Appendix Part 4. Conjunctive-Management Models for the Eastern Pawcatuck and Lower Wood River Model Areas

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Appendix Part 4. Conjunctive-Management Models for the Eastern Pawcatuck and Lower Wood River Model Areas

By Gregory E. Granato and Donald A. Walter

Introduction

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 different withdrawal-well networks. These conjunctive-management models are based on statistical analysis of water-use data, simulations with the transient numerical groundwater-flow (MODFLOW) models developed for the study areas, and simulations with the basinwide surface-water hydrology model to formulate linear-optimization models for water-resource management. 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 (Barlow and Dickerman 2001a,b; Granato and Barlow, 2005). 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). This appendix describes the mathematical formulation of the models and the response-matrix technique used to solve them.

Two conjunctive-management model areas, described herein as the eastern Pawcatuck River conjunctive-management model area (EPRCMM area) and the lower-Wood conjunctive-management model area (LWRCMM area) were selected to demonstrate concepts that may be useful for water-resource planning for the Pawcatuck River Basin and similar basins in the northeastern United States. These two areas were selected from the larger area simulated with the groundwater-flow (MODFLOW) models within the Pawcatuck River Basin (fig. A4–1) to demonstrate the application of conjunctive-management models for irrigation and municipal water-supply development (table A4–1) (Vicky Drew, U.S. Natural Resource Conservation Service, and Juan Marsical, Rhode Island Water Resources Board, oral commun., March 2006). The EPRCMM area has three streamflow-constraint sites (BEAVM, QUEENM, and PAWCD) shown on figure 4–1 and the constraints are defined in table A4–2. The 20 existing and potential water-withdrawal sites in this area are shown on figure 4–1 and described in table A4–1. The LWRCMM area has four streamflow-constraint sites (MEAD2, WOOD5, WOOD6, and PAWC4) shown on figure 4–2 and defined in table A4–2. The 12 existing and potential water-withdrawal sites in this area are shown on figure 4–2 and defined in table A4–1.

Formulation of the Conjunctive-Management Model

The formulation of each conjunctive-management model consists of defining a set of decision variables, an objective function, and a set of constraints. The decision variables are the monthly withdrawal rates calculated by the model for each of the simulated water-withdrawal sites. Mathematically, the decision variables were expressed as $Qw_{i,t}$, which represents the withdrawal rate at water-withdrawal site i in month t. The subscript t ranges from t=1 for January through t=12 for December. The decision variables are the withdrawal rate at each water-withdrawal site for each of the 12 months in a year, during which the site is active. The set of water-withdrawal sites used for specific formulations of the models in each area (table A4–1) differed from one model application to the next. For example, some groundwater-withdrawal sites were not included in the models that were used to evaluate the potential effects of withdrawals at community irrigation wells in the EPRCMM area. Also, it was assumed that municipal water-withdrawal sites will be active for all 12 months and irrigation sites will be active only during the growing-season months defined by the analysis of water-use data.

Management-Model Objective Function

The objective function of the model was formulated to maximize total annual groundwater withdrawals from the aquifer, and was written mathematically as

$$maximize \sum_{i=1}^{NW} \sum_{t=1}^{NM} ND_t \times Qw_{i,t} , \quad (1)$$

where

NW is the number of water-withdrawal sites,
NM is the number of months (12), and
ND_t is the number of days in month t.

Management-model constraints were formulated in terms of streamflow depletion and water-withdrawal rates for each month, but the objective function of the model is calculated as the total volume of water by weighting each monthly value by the number of days in each month. Values of the objective function were calculated in cubic feet of water withdrawn from the basin during the 12-month period. Total annual withdrawals were converted to units of million gallons because this

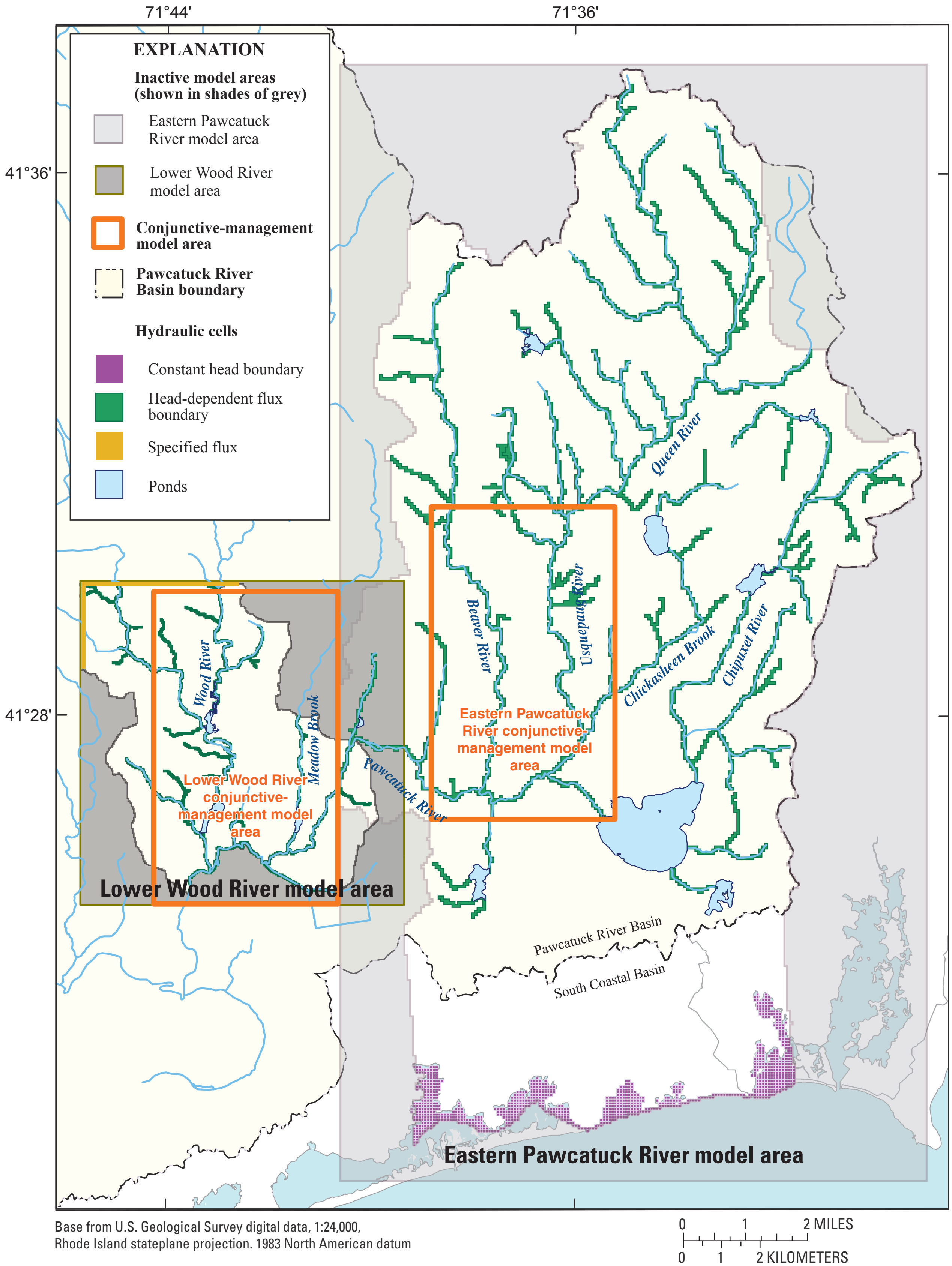

Figure A4–1. Locations of the lower Wood and eastern Pawcatuck River conjunctive-management model areas in the Pawcatuck River Basin, southwestern Rhode Island.

Table A4–1. 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.

[Index, conjunctive-management model index number; ID, identifier. Site type: SW, surface water; GW, groundwater; GW–P, groundwater-pond. Water use: IG, irrigation golf; MS, potential municipal supply; IT, irrigation turf; 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)]

Index	Site ID (site locations shown in figure 4–1)	Site type	Water use	MODFLOW row	MODFLOW column	Response coefficient information
Eastern Pawcatuck River conjunctive-management model (EPRCMM) area						
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
Index	**Site ID (site locations shown in figure 4–1)**	**Site type**	**Water use**	**MODFLOW row**	**MODFLOW column**	**Response coefficient information**
Lower Wood River conjunctive-management model (LWRCMM) area						
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 A4–2. Characteristics of selected streamflow constraint sites in the eastern Pawcatuck and lower Wood River conjunctive-management model areas, Pawcatuck River Basin, southwestern Rhode Island.

[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. Estimates of the minimum monthly one-day streamflow values without withdrawals are derived from the output of the basinwide surface-water model. mi², square miles; *, HSPF subbasin outlets]

Management-model site designation	River	MODFLOW row	MODFLOW column	Drainage area (mi²)	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*	Meadow Brook (RCHRES 48)	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*	Wood River (RCHRES 63)	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*	Wood River (RCHRES 65)	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*	Pawcatuck River (RCHRES 50)	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

Table A4–3. 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. Index, conjunctive-management model index number; ID, identifier]

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

unit is commonly used for evaluating water-supply scenarios in Rhode Island (Barlow and Dickerman, 2001a,b; Granato and Barlow, 2005).

The value of the objective function was limited by a set of specified constraints that included combinations of maximum rates of streamflow depletion at the streamflow-constraint sites, minimum and maximum withdrawal rates at each water-withdrawal site, and seasonal patterns of monthly water demands. The set of constraints differed from one model application to the next.

Streamflow-Depletion Criteria

Streamflow depletions were required to be less than or equal to maximum specified streamflow-depletion rates for each month. These streamflow-depletion criteria were applied at selected streamflow-constraint sites that corresponded to selected points of interest in the EPRCMM area (fig. 4–1; table A4–2) and the LWRCMM area (fig. 4–2; table A4–2). These constraints were written as

$$Qsd_{j,t} \leq \left(Qsd_{j,t}\right)_{max}, \qquad (2)$$

where

$Qsd_{j,t}$ is the streamflow depletion at streamflow-constraint site j in month t, and

$(Qsd_{j,t})_{max}$ is the maximum rate of streamflow depletion allowed at site j in month t.

Maximum rates of streamflow depletion for each of the 12 months were specified for each of the three constraint sites in the EPRCMM area and each of the four constraint sites in the LWRCMM area for a total of 36 and 48 streamflow-depletion constraints in each model, respectively.

Granato and Barlow (2005) evaluated 11 commonly referenced instream-flow criteria and determined that criteria based on the allowable monthly streamflow-depletion rate in the month with the lowest streamflows would effectively limit total annual groundwater withdrawals because of the long response times (about 3–12 months) for such withdrawals. Granato and Barlow (2005) also demonstrated that many aquatic-baseflow criteria, originally developed under the assumption of the availability of a substantial amount of water in storage in an actively managed upstream surface-water reservoir, may not be protective for groundwater withdrawals from a limited stream-aquifer system. This is especially true for municipal water suppliers with a limited ability to enforce dry-year water conservation efforts that may result in a 10- to 20-percent reduction in summer water withdrawals. For this reason, Granato and Barlow (2005) developed an alternative instream-flow paradigm based on the maintenance of some nonzero streamflow at a defined return period to limit or eliminate zero-flow days. Granato and Barlow (2005) used an estimated streamflow record for the period 1961–2000 to evaluate allowable depletion criteria based on the one-day monthly minimum streamflows during this period. In that study, postoptimization analysis indicated that the application of such criteria may prevent zero-flow events.

The calibrated basinwide HSPF model was used to estimate streamflows without any anthropogenic water withdrawals at selected sites during the study period January 1960 through September 2004. Data available from streamflow gaging stations in the area reflect an unknown amount of existing streamflow depletion because there is no long-term record of all existing municipal and irrigation withdrawals available for the 1960–2004 period. A long-term simulated record without withdrawals was used because the record would represent the range of hydrologic conditions that occurred during the period, including the drought of record, and thus would provide statistics representative of variations in hydrologic conditions in Rhode Island. The HSPF model-generated estimates of streamflows without withdrawals were used as the basis for calculating values of allowable streamflow depletion that represent various risks for inducing a zero-flow condition as an effect of water withdrawals.

In two cases (BEAVM and QUEENM), output from the calibrated HSPF model was adjusted to address differences in surface-water and groundwater contributing areas to the HSPF HRUs. In the EPRCMM area, MODFLOW model results indicated that withdrawals from some of the wells considered in the conjunctive-management model analysis may cause streamflow depletion below the outlets of the HRUs in the HSPF model for the Beaver and Usquepaug-Queen Rivers. The drainage-area-ratio method (Stedinger and others, 1993) was used to estimate streamflow values at the mouth of each river to include the contributing area to each well (table A4–2).

The one-day monthly minimum streamflows differ from one another over a large range of values. The boxplots in figure A4–2 indicate the variability from month to month and year to year in the populations of all estimated daily-mean streamflows and the one-day monthly minimum streamflows for each month of each year during the 1960–2004 period at streamflow-constraint site WOOD6 (defined in table A4–2). The daily mean streamflows ranged over one or two orders of magnitude, and one-day monthly minimum streamflows by a factor of three or more during each month. The maximum one-day monthly minimum streamflow value in each month exceeds the all of medians of the daily-mean values for the same month and exceeds 75 percent of all the daily-mean values in the months of March, July, August, November, and December.

Potential allowable streamflow-depletion rates were selected by identifying the one-day monthly minimum streamflow values for each station in each month of each year from the HSPF-generated streamflow record for 1960–2004. To select streamflow-depletion rates from the population of values, the one-day monthly minimum streamflow values were ranked and the percentage of the values that would equal or exceed each value was estimated by use of its Weibull plotting-position value (Helsel and Hirsch, 2002). Each Weibull plotting-position percentile value (WP_j) is calculated as

$$WP_j = 100 \quad \frac{R_j}{N+1}, \tag{3}$$

where

R_j is the rank of value j, and

N is the number of one-day monthly-minimum streamflow values (45 values for each month for January through September and 44 values for each month for October, November, and December).

Flow-duration curves commonly are expressed as the percentage of flows that may equal or exceed a given value. In setting minimum-flow criteria, however, the complementary probability percentile (100-WP_j) is of concern. For example, the low-flow value with a 20-percent chance of occurring in any given year is the 80-percent flow duration, and the low-flow value with a 10-percent chance of occurring in any given year is the 90-percent flow duration. The minimum flow for each month in this 45-year data set has about a 2-percent chance (98-percent flow duration) of occurring in any given year. The 80-, 90-, 95-, and 98-percent flow durations were used as maximum rates of streamflow depletion $(Qsd_{j,t})_{max}$ in each management model. The management models with these streamflow constraints indicate the probability that the water-supply-development plan calculated by use of the management model may result in zero flows in one or more streams in each model area.

