Effects of Alternative Instream-Flow Criteria and Water-Supply Demands on Ground-Water Development Options in the Big River Area, Rhode Island

By Gregory E. Granato and Paul M. Barlow

In cooperation with the
Rhode Island Water Resources Board

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Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer ($m^3/s/km^2$)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F - 32) / 1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929), formerly called the Sea Level Datum of 1929.

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) unless otherwise noted.

Transmissivity and Hydraulic Conductivity: In this report, the units of transmissivity and hydraulic conductivity are foot squared per day (ft^2/d) and foot per day (ft/d), respectively.

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Abstract

Transient numerical ground-water-flow simulation and optimization techniques were used to evaluate potential effects of instream-flow criteria and water-supply demands on ground-water development options and resultant streamflow depletions in the Big River Area, Rhode Island. The 35.7 square-mile (mi^2) study area includes three river basins, the Big River Basin (30.9 mi^2), the Carr River Basin (which drains to the Big River Basin and is 7.33 mi^2 in area), the Mishnock River Basin (3.32 mi^2), and a small area that drains directly to the Flat River Reservoir. The overall objective of the simulations was to determine the amount of ground water that could be withdrawn from the three basins when constrained by streamflow requirements at four locations in the study area and by maximum rates of withdrawal at 13 existing and hypothetical well sites. The instream-flow requirement for the outlet of each basin and the outfall of Lake Mishnock were the primary variables that limited the amount of ground water that could be withdrawn. A requirement to meet seasonal ground-water-demand patterns also limits the amount of ground water that could be withdrawn by up to about 50 percent of the total withdrawals without the demand-pattern constraint. Minimum water-supply demands from a public water supplier in the Mishnock River Basin, however, did not have a substantial effect on withdrawals in the Big River Basin. Hypothetical dry-period instream-flow requirements and the effects of artificial recharge also affected the amount of ground water that could be withdrawn.

Results of simulations indicate that annual average ground-water withdrawal rates that range up to 16 million gallons per day (Mgal/d) can be withdrawn from the study area under simulated average hydrologic conditions depending on instream-flow criteria and water-supply demand patterns. Annual average withdrawals of 10 to 12 Mgal/d are possible for proposed demands of 3.4 Mgal/d in the Mishnock Basin, and for a constant annual instream-flow criterion of 0.5 cubic foot per second per square mile ($ft^3/s/mi^2$) at the four streamflow-constraint locations. An average withdrawal rate of 10 Mgal/d can meet estimates of future (2020) water-supply needs of surrounding communities in Rhode Island. This withdrawal rate represents about 13 percent of the average 2002 daily withdrawal from the Scituate Reservoir (76 Mgal/d), the State's largest water supply. Average annual withdrawal rates of 6 to 7 Mgal/d are possible for more stringent instream-flow criteria that might be used during dry-period hydrologic conditions. Two example scenarios of dry-period instream-flow constraints were evaluated: first, a minimum instream flow of 0.1 cubic foot per second at any of the four constraint locations; and second, a minimum instream flow of 10 percent of the minimum monthly streamflow estimate for each streamflow-constraint location during the period 1961–2000.

The State of Rhode Island is currently (2004) considering methods for establishing instream-flow criteria for streams within the State. Twelve alternative annual, seasonal, or monthly instream-flow criteria that have been or are being considered for application in southeastern New England were used as hypothetical constraints on maximum ground-water-withdrawal rates in management-model calculations. Maximum ground-water-withdrawal rates ranged from 5 to 16 Mgal/d under five alternative annual instream-flow criteria. Maximum ground-water-withdrawal rates ranged from 0 to 13.6 Mgal/d under seven alternative seasonal or monthly instream-flow criteria. The effect of ground-water withdrawals on seasonal variations in monthly average streamflows under each criterion also were compared. Evaluation of management-model results indicates that a single annual instream-flow criterion may be sufficient to preserve seasonal variations in monthly average streamflows and meet water-supply demands in the Big River Area, because withdrawals from wells in the Big River Area cause streamflow depletions for 6 months to a year and the minimum allowable depletion limits total withdrawals throughout the year.

Ground-water withdrawals from basins in Rhode Island typically increase during the months of May through October to meet increased water demands during the summer. Simulations that mimicked typical patterns of increased summer demands resulted in rates of average annual ground-water withdrawals from the basin that were about one-half of withdrawal rates without the seasonal constraint because peak water use during the summer season coincides with the period of lowest annual streamflows. Average annual withdrawals of about 6 Mgal/d

from the network of 13 ground-water wells were determined for these seasonal-demand patterns under an annually constant instream-flow criterion of 0.5 $ft^3/s/mi^2$.

If the well network is reduced to nine wells by eliminating three hypothetical wells in the Carr River Basin and one hypothetical well in the Big River Basin, ground-water withdrawals are reduced by about 13 percent, from 12 Mgal/d to 10.4 Mgal/d. These four wells were eliminated in the scenarios because results of previous simulations indicated that, for the condition of an annually constant instream-flow criterion of 0.5 $ft^3/s/mi^2$, none of these wells would produce the 1 Mgal/d that is considered necessary to recover the cost of installing and operating a production well. This alternative well network would not affect the natural streamflow regime in the Carr River upstream of Capwell Mill Pond and would minimize the potential effects of water-supply development in the upper reaches of the Big River and its tributaries.

Introduction

Water demand is increasing throughout Rhode Island, and the Rhode Island Water Resources Board (RIWRB), which is responsible for developing and protecting the State's major water resources, is concerned that increasing demand may exceed the capacity of current sources. In the early 1960s, the State proposed construction of a surface-water reservoir in the Big River Basin in central Rhode Island to meet these growing demands. At that time, the Big River Management Area (fig. 1), which covers about 13.4 mi^2, was established under the responsibility of the Water Resources Coordinating Board, forerunner of the RIWRB. To date (2004), the U.S. Environmental Protection Agency has not given approval for construction of this reservoir. In the meantime, the RIWRB would like to develop the largely untapped ground-water resources of the basin as a temporary alternative to a surface-water reservoir.

In 1998, the RIWRB initiated a technical and economic feasibility study to determine if development of ground-water resources of the Big River Area was necessary for future population growth and economic development in central Rhode Island (Beta Engineering, Inc., 1999). The results of that study indicated that there will be a potential need for more than 16 Mgal/d of additional water supply in central Rhode Island by the year 2020. Authors of the study also noted that water-supply development in the Big River Area could forestall supply limitations of the Scituate Reservoir, the State's largest water-supply source, by reducing water transfers from the reservoir to water-supply agencies in central Rhode Island such as the Kent County Water Authority (KCWA), which operates production wells in the Mishnock River Basin. For example, the study found that water use in the KCWA service area will grow to a total of about 16 Mgal/d by the year 2020, even if moderate water-conservation measures are put in place. The current average capacity of the KCWA wellfields, however, is only about 5 Mgal/d. The Scituate Reservoir, which supplied an average daily water demand of about 76 Mgal/d in 2002, currently has excess capacity to meet this future demand, but increasing water demand in other areas of Rhode Island may reduce the supply available to Kent County from this source (Beta Engineering, Inc., 1999; Socolow and others, 2003; 2004). Furthermore, availability of ground-water resources from the Big River Area may be necessary in the event of a water-supply emergency that affects other supplies.

In an effort to understand the hydrogeology and ground-water-development options for the Big River Area, the U.S. Geological Survey (USGS) and RIWRB began a cooperative study of the area in 1995. Three reports were published: the first report provided hydrogeologic data collected in the area from July 1996 through October 1998 (Craft, 2001); the second report described the glacial geology and hydraulic properties of the glacial sediments within the area (Stone and Dickerman, 2002); the third report described the hydrogeology of the area and simulated effects of selected ground-water-development options on streamflow in the area (Granato and others, 2003).

In the third report (Granato and others, 2003), steady-state and transient numerical models were developed to simulate ground-water flow, ground-water withdrawals, and interactions between the ground-water and surface-water systems. Ground-water supplies cannot be developed in the area without a reduction in streamflow. The effects of ground-water withdrawals on streamflow described in the third report were based on constant withdrawal rates of 1.0 Mgal/d at each simulated well throughout the year; total annual rates of withdrawal from all wells in the area ranged from 2.0 to 11.0 Mgal/d. These models, which are based on long-term average hydrologic conditions, provide the basis for development of the conjunctive-management model.

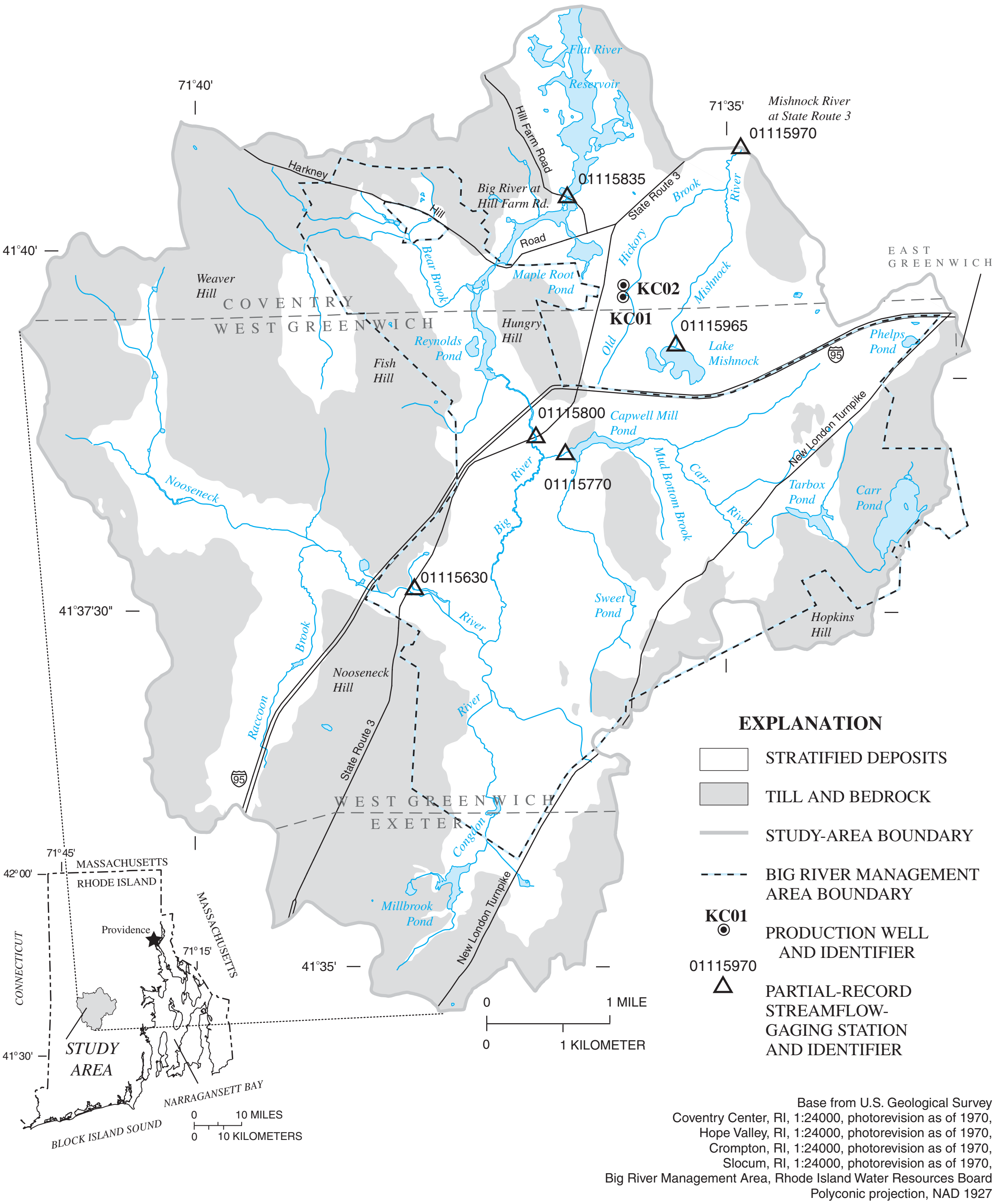

Figure 1. Location of the Big River Area, distribution of stratified sand and gravel deposits, and the boundary of the Big River Management Area, Rhode Island.

Purpose and Scope

This report demonstrates the potential effects of alternative instream-flow criteria and water-supply demands on ground-water-development options in the Big River Area, Rhode Island. The hydrogeology and previously developed numerical ground-water-flow models of the basin are briefly described, as well as a general description of the effects of ground-water withdrawals on streamflow. This background information is essential for understanding the results of the conjunctive-management models developed in this study. Potential instream-flow criteria and constraints on the design and operation of a ground-water-supply network are described. Conjunctive-management models were developed and applied to a number of hypothetical scenarios for the Big River Area. Results of the analysis may be used to help decisionmakers balance water-supply withdrawals with aquatic-habitat protection.

Streamflows presented in this report for streamflow-gaging stations in the Big River Area are estimated from partial-record-station data in each basin and data from long-term (40-year) continuous streamflow-gaging stations in nearby basins. The time period selected for analysis of streamflow statistics was January 1961 through December 2000. This 40-year period includes a wide range of hydrologic conditions (Walker, 1991), including a number of severe or extreme droughts (as defined by the National Climatic Data Center, 2003), as well as the entire period of ground-water withdrawals from the Mishnock River Basin.

In this report, the transient-simulation model developed for the Big River Area (Granato and others, 2003) was coupled with a linear optimization model to determine time-varying monthly withdrawal scenarios that meet ground-water-development goals and instream-flow criteria. The use of numerical-simulation and optimization techniques to determine and evaluate alternative strategies for simultaneous management of linked ground-water and surface-water systems is commonly referred to as "conjunctive management" in the hydrologic literature (Barlow and Dickerman, 2001a). In the context of this report, the term refers to the model that was developed with different definitions of streamflow requirements in selected streams to determine the ground-water-withdrawal patterns that would provide water supplies and sustain streamflows in the Big River Area to maintain aquatic and riparian ecosystems. The results of the study could help decisionmakers evaluate strategies for balancing ground-water development and streamflow reductions. Use of the term "conjunctive management," however, does not imply that the USGS recommends any specific instream-flow criteria or courses of action for management of the water resources of the Big River Area.

Location and Physiography

The Big River study area covers 35.7 mi^2 in the towns of Coventry, West Greenwich, Exeter, and a small part of East Greenwich, Rhode Island (fig. 1). The area includes the entire Big River Drainage Basin (30.9 mi^2), the part of the Mishnock River Drainage Basin (3.32 mi^2) that is upstream from a USGS partial-record streamflow-measurement site at State Route 3 (station 01115970; fig. 1), and a small area that drains directly to the Flat River Reservoir. The Big River drains to the north and is tributary to the east-flowing Flat River and South Branch of the Pawtuxet River (fig. 2). The primary tributaries of the Big River are the Congdon, Nooseneck, and Carr Rivers, and Bear Brook (fig. 1). The Big River flows into the Flat River Reservoir, which is controlled by a dam that maintains the reservoir's water level at an altitude of about 248 ft. The reservoir, which is connected to Maple Root Pond, floods the northern end of the Big River Basin. The reservoir is the largest surface-water body in the study area and is used for recreational purposes only. The Mishnock River originates at Lake Mishnock and flows northward through a large forested wetland called the Mishnock Swamp. Old Hickory Brook is a tributary to the Mishnock River. The Mishnock River joins the South Branch of the Pawtuxet River about 1 mi north of the partial-record site at State Route 3.

Most of the study area consists of woodlands and meadows. During the 1960s and 1970s, the State acquired land for construction of the proposed reservoir; as a consequence, most of the land is designated as open space and protected from development by State law. The study area is sparsely populated, with most of the population living along the Flat River Reservoir, Maple Root Pond, Lake Mishnock, and the upper reaches of tributaries to the Big River. Major roadways in the study area are State Route 3 and Interstate 95 (fig. 1).

Average annual precipitation measured at a climatological station in Kingston, RI, approximately 12 mi southeast of the center of the study area (fig. 2) was 50.3 in. during the period 1961–2000, and varied from 30.8 to 70.4 in. (National Oceanic and Atmospheric Administration, 2002). Monthly total precipitation measurements ranged from 0.05 to 14.4 in. The average monthly precipitation was 4.2 in. during the 1961–2000 period and was fairly evenly distributed throughout the year, within a range of 3.2 to 5.1 in. Average annual air temperature at the climatological station was 49.6°F during the 1961–2000 period, and monthly average temperatures ranged from 28.3°F in January to 70.7°F during July.

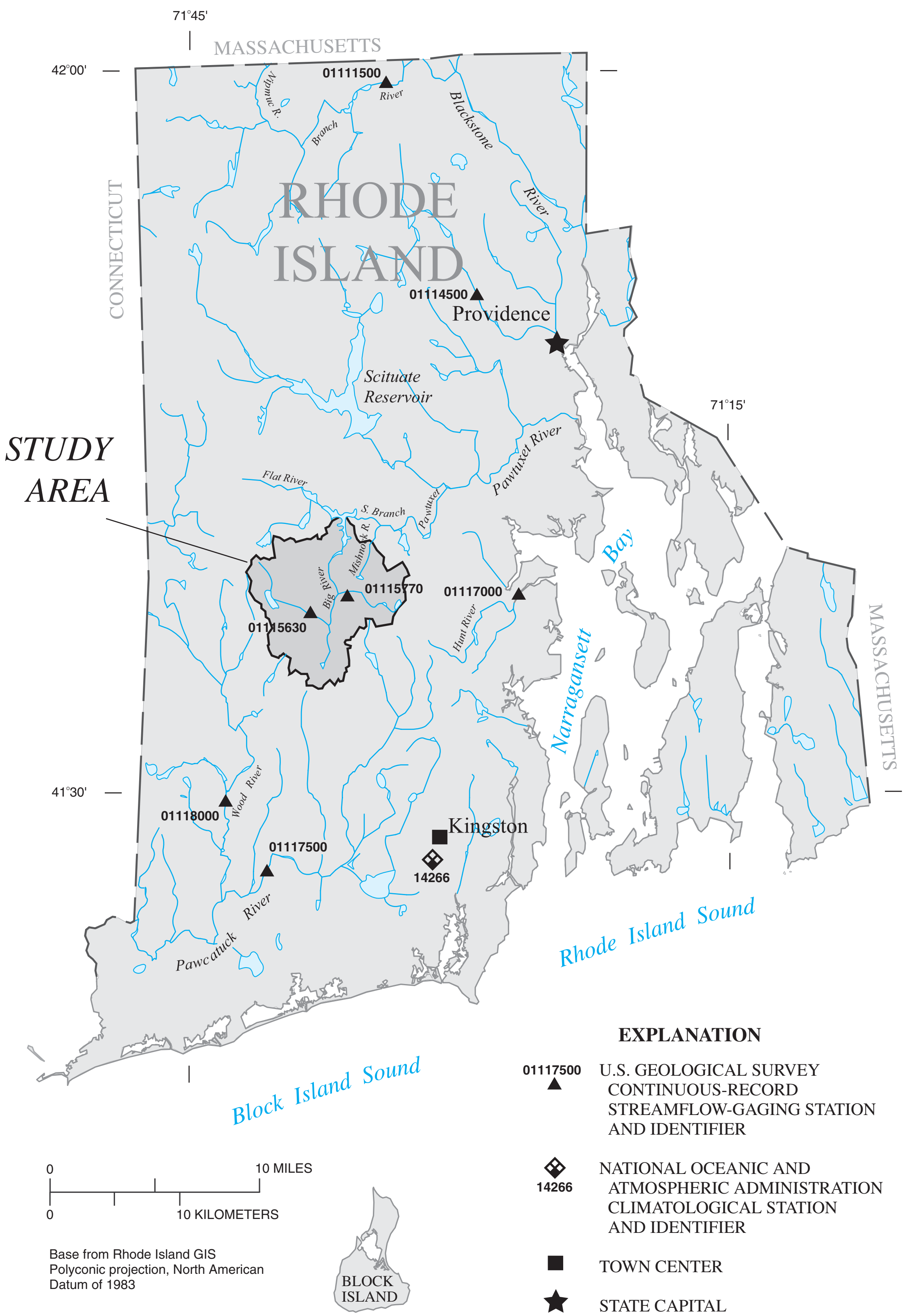

Figure 2. Location of U.S. Geological Survey continuous-record streamflow-gaging stations and a National Oceanic and Atmospheric Administration climatological station used to estimate hydrologic conditions in the Big River Area, Rhode Island.

Hydrogeology

The three major hydrogeologic units in the study area are glacial stratified deposits, glacial till, and bedrock. The distribution of these hydrogeologic units is shown on figure 1. The stratified sediments are composed of gravel, sand, silt, and clay that were carried away from the glacial ice front by meltwater streams. Thick coarse-grained stratified sediments that consist of highly transmissive fine sand to coarse gravel have the capacity to yield large quantities of water to wells, and form the principal (or surficial) aquifer in the study area. Hydraulic conductivity of the surficial aquifer has been estimated to range from 94 ft/d to 600 ft/d at six aquifer-test sites within the study area (Stone and Dickerman, 2002). Vertical hydraulic conductivity of the aquifer at these sites ranged from 0.9 to 39.4 ft/d. The estimated ratio of horizontal to vertical hydraulic conductivity ranged from 5:1 to 125:1. The specific yield of the aquifer is estimated to range from about 0.16 to 0.39 on the basis of measurements made in similar deposits in the Pawcatuck River Basin to the south of the study area (Allen and others, 1963).

The surficial aquifer is unconfined and in most places is in hydraulic connection with streams, ponds, and wetlands. The most transmissive parts of the surficial aquifer lie within a 10.9-mi^2 area that is the focus of this investigation. The area is shown on figure 3 as the active area of the simulation models. The saturated thickness of the aquifer within this area is estimated to be 10 ft or greater (Granato and others, 2003). The aquifer is recharged by precipitation, natural stream leakage, ground-water inflow from adjacent till and bedrock uplands, and locally by septic-system discharge. Recharge from precipitation is estimated to average 26.4 in/yr in the study area, with average monthly rates that ranged from 0.6 in. for September to 4.2 in. for March for the 1964–98 period. Ground water leaves the aquifer by direct discharge to streams, ponds, and wetlands; by evapotranspiration; by underflow to adjacent flow systems; and through withdrawal at two production wells owned and operated by the Kent County Water Authority (wells KC01 and KC02, figs. 1 and 3).

Ground water moves through the surficial aquifer in the direction of decreasing water levels. Within the 10.9-mi^2 model-focus area, ground-water levels range from a maximum of about 360 ft above NVGD 1929 in the southern part of the study area to a minimum of about 240 ft above NVGD 1929 along the Mishnock River at State Route 3 (fig. 3). The general direction of ground-water flow in the Big River Valley is eastward from the till and bedrock uplands on the western side of the basin and northward toward the Flat River Reservoir. In the Carr and Mishnock River Valleys, ground-water flow generally is westward from the eastern side of the study area and northeast toward the Mishnock River outflow point at State Route 3. Water-table contours shown on figure 3 indicate that ground-water flow in the Big River Valley is largely independent of flow in the Carr and Mishnock River Valleys because of the presence of a northwest-to-southeast-trending bedrock ridge that extends from Hungry Hill towards Capwell Mill Pond and continues southward through the unnamed hill south of the pond. The water-level contours shown in figure 3 were calculated with the steady-state model of the study area and are similar to those drawn on the basis of field measurements and reported in Granato and others (2003).

Numerical Models of the Big River Area

Steady-state and transient numerical models were developed to simulate ground-water flow and interactions between ground water and surface water in the Big River study area (Granato and others, 2003). The numerical models were developed with the USGS finite-difference ground-water-flow computer code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) and the associated streamflow-routing package (Prudic, 1989). The steady-state model simulates average hydrologic conditions within the aquifer that do not change with time, whereas the transient model simulates an average annual cycle of monthly hydrologic stresses. Models were calibrated to ground-water levels and streamflows in the basin that were representative of average withdrawal and hydrologic conditions during the 35-year period 1964–98. The calibrated model described by Granato and others (2003) was used in the current study because the hydrologic conditions for the 35-year period were similar to those of the 1961–2000 period that was used in this study in the development of representative streamflow statistics for the study area.

The numerical models consist of a three-dimensional grid of cells composed of 5 layers, 216 rows, and 204 columns (Granato and others, 2003). The grid is aligned in the north-south direction and is parallel to the north-trending valleys of the Congdon, Big, and Mishnock Rivers (fig. 4). The areal extent of the active area of the model—that is, the area of the model in which ground-water heads are simulated—is 10.9 mi^2. Horizontally, all cells have a uniform dimension of 200 ft on each side. The model extends vertically downward from the water table to the contact between the surficial aquifer and underlying bedrock. Flow within the bedrock, which is the lower boundary of the model, is assumed to be negligible; all recharge, therefore, is accounted for within the surficial aquifer. Individual cells range in thickness from about 3 ft to about 40 ft.

Values of horizontal hydraulic conductivity simulated in the model are 300 ft/d for buried sand and gravel, 200 ft/d for sand and gravel, 105 ft/d for sand, and 15 ft/d for fine deposits (very fine sand, silts, and clay). The ratio of horizontal to vertical hydraulic conductivity for buried sand and gravel, sand and gravel, and sand is 10:1 and for fine deposits is 50:1. Uniform values of 0.28 and 3.0 x 10^{-4} are specified for the specific yield and storage coefficient of the sediments, respectively, in the transient model. A specific yield of 1.0 is specified for the simulated ponds, lakes, and reservoirs.

