Part 4. Conjunctive-Management Models as Tools for Water-Resources Planning

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Conjunctive-management models were developed for selected areas in the Pawcatuck River Basin to evaluate relations between streamflow-depletion criteria and water-withdrawal volumes for several different withdrawal-well networks. The term “conjunctive-management model” commonly is used in the hydrologic literature to refer to the combined use of numerical simulation and optimization techniques to evaluate alternative strategies for balancing water withdrawals with aquatic-habitat protection goals (Barlow and Dickerman 2001a,b; Granato and Barlow, 2005). A conjunctive-management model consists of a mathematical formulation (statement) of the groundwater-development goals for the model area and a set of constraints that limit those goals. This part of the report describes information provided by the models that can be used for planning purposes by water-resource managers. The details of the mathematical formulation of the conjunctive-management models and the response-matrix technique used to solve the linear models are described in Appendix Part 4.

The conjunctive-management models described in this report were based on quantitative descriptions of groundwater/surface-water interactions and were used to maximize water withdrawals within a given set of constraints. Simulations made with the transient numerical groundwater (MODFLOW) models developed for the eastern Pawcatuck and lower Wood River groundwater-model areas were used to quantify relations between withdrawals and associated streamflow depletions at one or more sites. Allowable streamflow depletions calculated from streamflow statistics were the primary constraints on the solution of the conjunctive-management models. The results of a simulation made with the basinwide HSPF model without any withdrawals during the 1960–2004 simulation period were used to formulate streamflow constraints. Water-use patterns were also used to constrain management-model results. The water-use patterns used in the formulation of the conjunctive-management models were estimated from statistical analyses of water-use data.

The surface-water (HSPF) and groundwater (MODFLOW) models for these conjunctive-management model areas were developed, calibrated, and tested on the basis of local information. The models, however, are idealized mathematical representations of complex and dynamic hydrogeological systems. The conjunctive-management models are subject to some of the same uncertainties and limitations of the HSPF and MODFLOW models because the conjunctive-management model inputs were based on the results of the surface-water and groundwater modeling efforts. Furthermore, the 1960–2004 study period includes a substantial amount of variability in climatic conditions affecting streamflow, including the 1963–1967 drought of record for the New England area (Walker and Lautzenheiser, 1991). Walker and Lautzenheiser (1991) indicate that the total precipitation (25.4 in.) measured in Providence, R.I., in 1965 was the lowest precipitation measured in the last 185 years. Although the 1960–2004 period included this historical extreme, this period may or may not fully reflect future conditions; thus, risks for extreme low-flow events indicated by the duration curves can be regarded as planning-level estimates.

Information from the results of the conjunctive-management-modeling effort can be used as a generalized water-resource planning tool to help balance withdrawals needed for water supply with aquatic-habitat protection goals. The models developed and tested for the eastern Pawcatuck River conjunctive-management-model (EPRCMM) area and lower Wood River conjunctive-management model (LWRCMM) area represent different combinations of network design, withdrawal patterns, withdrawal rates, and streamflow-depletion criteria. With unlimited time and resources, an almost infinite number of combinations and permutations of these factors could be tested to evaluate different conditions. The purpose of this analysis, however, is to provide water-resource managers with an understanding of the hydrologic concepts necessary to make informed decisions about the current and future status of water withdrawals and streamflow depletions in selected areas of the Pawcatuck River Basin.

Streamflow-Response Coefficients

Streamflow-response coefficients are relations between groundwater withdrawals and streamflow depletions at selected surface-water constraint sites. A one-month unit withdrawal is simulated for each well to calculate the response coefficients caused by the withdrawal (Appendix Part 4). Each response coefficient is equal to the fraction of the unit withdrawal that is evident as a streamflow depletion in each month after the unit withdrawal. The sum of the response coefficients will be about one if the entire water withdrawal is accounted for in the stream (Barlow and Dickerman

2001a,b; Granato and Barlow, 2005). The areas of interest in both conjunctive-management model areas are bounded on three sides by different streams (figs. 4–1, 4–2). The response coefficients for each stream indicate the fractions of withdrawals that appear as streamflow depletions in each of the bounding streams. In each management-model area, a streamflow-constraint site was selected along the Pawcatuck River near the outlet of the active groundwater-model area (PAWCD in figure 4–1 and PAWC4 in figure 4–2) to ensure that response coefficients sum to about 1.0 within each management-model area. The response coefficients are used within the conjunctive-management model to maximize withdrawals while meeting streamflow-depletion criteria. However, examination of the response coefficients also provides useful water-resources planning information.

The groundwater models developed for each area were modified to calculate the response coefficients for each well by use of the dynamic-equilibrium technique (Barlow and Dickerman 2001a,b; Granato and Barlow, 2005) described in Appendix Part 4. Nineteen proposed and existing groundwater withdrawal sites in the EPRCMM area and nine proposed and existing groundwater withdrawal sites in the LWRCMM area were simulated with the groundwater models (table 4–1). The groundwater models can be used to simulate the effect of withdrawals throughout the model area. However, three sites in the EPRCMM area (fig. 4–1) and four sites in the LWRCMM area (fig. 4–2) were selected to analyze potential effects of withdrawals on streamflow depletions (table 4–2). These sites are at or near the HSPF model nodes in each conjunctive-management model area. A total of 224 groundwater-model runs were made to calculate response coefficients for each groundwater-withdrawal site at four withdrawal rates (0.1, 0.5, 1.0, and 2.0 Mgal/d) in January and June to ensure that response coefficients would be representative of different hydrological conditions.

Examination of the streamflow-response coefficients provides insights about the possible effects of withdrawals from potential well sites. Graphs of the response coefficients for groundwater-withdrawal sites in these management-model areas indicate that the response times between withdrawals and associated streamflow depletions are on the order of several months to a year (figs. 4–3A, B). Table 4–1 provides a list of figures in Appendix Part 4 that document response coefficients for each groundwater-withdrawal site in each management-model area. It was necessary to include one surface-water withdrawal site in the EPRCMM area and three surface-water withdrawal sites in the LWRCMM area to account for management of surface-water withdrawals. Surface-water-withdrawal sites are listed with a response coefficient of 1.0 because the entire withdrawal occurs instantly as a streamflow depletion as water is pumped from the stream. Limitations on the use of monthly withdrawal rates for irrigation supplies from surface-water-withdrawal sites are discussed in Appendix Part 4.

Response-coefficient graphs for the hypothetical well sites in the EPRCMM area (fig. 4–3A) illustrate the effect of well distance on the temporal distribution of streamflow depletion. For example, withdrawals from hypothetical well RIW–385 along the banks of Beaver River (fig. 4–1) have a substantial effect on streamflow in the Beaver River, but do not cause streamflow depletion in the Usquepaug-Queen River. Response coefficients for the Pawcatuck River (PAWCD) represent the sum of the depletions in the tributary rivers; and occur on the same time scale because depletions from tributaries appear as depletions at downstream sites within a few hours or days. The initial response coefficient for this well is 0.93, indicating that about 93 percent of the streamflow depletion occurs in the Beaver River during the first month after a groundwater withdrawal is made from this hypothetical well. The response-coefficient graph indicates that depletions decrease exponentially to zero during the 4 months after a groundwater withdrawal is made. The rate of decrease is greater for this well than for depletions from wells farther from the stream, but slower than for a surface-water withdrawal.

Hypothetical well PR–AB3B is farther from the Beaver River than hypothetical well RIW–385 (fig. 4–1), and the response coefficients for hypothetical well PR–AB3B indicate a slower streamflow response to withdrawals than for hypothetical well RIW–385. The initial response coefficient for well PR–AB3B is 0.43, indicating that about 43 percent of the streamflow depletion occurs in the Beaver River during the first month after a groundwater withdrawal is made from this hypothetical well (fig. 4–3A). Depletions caused by the withdrawal from this hypothetical well decrease exponentially during the 12 months after a groundwater withdrawal is made. Withdrawals from this well do not cause depletions in the Usquepaug-Queen River because of the proximity of this hypothetical well site to the Beaver River.

Hypothetical well PR–AB4A is distant from and roughly midway between the Beaver and the Usquepaug-Queen Rivers (fig. 4–1). Accordingly, the response coefficients for this well are approximately equal for each month at the mouth of the Beaver (BEAVM) and Usquepaug-Queen River (QUEENM). The initial response coefficients for this well are about 0.08, indicating that about 8 percent of the streamflow depletion from this hypothetical well occurs from each river during the first month after a groundwater withdrawal is made (fig. 4–3A). The peak response (about 0.13) occurs in the second month, and depletions continue for about 11 more months, after a groundwater withdrawal is made. About 8, 21, and 31 percent of the total streamflow depletion have been made at each constraint site by the ends of the first, second, and third months after a groundwater withdrawal, respectively. Response coefficients for the Pawcatuck River constraint site (PAWCD) represent the total monthly depletion from hypothetical well PR–AB4A because they are the summation of depletions in the tributaries upstream of PAWCD. About 16, 42, and 62 percent of the total streamflow depletions at this constraint site have been made by the ends of the first, second, and third months after a groundwater withdrawal, respectively (fig. 4–3A).