Management models also are developed from the minimum daily mean streamflow for each month of the year. Four percentages—75, 60, 50, and 25 percent—of the minimum daily-mean streamflow values estimated for the 45-year period were used as maximum rates of streamflow

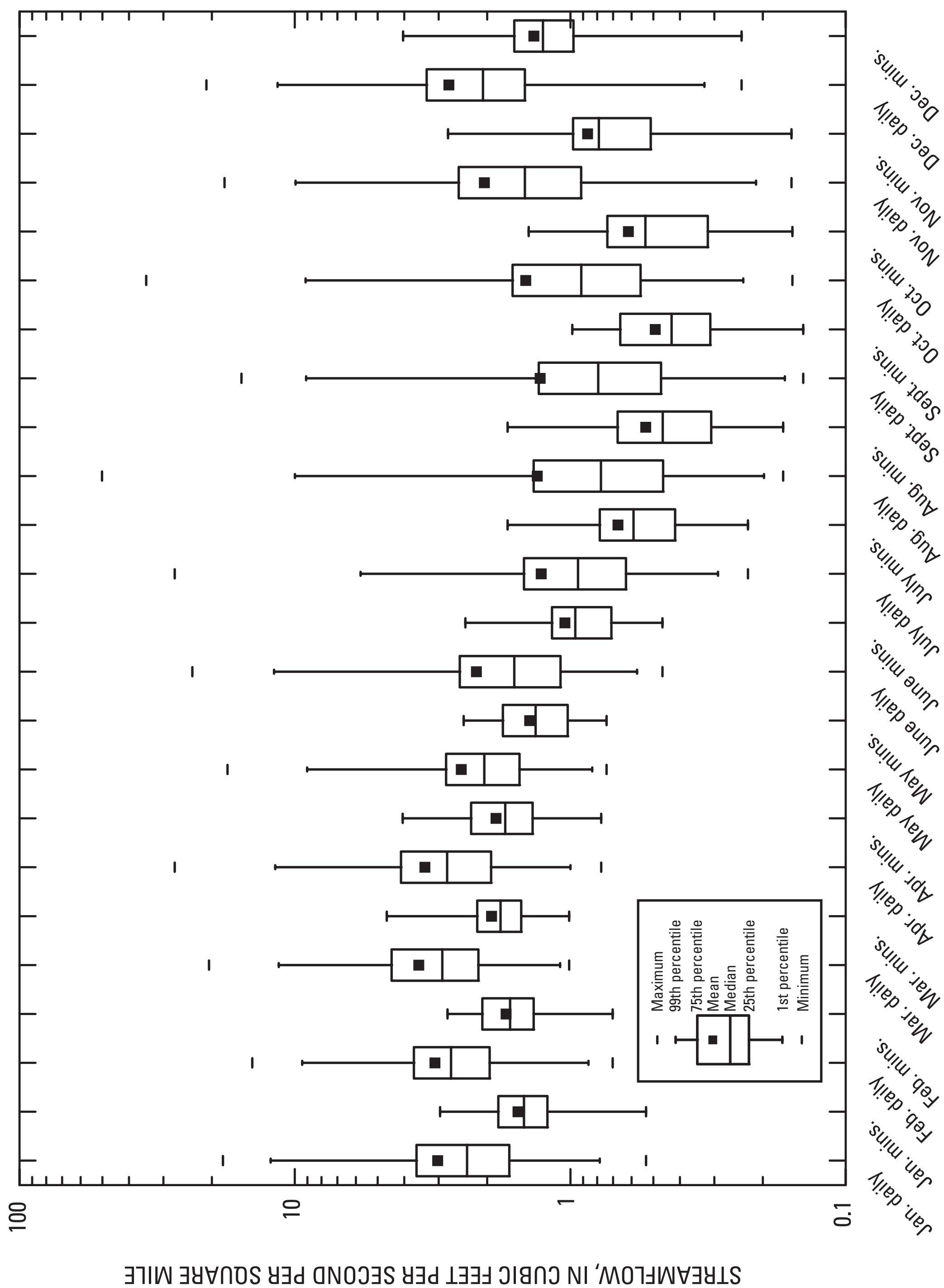

Figure A4–2. The distribution of all estimated daily mean streamflows (daily) and the minimum monthly streamflow of each year (mins.) during the 1960–2004 period from the HSPF model, at the streamflow-constraint site on the Wood River (WOOD6, RCHRES 65) in the Pawcatuck River Basin, southwestern Rhode Island. (Site location shown in figure 4–1 and described in table 4–2.)

depletion $(Qsd_{j,t})_{max}$ in each management model. These streamflow-depletion constraints were used to evaluate water-withdrawal plans that may be sustainable for dry periods when agricultural, golf, and municipal water demands are driven by irrigation needs. These allowable-depletion criteria would not result in a condition of zero flow on the day of lowest flow on record because these values are a only a fraction of the minimum streamflow value.

The percentages of September months during the study period which have one-day monthly minimum streamflows that are equaled or exceeded a given value are shown for each model area in figure A4–5. In each model area, the minimum of the one-day minimum September streamflow values is about 0.18 $ft^3/s/mi^2$. Flow-duration curves for the one-day monthly minimum streamflows (in ft^3/s) during each month at each streamflow-constraint location are shown in figures A4–3–A4–9.

Use of the one-day monthly minimum streamflows to estimate the maximum streamflow-depletion constraint $(Qsd_{j,t})_{max}$ does not preclude the potential for surface-water withdrawals to exceed the instantaneous streamflow during the hours when the surface-water withdrawals are active. The potential effects of the differences in the time scales between variable hourly irrigation withdrawals with instantaneous depletions from surface-water sites and the monthly average rates calculated by the management model are minimized as surface-water withdrawals are converted to groundwater withdrawals. This is because the effects of variations in withdrawals at wells are damped by the long streamflow-depletion response times for groundwater withdrawals. For example, Barlow (1997) calculated the hypothetical effects on streamflow depletion from a 180-day-long period of well withdrawals at 1.0 Mgal/d. This example shows that the effect of changes in withdrawals in wells at various distances from the stream would not be fully realized in the amount of streamflow depletion for one or more months (fig. A4–10).

Water-Withdrawal Criteria

Constraints on minimum and maximum withdrawal rates at each potential water-withdrawal site were written as

$$\left(Qw_{i,t}\right)_{min} \leq Qw_{i,t} \leq \left(Qw_{i,t}\right)_{max}, \quad (4)$$

where

$(Qw_{i,t})_{min}$ and $(Qw_{i,t})_{max}$ are the minimum and maximum withdrawal rates, respectively, at water-withdrawal site *i* in month *t*; and

$Qw_{i,t}$ is the withdrawal rate at site *i* in month *t*.

The minimum withdrawal rate at each water-withdrawal site, which was zero, did not need to be specified explicitly in the model. The maximum water-withdrawal rates were selected to evaluate relations between the total maximum withdrawals estimated by use of optimization methods and the associated streamflow depletions. The maximum withdrawal rates at each water-withdrawal site for each month were 1.0, 1.4, and 2.0 Mgal/d in each set of models.

Many of the water-withdrawal sites in each management model area are hypothetical wells, and thus, lack long-term well-yield information. For this reason, potential maximum groundwater-withdrawal rates were selected on the basis of generalized information about the extent and properties of the aquifer in each management-model area. These rates, however, should not be viewed as estimates of actual production capacities. Furthermore, the locations of selected sites should be viewed as hypothetical. The sites were chosen to demonstrate concepts rather than to produce a specified water yield; aquifer tests would be needed to explore the potential of each site to produce a desired water yield. Similarly, maximum withdrawal rates at the surface-water-withdrawal sites depend on streamflow availability, local channel geometry, and pump rating. Instantaneous surface-water withdrawals may greatly exceed monthly average values calculated by the management models.

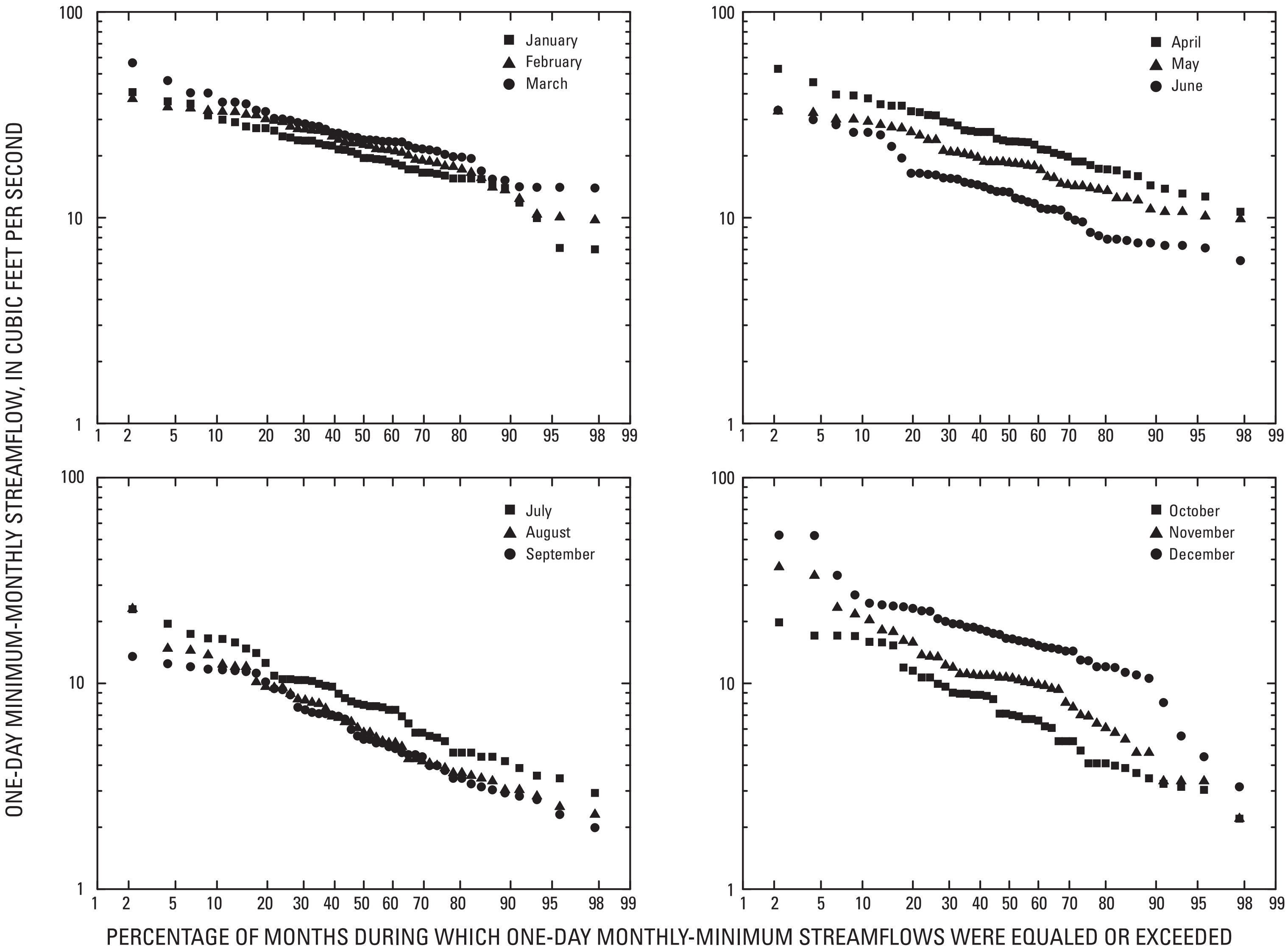

Figure A4–3. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site BEAVM on the Beaver River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–1 and described in table 4–2.)

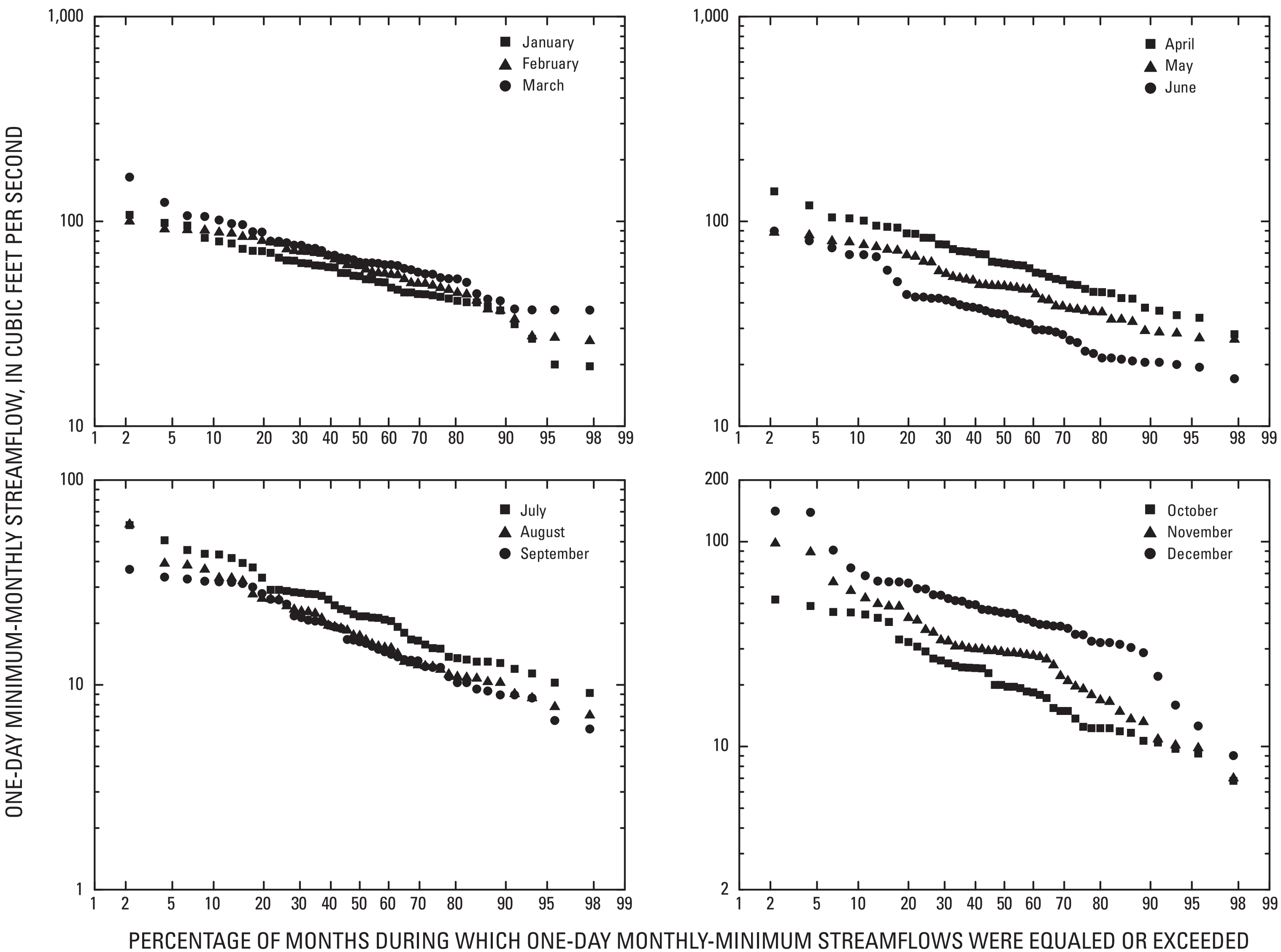

Figure A4–4. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site QUEENM on the Usquepaug-Queen River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–1 and described in table 4–2.)