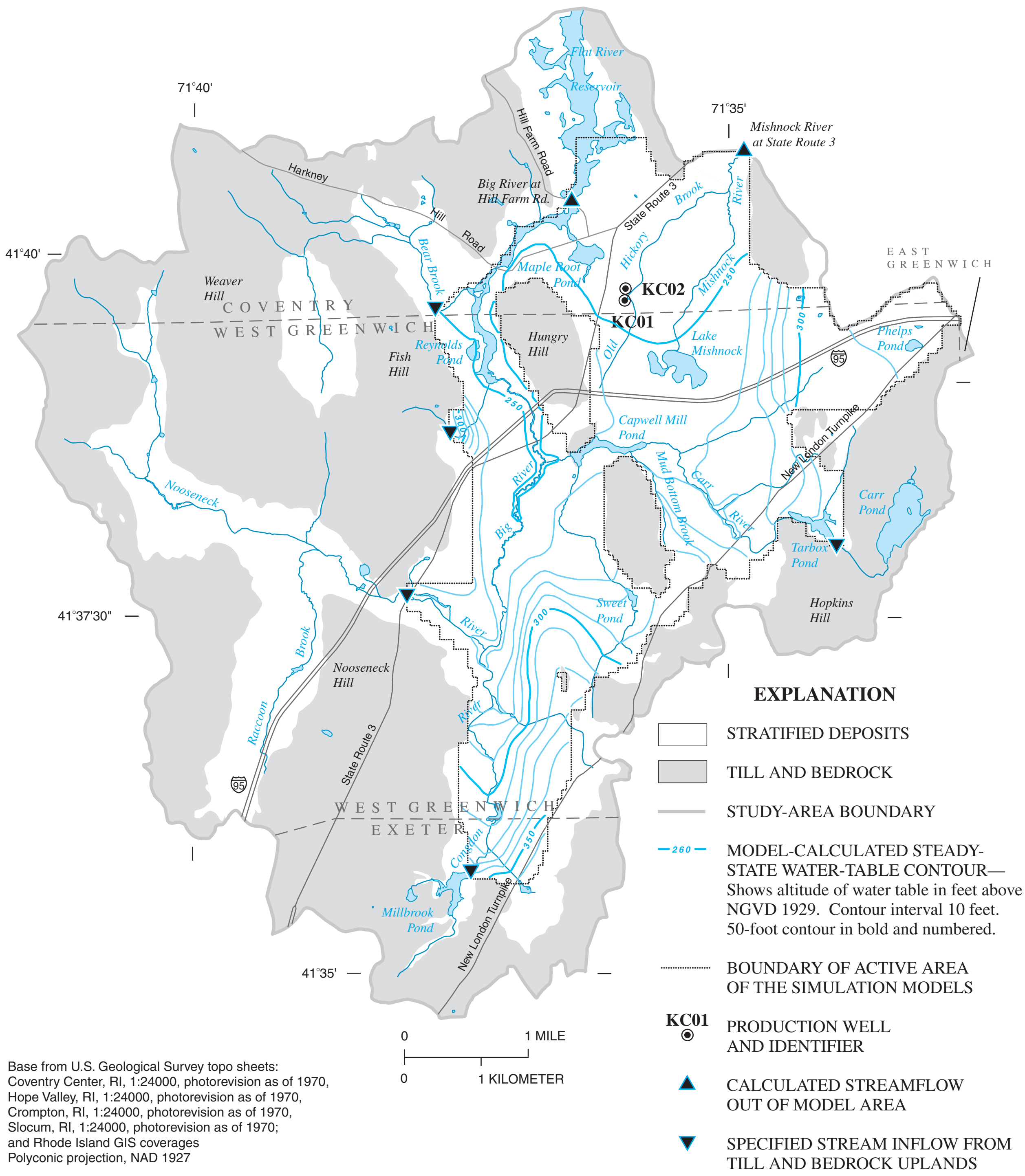

Figure 3. Spatial extent of the study area, active area of simulation model, specified stream-inflow locations, and location of model-calculated streamflows out of the Big River Area, Rhode Island.

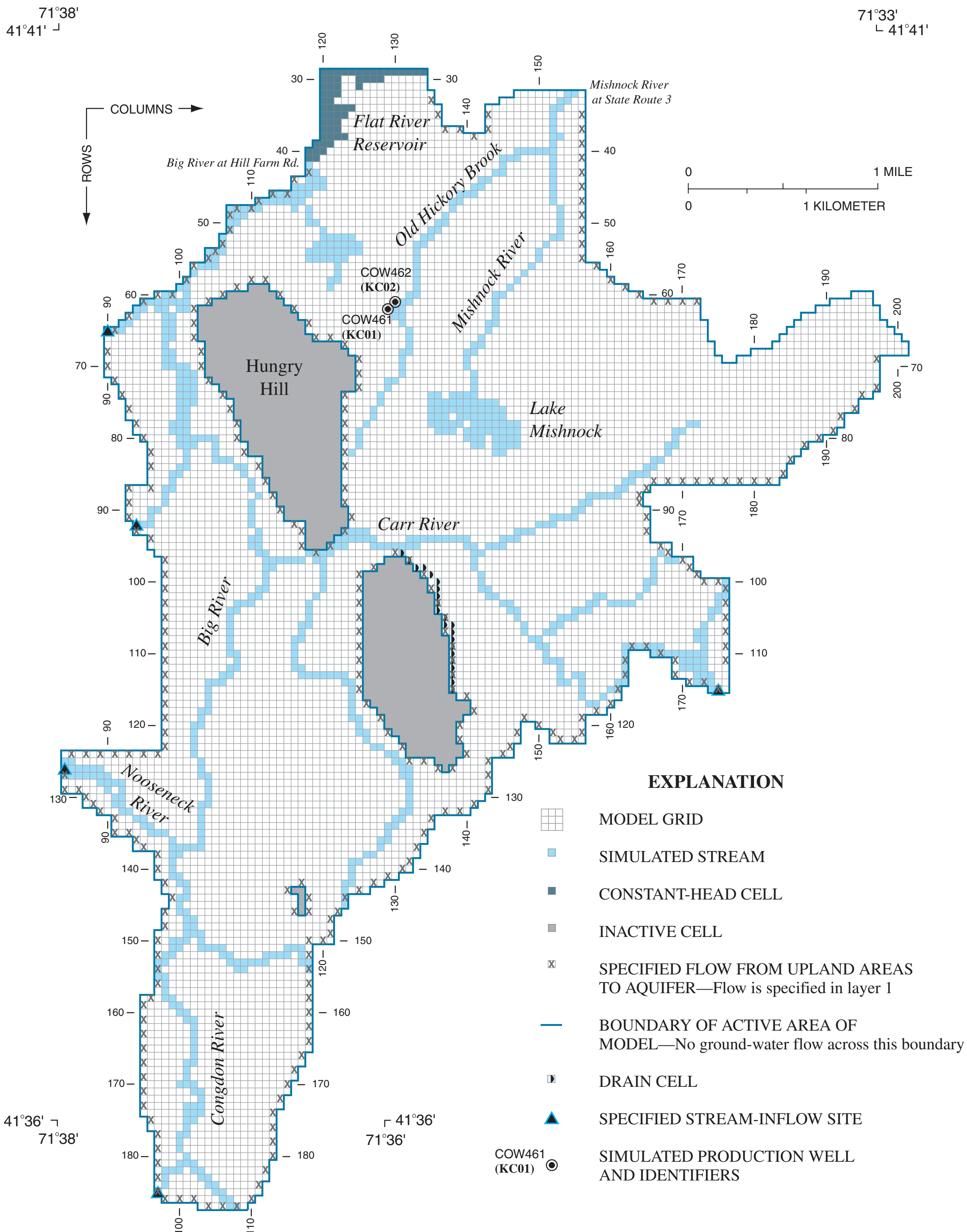

Figure 4. Grid and boundary conditions of the active model cells for the simulation model of the Big River Area, Rhode Island.

Several types of boundary conditions were used to simulate inflows and outflows of water to and from the modeled area (table 1). The sources of water to the model are recharge, streamflow from upland areas, and lateral ground-water inflow. Recharge was specified for the uppermost layer of the model (layer 1), which is the water table. Recharge in the study area consists of two components. The largest component is from precipitation, and is estimated to be 26.4 in/yr in all areas of the model except those overlain by ponds and lakes, where recharge was estimated to be about 22.3 in/yr. Total simulated precipitation recharge to the model was 20.9 ft^3/s for average steady-state conditions. The second component of recharge is wastewater return flow in seven small unsewered areas of the model that are on public water supplies. Total estimated wastewater recharge was 0.4 ft^3/s. Streamflow into the model from upland areas of till and bedrock was simulated at five locations shown on figures 3 and 4. Total steady-state flow into the model at these five locations was estimated to be about 30.1 ft^3/s. Lateral ground-water inflow from upland areas also was simulated at the cells shown with an "x" along the perimeter of the model area on figure 4; total inflow along the lateral boundaries was 15.7 ft^3/s. Total model-calculated steady-state inflow to the model area from all sources, therefore, was 67.1 ft^3/s.

Water leaves the modeled area by four processes: streamflow out of the basin at the Big and Mishnock Rivers, evapotranspiration from the water table, ground-water withdrawals, and ground-water underflow to adjoining areas in the surficial aquifer. The largest component of outflow is to the Big and Mishnock Rivers, which receive drainage from all upstream sources. Streams that are simulated in the models are shown in figure 4. Total calculated average stream outflow in the streams was 61.5 ft^3/s, of which 54.6 ft^3/s was from the Big River, 6.7 ft^3/s was from the Mishnock River, and 0.2 ft^3/s was from direct ground-water discharge to the Flat River Reservoir. Evapotranspiration directly from the water table was calculated to be 3.4 ft^3/s, or about 5 percent of the total inflow to the modeled area. Simulated average annual ground-water withdrawals from production wells KC01 and KC02 in the modeled area were 2.2 ft^3/s (1.0 ft^3/s at KC01 and 1.2 ft^3/s at KC02). A small amount of ground-water underflow (0.1 ft^3/s) was estimated for the northern boundary of the model near where the Mishnock River leaves the basin, but was not simulated in the models. Total model-calculated steady-state outflow from the model area from all sources, therefore, was 67.1 ft^3/s.

Granato and others (2003) did a sensitivity analysis of the models and found that model results may be limited by the quantity and quality of input data. Calculated ground-water levels and streamflows are affected by estimates of recharge, horizontal and vertical hydraulic conductivity, and the estimated specific yield of aquifer materials. Calculated streamflows are most sensitive to variations in values specified for recharge.

Table 1. Model-calculated steady-state and transient average annual hydrologic budgets for the Big River Area, central Rhode Island.

[Modified from Granato and others, 2003. Does not include direct runoff (about 8.3 cubic feet per second) in model area. Budget components are in cubic feet per second, and in parentheses, million gallons per day]

Hydrologic budget component	Steady-state model budget		Transient-model budget	
Estimated inflow				
Ground-water recharge from:				
Precipitation	20.9	(13.5)	20.9	(13.5)
Wastewater-return flow	.4	(.3)	.4	(.3)
Streamflow from uplands	30.1	(19.5)	30.1	(19.5)
Lateral ground-water inflow	15.7	(10.1)	15.7	(10.1)
Total inflow	67.1	(43.4)	67.1	(43.4)
Estimated outflow				
Streamflow	61.5	(39.7)	61.2	(39.6)
Evapotranspiration	3.4	(2.2)	3.4	(2.2)
Ground-water withdrawal	2.2	(1.4)	2.2	(1.4)
Total outflow	67.1	(43.4)	66.8	(43.2)
Budget error (inflow–outflow)	0.0	(0.0)	0.3	(0.2)

Streamflow Response to Ground-Water Withdrawals

The physical response of streamflow to ground-water withdrawals at pumping wells determines the withdrawal strategies that may be used to balance ground-water withdrawals needed for water supply and aquatic-habitat protection goals. The interaction of a typical stream in the Big River study area with underlying ground water is shown schematically in figure 5. Under conditions of no ground-water withdrawals (the natural condition shown in fig. 5*A*), most of the water that is recharged to the aquifer eventually discharges to streams and other surface-water bodies. This discharge occurs at the bottom of the streambed, where ground-water levels are higher than water levels in the stream. The hydraulic gradient toward the stream causes ground water to seep through the streambed and into the stream. The stream is referred to as gaining because there is a gain of water from ground-water discharge. There also may be a small amount of additional ground-water discharge from the aquifer caused by evaporation and transpiration in the riparian zone near the stream where the water table is close to the land surface. Such riparian evapotranspiration has been found to be about 5 to 10 percent of total aquifer recharge in southern Rhode Island and southeastern Massachusetts (Bent, 1995; Barlow, 1997; Dickerman and others, 1997).

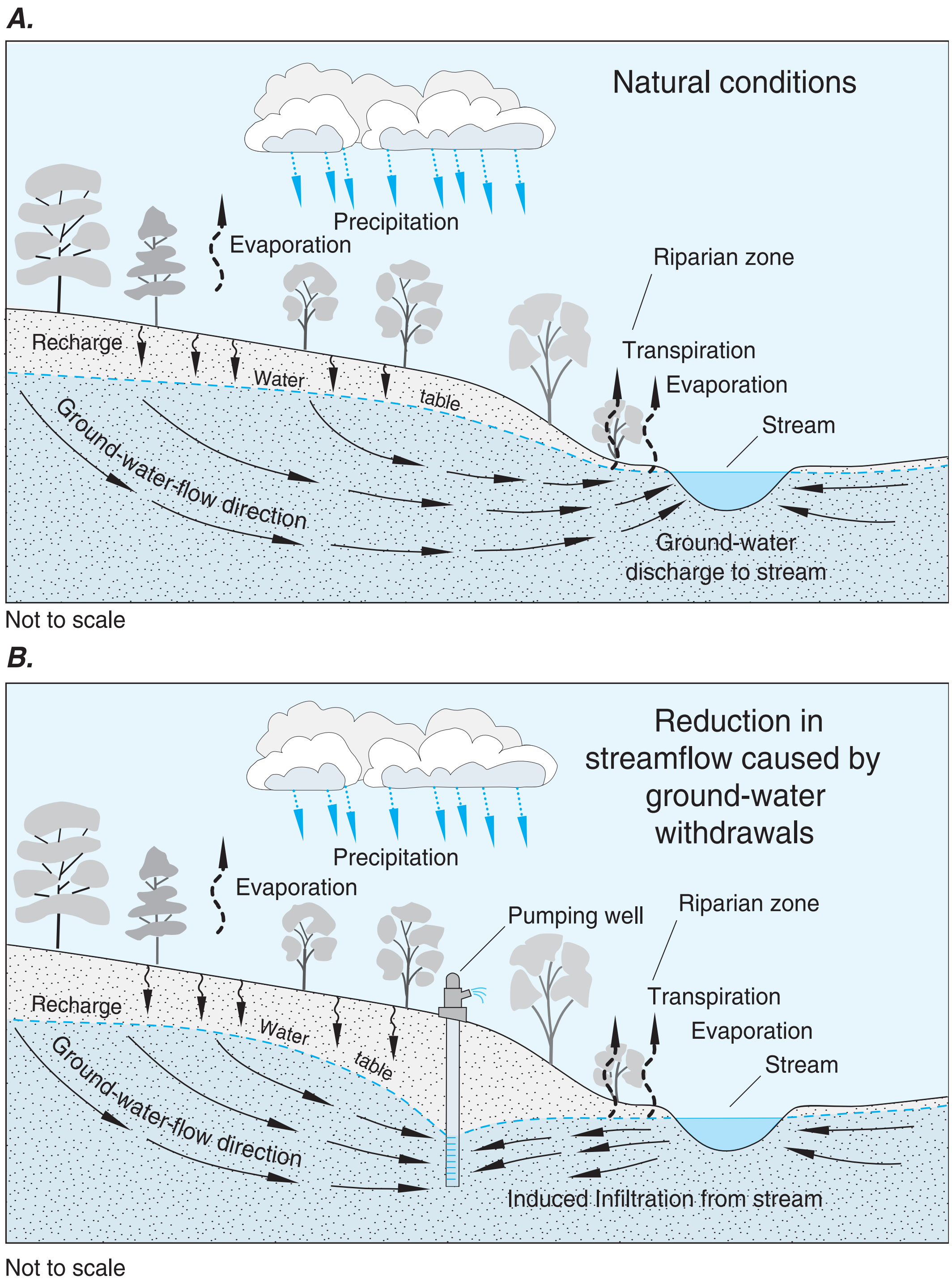

Figure 5. Ground-water flow to a stream in the Big River Area, Rhode Island, illustrating *A*, natural conditions; and *B*, reductions in streamflow caused by ground-water withdrawals.

With the initiation of ground-water withdrawals, ground-water levels in the aquifer are lowered and the direction of ground-water flow near the well is altered (fig. 5*B*). Some of the ground water that flowed to the stream in the absence of withdrawals is now captured by the well and, if the pumping rate is large enough, streamflow can be drawn into the aquifer (a process called induced infiltration) and possibly captured by the well. The net effect of these two processes (captured ground-water discharge and induced infiltration) is to reduce the amount of streamflow. Reductions in streamflow caused by ground-water withdrawals are referred to as streamflow depletions, and the source of water to the well is referred to as streamflow capture.

The hydrologic conditions near the pumping well and stream illustrated in figure 5*B* are those that occur after a period of time that is long enough for the hydrologic system to stabilize to the pumping rate of the well. There is, however, a period of time between the initiation of pumping and stabilization of the hydrologic system during which some or all of the water captured by the well consists of ground water released from aquifer storage. The transition from the predominance of ground-water storage to the predominance of streamflow capture as the source of water to the well is illustrated by the graph in figure 6. At the start of pumping, all of the water pumped by the well comes from ground-water storage. With time, as the hydrologic system stabilizes to the pumping stress, the dominant source changes from water released from aquifer storage to streamflow capture. In the long term, the amount of streamflow capture approaches the quantity of water pumped from the well. For example, the transition time for wells pumping in the Big River Area lasts from a few days to several months.

An important implication of figure 6 is that the amount of streamflow depletion does not equal the pumping rate from the well immediately after pumping begins. Moreover, streamflow depletion does not cease immediately after pumping stops. This is illustrated by the two curves in figure 7, which show the amount of streamflow depletion that occurs with time in response to pumping at two hypothetical wells located 250 ft (well A) and 1,000 ft (well B) from a stream. The curves are based on concepts of streamflow depletion discussed by Jenkins (1968) and Barlow (1997). Each well is pumped independently at a rate of 1.0 Mgal/d for a period of 180 days and is then turned off. After 180 days of pumping, the streamflow-depletion rate caused by well A, which is closest to the stream, is about 95 percent of the withdrawal rate of the well, whereas that caused by well B is only 70 percent. After pumping stops, the streamflow-depletion rate caused by well A quickly decreases to about 0.1 Mgal/d, which is less than 10 percent of the withdrawal rate of the well, after about 25 days without pumping (day 205). The decrease in the rate of streamflow depletion in response to well B being turned off, however, is much slower, with the streamflow-depletion rate remaining at about 0.1 Mgal/d (about 10 percent of the withdrawal rate of the well) even after 150 days without pumping (day 330). The maximum streamflow-depletion rate occurs about 3 to 4 days after well B is turned off because of the distance from the well to the stream (fig. 7).

The key point to the graphs shown on figures 6 and 7 that affects results of the ground-water development scenarios evaluated in this report is that there is a delay in the response of a stream to the initiation or cessation of pumping at a well. The magnitude of the delay is a function of several variables, including the three-dimensional structure and hydraulic properties of the aquifer, the distribution and hydraulic properties of streambed materials, the depth of penetration of the stream and well into the aquifer, and the distance of the well from the stream.

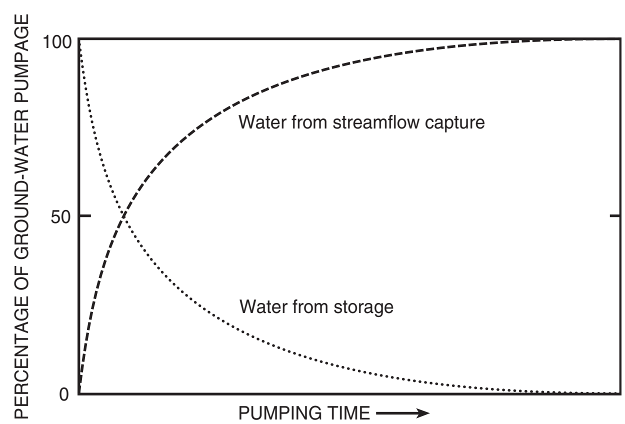

Figure 6. Sources of water to a well as a function of pumping time.

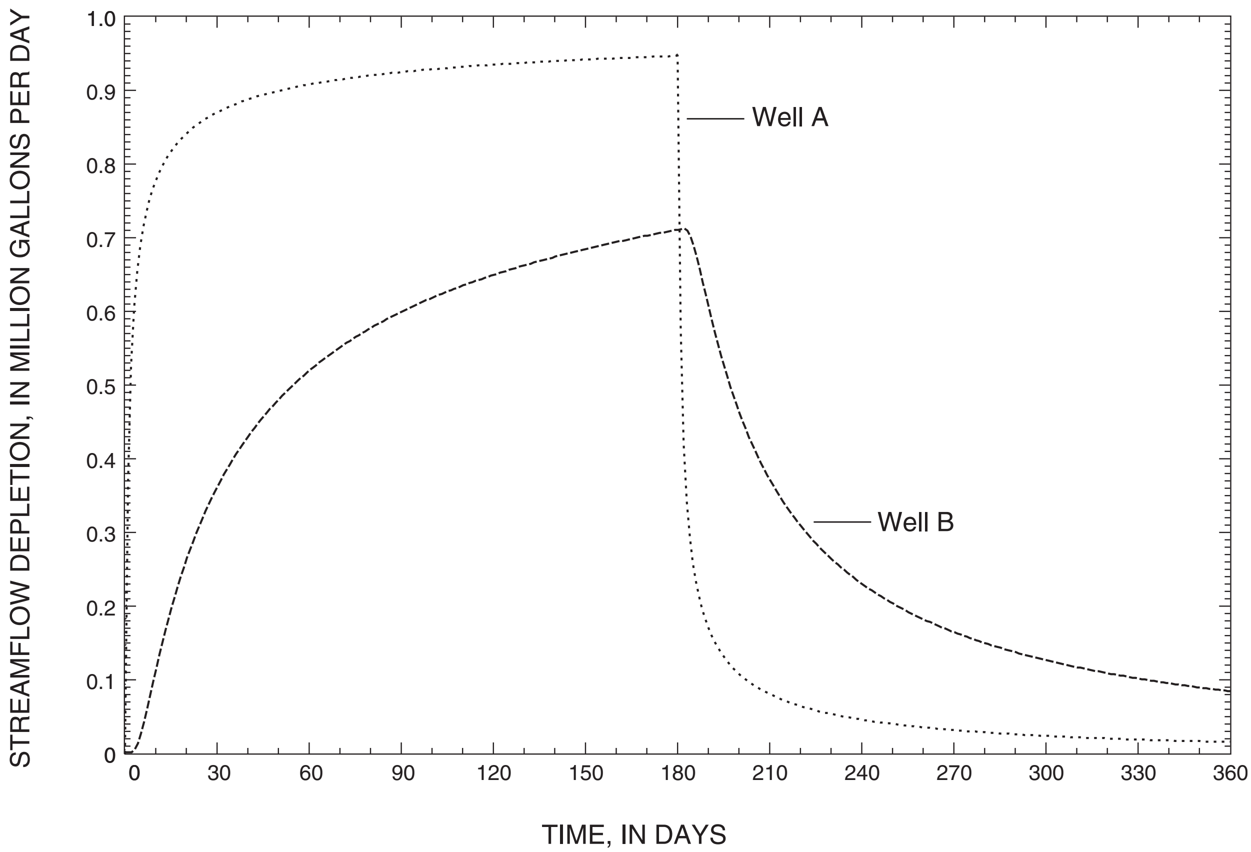

Figure 7. Hypothetical streamflow depletion caused by two wells pumping independently for 180 days at 1.0 million gallons per day. Well A is 250 feet from the streambank and well B is 1,000 feet from the streambank (modified from Barlow, 1997).

Streamflow and Instream-Flow Criteria Applied to Basins in the Big River Area

Estimates of streamflow and definitions of instream-flow criteria are necessary to determine potential water availability in the Big River Area within the constraints of maintaining streamflows that support aquatic habitat. Streamflow was estimated and different instream-flow criteria were applied to four sites of interest in the study area. Estimates of streamflow are critical for this analysis because instream-flow criteria that have been proposed or applied for use in New England are based on the assumption that the quality of riparian and aquatic habitat depends on available streamflows (Armstrong and others, 2004).