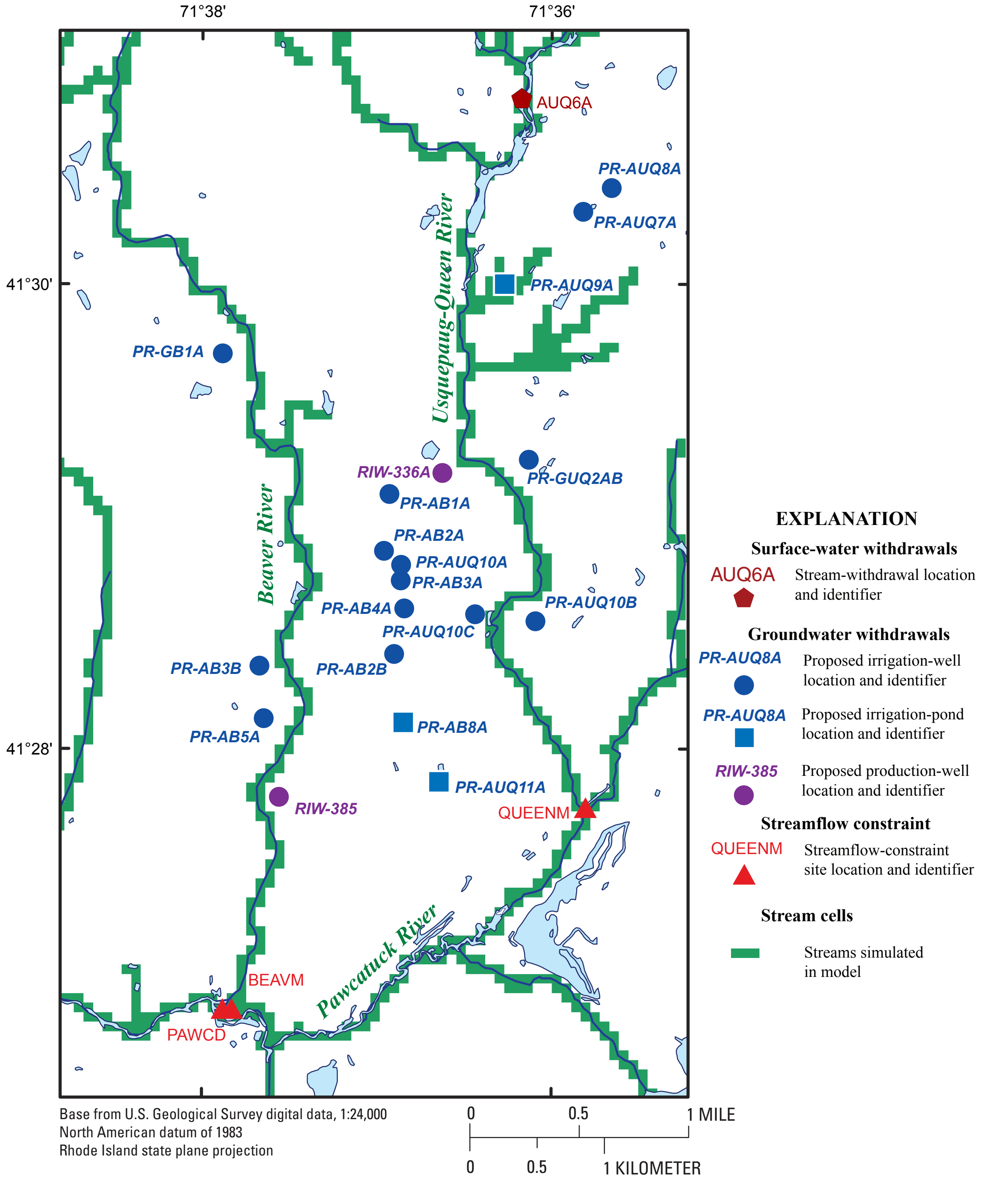

Figure 4–1. The eastern Pawcatuck River conjunctive-management model (EPRCMM) area with three streamflow-constraint sites (defined in table 4–2) and 20 existing or potential water-withdrawal sites (defined in table 4–1) in the Pawcatuck River Basin, southwestern Rhode Island.

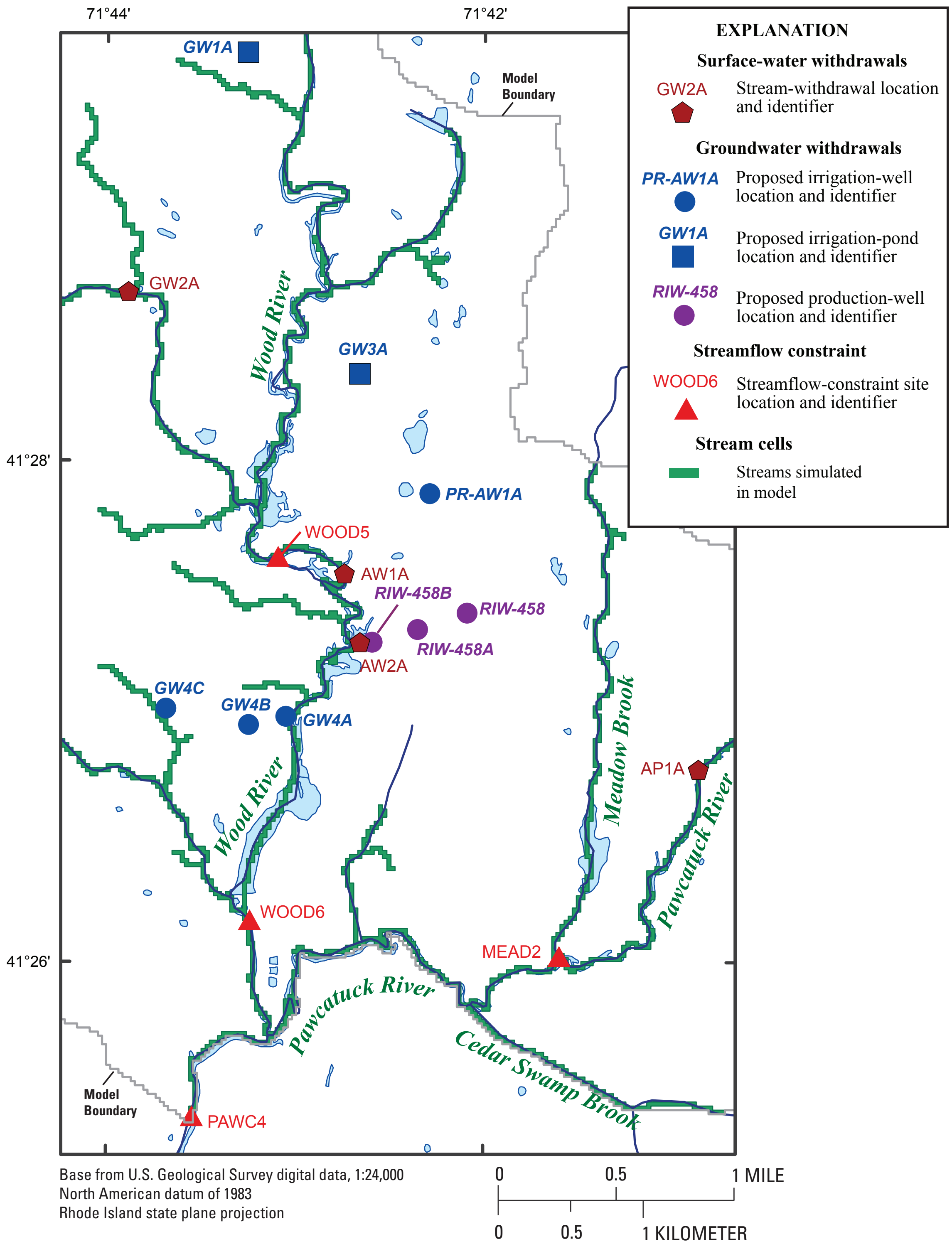

Figure 4–2. The lower Wood River conjunctive-management model (LWRCMM) area with four streamflow-constraint sites (defined in table 4–2) and 12 existing or potential water-withdrawal sites (defined in table 4–1) in the Pawcatuck River Basin, southwestern Rhode Island.

Table 4–1. Characteristics of existing and potential water-withdrawal sites in the eastern Pawcatuck and lower Wood River conjunctive-management model areas, Pawcatuck River Basin, southwestern Rhode Island.

[ID, identifier. Index: Conjunctive-management model index number. Site type: GW, groundwater; GW–P, groundwater-pond; SW, surface water. Water use: IT, irrigation turf; IG, irrigation golf; MS, potential municipal supply; IV, irrigation vegetable. Response coefficient information: the number of the appendix which shows a graph of the response coefficients for the withdrawal site (response coefficient information equal to 1 indicates a surface-water site where streamflow depletion occurs simultaneously with withdrawals)]

Eastern Pawcatuck River conjunctive-management model (EPRCMM) area						
Index	Site ID (Site locations shown in figure 4–1)	Site type	Water use	MODFLOW row	MODFLOW column	Response coefficient information
1	AUQ6A	SW	IT	166	82	1
2	PR–AUQ8A	GW	IT	175	91	A4–15
3	PR–AUQ9A	GW–P	IT	185	80	A4–15
4	PR–AUQ11A	GW–P	IT	236	74	A4–15
5	PR–AB8A	GW–P	IT	231	69	A4–15
6	PR–GB1A	GW	IG	193	48	A4–18
7	RIW–336A	GW	MS	205	70	A4–18
8	RIW–385	GW	MS	239	56	A4–14
9	PR–AUQ7A	GW	IT	178	88	A4–18
10	PR–AUQ10A	GW	IT	215	69	A4–17
11	PR–AUQ10B	GW	IT	221	83	A4–17
12	PR–AUQ10C	GW	IT	220	76	A4–17
13	PR–AB1A	GW	IT	207	67	A4–16
14	PR–AB2A	GW	IT	213	67	A4–16
15	PR–AB2B	GW	IT	224	68	A4–16
16	PR–AB3A	GW	IT	216	69	A4–16
17	PR–AB3B	GW	IT	225	54	A4–14
18	PR–AB4A	GW	IT	219	69	A4–14
19	PR–AB5A	GW	IV	231	54	A4–17
20	PR–GUQ2AB	GW	IG	204	82	A4–18
Lower Wood River conjunctive-management model (LWRCMM) area						
Index	Site ID (Site locations shown in figure 4–2)	Site type	Water use	MODFLOW row	MODFLOW column	Response coefficient information
1	AW2A	SW	IT	165	138	1
2	AP1A	SW	IT	196	220	1
3	GW1A	GW–P	IG	22	111	A4–20
4	GW2A	SW	IG	80	82	1
5	GW3A	GW–P	IG	100	138	A4–20
6	GW4A	GW	IG	183	120	A4–20
7	GW4B	GW	IG	185	111	A4–21
8	GW4C	GW	IG	181	91	A4–21
9	RIW–458	GW	MS	158	164	A4–19
10	RIW–458A	GW	MS	162	152	A4–19
11	RIW–458B	GW	MS	165	141	A4–19
12	PR–AW1A	GW	IT	129	155	A4–21

Table 4–2. Characteristics of selected streamflow constraint sites in the eastern Pawcatuck and lower Wood River conjunctive-management model areas, Pawcatuck River Basin, southwestern Rhode Island.

[Estimates of the minimum monthly one-day streamflow values without withdrawals are derived from the output of the basinwide surface-water model. ID, identifier; mi^2, square miles; *, HSPF subbasin outlets. Site locations for EPRCMM shown in figure 4–1 and site locations for LWRCMM shown in figure 4–2 and described in table A2–4.]

Management-model site designation	River	MOD-FLOW row	MOD-FLOW column	Drain-age area (mi^2)	Description	Minimum monthly one-day streamflow without withdrawals during 1960–2004, in cubic feet per second											
						Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.
Eastern Pawcatuck River conjunctive-management model (EPRCMM) area																	
BEAVM	Beaver River	261	50	12.47	Model cell at confluence of the Beaver and Pawcatuck Rivers.	7.02	9.74	13.93	10.68	9.84	6.18	2.93	2.30	1.99	2.20	2.20	3.14
QUEENM	Usquepaug-Queen River	240	87	36.57	Model cell at confluence of the Usquepaug-Queen and Pawcatuck Rivers.	19.6	26.1	36.8	28.1	26.5	17.0	9.13	7.10	6.09	6.80	7.00	9.03
PAWCD	Pawcatuck River	261	49	90.91	Model cell downstream of the confluence of the Usquepaug-Queen and Pawcatuck Rivers.	56.5	79.1	106	87.1	81.2	54.4	30.3	23.0	19.5	23.7	27.6	34.7
Lower Wood River conjunctive-management model (LWRCMM) area																	
MEAD2* (RCHRES 48)	Meadow Brook	241	186	7.21	Model cell at confluence of the Meadow Brook and the Pawcatuck River.	3.00	4.40	6.50	5.10	5.30	3.40	2.00	1.60	1.40	1.50	1.40	1.70
WOOD5* (RCHRES 63)	Wood River	144	118	85.13	Model cell downstream of the confluence of Canonchet Brook and the Wood River.	41.9	55.1	79.5	60.9	58.2	36.3	17.5	12.9	10.8	13.1	12.1	18.6
WOOD6* (RCHRES 65)	Wood River	232	111	88.31	Model cell downstream of the confluence of an unnamed tributary and the Wood River.	46.9	62.0	89.3	68.3	65.3	40.9	20.0	14.9	12.6	13.8	13.9	21.1
PAWC4* (RCHRES 50)	Pawcatuck River	281	98	204.33	Model cell on the Pawcatuck River at the outlet of the MODFLOW model below the confluence with the Wood River.	118	160	223	177	170	112	60.8	45.8	39.0	44.8	46.9	65.6