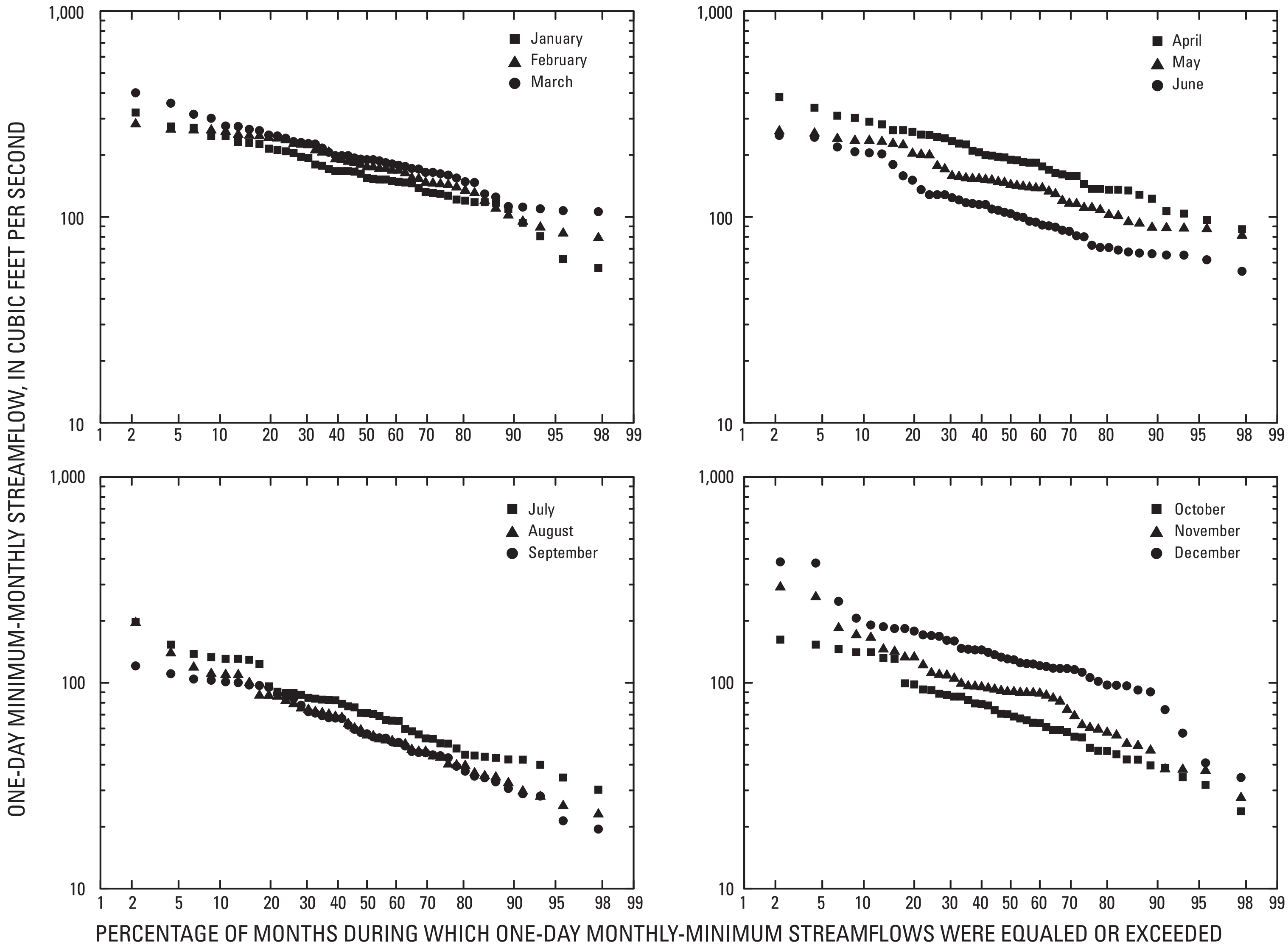

Figure A4–5. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site PAWCD on the Pawcatuck River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–1 and described in table 4–2.)

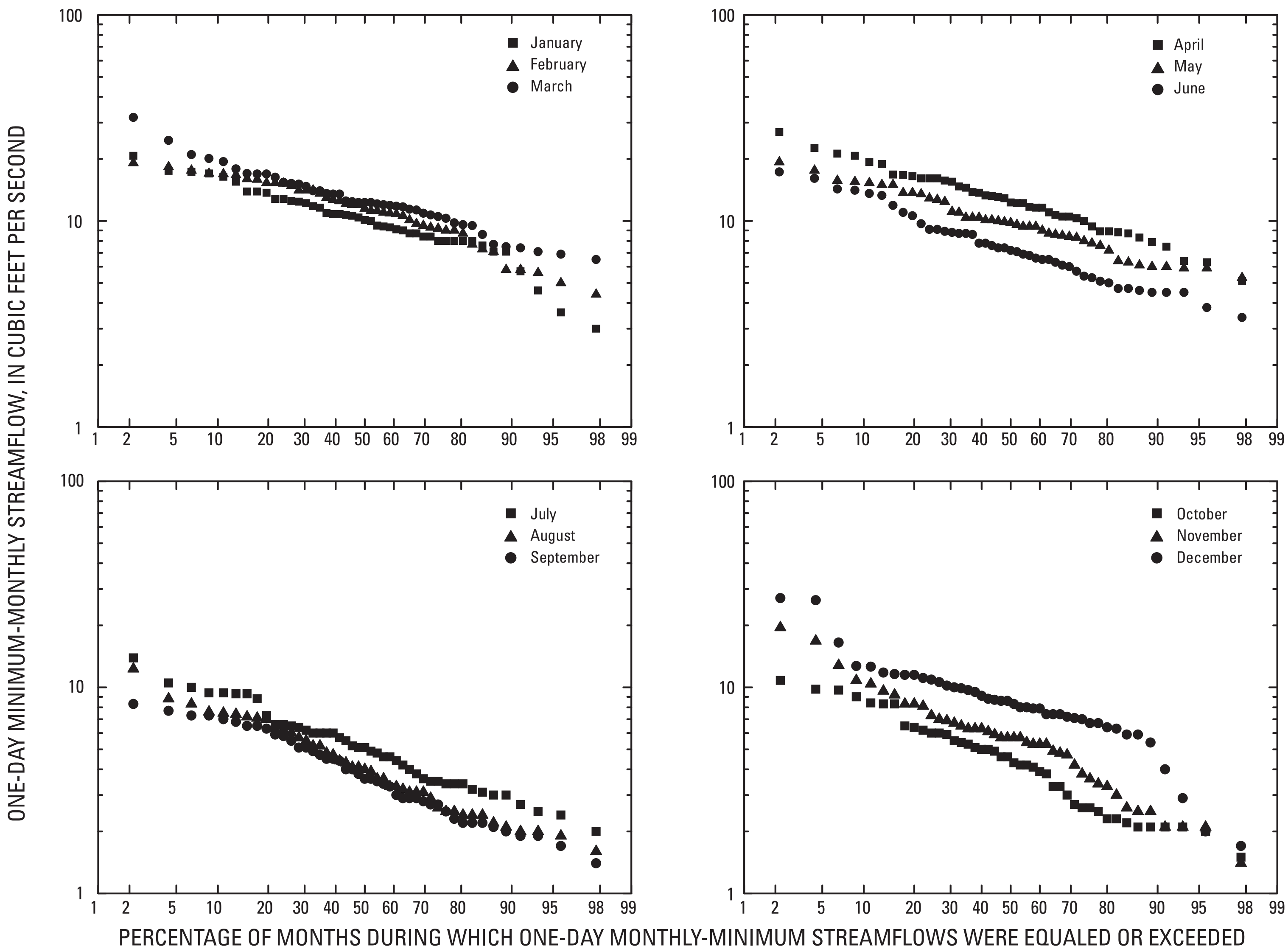

Figure A4–6. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site MEAD2 (RCHRES 48) on Meadow Brook, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–2 and described in table 4–2.)

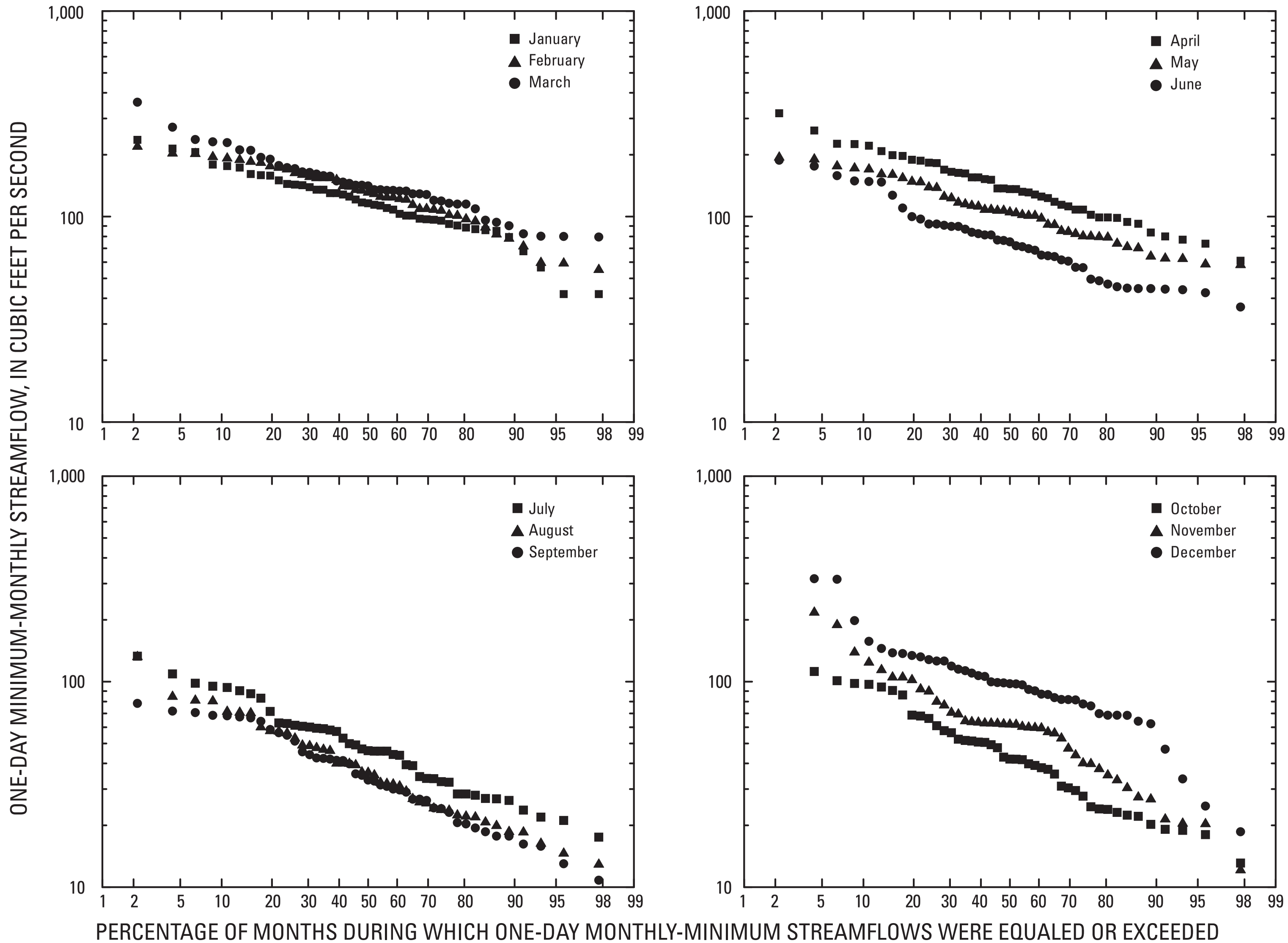

Figure A4–7. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site WOOD5 (RCHRES 63) on the Wood River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–2 and described in table 4–2.)

