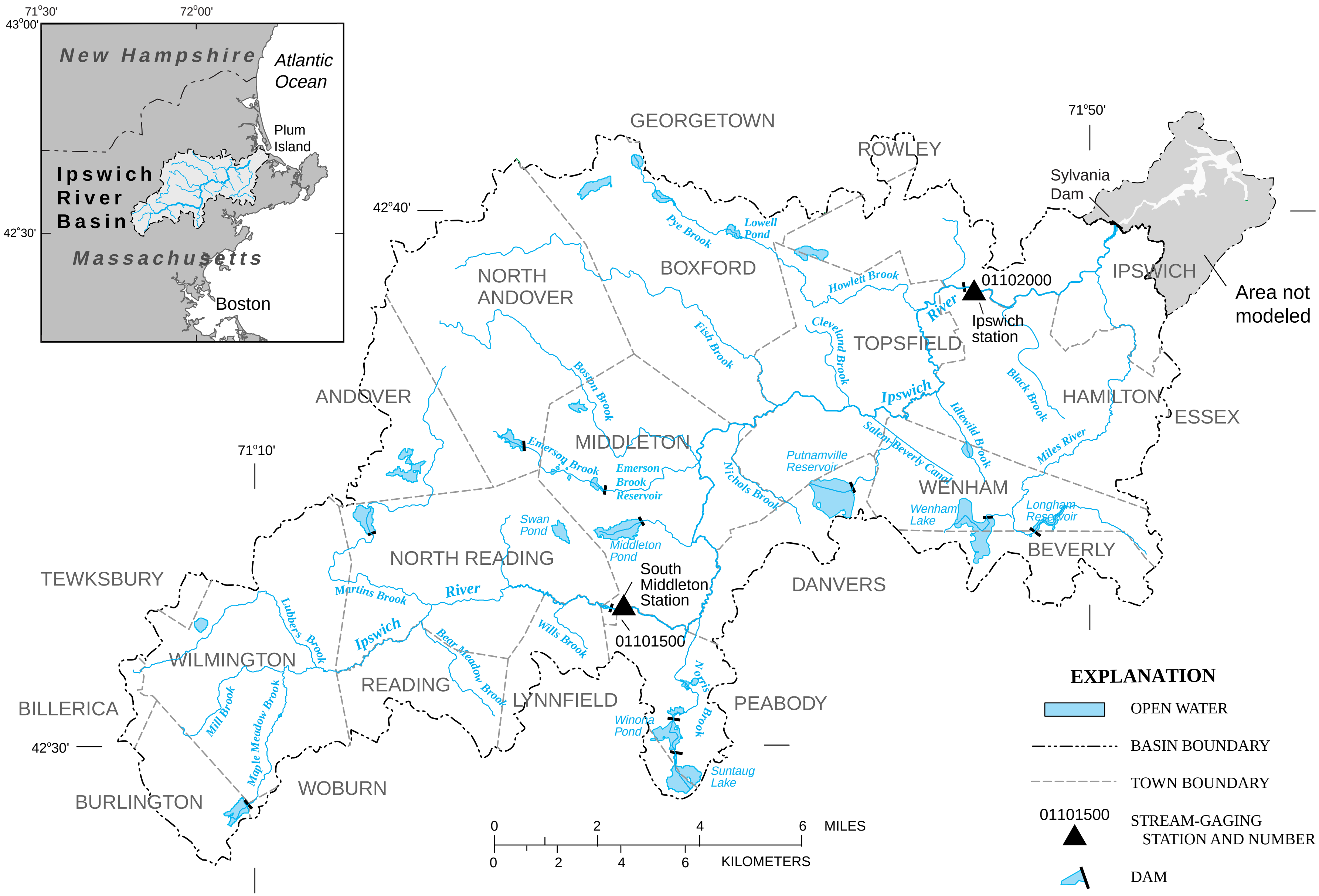

Figure 1. Municipalities, drainage network, and stream-gaging stations in the Ipswich River Basin, Massachusetts.

For each management alternative withdrawal-rate, the computed streamflow depletion rates associated with that plan were saved to a unique data-set number (DSN) in the water data management (WDM) file. The DSN associated with each management alternative being simulated were read into the HSPF model through the EXTERNAL SOURCE block of the user control file (uci) to specify the new streamflow depletion rate from the first exit gate of a model reach. A model reach can have up to five exit gates; typically the first exit gate was used to specify outflow from a reach for the combined streamflow depletion rates from pumped wells and surface-water withdrawals, and the second exit gate was used to specify the flow to the next downstream model reach. Wastewater-return flow rates were read into the model through the EXTERNAL SOURCE block of the uci file as an additional source of water to the upstream end of a model reach.

DESCRIPTION OF SIMULATED WATER-MANAGEMENT ALTERNATIVES

Water-management alternatives under consideration by the Ipswich River Watershed Management Council include changes in water withdrawals, wastewater management, and combinations of these options (Kerry Mackin, Ipswich River Watershed Association, written commun., 2000). Changes in simulated water-withdrawal rates were restricted to the headwater subbasins, particularly model reach numbers (RCHRES) 1, 5, 8, 12, and 13, where the towns of Wilmington and Reading obtain water from pumped wells (fig. 2). Wilmington obtains water from five wells along Maple Meadow Brook (RCHRES 1), two wells along Lubbers Brook (RCHRES 5), and three wells along Martins Brook (RCHRES 12 and 13). Reading obtains water from 10 wells along the Ipswich River in RCHRES 8. Zarriello and Ries (2000) summarize well names and numbers in table 5 of the Ipswich River Basin model report.

Simulations of water-supply-withdrawal alternatives included seasonal restrictions, streamflow triggered restrictions, and increased withdrawals. Simulations of wastewater management alternatives included return flows of 1.1 and 1.7 Mgal/d at four sites in Wilmington, return flows of 1.5 Mgal/d at one site in Reading, and elimination of septic-effluent inflow that would result from expansion of public sewers. Simulations also included seasonal decrease in withdrawal rate combined with wastewater-return flow, and seasonal decrease in withdrawal rate combined with no septic effluent inflow. The scenarios simulated are named by the prefix of the HSPF model uci file for the management option simulated and the attribute (IDSCEN) used to identify the scenario in the associated WDM file. The modified uci files reflect the HSPF model calibrated to 1991 land-use conditions. The water-management alternatives simulated are summarized in table 1 and are described in more detail below.

LT-NoDem—Previously run simulation made to evaluate how no withdrawals affect streamflow (Zarriello and Ries, 2000). The MFACT (a multiplier used when reading time-series data into the model) in the EXTERNAL SOURCE block of the LT-NoDem.uci file was set to zero to stop withdrawals.

LT-Demd—Previously run simulation made to evaluate how average 1989–93 withdrawals affect streamflow over long-term climatic conditions (Zarriello and Ries, 2000). All subsequent simulations of alternative water-withdrawals options are derivative from the average 1989–93 rates used in this simulation.

NSea-dmd—This simulation is used is to evaluate the effects on streamflow of no seasonal withdrawals in the headwater reaches (RCHRES 1, 5, 8, 12, and 13) of the basin (fig. 2). The STRMDEPL was run for each well in each of these reaches using a multiplication factor of zero during May through October to compute new streamflow-depletion rates. Although withdrawals were stopped in these reaches from May 1 to October 31, streamflow depletion continues throughout the summer because of the delayed response of past pumping (fig. 3). For example, in RCHRES 1 (fig. 3*A*) the streamflow-depletion rate drops sharply in May when pumping stops, but reaches only about 0.3 to 0.2 ft^3/s by the end of October when pumping resumes.

Figure 2. Water-supply withdrawal sites and hypothetical wastewater-return flow sites in the headwaters of the Ipswich River Basin, Massachusetts.

Table 1. Water-management alternatives simulated with the Hydrologic Simulation Program—Fortran (HSPF) of the Ipswich River Basin, Massachusetts

[DSN, Data Set Number in the WDM file, where xx (last two digits) corresponds to the model reach number; IDSCEN, attribute in the WDM file that IDentifies the SCENario; WDM is the Watershed Data Management system used with the HSPF model; Mgal/d, millions of gallons per day].

Target data set number for model output (DSN)	Scenario identification (IDSCEN)	Water-management alternative description	External source data set number for streamflow depletion (DSN)
		Previously run simulations	
63xx	LT-NoDem	No withdrawals	5xx
65xx	LT-Demd	Average 1989–93 withdrawals	5xx
		Water-supply-withdrawal simulations	
69xx	NSea-dmd	No seasonal withdrawals May 1 to October 31	4xx
70xx	QMin-dmd	Flow-threshold-limited streamflow depletion	5xx
71xx	RSea-dmd	Reduced seasonal withdrawals by 50 percent May 1 to October 31	7xx
72xx	Inc-dmd	Increased withdrawals by 20 percent	5xx
78xx	Dec-dmd2	Decreased withdrawals by 20 percent June 1 to September 30	6xx
		Wastewater-return simulations	
67xx	LT-WWR1	Wastewater return of 1.1 Mgal/d in Wilmington	5xx
68xx	LT-WWR2	Wastewater return of 1.7 Mgal/d in Wilmington	5xx
73xx	WWR4	Wastewater return of 1.5 Mgal/d in Reading	5xx
74xx	NoSeptic	No septic effluent inflow	5xx
		Combined simulations	
75xx	Rdmd-WWR	Reduced withdrawal by 50 percent and wastewater return flow of 2.6 Mgal/d	7xx
76xx	Rdmd-Nsp	Reduced withdrawal by 50 percent and no septic effluent inflow	7xx

QMin-dmd—This simulation is used to evaluate the effects on streamflow of no withdrawals in the headwater reaches (RCHRES 1, 5, 8, 12, 13, 17, and 18) when streamflow at the South Middleton gaging station (RCHRES 19) is less than 22 ft^3/s, the aquatic-base flow (ABF) default minimum flow threshold (0.5 ft^3/s per mile square). This simulation required the use of the ‘Special Action’ feature (Jobes and others, unpublished report) to adjust the streamflow depletion when the flow at RCHRES 19 is below 22 ft^3/s. The special action feature adjusts streamflow-depletion rate by subtracting the previous time step streamflow-depletion rate from the current rate. The time step lag was necessary because of the order in which the HSPF executes the special action relative to when the streamflow depletion rate is read into the model. In most cases, the streamflow-depletion rate does not change abruptly from one time step to another, and the special action sets the streamflow depletion rate at the current time step to zero when flow in RCHRES 19 falls below 22 ft^3/s (as shown in fig. 4). In a few instances, the adjusted streamflow may not be set to zero because the streamflow-depletion rate at the previous time step differs from the rate of the current time step. In addition, the actual streamflow-depletion rate would be greater if a river-flow criterion is used to manage pumping operations because of the delayed effects between pump operations and streamflow depletion, which are influenced by the aquifer hydraulic properties and the distance of the well from the stream.