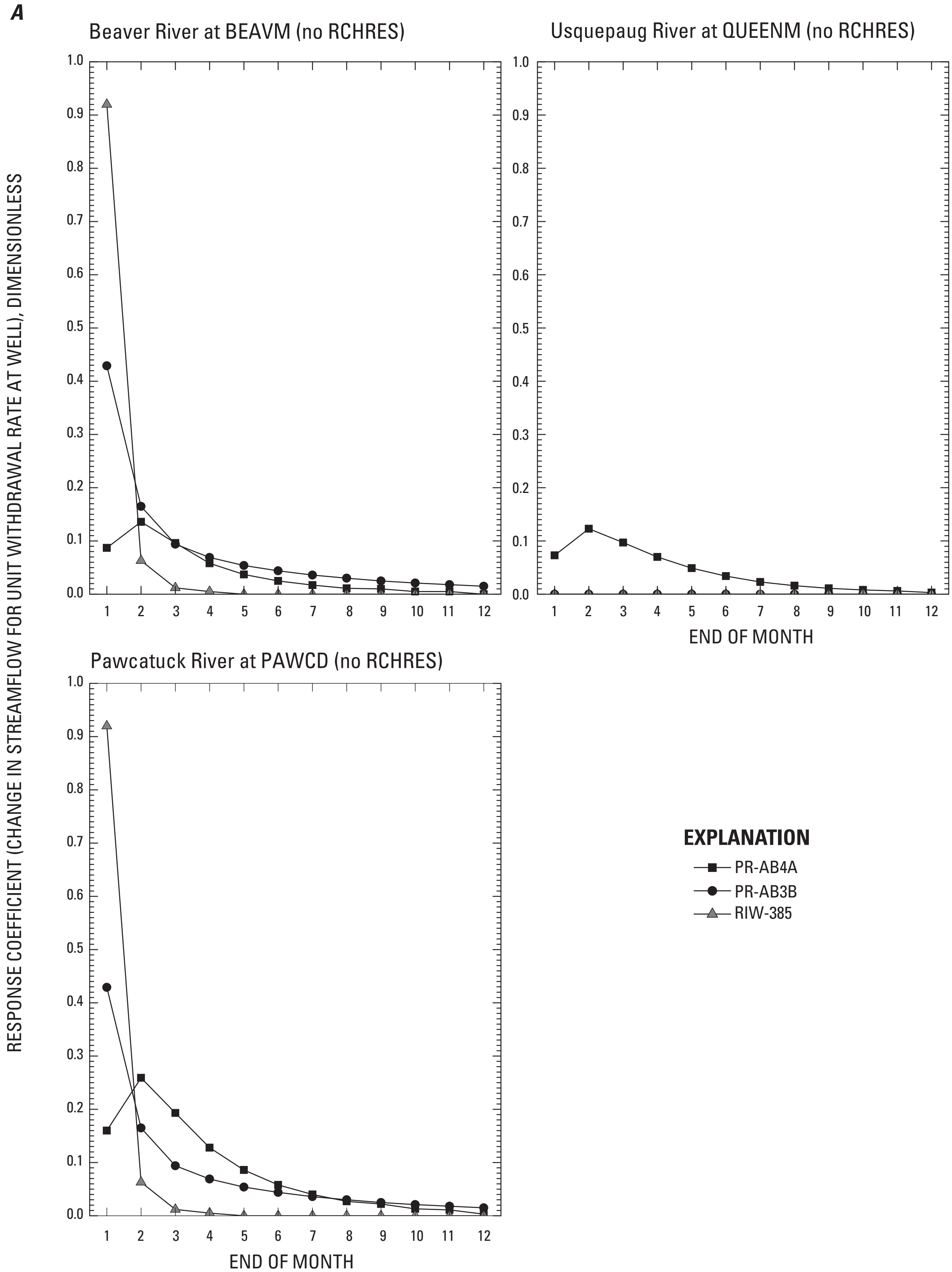

Figure 4–3A. Selected examples of simulated response coefficients for streamflow-constraint sites on the Beaver (at BEAVM), Usquepaug-Queen (at QUEENM), and Pawcatuck (at PAWCD) Rivers, in the eastern Pawcatuck River conjunctive-management model (EPRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. Graphs show the fraction of the unit withdrawal from each well that is evident as streamflow depletion at the end of each month after the withdrawal. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

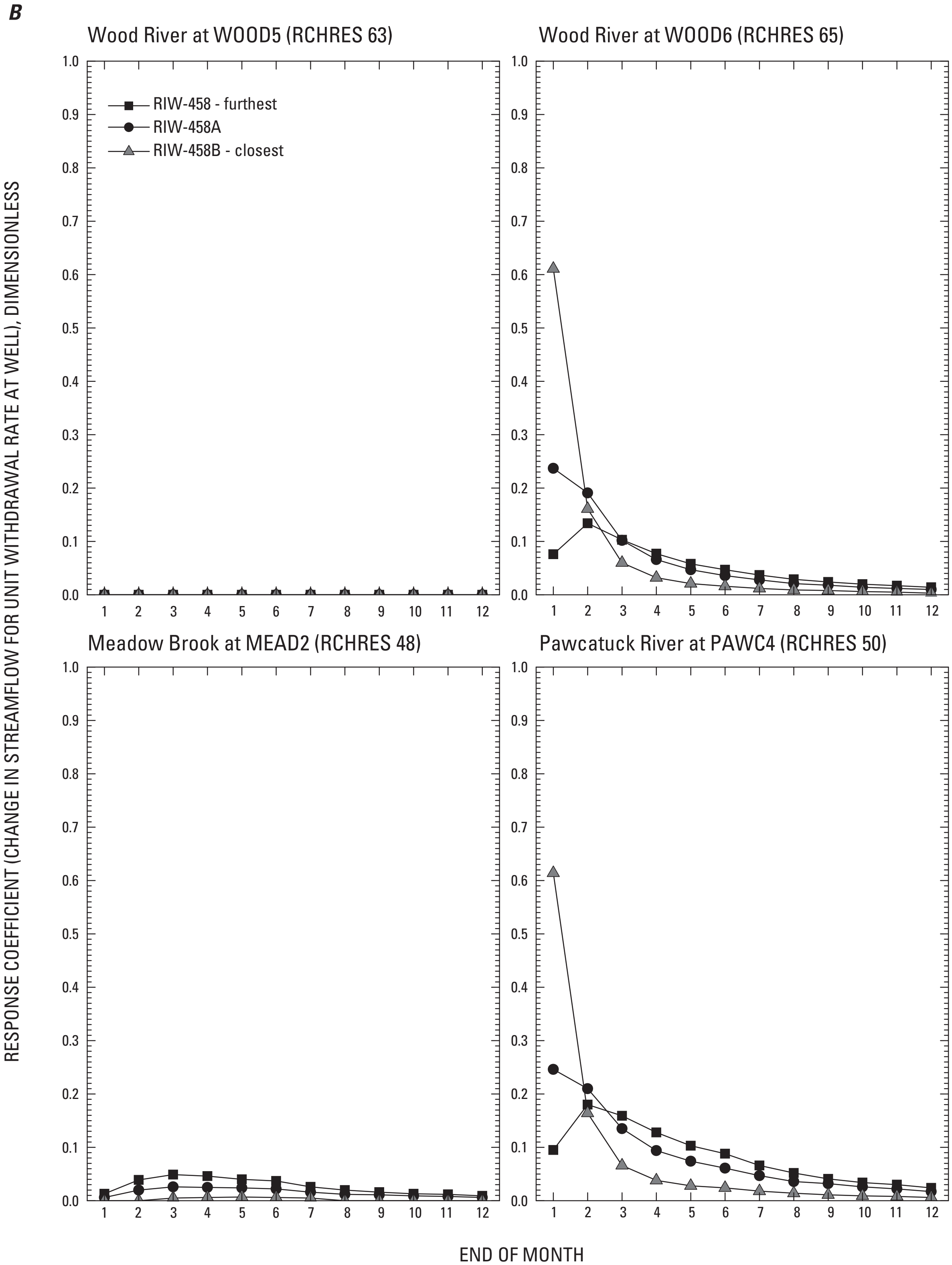

Figure 4–3B. Selected examples of simulated response coefficients for streamflow-constraint sites on the Wood River (at WOOD5 and WOOD6), Meadow Brook (at MEAD2), and Pawcatuck (at PAWC4) Rivers, in the lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. Graphs show the fraction of the unit withdrawal from each well that is evident as streamflow depletion at the end of each month after the withdrawal. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

Response-coefficient graphs for three hypothetical well sites in the LWRCMM area (fig. 4–3B) also illustrate the effect of well distance on the temporal distribution of streamflow depletions. The three hypothetical well sites (RIW–458, RIW–458A, and RIW–458B) are at different distances between the Wood River and Meadow Brook (fig. 4–2). A comparison of the response-coefficient graphs for the streamflow-constraint sites WOOD5 (RCHRES 63) and WOOD6 (RCHRES 65) indicates that all depletions in the Wood River from these hypothetical well sites occur downstream of the WOOD5 constraint site. Depletions at WOOD6 peak in the second month after each unit withdrawal from hypothetical well RIW–458 because this site is farther from the Wood River (within about 2,000 ft) than the other wells. Depletions at WOOD6 peak in the first month after each withdrawal from hypothetical wells RIW–458A and RIW–458B because these sites are closer to the Wood River (about 1,000 and 300 ft away from the Wood River, respectively). About 8, 24, and 62 percent of the total depletions caused by withdrawals from wells RIW–458, RIW–458A, and RIW–458B, respectively, occur in the first month after a unit withdrawal at each hypothetical well site. Total streamflow depletions at WOOD6 caused by withdrawals from these wells do not equal the amounts withdrawn. This is because withdrawals at these sites cause a shift in the location of the groundwater divides in the aquifer so that each well also intercepts groundwater that otherwise would flow toward the Meadow Brook or the Pawcatuck River.

Response coefficients from the groundwater model indicate that withdrawals from potential well sites RIW–458, RIW–458A, and RIW–458B have a small but sustained effect on streamflow depletions in Meadow Brook at constraint site MEAD2 (RCHRES 48) (fig. 4–3B). The amount of depletion at MEAD2 increases as the withdrawal location is shifted to the east away from the Wood River and toward Meadow Brook (fig. 4–3B). Although the fraction of depletion during each individual month is low (less than or equal to a maximum of about 5 percent of the unit withdrawals), the annual sum of the depletions could be substantial, especially if withdrawals were to be made at these wells throughout the year. In addition, the response coefficients (fig. 4–3B) indicate that withdrawals from these potential well sites may intercept a small amount of groundwater that would otherwise flow southward toward the Pawcatuck River and a small unnamed tributary in the area between Meadow Brook and the Wood River (fig. 4–2). The calculated depletions are caused by small shifts in the natural groundwater divides. These depletions are small, are sustained for many months, and have a pattern similar to depletions from Meadow Brook at MEAD2. The depletions caused by intercepting groundwater discharge from these areas are calculated by subtracting the total streamflow depletions at WOOD6 and MEAD2 from the total depletion in the Pawcatuck River at PAWC4 (RCHRES 50).