Estimated and Simulated Streamflow

Streamflow was not measured continuously on any stream in the Big River Area during the entire 1961–2000 study period. Therefore, it was necessary to estimate streamflows at sites in the basin by correlating measurements collected in the Big River Area with streamflow data collected in nearby basins. The Lake Mishnock Outflow (station 01115965), the Mishnock River at State Route 3 (station 01115970), the Carr River below Capwell Mill Pond (station 01115770), and the Big River at Hill Farm Road (station 01115835) were selected for estimation of the potential effects of ground-water withdrawals in the basin (fig. 1). Records from the Big River at State Route 3 (station 01115800) were used to calculate a drainage-area-ratio estimate of streamflow in the Big River at Hill Farm Road (station 01115835). The Nooseneck River (station 01115630) was selected for use in verification of streamflow estimates for partial-record stations because of the availability of continuous-streamflow records at this station for the period 1964–81.

Correlations between streamflow data from long-term (40-year) continuous-record streamflow-gaging stations near the study area (table 2, fig. 2) and data collected at partial-record streamflow-gaging stations (table 3) were made for the purpose of estimating streamflows and streamflow statistics at selected points within the Big River Area for the period 1961–2000. These correlations were made with the method of maintenance of variance extension, type 1 (MOVE.1) (Hirsch, 1982). The MOVE.1 method, otherwise known as the line of organic correlation, is a regression procedure that minimizes the sum of the areas of right triangles formed by horizontal and vertical lines extending from observations to the fitted line, and so minimizes the effect of uncertainties in both the independent and dependent variables. The Branch River at Forestdale, RI (station 01111500), Woonasquatucket River at Centerdale, RI (station 01114500), Hunt River near East Greenwich, RI (station 01117000), Pawcatuck River at Wood River Junction, RI (station 01117500), and the Wood River at Hope Valley, RI (station 01118000), were selected for analysis from among all the continuous-record streamflow-gaging stations in Rhode Island because these stations are generally unregulated and have a complete and continuous record of daily average flows for the period from January 1961 through December 2000.

Table 2. Summary statistics for streamflow-gaging stations in Rhode Island that have a continuous period of record for January 1961 through December 2000.

[Drainage areas and percentage stratified deposits from Zarriello and Socolow, 2003. Station locations shown on figure 2. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile]

Station identification number	Station name	Drainage area (mi^2)	Percentage of sand and gravel deposits	1996–98 Average annual flow (ft^3/s)	1996–98 Average annual flow per unit area ($ft^3/s/mi^2$)	1961–2000 Average annual flow (ft^3/s)	1961–2000 Average annual flow per unit area ($ft^3/s/mi^2$)
01111500	Branch River at Forestdale	91.2	5.8	207	2.27	179.6	1.97
01114500	Woonasquatucket River at Centerdale	38.3	22	88.5	2.31	75.3	1.97
01117000	Hunt River near East Greenwich	22.9	51	56.0	2.45	48.5	2.12
01117500	Pawcatuck River at Wood River Junction	100	44	226	2.26	199	1.99
01118000	Wood River at Hope Valley	72.4	25	177	2.44	158	2.18

Table 3. Partial-record streamflow-gaging stations, streamflow statistics for the 1996–98 data-collection period, and estimates of associated streamflow statistics during the 1961–2000 period in the Big River Area, central Rhode Island.

[Twenty-eight instantaneous streamflow measurements made between July 1996 and October 1998. Streamflows estimated without ground-water withdrawals were calculated by adding the monthly streamflow depletion, which is based on ground-water withdrawal records, to measured or estimated streamflows. Station locations shown on figure 1. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile; --, not applicable]

Station identification number	Station name	Drainage area (mi^2)	Percentage of sand and gravel deposits	Streamflow measured during 1996–98 Range (ft^3/s)	Streamflow measured during 1996–98 Average (ft^3/s)	Streamflow measured during 1996–98 Average per unit area ($ft^3/s/mi^2$)	MOVE.1 estimate of streamflow during the 1961–2000 period Average (ft^3/s)	MOVE.1 estimate of streamflow during the 1961–2000 period Average per unit area ($ft^3/s/mi^2$)
01115630	Nooseneck River near Nooseneck	8.23	30	1.96–44.6	16.0	1.94	16.6	2.02
01115770	Carr River below Capwell Mill Pond	7.33	63	0.94–28.9	11.1	1.51	12.7	1.73
01115800	Big River at State Route 3	23.1	47	5.83–121	41.0	1.77	44.1	1.91
01115835[1]	Big River at Hill Farm Road	30.88	42	--	--	--	59.0	1.91
01115965	Lake Mishnock Outflow near Washington	.29	90	2.28–8.33	3.82	13.2	3.96	13.7
	Estimated streamflows without ground-water withdrawals			2.41–8.45	3.96	13.6	4.08	14.1
01115970	Mishnock River at State Route 3	3.32	86	2.43–12.9	6.40	1.93	6.70	2.02
	Estimated streamflows without ground-water withdrawals			3.28–13.6	7.18	2.16	7.44	2.24

[1]Flows at station 01115835 estimated by the drainage-area-ratio method from station 01115800.

Of the five continuous-record streamflow-gaging stations initially selected, three stations—Hunt River near East Greenwich, RI, Pawcatuck River at Wood River Junction, RI, and the Wood River at Hope Valley, RI (table 4)—had records that correlated best with the partial-record streamflow measurements collected in the study area during 1996–98. Their correlation coefficients with measurements from the Nooseneck River, Carr River , Big River, and Mishnock River partial-record stations were greater than 0.95 and were highly correlated with the Lake Mishnock Outflow (table 4). Correlations between streamflows at the continuous-record stations and streamflows at the Lake Mishnock Outflow are lower than correlations for the other partial-record sites because the hydrology of the Hunt, Pawcatuck and Wood River systems is different from the hydrology of Lake Mishnock. Natural ground-water underflow from the Carr River Basin to Lake Mishnock augments streamflow and dampens seasonal variability in streamflows at the Lake Mishnock Outflow (Granato and others, 2003).

MOVE.1 estimates of daily flows during the period 1961–2000 were used to calculate streamflow statistics necessary to characterize historical streamflows. MOVE.1 estimates of average monthly and median monthly streamflows for the Nooseneck River and the Carr River for the 1961–2000 period are comparable to statistics for continuous-record streamflows measured during the period 1964–79 at these sites (figs. 8*A* and 8*B*, respectively). An estimate of the long-term mean monthly streamflow for the Big River at State Route 3 was based on an area-weighted average of streamflow in the Nooseneck and Carr River tributaries (fig. 8*C*). Ries and Friesz (2000) determined that use of this type of drainage-area ratio to estimate streamflows at different places along a stream was an accurate streamflow-estimation method if the drainage area at the site of interest was between 0.3 and 1.5 times the drainage area of the data-collection site. The MOVE.1 estimates for the Big River compare favorably to the area-weighted estimates based on the continuous record for 1964–79 from the Nooseneck and Carr River tributaries. This result also indicates that MOVE.1 estimates at partial-record stations can be extrapolated by use of the drainage-area ratio method (fig. 8). The Big River at Hill Farm Road, designated as station 01115835 in table 3, is the surface-water-outflow point from the Big River Basin to the Flat River Reservoir (figs. 1, 3). Extrapolation by drainage area is necessary to estimate streamflows at this site because the river is in the backwater of the reservoir. Therefore, streamflows at the Big River at Hill Farm Road (station 01115835), with a drainage area of 30.88 mi^2, were estimated from the data collected for the Big River at State Route 3 (station 01115800), with a drainage area of 23.1 mi^2 (fig. 1).

Streamflow in the Mishnock River Basin has been reduced by ground-water withdrawals at the two KCWA wells (Granato and others, 2003). Estimates of streamflow unaffected by withdrawals for the period 1961–2000 in the Mishnock River Basin were calculated by adding estimated streamflow depletions to the partial-record measurements before applying the MOVE.1 analysis. Estimates of average daily streamflow, which were calculated for the 1996–98 data-collection period by subtracting estimated monthly streamflow depletions from the MOVE.1 estimated streamflows without withdrawals, are comparable to instantaneous streamflow measurements made at this site (fig. 9). Simulation results (Granato and others, 2003) indicate that streamflows in the Carr River and the Big River at State Route 3 are not affected by KCWA ground-water withdrawals. MOVE.1 streamflow estimates for the period 1961–2000 were calculated with unadjusted partial-record data for these two streamflow-gaging stations. Granato and others (2003) also indicate that streamflow in Big River at Hill Farm Road was affected by KCWA ground-water withdrawals. Streamflow at this station, however, was estimated by drainage-area ratio from measured partial-record data collected on the Big River at State Route 3, and, thus, reflects conditions without KCWA ground-water withdrawals at this site.

Table 4. Correlation coefficients for log-transformed streamflow data from selected continuous-record streamflow-gaging stations and selected partial-record streamflow-gaging stations monitored during the period 1996–98 in the Big River Area, central Rhode Island.

Station identification number	Station name	Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Nooseneck River near Nooseneck (01115630)	Carr River below Capwell Mill Pond (01115770)	Big River at State Route 3 (01115800)
01111500	Branch River at Forestdale	0.588	0.875	0.892	0.844	0.848
01114500	Woonasquatucket River at Centerdale	.582	.872	.889	.863	.875
01117000	Hunt River near East Greenwich	.743	.968	.953	.963	.964
01117500	Pawcatuck River at Wood River Junction	.756	.955	.958	.962	.970
01118000	Wood River at Hope Valley	.786	.958	.987	.965	.990

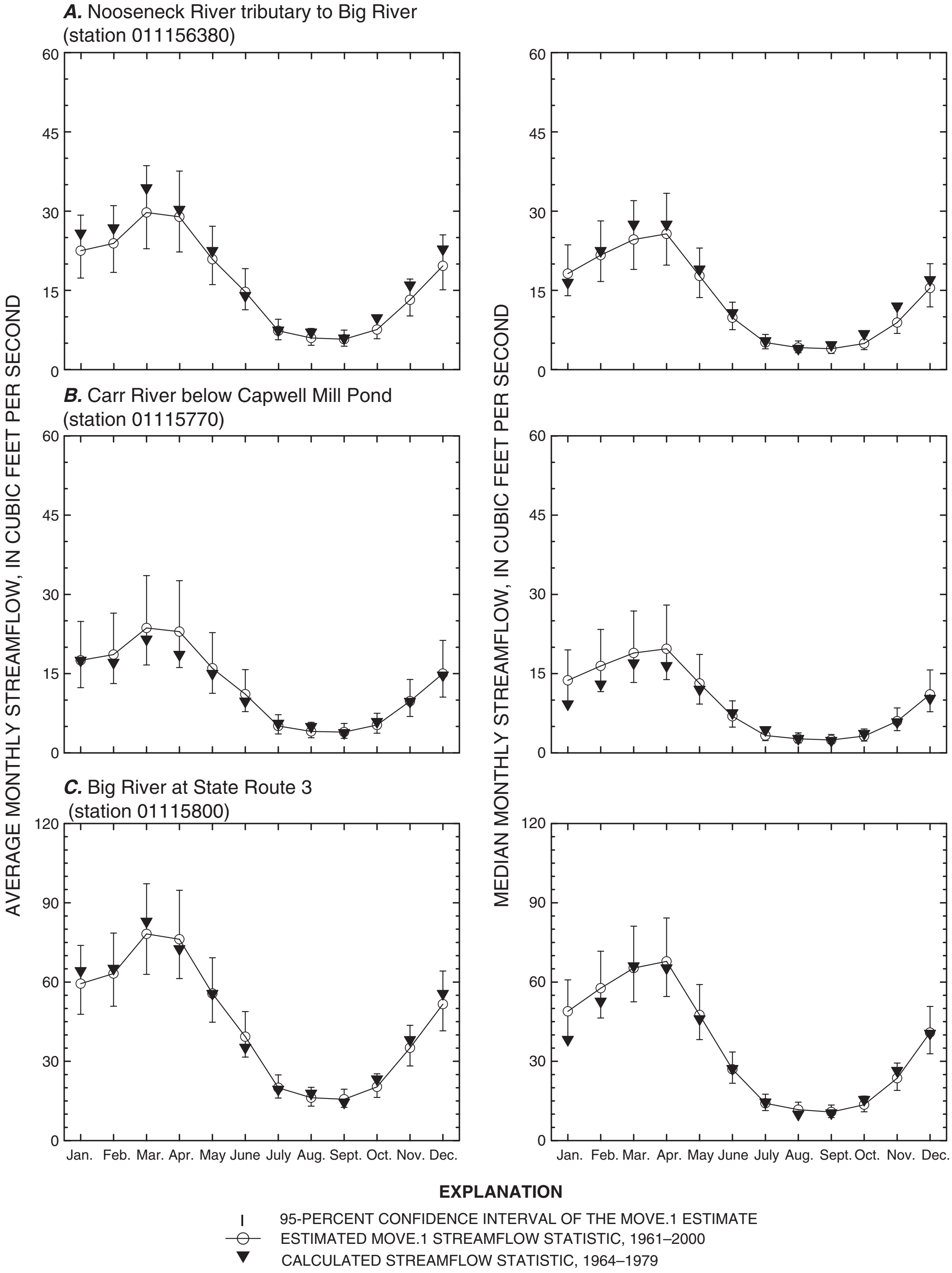

Figure 8. Estimated monthly streamflow statistics at the Nooseneck River, Carr River, and Big River partial-record streamflow-gaging stations, Rhode Island, during the period 1961–2000 compared to calculated monthly flow statistics from the 1964–79 period. Calculated statistics for the *A*, Nooseneck River; and *B*, Carr River stations are based on continuous-record streamflow measurements made during the 1964–79 period. Calculated statistics for the *C*, Big River are based on an area-weighted estimate of calculated monthly streamflow statistics from the Nooseneck River and Carr River tributaries. (Station-identification information listed in table 3. Locations of stations shown on figure 1.)

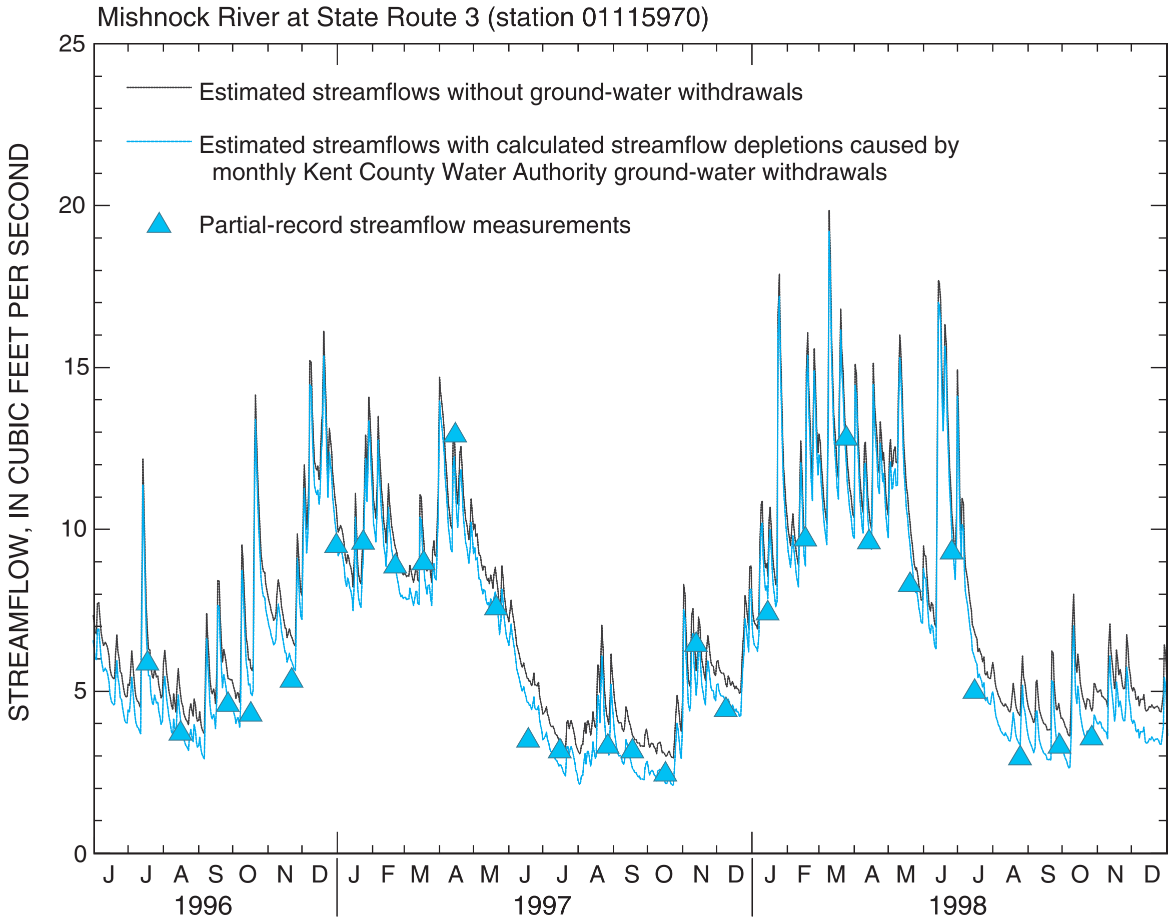

Figure 9. Estimated average daily streamflows in the Mishnock River at State Route 3 (station 01115970) with and without depletions caused by documented monthly ground-water withdrawal rates at wells KC01 and KC02 in the Mishnock River Basin, central Rhode Island, and measured partial-record flow data collected during the period from June 1996 through December 1998.

Wastewater return flows within the area increase total available streamflow. Return flows were calculated as water withdrawals minus consumptive use. Future wastewater return flows are expected to remain at about 0.4 ft^3/s (0.3 Mgal/d) because most of the land is protected from development and the proposed increases in withdrawals are currently (2004) planned to meet increasing water demands outside the Big River Area (Camp Dresser and McKee, Inc., 1999, 2000, 2001; Granato and others, 2003). Therefore, withdrawals beyond the 0.3 Mgal/d return flow will result in streamflow depletion in the Big River Area. Streamflow augmentation from wastewater recharge was factored into the streamflows estimated without ground-water withdrawals for the period 1961–2000. Streamflow depletions were calculated as the difference between a predevelopment scenario (without ground-water withdrawals or wastewater recharge) and a scenario with the KCWA withdrawals (and wastewater recharge).

The estimated average monthly streamflow in the absence of ground-water withdrawals for the 40-year period 1961–2000 has a strong seasonal pattern (table 5, fig. 10). Several streamflow statistics, including average monthly flows, the median of average monthly flows, and the median of median monthly flows, have been used or have been proposed for use in determining instream-flow requirements. These statistics were calculated for the 1961–2000 period for each station from the MOVE.1 estimates of daily streamflows (fig. 10). Estimates of average monthly flows are about 10 percent higher than estimates of the median of average monthly flows except during February, when they are about equal. Estimates of average monthly flows are about 20 percent higher than estimates of the median of median monthly flows during the 1961–2000 period (fig. 10). Flow-duration curves for estimated average daily and average monthly streamflows are shown for each station in figure 11. As expected, the extreme average daily flows diverge from average monthly flows, but the flow-duration curves indicate that the two are comparable from about the 5th to the 95th percentiles of streamflow during the period 1961–2000.

Table 5. Estimated average monthly streamflows without ground-water withdrawals in the Big River Area, central Rhode Island.

[Stations selected for analysis of streamflow depletion in the Big River Area, central Rhode Island, shown in figure 1. Estimated average monthly streamflow rounded to three significant figures]

Month	Average monthly streamflow, in cubic foot per second			
	Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River near Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	4.61	8.89	17.5	79.4
February	4.75	9.28	18.6	84.5
March	5.09	10.3	23.6	105
April	5.04	10.2	23.0	102
May	4.61	8.82	16.0	74.4
June	4.02	7.16	11.1	52.5
July	3.31	5.26	5.10	26.7
August	3.08	4.70	4.07	21.7
September	3.02	4.57	3.93	20.9
October	3.27	5.20	5.29	27.2
November	3.87	6.78	9.78	46.9
December	4.39	8.27	15.0	69.0

Instream-Flow Criteria

Currently (2004), the State of Rhode Island is developing statewide instream-flow policies needed for water-supply and aquatic-habitat protection goals to help balance ground-water and surface-water withdrawals (Rhode Island Water Resources Board, 2003). Instream-flow criteria are intended to protect aquatic and riparian ecosystems, but minimum ecological requirements are not well defined. Each flow-related habitat-assessment technique has benefits, limitations, and applicability issues for conditions in southeastern New England (Armstrong and others, 2001; Ipswich River Fisheries Restoration Task Group, 2002; Rhode Island Water Resources Board, 2003). These techniques—whether they use channel geometry, geomorphological characteristics, streamflow statistics, or other measures—are, to some degree, based on the assumption that historical regional streamflow regimes have shaped the habitat and defined the current ecosystem at a given site. Various measures of regional average streamflow statistics are commonly used as surrogate measures of ecological viability for stream habitat. Methods based on historical streamflow statistics are widely used in New England because they are based on an existing, available, and widely accepted data set (USGS streamflow-gaging data), and because the U.S. Fish and Wildlife Service (USFWS) has used regional streamflow data to define instream-flow criteria downstream of surface-water impoundments since 1981 (U.S. Fish and Wildlife Service, 1981; Lang, 1994, 1999).

Historically, assessment of the potential for acceptable streamflow depletions by ground-water withdrawals (and, therefore, the potential availability of ground water for public-supply development) has been estimated by subtracting calculated or estimated average monthly streamflows from a value of recommended minimum monthly flows. For example, the 7-day, 10-year low flow (7Q10) has been used to compare potential ecological water needs and water availability (Dickerman and others, 1997; Rhode Island Water Resources Board, 2003). A policy of allowing water withdrawals to deplete streamflows to 7Q10 levels in the "average year" would increase the likelihood that withdrawals could cause drought-like streamflow conditions on a regular basis.

The Rhode Island Water Resources Board (2003) has formed a Rhode Island Water Allocation Program Advisory Committee (RIWAPAC) to "develop instream-flow standards that allow for maximum sustainable use of the State's waters, are protective of the biological, chemical and physical integrity of those waters, and allow site-specific standards." The advisory committee has determined that use of long-term streamflow statistics from USGS streamflow gaging stations in Rhode Island may provide the most robust method to determine potential instream-flow criteria and to estimate water potentially available for water-supply development (Rhode Island Water Resources Board, 2003). The primary criterion throughout New England has been the USFWS interim regional policy for New England instream-flow criteria downstream of impoundments (U.S. Fish and Wildlife Service, 1981; Lang 1994; 1999); this policy continues to underlie alternative criteria that are defined by area-based application of regional streamflow statistics.

The effects of various example instream-flow criteria on potential allowable depletions and resultant ground-water withdrawal options were evaluated (table 6). Potential allowable depletions are calculated as the difference between these instream-flow criteria and a comparable estimate of monthly streamflow during the period 1961–2000 in the absence of ground-water withdrawals. These values are described as potential depletions because the full amount of water in any given month may not be obtainable from ground-water withdrawals without violating instream-flow criteria in subsequent months (the lagged effect of ground-water withdrawals on streamflow depletion). Each alternative instream-flow criterion for each month of the year in cubic foot per second per square mile and the associated potential streamflow depletion in cubic foot per second at each of the four sites of interest within the Big River Area is documented in the 11 tables in Appendix 1.

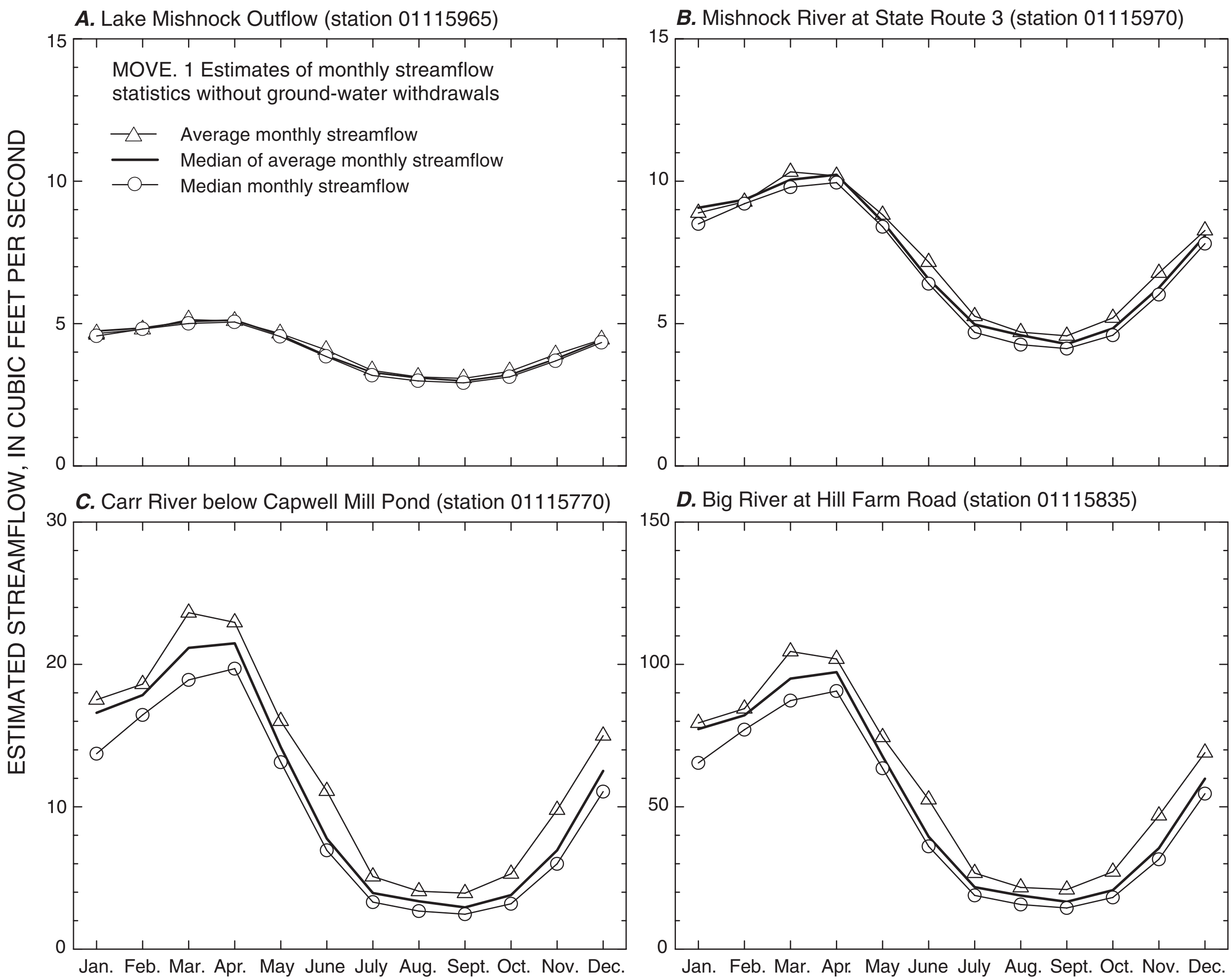

Figure 10. Estimates of average monthly flows, the median of monthly average flows, and the median of monthly median flows during the period 1961–2000 at the *A*, Lake Mishnock Outflow (station 01115965); *B*, Mishnock River at State Route 3 (station 01115970); *C*, Carr River below Capwell Mill Pond (station 01115770); and *D*, Big River at Hill Farm Road (station 01115835), central Rhode Island.