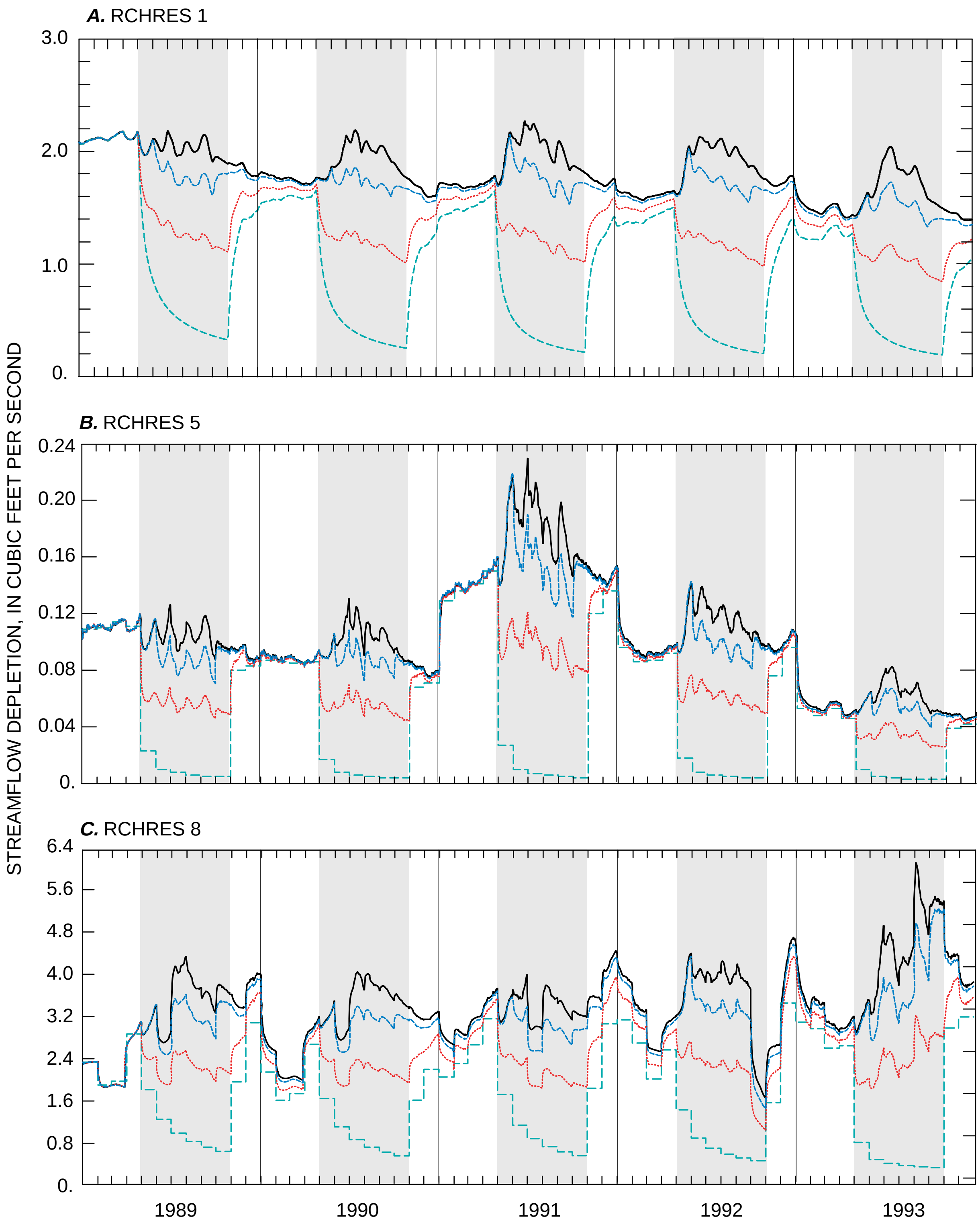

Figure 3. Daily streamflow-depletion rates calculated for alternative withdrawal rates at selected model reaches in the Ipswich River Basin, Massachusetts.

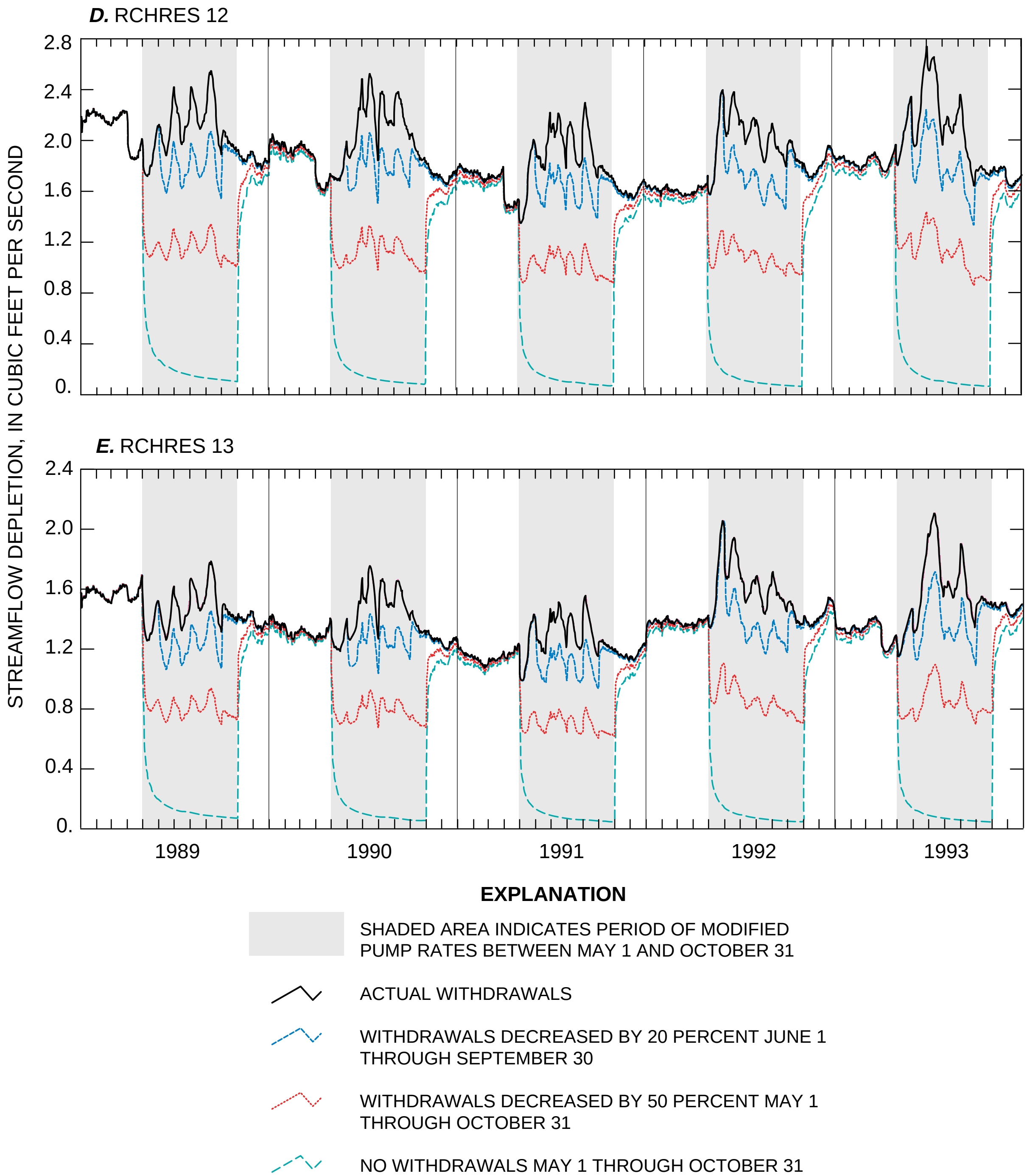

Figure 3. Daily streamflow-depletion rates calculated for alternative withdrawal rates at selected model reaches in the Ipswich River Basin, Massachusetts—*Continued*.

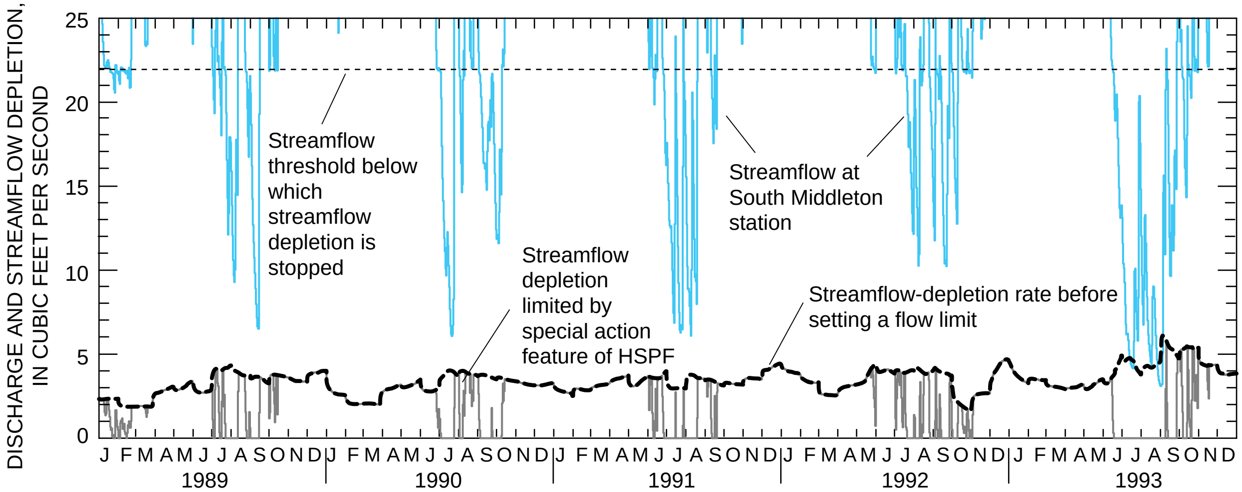

Figure 4. Example of the streamflow depletion at model reach 8 limited by a special action developed for the Hydrological Simulation Program—Fortran (HSPF) when model reach 19 is below 22 cubic feet per second, Ipswich River Basin, Massachusetts.

For example, if a water supplier is required to stop pumping when streamflow in RCHRES 19 falls below 22 ft^3/s, the actual streamflow depletion rate will not immediately go to zero as simulated by the special action. Streamflow-depletion rates will, however, substantially decrease and approach zero at most wells in response to the cessation of pumping because of their proximity to the stream, but the streamflow-depletion-rate response to the change in pump rate will vary from well to well depending on the aquifer properties and distance of the well from the stream.

RSea-dmd—This simulation is used to evaluate the effects on streamflow of a 50-percent decrease in seasonal withdrawals in RCHRES 1, 5, 8, 12 and 13, which affects the supply to the towns Wilmington and Reading. To decrease the water-supply withdrawals from the Ipswich River Basin one or more of the following management practices are needed; (1) aggressive water conservation, (2) obtaining water from outside of the basin, and (3) optimizing the pumping rates from wells at various distances from the stream to maximize withdrawals while minimizing streamflow depletion during low-flow periods.

New streamflow-depletion rates were computed for wells in RCHRES 1, 5, 8, 12, and 13 using a multiplication factor of 0.5 for May through October. Combined streamflow-depletion rates (table 2) for 1989–93 for Wilmington supply wells ranged from 5.00 to 5.90 ft^3/s (3.23 to 3.81 Mgal/d, respectively) and averaged 5.50 ft^3/s (3.56 Mgal/d). A 50-percent decrease in withdrawal rates would require conserving water, importing water, and optimizing pumping rates or combinations of these practices at a rate of 2.50 to 2.96 ft^3/s (1.62 to 1.91 Mgal/d) or, on average, 2.75 ft^3/s (1.78 Mgal/d) from May through October. Combined streamflow depletion rates for 1989–93 for Reading supply wells ranged from 3.29 to 3.98 ft^3/s (2.13 to 2.57 Mgal/d, respectively)

Table 2. Average 1989–93 withdrawal rates and a 50-percent reduction in withdrawal rate from the Ipswich River Basin from May and October for the towns of Wilmington and Reading, Massachusetts

[**Wilmington:** Includes withdrawals from wells along model reaches 1, 5, 12, and 13. **Reading:** Includes withdrawals from wells along model reach 8. ft^3/s, cubic feet per second]

Month	Wilmington		Reading	
	Average 1989–93 withdrawal rate (ft^3/s)	50-percent rate decrease (ft^3/s)	Average 1989–93 withdrawal rate (ft^3/s)	50-percent rate decrease (ft^3/s)
May	5.00	2.50	3.29	1.64
June	5.53	2.76	3.43	1.71
July	5.90	2.95	3.87	1.94
August	5.61	2.85	3.93	1.97
September	5.68	2.84	3.98	1.99
October	5.20	2.60	3.57	1.78
Average	5.50	2.75	3.68	1.84

and averaged 3.68 ft^3/s (2.38 Mgal/d). A 50-percent decrease in withdrawal rates would require conserving water, importing water, and optimizing pumping rates or combinations of these practices at a rate of 1.06 to 1.29 Mgal/d or on average 1.19 Mgal/d from May through October.

Inc-dmd—The purpose of this simulation is to evaluate the effects on streamflow of increased withdrawals. Although increasing withdrawal in an already stressed system is undesirable, this simulation provides evidence of how conditions could worsen if further demands were placed on the system. Streamflow depletion rates were increased uniformly by 20 percent in RCHRES 1, 5, 8, 12, and 13 by modifying the MFACT in the EXTERNAL SOURCE block of the Inc-dmd.uci file.

Dec-dmd2—This simulation is used to evaluate the effects on streamflow of decreased withdrawals that could be achieved through water conservation alone during the summer. Streamflow-depletion rate was reduced in RCHRES 1, 5, 8, 12, and 13 by decreasing withdrawals by 20-percent from June through September.

LT-WWR1—This simulation is used to evaluate how returning 1.1 Mgal/d of wastewater at four potential sites in Wilmington affects streamflow (Richard Tomczyk, Ipswich River Watershed Team Leader, written commun., 2000). All wastewater-return sites are in the southwestern headwaters of the Ipswich River Basin; 3 in Lubbers Brook and 1 in Maple Meadow Brook, identified by numbers 1, 2, 3, and 4 (fig. 2). Wastewater-return-flow rates are summarized for each site in table 3.

The return-flow rates in table 3 were converted to acre-ft/hr, the input units required in the HSPF model, and added to the model at the reach identified in table 3 in the EXTERNAL SOURCE block of the uci file. Inflows are considered to enter the stream at the top of the reach identified; therefore, the model reaches associated with the return flow were selected on basis of the location of the top of the model reach closest to the wastewater-return site.