The response coefficients in figure 4–3B also may be used to guide the well-site selection process. Granato and Barlow (2005) noted that groundwater-supply systems in Rhode Island substantially increase withdrawals during the months of May through September with a peak monthly withdrawal rate in July (see Appendix Part 4). This annual withdrawal pattern is shown in figure 4–4 with the fraction of the total annual depletions that would occur in each month if well RIW–458, RIW–458A, or RIW–458B were pumped according to this Rhode Island demand pattern. These monthly streamflow-depletion patterns indicate that the monthly depletion rate from well RIW–458, which is farthest from the Wood River, would peak in September. The peak monthly depletion rate from well RIW–458A, which is at the intermediate location, would occur in August. The monthly depletion rate from well RIW–458B, which is closest to the Wood River, would peak concurrently with peak withdrawal rates in July. The delay between peak withdrawals and peak depletions from RIW–458 and RIW–458A may not be advantageous because the maximum depletions occur in August or September concurrently with the lowest daily streamflows in the Wood River (see Appendix Part 4). In this hypothetical case, if all three wells were available, well RIW–458B could be used during the early summer through July to minimize residual depletions in August and September and well RIW–458 could be used in July and August to delay peak depletions from these withdrawals until later in the fall.

The response-coefficient graphs (fig. 4–3B) and the associated depletion graph (fig. 4–4) provide insight into the time frames necessary to make effective water-management decisions as a drought condition evolves. These graphs indicate that withdrawal reductions made in response to a developing summer drought will not have an immediate effect on depletions if wells are far from the stream. Response-coefficient graphs provide information about the effects of individual water-withdrawal sites in an area of interest, but conjunctive-management models are necessary to evaluate complex interactions caused by various constraints, such as streamflow-depletion criteria, water-withdrawal patterns, and well-network designs.

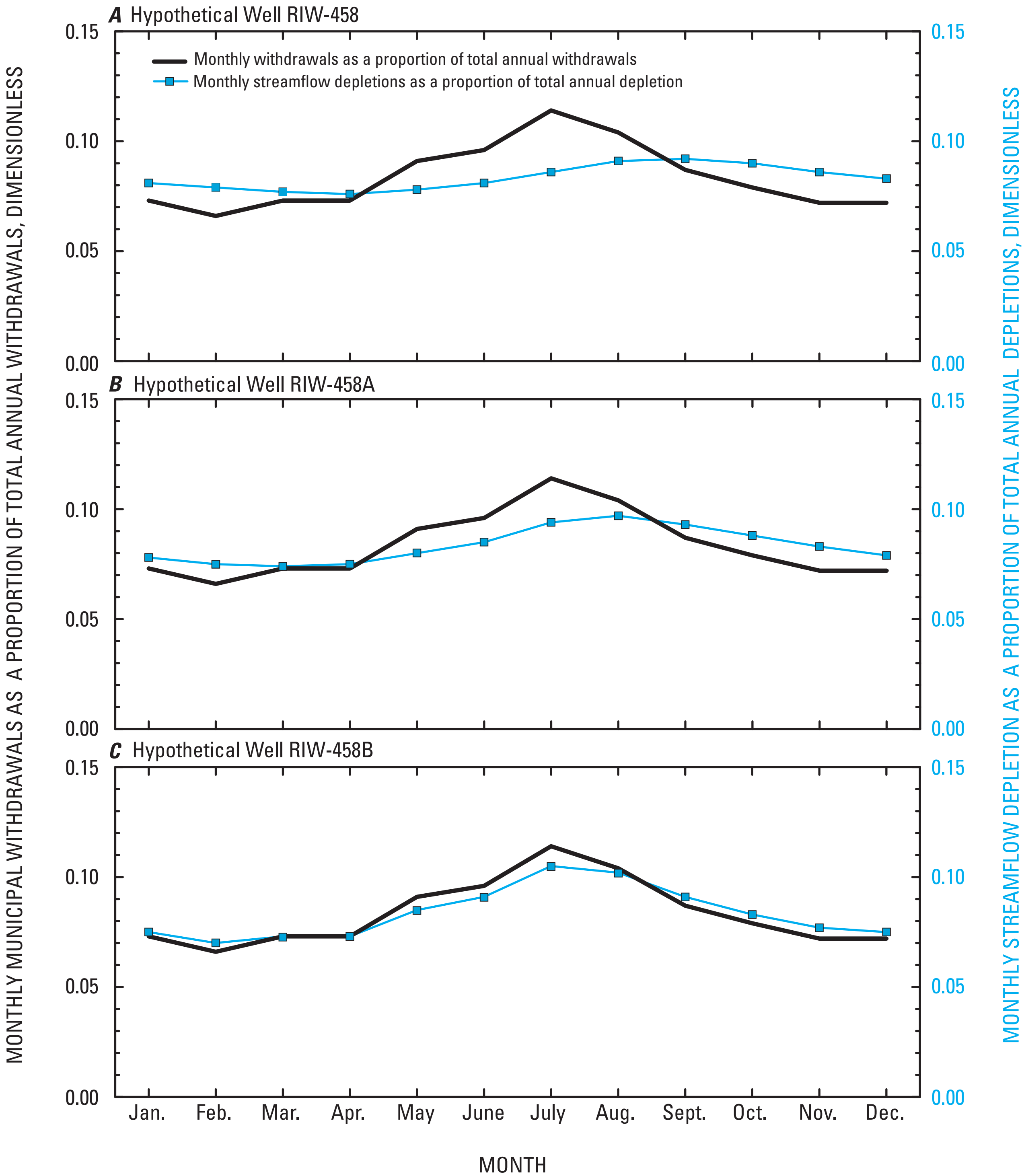

Figure 4–4. The annual pattern in streamflow depletion caused by withdrawals from potential water-withdrawal sites at hypothetical well *(A)* RIW–458, *(B)* RIW–458A, and *(C)* RIW–458B indicating in the Wood River (WOOD6, RCHRES 65) in the lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

Potential Allowable Streamflow-Depletion Criteria

Knowledge of relations between streamflow criteria and maximum potential water withdrawals is crucial for water-resource-planning efforts. Many instream-flow criteria were formulated on the basis of the assumption that a substantial amount of water is available in storage for maintaining instream flows by release from an actively managed surface-water reservoir (Granato and Barlow, 2005). Granato and Barlow (2005) evaluated 11 commonly referenced flow criteria and determined that application of such criteria could overrestrict (or preclude) groundwater withdrawals even under average hydrologic conditions. Granato and Barlow (2005) also determined that criteria based on central-tendency statistics (averages or medians of monthly or annual streamflows) may not be protective for extreme lowflows if differences between these local streamflow statistics and regional streamflow-criteria values were greater than or equal to the low-flow values.

Groundwater-supply system operators cannot control the total volume of streamflow if they do not also operate a surface-water reservoir that can be used to intercept and store high flows for later release during dry periods to maintain streamflows. Most groundwater-supply systems in Rhode Island do not have surface-water reservoirs with adequate capacities for public supply and streamflow maintenance. Groundwater-supply system operators, however, can affect the magnitude and timing of streamflow depletions caused by groundwater withdrawals within operational constraints. Managing groundwater withdrawals in response to short-term (days or weeks) streamflow variation is not possible because it may take one or more months for changes in groundwater withdrawals to have a substantial effect on streamflow depletions (Barlow and Dickerman, 2001a,b; Barlow and others, 2003; Granato and Barlow, 2005).

Granato and Barlow (2005) explored an alternative depletion-management paradigm for groundwater-supply systems. This approach uses potential allowable streamflow-depletion criteria rather than streamflow target criteria to identify a range of streamflow depletions that can be used by decisionmakers to balance water-supply needs with ecological protection goals. The objective of that effort was to use optimization methods to maximize withdrawals, control the magnitude and timing of depletions, and minimize the probability of reducing streamflow beyond a specified nonzero streamflow value. Granato and Barlow (2005) used an estimated streamflow record for the period 1960–2000 to evaluate potential-allowable depletion criteria based on the one-day monthly minimum streamflow for each month during this period. The one-day monthly minimum streamflow is the minimum of the daily mean streamflows for each month of the period of record. In that study, post-optimization analysis indicated that the selected potential allowable-depletion criteria were adequate to provide water for public supply while maintaining nonzero streamflows during the simulated 1960–2000 period. This approach also resulted in a high degree of natural variability at higher streamflow rates because withdrawals were a small fraction of these flows.

In this study, potential allowable-depletion criteria were formulated from the population of minimum daily-mean streamflow values in each month of each year during the 1960–2004 period. The HSPF-generated record of daily-mean streamflows without water withdrawals was used to identify these minimum daily-mean streamflow values. This results in about 45 minimum daily mean streamflow values for each month of the 45-year period for each of the seven streamflow constraint sites. The minimum of these 45 daily-mean streamflow values for each of the seven streamflow-constraint sites for each month of the entire period are listed in table 4–2. The lowest minimum daily-mean streamflows for the period of record for each constraint site occurred in the month of September.

The 45 one-day monthly minimum streamflow values were ranked for each month of the year by using the Weibull plotting-position values (Appendix Part 4). The Weibull plotting-position values indicate the percentages of minimum daily flow values that would equal or exceed a given streamflow value in a given month for each site. The monthly flow-duration curve for each site consists of about 45 points each of which represents one daily minimum streamflow value for each month of each year during the period 1960–2004. For example, the percentages of September months with one-day monthly minimum streamflows (normalized by drainage area to cubic feet per second per square mile) that equal or exceed a given value for streamflow-constraint sites in the EPRCMM and LWRCMM areas are shown in figures 4–5A and B, respectively. The minimum one-day-minimum September streamflow is about 0.15 $ft^3/s/mi^2$ for all streamflow-constraint sites. The flow duration (Weibull plotting position) for this minimum one-day September streamflow value for the 1960–2004 period is 98 percent. This value indicates that the chance that a streamflow value may be lower than 0.15 $ft^3/s/mi^2$ is about 2 percent, based on the 45 years of data. The 90th-percentile value for normalized streamflows at these sites is about 0.2 $ft^3/s/mi^2$; thus the chance that the one-day minimum September streamflow will be below this value is about 10-percent. As such, the use of an allowable-depletion criterion of about 0.2 $ft^3/s/mi^2$ would have a 10-percent chance of reducing streamflow to zero for one day in any given year, again, based on the 45-year record. Flow-duration curves for the one-day monthly minimum streamflows during each month of the year are shown in Appendix Part 4 for each streamflow-constraint location.