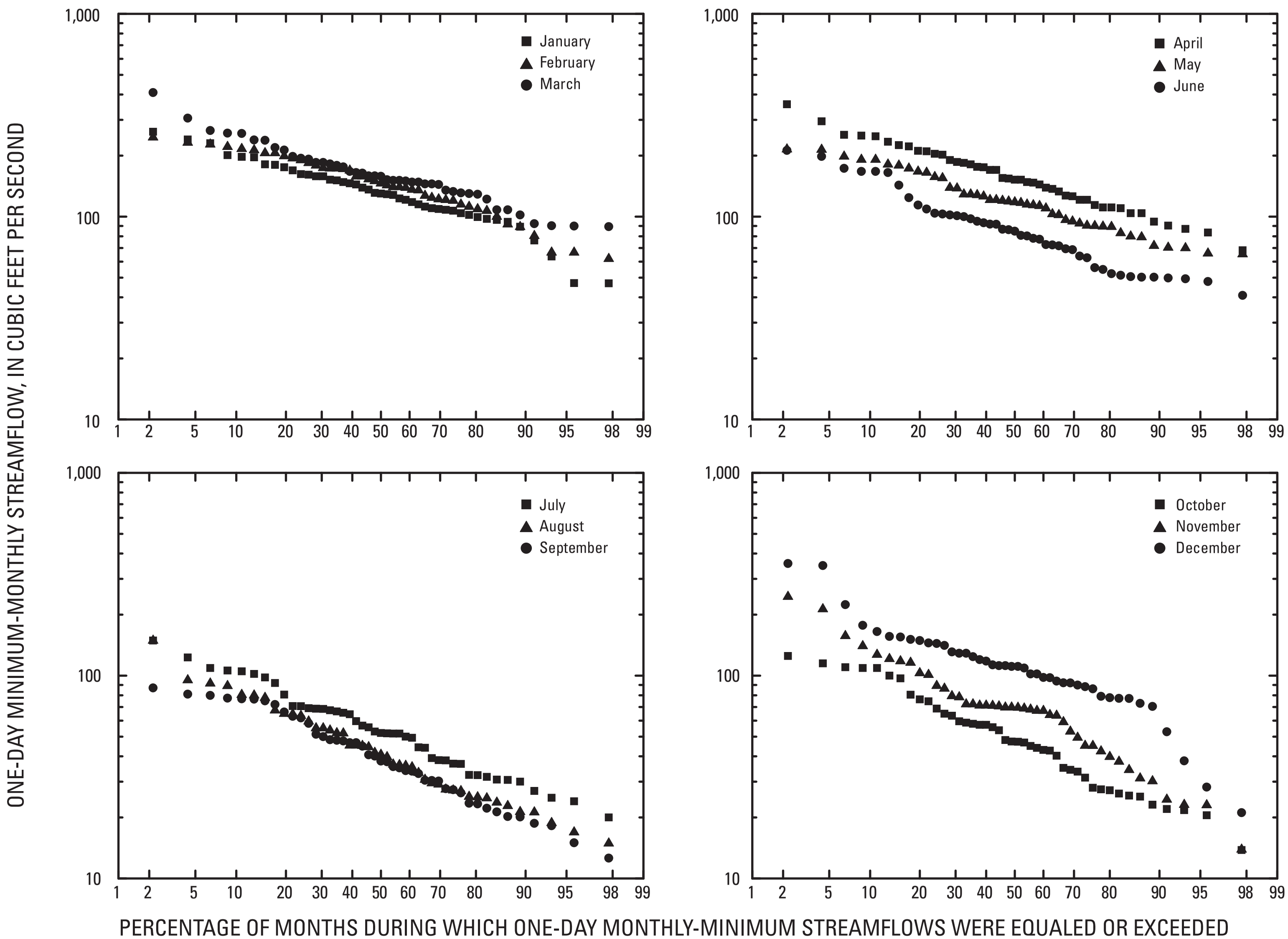

Figure A4–8. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site WOOD6 (RCHRES 65) on the Wood River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–2 and described in table 4–2.)

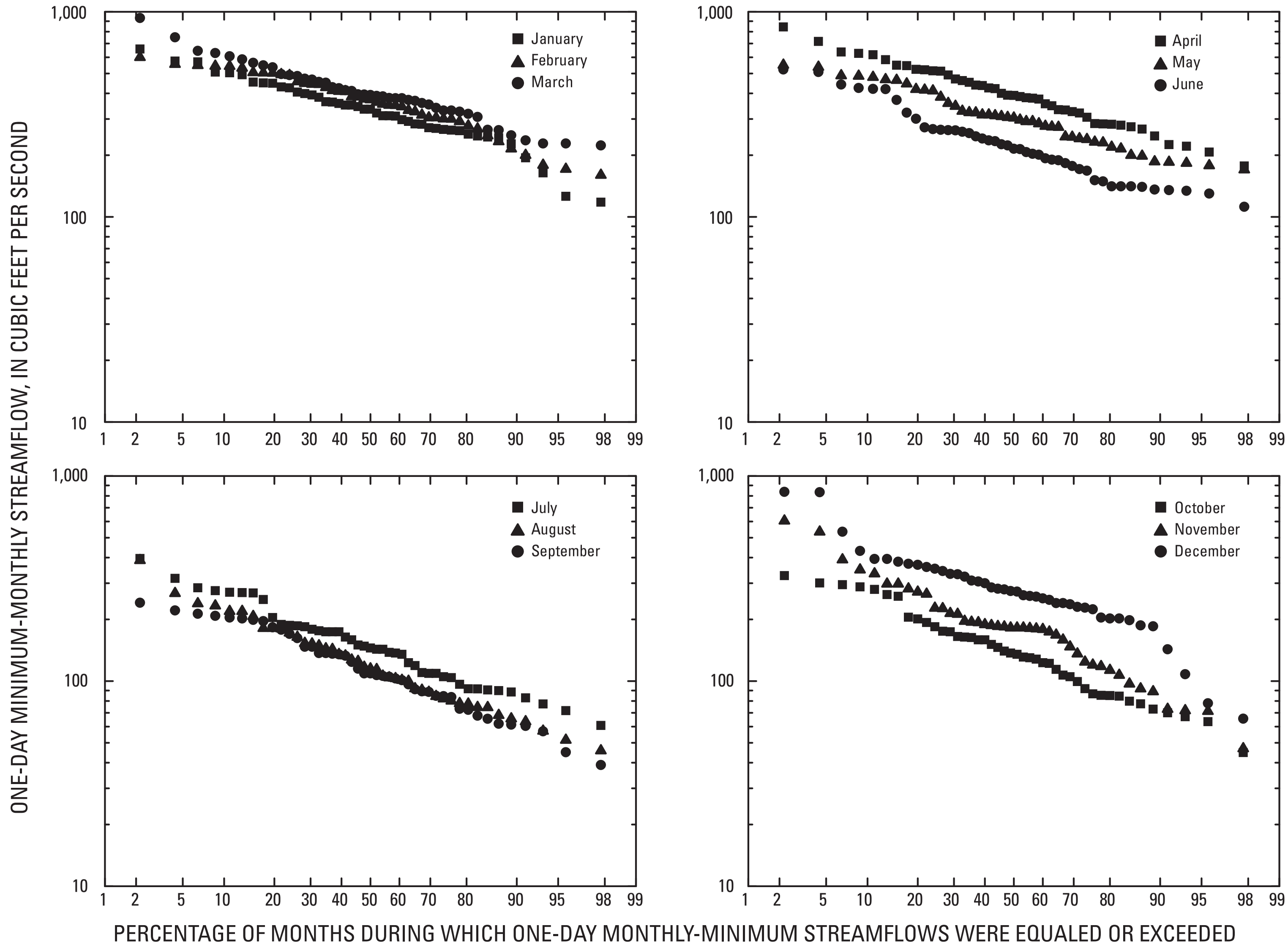

Figure A4–9. Monthly flow-duration curves (data from the HSPF model of conditions without withdrawals) showing the percentage of months during which one-day monthly-minimum streamflows equaled or exceeded a selected streamflow value at conjunctive-management model constraint site PAWC4 (RCHRES 50) on the Pawcatuck River, in the Pawcatuck River Basin in southwestern Rhode Island, during 1960–2004. (Site location shown in figure 4–2 and described in table 4–2.)

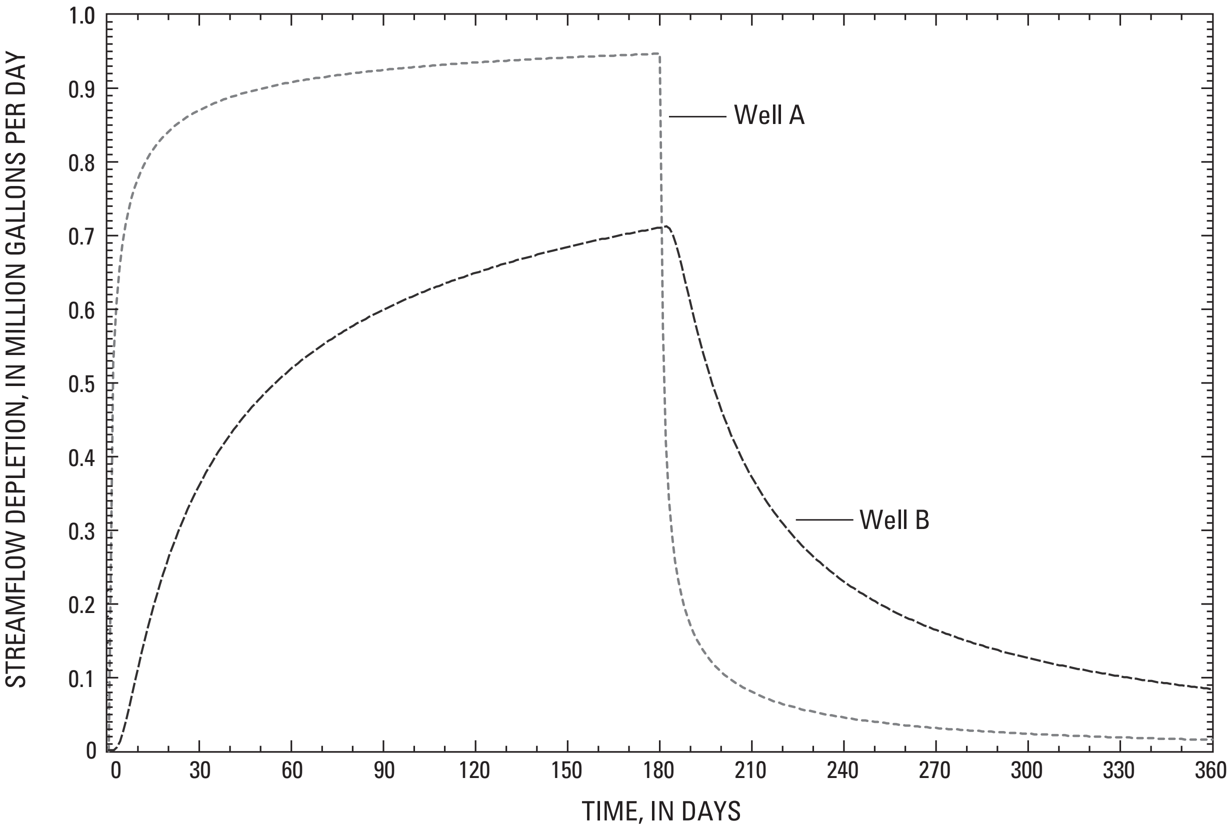

Figure A4–10. Hypothetical streamflow depletion caused by two wells pumping independently for 180 days at 1.0 million gallons per day. Well A is 250 feet from the streambank and well B is 1,000 feet from the streambank (Modified from Barlow, 1997).

Seasonal Water-Demand Criteria

The conjunctive-management models developed for both areas include seasonal water-demand patterns for municipal water use, and irrigation for agriculture and golf courses. The timing of water demands in Rhode Island is a critical factor because evapotranspiration reduces available streamflows during the summer months when monthly water demands commonly peak. Factors that influence the annual distribution of monthly demands for municipal water-supply systems include increased lawn and garden irrigation, implementation of water-use restrictions, and increased summer populations in recreational areas (L.K. Barlow and E.C. Wild, U.S. Geological Survey, written commun., September 2003). The logistic-regression equations developed to predict water-use patterns (see Part 1) indicate that the factors influencing the annual distribution of monthly demands for agricultural and golf-course irrigation are precipitation and potential evapotranspiration. Furthermore, municipal and agricultural water demands commonly increase during dry years, which may exacerbate the effect of precipitation deficits on instream flow.

Granato and Barlow (2005) demonstrated that management-models with the same streamflow constraints and no prespecified monthly demand-pattern constraints could produce substantially more water withdrawals than management models with the monthly demand-pattern constraint. The actual implementation of a management model without such constraints, however, requires the availability of a large reservoir as an alternate or supplemental summer supply or as a storage facility to retain excess fall, winter, and spring withdrawals to meet peak summer demands. Water suppliers typically have distribution reservoirs (small surface-water reservoirs, standpipes, or tanks) that are used to meet fluctuations in daily demand, maintain pressure in the system, and provide water for emergencies. The amount of storage provided for these objectives, however, is commonly sufficient for only several days, not months or seasons (Viessman and Hammer, 1985). For example, the Kent County Water Authority currently has a storage capacity for a 1- to 3-day supply in water tanks connected to the distribution network (Timothy Brown, Kent County Water Authority, written commun., 2003).

The monthly demand pattern constraint was specified as a set of 11 constraints that control the relation among total withdrawals from one month to the next for each withdrawal point as

$$\sum_{i=1}^{NW} Qw_{i,t_1} = \alpha_{1,2} \times \sum_{i=1}^{NW} Qw_{i,t_2} \,, \qquad (5)$$

where

NW is the number of active withdrawal sites in each model (table A4–1); and

$Qw_{i,t}$ are the withdrawal rates at water-withdrawal point i in months t_1 and t_2, respectively; and

$\alpha_{1,2}$ is the ratio of the percentage of total demands in month t_1 to total demands in month t_2 (adjusted for the number of days in each month).

All calculations of $\alpha_{1,2}$ were normalized to the July demand for each type of withdrawal and to the number of days in each month because irrigation demands do not occur over the entire year and the July value is the maximum of all 12 monthly values for municipal and irrigation withdrawals.

Monthly water-withdrawal patterns for four water-supply systems (Kingston, Richmond, United Water, and Westerly) that are largely dependent on groundwater (fig. A4–11) were used to estimate the monthly distribution of withdrawals from the hypothetical wells included in the management models. These data, which were collected as part of the current study and for USGS water-use studies in Rhode Island (Wild and Nimiroski, 2004), were provided by water suppliers and include the period from October 1995 through September 2004. The boxplots in figure A4–11 indicate the month-to-month and year-to-year variability in water withdrawals for each month. The thick line in figure A4–11 connects the average monthly fractions, which add up to one. The fractions are printed along the top of the graph. The boxplots indicate both the higher fractions of water demand and higher within-month variability during the warm months (May through October for municipal wells). This indicates that the highest municipal water-supply demands occur during the irrigation season when streamflows are lowest. The boxplots also indicate lower demand and less variability during the rest of the year (November through April for municipal wells). These patterns are similar to the monthly distribution of water-supply withdrawals defined by Granato and Barlow (2005) as the Rhode Island groundwater-demand pattern for six groundwater-based water-supply systems throughout Rhode Island for the period 1995–1999. The monthly water-supply factor ($\alpha_{1,2}$) was calculated by dividing the fraction of annual withdrawals for each month, August through June, by the July fraction shown in figure A4–11.