LT-WWR2— This simulation is used to evaluate how returning 1.7 Mgal/d of wastewater at four potential sites in Wilmington affects streamflow. This simulation is the same as WWR1, except that the return flow rate was increased.

WWR4— This simulation is used to evaluate how returning 1.5 Mgal/d of wastewater at one site above the Reading well field, RCHRES 8 (number 5, fig. 2), affects streamflow. The 1.5 Mgal/d flow rate (in acre-ft/hr) was added as an EXTERNAL SOURCE to RCHRES 8 as described above for simulation LT-WWR1.

NoSeptic— This simulation is used to evaluate the effects of stopping septic effluent inflow on streamflow. Expansion of public sewers would eliminate the lateral inflow from septic effluent to the upper soil zone in areas on public water and on-site septic systems. These areas were included in the calibrated HSPF model (Zarriello and Ries, 2000) as an inflow to the

Table 3. Hypothetical wastewater-return flow rates, and associated model reach of the return flow in the Town of Wilmington, Ipswich River Basin, Massachusetts

[Locations are shown in figure 2. Mgal/d, millions of gallons per day]

Site No.	Location	Reach		Return Flow (Mgal/d)	
		Name	Model No.	Scenario WWR1	Scenario WWR2
1	Blanchard Road	Lubbers Brook	5	0.2	0.3
2	Yentle Farm	Maple Meadow Brook	2	.4	.6
3	Salem Street	Lubbers Brook	7	.1	.2
4	Town Hall	Lubbers Brook	6	.4	.6
Total				1.1	1.7

basin at a rate consistent with the average daily household water use and density of housing. This scenario does not include (1) areas on private wells and public sewers that export water from the basin, (2) the effects of sewer lines leaking into the surrounding soil or ground-water infiltrating into the sewer lines and draining out of the basin, and (3) the effects of sewering from future development.

Rdmd-WWR—This simulation is used to evaluate the combined effects on streamflow of reducing seasonal withdrawals and returning wastewater. Withdrawal rates were decreased seasonally by 50 percent for pumped wells in RCHRES 1, 5, 8, 12, and 13 (same as simulation—RSea-dmd) and combined with wastewater-return flows of 1.1 Mgal/d at four sites in Wilmington (same as simulation—LT-WWR1) and 1.5 Mgal/d at one site in Reading (same as simulation—WWR4). A combined total wastewater-return-flow rate of 2.6 Mgal/d was used in this simulation.

Rdmd-Nsp—This simulation is used to evaluate the combined effects on streamflow of reduced seasonal withdrawals and no septic-effluent inflow. Withdrawal rates were decreased seasonally by 50-percent for pumped wells in RCHRES 1, 5, 8, 12, and 13 (same as simulation—RSea-dmd) and combined with the simulation no septic-effluent inflow (same as simulation—NoSeptic).

EFFECTS OF WATER-MANAGEMENT ALTERNATIVES ON STREAMFLOW

The effects of water-management alternatives on streamflow were examined at RCHRES 8 (Ipswich River at Town of Reading well field) and 19 (Ipswich River at the South Middleton gaging station). RCHRES 8 has a drainage area of 18.5 mi^2 and was selected for analysis because (1) this reach contains one of the few critical habitat reaches in the basin (Armstrong and others, 2001), and (2) water-management alternatives under consideration are targeted primarily to improve flow in this reach. Simulation results are also presented for RCHRES 19 (drainage area of 44.4 mi^2), because it was included in the results of model simulations by Zarriello and Ries (2000) and the reach is far enough upstream in the basin to illustrate changes in streamflow that could result from the water-management alternatives being simulated.

Streamflow in RCHRES 8 is affected by nineteen pumped wells and one surface-water withdrawal (fig. 2); the combined annual withdrawals up to and including RCHRES 8 averaged 3.67 Mgal/d from 1989–93. Streamflow in RCHRES 19 is affected by 14 additional pumped wells and three additional surface-water withdrawals; the combined withdrawals above RCHRES 19 averaged 6.92 Mgal/d from 1989–93. Average 1989–93 withdrawals normalized for drainage area were about 22 percent greater at RCHRES 8 than at RCHRES 19.

The effects of water-management alternatives on streamflow were examined by comparing various simulation results for the 1993 summer hydrographs, and analyzing flow-duration curves and log-Pearson Type III low-flow-frequency curves for 1-, 7-, and 30-day duration intervals for simulated 1961–95 daily-mean flow values. Results of the water-management simulations are presented for comparison with simulations previously made for the same period under no withdrawals and under average 1989–93 withdrawals (Zarriello and Ries, 2000). The baseline simulation of average 1989–93 withdrawal conditions indicates the effect these average pumping conditions have on flow characteristics over the long-term (1961–95) climatic conditions. Simulations of no withdrawals indicate what the flow characteristics would have been over the same period without withdrawals. Management options can be evaluated by the degree the flow characteristics change between these two sets of conditions.

Figures for each analysis are presented for RCHRES 8 and 19 in groups related to the management type. Simulations were grouped by alternative (A) water-supply management, (B) wastewater management, and (C) combined water-supply and wastewater management options.

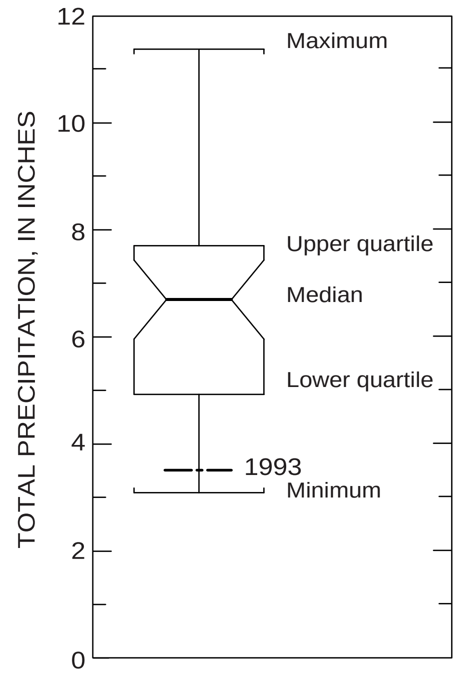

Figure 5. Total precipitation during July and August 1961 through 1995 relative to total precipitation during July and August 1993, Ipswich River Basin, Massachusetts.

Summer of 1993 Hydrographs

The summer of 1993 had the lowest flow recorded in the Ipswich River from 1989–93 for which actual data from pumped wells were available. Total precipitation during July and August 1993 was the fourth lowest in the same two months for the 35-year period—1961–95 (fig. 5). A comparison of hydrographs during this period illustrates the changes in low flow that can be achieved by the management alternatives examined.

RCHRES 8

Streamflow simulated under actual withdrawals for July and August, 1993 was zero; streamflow simulated under no withdrawals ranged from 1.2 to 11 ft^3/s and averaged 3.8 ft^3/s during this same period (fig. 6). Simulations of no seasonal withdrawals (NSea-dmd) and simulations that stopped streamflow depletion when flows are below 22 ft^3/s at RCHRES 19 (QMin-dmd) produced flows similar to the flows under no withdrawals. Simulations of reduced seasonal demands produced similar results; flow averaged 0.60 and 0.75 ft^3/s for the July and August for simulations of 20-percent (Dec-dmd2) and 50-percent (RSea-dmd) decrease in seasonal withdrawals, respectively. Simulations of reduced seasonal withdrawals resulted in zero flow 61- and 53-percent of the time during July and August of 1993 for a 20-percent decrease and a 50-percent decrease in seasonal withdrawals, respectively.

The relation of cumulative-withdrawal volume to cumulative-streamflow volume is non-linear over short periods because of the delay effects of the aquifer and distance of the wells from the stream. Figure 7 illustrates that a 20-percent decrease in seasonal withdrawals produced nearly the same amount of cumulative streamflow as a 50-percent decrease in seasonal withdrawals in July and August 1993. This indicates that under these conditions, decreases in withdrawals from 20 to 50 percent do not appreciably change the streamflow-depletion rate during these months. Therefore, management practices that target a narrow window during the summer may not achieve the desired streamflow objectives.

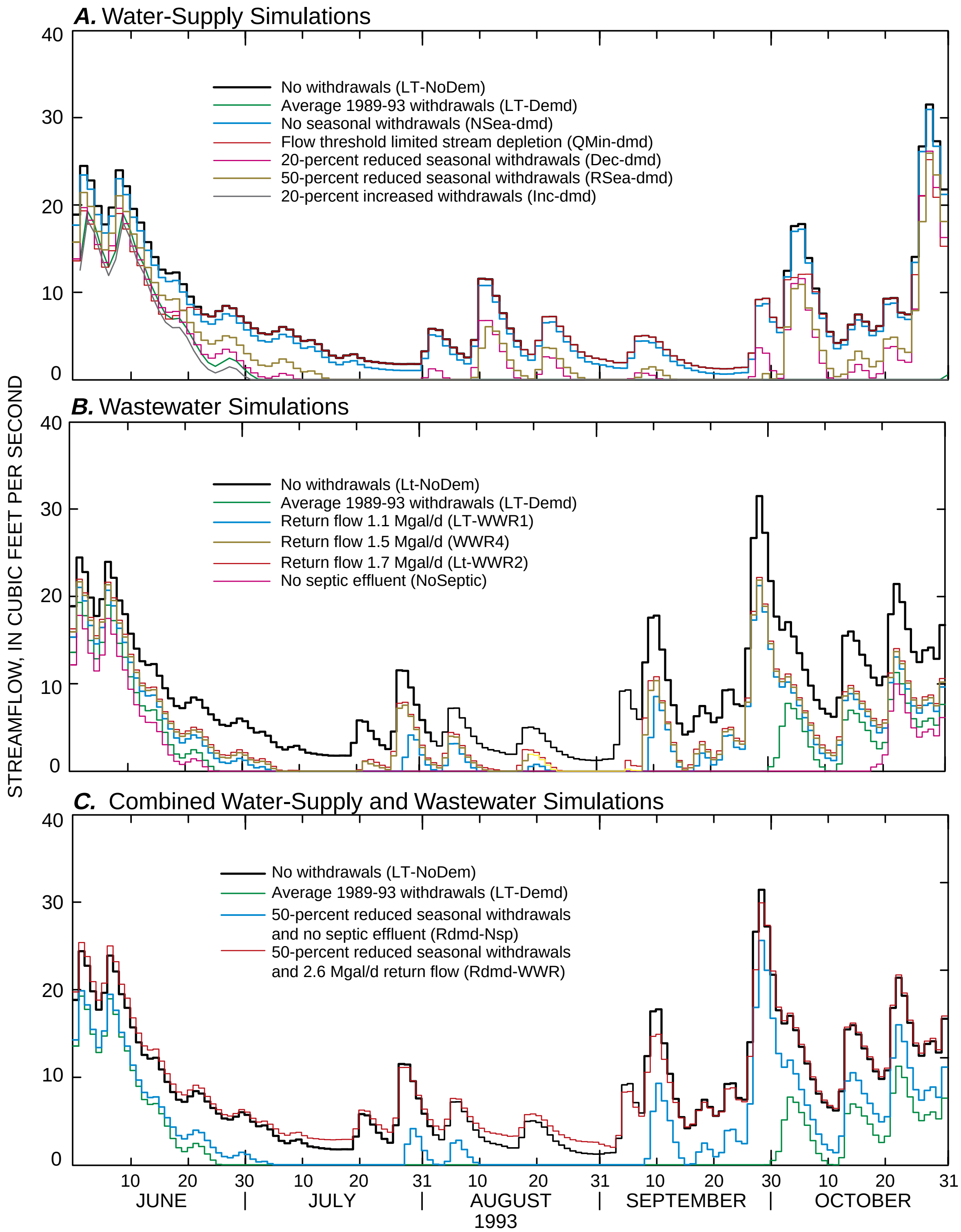

Figure 6. Daily flow at model reach 8 simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, Ipswich River Basin, Massachusetts, June through October 1993.

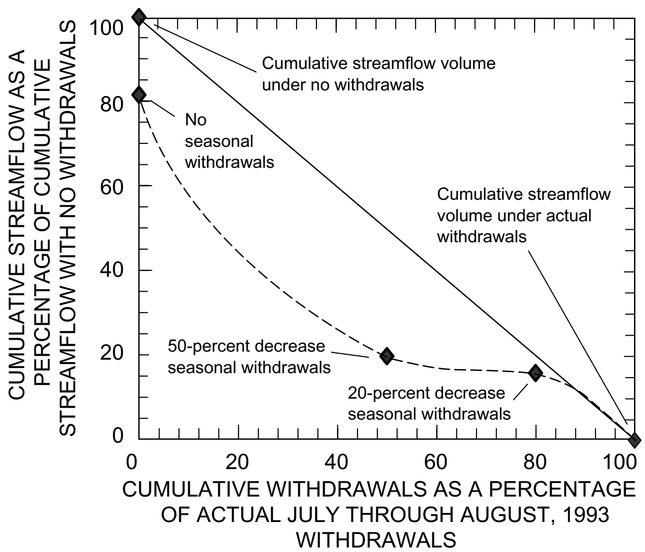

Figure 7. Cumulative-streamflow volume as a percentage of cumulative-streamflow volume under no withdrawals in relation to cumulative withdrawals as a percentage of the actual withdrawals in model reach 8, July 1 through August 31, 1993, Ipswich River, Massachusetts.