These streamflow-duration curves were used as the basis for calculating values of allowable streamflow depletions that represent specific risks for inducing a zero-flow condition as an effect of water withdrawals. Allowable streamflow depletions were based on either a flow duration (expressed as a percentile flow duration) or a fraction of the 45-year one-day minimum flow (expressed as a percentage of the minimum). Selected flow-duration values for each month of the year were

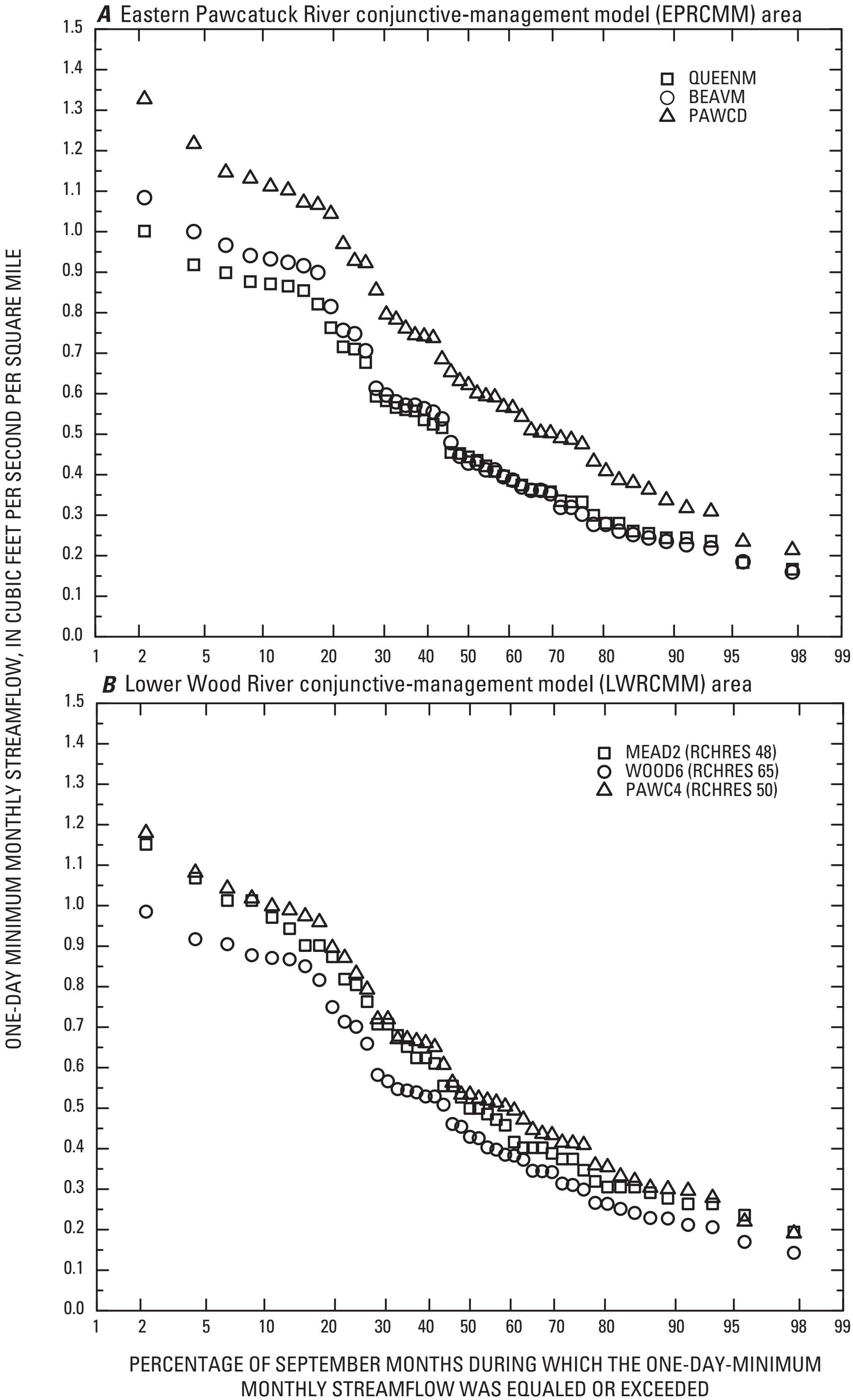

Figure 4–5. Monthly streamflow-duration curves showing the percentage of one-day-minimum September streamflows that would equal or exceed a selected streamflow value at selected sites in the *(A)* eastern Pawcatuck River conjunctive-management model (EPRCMM) area and the *(B)* lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island. (Site locations for EPRCMM shown in figure 4–1, and site locations for LWRCMM shown in figure 4–2 and described in table 4–2.)

used to evaluate relations between the allowable-depletion criteria and the maximum water-withdrawal yield for a given well network with different operational constraints; these constraints are described in the section entitled "Formulation of the Conjunctive-Management Model" in Appendix Part 4. Four flow-duration values—the 80-, 90-, 95-, and 98-percentile flow durations—were selected as examples of potential allowable-depletion values (fig. 4–6). As potential allowable depletions, these values represent 20-, 10-, 5- and 2-percent chances of causing a zero-flow event in each year, respectively. Four potential allowable-depletion values that are equal to 75, 60, 50, and 25 percent of the 45-year minimum daily streamflow value for each month (table 4–2) also were selected to evaluate water-withdrawal yields that would further reduce the risk of a zero-flow event (fig. 4–6). These allowable-depletion criteria would maintain 45-year minimum daily mean streamflows for each month that are 25, 40, 50, and 75 percent of the estimated historical minimums without withdrawals, respectively.

Optimization techniques can be used to estimate the maximum groundwater withdrawals that can be achieved within the allowable-depletion criteria. The relations between estimated maximum-withdrawal rates and the allowable-depletion criteria can be expressed visually with a conjunctive-management-model yield graph (for example, fig. 4–6). The yield graph can be used by water managers to balance water-supply needs with environmental protection goals. The x-axis represents the allowable depletion, which may be less than, equal to, or greater than the minimum daily mean streamflow. An increase in allowable depletion represents an equal reduction in streamflows. The streamflow-depletion criteria are established on the basis of historical minimum daily-mean streamflows in each month of the year, but the yield graphs that are presented are for annual total withdrawals. Rather than repeat the same yield curve for each of the 12 monthly allowable-depletion criteria, the allowable-depletion criteria for the month with the lowest minimum daily-mean streamflows were selected. This is because allowable depletion criteria for the

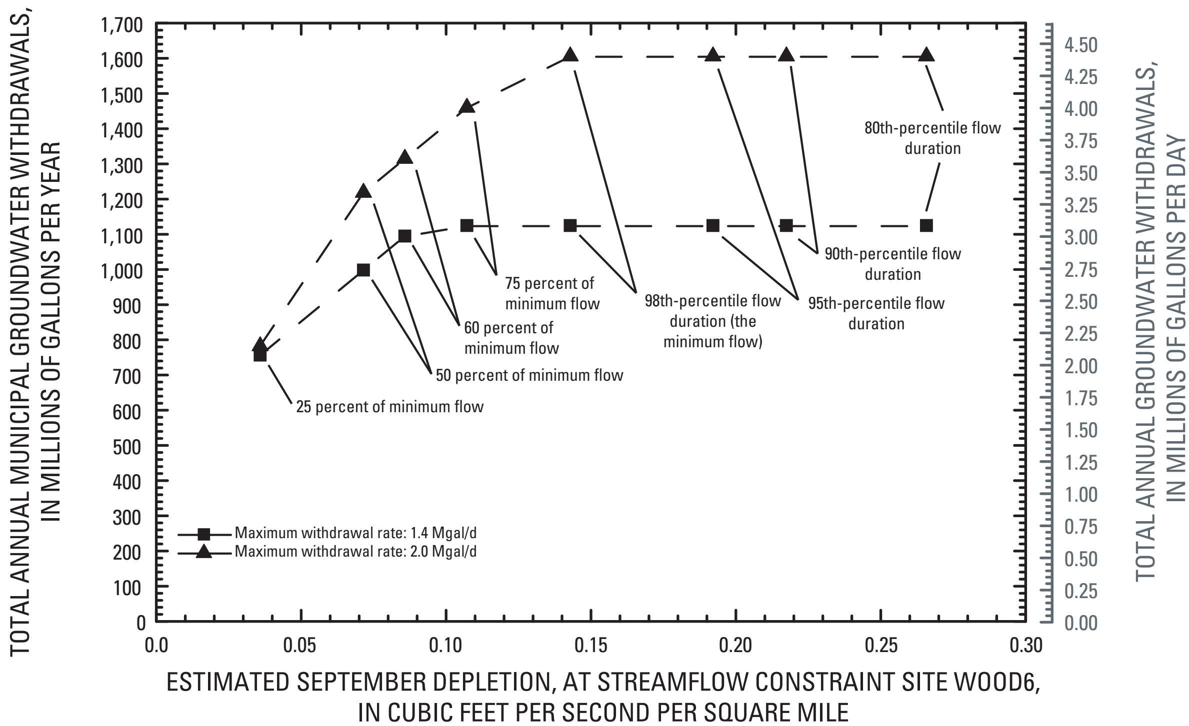

Figure 4–6. Conjunctive-management-model yield relations between potential allowable streamflow depletion criteria in the Wood River (WOOD6, RCHRES 65) and total annual groundwater withdrawals at the specified Rhode Island withdrawal rates from hypothetical wells RIW–458, RIW–458A, and RIW–458B in the lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island. Withdrawals are graphed with respect to potential allowable-depletion values for September because these values are the primary groundwater withdrawal constraints throughout the year. Each conjunctive-management model, however, is based on the same flow statistics for each month of the year. Mgal/d, million gallons per day. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

month with the minimum daily-mean streamflows, in this case September, are the binding criteria in the conjunctive-management models that limit total annual withdrawals.

The shape of the curve or curves on the yield graph indicates the change in total annual withdrawals with a change in allowable depletion (fig. 4–6). A steep slope in the curve indicates a large change in allowable withdrawals with a small change in allowable depletion. If the slope is steep, selection of an allowable depletion criterion (and therefore the minimum daily mean streamflow that will occur with allowable withdrawals) is critical for determining available water supplies. A low slope in the curve indicates that a small change in allowable depletions will occur with a small change in allowable withdrawals; in this case, a compromise in the allowable depletion criterion may not have a large effect on available water supplies. A zero slope indicates that selection of an allowable depletion criterion will not affect the available water supply. In this case, another factor (for example, the number and capacity of available water-withdrawal sites) controls the amount of available water supplies. Both yield curves in figure 4–6 have steep slopes at small values of allowable depletion, intermediate slopes as allowable depletions increase, and a plateau with a zero slope above an allowable-depletion criterion that equals the maximum production capacity of the production-well network within the specified withdrawal-pattern constraint.

Sixteen conjunctive-management models (fig. 4–6) were developed to demonstrate the relations between potential allowable-depletion criteria and maximum water yields if hypothetical wells RIW–458, RIW–458A, and RIW–458B (fig. 4–2) in the LWRCMM area were modeled according to the Rhode Island municipal water-demand pattern (Appendix Part 4). In this case, the streamflow-depletion criterion that is 25 percent of the minimum streamflow limits withdrawals to about 760 Mgal/yr, with very little difference between the two management models with different (1.4 and 2.0 Mgal/d) maximum withdrawal rates (fig. 4–6).

As potential allowable-depletion criteria are increased, annual withdrawals increase until the maximum withdrawal rates limit the total annual water withdrawals. The management models with a maximum withdrawal rate of 1.4 Mgal/d reach a plateau of about 1,120 Mgal/yr when allowable depletions are about 75 percent of the minimum streamflow value (fig. 4–6). The total annual water withdrawals are less than the 1,530 Mgal/yr one would expect for three wells each withdrawing 1.4 Mgal/d throughout the year because the Rhode Island municipal-withdrawal pattern is not constant throughout the year. Therefore, the wells operate at maximum capacity only to meet peak (monthly) July water demands. In this situation, an alternative to decisionmakers could be to consider specifying a maximum allowable depletion that is less than the historical minimum streamflow value and greater than 75 percent of the minimum streamflow value without having a substantial effect on groundwater withdrawals from this well network under the specified constraints.