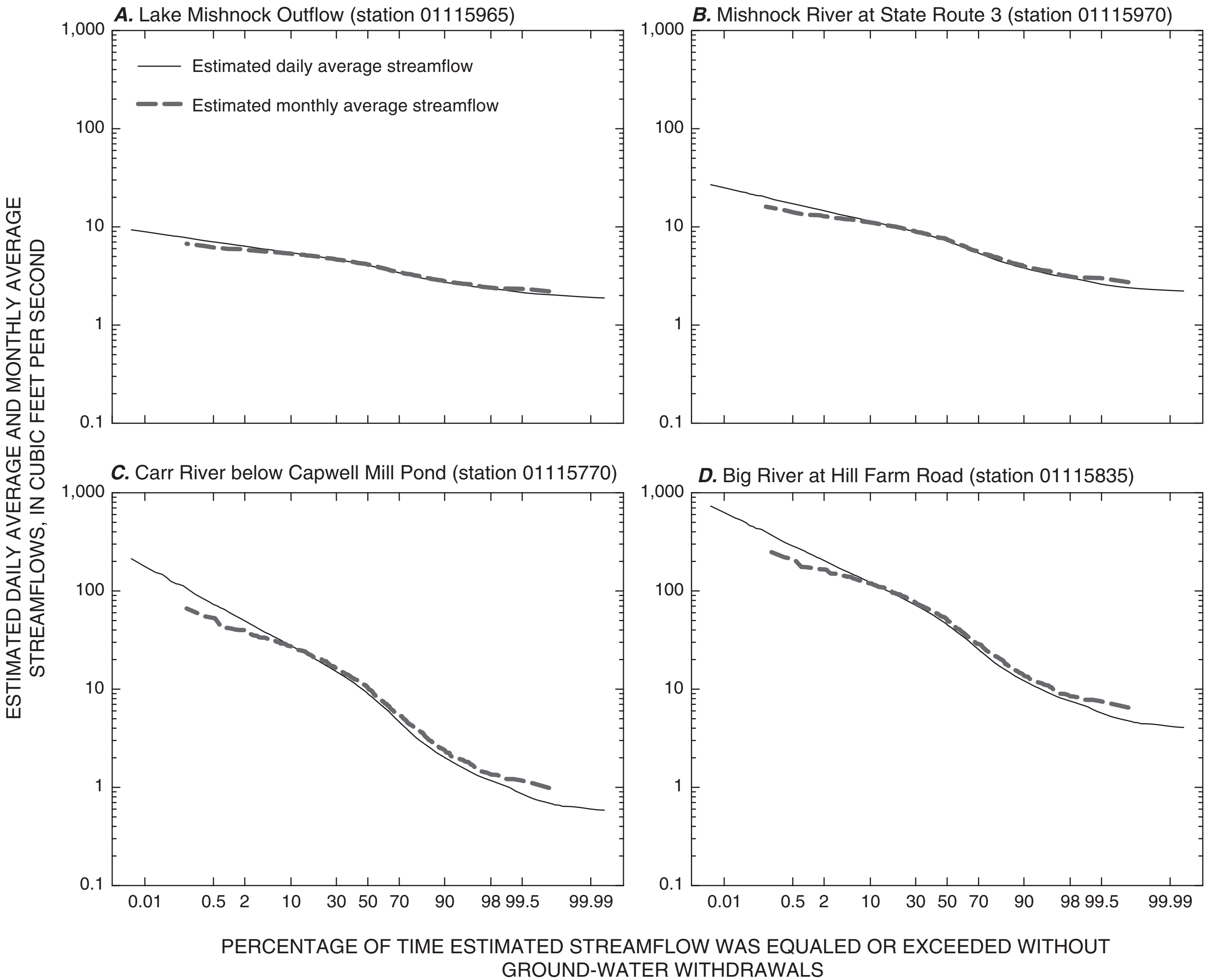

Figure 11. Daily and monthly streamflow-duration curves showing the percentage of time that the estimated streamflow would be equaled or exceeded without any ground-water withdrawals for *A*, Lake Mishnock Outflow (station 01115965); *B*, Mishnock River at State Route 3 (station 01115970); *C*, Carr River below Capwell Mill Pond (station 01115770); and *D*, Big River at Hill Farm Road (station 01115835), central Rhode Island, 1961–2000.

Table 6. Summary of selected instream-flow criteria considered in this study.

[**Abbreviations:** 4B3, 4-day 3-year biologically based low flow; 4B2, 4-day 2-year biologically based low flow; 4Q3, 4-day 3-year statistically based low flow; 4Q2, 4-day 2-year statistically based low flow; 7Q10, 7-day 10-year statistically based low flow. **Type:** The type of criteria defines the sometimes simplified application as described in this report—Annual, one criterion value is applied throughout the year; Monthly, criteria values are applied within each month; Seasonal, criteria values are applied to groups of 2 or more months. --, not applicable]

Criterion name	Abbreviation(s)	Type	Reference(s)	Text table	Appendix 1 table
U.S. Fish and Wildlife Service Aquatic Base Flow	USFWS ABF	Seasonal	U.S. Fish and Wildlife Service, 1981 Lang, 1994, 1999	--	1-1
Historical Connecticut (1977) Minimum Flow Standard	--	Annual	Connecticut General Assembly, 2003	--	1-2
Low-Flow Statistics	4B3, 4B2, 4Q3, 4Q2, 7Q10	Annual	U.S. Environmental Protection Agency, 2003	7	[1]1-2
Wetted-Perimeter Method	--	Annual	Armstrong and Parker, 2003	--	1-3
Kent County Water Authority Mishnock River Permit	--	Annual	Camp Dresser and McKee, Inc., 1999, 2000, 2001	--	1-4
R2Cross Methodology	--	Annual	Armstrong and Parker, 2003	--	1-5
Instream-Flow Incremental Methodology	IFIM	Seasonal	Gomez and Sullivan Engineers, 2002	8	1-6
Massachusetts Department of Environmental Protection streamflow-diversion threshold	MDEP limit	Seasonal	Massachusetts Department of Environmental Protection, 2003; Zarriello, 2004	9	1-7
Ipswich River Fisheries Restoration Task Group instream-flow criteria	IRFRTG limit	Seasonal	Ipswich River Fisheries Restoration Task Group, 2002	10	1-8
Median of Median Monthly Flows	MMM	Monthly	Apse, 2000	11	1-9
Hybrid Method	--	Seasonal	Apse, 2000	12	1-10
Median of Monthly Average Flows	MMA	Monthly	Apse, 2000	13	1-11

[1]Low-flow statistics are approximated by the Historical Connecticut (1977) Minimum Flow Standard value.

Streamflow constraints discussed in the following sections were selected as examples to illustrate the potential effects of a range of instream-flow criteria on the maximum attainable ground-water withdrawals calculated by use of the conjunctive-management model. These instream-flow criteria and associated depletion-limit estimates should not be construed as recommendations for implementation of specific regulatory streamflow standards. Rather, these simulations provide information from which regulatory decisions may be made. The New England Aquatic base flow, constant annual criteria, and seasonal or monthly criteria are discussed. Alternative methods are described in order of increasing restrictions on potential depletions.

U.S. Fish and Wildlife Service New England Aquatic Base Flow

The USFWS New England aquatic base flow (ABF) default criteria are derived from the median of measured monthly average flows in the region for the period of record. The ABF criteria are 0.5 $ft^3/s/mi^2$ during "summer" (June through October) to maintain habitat, temperature and dissolved oxygen; 1.0 $ft^3/s/mi^2$ during "fall and winter" (November through February); and 4.0 $ft^3/s/mi^2$ during "spring" (March through May) to maintain spawning and incubation habitat (U.S. Fish and Wildlife Service, 1981; Lang 1994; 1999). The USFWS (1981), however, recognized the potential for low-flow periods and specified, "when inflow immediately upstream of a project falls below flow releases prescribed for that period, the outflow be made no less than the inflow." The seasonal ABF criteria are averages of the median of average monthly flows from 48 USGS streamflow-gaging stations throughout New England with at least 50 mi^2 of drainage area. Twenty-five years of streamflow records that have been unaffected by withdrawals or regulation at a streamflow-gaging station are required by the USFWS to define data-based ABF criteria for that station; otherwise, the New England area-based ABF criteria are applied. The USFWS ABF criteria were designed to regulate hydroelectric-power releases to ensure minimum streamflows for aquatic-habitat maintenance. The criteria are based on the assumptions that the party responsible for maintaining minimum streamflows can respond to natural variations in streamflow on a daily basis and that a large volume of water is available in storage and can be released to maintain streamflows. The USFWS criteria also allow for alternative proposals if supported by biological justification (U.S. Fish and Wildlife Service, 1981).

Area-based USFWS instream-flow criteria are shown with estimates of the median of average monthly flows for the Lake Mishnock Outflow, the Mishnock River at State Route 3, the Carr River below Capwell Mill Pond and the Big River at Hill Farm Road for the 1961–2000 period (fig. 12). The medians of monthly average streamflows at the Lake Mishnock Outflow are about four times greater than the USFWS area-based ABF values throughout the year (fig. 12*A*) because the model-calculated ground-water-recharge area contributing to the lake is about 5.5 times the surface-water drainage area of the lake (0.29 mi^2) (Granato and others, 2003). The medians of monthly average streamflows in the Mishnock River at State Route 3 are about two to three times greater than the USFWS area-based ABF values, except during the springtime high-flow period when streamflows are about one-half to one-third less than the ABF values (fig. 12*B*). The medians of monthly average streamflows in the Carr River below Capwell Mill Pond are below the USFWS area-based ABF values during the springtime high-flow period (March, April, and May) and in August, September, October, and November (fig. 12*C*). Streamflows in the Carr River Basin are low relative to the ABF values because the Carr River naturally loses ground water to the Mishnock River Basin (Granato and others, 2003). The medians of monthly average streamflows in the Big River at Hill Farm Road are above the USFWS area-based ABF values except during the springtime high-flow period (fig. 12*D*). Potential allowable streamflow depletions under the USFWS criteria were calculated by subtracting the minimum streamflow standards from the estimates of the medians of monthly average streamflows, without ground-water withdrawals, at each station (Appendix 1, table 1-1). Potential maximum allowable streamflow depletions are set to zero in months when the ABF values are greater than the median of monthly average streamflows at each station.

The USFWS criteria are, in theory, attainable for hydroelectric reservoir projects because the reservoir provides a substantial storage buffer and because hydroelectric-power generation is generally an instream nonconsumptive use (U.S. Fish and Wildlife Service, 1981; Lang 1994; 1999). Ground-water-supply withdrawals, however, commonly represent off-stream (sometimes interbasin) water uses, which are in whole or in part consumptive uses (water uses that do not return water of the same quantity, temperature, or quality to the local stream). By definition, natural streamflows (without withdrawals) will be below (in violation of) statistical ABF values for 50 percent of the months that have monthly means below the medians of monthly average streamflows. Any ground-water-supply development in the basin will proportionally decrease flows and increase the frequency of these violations. The USFWS instream-flow criteria require that dam managers release waters to maintain daily average flows that equal or exceed the median of monthly average flows except on days when upstream inputs are less than the median of monthly average flows. Estimated streamflows in the absence of ground-water withdrawals were examined to determine the potential frequency of natural violations. About 5 percent of the estimated average daily streamflows in the Mishnock River at State Route 3 are below the 1.0 $ft^3/s/mi^2$ minimum-flow criterion and about 96 percent are below the 4.0 $ft^3/s/mi^2$ minimum-flow criterion. About 24 percent of estimated average daily streamflows in the Carr River below Capwell Mill Pond are below the 0.5 $ft^3/s/mi^2$ minimum-flow criterion, about 43 percent are below the 1.0 $ft^3/s/mi^2$ minimum-flow criterion and about 91 percent are below the 4.0 $ft^3/s/mi^2$ minimum-flow criterion. About 16 percent of estimated average daily streamflows in the Big River at Hill Farm Road are below the 0.5 $ft^3/s/mi^2$ minimum-flow criterion, about 36 percent are below the 1.0 $ft^3/s/mi^2$ minimum-flow criterion, and about 90 percent are below the 4.0 $ft^3/s/mi^2$ minimum-flow criterion. Therefore, strict interpretation of this criterion would have precluded all water-supply withdrawals for a substantial amount of time during the 1961–2000 period.

The USFWS-recommended minimum springtime streamflow of 4.0 $ft^3/s/mi^2$ is not a feasible minimum flow limit for rivers in southeastern New England because this criterion, which is the median of monthly average flow, is based on large meltwater flows from winter snowpack in northern New England basins (Ipswich River Fisheries Restoration Task Group, 2002; Armstrong and others, 2001; Armstrong and Parker, 2003). Furthermore, the average of the medians of the monthly average streamflows at the 48 streamflow-gaging stations that were used to develop the USFWS recommended streamflows was less than the 4.0 $ft^3/s/mi^2$ in March and May (U.S. Fish and Wildlife Service, 1981; Lang 1994, 1999). Therefore, this USFWS-recommended springtime streamflow is not currently considered to be suitable for use as a flow criterion in Rhode Island (Alisa Richardson, Rhode Island Department of Environmental Management, written commun., 2003).

Alternative Annual Instream-Flow Criteria

An annual instream-flow criterion is a single minimum instream-flow value that is applied throughout the year. These annual instream-flow criteria are commonly established to provide protection of aquatic and riparian ecology during the driest period of the year, which in New England is commonly during the summer months. Use of an annual dry-period ABF criterion is considered protective of aquatic habitat throughout the year because the high temperatures, low dissolved oxygen, and limited habitat available during August are considered to be the limiting conditions for aquatic biota (U.S. Fish and Wildlife Service, 1981; Lang 1994, 1999; Apse, 2000). About two-thirds of the cases subject to the USFWS low-flow criteria have been shown to be limited by the August-median streamflow throughout the year (Apse, 2000). Annual instream-flow criteria do not explicitly provide for variability in seasonal or monthly flows, but may implicitly limit ground-water withdrawals during springtime months in which ground-water withdrawals will have a delayed effect on dry-season low flows. The following five methods are described in order of increasing protection for instream flows and thus in order of increasing restrictions on potential withdrawals in the basin.

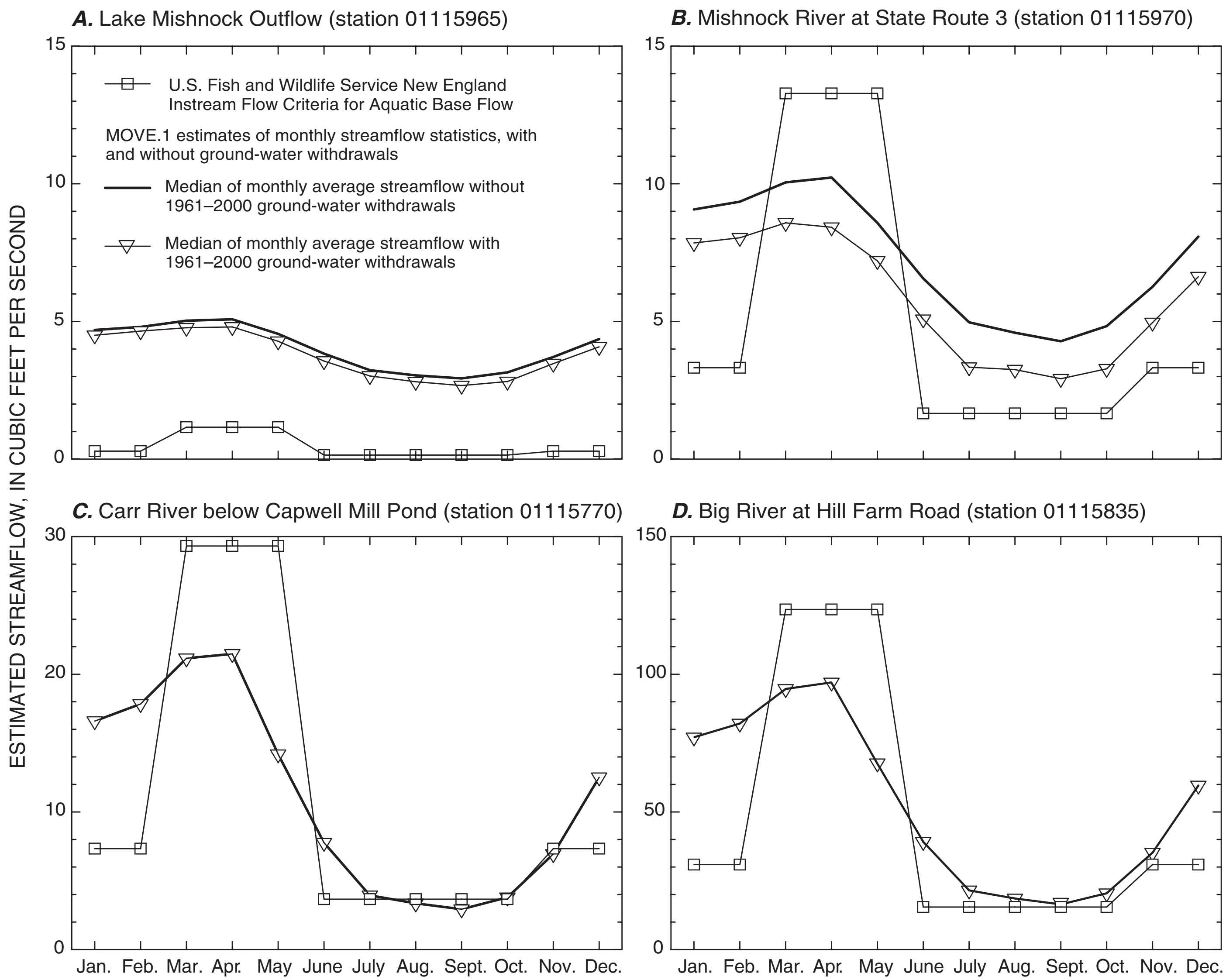

Figure 12. Area-based U.S. Fish and Wildlife Service monthly minimum streamflow recommendations and estimates of the median of monthly average flows for *A*, Lake Mishnock Outflow (station 01115965); *B*, Mishnock River at State Route 3 (station 01115970); *C*, Carr River below Capwell Mill Pond (station 01115770); and *D*, Big River at Hill Farm Road (station 01115835), central Rhode Island, 1961–2000.

Historic Connecticut Minimum-Instream Flow Standard: In 1977, the Connecticut Department of Environmental Protection established instream-flow standards to specify minimum average daily releases from impoundments constructed after 1977 into watersheds where the State stocks game fish (Connecticut General Assembly, 2003). The Connecticut regulations specify minimum releases that range from 0.25 to 0.02 $ft^3/s/mi^2$ as available water in storage decreases to 90 percent of the safe yield of the subject impoundment. Potential monthly streamflow depletions, calculated by subtracting the Connecticut minimum-streamflow limit of 0.25 $ft^3/s/mi^2$ from the estimated average monthly streamflows at sites in the Big River Area without ground-water withdrawals, are summarized in Appendix 1, table 1-2. This Connecticut standard includes a 1-to-5-day spring freshet release, but the flow rate and duration are based on inflow and reservoir storage. Like the USFWS ABF, the Connecticut standard is based on the assumption that there is an available pool of water that may be used to maintain streamflow; neither standard addresses the potential effects of ground-water withdrawals. All the estimated average daily streamflows for the 1961–2000 period exceed this minimum instream-flow standard of 0.07 ft^3/s at the Lake Mishnock Outflow and 0.83 ft^3/s in the Mishnock River at State Route 3 (figs. 11*A* and *B*). About 8 percent of average daily streamflows (the 92nd percentile) in the Carr River below Capwell Mill Pond are estimated to be below the minimum instream-flow standard of 1.83 ft^3/s during the period 1961–2000 (fig. 11*C*). About 2.3 percent of average daily streamflows (the 98th percentile) in the Big River at Hill Farm Road are estimated to be below the minimum instream-flow standard of 7.72 ft^3/s during the period 1961–2000 (fig. 11*D*).

Allowable Depletions Based on Low-Flow Statistics: Historically, low-flow statistics have been used to determine allowable depletions in comparison to long-term average flows. This approach provides for a substantial amount of ground-water development capacity, but is not protective of the biological, chemical or physical integrity of aquatic and riparian ecosystems because development to this extent would cause drought-like flows in the average year. The U.S. Environmental Protection Agency streamflow-statistics program DFLOW 3 (Rossman, 1990; U.S. Environmental Protection Agency, 2003) was used to estimate the 4B3, 4B2, 7Q10, 4Q3, and 4Q2 low-flow statistics from the MOVE.1 estimates of average daily flows during the period 1961–2000. The 4B3 and 4B2 are biologically based 4-day average-flow events that occur, on average, once every 3 and 2 years, respectively. The 7Q10 is the minimum 7-day average flow that has a 10-percent chance of occurring in any given year. The 4Q3 and 4Q2 are the minimum 4-day average flows that have a 33-percent chance and a 50-percent chance of occurring in any given year, respectively. The 4B3 and 4B2 are nonparametric values derived as dilution factors for wastewater-discharge permits for the protection of aquatic life, and are not statistical estimates of streamflow like the respective 4Q3 and 4Q2 values (Rossman, 1990). Estimates of low-flow statistics for the period January 1961–December 2000 are presented in table 7.

Table 7. Calculated and estimated low-flow statistics for selected streamflow-gaging stations in central Rhode Island for the period January 1961–December 2000.

[Low-flow statistics calculated from the daily average streamflow records for the continuous-record stations (table 1) and MOVE.1 estimates of the daily flow record for partial-record streamflow-gaging stations (table 2) by use of DFLOW3 (U.S. Environmental Protection Agency, 2003). Low flows are estimated for the period 1961–2000 in the absence of ground-water withdrawals. $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile; -- not applicable]

Low-flow statistic	Calculated low-flow statistic at continuous-record streamflow-gaging stations ($ft^3/s/mi^2$)			Estimated low-flow statistic at partial-record streamflow-gaging stations ($ft^3/s/mi^2$)					
	Hunt River near East Greenwich (01117000)	Pawcatuck River at Wood River Junction (01117500)	Wood River at Hope Valley (01118000)	Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)	Area-weighted average of the Big River and Mishnock River stations	Percentage of estimated daily streamflows equal to or less than low-flow statistic (approximate)
Drainage area (mi^2)	22.9	100	72.4	0.29	3.32	7.33	30.88	34.20	--
4B3[1]	.07	.24	.23	7.21	.73	.11	.17	.22	0.3
4B2[1]	.07	.26	.25	7.34	.79	.12	.19	.25	.5
7Q10[2]	.07	.30	.29	7.55	.81	.13	.20	.26	.7
4Q3[3]	.11	.32	.29	8.00	.89	.15	.24	.30	1.7
4Q2[3]	.16	.36	.31	8.48	.97	.19	.28	.35	3.8

[1]The 4B3 and 4B2 are biologically based 4-day average flows that occur on average once every 3 years and every 2 years, respectively.

[2]The 7-day 10-year low flow (7Q10) is the minimum 7-day average flow with a 10-percent chance of occurring in any given year.

[3]The 4Q3 and 4Q2 are the minimum 4-day average flows with a 33-percent chance and a 50-percent chance of occurring in any given year, respectively.

Calculated low-flow statistics for the Pawcatuck River (station 01117500) and Wood River (station 01117800) are comparable (table 7). Calculated low-flow statistics for the Hunt River (station 01117000), however, are less than the low-flow statistics calculated for the other two stations on the basis of streamflows per unit area. The large differences between statistics for the Hunt River (station 01117000) and statistics for the other two stations are caused, in part, by ground-water withdrawals in the Hunt River Basin (Barlow and Dickerman, 2001a).