Streamflow in RCHRES 8 during July and August 1993 simulated under wastewater-return flows (fig. 6*B*) of 1.1 (LT-WWR1), 1.5 (WWR4), and 1.7 Mgal/d (LT-WWR2) averaged 0.4, 1.0, and 1.2 ft^3/s, respectively. Zero flow was simulated 61-, 37- and 29-percent of the time for simulations of wastewater-return flows of 1.1, 1.5, and 1.7 Mgal/d, respectively. Simulation of no septic-effluent inflow (NoSeptic) indicated zero flow during July through August 1993 (fig. 7*B*).

Streamflow during July and August, 1993 for simulations of 50-percent decrease in seasonal withdrawals and no septic-effluent inflow (Rdmd-Nsp) averaged 0.4 ft^3/s (fig. 6*C*) and indicated zero flow 71 percent of the time during this period. Streamflow during July and August 1993, for simulations of 50-percent decrease in seasonal withdrawals and wastewater return flows of 2.6 Mgal/d (Rdmd-WWR) averaged 4.6 ft^3/s (fig. 6*C*) and had a minimum flow of 2.6 ft^3/s during this period.

RCHRES 19

Simulated streamflow under actual withdrawals for July and August 1993 ranged from 0.3 to 6.0 ft^3/s and averaged 1.3 ft^3/s; in simulations with no withdrawals, flows ranged from 3.1 to 20 ft^3/s and averaged 7.8 ft^3/s (fig. 8*A*). Simulations of no seasonal withdrawals (NSea-dmd) and simulations of no streamflow depletion when RCHRES 19 falls below 22 ft^3/s (QMin-dmd) produced flows similar to the flows under no withdrawals. Simulations of reduced seasonal withdrawals by 50-percent (RSea-dmd) and 20-percent (Dec-dmd2) averaged 2.3 and 2.0 ft^3/s for the two months, respectively.

Simulated streamflow during July and August 1993 under wastewater-return flows of 1.1 (LT-WWR1), 1.5 (WWR4), and 1.7 (LT-WWR2) Mgal/d averaged 1.7, 2.4, and 2.8 ft^3/s, respectively (fig. 8*B*). A minimum streamflow of 0.3 ft^3/s was simulated under all return flow rates. Simulated streamflow under no septic effluent inflow (NoSeptic) averaged 1.1 ft^3/s during July though August 1993.

Simulated streamflow during July and August 1993 (fig. 8*C*) averaged 1.6 ft^3/s under 50-percent decreased seasonal withdrawals and no septic-effluent inflow (Rdmd-Nsp), and averaged 6.2 ft^3/s under 50-percent decreased seasonal withdrawals and wastewater-return flows of 2.6 Mgal/d (Rdmd-WWR). The minimum streamflow simulated under 50-percent decrease in seasonal withdrawals and no septic-effluent inflow (0.3 ft^3/s) was similar to the minimum streamflow simulated under actual withdrawals; minimum streamflow simulated under 50-percent decrease in seasonal withdrawals and wastewater return flows (2.9 ft^3/s) was slightly less than the simulated streamflow simulated under no withdrawals.

Flow Duration

Flow-duration analysis provides information about the distribution of flows over the analyzed period of record. The lower end of the flow-duration curve is an expression of the low-flow characteristics at a site and integrates conditions upstream from the selected point (Riggs, 1972). Flow-duration curves were computed from simulated daily-mean flows over the 1961–95 period under each of the management alternatives evaluated. Differences in the lower end of the flow-duration curves resulting from management alternatives provide a comparison of the over-all low-flow characteristics that management-practices represent.

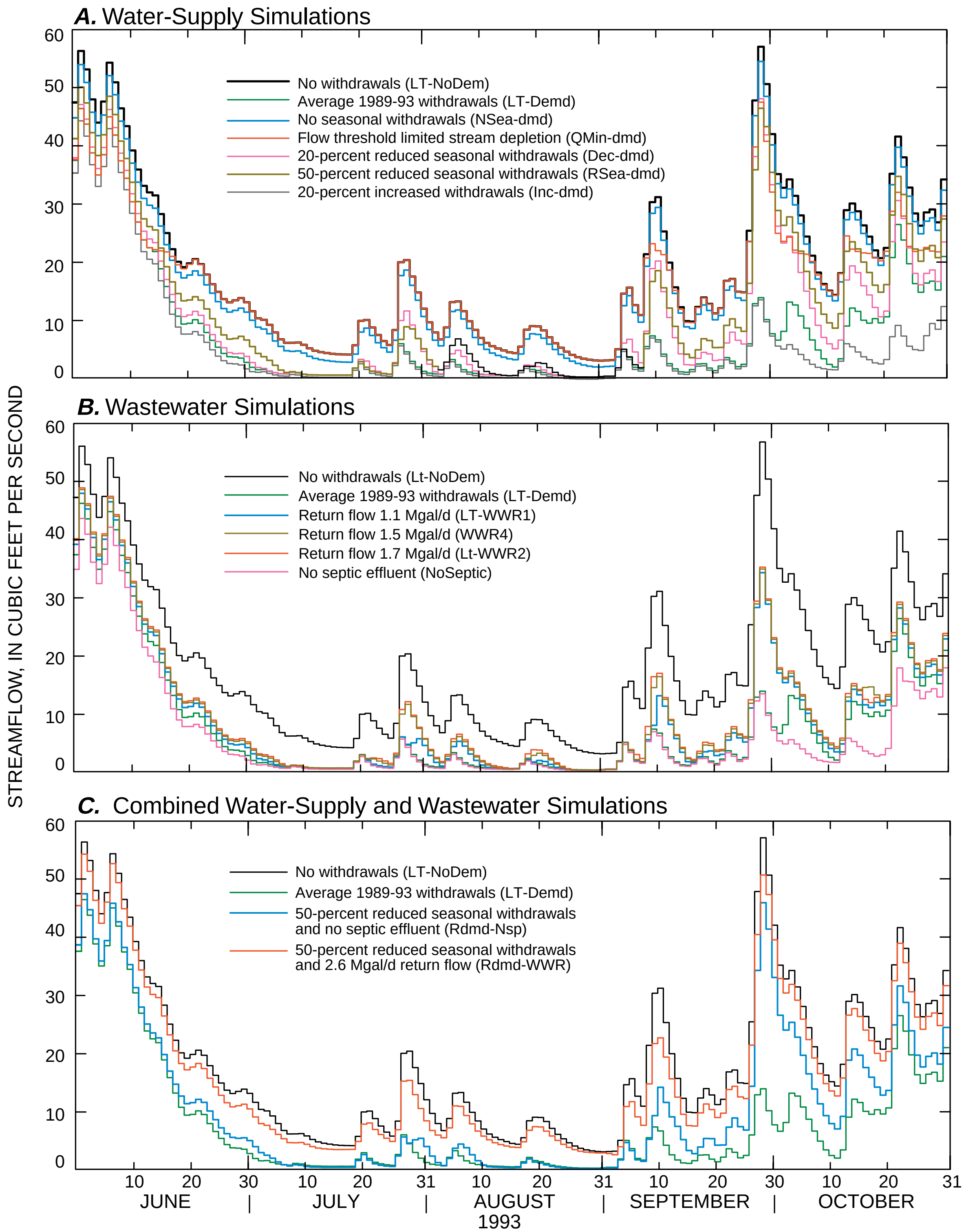

Figure 8. Daily flow at model reach 19 (South Middleton gaging station) simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, Ipswich River Basin, Massachusetts, June through October 1993 (model reach location is shown in fig. 2).

RCHRES 8

Flow-duration curves (fig. 9) indicated that daily mean flow exceeds 1.8 ft^3/s about 99.8 percent of the time under no withdrawals; under average 1989–93 withdrawals value this flow value is exceeded about 85-percent of the time. Under average 1989–93 withdrawals, streamflow was at or below 0.1 ft^3/s about 10 percent of the time.

The flow-duration curve (fig. 9*A*) for simulated flow with no streamflow depletion below 22 ft^3/s (QMin-dmd) was nearly identical to the curve without withdrawals; only a slight difference in the duration curve was seen between about the 30 and 90 percent exceedence interval. The flow-duration curve for simulated flow under no seasonal withdrawals (NSea-dmd) was slightly lower at the higher exceedence intervals relative to that for no withdrawals; flows less than 1.8 ft^3/s were indicated less than about 2 percent of the time. Reduced seasonal water-supply withdrawal simulations indicated a less profound change in the flow-duration curve relative to the curve for average 1989–93 withdrawals. A 20-percent decrease in seasonal withdrawals (Dec-dmd2) decreased the time that flows were below 0.1 ft^3/s only slightly less often than the time flows were below 0.1 ft^3/s under average 1989–93 withdrawals; a 50-percent decrease in seasonal withdrawals (RSea-dmd) decreased the time that flows were below 0.1 ft^3/s to about 5 percent. The simulation of increased water-supply withdrawals (Inc-dmd) indicated that flows were below 0.1 ft^3/s slightly more often than the simulated flows under average 1989–93 withdrawals.

Flow-duration curves (fig. 9*B*) of simulated return flows of 1.1 (LT-WWR1), 1.5 (WWR4), and 1.7 (LT-WWR2) Mgal/d indicated streamflow fell below 0.1 ft^3/s about 5, 2, and 1 percent of the time, respectively. Flow-duration curves for simulated flows with no septic-effluent inflows (NoSeptic) indicated flows were below 0.1 ft^3/s about 18 percent of the time. This simulation indicated that expansion of public sewers and the consequent loss of septic-effluent inflow can appreciably decrease low flows in the upper parts of the basin.

Flow-duration curves (fig. 9*C*) of reduced seasonal withdrawals, combined with wastewater-return flows of 2.6 Mgal/d, indicated flows would be greater than the flows under no withdrawals at or above the 90-percent exceedence interval. Daily mean streamflow exceeded 3.0 ft^3/s about 99.8 percent of the time under decreased seasonal withdrawals and wastewater-return flow; this is about 1 ft^3/s greater than the flow without withdrawals at the same exceedence interval. Flow-duration curves under reduced seasonal demands and no septic-effluent inflow indicate only a modest increase in low flows compared to the curve for average 1989–93 withdrawals; flows at or below 0.1 ft^3/s are about 5 percent less likely under reduced seasonal withdrawals and no septic-effluent inflow than under average 1989–93 withdrawals.

RCHRES 19

The flow-duration curve indicated that daily mean streamflow exceeded 3 ft^3/s about 99.8 percent of the time under no withdrawals, but streamflow simulated under average 1989–93 withdrawals exceeded only 0.4 ft^3/s at the same exceedence interval (fig. 9). The flow-duration curve for average 1989–93 withdrawals indicated streamflow has about a 5 percent likelihood of being at or below 1.0 ft^3/s.

Flow-duration curves (fig. 9*A*) for alternative water-supply withdrawals produced similar patterns as the flow-duration curves in RCHRES 8, except that the differences between curves are generally less pronounced at RCHRES 19. The flow-duration curve for the simulation of no streamflow depletion below the 22 ft^3/s (QMin-dmd) is nearly identical to the curve for no withdrawals. Simulation of no seasonal withdrawals (NSea-dmd) resulted in slightly less flow above the 50-percent exceedence interval; streamflow at the 99.8 percent exceedence interval (2.0 ft^3/s) is about 1.0 ft^3/s less than the flow at that exceedence interval for no withdrawals. Reduced seasonal withdrawals indicated little change in flow duration above the 95-percent exceedence interval. The simulation of increased withdrawals (Inc-dmd) indicated that streamflow fell below 1 ft^3/s slightly more frequently than under average 1989–93 withdrawals.

Wastewater-return flows only slightly changed the flow-duration curve (fig. 9*B*) from the average 1989–93 withdrawals between the 80- and 99-percent exceedence probabilities. The change in flow duration curves at RCHRES 19, compared to the change in the flow-duration curves at RCHRES 8 for the same simulations, is relatively small. This relatively small change results from a proportionately small increase in withdrawals relative to the increase in drainage area between these reaches. Thus, while management practices that target headwater reaches have a large affect in these reaches their effects increasingly diminish as the drainage area increases.