Three different monthly water-withdrawal patterns for irrigation were used in the management-model formulations (fig. A4–12). The records of precipitation and potential evapotranspiration during the 1960–2004 period were used with the logistic-regression equations and daily water-use data to estimate irrigation withdrawals during this period. The pattern for agricultural irrigation was based on irrigation data from turf farms (fig. A4–12). It was assumed that the vegetable farms follow a similar irrigation pattern. Results of the logistic-regression analysis indicate that there was a sharp peak in the fraction of agricultural irrigation patterns in July. The results also indicate that small amounts of agricultural irrigation may have occurred in the months of April and October in only few years during the 45-year simulation period. The pattern of surface-water golf-course irrigation (fig. A4–12B) was similar to the pattern for agricultural irrigation (fig. A4–12A). However, golf courses on surface-water irrigation systems (fig. A4–12B) followed different irrigation patterns than golf courses on groundwater irrigation systems (fig. A4–12C). The data indicated that golf courses irrigating with groundwater withdrawals used automated watering systems, with a regular irrigation pattern that was fairly consistent from month to month during the irrigation season (fig. A4–12C) and daily peak-irrigation rates occurring in the middle of the night. Furthermore, the logistic-regression equation for golf courses irrigating with groundwater withdrawals indicates that the irrigation season for these systems includes parts of March and November (although it should be noted that the equation indicates the potential for withdrawals during March in only a few years during the 1960–2004 period).

The boxplots in figure A4–12 indicate that the fraction of irrigation withdrawals within each month varied substantially with differences in weather patterns. Average monthly fractions were used to formulate the conjunctive-management models because the effect of such variation cannot be predicted with great certainty for any future year. The thick line in each panel of figure A4–12 connects the mean monthly fractions, which are printed along the top of the graph and add up to one. As with the municipal withdrawal pattern, the monthly water-supply factors ($\alpha_{1,2}$) for irrigation withdrawals are calculated by dividing the fraction of annual withdrawals for each month in the irrigation season by the July fraction shown in figure A4–12.

Because the objective of the example management models is to maximize water withdrawals for a given set of streamflow criteria, a management model that is not constrained by a monthly water-withdrawal pattern will indicate that the optimal solution for maximizing irrigation withdrawals would be to make such withdrawals during months when the ensuing streamflow depletion would occur during the high-flow months of the year (for example, fig. A4–2). The resulting withdrawal pattern would not be useful for irrigation needs, however, because the withdrawals would be made in the late fall, winter, and early spring when irrigation is unnecessary. This example illustrates why monthly withdrawal-pattern constraints are necessary to formulate the optimization models. It should be noted, however, that use of the mean withdrawal

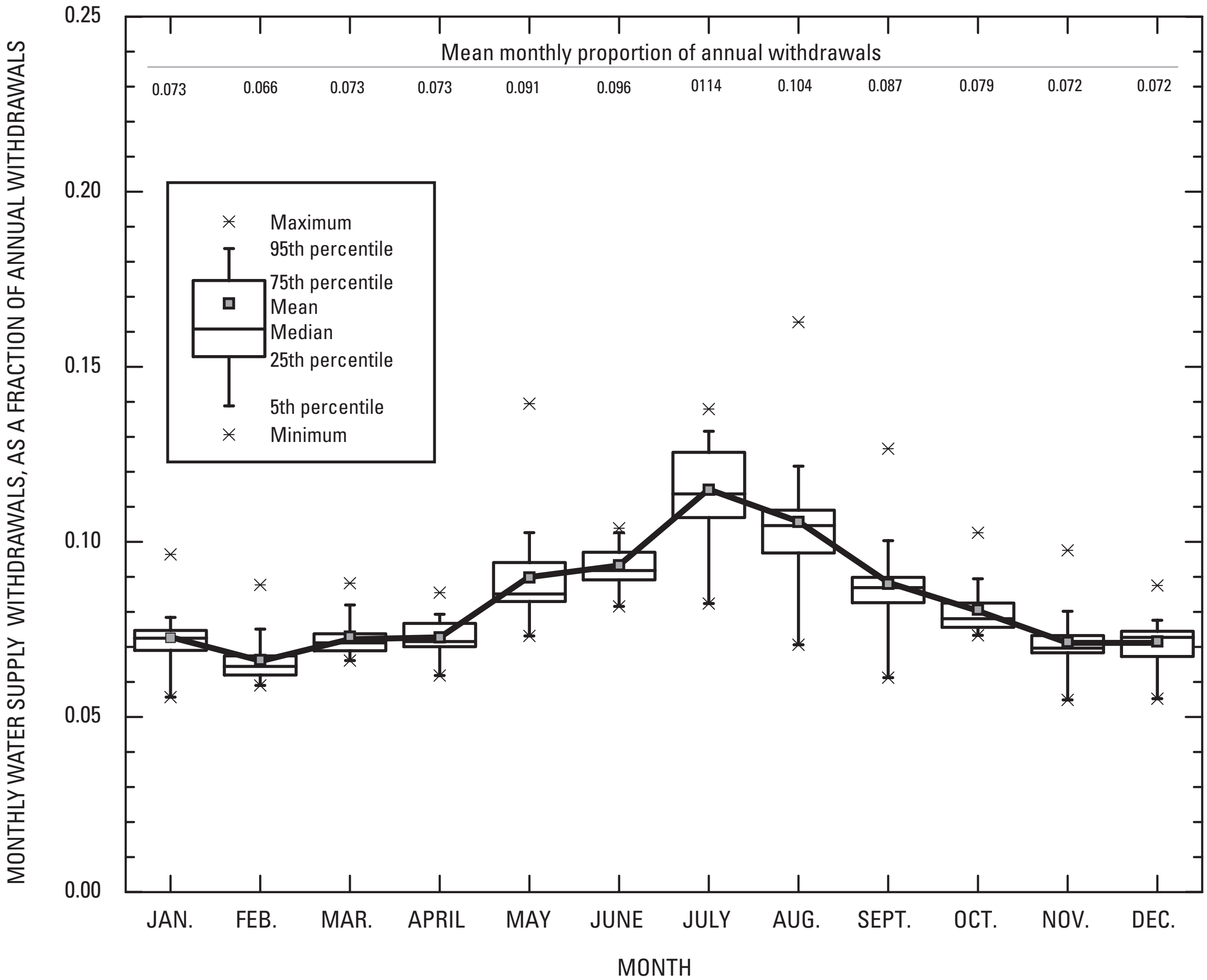

Figure A4–11. The distribution of monthly withdrawals as a fraction of total annual withdrawals during the period 1995–2004 from four water-supply systems that withdraw primarily from groundwater sources in the Pawcatuck River Basin, southwestern Rhode Island.

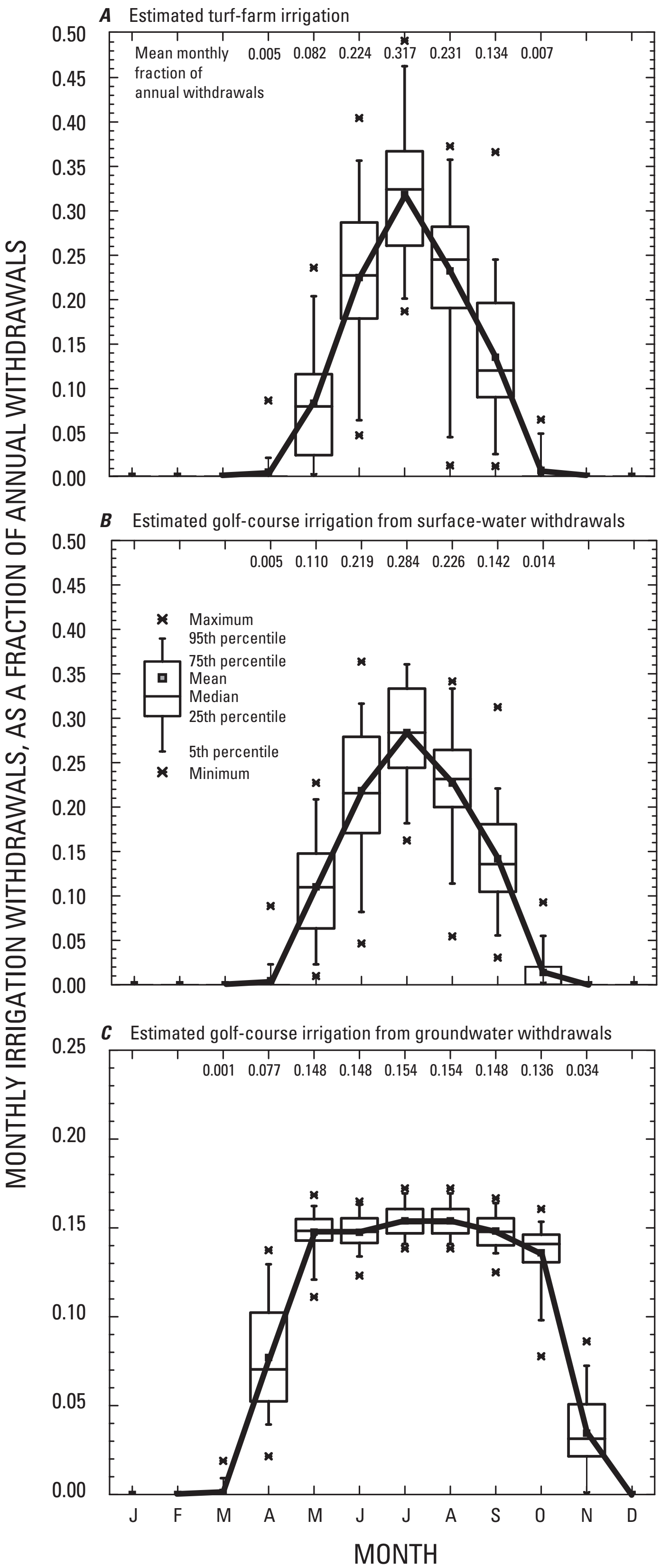

Figure A4–12. The distribution of monthly irrigation withdrawals as a fraction of total annual withdrawals during the period January 1960 through September 2004 estimated by use of logistic-regression equations developed for *(A)* turf-farm irrigation, *(B)* golf-course irrigation from surface-water withdrawals, and *(C)* golf-course irrigation from groundwater withdrawals in southwestern Rhode Island.

fractions may not produce optimal irrigation patterns for every year because irrigation patterns vary with climate conditions from year to year. Further refinement of withdrawal patterns or the generation of multiple optimization models based on irrigation patterns for the 45-year record would not be useful because it is impossible to produce accurate estimates of daily precipitation and potential evaporation at the beginning of the irrigation season. For example, results of the logistic-regression equations indicate that total annual irrigation withdrawals would range from 147 to 445 Mgal/yr in the EPRCMM area and from 102 to 279 Mgal/yr in the LWRCMM area under 1960–2004 the climatic conditions (fig. A4–13).

Response-Matrix Technique for Solution of the Conjunctive-Management Model

The optimization method used to solve the conjunctive-management model is based on a widely applied technique for solving many types of groundwater-management problems. Called the response-matrix technique, the method is based on the assumption that the rate of streamflow depletion at each streamflow-constraint site is a linear function of the rate of groundwater withdrawal at each production well. By assuming linearity, it is possible to estimate total streamflow depletion at a constraint site by summation of the individual streamflow depletions caused by each well. Detailed descriptions of the response-matrix technique are given by Gorelick and others (1993) and Ahlfeld and Mulligan (2000). Specific applications of the technique to problems in stream-aquifer management in Massachusetts and Rhode Island are given by Male and Mueller (1992), Mueller and Male (1993), Barlow (1997), Barlow and Dickerman (2001a,b), DeSimone and others (2002), Barlow and others (2003), DeSimone (2004), Eggleston (2004), and Granato and Barlow (2005).

The response-matrix technique is developed using a transient dynamic-equilibrium groundwater modeling technique. The monthly hydrologic inputs for an average year are used repeatedly a transient groundwater model over a number of simulation years so the system will reach a dynamic-equilibrium from year-to-year to quantify the effect of one monthly withdrawal on streamflow depletions in the months following each withdrawal period (Barlow, 1997; Barlow and Dickerman, 2001a,b; DeSimone and others, 2002; Barlow and others, 2003; DeSimone, 2004; Eggleston, 2004; Granato and Barlow, 2005). The technique is valid as long as the saturated thickness and transmissivity of the aquifer do not vary substantially with changes in withdrawal rates, and other nonlinear effects simulated by the transient model, such as head-dependent boundary conditions, are not large.

To employ this technique, the monthly inputs for the year 2000 in the calibrated transient MODFLOW models developed for each of the conjunctive-management model area were used in a 5-year dynamic-equilibrium simulation for each model area. Eight MODFLOW simulations were run to calculate a characteristic streamflow-depletion response in

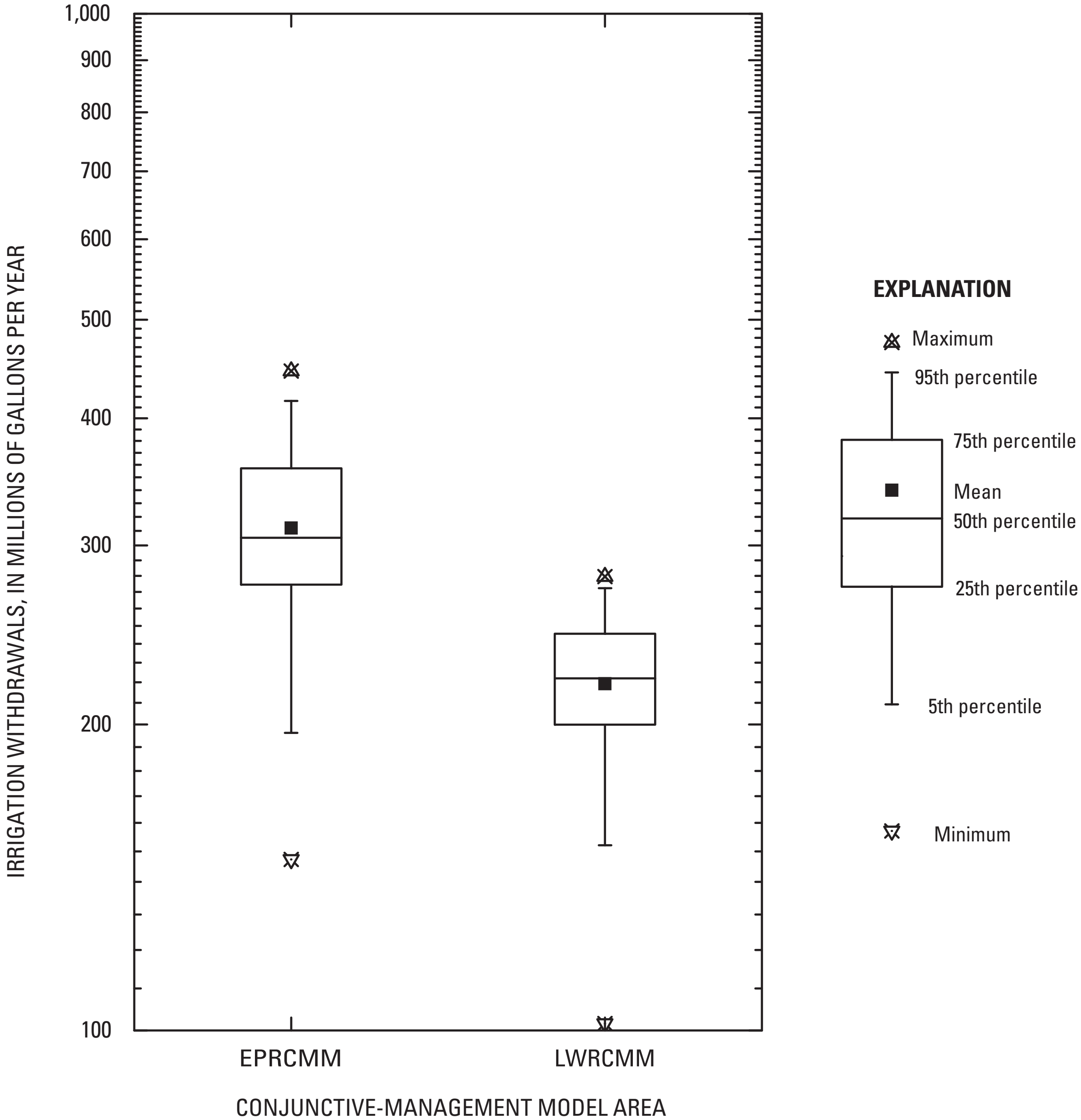

Figure A4–13. The distribution of annual irrigation withdrawals as estimated from the logistic-regression equations for irrigation withdrawals for the eastern Pawcatuck River conjunctive-management model (EPRCMM) area and the lower Wood River conjunctive-management model (LWRCMM) area in the Pawcatuck River Basin, southwestern Rhode Island, 1960–2004.