The conjunctive-management models for the higher withdrawal rate (2 Mgal/d per well) indicate a similar pattern with a higher plateau (fig. 4–6). The management models with a maximum withdrawal rate of 2 Mgal/d reach a plateau of about 1,600 Mgal/yr when allowable depletions are about equal to the estimated minimum streamflow value for the 45-year period. The total annual withdrawals are higher and the plateau begins at a higher potential allowable-depletion value as the maximum withdrawal rate becomes the binding criterion. Setting the potential allowable depletion to 75 percent of the minimum streamflow value would result in a decrease in the total annual withdrawal of about 120 Mgal/yr; at 50 percent of the minimum streamflow, the decrease would be about 380 Mgal/yr.

Water-resource decisionmakers also may use such groundwater-yield curves to set different allowable-depletion criteria for wet and dry years. For example, if the allowable-depletion criterion is equal to the minimum daily-mean streamflow value in wet and normal years, the three-well network with a maximum withdrawal rate of 1.4 Mgal/d could produce 1,120 Mgal/yr. Although the allowable-depletion criterion equals the historical minimum daily-mean streamflow values, use of this criterion would not result in a zero-flow event in wet or normal years. If water-conservation measures could be expected to reduce annual withdrawals by 10 percent in dry years, an annual production rate of about 1,000 Mgal/yr might be achievable with a dry-year allowable-depletion value that is about 50 percent of the minimum streamflow (fig. 4–6). In this example, the probability is about 2 percent in any given year that this dry-year allowable-depletion criterion would produce a minimum daily-mean streamflow value that is 50 percent of the minimum streamflow without withdrawals.

Well-Site Selection for Groundwater Withdrawals

A set of 72 conjunctive-management models for the LWRCMM area were formulated and tested to evaluate the effect of well-site selection on water withdrawals (fig. 4–7). These models included site-specific withdrawal patterns defined by site type and water use in table 4–1. The irrigation-withdrawal patterns and the municipal withdrawal patterns are described in Appendix Part 4. The effect of well-site selection was tested by using hypothetical wells RIW–458, RIW–458A, or RIW–458B, which are about 2,500, 1,000, and 300 ft east of the Wood River), respectively (fig. 4–2). Well-site selections for these hypothetical wells were tested because of differences in their response coefficients (fig. 4–3B) and associated depletion graphs (fig. 4–4). The additional irrigation withdrawals also are useful for further defining relations between potential allowable-depletion criteria and maximum water withdrawals.

Irrigation withdrawals are included in the management model to represent potential agricultural demands, but the conjunctive-management models have limited applicability

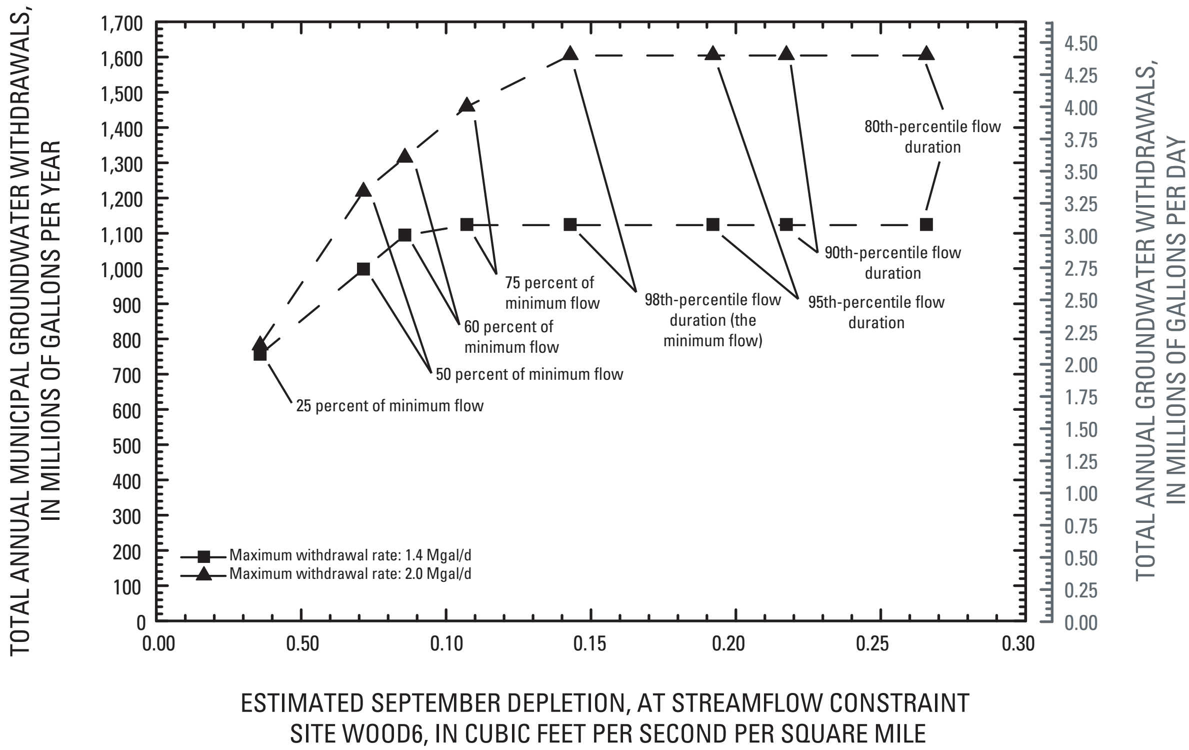

Figure 4–7. Conjunctive-management-model yield relations between potential allowable streamflow depletion criteria in the Wood River (WOOD6, RCHRES 65) and total annual groundwater withdrawals from hypothetical agricultural locations that follow irrigation-withdrawal patterns and groundwater withdrawals at the specified Rhode Island withdrawal rates from hypothetical wells RIW–458, RIW–458A, or RIW–458B in the lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island. Withdrawals are graphed with respect to potential allowable-depletion values for September because these values are the primary groundwater withdrawal constraints. Each conjunctive-management model, however, is based on the same flow statistics for each month of the year. Mgal/d, million gallons per day. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

for optimizing irrigation withdrawals. Irrigation withdrawals are made on a daily basis in response to precipitation deficits. The conjunctive-management models are used to maximize withdrawals on a monthly time scale and are not suitable for daily variations in irrigation needs. For this reason, the monthly average irrigation-withdrawal patterns documented in Appendix Part 4 were used in this analysis. This time scale is appropriate for groundwater withdrawals because it is consistent with the response times of streamflow depletions from wells, which are on the order of several months to a year. Use of one-day monthly minimum streamflows during each month of the year to estimate the maximum streamflow-depletion constraint, however, does not preclude the potential for short-term surface-water withdrawals to exceed the instantaneous streamflow during the hours when the surface-water withdrawals are active. The potential effects of these differences in time scale between variable hourly irrigation withdrawals with instantaneous depletions from surface-water sites and monthly groundwater withdrawals from wells are demonstrated in the HSPF modeling results (Part 3). The monthly average withdrawal rates calculated by the management model are used to demonstrate groundwater-management concepts rather than the management of surface-water withdrawals. In the conjunctive-management models, the surface-water withdrawals are approximated by the use of monthly average withdrawal rates and a response coefficient of one.

Streamflow depletion criteria and maximum annual water-withdrawal yields are shown in figure 4–7. These models include withdrawals from hypothetical municipal wells, and irrigation withdrawals from nine hypothetical or existing water-withdrawal sites. The models were constrained by maximum withdrawal rates of 1.0, 1.4 or 2.0 Mgal/d at each withdrawal site. Total annual withdrawal yields increase from about 800 Mgal/yr with a depletion criterion that is about 25 percent of the minimum of one-day monthly minimum streamflow measurements during 1960 to 2004 and diverge at plateaus representing the maximum yields of about 1,650, 2,300, and 3,300 Mgal/yr for withdrawal rates of 1.0, 1.4, and 2.0 Mgal/d, respectively. This graph indicates that, at this site, maximum withdrawal capacities have a greater effect on total annual withdrawals than distance from the stream because the management model results for this area are limited more by maximum withdrawal capacity than by withdrawal-site location. Differences among total annual withdrawals for the different hypothetical withdrawal locations are on the order of 2 to 4 percent until the maximum withdrawal capacity is reached, at which point withdrawals from the three sites are identical for each maximum withdrawal rate.

There is a perception that wells next to a stream may have more deleterious effects on streamflow than wells that are farther away. However, the relative merit of different well locations is more complex then that because it depends on the characteristics of the aquifer, the water-demand pattern, the maximum withdrawal capacity of the well, and the effects of applying monthly streamflow depletion criteria in different areas. For example, in the LWRCMM area, the well that is 2,500 ft away from the Wood River (RIW–458) can produce about 55 percent less water than the well next to the river (RIW–458B) at a maximum withdrawal rate of 2.0 Mgal/d and a streamflow depletion criterion of about 0.036 $ft^3/s/mi^2$. (These differences are not apparent in figure 4–7 because of the interplay that occurs between municipal and agricultural withdrawals as allowable stream-depletion criteria vary.) The large differences in total withdrawals between hypothetical well RIW–458 and RIW–458B occur because of the timing of minimum streamflows (in September), peak demands (in July), and the differences in the timing of depletions caused by withdrawals from each well (fig. 4–4). Differences in total withdrawals for these different well locations disappear as the allowable streamflow depletion constraints increase because the specified maximum withdrawal capacity of the withdrawal sites becomes the limiting criterion. This information is important for evaluating water-supply alternatives specific to the LWRCMM area, but the details concerning withdrawal capacities and distances of hypothetical wells from the stream may not be transferable to different locations.

Well RIW–458 also has a greater effect on streamflow in the Meadow Brook than the wells that are closer to the Wood River. This may be of concern because monthly minimum streamflows in the Wood River are almost an order of magnitude higher than monthly minimum streamflows in the Meadow Brook (table 4–2). Depletions in the Meadow Brook caused by withdrawals from this well peak in the third month after a given withdrawal (fig. 4–3B). As a result of the three-month lag time, peak July water demands cause depletions in Meadow Brook during the dry months (August to October). Although September depletions in Meadow Brook may be the binding criteria in some management models, groundwater yield curves are graphed with respect to normalized depletions (in cubic feet per second per square mile) in the Wood River to maintain consistency with the presentation of other results in this section of the report. The normalized allowable depletions at the two constraint sites, which were developed with the same statistical thresholds, are comparable because normalized streamflows in both streams are similar (fig. 4–5B).

As the potential allowable streamflow depletion criteria are reduced, total irrigation withdrawals are disproportionally reduced by conjunctive-management models that are designed to maximize total annual withdrawals from the entire withdrawal-site network within streamflow-depletion constraints and water-use pattern constraints. The hypothetical municipal supply well sites have higher withdrawal volumes because these wells are used throughout the year, and withdrawals in the fall, winter, and spring are a fixed proportion of summer withdrawals. If this area of Rhode Island had an alternative municipal water source (for example, the proposed Big River Reservoir) to meet nonagricultural peak-summer demand, then the fraction of total withdrawals for agricultural use in the summer could increase, and the total amount of nonagricultural withdrawals could increase in the winter months. For example, Granato and Barlow (2005) demonstrated that proposed wells in the Big River area could produce twice as much water per year if withdrawals were not limited by the municipal-demand pattern. This is because the alternative source would be used to meet municipal demands in the summer so that the wells can produce more in the winter and less in the summer while meeting the summer low-flow constraints.