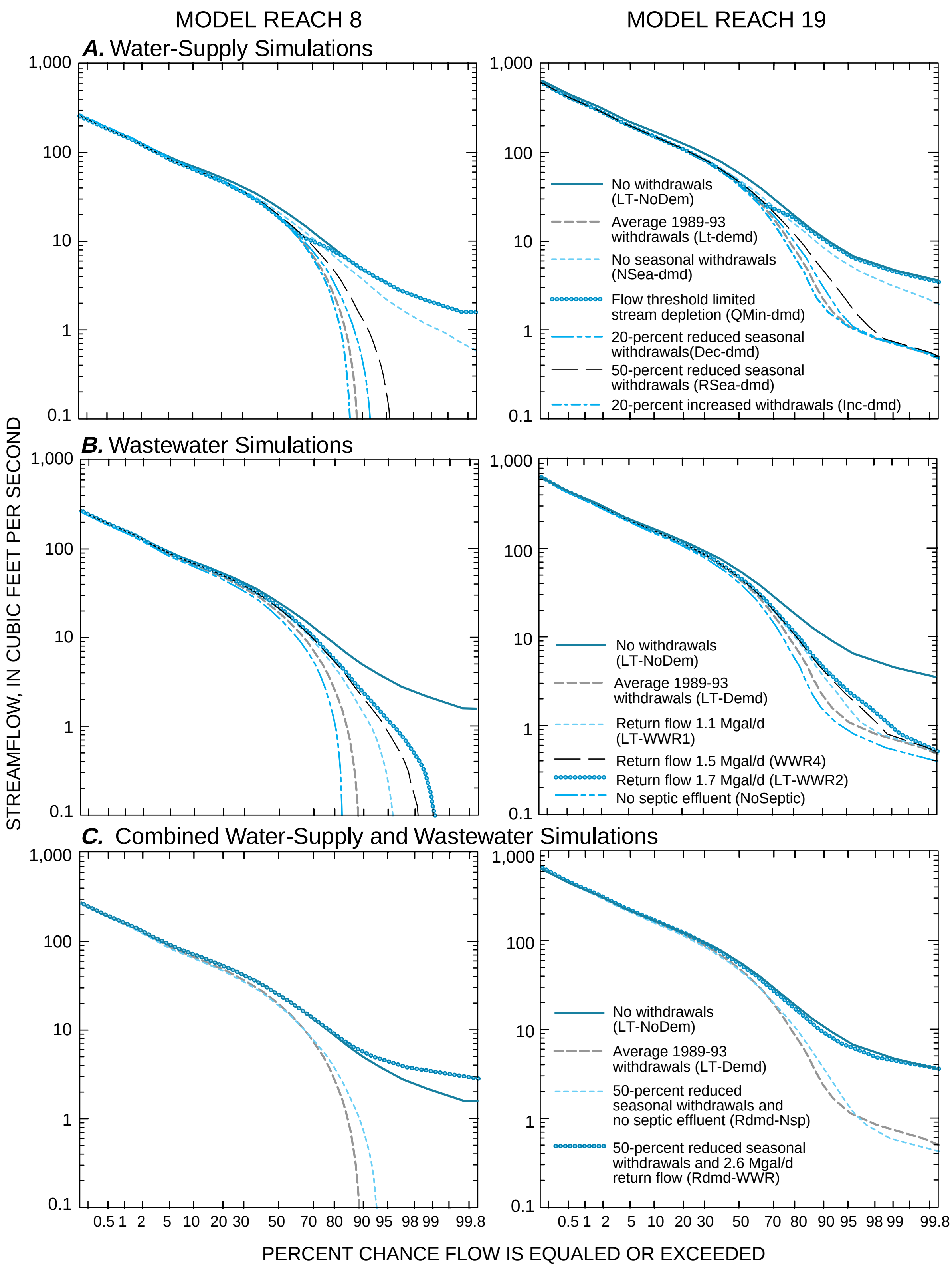

Figure 9. Flow-duration curves of simulated daily mean discharge at model reaches 8 and 19 made under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, Ipswich River Basin, Massachusetts, 1961–95 (model reach locations are shown in fig. 2).

The flow-duration curve (fig. 9*C*) under reduced seasonal withdrawals and no septic-effluent inflow (Rdmd-NSp) was about the same as the curve under average 1989–93 withdrawals. The flow-duration curve under reduced seasonal withdrawals and wastewater-return flow (Rdmd-WWR) was comparable to the curve without withdrawals.

Low-Flow Frequency

Low-flow frequency curves provide information about the likelihood of a flow of a specified magnitude in a given year, rather than over the entire record as shown in a flow-duration curve. Low-flow frequency characteristics are provided for 1-, 7-, and 30-consecutive day annual minimum-duration intervals calculated by log-Pearson Type III analysis of the HSPF simulated daily flow for the 1961–95 at RCHRES 8 and 19. The computer program SWSTAT (Lumb and others, 1994) was used to compute the annual series of 1-, 7-, and 30-day (n-day) flows, to rank them, and to fit them to a log-Pearson Type III distribution. The annual n-day low-flow values were computed for the climatic year—April through March. Table 4 summarizes the median annual n-day flows used in the low-flow frequency analysis.

In RCHRES 8, many zero values were calculated for annual n-day periods for simulations that included withdrawals. The number of zero values increased as the length of the low-flow duration period decreased and as the withdrawal rate increased. Confidence in the reported log-Pearson Type III flow frequency value typically decreased because of increased variance and skew in the data from a normal distribution as the number of zero values increased. In many instances, the log-Pearson Type III fit was modified by visually fitting the log transformed annual n-day low-flow data on probability paper using the Weibull plotting position formula (Chow and others, 1988).

In general, low-flow frequency curves computed for RCHRES 8 and 19 showed similar patterns for similar management plans. Simulations of no streamflow depletion below 22 ft^3/s (QMin-dmd) resulted in low-flow frequency curves that were about the same as the curves without withdrawals for each n-day duration interval at each site. Simulations of no seasonal withdrawals (NSea-dmd) resulted in slightly less flow than flows under no withdrawals, and this management plan maintained flow in RCHRES 8 for all duration and recurrence intervals. Other simulations of reduced withdrawal rates did not appreciably change the low-flow frequency curves from curves under average 1989–93 withdrawals for recurrence intervals greater than about 2 to 5 years. Flows progressively increased,

Table 4. Median 1-, 7-, and 30-day annual low-flow at model RCHRES 8 and 19, simulated under water-management alternatives, Ipswich River, Massachusetts, 1961–95

[All values are in cubic feet per second. Mgal/d, million gallons per day]

Simulation	Model Reach 8			Model Reach 19		
	1-Day	7-Day	30-Day	1-Day	7-Day	30-Day
Average 1989–93 withdrawals	0	0	0.39	0.74	0.99	2.06
No withdrawals	2.35	2.89	4.37	5.28	6.16	9.37
No seasonal withdrawals	1.36	1.82	3.37	3.51	4.63	7.51
Flow threshold limited streamflow depletion	2.35	2.89	4.37	5.27	6.16	9.37
50-percent decreased seasonal withdrawals	0	.09	1.23	.85	1.31	3.98
20-percent decreased seasonal withdrawals	0	0	.60	.75	1.01	2.70
20-percent increased withdrawals	0	0	.15	.74	.99	1.80
Return flow 1.1 Mgal/d	0	.03	1.25	.81	1.12	3.34
Return flow 1.7 Mgal/d	.42	.81	2.14	1.19	1.96	4.14
Return flow 1.5 Mgal/d	.13	.54	1.84	1.02	1.68	3.78
No septic effluent	0	0	0	.57	.78	1.52
50-percent decreased seasonal withdrawal and no septic effluent inflow	0	0	.74	.62	.90	3.03
50-percent decreased seasonal withdrawal and 2.6 Mgal/d wastewater return flow	3.50	3.91	5.20	4.58	5.28	7.91

however, at more frequent recurrence intervals relative to flows under the average 1989–93 withdrawals in proportion to the decrease in the rate of withdrawal.

Simulations of returning wastewater to the basin increased low flows slightly in proportion to the rate of return flow relative to flows under average 1989–93 withdrawals for all recurrence intervals. Simulations of no septic-effluent inflow resulted in lower flows and more frequent periods of no flow relative to flows for the same withdrawals with septic-effluent inflow. The minimum flow under reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), was about the same as the minimum flow under average 1989–93 withdrawals for recurrence intervals of about 5 years or more, but provided somewhat more flow at more frequent recurrence intervals. Reduced seasonal withdrawals, combined with 2.6 Mgal/d wastewater-return flow (Rdmd-WWR), indicated larger low flows for all recurrence intervals relative to those flows under no withdrawals at RCHRES 8, but somewhat smaller low flows for most recurrence intervals relative to those flows under no withdrawals at RCHRES 19.

1-Day Low Flow

The 1-day low-flow frequency value is the minimum expected annual daily-mean flow for a specified recurrence interval. For example, RCHRES 8 (fig. 10*A*) is expected to sustain a daily-mean flow of at least 0.4 ft^3/s over a 20-year period under no seasonal withdrawals. The daily-mean flow could drop below 0.4 ft^3/s in RCHRES 8 in any given year; but on average, over the long term, flows less than this would be expected only once every twenty years or more.

RCHRES 8

The simulation of average 1989–93 withdrawals indicated no flow in RCHRES 8 for all recurrence intervals (fig. 10*A*); under no withdrawals, the simulated minimum value ranged from 5.4 ft^3/s for a recurrence interval of about once every year to 1.0 ft^3/s for the 100-year recurrence interval. These simulations indicated that no flow is expected at least one day almost every year under 1989–93 withdrawals, but a minimum value of at least 1 ft^3/s could be expected without withdrawals even during dry periods expected only once every 100 years.

Simulations of no withdrawals (LT-NoDem), no seasonal withdrawals (NSea-dmd), and streamflow-limited withdrawals (QMin-dmd) maintained a daily mean flow above zero beyond a 2-year recurrence interval (fig. 10*A*). Simulated values under 50-percent reduced seasonal withdrawals (RSea-dmd) indicated that RCHRES 8 has a 50 percent chance of drying every year. Other water-supply simulations did not change the minimum values appreciably from the values under average 1989–93 withdrawals.

The simulations of wastewater-return flows indicated that RCHRES 8 would stop flowing at least 1-day for recurrence intervals of 1.25, 2, and 5 years under return flow rates of 1.1, 1.5, and 1.7 Mgal/d, respectively (fig. 10*B*). The minimum values expected at about the 1-year recurrence interval ranged from 0.9, 1.6, and 2.3 ft^3/s for simulations with a return flow rate of a 1.1, 1.5, 1.7 Mgal/d, respectively. Simulations of average 1989–93 withdrawals and no septic-effluent inflow indicated that RCHRES 8 would stop flowing at least one day every year.

The simulation of 50-percent reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), indicated the minimum daily-mean flow was zero for recurrence intervals of 1.25 years or more and 0.9 ft^3/s for a recurrence interval of about 1 year (fig.10*C*). Under reduced seasonal withdrawals, combined with wastewater-return flows of 2.6 Mgal/d (Rdmd-WWR), the minimum value increased by about 1 ft^3/s at the 100-year recurrence interval, but did not change appreciably at the 1-year recurrence interval relative to simulations with no withdrawals.

RCHRES 19

The simulation of average 1989–93 withdrawals indicated the minimum daily-mean flow ranged from 2.0 ft^3/s for a recurrence interval of about once every year to 0.3 ft^3/s for the 100-year recurrence interval (fig. 11*A*). Under no withdrawals, the minimum value ranged from 11 ft^3/s for a recurrence interval of about once every year to 2.8 ft^3/s for the 100-year recurrence interval.