each month to a unit withdrawal at each potential groundwater-withdrawal site in each model area. Different simulations for the four withdrawal rates 0.1, 0.5, 1.0, and 2.0 Mgal/d in two different months (January and June) were run to calculate response coefficients for different withdrawal rates and different seasons. Each groundwater withdrawal site was simulated independently to isolate the effects of withdrawals at that site on flows in neighboring streams. In each simulation, the withdrawal rate for one of the wells was specified in the groundwater model for a duration of one month; at the end of the month, the withdrawal rate at the well was returned to zero. The single-month increase in withdrawals is referred to as the unit withdrawal $Q_{wi}*$ at well *i*. The amount of streamflow depletion resulting from the unit withdrawal was determined by subtracting streamflow rates calculated by the model with the unit withdrawal active from those calculated by the model without any withdrawals. Streamflow-depletion responses to the unit withdrawals are defined as $Qsd*_{j,i,t}$, in which the subscripts indicate that the streamflow depletion occurs at site *j* in month *t* in response to a withdrawal at well *i*. Streamflow-depletion response coefficients ($r_{j,i,t}$) are then defined as

$$r_{j,i,t} = \frac{Qsd*_{j,i,t}}{Qw*_i} . \qquad (6)$$

The response coefficients are dimensionless and can range from 0.0 to 1.0. A response of 1.0 in the first month of withdrawals indicates that all of the water removed by the well can be accounted for as streamflow depletion in the first month. Similarly, surface-water withdrawals, which are taken directly from a site on the stream, are assigned a response of 1.0 in the first month of withdrawals. Response coefficients for groundwater withdrawals may represent depletions induced directly from the stream (by lowering groundwater levels below the local stream stage) and depletions caused by intercepting groundwater that would otherwise have discharged to the stream in the current and subsequent months (Granato and Barlow, 2005).

If a well causes depletions in only one stream, the sum of the response coefficients for that stream would be to almost 1.0; the remainder would be attributable to minor reductions in riparian evapotranspiration under dynamic equilibrium. Similarly, if a well affects streamflow in more than one stream, the sum of the response coefficients from the affected streams would be about 1.0. Response coefficients for both areas were adjusted to a value of 1.0 because the groundwater models did not simulate variable riparian-evapotranspiration rates or variable water-withdrawal rates. In addition, the use of response coefficients that add up to 1.0 provides a small margin of safety for the effects of withdrawals on streamflow depletion.

Response coefficients for each potential groundwater withdrawal site were determined by interpretation of transient groundwater model results for the streamflow-constraint sites in each area. Figures 4A–14–A4–21 show the nonzero response coefficients for all potential groundwater withdrawal sites that affect each streamflow constraint site in each conjunctive-management model area. Factors that affect the values of the response coefficients are the relative positions of the withdrawal wells and streamflow-constraint sites (including the vertical positions of the screened intervals of the wells), the geometry and hydraulic properties of the aquifer, the streambed conductance, and other physical characteristics of the streams as simulated with the groundwater models. Graphs of the response coefficients indicate substantial variability in the quantity and timing of streamflow-depletion responses to the simulated unit withdrawals.

Because of the assumed linearity of the system, the total streamflow depletion $Qsd_{j,t}$ at each constraint site *j* and for each month *t* can be calculated with the response coefficients by summation of the individual streamflow depletions caused by withdrawals at each well in each month. This summation is written as

$$Qsd_{j,t} = \sum_{i=1}^{NW} \sum_{k=1}^{12} r_{j,i,k} \times Qw_{i,k'} , \qquad (7)$$

where

$$\begin{cases} k' = t - k + 1 \;\; for \;\; t - k + 1 > 0 \\ k' = 12 + (t - k + 1), \;\; for \;\; t - k + 1 \le 0 \end{cases}$$

The two-part definition of *k′* (the monthly withdrawal index number) is required as a consequence of the annual cycle of withdrawals. For example, streamflow depletions in January (*t*=1, *k′*=1) can be affected by withdrawals in December (*t*=12, *k′*=2). For example, to calculate depletions in the Beaver River at BEAVM from withdrawals at well RIW-385 a response coefficient of about 0.06 would be used for December withdrawals and a response coefficient of about 0.93 would be used for January withdrawals (fig. A4–14). Although the summation includes 12 terms for each well/streamflow-constraint-site pair, many of the terms may equal zero if many of the response coefficients equal zero. Implementation of equation 7 provides the information necessary to estimate the cumulative effect of multiple withdrawals on streamflow depletion from one or more withdrawal sites on a selected streamflow-depletion site in the area of interest.

The response coefficients are the link between the groundwater flow model and the conjunctive-management models in the Pawcatuck River Basin, and are incorporated into the water-resource-management model by replacing the definition of $Qsd_{j,t}$ in the expression defining the streamflow-depletion constraints (equation 2) by the right-hand side of equation 7. The constraints are then written as

$$\sum_{i=1}^{NW} \sum_{k=1}^{12} r_{j,i,k} \times Qw_{i,k'} \le \left(Qsd_{j,t} \right)_{max} . \qquad (8)$$

Equation 8 replaces equation 2 in the conjunctive-management model.

The use of the response-matrix technique is limited because relations between groundwater head and groundwater discharge to streamflow in unconfined aquifers commonly are weakly nonlinear (Barlow and Dickerman 2001a,b; Granato and Barlow, 2005). These nonlinearities commonly are the result of two factors under normal conditions and an additional factor under extreme drought conditions. First, the saturated thickness and transmissivity in an unconfined aquifer change as recharge, evapotranspiration, and withdrawal rates at the wells change. These nonlinearities were not characterized by the transient groundwater models because the models were developed with the fixed-transmissivity option. The fixed-transmissivity option was used to address numerical-stability issues in areas where relatively steep-slope low-transmissivity till areas contact high-transmissivity aquifer areas. Second, streamflow leakages were simulated as piecewise-linear functions of calculated groundwater heads. Under extreme drought conditions (or with water withdrawals that exceed available streamflow), a stream reach may go dry. In this case, the stream is no longer a source of water to the well, and aquifer storage becomes the sole source of water to the well. Theoretically, the amount of water taken from aquifer storage will appear as streamflow depletion in subsequent months because the well will capture water that would otherwise discharge to the stream until the deficit in aquifer storage is replaced by subsequent increases in recharge. Because of these nonlinearities, the response coefficients for each well/streamflow-constraint-site pair can change as withdrawal rates change, and such changes can affect the solution of the conjunctive-management model.

Conjunctive-management models for both areas are affected by an additional source of potential nonlinearity. In each are the watersheds consist of large relatively low-relief sand and gravel aquifers that span the groundwater divide between two streams. In the EPRCMM area, 10 of the existing and potential groundwater withdrawal sites are between the Beaver and the Usquepaug-Queen Rivers, and some sites cause streamflow depletion in the main stem of the Pawcatuck River (fig. 4–1). In the LWRCMM area, five of the existing and potential groundwater withdrawal sites are between the Wood River and Meadow Brook (fig. 4–2). Variations in recharge and groundwater withdrawal rates near the natural groundwater divides may alter the fraction of withdrawals that cause depletions in each stream leading to the potential for variations in the response coefficients for different hydrologic conditions.

These types of nonlinearities have been addressed in groundwater-management problems by sequential (or iterative) linearization of the nonlinear problem (Danskin and Gorelick, 1985; Danskin and Freckleton, 1989; Gorelick and others, 1993, p. 206–208; Barlow, 1997; Ahlfeld and Mulligan, 2000, p. 160–163). Barlow and Dickerman (2001) indicated that such sequential-linearization approaches were not necessary for conjunctive-management models of the unconfined Hunt-Annaquatucket-Pettasquamscutt stream-aquifer system because the methods were computationally intensive and because simulations with transient groundwater models indicated that the response coefficients changed very little with the simulated withdrawal conditions. Granato and Barlow (2005) obtained similar results for the unconfined sand and gravel aquifer in the Big River Area.

Another complicating factor in the use of the response-matrix technique is that the lengths of the stress periods in the transient model were not constant, but ranged from 28 to 31 days. This difference violates the assumption of equal-length stress periods. Equal-length stress periods divide the response over the same number of days. Barlow and Dickerman (2001) indicated that violation of this assumption should not have a substantial effect on the model solution because the lengths of the stress periods used in the model do not differ substantially. This factor may affect the calculation of response coefficients, but does not directly affect the solution of the management model because the components are weighted by month length.

For the linearity approximation to be valid for solution of the management models, the values of the response coefficients for each well/streamflow-constraint-site pair must be approximately constant for all simulated withdrawal and hydrologic conditions. The assumption of linearity was tested in the eastern Pawcatuck and lower Wood River groundwater models by calculating response coefficients with four different pumping rates (0.1, 0.5, 1.0, and 2.0 Mgal/d) for different seasons of the year (January and June). The differences in calculated response coefficients were within the precision of the numerical solution for most of the stressed and unstressed conditions tested. The primary reason the response coefficients change very little for different simulated withdrawal conditions is that the aquifer is assumed to be highly transmissive near many of the wells. As a consequence, drawdowns caused by different conditions do not cause substantial changes in the saturated thickness or transmissivity of the aquifer beyond the immediate area of the well, unless the local stream goes dry. The median response coefficients from among different groundwater-model runs were selected to obtain the most representative response coefficients for different conditions.

The modified conjunctive-management model defined by equations 1, 3–5, and 8 constitutes a linear program based on the assumption of the linearity of the streamflow responses to groundwater withdrawals. The LINDO linear-programming computer software (LINDO Systems, 1996; Schrage, 1997) was used to solve each specific application of the conjunctive-management models for each area. The program mathematically searches for the monthly withdrawal rates at each well that maximize the yield of the aquifer subject to the set of constraints. Output from the LINDO program includes the total withdrawal rate, withdrawal rates for each well, and information about binding criteria.

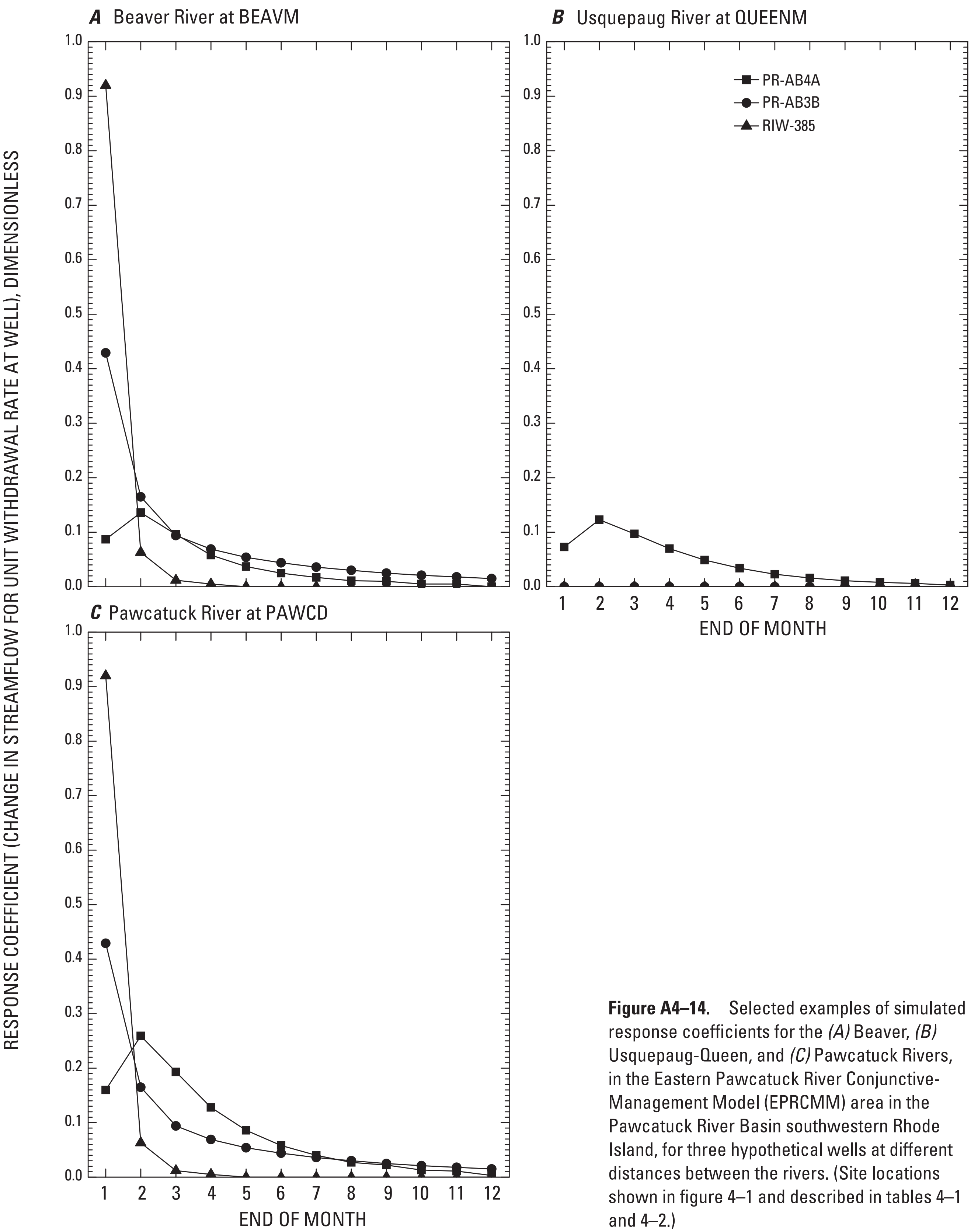

Figure A4–14. Selected examples of simulated response coefficients for the *(A)* Beaver, *(B)* Usquepaug-Queen, and *(C)* Pawcatuck Rivers, in the Eastern Pawcatuck River Conjunctive-Management Model (EPRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