Use of Community Wells for Irrigation

Potential yields from individual water-withdrawal sites and two alternative irrigation networks were tested under different criteria for the EPRCMM area. The alternative well-network designs include community wells (irrigation wells that are shared by several farmers in the same area) to supply irrigation water for all the farms in the area. Several factors may favor the use of community irrigation wells for adjacent farms. For example, one factor is the potential economic benefits of community wells, which may include reduced infrastructure costs. Community wells also may provide water from more advantageous water-withdrawal sites if water restrictions preclude withdrawals from other sites. Water-withdrawal sites for the community-well scenarios were not selected by using optimization techniques; the NRCS selected 18 potential well sites for this analysis (table 4–3, fig. 4–1) on the basis of logistical considerations, such as proximity to roads and electrical power (Vicky Drew, Natural Resources Conservation Service, written commun., 2006). The conjunctive-management models for individual water-withdrawal sites include 18 potential sites. Fourteen of the

Table 4–3. Irrigation management-model scenarios for existing and potential water-withdrawal sites in the eastern Pawcatuck River conjunctive-management model (EPRCMM) area, Pawcatuck River Basin, southwestern Rhode Island.

[Site locations shown in figure 4–1 and described in table 4–1. ID, identifier. Index: Conjunctive-management model index number]

Index	Site ID	Scenarios		
		Individual irrigation wells	Community-well option A	Community-well option B
1	AUQ6A	X	X	X
2	PR–AUQ8A	X	X	X
3	PR–AUQ9A	X	X	X
4	PR–AUQ11A	X	X	X
5	PR–AB8A	X	X	X
6	PR–GB1A	X	X	X
7	RIW–336A			
8	RIW–385			
9	PR–AUQ7A	X	X	X
10	PR–AUQ10A	X		
11	PR–AUQ10B	X	X	X
12	PR–AUQ10C	X	X	X
13	PR–AB1A	X	X	
14	PR–AB2A	X		
15	PR–AB2B	X		
16	PR–AB3A	X		
17	PR–AB3B	X	X	X
18	PR–AB4A	X	X	X
19	PR–AB5A	X	X	X
20	PR–GUQ2AB	X	X	X

sites were assigned to community-well option A, and 13 to community-well option B (table 4–3).

Sixty-three management models were formulated and tested to evaluate the potential effects of well-network design on the total groundwater-withdrawal yields for different potential-allowable-streamflow-depletion criteria (fig. 4–8). Potential allowable streamflow-depletion criteria ranged from a fraction (25 percent) of the 45-year minimum streamflow to the 80-percent flow duration of monthly minimum streamflows (meaning that 80 percent of the monthly minimum flows exceed this value during the period 1960–2004). The conjunctive-management models were constrained by maximum withdrawal rates of 1.0, 1.4 or 2.0 Mgal/d at each withdrawal site. Withdrawals for golf courses, turf farms, and vegetable farms (table 4–1) also were constrained to match irrigation patterns (Appendix Part 4).

The groundwater withdrawal yields are limited by the potential allowable-depletion criteria in all of these community-well management models for the EPRCMM area (fig. 4–8). This is evident because the yield curves do not fully plateau in the range of allowable depletions that were tested. Estimated streamflow statistics without withdrawals for the Wood, Beaver, and Usquepaug-Queen Rivers in both management-model areas are similar if the values are normalized by drainage area (table 4–2, fig. 4–5A). However, the combined drainage area of the Beaver and Usquepaug-Queen Rivers is about half of the drainage area of the Wood River so the tributaries to the Pawcatuck in the EPRCMM area have lower flows than the Wood River. The number of potential water-withdrawal sites in the EPRCMM area is larger than the number of sites in the LWRCMM area in all of the scenarios tested. Thus, management models for hypothetical well networks in EPRCMM area do not reach full network capacity (the number of wells multiplied by the maximum withdrawal rate and the withdrawal-pattern constraint) within the range of potential-allowable depletion criteria that were used. The streamflow-depletion limitation is evident in figure 4–8 because the total annual groundwater withdrawals do not substantially diverge at low potential allowable depletions and do not reach a plateau as in figures 4–6 and 4–7.

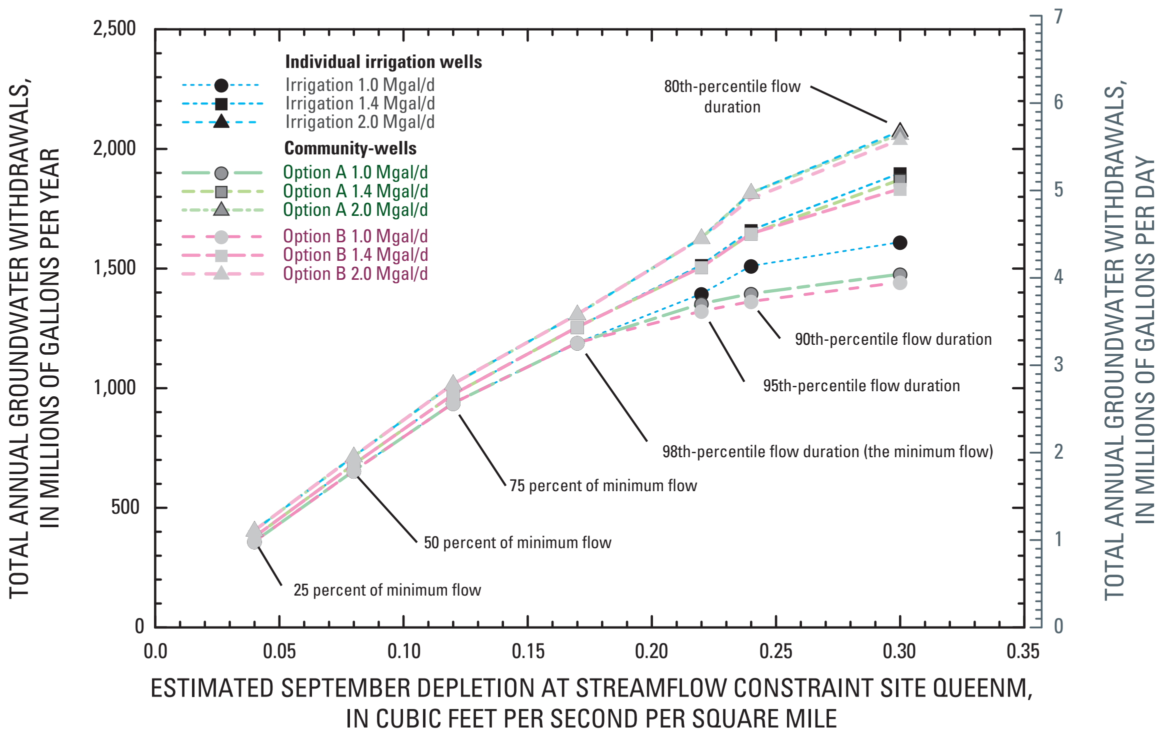

Figure 4–8. Conjunctive-management-model yield relations between potential allowable streamflow depletion criteria in the Usquepaug-Queen River (QUEENM) and total annual groundwater withdrawals from hypothetical agricultural locations that follow irrigation-withdrawal patterns in the eastern Pawcatuck River conjunctive-management model (EPRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island. Withdrawals are graphed with respect to potential allowable-depletion values for September because these values are the primary groundwater withdrawal constraints. Each conjunctive-management model, however, is based on the same flow statistics for each month of the year. Mgal/d, million gallons per day. (Site locations shown in figure 4–1 and described in tables 4–2 and 4–3.)

Management models that have higher maximum withdrawal rates produce slightly more water as potential allowable-depletion criteria increase because higher maximum withdrawal rates at the more optimal withdrawal sites increase the total annual withdrawals for the given allowable-depletion criteria (fig. 4–8). Total annual withdrawals in all management models for the EPRCMM area are about 377 Mgal/yr if the depletion criterion is a fraction (25 percent) of the one-day monthly minimum streamflow for each month of the year. As the potential allowable-depletion criteria increase to the 98 percent flow-duration value for monthly minimum streamflows, differences in total annual withdrawals among the irrigation-withdrawal networks increase to about 10 percent of the total annual withdrawals. If potential allowable depletions are increased from the 98th percentile to the 80th percentile one-day minimum-monthly flow duration, the differences between management models increase to about 35 percent of the annual withdrawal at the 80th percentile flow duration. For example, the total annual withdrawals for the models for community-well option B with maximum withdrawal rates of 1.0 Mgal/d and 2.0 Mgal/d are about 1,440 and 2,060 Mgal/yr, respectively (a 35-percent difference). In comparison, the maximum difference in total annual withdrawals is about 11 percent among the three well-network designs (individual irrigation wells, community-well option A, and community-well option B) with a maximum withdrawal rate of 1.0 Mgal/d (fig. 4–8). This is because the maximum withdrawal rates differ by a factor of 2 but the number of wells differ by a factor of 1.4 among the conjunctive-management models.

The maximum difference among the three well-network designs for a given withdrawal rate occurs with the withdrawal rate of 1.0 Mgal/d because the maximum withdrawal capacity of a well network is the product of the number of wells and the maximum withdrawal rate of each well. Management models with the maximum withdrawal rates of 1.4 and 2.0 Mgal/d are substantially limited by the streamflow depletion criteria at the 80th percentile flow duration, but the management models with the maximum withdrawal rate of 1.0 Mgal/d have almost reached the network-capacity threshold (fig. 4–8). At this point, differences among these management modes with the same maximum withdrawal rate occur because of differences in the total number of wells; the individual irrigation-well option has 18 active wells, community-well option A has 14 active wells, and community-well option B has 13 active wells (table 4–3).

Post-Optimization Analysis

Post-optimization analysis provides information that can be used by water-resource managers to evaluate relations between withdrawal plans and the potential effects of withdrawal plans on streams in the area. In the post-optimization analysis for this investigation, the conjunctive-management model results are used to estimate streamflows that might have occurred if the optimized withdrawal plans had been utilized during the period 1960–2004. These estimates were made by calculating monthly streamflow depletions caused by each management model and then interpolating the monthly depletions to estimate a record of daily depletions. These depletions were then subtracted from the simulated record of daily-mean streamflows without withdrawals that was computed with the basinwide surface-water model (HSPF). This information provides an estimate of the relative risks posed by each withdrawal plan to streamflow for future conditions under the assumptions that optimization methods are applicable for irrigation withdrawals, the streamflow-depletion response times for groundwater withdrawal sites even out daily fluctuations in irrigation demands, and the estimates of historical streamflows will represent future streamflows.

The following discussion is intended to provide examples of the effects of the application of allowable-depletion criteria on the potential distribution of instream flows. Streamflows discussed in the following paragraphs are not described as suggested instream-flow targets that may balance water withdrawals and ecological protection; instead, they are descriptive examples of potential relations between withdrawals, depletions, and instream flows. They also show the potential benefits of using a depletion-based criterion that can be related to withdrawals (and therefore, to water-conservation methods) in comparison to a minimum-flow criterion that cannot be explicitly addressed with demand-management efforts.