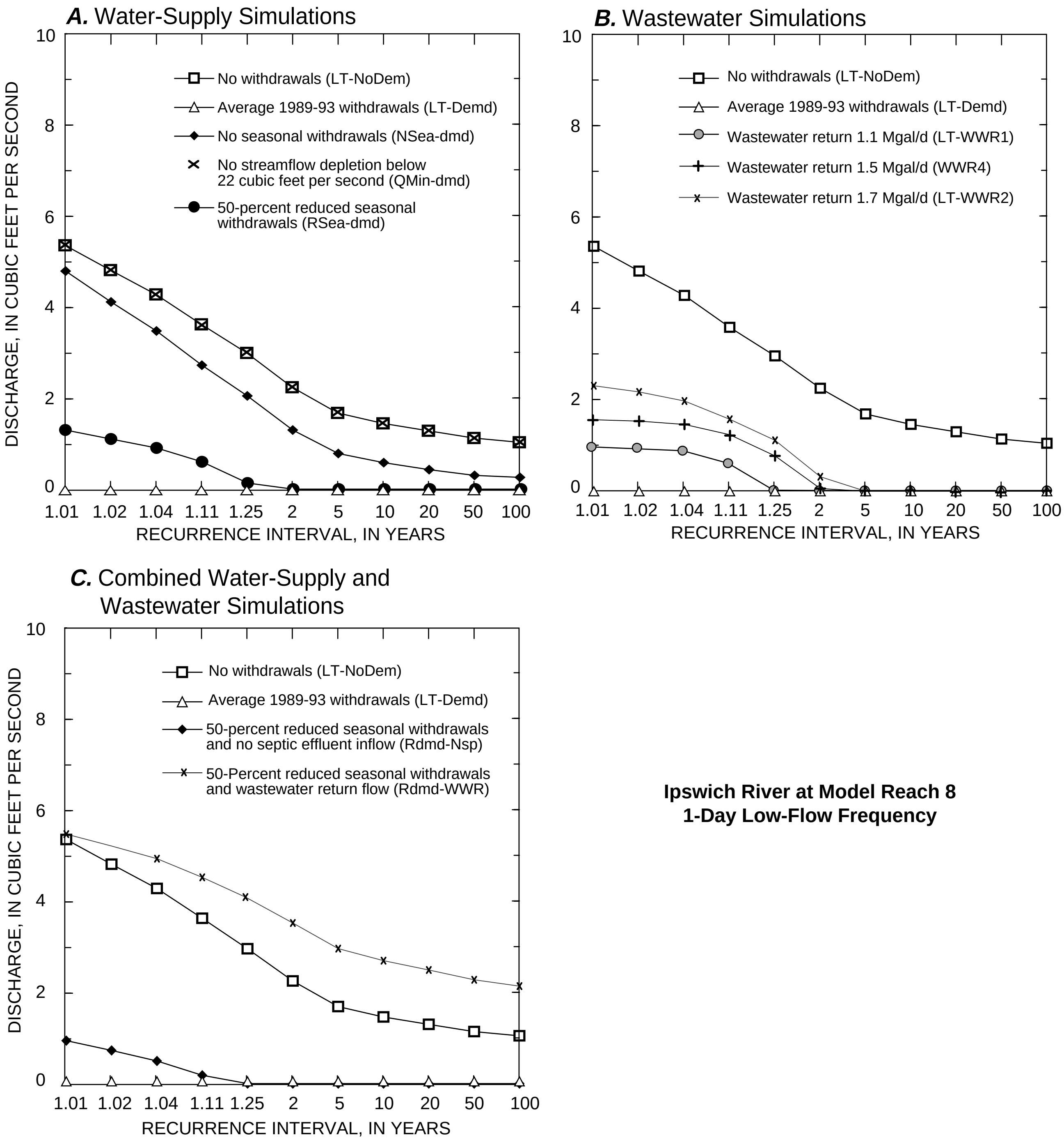

Figure 10. Log-Pearson type III low-flow frequency curves for 1-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 8, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

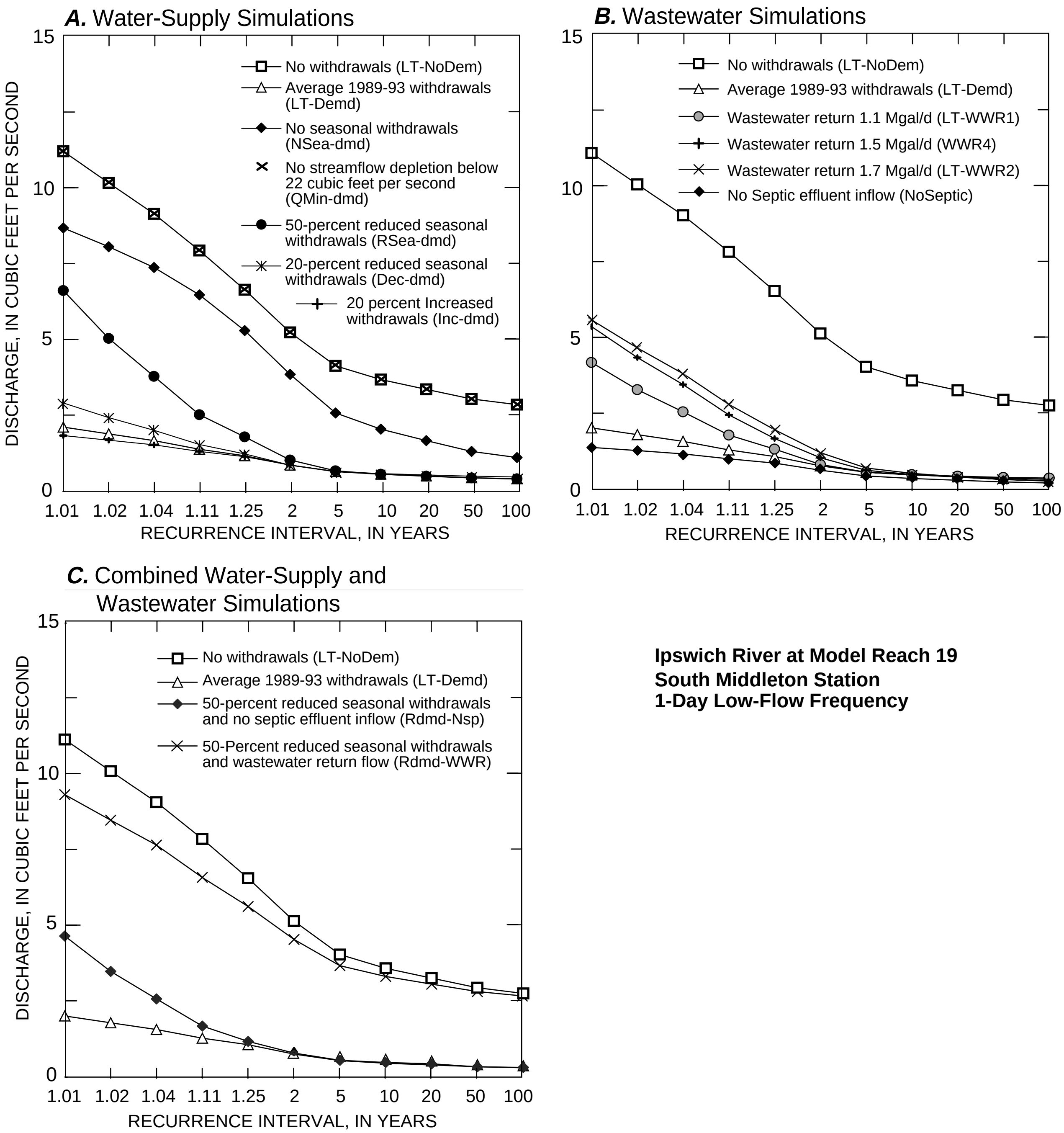

Figure 11. Log-Pearson type III low-flow frequency curves for 1-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 19, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

The simulation of no seasonal withdrawals (NSea-dmd) indicated the minimum daily-mean flow was about 2 ft^3/s less than the flow under no withdrawals for all recurrence intervals (fig. 11*A*). The minimum value under 50-percent reduced seasonal withdrawals (RSea-dmd) was about 6.5 ft^3/s at about the 1-year recurrence interval, but did not increase the minimum value beyond about the 2-year recurrence interval. The simulation of a 20-percent reduced seasonal withdrawal did not appreciably change minimum value from the value under average 1989–93 withdrawals.

Simulations of wastewater-return flows indicated the expected minimum daily-mean flow at about the 1-year recurrence interval increased from 2.0 ft^3/s under average 1989–93 withdrawals to 4.2, 5.4, and 5.6 ft^3/s for return flows of 1.1, 1.5, and 1.7 Mgal/d, respectively (fig. 11*B*). The expected minimum value at about the 1-year recurrence interval decreased from the average 1989–93 withdrawals to 1.4 ft^3/s under average 1989–93 withdrawals and no septic-effluent inflow.

The simulation of 50-percent reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), indicated the minimum annual daily-mean flow was about the same as the value under average 1989–93 withdrawals for recurrence intervals of 1.25 years or more; a minimum value of 4.6 ft^3/s is expected at about the 1-year recurrence interval (fig. 11*C*). The simulation of reduced seasonal withdrawals, combined with wastewater-return flows of 2.6 Mgal/d (Rdmd-WWR), indicated the minimum value was about the same as the minimum value under no withdrawals at the 100-year recurrence interval; the minimum value was about 16 percent less than value under no withdrawals at about the 1-year recurrence interval.

7-Day Low Flow

The 7-day low-flow frequency values represent the minimum annual daily-mean flow over 7 consecutive days. The 7-day low-flow values are generally larger than the 1-day low-flow values at the same location for the same simulated conditions because the values are averaged over for longer time. The U.S. Environmental Protection Agency and other state and local agencies commonly use the 7-day, 10-year recurrence low-flow value (7Q10) for regulatory purposes.

RCHRES 8

The simulation of average 1989–93 withdrawals indicated the minimum 7-day mean flow was zero for all return intervals except for about the 1-year recurrence interval, which was 1.3 ft^3/s (fig. 12*A*). Under no withdrawals, the value ranged from 5.9 ft^3/s about once every year, to 1.2 ft^3/s for the 100-year recurrence interval. This result indicated that RCHRES 8 under existing 1989–93 withdrawals is expected to stop flowing for a 7-day period about every other year. Under no withdrawals, the minimum 7-day flow would be at least 1.2 ft^3/s.

The minimum 7-day mean flow under no seasonal withdrawals (NSea-dmd) was about 1 ft^3/s less than the value relative to no withdrawals for all recurrence intervals (fig. 12*A*). Simulation of 50-percent reduced seasonal withdrawals (RSea-dmd) indicated the value flow was about 3 ft^3/s at about the 1-year recurrence interval. The simulation of reduced seasonal withdrawals did not change the value relative to the value under average 1989–93 withdrawals beyond the 2-year recurrence interval, however. Reduced seasonal withdrawals by 20-percent did not appreciably change the minimum 7-day flow from the value under average 1989–93 withdrawals.

The 7-day low-flow frequency curve is not shown for simulated wastewater-return flows of 1.7 Mgal/d (LT-WWR2), because the skew in the data distribution prohibited the calculation of a log-Pearson Type III frequency curve. The Weibull plotting position of the annual 7-day low values indicated that RCHRES 8 would stop flowing about once every 10 years, however. The values under wastewater-return flows of 1.1 and 1.7 Mgal/d (fig. 12*B*) indicated RCHRES would stop flowing about once every 2 and 5 years, respectively; the values progressively increased to 3.9 and 4.8 ft^3/s at about the 1-year recurrence interval for these return flows, respectively. The minimum annual 7-day mean flow was zero for 33 of 34 years under simulations of no septic-effluent inflow and average 1989–893 withdrawals.