Estimated low-flow statistics per unit area for the Lake Mishnock outflow (station 01115965) are about 25 to 30 times the comparable statistics for the Pawcatuck River and Wood River (table 7) because of the effect of natural interbasin ground-water flow from the Carr River Basin to Lake Mishnock (Granato and others, 2003). Estimated low-flow statistics per unit area for the Mishnock River are about three times the comparable statistics for the Pawcatuck River and Wood River, in part because of the relatively high flows per unit area at the Lake Mishnock Outflow. Estimated streamflow statistics without ground-water withdrawals for the Carr River below Capwell Mill Pond (station 01115770) are about 50 percent of equivalent low-flow statistics for the Pawcatuck River and Wood River. This difference in flows per unit area is caused by ground-water underflows from the Carr River Basin to the Mishnock River Basin (Granato and others, 2003). Estimated streamflow statistics, without ground-water withdrawals, for the Big River at Hill Farm Road (station 01115835) are about 75 percent of values for the Pawcatuck River and Wood River, in part because of the low flows per unit area from the Carr River tributary. Area-weighted averages of low-flow statistics for the combined outflow from the Mishnock River and the Big River are calculated to assess availability of water in the basin as a whole (table 7). These low-flow estimates for the Big River Area are comparable to low flows calculated for the Pawcatuck River and Wood River stations. Finally, area-weighted averages of the low-flow statistics in table 7 are comparable to the historic Connecticut minimum-flow standard of 0.25 $ft^3/s/mi^2$ (Connecticut General Assembly, 2003); therefore, allowable depletions based on these statistics would be comparable to the depletions listed in table 1-2 in Appendix 1.

Wetted-Perimeter Method: Armstrong and Parker (2003) used the wetted-perimeter method at seven sites in the neighboring Usquepaug–Queen River Basin to assess streamflow requirements for habitat protection. The wetted-perimeter method is used to estimate the minimum flow required to maintain habitat in which the flowing stream water extends over the entire riverbed to the toe of each bank. Armstrong and Parker (2003) estimated wetted-perimeter flows that ranged from 0.21 to 0.66 $ft^3/s/mi^2$ and chose the median value of 0.41 $ft^3/s/mi^2$ as representative of flows in the Usquepaug–Queen River Basin. All the estimated streamflows for the 1961–2000 period exceed this instream-flow criterion of 0.12 ft^3/s for the Lake Mishnock Outflow and 1.36 ft^3/s for the Mishnock River at State Route 3 (figs. 11*A* and *B*). About 19 percent of estimated average daily streamflows (the 81st percentile) in the Carr River below Capwell Mill Pond are estimated to be below the wetted-perimeter instream-flow criterion of 3.01 ft^3/s during the period 1961–2000 (figs. 11*C*). About 11 percent of estimated average daily streamflows (the 89th percentile) in the Big River at Hill Farm Road are estimated to be below the wetted-perimeter instream-flow criterion of 12.7 ft^3/s during the period 1961–2000 (fig. 11*D*). Potential monthly streamflow depletions, calculated by subtracting the Usquepaug–Queen River Basin wetted-perimeter streamflow estimate of 0.41 $ft^3/s/mi^2$ from the estimated average monthly streamflows without ground-water withdrawals at sites in the Big River Area, are summarized in table 1-3 in Appendix 1. Application of the wetted-perimeter method in the Big River Area would require site-specific measurements to establish an instream-flow criterion.

Kent County Water Authority Mishnock River Permit Instream-Flow Criterion: The Rhode Island Department of Environmental Management (RIDEM) established a long-term average-streamflow limit of 0.5 $ft^3/s/mi^2$ as one of the primary requirements for the KCWA ground-water-supply application for wells in the Mishnock River Basin (Camp Dresser and McKee, Inc., 1999, 2000, 2001). The RIDEM agreed to this average annual low-flow limit as an alternate ABF during the 1990s because streams in southeastern Rhode Island do not have the high winter and spring flows set forth in the USFWS ABF criteria (Alisa Richardson, Rhode Island Department of Environmental Management, oral commun., 2003). All estimated streamflows for the 1961–2000 period exceed the instream-flow criteria of 0.15 ft^3/s for the Lake Mishnock Outflow and 1.66 ft^3/s in the Mishnock River at State Route 3 (figs. 11*A* and *B*). About 24 percent of average daily streamflows (the 76th percentile) in the Carr River below Capwell Mill Pond are estimated to be below the instream-flow criterion of 3.67 ft^3/s during the period 1961–2000 (fig. 11*C*). About 17 percent of average daily streamflows (the 83rd percentile) in the Big River at Hill Farm Road are estimated to be below the instream-flow criterion of 15.4 ft^3/s during the period 1961–2000 (fig. 11*D*). Potential monthly depletions, calculated by subtracting 0.5 $ft^3/s/mi^2$ from the estimated average monthly streamflows without ground-water withdrawals at sites in the Big River Area, are summarized in table 1-4 in Appendix 1. It is notable that use of a streamflow criterion of 0.5 $ft^3/s/mi^2$ reduces potential depletions in the Carr River Basin to about 0.3 ft^3/s (less than 0.2 Mgal/d) during the month of September under long-term average monthly conditions (table 1-4).

R2Cross Method: Armstrong and Parker (2003) also applied the R2Cross method at the same seven sites in the neighboring Usquepaug–Queen River Basin to assess streamflow requirements for habitat protection. Three hydraulic variables (mean depth, percent of bankfull wetted perimeter, and average velocity) are used at stream riffle sites in the R2Cross method to estimate the minimum flow required to maintain habitat. Armstrong and Parker (2003) estimated R2Cross flows that ranged from 0.28 to 1.86 $ft^3/s/mi^2$ with a median of 0.72 $ft^3/s/mi^2$. All the estimated streamflows for the 1961–2000 period exceed the 0.72 $ft^3/s/mi^2$ R2Cross instream-flow criterion, which is 0.21 ft^3/s for the Lake Mishnock Outflow (fig. 11*A*). About 0.2 percent of average daily streamflows (the 99.8th percentile) are below the median R2Cross streamflow criterion of 2.39 ft^3/s in the Mishnock River at State Route 3 (fig. 11*B*). About 33 percent of average daily streamflows (the 77th percentile) in the Carr River below Capwell Mill Pond are estimated to be below the R2Cross instream-flow criterion of 5.28 ft^3/s during the period 1961–2000 (fig. 11*C*). About 26 percent of average daily streamflows (the 74th percentile) in the Big River at Hill Farm Road are estimated to be below the R2Cross instream-flow criterion of 22.2 ft^3/s during the period 1961–2000 (fig. 11*D*).

Potential monthly streamflow depletions, calculated by subtracting the median Usquepaug–Queen River Basin R2Cross flows of 0.72 $ft^3/s/mi^2$ from the estimated average monthly streamflows without ground-water withdrawals at sites in the Big River Area, are summarized in table 1-5 in Appendix 1 as an upper limit of alternative annual instream-flow criteria. It is notable that use of the R2Cross limit of 0.72 $ft^3/s/mi^2$ eliminates potential depletions in the Carr River Basin during July through September and eliminates potential depletions in the Big River Basin during the months of August and September under long-term average monthly conditions (table 1-5). The R2Cross method, however, is sensitive to channel geometry, so anthropogenic changes to stream channels will affect estimated R2Cross flows (Armstrong and Parker, 2003). Therefore, application of the R2Cross method in the Big River Area would require site-specific measurements of hydraulic variables to establish site-specific instream-flow criteria.

Alternative Seasonal and Monthly Instream-Flow Criteria

Seasonal or monthly methods for establishing instream-flow criteria are commonly established to provide a range of natural flows in the fall, winter, and spring as well as protection of aquatic and riparian ecology during the summer dry period (U.S. Fish and Wildlife Service, 1981; Lang, 1994, 1999; Armstrong and others, 2001; Ipswich River Fisheries Restoration Task Group, 2002). The following methods are described in order of increasing restrictions on potential withdrawals in the subject basin.

Instream Flow Incremental Methodology (IFIM) criteria for the Saugus River, Massachusetts: Gomez and Sullivan Engineers (2002) estimated minimum streamflows necessary for protection of aquatic and riparian ecology in the Saugus River Basin, Massachusetts, by use of the IFIM method. The IFIM is an analytical approach developed by the USFWS in cooperation with other agencies to relate flow and habitat suitability for fish and aquatic life (Stalnaker and others, 1995). The minimum-flow guidelines developed for the Saugus River were used to estimate potential depletions in the Big River Area because the Saugus River Basin is similar to the Big River Area. The Saugus River Basin is part of the seaboard lowland section of the New England physiographic province (Fenneman, 1938, pl. 1), and is estimated to be about 42 percent stratified deposits by area (Zarriello and Socolow, 2003), which is comparable to the Big River Basin (table 3). Gomez and Sullivan Engineers (2002) estimated that the Saugus River Basin receives about 94 percent of the annual average precipitation received in the Big River Area, Rhode Island. The Saugus River Basin, however, also has a proportionally lower evapotranspiration rate than is estimated for the Big River Area (Randall, 1996, pl.2). Streamflows at the Saugus River streamflow-gaging station (station 01102345) are also affected by seasonal regulation by ponds upstream (Socolow and others, 2003). Therefore, the IFIM is used as an example; if the IFIM method were to be used in the Big River Basin, a site-specific analysis would be needed to establish site-specific instream-flow criteria.

Gomez and Sullivan Engineers (2002) estimated minimum recommended streamflow criteria of 0.29 $ft^3/s/mi^2$ for June through September, 0.57 $ft^3/s/mi^2$ for October through February, 1.14 $ft^3/s/mi^2$ for March and April, and 0.95 $ft^3/s/mi^2$ for May (table 8). All the streamflows at the Lake Mishnock Outflow and the Mishnock River at State Route 3 are above the Saugus River IFIM criteria. Except during the month of October, a low percentage of average daily flows in the Carr River below Capwell Mill Pond and the Big River at Hill Farm Road are less than the Saugus River IFIM criteria (table 8). A higher percentage of October flows are below the IFIM criteria in these two streams because October is included as one of the winter-flow months in these criteria (Gomez and Sullivan Engineers, 2002). October, however, is considered a low-flow month in southeastern New England (Armstrong and others, 2003). Potential monthly streamflow depletions, calculated by subtracting the Saugus River minimum-flow criteria from the estimated average monthly streamflows without ground-water withdrawals at sites in the Big River Area, are summarized in table 1-6 in Appendix 1. Under the IFIM criteria, October has the lowest potential monthly streamflow depletions for each station except the Lake Mishnock Outflow, for which September has the lowest potential monthly streamflow depletion.

Table 8. Percentage of average daily streamflows that are less than the Gomez and Sullivan Instream-Flow Incremental Methodology (IFIM) instream-flow criteria for the Saugus River, Massachusetts, in the absence of ground-water withdrawals in the Big River Area, central Rhode Island, during each month.

[Source: Gomez and Sullivan Engineers, 2002. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed on table 2. IFIM, Instream-Flow Incremental Methodology; $ft^3/s/mi^2$, cubic foot per second per square mile; <, actual value is less than value shown]

Month	IFIM flow ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.57	0.0	0.0	5.4	4.2
February	.57	.0	.0	1.5	1.0
March	1.14	.0	.0	4.3	1.2
April	1.14	.0	.0	4.9	2.7
May	.95	.0	.0	7.6	1.8
June	.29	.0	.0	.1	<.1
July	.29	.0	.0	17.4	3.5
August	.29	.0	.0	36.4	14.5
September	.29	.0	.0	39.3	18.8
October	.57	.0	.0	60.4	45.9
November	.57	.0	.0	28.5	16.7
December	.57	.0	.0	8.7	5.0

Massachusetts Department of Environmental Protection (MDEP) Streamflow-Diversion Threshold for the Ipswich River, Massachusetts: The MDEP (2003) established minimum-flow thresholds for surface-water withdrawals along the Ipswich River, Massachusetts (Zarriello, 2004). The Ipswich River, which is adjacent to the Saugus River Basin, is in the coastal lowland province (Fenneman, 1938, pl. 1); has comparable precipitation and evapotranspiration (Randall, 1996, pl. 2); and has a comparable percentage of stratified deposits (about 42 percent by area; Zarriello and Socolow, 2003) to the Big River Area. The MDEP (2003) established minimum-flow thresholds of 0.42 $ft^3/s/mi^2$ for June through October and 1.00 $ft^3/s/mi^2$ for November through May (table 9) for surface-water permits (Zarriello, 2004). All of the estimated average daily streamflows at the Lake Mishnock Outflow, without ground-water withdrawals, during the period 1961–2000 are above the MDEP criteria (table 9). More than 97 percent of estimated average daily streamflows in the Mishnock River at State Route 3, without ground-water withdrawals, are above the MDEP criterion for each month. The percentage of estimated average daily streamflows in the Carr River below Capwell Mill Pond that are less than the MDEP criteria, without ground-water withdrawals, range from 2.3 percent in March to 60.5 percent in September. The percentage of estimated average daily streamflows that are less than the MDEP criteria in the Big River at Hill Farm Road, without ground-water withdrawals, range from 0.2 percent in June to 44.3 percent in November. Potential monthly streamflow depletions, calculated by subtracting the MDEP minimum-flow criteria from the estimated average monthly streamflows without ground-water withdrawals for sites in the Big River Area, are summarized in table 1-7 in Appendix 1. September has the lowest potential monthly streamflow depletions for all four stations. The MDEP (2003) criteria are based on a number of factors, including streamflow statistics, but they do not directly address ground-water withdrawals; therefore, these criteria may not be directly applicable to ground-water withdrawals in the Big River Area. These instream-flow criteria are included as an example because surface-water-diversion criteria, for example the USFWS ABF, are commonly applied as ground-water-withdrawal criteria. Also, the MDEP monthly instream-flow criteria present an example criteria between the Saugus River IFIM and the Ipswich River Restoration Task Group instream-flow criteria.

Table 9. Percentage of average daily streamflows that are less than the Massachusetts Department of Environmental Protection permitted streamflow-diversion thresholds for the Ipswich River, Massachusetts, in the absence of ground-water withdrawals in the Big River Area, central Rhode Island, during each month.

[Source: Massachusetts Department of Environmental Protection, 2003. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed on table 2. MDEP, Massachusetts Department of Environmental Protection; $ft^3/s/mi^2$, cubic foot per second per square mile; <, actual value is less than value shown]

Month	MDEP streamflow threshold ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.00	0.0	<0.1	15.9	8.5
February	1.00	.0	<.1	12.5	5.7
March	1.00	.0	<.1	2.3	.7
April	1.00	.0	<.1	3.5	1.2
May	1.00	.0	<.1	8.9	2.6
June	.42	.0	.0	5.6	.2
July	.42	.0	.0	42.1	19.1
August	.42	.0	.0	57.0	37.4
September	.42	.0	.0	60.5	40.6
October	.42	.0	.0	46.3	28.2
November	1.00	.0	2.4	56.4	44.3
December	1.00	.0	.6	26.4	16.9

Ipswich River Fisheries Restoration Task Group (IRFRTG) Instream-Flow Criteria: The IRFRTG (2002) recommended minimum streamflows of 0.49 $ft^3/s/mi^2$ for June through October, 1.00 $ft^3/s/mi^2$ for November through February, and 2.50 $ft^3/s/mi^2$ for March through May (table 10). The IRFRTG criteria are based on historical streamflows in the Ipswich Basin and results of a number of habitat-based methods specific to the Ipswich River Basin (Ipswich River Fisheries Restoration Task Group, 2002). All of the estimated average daily streamflows during the period 1961–2000 at the Lake Mishnock Outflow, without ground-water withdrawals, are above the IRFRTG criteria (table 10). The percentage of estimated average daily streamflows less than the IRFRTG criteria in the Mishnock River at State Route 3, without ground-water withdrawals during the period 1961–2000, ranges from 0.0 percent in the summer dry period to about 45 percent in May. The percentage of estimated average daily streamflows that are less than the IRFRTG criteria in the Carr River below Capwell Mill Pond, without ground-water withdrawals, ranges from about 11 percent in June to 72 percent in May. The percentage of estimated average daily streamflows that are less than the IRFRTG criteria in the Big River at Hill Farm Road, without ground-water withdrawals, ranges from 2.5 percent in June to about 65 percent in May. Potential monthly streamflow depletions, calculated by subtracting the IRFRTG flow criteria from the estimated average monthly streamflows for sites in the Big River Area, without ground-water withdrawals, are summarized in table 1-8 in Appendix 1. The use of the IRFRTG criteria (2.5 $ft^3/s/mi^2$) would eliminate potential depletions at the Carr River and Big River stations during the month of May under long-term average monthly conditions.

Median of Median Monthly (MMM) Streamflows in Connecticut: In an evaluation of various flow-standard methods for Connecticut, Apse (2000) calculated a monthly statistic that is the median of monthly median streamflows at 10 streamflow-gaging stations in Connecticut that have little or no upstream flow regulation. The theory behind the use of median flows is that the average flows reflect the influence of runoff from one or more large storms and that these peak flows would not be available for either instream or offstream use, especially in wet months when runoff would most likely exceed the capacity of retention structures. Apse (2000) calculated the mean of the MMM statistic for the 10 streamflow-gaging stations in Connecticut as an estimate of available flows in ungaged basins in Connecticut. These drainage basins in Connecticut contain areas of stratified deposits ranging from 0 to 33 percent; 9 of the

Table 10. Percentage of average daily streamflows that are less than the Ipswich River Fisheries Restoration Task Group instream-flow criteria for the Ipswich River, Massachusetts, in the absence of ground-water withdrawals in the Big River Area, central Rhode Island, during each month.

[Source: Ipswich River Fisheries Restoration Task Group, 2002. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed on table 2. IRFRTG, Ipswich River Fisheries Restoration Task Group; $ft^3/s/mi^2$, cubic foot per second per square mile; <, actual value is less than value shown]

Month	IRFRTG instream-flow criteria ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.00	0.0	<0.1	15.9	8.5
February	1.00	.0	<.1	12.5	5.7
March	2.50	.0	17.6	45.2	36.9
April	2.50	.0	22.6	46.5	38.7
May	2.50	.0	44.6	72.3	64.5
June	.49	.0	.0	11.1	2.5
July	.49	.0	.0	51.1	28.2
August	.49	.0	.0	63.6	46.5
September	.49	.0	.0	68.2	50.0
October	.49	.0	.0	53.6	36.7
November	1.00	.0	2.4	56.4	44.3
December	1.00	.0	.6	26.4	16.9

10 have areas of stratified deposits less than 20 percent (Apse, 2000). The flow-duration patterns of these Connecticut streamflow-gaging stations are not considered to be representative of flow durations in the Big River Area because of the low percentages of stratified deposits in most of the Connecticut basins. In comparison, the Mishnock River and the Big River Basins are composed of about 86 percent and 42 percent stratified sand and gravel deposits, respectively (table 3). Use of the median of monthly median streamflows as an instream-flow criterion (Apse, 2000) was applied with statistics from the Hunt River near East Greenwich, RI (station 01117000), Pawcatuck River at Wood River Junction, RI (station 01117500), and the Wood River at Hope Valley, RI (station 01118000) (table 2) for the period 1961–2000 to estimate potential depletions under this type of instream-flow criteria in the Big River Area.

The Apse (2000) median of monthly medians (MMM) method yields a different instream-flow criterion for each month (table 11). All of the estimated average daily streamflows for the period 1961–2000 at the Lake Mishnock Outflow, without ground-water withdrawals, are above the MMM criteria. The percentage of estimated average daily streamflows that are less than the MMM criteria at the Mishnock River at State Route 3, without ground-water withdrawals, ranges from less than 0.1 percent in the summer dry period to 67.3 percent in April. The percentage of estimated average daily streamflows that are less than the MMM criteria in the Carr River below Capwell Mill Pond, without ground-water withdrawals, ranges from 59 percent in January to 69 percent in September. The percentage of estimated average daily streamflows that are less than the MMM criteria in the Big River at Hill Farm Road, without ground-water withdrawals, ranges from 50 percent in October to about 60 percent in April. Potential monthly streamflow depletions, calculated by subtracting the MMM flow criteria from the estimated median monthly streamflows for sites in the Big River Area, without ground-water withdrawals, are summarized in table 1-9 in Appendix 1. The MMM criteria eliminate potential depletions in the Mishnock River during March and April, and eliminate all potential depletions in the Carr River and Big River Basins for any year in which streamflows are below long-term median-flow conditions for the period 1961–2000.

Hybrid Method for Connecticut Streamflows: Apse (2000) advocated a hybrid method to set instream-flow criteria in Connecticut. Apse (2000) selected values of the median of monthly average flows (rounded to one decimal place) from 10 selected streamflow-gaging stations in Connecticut for the dry months (July, August, and September) and rounded values of the median of monthly median flows from these stations for the remaining months (October through June) as a proposed standard for ungaged sites in Connecticut. The rationale for the use of the median of monthly average flows in dry months is that the higher recommended flows would compensate for potential anthropogenic effects such as loss of recharge from increases in impervious area (Apse, 2000). The Apse (2000) hybrid method was applied with statistics for the Hunt River near East Greenwich, RI (station 01117000), Pawcatuck River at Wood

Table 11. Percentage of average daily streamflows that are less than the Apse median of monthly median streamflows instream-flow criteria estimated from records from the Hunt River, the Pawcatuck River at Wood River Junction, and the Wood River at Hope Valley streamflow-gaging stations, central Rhode Island, in the absence of ground-water withdrawals in the Big River Area during each month.

[Source: Apse, 2000. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed on tables 1 and 2. **Station numbers:** Hunt River, 01117000; the Pawcatuck River at Wood River Junction, 01117500; the Wood River at Hope Valley, 01118000. MMM, median of monthly median streamflows; $ft^3/s/mi^2$, cubic foot per second per square mile; <, actual value is less than value shown]

Month	Apse (2000) MMM instream-flow criteria ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	2.20	0.0	30.0	59.0	51.6
February	2.68	.0	45.4	62.5	56.0
March	3.09	.0	56.2	60.4	53.5
April	3.27	.0	67.3	66.4	59.5
May	2.28	.0	26.7	65.9	57.0
June	1.27	.0	2.5	63.6	52.0
July	.68	.0	<.1	67.8	53.3
August	.53	.0	<.1	66.9	51.5
September	.50	.0	<.1	69.1	51.3
October	.61	.0	<.1	63.3	50.3
November	1.13	.0	5.4	60.9	51.9
December	1.81	.0	17.8	60.0	52.3

River Junction, RI (station 01117500), and the Wood River at Hope Valley, RI (station 01118000) (table 2) for the period 1961–2000 to estimate potential depletions under this type of instream-flow criteria in the Big River Area.

The Apse (2000) hybrid method yields a different minimum flow for each month (table 12). All of the estimated average daily streamflows for the period 1961–2000 at the Lake Mishnock Outflow, without ground-water withdrawals, are above the hybrid-method criteria. The percentage of estimated average daily streamflows that are less than the hybrid-method criteria in the Mishnock River at State Route 3, without ground-water withdrawals, ranges from 0 percent in the summer dry period to about 67 percent in April. The percentage of estimated average daily streamflows that are less than the hybrid-method criteria in the Carr River below Capwell Mill Pond, without ground-water withdrawals, ranges from 59 percent in January to about 76 percent in September. The percentage of estimated average daily streamflows that are less than the hybrid-method criteria in the Big River at Hill Farm Road, without ground-water withdrawals, ranges from 47 percent in June to 63 percent in September. Potential monthly streamflow depletions, calculated by subtracting the hybrid-method flow criteria from the estimated median monthly streamflows for sites in the Big River Area, without ground-water withdrawals, are summarized in table 1-10 in Appendix 1. The hybrid-method criteria eliminate potential depletions in the Mishnock River at State Route 3 during March and April, and eliminate all potential depletions in the Carr River and Big River Basins for any year in which streamflows are below long-term median flows for the period 1961–2000.

Median of monthly average (MMA) Streamflows in Connecticut: Apse (2000) also calculated the USFWS monthly statistic, the median of monthly average (MMA) streamflows, but his values differ from the standard New England ABF statistics. When compared to characteristics of the streamflow-gaging stations used to develop the USFWS ABF statistics, the locations and hydrogeologic watershed characteristics of the selected Connecticut streamflow-gaging stations affect the timing and magnitude of monthly instream-flow criteria (Apse, 2000). Furthermore, Apse (2000) did not average between different months in the annual cycle; as a result, each month has an individual minimum-flow criterion. To provide an estimate of ABF statistics for the Big River Area, the MMA method as an instream-flow criteria (Apse, 2000) was applied with statistics from the Hunt River near East Greenwich, RI (station 01117000), Pawcatuck River at Wood River Junction, RI (station 01117500), and the Wood River at Hope Valley, RI (station 01118000) for the period 1961–2000 to estimate potential depletions under this type of instream-flow criteria in the Big River Area.

Table 12. Percentage of average daily streamflows that are less than the Apse hybrid instream-flow criteria estimated from records from the Hunt River, the Pawcatuck River at Wood River Junction, and the Wood River at Hope Valley streamflow-gaging stations, central Rhode Island, in the absence of ground-water withdrawals in the Big River Area during each month.