The conjunctive-management models for individual irrigation wells in the EPRCMM area (table 4–3) with a maximum sustained withdrawal capacity of 1.4 Mgal/d were selected as examples. Flow-duration curves for the Usquepaug-Queen River at site QUEENM indicate the potential effects of the optimized withdrawal plan on daily streamflows during the 1960–2004 period for each of the seven streamflow-depletion criteria (fig. 4–9). Hydrographs for the 1960–2003 period show the estimated records of streamflow without withdrawals and for two specific withdrawal plans (fig. 4–10). The period 1960–2003 was selected for presentation of the hydrographs in figure 4–10 to show streamflow records for complete calendar years.

Streamflows are presented in cubic feet per second per square mile ($ft^3/sec/mi^2$) to facilitate comparison with streamflow-maintenance criteria, which are commonly normalized by drainage area. For example, the aquatic baseflow (ABF) criterion of 0.5 $ft^3/sec/mi^2$ has been proposed as a minimum-flow criterion for use in Rhode Island. Figure 4–9 indicates that streamflows in the Usquepaug-Queen River at site QUEENM without withdrawals would be below this criterion about 9 percent of the time. Use of the withdrawal plan with allowable depletions that equal the estimated historical monthly minimum streamflows would result in daily flows that were less than 0.5 $ft^3/sec/mi^2$ about 14 percent of the time. The hydrographs for the 1960–2003 period (fig. 4–10) indicate that for both scenarios, streamflows would be equal to or below the ABF criterion in many of the same years.

Flow-duration curves and hydrographs are presented for all daily-mean streamflows rather than for one-day monthly minimum streamflows in this example because ecological streamflow criteria commonly include objectives for maintenance of natural flow variations as well as minimum-flow targets (David Armstrong, U.S. Geological Survey, written commun., 2004). The flow durations for the one-day monthly minimum streamflows (for example fig. 4–5) are not equal to the flow durations for all daily mean streamflows. For example, daily flows are estimated to be below 0.01 $ft^3/sec/mi^2$ about 1.4 percent of the time (the 98.6th percentile flow duration) if withdrawals based on the 80th percentile of the monthly minimum streamflows are used (fig. 4–9).

Land and water managers may use information about the relative risk of using different depletion criteria, associated withdrawal plans, and the resultant effects on instream flows to select withdrawal plans for different years based on drought projections and water needs. For example, if a moderately dry year is predicted, then a water-withdrawal plan that allows depletions that are greater than the one-day monthly minimum streamflow may be adopted if depletions under this plan will meet ecological protection goals. If an extreme drought is projected, managers may be able to use knowledge about withdrawal plans and streamflow depletions to make informed decisions about municipal water conservation and crop selection to reduce the probability of extreme low-flow events (Vicky Drew, Natural Resources Conservation Service, oral commun., 2005). Such decisions are especially critical for agriculture because crop-irrigation needs would otherwise increase in the drier years. Examination of these flow-duration curves and historical hydrographs reinforces the concept of managing depletions (Granato and Barlow, 2005), which are under anthropogenic control, rather than attempting to manage instream flow. Water and land managers cannot effectively control streamflow in basins without a large controlled surface-water reservoir that can be used to augment available flow. However, managers can use drought projections and management-model information to make decisions about withdrawals and subsequent streamflow depletions.

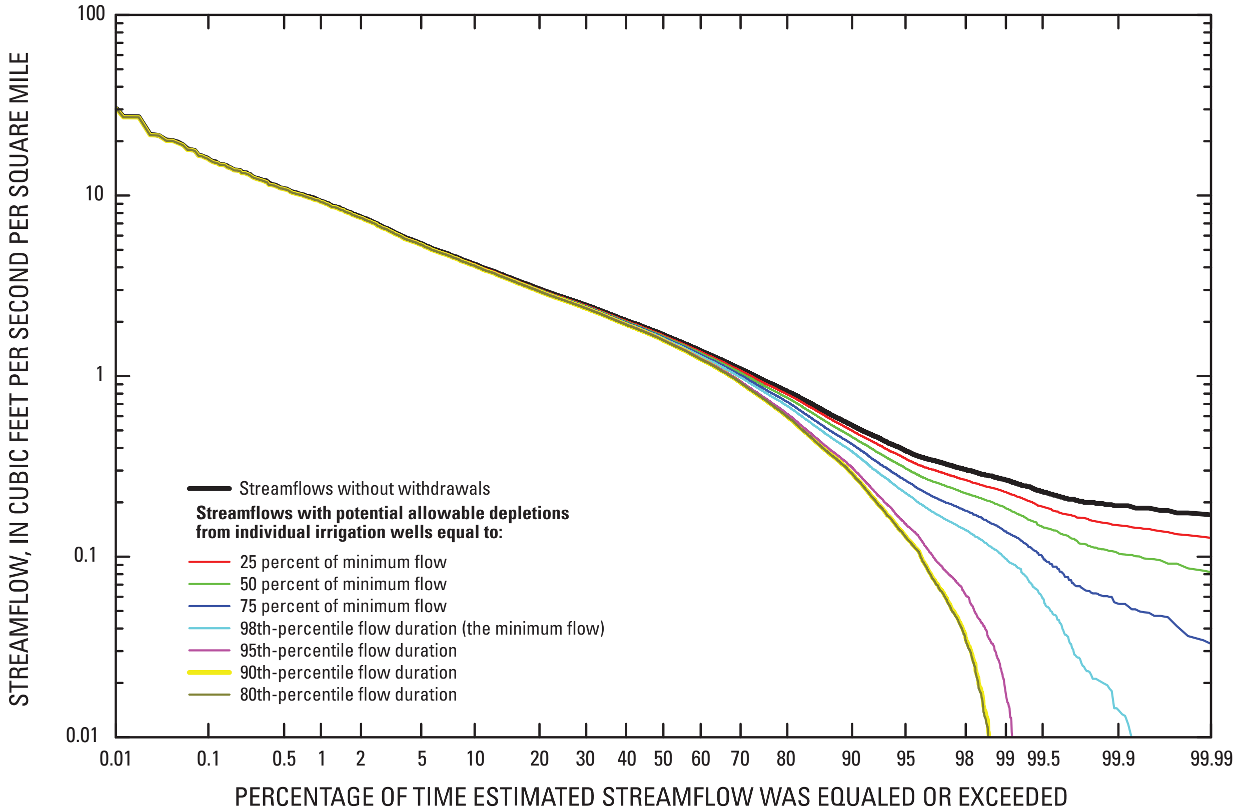

Figure 4–9. Daily-mean flow-duration curves showing the percentage of time estimated streamflow was equaled or exceeded in the Usquepaug-Queen River in the eastern Pawcatuck River conjunctive-management model (EPRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island at QUEENM, the streamflow constraint site for the period 1960–2004. Estimated streamflows are shown without withdrawals and with streamflow depletions caused by the application of the optimized withdrawal plans for individual irrigation wells operated at a maximum withdrawal capacity of 1.4 million gallons per day. (Site location shown in figure 4–1 and described in table 4–2.)

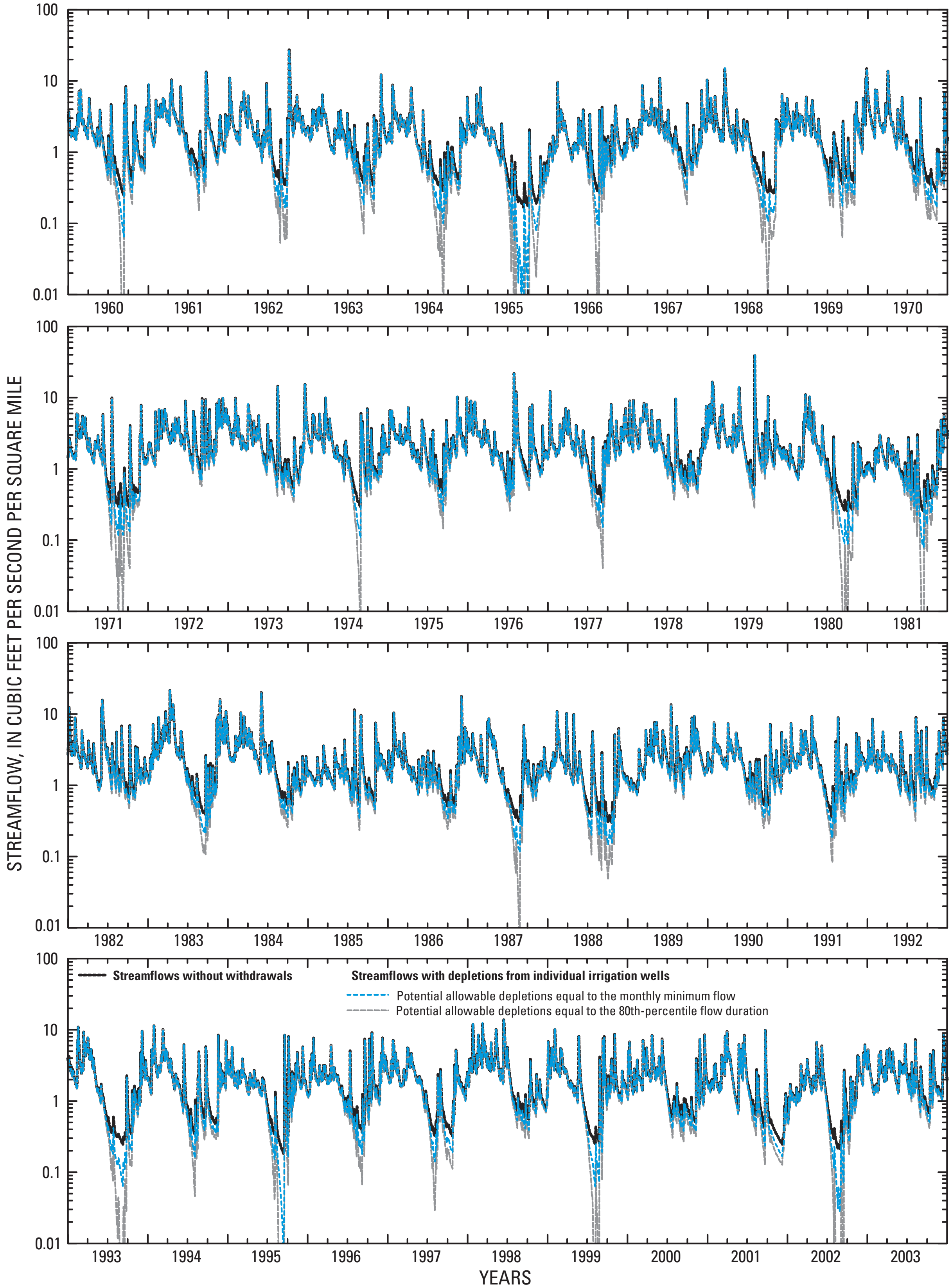

Figure 4–10. Estimated streamflow in the Usquepaug-Queen River at streamflow constraint site QUEENM in the eastern Pawcatuck River conjunctive-management model (EPRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island for the period 1960–2003. Estimated streamflows are shown without withdrawals and with streamflow depletions caused by the application of the optimized withdrawal plans for individual irrigation wells operated at a maximum withdrawal capacity of 1.4 million gallons per day. (Site location shown in figure 4–1 and described in table 4–2.)

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