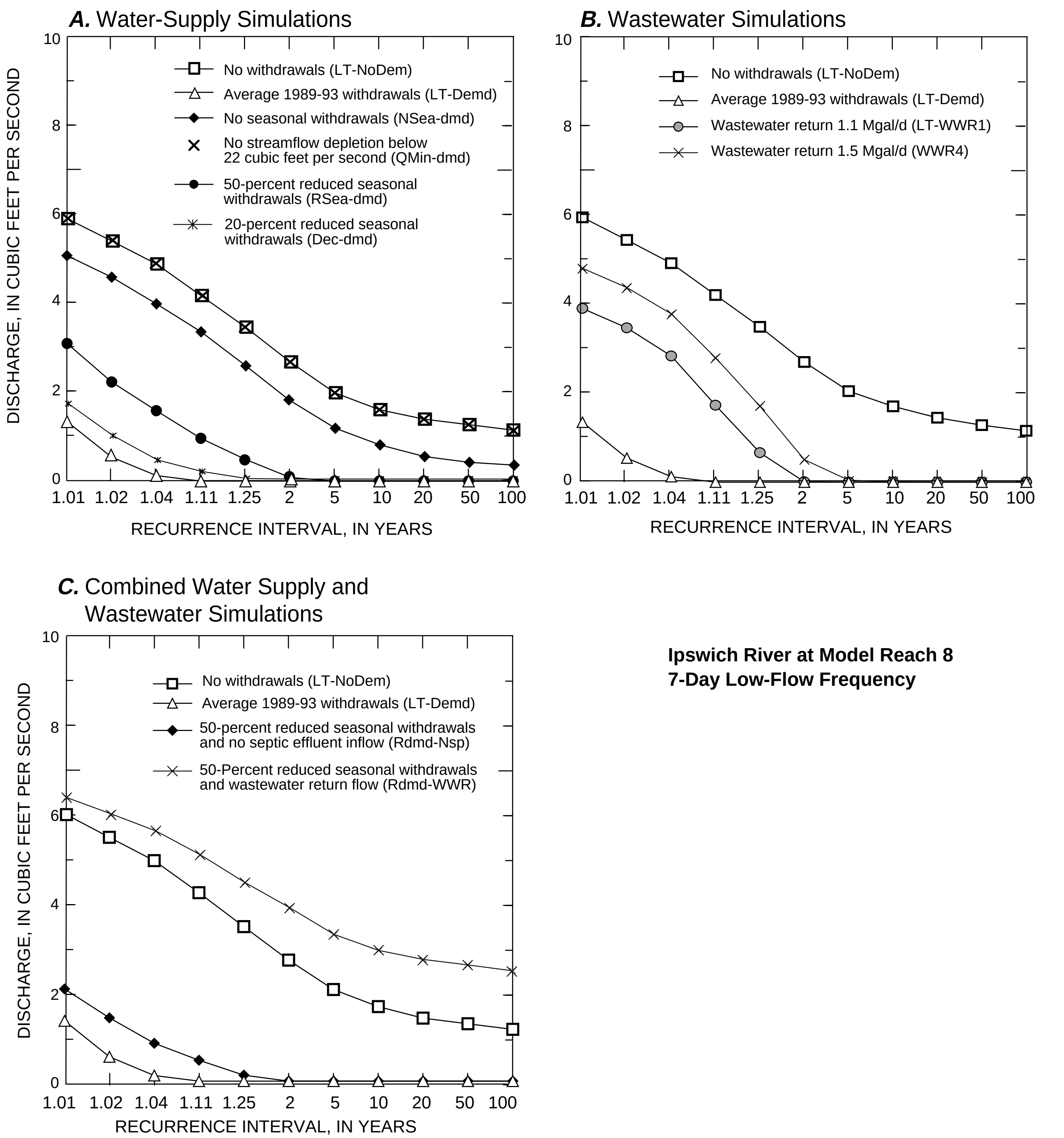

Figure 12. Log-Pearson type III low-flow frequency curves for 7-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 8, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

The simulation of 50-percent reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), indicated RCHRES 8 would stop flowing for a 7-day period about once every 2 years; the value at about 1 year recurrence interval was 2.1 ft^3/s (fig. 12*C*). Reduced seasonal withdrawals, combined with 2.6 Mgal/d of wastewater-return flow (Rdmd-WWR), indicated the 7-day daily mean was 0.5 to 1.0 ft^3/s larger than flow under no withdrawals for all recurrence intervals; the values increased as the recurrence interval increased.

RCHRES 19

The simulation of average 1989–93 withdrawals indicated the minimum annual 7-day mean flow ranged from 3.0 ft^3/s for a recurrence interval of about once every year to 0.4 ft^3/s for the 100-year recurrence interval (fig. 13). Under no withdrawals, the value ranged from 13 ft^3/s for a recurrence interval of about once every year to 2.9 ft^3/s for the 100-year recurrence interval.

The simulation of no seasonal withdrawals (NSea-dmd) indicated the minimum 7-day mean flow was about 2 to 3 ft^3/s less than the value under no withdrawals for all recurrence intervals (fig. 13*A*). The simulation of 50-percent reduced seasonal withdrawals resulted in a value of 8.1 ft^3/s at about the 1-year recurrence interval, but did not change the minimum 7-day mean flow from the flow under average 1989–93 withdrawals beyond about the 5-year recurrence interval.

Simulations of wastewater-return flow indicated minimum 7-day mean flows of 5.5, 6.4, and 6.6 ft^3/s for return flows of 1.1, 1.5, and 1.7 Mgal/d, respectively, at about the 1-year recurrence interval; the values did not change appreciably relative to the minimum flow under average 1989–93 withdrawals beyond the 10-year recurrence interval (fig 13*B*). The values decreased from the average 1989–93 withdrawals to 2.1 ft^3/s under no septic-effluent inflow and average 1989–93 withdrawals at about the 1-year recurrence interval.

The simulation of 50-percent reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), indicated a minimum 7-day mean flow of 6.0 ft^3/s at about the 1-year recurrence interval, but indicated no difference in the minimum flow relative to the flow under average 1989–93 withdrawals for recurrence intervals of 2 years or more. Reduced seasonal withdrawals, combined with 2.6 Mgal/d wastewater-return flow (Rdmd-WWR), was about the same as the flow under no withdrawals at the 100-year recurrence interval and about 2.2 ft^3/s less than the flow at about the 1-year recurrence interval.

30-Day Low Flow

The 30-day low-flow frequency value represents the minimum annual daily-mean flow over 30 consecutive days. The length of the stress period and the magnitude of the flow are important considerations in the evaluation of a management plans on habitat protection. Periods of protracted low flow will often segment the river into disconnected pools that restrict fish movement and make their survivability increasingly precarious. Under these conditions, fish become increasingly susceptible to predation, and to thermal and anoxic stresses (Matthews, 1998).

RCHRES 8

The simulation of average 1989–93 withdrawals indicated the minimum 30-day mean flow ranged from 4.0 ft^3/s for a recurrence interval of about once every year to zero for recurrence intervals of 5 years or more (fig. 14). Under no withdrawals, the values ranged from about 10 ft^3/s for a recurrence interval of about once every year to 1.9 ft^3/s for the 100-year recurrence interval.

The simulation of no seasonal withdrawals (NSea-dmd) indicated the minimum 30-day flow ranged from 9.2 ft^3/s at about the 1-year recurrence interval to 1.1 ft^3/s at the 100-year recurrence interval (fig. 14*A*). Simulations of 20- and 50-percent reduced seasonal withdrawals indicated flows of 5.3 and 7.8 ft^3/s, respectively, at about the 1-year recurrence interval, but indicated no appreciable change in the flows relative to the minimum flow under average 1989–93 withdrawals for recurrence intervals greater than about 5 years.

Simulations of wastewater-return flows indicated a minimum 30-day mean flow of 6.2, 7.5, and 7.8 ft^3/s for return flows of 1.1, 1.5, and 1.7 Mgal/d, respectively at about the 1-year recurrence interval, and 0.03 to 0.3 ft^3/s at the 100-year recurrence interval (fig. 14*B*). The simulation of no septic-effluent inflow indicated no flow over a 30-day period for recurrence intervals of about 2 years or more, and flows of 3 ft^3/s at about the 1-year recurrence interval.

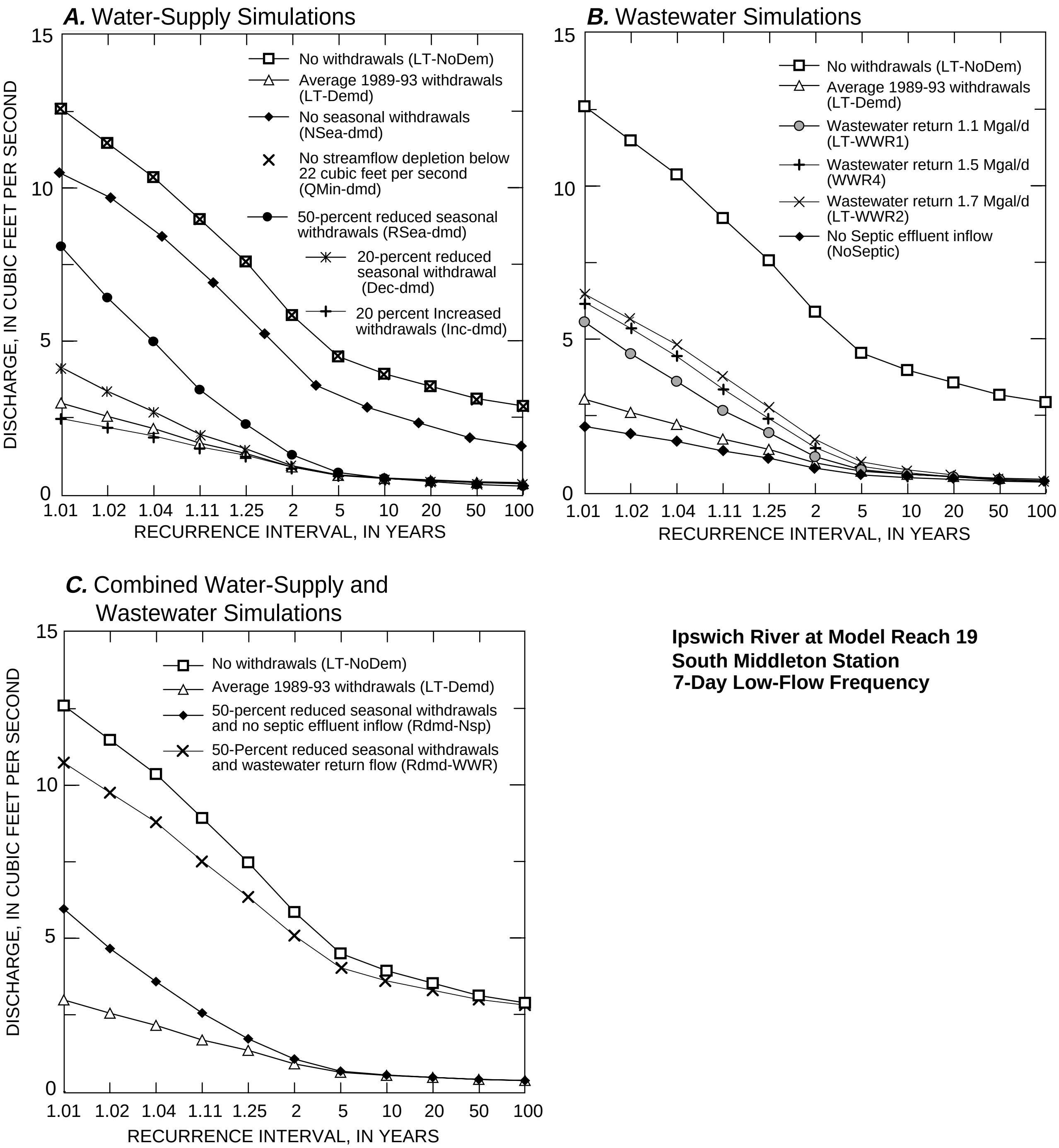

Figure 13. Log-Pearson type III low-flow frequency curves for 7-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 19, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

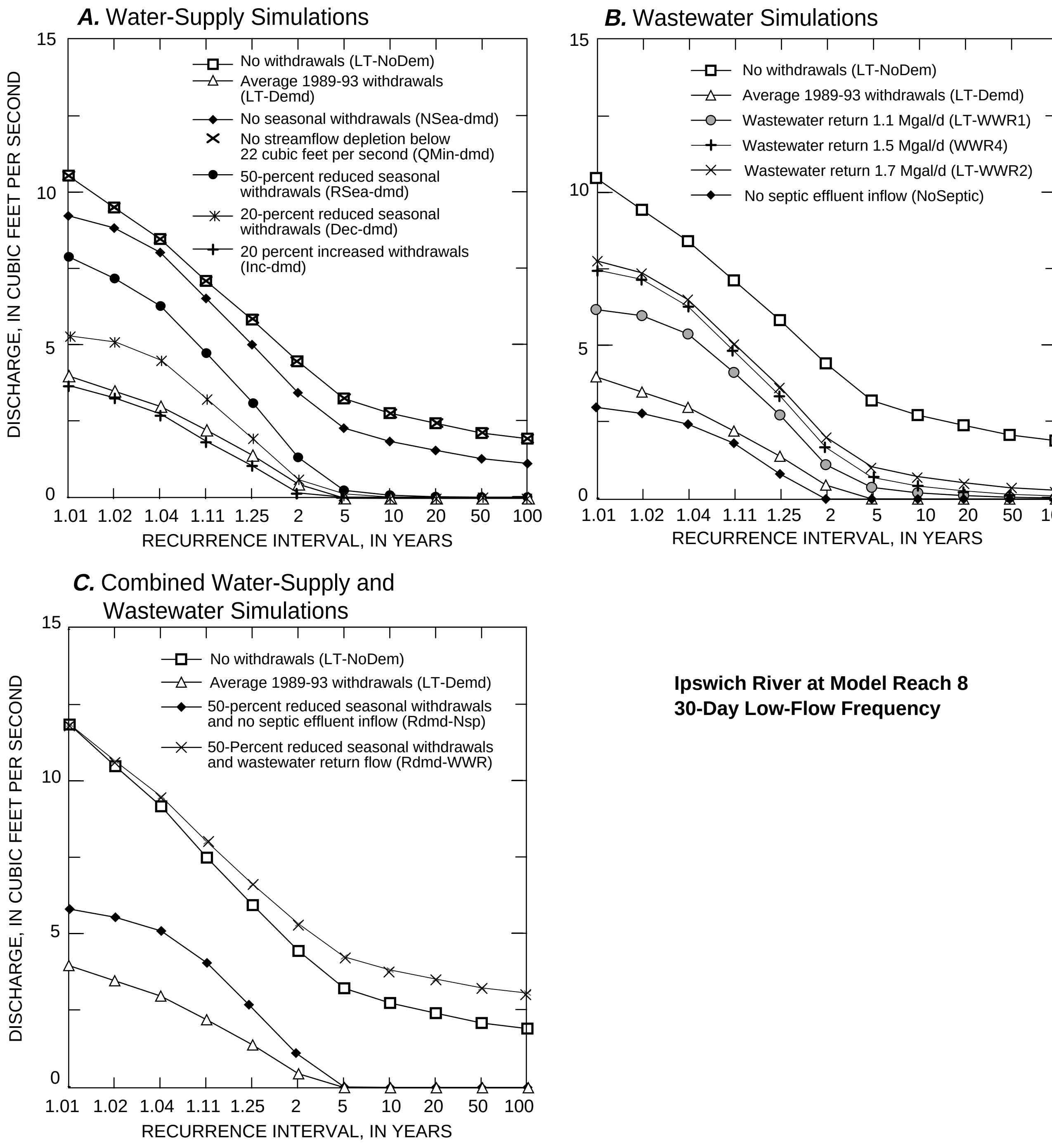

Figure 14. Log-Pearson type III low-flow frequency curves for 30-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 8, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