[Source: Apse, 2000. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed in tables 1 and 2. **Station numbers:** Hunt River, 01117000; the Pawcatuck River at Wood River Junction, 01117500; the Wood River at Hope Valley, 01118000. $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Apse (2000) hybrid instream-flow criteria ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.5	0.0	30.0	59.1	51.6
February	1.8	.0	46.3	63.3	56.7
March	2.6	.0	56.5	61.1	54.9
April	2.5	.0	66.8	66.9	60.4
May	1.6	.0	28.8	66.6	58.1
June	.8	.0	3.2	64.2	46.5
July	.5	.0	.2	74.1	62.4
August	.4	.0	.0	72.0	59.4
September	.4	.0	.0	76.4	63.1
October	.5	.0	.0	62.2	49.5
November	1.1	.0	4.9	60.0	49.5
December	1.5	.0	17.3	59.9	51.9

The Apse (2000) MMA method yields a different minimum flow for each month (table 13). All of the estimated average daily streamflows for the period 1961–2000 at the Lake Mishnock Outflow, without ground-water withdrawals at the Mishnock River at State Route 3, are above the MMA method instream-flow criteria. The percentage of estimated average daily streamflows that are less than the MMA-method flow criteria at the Mishnock River at State Route 3, without ground-water withdrawals, ranges from 0 percent in August and September to about 75 percent in April. The percentage of estimated average daily streamflows that are less than the MMA-method flow criteria in the Carr River below Capwell Mill Pond, without ground-water withdrawals, ranges from about 67 percent in November to about 76 percent in September. The percentage of estimated average daily streamflows that are less than the MMA-method flow criteria in the Big River at Hill Farm Road, without ground-water withdrawals, ranges from 58 percent in October to about 66 percent in January and April. Potential monthly streamflow depletions, calculated by subtracting the MMA-method flow criteria from the estimated median of average monthly streamflows for sites in the Big River Area, without ground-water withdrawals, are summarized in table 1-11 in Appendix 1. The MMA method instream-flow criteria preclude potential depletions in the Mishnock River at State Route 3 during February, March, and April, and eliminate all potential depletions in the Carr River and Big River Basins for any year in which streamflows are below the median of monthly average flows for the period 1961–2000.

Table 13. Percentage of average daily streamflows that are less than the Apse median of monthly average streamflows instream-flow criteria estimated from records from the Hunt River, the Pawcatuck River at Wood River Junction, and the Wood River at Hope Valley streamflow-gaging stations, central Rhode Island, in the absence of ground-water withdrawals in the Big River Area during each month.

[Source: Apse, 2000. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Drainage areas for each station listed in tables 1 and 2. **Station numbers:** Hunt River, 01117000; the Pawcatuck River at Wood River Junction, 01117500; the Wood River at Hope Valley, 01118000. MMA, median of monthly average flows; $ft^3/s/mi^2$, cubic foot per second per square mile; <, actual value is less than value shown]

Month	Apse (2000) MMA instream-flow criteria ($ft^3/s/mi^2$)	Percentage of average daily streamflows below instream-flow criteria in the absence of ground-water withdrawals			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	2.08	0.0	57.3	72.3	66.4
February	2.23	.0	63.8	71.5	65.5
March	3.35	.0	69.4	68.3	61.6
April	3.26	.0	75.4	70.4	66.4
May	2.07	.0	32.3	68.5	59.9
June	.91	.0	9.1	68.5	60.4
July	.51	.0	<.1	73.2	60.5
August	.37	.0	.0	72.8	60.6
September	.38	.0	.0	75.7	61.6
October	.62	.0	<.1	68.2	58.1
November	1.45	.0	13.2	66.5	59.1
December	1.95	.0	31.2	67.8	59.9

Ground-Water Demand and Potential Ground-Water Supplies in the Big River Area

Population growth and concurrent economic development are expected to create an additional water demand of about 16 Mgal/d in central Rhode Island by the year 2020 (Beta Engineering, Inc., 1999). Domestic water use for households on public supply in Rhode Island has been estimated at 67 gal/d/person and census figures indicate that there are, on average, about 2.5 people per household (Wild and Nimiroski 2004; E.C. Wild, U.S. Geological Survey, written commun., 2005). Therefore, a production well that produces 1 Mgal/d throughout the year would be needed to support a population of about 15,000 individuals, or about 6,000 households in Rhode Island. However, water demand in Rhode Island follows a seasonal pattern with a peak demand during the summer. Because aquifers, unlike large surface-water reservoirs, do not retain and store the peak spring-streamflows, seasonal water-demand patterns may limit total withdrawals for communities that are solely dependent on ground-water supplies.

The Big River Area is currently (2004) being considered as a source for ground-water supply development to meet current and future water demand in central Rhode Island. The KCWA has operated production wells in the Mishnock River Basin since 1965 and has proposed two alternative ground-water-development plans to meet current and future water-supply needs. The RIWRB also is currently planning to develop potential water supplies within the Big River Management Area to meet future water-supply needs (Beta Engineering, Inc., 1999).

Seasonal Ground-Water Demand in Rhode Island

The timing of water demands in Rhode Island is a critical factor in water-resource planning. Monthly water-withdrawal patterns for six water-supply systems that are largely dependent on ground water are shown in figure 13. These data, which were collected as part of USGS water-use studies in Rhode Island (Barlow, 2003; Wild and Nimiroski, 2004; E.C. Wild, U.S. Geological Survey, written commun., 2005), were provided by water suppliers and include the period from January 1995 through December 1999. Individual average monthly water-supply withdrawals range from a minimum of about 6 percent of average annual water withdrawals in April (for the KCWA) to a maximum of about 13 percent of average annual water withdrawals in July (for the United Water System, North Kingstown). The thick line in figure 13 is a smoothed average of monthly ground-water-withdrawal rates for all six water-supply systems.

Factors that determine the annual distribution for each water-supply system 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., 2003). The general trend for all of the systems shown in figure 13, however, indicates that the highest water-supply demands occur during the summer when streamflows are lowest. 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 supply, not monthly or interseasonal demand (Viessman and Hammer, 1985). For example, the KCWA currently has a storage capacity of only a 1 to 3-day supply in water tanks connected to the distribution network (Timothy Brown, Kent County Water Authority, written commun., 2003).

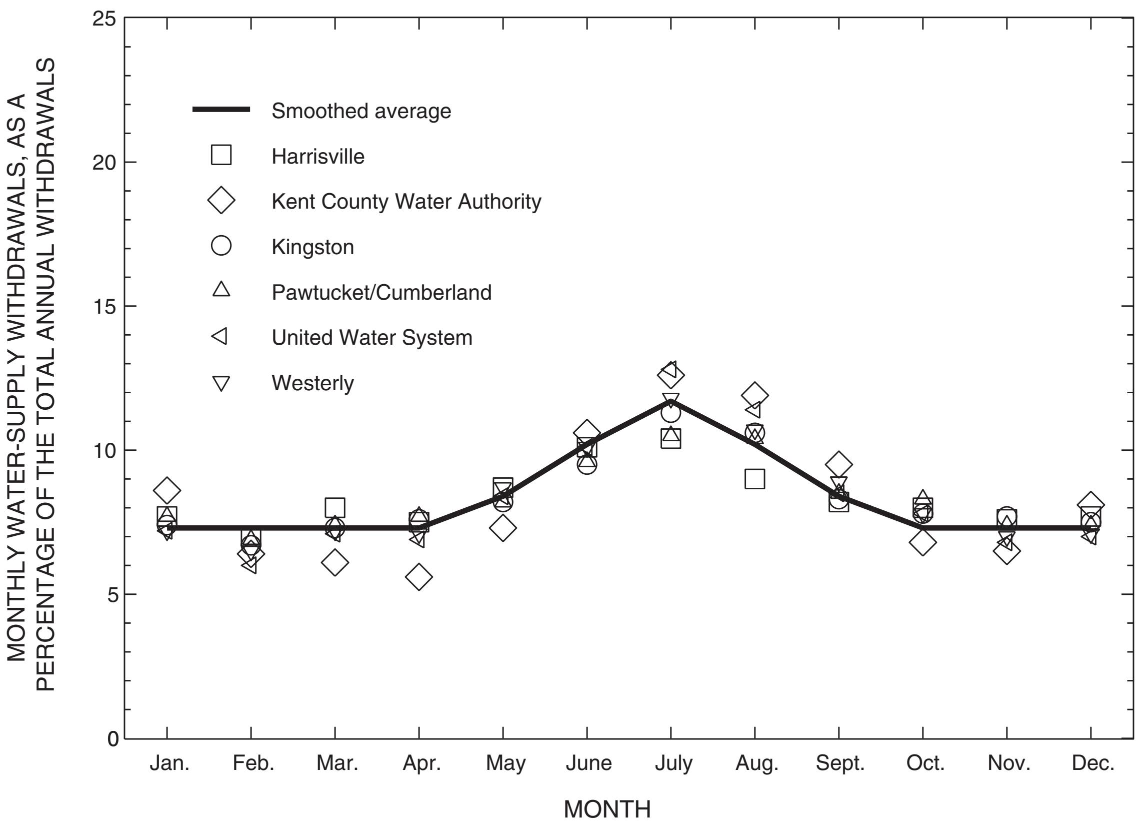

Figure 13. Monthly water-supply withdrawals as a percentage of the total annual withdrawals during the period 1995–99 from six water-supply systems in Rhode Island that obtain a substantial amount of their water supply from ground-water sources.

Ground-Water Supplies in the Big River Area

The KCWA has owned and operated production wells in the Mishnock River Basin since June 1965 (Timothy Brown, Kent County Water Authority, written commun., 2003). Well KC01 (fig. 1) was activated in June 1965 and operated through March 2000. Average monthly withdrawals from KC01 during the period 1965–2000 were about 0.66 Mgal/d and ranged from 0 to 1.68 Mgal/d. Well KC02 (fig. 1) was activated in July 1966 and operated through October 1999. Average monthly withdrawals from KC02 during the period 1966–99 were about 0.79 Mgal/d and ranged from 0 to 2.17 Mgal/d. Well KC03 was drilled on the same well site as well KC02 and began operation as a replacement well for KC02 at the end of March 2000. Average monthly withdrawals from KC03 during the period April through December 2000 were about 0.85 Mgal/d and ranged from 0.78 to 0.95 Mgal/d.

Total average monthly ground-water withdrawals in the basin during the period 1965–2000 ranged from a minimum of 0.36 Mgal/d in August 1965 to 3.14 Mgal/d in June of 1976 (fig. 14). The combined average annual rate of withdrawal from the wells during the period 1965–2000 was 1.4 Mgal/d. The yield from the wells in the Mishnock River Basin is about 28 percent of the estimated sustained yield of 5 Mgal/d from all KCWA wellfields in central Rhode Island (Beta Engineering, Inc., 1999). Water demands in Kent County commonly exceed current KCWA ground-water-production capabilities (Beta Engineering, Inc., 1999).

Ground-water withdrawals in the Mishnock River Basin during the period 1965–2000 caused streamflow depletions in the Mishnock River and the Big River at Hill Farm Road. These depletions were estimated by use of the transient numerical model. The resulting streamflow at the Mishnock River at State Route 3 (station 01115970) during the period 1961–2000 is shown in figure 15. The estimated daily mean streamflow in the Mishnock River at State Route 3 during the period 1961–2000 with and without estimated streamflow depletions by ground-water withdrawals was 5.91 and 7.44 ft^3/s, respectively. The estimated daily minimum streamflow with and without these depletions was 0.36 and 2.22 ft^3/s, respectively. The effect of these withdrawals on streamflows is evident in the flow-duration curves shown in figure 16. Estimated streamflow depletions caused by ground-water withdrawals at the Kent County wells at the Lake Mishnock Outflow and the Big River at Hill Farm Road were minor (about 0.25 and 0.22 ft^3/s, on average, respectively). Ground-water withdrawals from Kent County wells KC01 and KC02 in the Mishnock River Basin would not cause streamflow depletion in the Carr River Basin (Granato and others, 2003).

Decreasing yield from wells KC01 and KC02 and increased water demand within the KCWA supply area prompted recent studies to evaluate the feasibility of replacement wells and expansion of the KCWA production wellfield in the Mishnock River Basin (Timothy Brown, Kent County Water Authority, written commun., 1996). To meet current and projected water needs, the KCWA explored two water-supply development alternatives. These alternatives were not designed to meet the peak summer water-supply demands of the area, but were designed to maximize total annual withdrawals from the Mishnock River Basin (Timothy Brown, Kent County Water Authority, written commun., 2003). The first alternative was designed to use replacement wells in the existing Mishnock well-field area under an existing water-supply permit to produce an annual average withdrawal rate of about 2.6 Mgal/d (Camp Dresser and McKee, Inc., 1999, 2000, 2001). These wells, designated as KC03 and KC04, are listed in table 14 and are shown in relation to the ground-water model grid in figure 17. The annual pattern of withdrawals for this proposed ground-water development scenario is shown in figure 18*A*. The average streamflow at the Mishnock River at State Route 3 for the period 1961–2000 is estimated to be 4.26 ft^3/s if the withdrawal pattern specified in figure 18*A* was to be followed during the entire 1961–2000 period. This ground-water development scenario would meet the year-round monthly average instream-flow criterion of 0.5 $ft^3/s/mi^2$ (fig. 18*B*). This ground-water development scenario also would maintain seasonal variability in monthly average flows at the Mishnock River at State Route 3 in the average year (fig. 18*B*). Under this scenario, streamflows in the Mishnock River at State Route 3 are estimated to be less than or equal to 0.1 ft^3/s for about 2 percent of the time during the 40-year period 1961–2000 (fig. 16*B*). Streamflow depletions at the Lake Mishnock Outflow and the Big River at Hill Farm Road caused by ground-water withdrawals at these Kent County wells would be about 0.53 and 0.45 ft^3/s, on average, respectively. Ground-water withdrawals from these wells in the Mishnock River Basin would not cause streamflow depletion in the Carr River Basin (Granato and others, 2003).

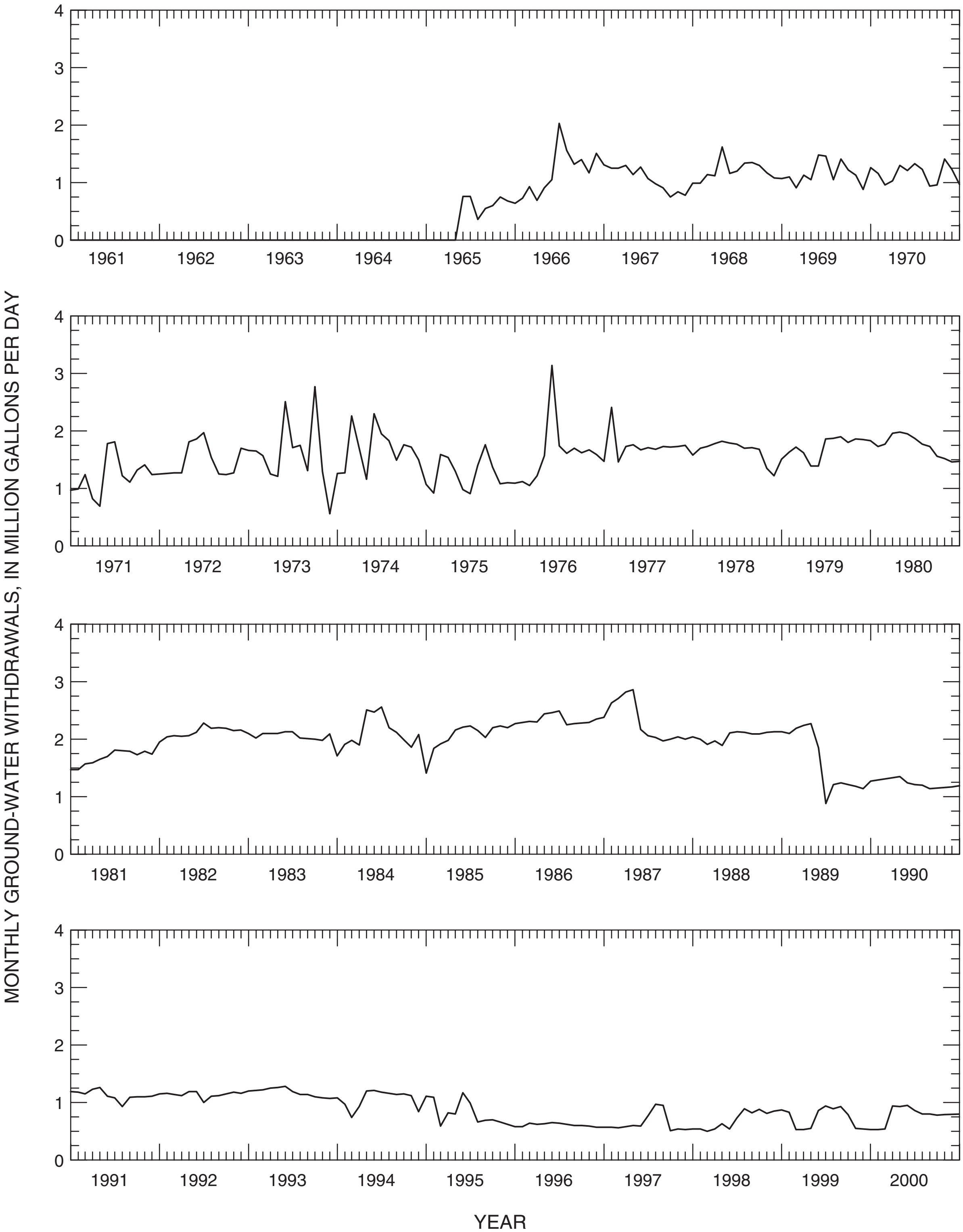

Figure 14. Total monthly ground-water withdrawals from Kent County Water Authority production wells in the Mishnock River Basin, central Rhode Island, 1961–2000.

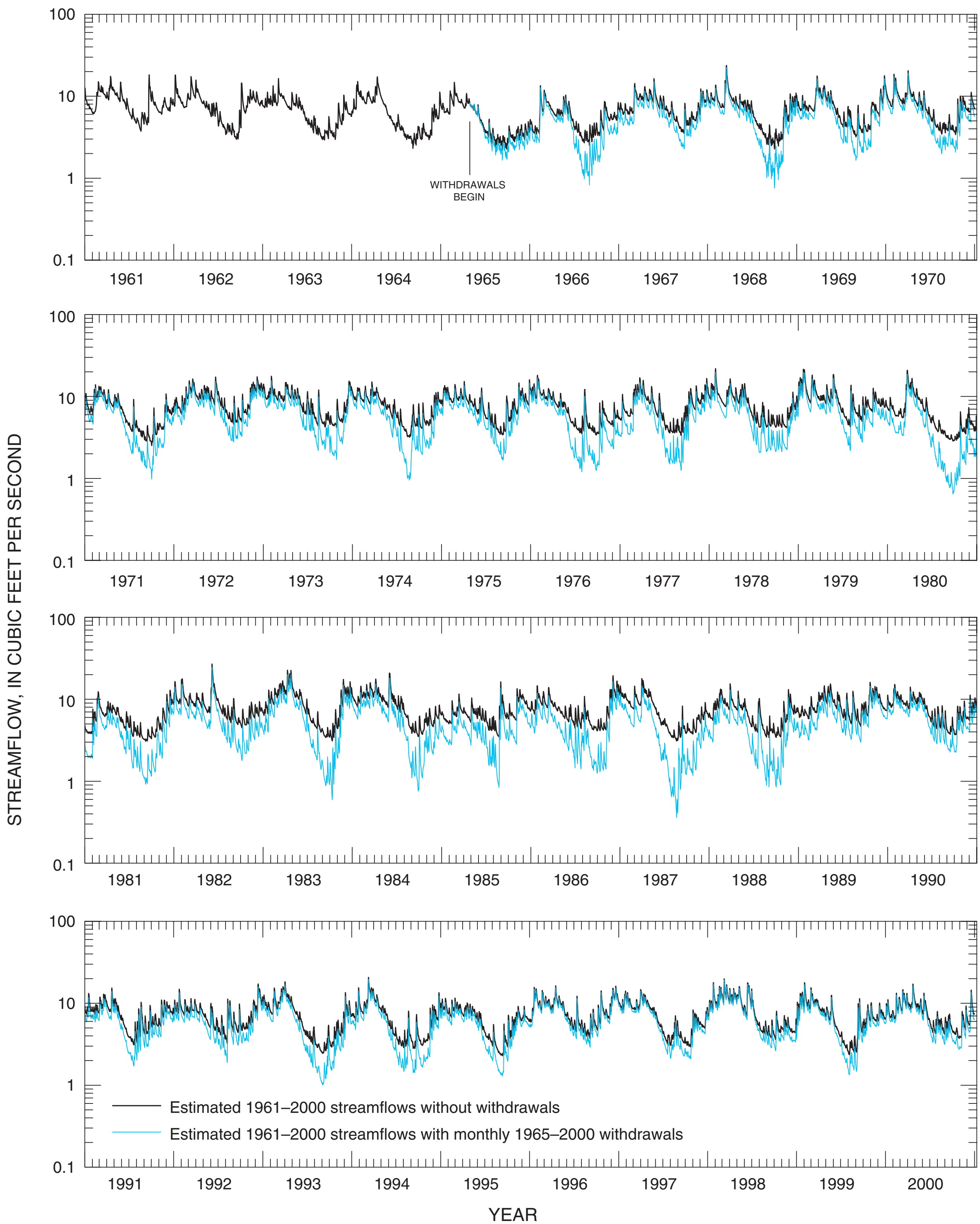

Figure 15. Estimated average daily streamflows at the Mishnock River at State Route 3 (station 01115970) with and without documented monthly ground-water withdrawals in the Mishnock River Basin, central Rhode Island, 1961–2000.

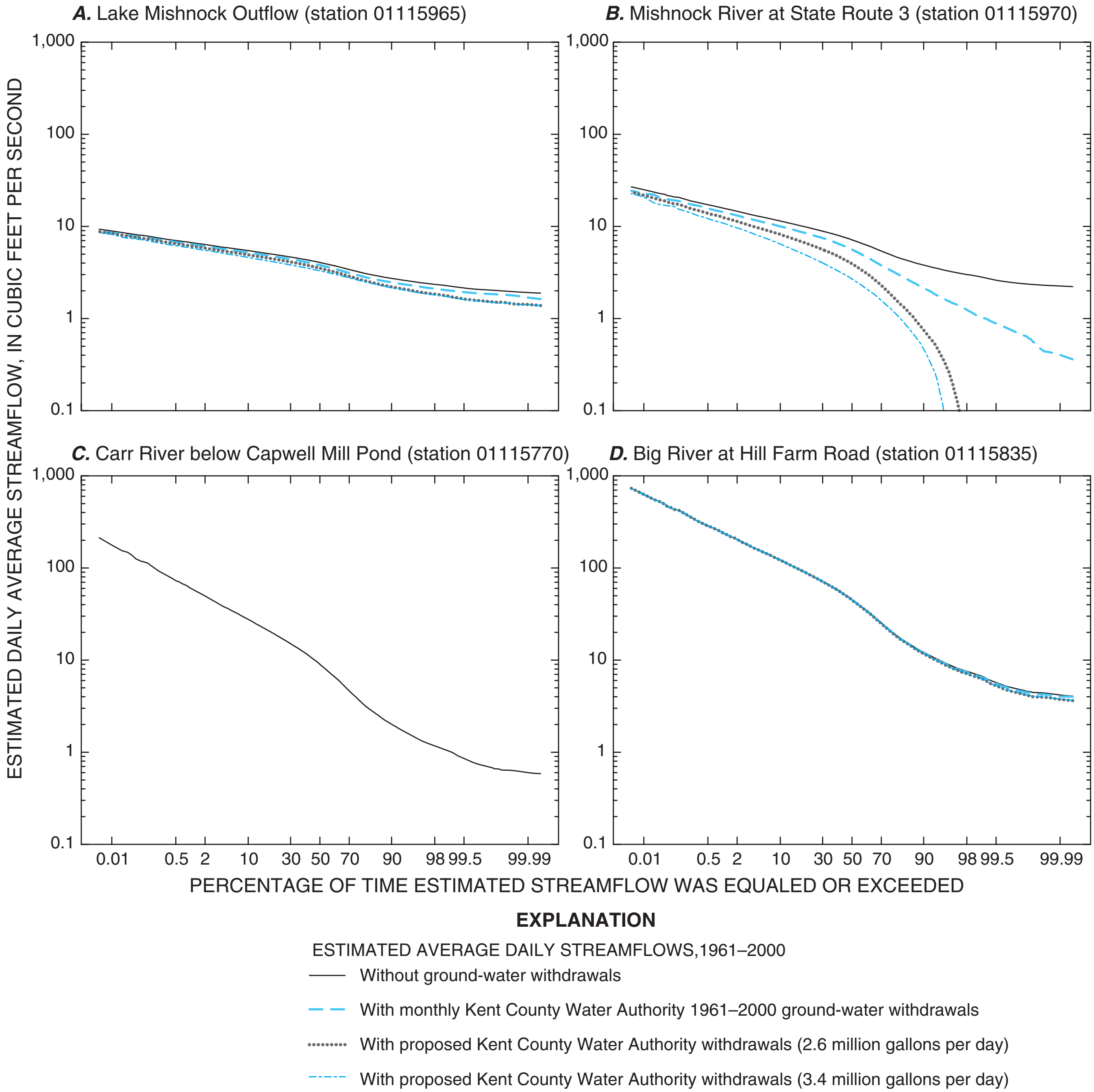

Figure 16. Daily streamflow-duration curves showing the percentage of time that the estimated streamflow would be equaled or exceeded in four different ground-water withdrawal scenarios for the *A*, Lake Mishnock Outflow (station 01115965); *B*, Mishnock River at State Route 3 (station 01115970); *C*, Carr River below Capwell Mill Pond (station 01115770); and *D*, Big River at Hill Farm Road (station 01115835), central Rhode Island, 1961–2000.