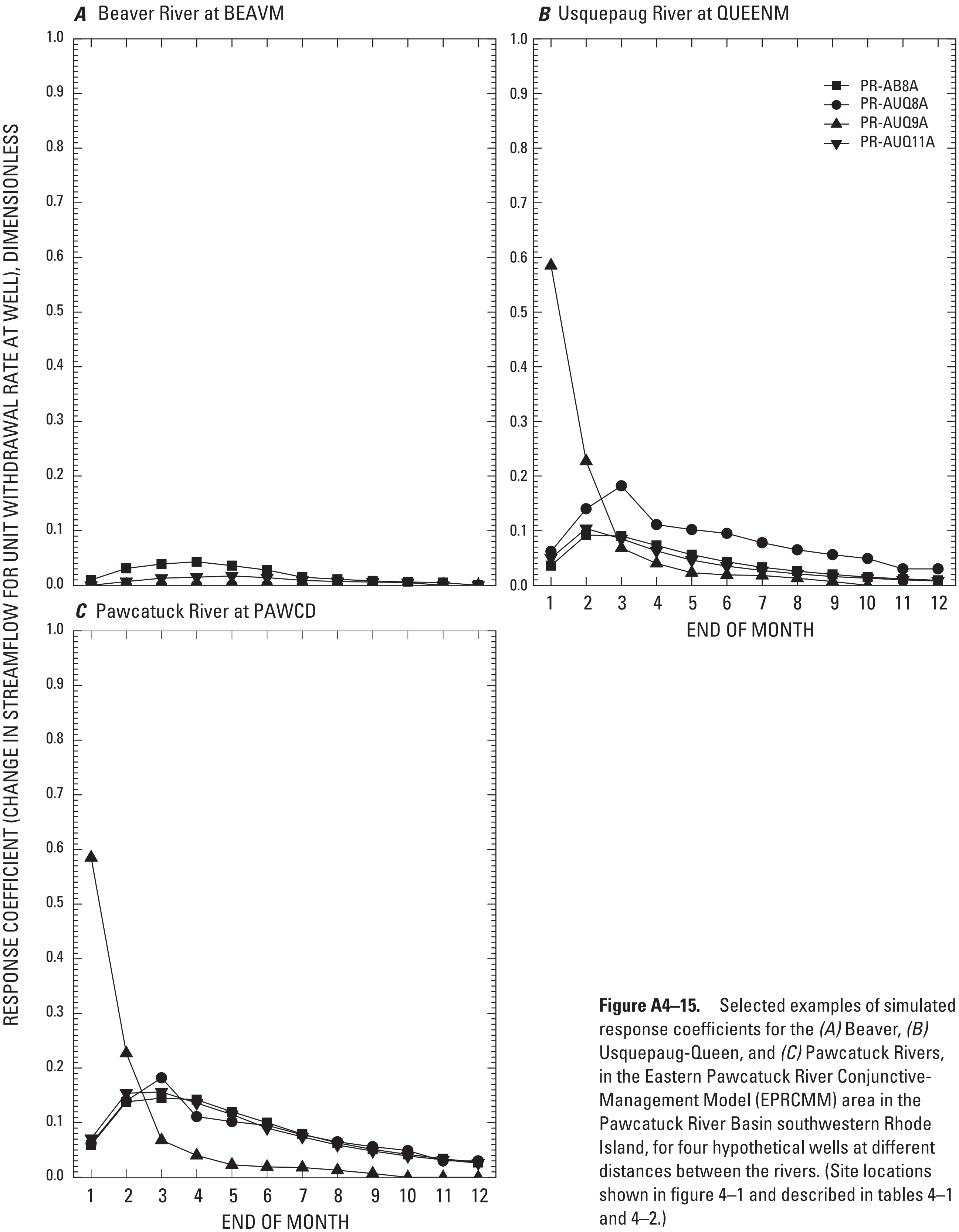

Figure A4–15. Selected examples of simulated response coefficients for the *(A)* Beaver, *(B)* Usquepaug-Queen, and *(C)* Pawcatuck Rivers, in the Eastern Pawcatuck River Conjunctive-Management Model (EPRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for four hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

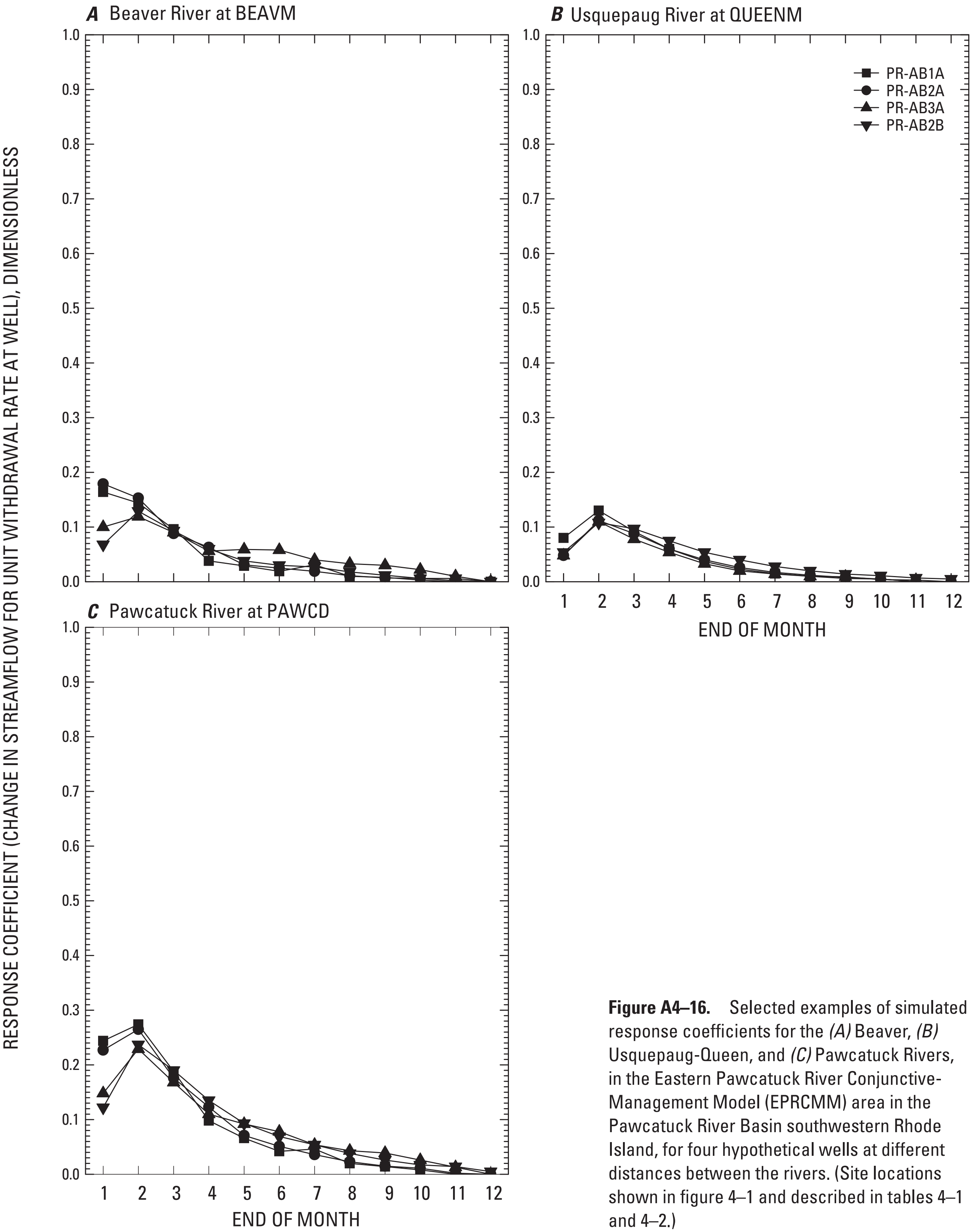

Figure A4–16. Selected examples of simulated response coefficients for the *(A)* Beaver, *(B)* Usquepaug-Queen, and *(C)* Pawcatuck Rivers, in the Eastern Pawcatuck River Conjunctive-Management Model (EPRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for four hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

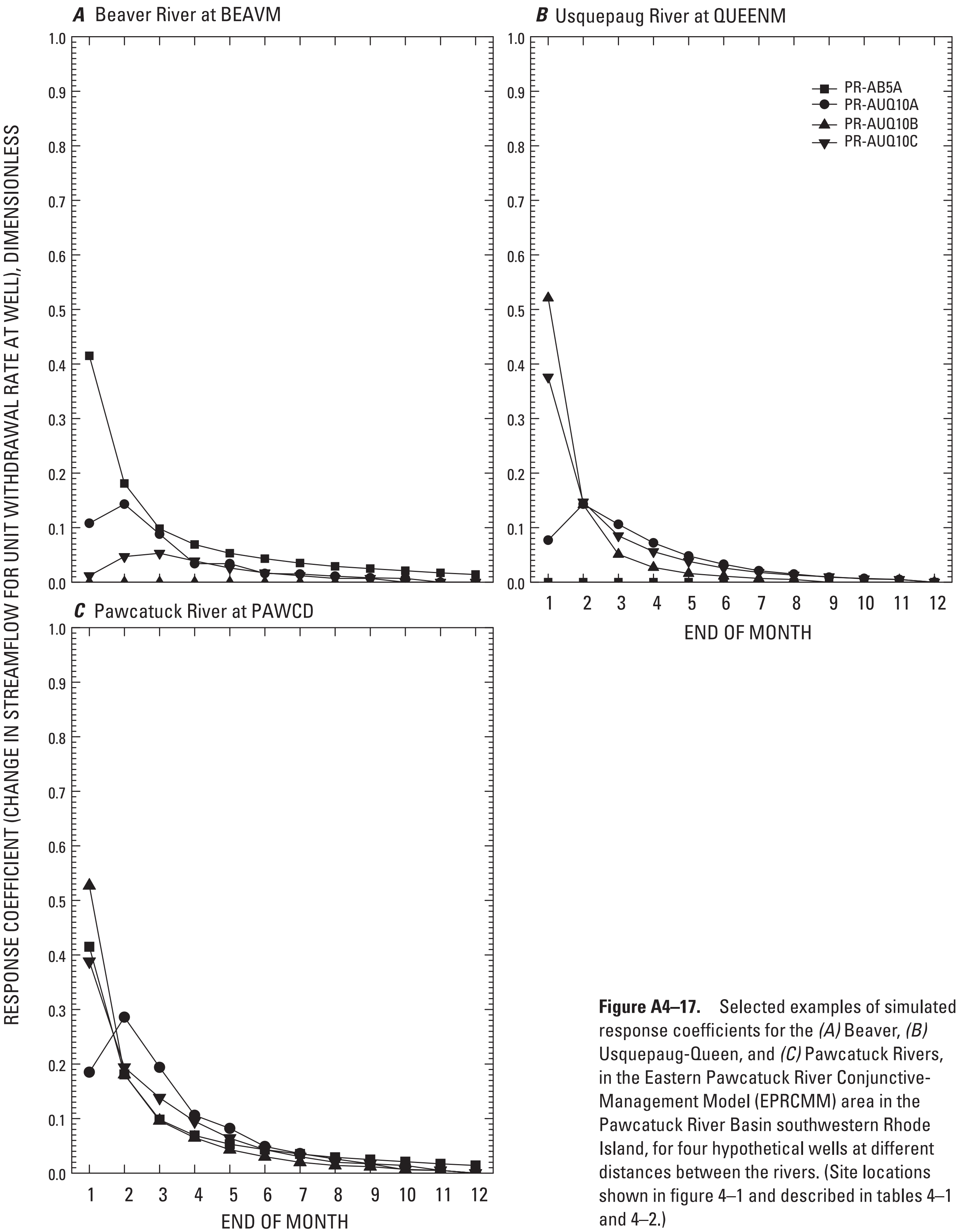

Figure A4–17. Selected examples of simulated response coefficients for the *(A)* Beaver, *(B)* Usquepaug-Queen, and *(C)* Pawcatuck Rivers, in the Eastern Pawcatuck River Conjunctive-Management Model (EPRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for four hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