The simulation of 50-percent reduced seasonal withdrawals, combined with no septic-effluent inflow (Rdmd-NSp), indicated the minimum 30-day mean flow at recurrence intervals about 5 years or more was zero, which is about the same as the values under average 1989–93 withdrawals (fig. 14*C*). The minimum 30-day mean flow was 5.8 ft^3/s at about the 1-year recurrence interval for this simulation. Reduced seasonal withdrawals, combined with a 2.6 Mgal/d wastewater-return flow (Rdmd-WWR), indicated the flow was about the same as the flow under no withdrawals at the 1-year recurrence interval, but was about 1.2 ft^3/s more than the flow under no withdrawals at the 100-year recurrence interval.

RCHRES 19

The simulation of average 1989–93 withdrawals indicated the minimum 30-day mean flow ranged from 17 ft^3/s for a recurrence interval of about once every year to 0.5 ft^3/s at the 100-year recurrence interval. Under no withdrawals, the values ranged from 25 ft^3/s for a recurrence interval of about once every year to 4.1 ft^3/s at the 100-year recurrence interval (fig. 15).

The simulation of no seasonal withdrawals (NSea-dmd) indicated the minimum 30-day mean flow ranged from 23 ft^3/s at about the 1-year recurrence interval to 2.8 ft^3/s at the 100-year recurrence interval (fig. 15*A*). Simulations of 20- and 50-percent decreased seasonal withdrawals resulted in flows of 19 and 22 ft^3/s, respectively, at about the 1-year recurrence interval. These simulations did not produce minimum 30-day flows that were appreciably different from the values under average 1989–93 withdrawals for recurrence intervals greater than 5 years. The simulation of a 20-percent increased withdrawals indicated the flow would be expected to decrease by about 5 ft^3/s below the flow under average 1989–93 withdrawals at about the 1-year recurrence interval.

Simulations of wastewater-return flows increased the minimum 30-day mean flow by about 1 ft^3/s at about the 1-year recurrence interval relative to the values under average 1989–93 withdrawals (fig. 15*B*); the values only slightly increased relative to the values under average 1989–93 withdrawals at the 100-year recurrence interval. Simulations of no septic-effluent inflow indicated the flow is about 4 ft^3/s less relative to the flow under average 1989–93 withdrawals at about the 1-year recurrence interval.

The simulation of 50-percent reduced seasonal withdrawals, combined no septic-effluent inflow (Rdmd-NSp), indicated a minimum 30-day mean flow of 20 ft^3/s at about the 1-year recurrence interval, but indicated no appreciable difference in the values relative to the values under average 1989–93 withdrawals beyond the 5-year recurrence interval (fig. 15*C*). Reduced seasonal withdrawals, combined with wastewater-return flow (Rdmd-WWR), indicated a flow of 23 ft^3/s at about the 1-year recurrence interval and 3.5 ft^3/s at 100-year recurrence interval, which is slightly less than the values relative to the flow under no withdrawals for all recurrence intervals.

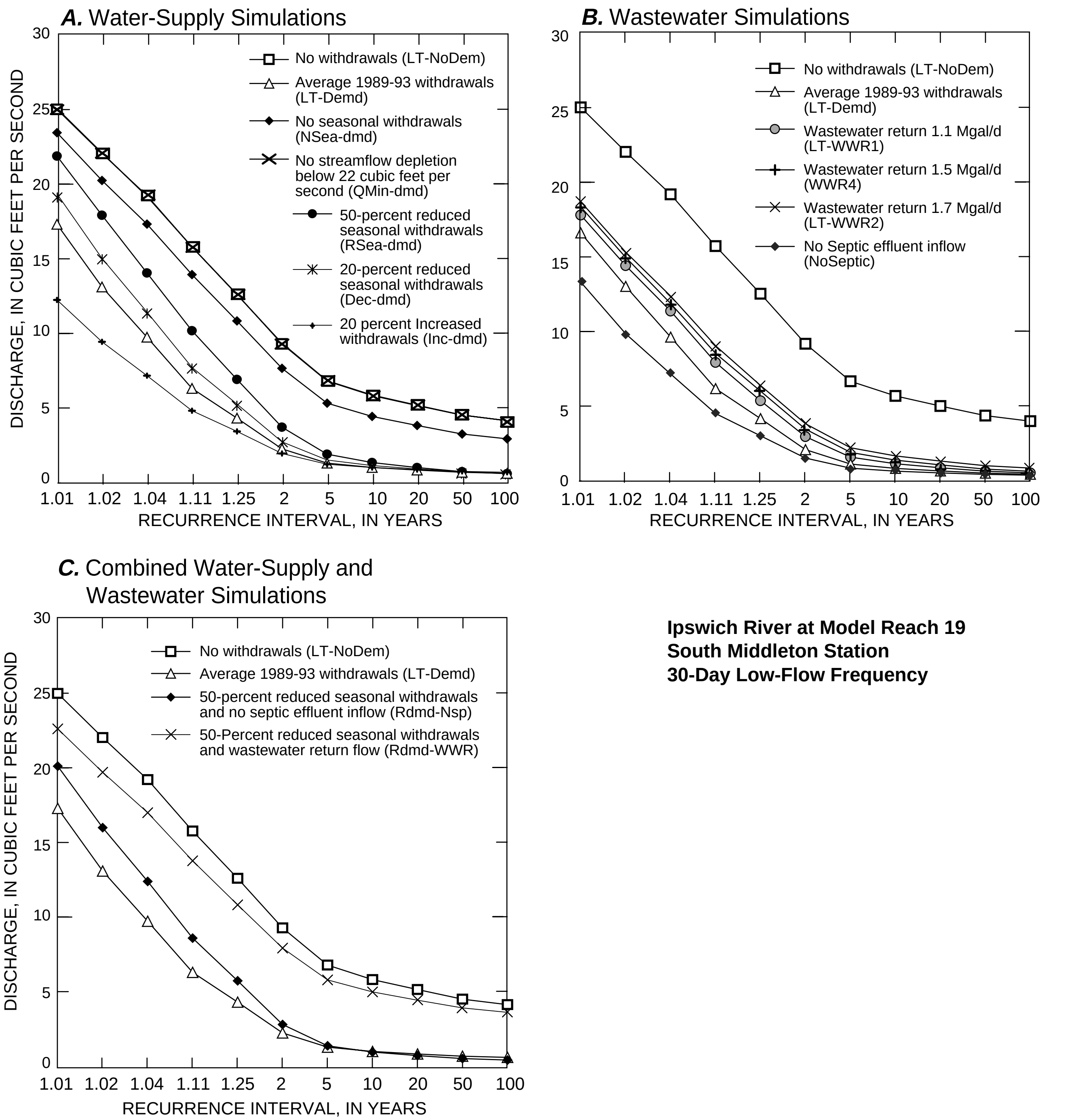

Figure 15. Log-Pearson type III low-flow frequency curves for 30-day annual minimum daily-mean streamflow simulated under management alternatives for (*A*) water supply, (*B*) wastewater, and (*C*) combined water supply and wastewater, model reach 19, Ipswich River Basin, Massachusetts, 1961–95 (model reach is shown in fig. 2; Mgal/d, million gallons per day).

SUMMARY AND CONCLUSIONS

The effects of water-management alternatives on streamflow in the Ipswich River Basin were evaluated with an existing HSPF model of the basin. The HSPF model was modified to simulate eleven hypothetical water-management options. Information obtained from this study will help those concerned with water resource in the Ipswich River Basin develop effective watershed management plans to sustain flow for habitat protection and the needs for water supply.

Water-resource-management alternatives evaluated include changing withdrawal rates, returning wastewater to the basin, stopping septic-effluent inflow, and combining these options. Management options were evaluated for the upper part of the basin at model reach 8 (a critical habitat reach near the Town of Reading well field) and model reach 19 (South Middleton stream-gaging station). Changes in withdrawal rates (relative to average 1989–93 withdrawals) were mostly simulated in model reaches where the towns of Wilmington and Reading have supply wells. Simulation of water-supply alternatives include no seasonal withdrawals from May 1 to October 31 (NSea-dmd), reducing seasonal withdrawals from May 1 to October 31 by 50 percent, reducing withdrawals from June 1 to September 30 by 20 percent, stopping streamflow depletion when flow at model reach 19 is below 22 ft^3/s, and increasing withdrawals by 20 percent. Wastewater-management options include returning 1.1, 1.5, and 1.7 Mgal/d and stopping septic-effluent inflow in residential areas on public water and private septic. Combined simulations of water-supply and wastewater alternatives include reducing seasonal withdrawals by 50 percent along with stopping septic-effluent inflow, and reducing seasonal withdrawals 50-percent along with returning 2.6 Mgal/d of wastewater. Simulations of water-management options were compared to simulations of average 1989–93 withdrawals and simulations with no withdrawals. All simulations were run under the 1991 land-use conditions from 1961 through 1995.

All management options examined provided some degree of low-flow restoration, except for simulations of no septic-effluent inflow and increased withdrawals, which further reduced low-flows or caused the stream to stop flowing for longer periods. Simulation results indicated that reducing seasonal withdrawals by 20 or by 50 percent slightly increased low flows relative to low flows under average 1989–93 withdrawals. Both of these simulations indicated that model reach 8 would stop flowing for at least a 7-day period every other year. Simulations of no seasonal withdrawals resulted in slightly lower minimum flows than the minimum flows under no withdrawals. Simulations that stopped streamflow depletion below a flow 22 ft^3/s resulted in about the same minimum flow as no withdrawals because the special action feature stopped streamflow depletion as opposed to stopping pumping. Stopping pumping below a streamflow threshold would continue to result in streamflow depletion for a period of time because the aquifer and the distance of the well from the stream delays response of altering pump rates on streamflow depletion. Simulation results of no seasonal withdrawals and flow threshold limited streamflow depletions indicated flow would be maintained in model reach 8 at all times.

Simulation results indicated that wastewater-return flows increased low flows in proportion to rate of return flow. The simulation of returning 1.7 Mgal/d indicated model reach 8 would stop flowing for seven consecutive days about once every 5 years; simulated return-flow rates of 1.1 indicated that model reach 8 would stop flowing for seven consecutive days about every other year. Without wastewater-return flow simulations under average 1989–93 withdrawals indicated model reach 8 would stop flowing for seven consecutive days in most years.

Simulations of 50 percent reduced seasonal withdrawals, combined with no septic-effluent inflow, provided only a slight increase in low flow compared to the flow under for the average 1989–93 withdrawals. Simulations of 50 percent reduced seasonal withdrawals, combined with 2.6 Mgal/d wastewater-return flow, increased low flows in model reach 8 above the values simulated under no withdrawals. Simulation of alternative water-supply withdrawals and wastewater-return flows indicated that different rates of return flow and reduced withdrawals could maintain streamflow in model reach 8 at a level similar to the flow expected under no withdrawals. Further analysis would be required to determine what combinations of water-supply withdrawals and wastewater-return flow rates would meet the desired flow objectives.

Water-management alternatives evaluated effect low flows to a greater extent in model reach 8 than in model reach 19. The management alternatives evaluated primarily targeted the headwater reaches, which are least capable of sustaining flow under average 1989–93 withdrawals because of the relatively small contributing drainage relative to the withdrawals at and above these reaches. Water-management strategies designed to increase low flows will be most effective when applied at or above reaches that have large withdrawals relative to their contributing area. As the ratio of drainage area to withdrawals increases, the effects that water-management alternatives have on low flows will decrease.

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