Table 14. Characteristics of simulated production wells in the Big River Area, central Rhode Island.

[Well locations are shown in figure 17. KC, Kent County well; KCWA, Kent County Water Authority; USGS, U.S. Geological Survey. WGW West Greenwich well]

Well number	Well name	Model location			Comments
		Layer	Row	Column	
Mishnock River Basin					
1	KC03	3	62	129	Replacement for KC02; in operation since March 2000
2	KC04	3	61	130	KCWA test well; replacement for KC01
3	South-01	4	62	136	KCWA test well
4	North-01	5	59	139	KCWA test well
Carr River Basin					
5	WGW 354	4	94	148	USGS test well
6	WGW 355	4	94	142	USGS test well
7	WGW 374	5	96	146	USGS test well
Big River Basin					
8	WGW 356	2	116	114	USGS test well
9	WGW 363	3	71	96	Hypothetical well 1 based on observation-well data and Stone and Dickerman (2002)
10	WGW 366	4	85	102	Hypothetical well 2 based on observation-well data and Stone and Dickerman (2002)
11	WGW 410	4	98	109	USGS test well
12	WGW 411	3	107	109	USGS test well
13	H3	2	68	97	Hypothetical well 3 based on Stone and Dickerman (2002)

The KCWA also proposed a second water-supply development alternative designed to use the two replacement wells in the existing Mishnock well-field area (KC03 and KC04) and two additional wells (South-01 and North-01) on an adjacent area of land between the wetlands along the Mishnock River and Old Hickory Brook (fig. 17). The annual pattern of withdrawals for this proposed ground-water development scenario is shown in figure 19*A*. The average annual withdrawal for this scenario is about 3.4 Mgal/d, which would meet a year-round monthly average instream-flow criterion of 0.5 $ft^3/s/mi^2$ in the average year (Camp Dresser McKee, Inc., 1999, 2000, 2001). These ground-water withdrawals vary seasonally from about 2.2 Mgal/d during the summer and early fall to about 4.5 Mgal/d during the late fall, winter, and spring (fig. 19*A*). The average streamflow at the Mishnock River at State Route 3 during the period 1961–2000 is estimated to be 2.78 ft^3/s if the wells were operated following the withdrawal pattern specified in figure 19*A* during this period. Estimated average monthly flows in this withdrawal scenario have seasonal variation that is less than the variation under the condition without ground-water withdrawals (fig. 19*B*). Under this water-supply development scenario, streamflows in the Mishnock River are estimated to be less than or equal to 0.1 ft^3/s for about 4 percent of the time during the 40-year period 1961–2000 (fig. 16*B*). Streamflow depletions at the Lake Mishnock Outflow and the Big River at Hill Farm Road caused by these ground-water withdrawals at these Kent County wells would be about 0.73 and 0.43 ft^3/s, on average, respectively. Ground-water withdrawals from these wells in the Mishnock River Basin would not cause streamflow depletion in the Carr River Basin.

The USGS examined the potential for ground-water withdrawals from six well sites in the Carr River and Big River Basins (USGS wells WGW 354, WGW 355, WGW 356, WGW 374, WGW 410, and WGW411; table 14) based on the glacial geology and estimated aquifer characteristics of the area (Stone and Dickerman, 2002). Granato and others (2003) examined two additional hypothetical production-well sites (WGW 363 and WGW 366) in the Big River Basin. These sites were selected for examination on the basis of well logs taken during the drilling of 2-in. monitoring wells (Craft, 2001), the geologic map, and geologic sections (Stone and Dickerman, 2002). This information indicates that these sites overlie an extensive area of semiconfined sand and gravel deposits estimated to have a high transmissivity (greater than 10,000 ft^2/d). Granato and others (2003) simulated the potential effects of withdrawals from these eight wells in the Big River and the Carr River Basins and from the four well sites identified by the KCWA in the Mishnock River Basin to examine the potential effects of ground-water withdrawals on streamflows in the area under long-term average monthly conditions. In the current study, a third hypothetical production well site (designated as H3; table 14) was identified in the Big River Basin in sand and gravel deposits that border the Big River in the backwater of the Flat River Reservoir. This additional site was selected because it is in a highly transmissive area and is not expected to be ecologically sensitive. The 13 simulated well sites are shown in relation to the ground-water model grid in figure 17.

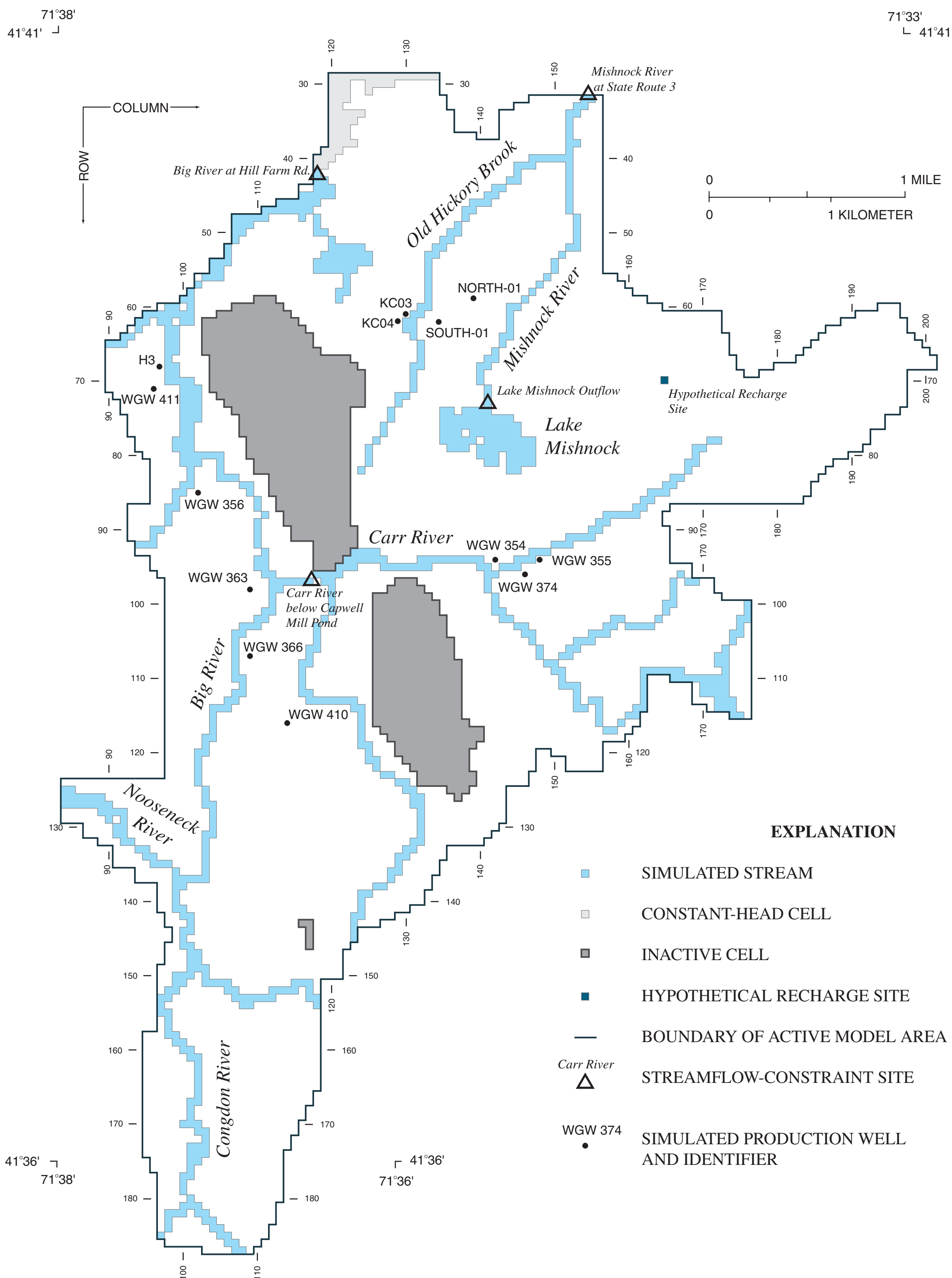

Figure 17. Simulated production wells and streamflow-constraint sites identified for management-model formulations in the Big River model area, central Rhode Island.

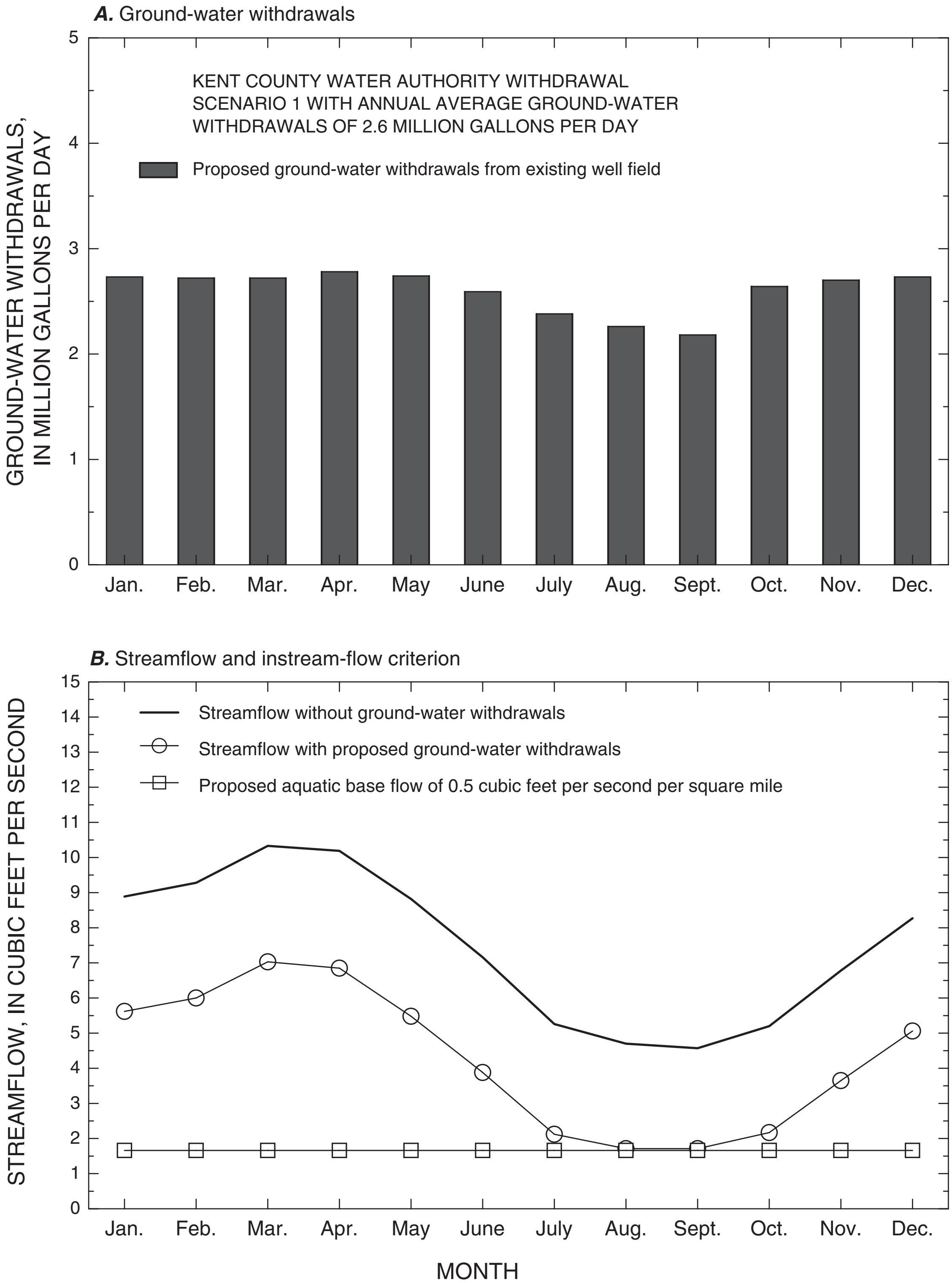

Figure 18. *A*, proposed monthly ground-water withdrawals from the simulated Kent County Water Authority production wells KC03 and KC04; and *B*, estimated average monthly streamflows with and without proposed ground-water withdrawals during the period 1961–2000, and annual instream-flow criteria values for the Mishnock River Basin, central Rhode Island.

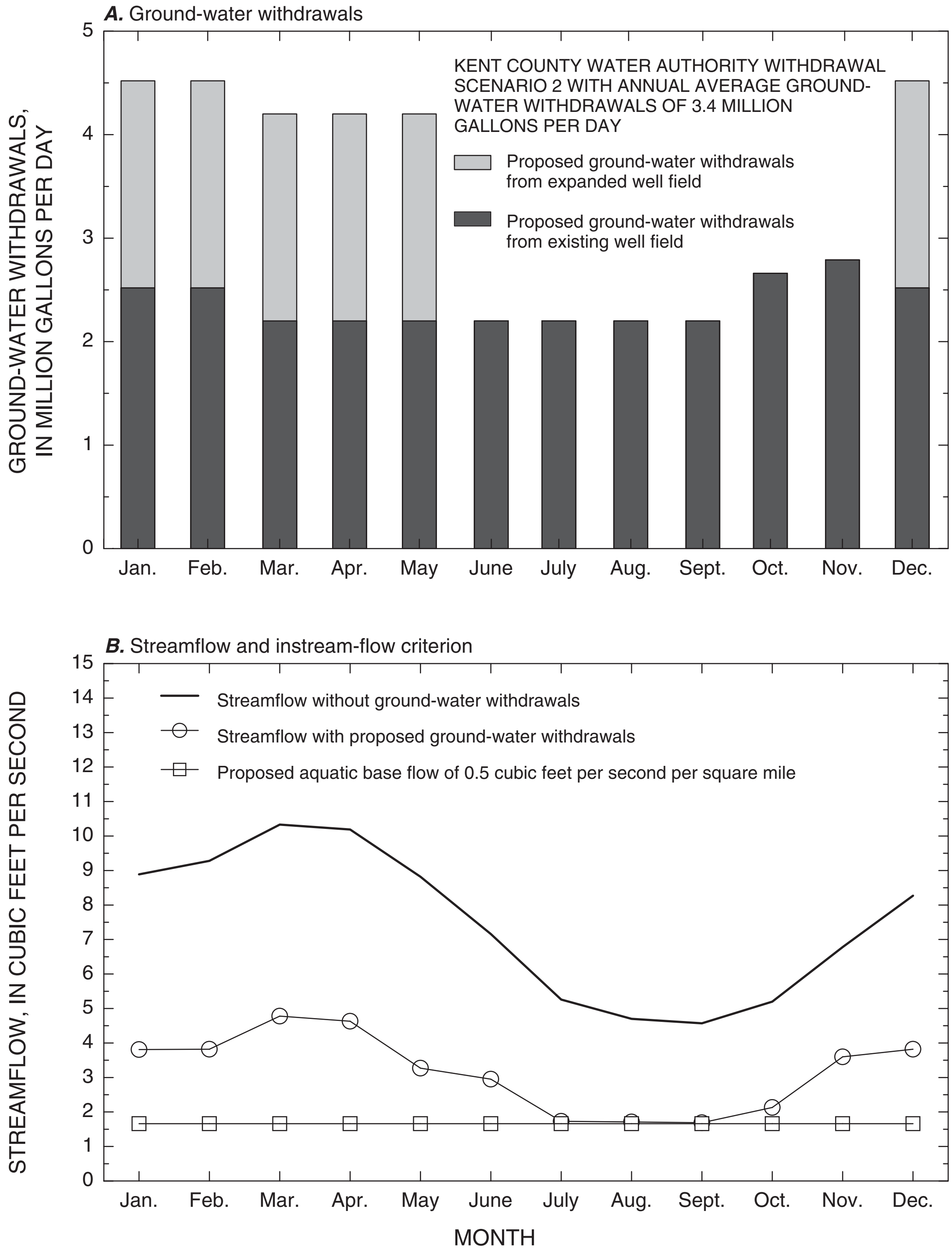

Figure 19. *A*, proposed monthly ground-water withdrawals from the simulated Kent County Water Authority production wells KC03, KC04, South-01, and North-01; and *B*, estimated average monthly streamflows with and without proposed ground-water withdrawals during the period 1961–2000, and annual-instream flow criteria values for the Mishnock River Basin, central Rhode Island.

Conjunctive-Management Model to Evaluate Ground-Water-Development Options

A conjunctive-management model was developed for the Big River Area to evaluate how alternative instream-flow criteria and water-supply demands affect ground-water development options in the Big River study area. The conjunctive-management model combines results of simulations with the transient-numerical model developed for the study area with a linear-optimization model of water-resource management. The linear-optimization model consists of a mathematical formulation (statement) of the ground-water-development goals in the basin and a set of constraints that limit those goals. This section describes the mathematical formulation of the conjunctive-management model, the response-matrix technique used to solve the linear model, and five applications of the model.

Formulation of the Conjunctive-Management Model

Formulation of the conjunctive-management model consists of defining a set of decision variables, an objective function, and a set of constraints. The decision variables were monthly withdrawal rates at each of the simulated production wells. The solution of the conjunctive-management model provides the withdrawal rates for each well. Mathematically, the decision variables were expressed as $Qw_{i,t}$, which is the withdrawal rate at well i in month t. The subscript t ranges from $t = 1$ for January through $t = 12$ for December. The model had 156 decision variables, which are the withdrawal rates at each of the 13 wells (table 14) during the 12 months of a year.

The objective function of the model was to maximize total annual ground-water withdrawals from the aquifer, which was written mathematically as

$$maximize \sum_{i=1}^{13} \sum_{t=1}^{12} ND_t Qw_{i,\ t} , \tag{1}$$

where ND_t is the number of days in month t. Values of the objective function were calculated in million gallons of water withdrawn from the aquifer during the 12-month period.

The value of the objective function was limited by a set of specified constraints that included combinations of (1) maximum rates of streamflow depletion in the Mishnock, Carr, and Big River Basins; (2) minimum and maximum withdrawal rates at each well; and (3) alternative patterns of monthly water demands. The set of constraints used for a specific formulation of the management model varied from one model application to the next.

Maximum rates of streamflow depletion were required to be less than or equal to maximum specified rates at the four streamflow-constraint sites, which correspond to partial-record stations in the basin (fig. 17): Lake Mishnock Outflow, Mishnock River at State Route 3, Carr River below Capwell Mill Pond, and Big River at Hill Farm Road. These constraints were written as

$$Qsd_{j,\ t} \le (Qsd_{j,\ t})_{max} , \tag{2}$$

where $Qsd_{j,t}$ is 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 were specified for each of the four constraint sites and for each of the 12 months, for a total of 48 streamflow-depletion constraints.

Constraints on minimum and maximum withdrawal rates at each well were written as

$$(Qw_{i,\ t})_{min} \le Qw_{i,\ t} \le (Qw_{i,\ t})_{max}, \tag{3}$$

where $(Qw_{i,\ t})_{min}$ and $(Qw_{i,\ t})_{max}$ are the minimum and maximum withdrawal rates at well i in month t. The minimum withdrawal rate at each well was zero and did not need to be specified explicitly in the model. The maximum withdrawal rate at each well for each month was set at 1.40 Mgal/d. There were 156 specified constraints on maximum withdrawal rates in the model.

For some model applications, total monthly withdrawals from the four simulated wells in the Kent County Water Authority water-supply system were required to be either equal to or greater than the monthly demands proposed by the water authority (figs. 18*A* and 19*A*). These constraints were written as

$$\sum_{i=1}^{4} Qw_{i,\ t} = D_{KCWA,\ t} , \tag{4a}$$

for the case in which total withdrawals must be equal to the proposed demands, and as

$$\sum_{i=1}^{4} Qw_{i,\ t} \ge D_{KCWA,\ t} , \tag{4b}$$

for the case in which total withdrawals must be greater than or equal to the proposed demands. The variable $D_{KCWA,t}$ is the water-authority demand in month t. Constraints were specified for each of the 12 months of the year.

For some model applications, a requirement also was made that the annual pattern of total monthly withdrawals in the entire basin must be consistent with the annual pattern of monthly water demands (that is, ground-water withdrawals) for Rhode Island (fig. 13). This requirement was specified as a set of 11 constraints that control the relation among total withdrawals from one month to the next:

$$\sum_{i=1}^{NW} Qw_{i,t_1} = \alpha_{t_{1,2}} \sum_{i=1}^{NW} Qw_{i,t_2} \ , \tag{5}$$

where NW is the number of wells in the entire basin (13); Qw_{i,t_1} and Qw_{i,t_2} are the withdrawal rates at well i in months t_1 and t_2, respectively; and $\alpha_{t_{1,2}}$ is the ratio of the percentage of total demands in month t_1 to total demands in month t_2 (adjusted for the ratio of the number of days in each month). The percentage of total demands for each month were: 7.26 percent for the months of October through April, 8.71 percent for May and September, 10.15 percent for June and August, and 11.60 percent for July (fig. 13). All calculations of $\alpha_{t_{1,2}}$ were normalized to the February demand (7.26 percent) and days in the month (28.25) because this value is the minimum of all 12 monthly values.

Lastly, some model formulations required a seasonal pattern of pumping in which total monthly withdrawals were equal from June through October (the dry season) and were equal from November through May (the wet season). This formulation is equivalent to equation 5 except that $\alpha_{t_{1,2}}$ is simply the ratio of the number of days in each month and each summation includes the months defined for each season.

In summary, the conjunctive-management model was formulated to maximize total annual ground-water withdrawals from the aquifer (eq. 1). All applications of the model included constraints on streamflow depletions caused by ground-water withdrawals (eq. 2) and withdrawal rates at the wells (eq. 3); in addition, some applications of the model also included constraints on monthly water demands by Kent County Water Authority (eq. 4a or 4b) and constraints that ensured that the annual pattern of monthly withdrawals from the entire basin mimicked monthly water demands for Rhode Island (eq. 5) or a withdrawal pattern in which withdrawals were equal within the dry season and within the wet season.

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

The response-matrix technique was used to solve the conjunctive-management model. The technique is based on the assumption that the rate of streamflow depletion at each streamflow-constraint site is a linear function of the rate of ground-water withdrawal at each production well. By assuming linearity, it is possible to determine 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), and Eggleston (2004). 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 that other nonlinear effects simulated by the transient model, such as head-dependent boundary conditions, are not large.

Implementation of the response-matrix technique requires calculation of characteristic streamflow-depletion responses at each of the four streamflow-constraint sites to simulated unit withdrawals at each of the 13 simulated wells. To calculate the characteristic responses, 13 simulations of the transient numerical model of the Big River Area were made. In each simulation, the withdrawal rate for one of the wells was specified as 1.0 Mgal/d for one month (the month of January was used); at the end of the month, the withdrawal rate at the well was returned to zero. The single-month increase of 1.0 Mgal/d is referred to as the unit withdrawal Qw_i^* 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 with the unit withdrawal inactive. 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 withdrawal at well i. Streamflow-depletion response coefficients ($r_{j,i,t}$) are then defined as

$$r_{j,\,i,\,t} = \frac{Qsd^*_{j,\,i,\,t}}{Qw_i^*} \ . \tag{6}$$

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 production well can be accounted for as streamflow depletion in the first month. If a well causes depletions in only one stream, the response coefficients for that stream would add up almost to 1.0; the remainder would be attributable to small reductions in riparian evapotranspiration. Similarly, if a well affects streamflow in more than one basin, the sum of response coefficients from the basins that are affected would be about 1.0. For the assumption of linearity to be valid, the values of the response coefficients for each well/streamflow-constraint-site pair must remain constant for all simulated withdrawal and hydrologic conditions.

Response coefficients for several of the well/streamflow-constraint-site pairs are shown in figures 20–23. Factors that affect the values of the response coefficients are the relative positions of the wells and streamflow-constraint sites (including the vertical positions of the screened interval of each well), the geometry and hydraulic properties of the aquifer, the streambed conductance, and other physical characteristics of the streams as simulated with the numerical model. Streamflow at the two Mishnock River constraint sites was not affected by simulated withdrawals in the Big River Basin, and streamflow at the Carr River site was not affected by simulated withdrawals in the Mishnock River Basin. Streamflow in the Big River Basin, however, was affected by simulated withdrawals in all three basins (fig. 23). Withdrawals in the Mishnock River Basin cause depletion at the Big River constraint site because the withdrawals capture ground water that otherwise would have discharged to Maple Root Pond, which is a tributary to the Big River (Granato and others, 2003).