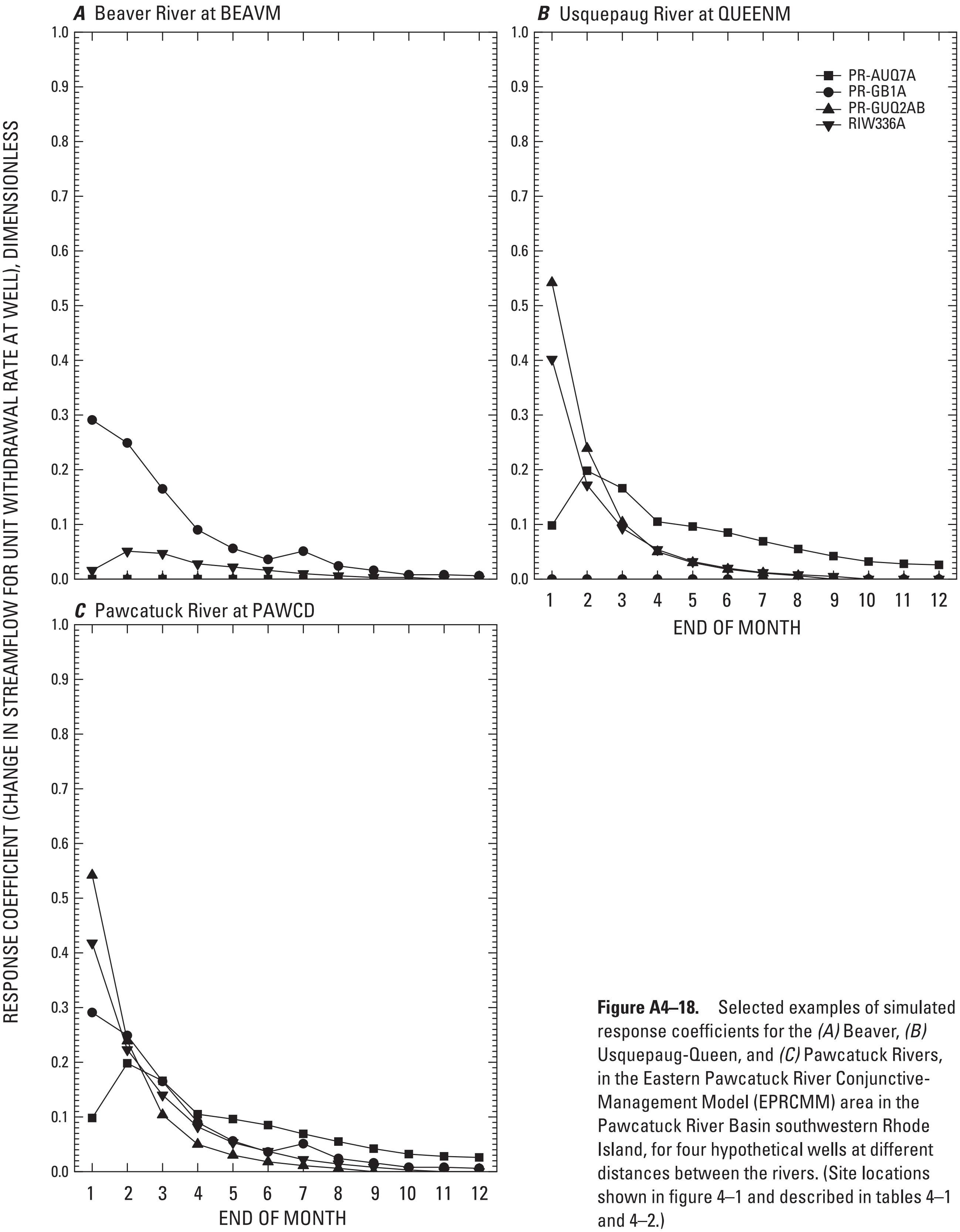

Figure A4–18. Selected examples of simulated response coefficients for the *(A)* Beaver, *(B)* Usquepaug-Queen, and *(C)* Pawcatuck Rivers, in the Eastern Pawcatuck River Conjunctive-Management Model (EPRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for four hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–1 and described in tables 4–1 and 4–2.)

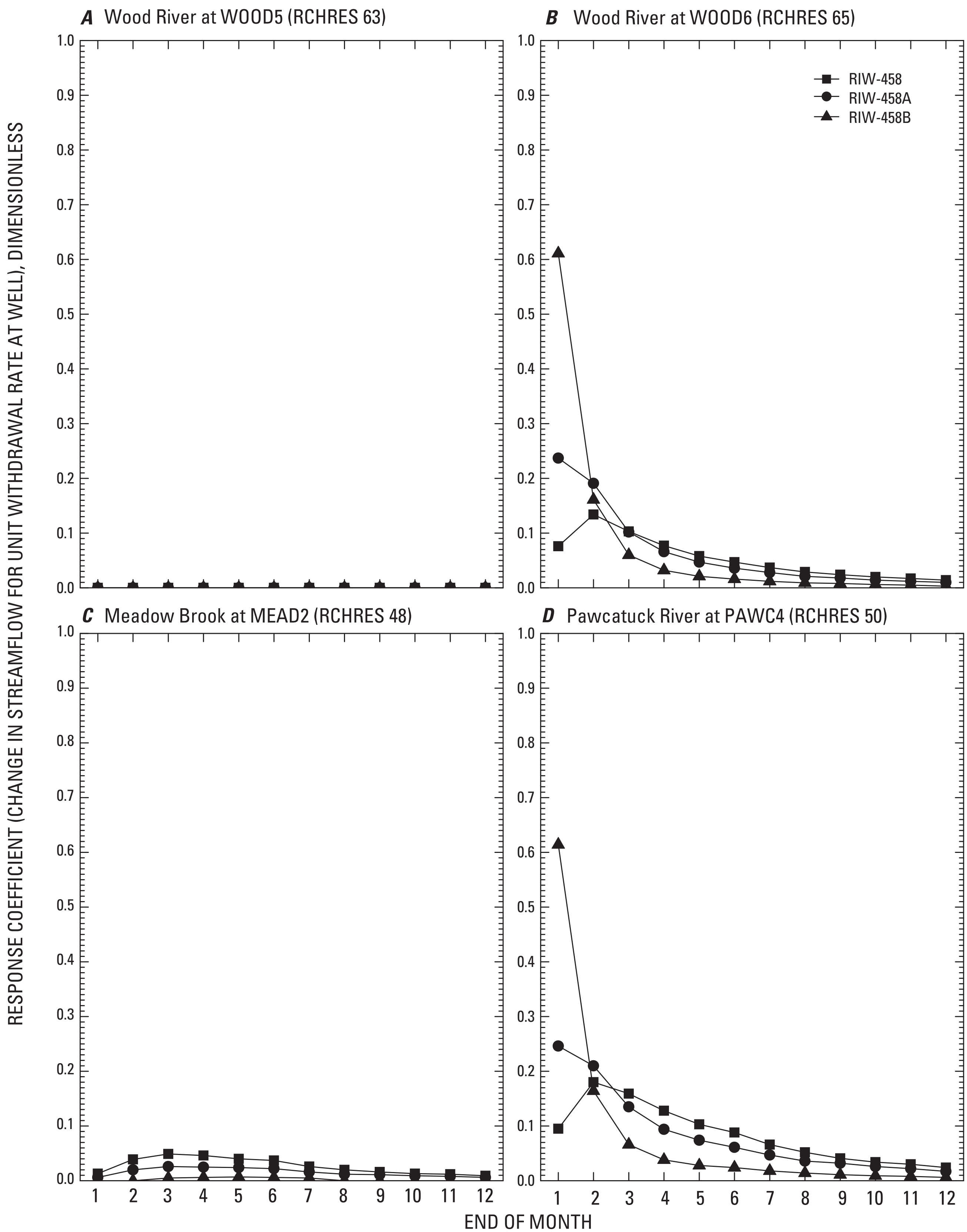

Figure A4–19. Selected examples of simulated response coefficients for *(A,B)* Wood River, *(C)* Meadow Brook, and *(D)* Pawcatuck River, in the Lower Wood River Conjunctive-Management Model (LWRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

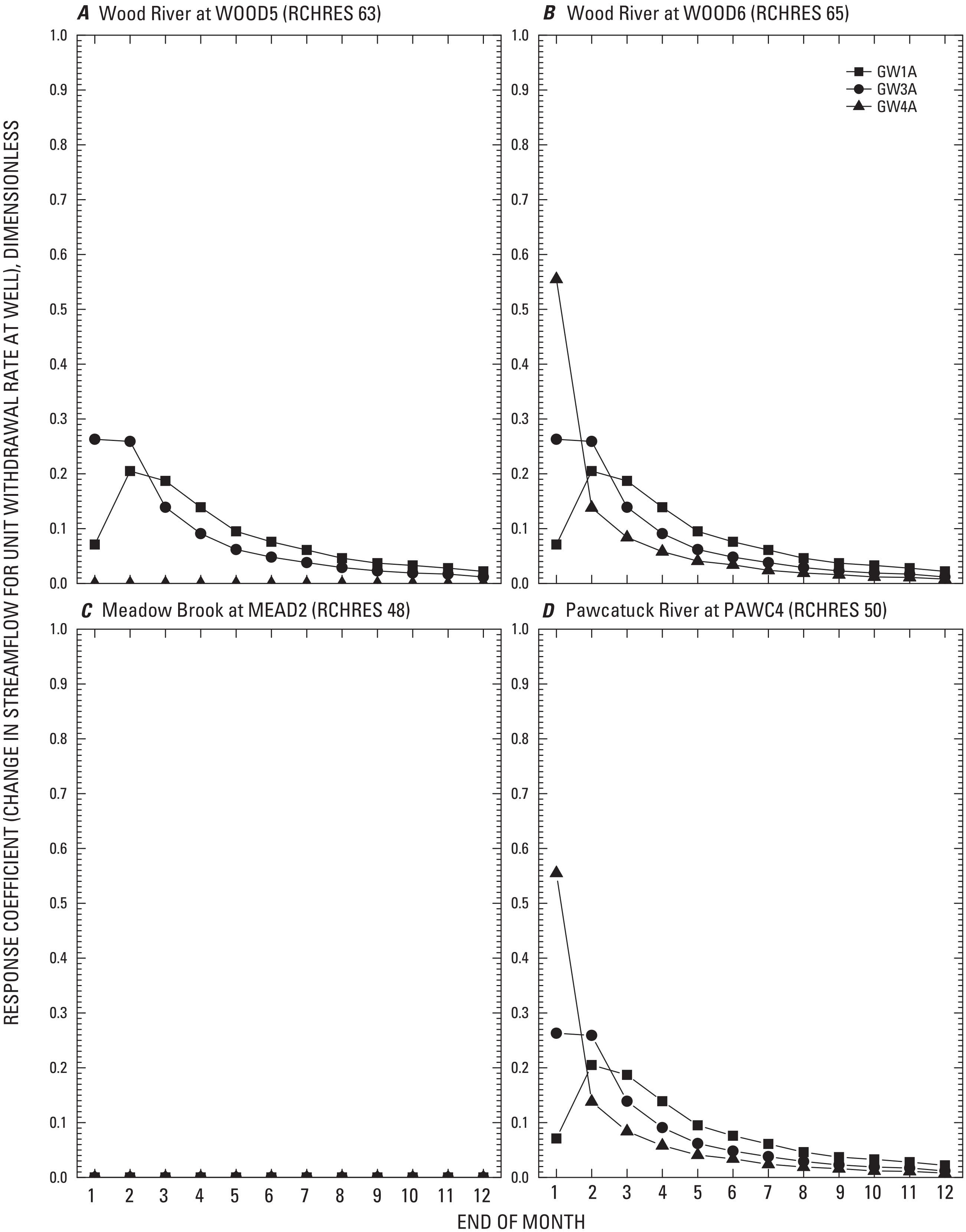

Figure A4–20. Selected examples of simulated response coefficients for *(A,B)* Wood River, *(C)* Meadow Brook, and *(D)* Pawcatuck River, in the Lower Wood River Conjunctive-Management Model (LWRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

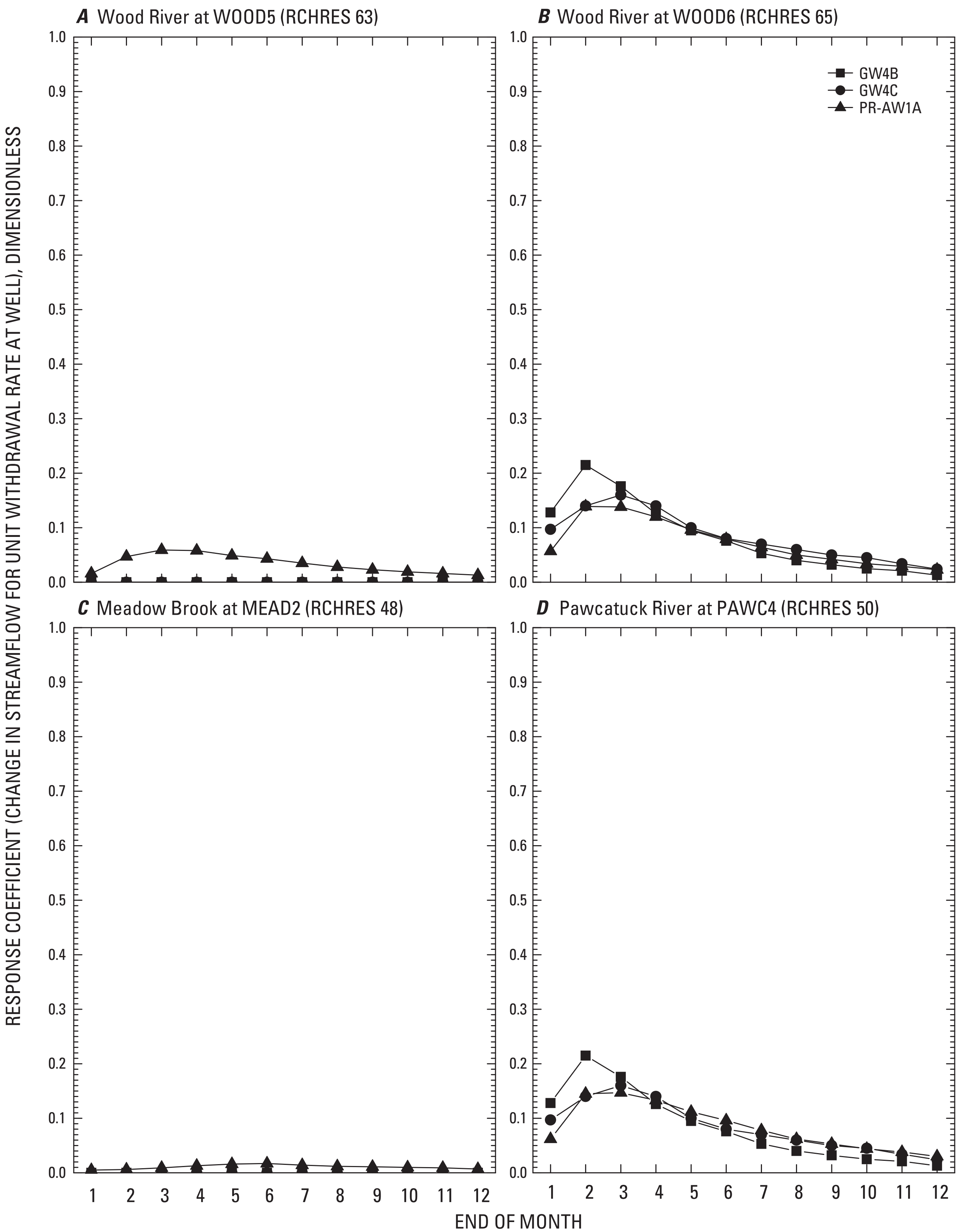

Figure A4–21. Selected examples of simulated response coefficients for *(A,B)* Wood River, *(C)* Meadow Brook, and *(D)* Pawcatuck River, in the Lower Wood River Conjunctive-Management Model (LWRCMM) area in the Pawcatuck River Basin southwestern Rhode Island, for three hypothetical wells at different distances between the rivers. (Site locations shown in figure 4–2 and described in tables 4–1 and 4–2.)

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