The response coefficients shown in figures 20–23 indicate that there is substantial variability in the quantity and timing of streamflow-depletion responses to the simulated unit withdrawals. For example, the effects of the unit withdrawal at well WGW 366 on streamflow in the Big River (fig. 23*C*) change rapidly, with a large streamflow depletion in the first month (0.7) and smaller depletions in the following months (less than or equal to 0.15). Simulated well WGW 366 is relatively close to the stream (within 500 ft) and is screened in a sand and gravel unit that is in good hydraulic connection with the Big River (Stone and Dickerman, 2002). In contrast, the effects of unit withdrawals at wells in the Mishnock and Carr River Basins on estimated streamflow in the Mishnock River at the Lake Mishnock Outflow (fig. 20) change slowly, with a small streamflow depletion in the first month and even smaller depletions that continue for several months after the unit withdrawals have ended.

Because of the assumed linearity of the system, 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

$$Qsd_{j,\,t} = \sum_{i=1}^{13} \sum_{k=1}^{12} r_{j,\,i,\,k} Qw_{i,\,k'}\,, \tag{7}$$

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' is required as a consequence of the annual cycle of withdrawals. For example, streamflow depletions in January ($t = 1$) can be affected by withdrawals in December ($t = 12$). Although the summation includes 12 terms for each well/streamflow-constraint-site pair, many of the terms equal zero, because many of the response coefficients equal zero.

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

$$\sum_{i=1}^{13} \sum_{k=1}^{12} r_{j,\,i,\,k} Qw_{i,\,k'} \le (Qsd_{j,\,t})_{max}\,. \tag{8}$$

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

Difficulties arose in the use of the response-matrix technique because the numerical model of the basin is weakly nonlinear. These nonlinearities are the result of two factors. First, the aquifer is unconfined, which means that the saturated thickness and transmissivity change as withdrawal rates at the wells change. Second, evapotranspiration and streamflow leakage were simulated as piecewise-linear functions of calculated ground-water heads. 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. These types of nonlinearities have been addressed in ground-water-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; and Ahlfeld and Mulligan, 2000, p. 160–163). This sequential-linearization approach was not used, however, because it is computationally intensive and because simulations with the transient model indicated that the response coefficients change very little as the simulated withdrawal conditions change. These simulations consisted of different unit-withdrawal rates, different background withdrawal conditions, and different months in which the unit withdrawal was active. The primary reason that the response coefficients change very little for the different withdrawal conditions is that the aquifer is highly transmissive near many of the wells. As a consequence, drawdowns caused by different simulated withdrawal conditions do not cause substantial changes in the saturated thickness or transmissivity of the aquifer beyond the immediate area of the well.

Another complicating factor in the use of the response-matrix technique is that the lengths of the stress periods in the transient model are not constant, but range from 28 to 31 days. This difference contradicts one of the assumptions of the response-matrix technique, which requires stress periods to be of equal length. Because the lengths of the stress periods used in the model do not vary substantially, however, violation of this assumption is unlikely to affect the model solution markedly.

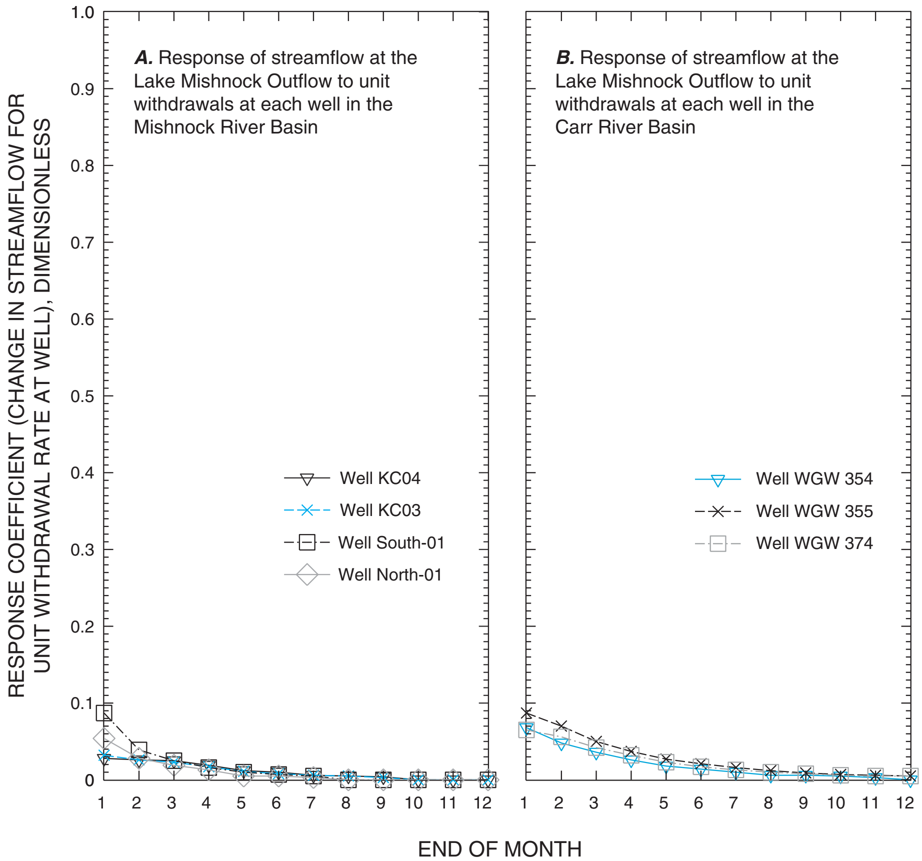

Figure 20. Simulated response coefficients for the Lake Mishnock Outflow (station 01115965), Rhode Island, from individual wells in the *A*, Mishnock River Basin; and *B*, the Carr River Basin, each with a unit withdrawal rate of 1.0 million gallons per day. (Well locations and streamflow-gaging stations are shown in relation to the model grid on fig. 17).

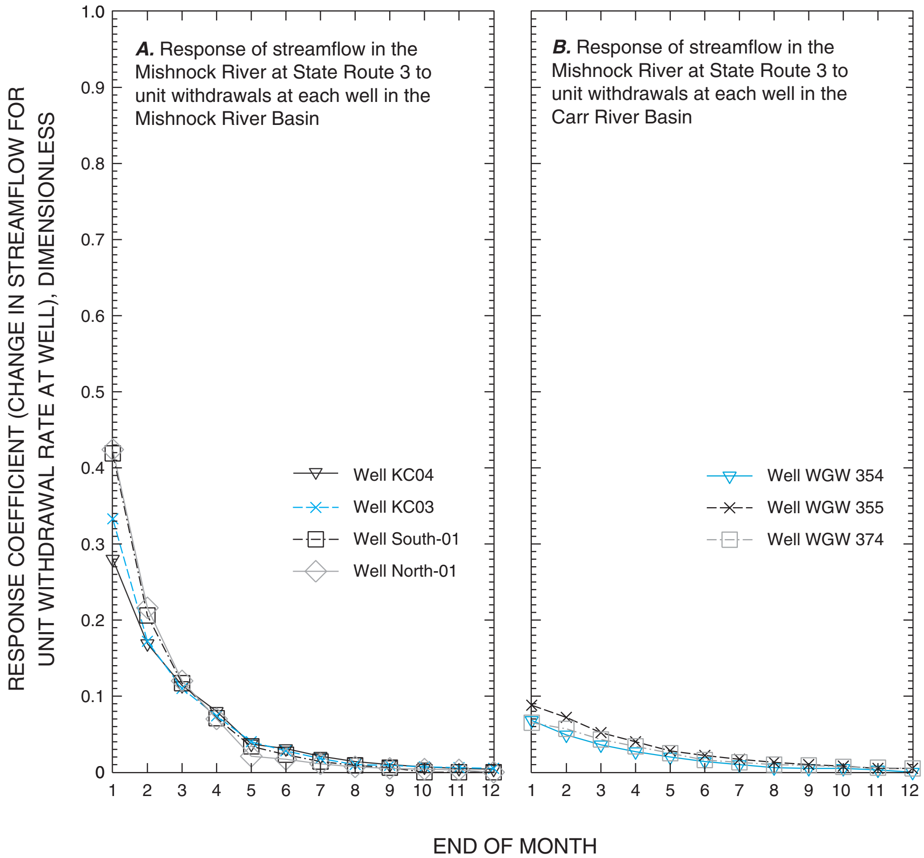

Figure 21. Simulated response coefficients for the Mishnock River at State Route 3 (station 01115970), Rhode Island, from individual wells in the *A*, Mishnock River Basin; and *B*, the Carr River Basin, each with a unit withdrawal rate of 1.0 million gallons per day. (Well locations and streamflow-gaging stations are shown in relation to the model grid on fig. 17).

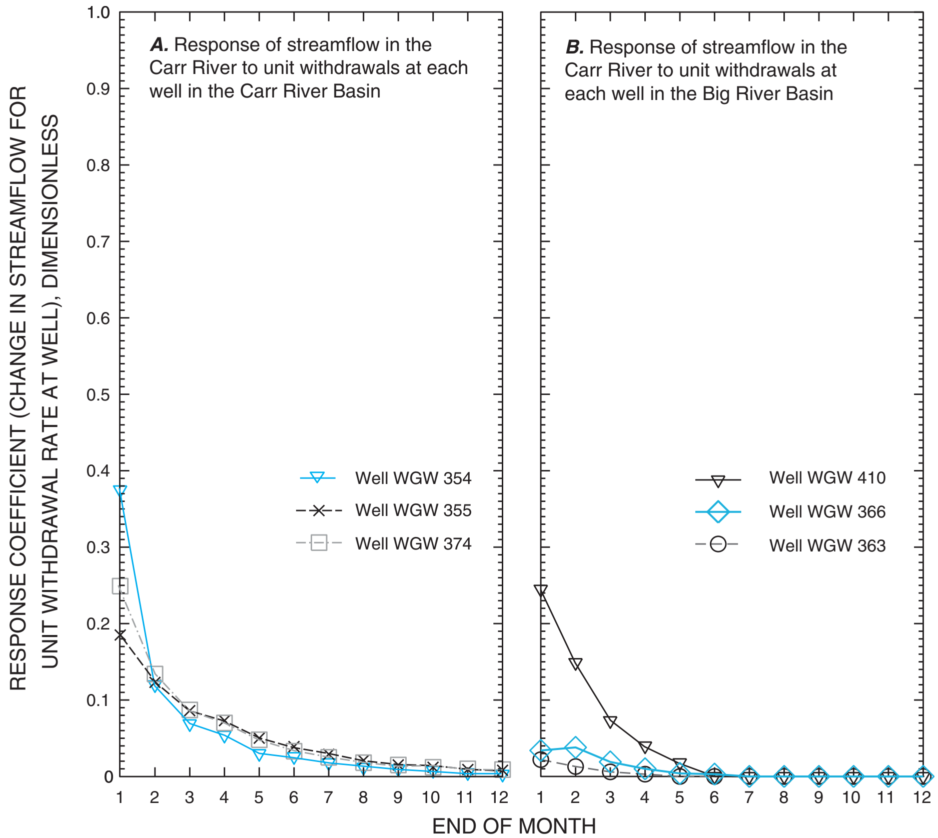

Figure 22. Simulated response coefficients for the Carr River below Capwell Mill Pond (station 01115765), Rhode Island, from individual wells in the *A*, Carr River Basin; and *B*, the Big River Basin, each with a unit withdrawal rate of 1.0 million gallons per day. (Well locations and streamflow-gaging stations are shown in relation to the model grid on fig. 17).

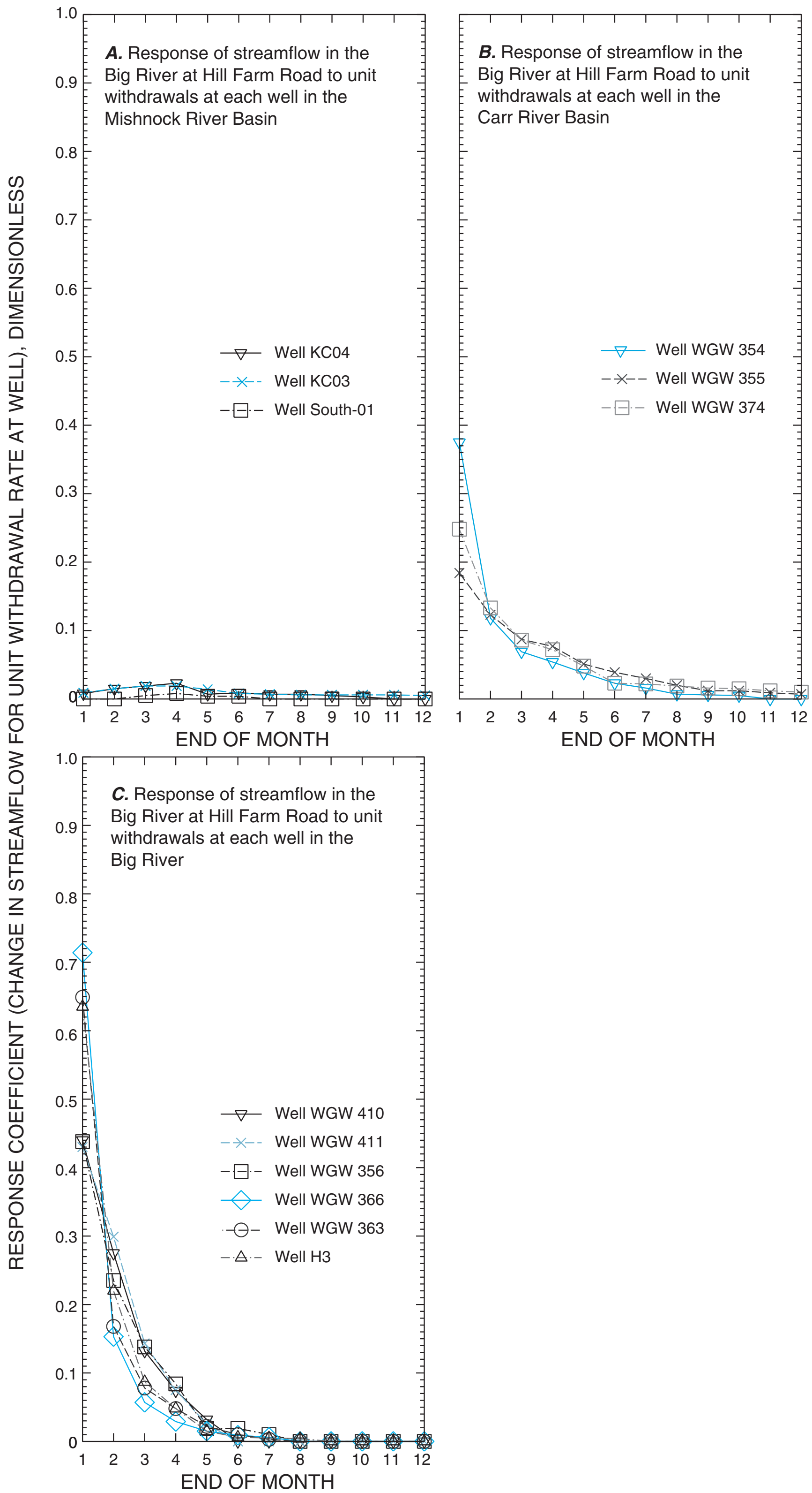

Figure 23. Simulated response coefficients for the Big River at Hill Farm Road (station 01115835), Rhode Island, from individual wells in the *A*, Mishnock River Basin; *B*, Carr River Basin; and *C*, the Big River Basin, each with a unit withdrawal rate of 1.0 million gallons per day. (Well locations and streamflow-gaging stations are shown in relation to the model grid on fig. 17).

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 ground-water withdrawals. The LINDO linear-programming computer software (LINDO Systems, 1996; Schrage, 1997) was used to solve each specific application of the conjunctive-management model described in the next section. 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.

Applications of the Model

Five sets of applications of the conjunctive-management model were made to examine the effect of alternative instream-flow criteria and water-supply demands on ground-water-development options in the Big River Area. Each set of model applications indicates the maximum ground-water withdrawals at each simulated well that may be feasible for a given set of constraints, to assist water-resources managers in evaluation of environmental-protection goals and water-supply needs. The five sets of alternatives include:

- Alternative annual, seasonal, and monthly instream-flow criteria to assess their effects on withdrawals and streamflow statistics;
- Alternative ground-water-demand constraints to evaluate the Rhode Island demand pattern and proposed KCWA ground-water-withdrawal plans;
- Alternative water-supply-network constraints to address network-design issues;
- Alternative instream-flow criteria for dry periods, to examine potential ground-water withdrawal plans in drought years; and
- Artificial recharge as an alternative management option to examine potential benefits of wastewater recharge in the Mishnock River Basin.

The results for each set of alternatives are described in the following five subsections. Monthly ground-water-withdrawal rates calculated for each well in each alternative of the conjunctive-management model are listed in Appendix 2.

Alternative Instream-Flow Criteria

The State of Rhode Island is evaluating proposed changes in instream-flow criteria for regulation of water-supply withdrawals. Conjunctive-management model formulations are examined to quantify relations between potential instream-flow criteria and the potential ground-water withdrawals from the entire Big River Area. These formulations are designed to maximize annual withdrawals (eq. 1). Monthly ground-water-withdrawal rates were constrained by the allowable streamflow depletions (eq. 2) and the maximum monthly withdrawal rates at each well (eq. 3). The monthly withdrawal rates at each well were constrained to be less than or equal to 1.4 Mgal/d at each of the 13 simulated production-well sites in the study area (fig. 17) without regard to withdrawal rates proposed by the KCWA or the annual pattern of monthly ground-water demands typical for Rhode Island. The results of these scenarios indicate the maximum annual withdrawal rates that may be obtainable as a function of the instream-flow criteria under average conditions for the period 1961–2000.

Alternative Annual Instream-Flow Criteria: Instream-flow criteria were selected from a range of 0 to 0.8 $ft^3/s/mi^2$. Although annual instream-flow criteria are constant throughout the year, allowable depletions for each month are different because allowable depletions (tables 1-2 to 1-5 in Appendix 1) are calculated by subtracting each instream-flow criterion from the estimated average streamflow for each month (table 5) at each of the four constraint sites. September has the lowest allowable depletion and March has the highest allowable depletion at each of the four constraint sites. The total average annual ground-water withdrawal is shown as a function of instream-flow criterion in figure 24. The conjunctive-management model was run 26 times to determine ground-water withdrawals for each criterion value in the range (0 to 0.8 $ft^3/s/mi^2$). Of these 26 runs, the results of 5 runs (labeled A through E on fig. 24) are discussed because they correspond to instream-flow criteria that have been considered for use in New England.

The hydrologic limit (0 $ft^3/s/mi^2$) (point A on fig. 24) is defined as the point at which potential streamflow depletions equal the estimated 1961–2000 average monthly streamflow (table 5). The maximum ground-water withdrawal rate under this instream-flow criterion (management model MM01A**;** table 15) is about 16.2 Mgal/d (fig. 24, point A). The hydrologic limit may be considered as the maximum sustainable ground-water-withdrawal rate because ground-water withdrawals equal long-term-average streamflows in the absence of withdrawals. If ground water is withdrawn and exported from the basin at this rate, however, the streams would stop flowing at the constraint location and in the vicinity of the withdrawal wells in any year in which precipitation, recharge, and resulting natural streamflow were at or below the average conditions for the period 1961–2000. Use of the hydrologic limit (0 $ft^3/s/mi^2$) as a minimum-flow standard would not be protective of the biological, chemical, or physical integrity of aquatic and riparian ecosystems within the Big River Area.

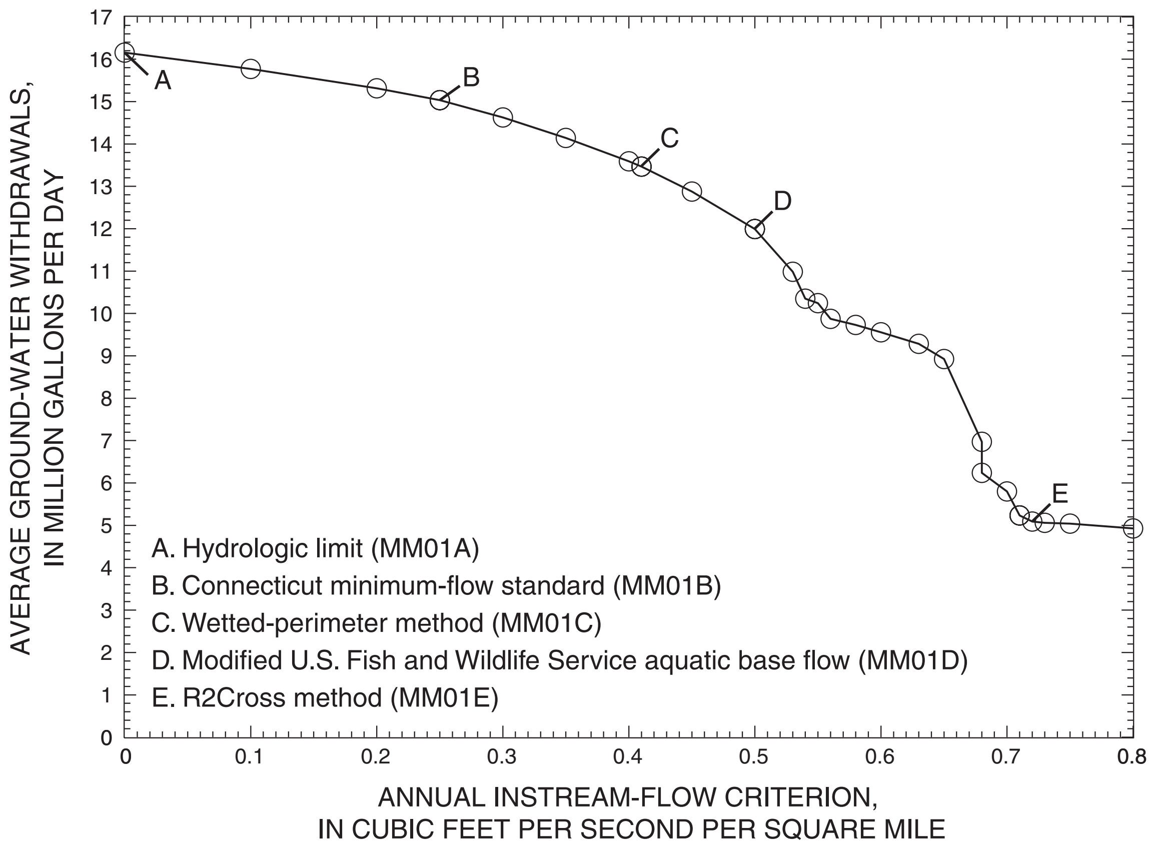

Figure 24. Effect of alternative annual instream-flow criteria on model-calculated average annual ground-water withdrawals from the Big River Area, Rhode Island.

The maximum obtainable ground-water withdrawal rate decreases gradually as the instream-flow criterion is increased from 0 $ft^3/s/mi^2$ to about 0.5 $ft^3/s/mi^2$ (fig. 24). Use of the historic Connecticut minimum-instream-flow standard (0.25 $ft^3/s/mi^2$; point B on fig. 24) as an instream-flow criterion (management model MM01B) is more protective than the hydrologic limit. Total ground-water withdrawals under the Connecticut standard are 15.1 Mgal/d (table 15). Use of the wetted-perimeter estimate (0.41 $ft^3/s/mi^2$; point C on fig. 24) as an instream-flow criterion (management model MM01C) reduces total withdrawals to about 13.5 Mgal/d. Use of the modified USFWS aquatic base flow (0.50 $ft^3/s/mi^2$; point D on fig. 24) as an instream-flow criterion (management model MM01D) reduces total simulated withdrawals to 12 Mgal/d. Total simulated ground-water withdrawals in the Mishnock River Basin are slightly higher under the modified USFWS aquatic base flow than under the wetted-perimeter estimate (table 15), because wells in the Carr River Basin intercept ground water that would naturally discharge to the Mishnock River Basin (Granato and others, 2003). Therefore, more water is available for withdrawals in the Mishnock River Basin as withdrawals are restricted in the Carr River Basin.

The maximum obtainable ground-water withdrawal rates decrease by almost 2 Mgal/d as the instream-flow criterion increases from 0.50 to 0.54 $ft^3/s/mi^2$ (fig. 24). This decrease occurs because the instream-flow criteria are approaching the average September streamflow value for the Carr River below Capwell Mill Pond for the period 1961–2000. As the instream-flow criterion approaches the estimated average monthly streamflow, the potential depletion in that month in that basin approaches zero (Appendix 1). Response coefficients for wells in the Big River Area indicate that ground-water withdrawals in one month may cause streamflow depletions for periods as long as a year (figs. 20–23). As potential depletion in one month approaches zero, the criterion reduces or precludes the amount of ground-water withdrawals in the current month and in previous months that cause depletions in the current month. Therefore, reductions in potential depletions may not have a linear relation with reductions in the total ground-water withdrawals. Similarly, maximum obtainable withdrawals are reduced by almost 4 Mgal/d as the instream-flow criterion increases from 0.65 to 0.72 $ft^3/s/mi^2$ (the R2Cross Criteria, point E on fig. 24) (management model MM01E) because the higher value is greater than the average September streamflow value for the

Table 15. Potential average annual ground-water withdrawal rates under average hydrologic conditions for the period 1961–2000 with 5 alternative annual instream-flow criteria and 7 alternative seasonal or monthly instream-flow criteria for 13 simulated production wells in the Mishnock, Carr, and Big River Basins, central Rhode Island.

[ABF, Aquatic Base Flow; IFIM, Instream Flow Incremental Methodology; IRFRTG, Ipswich River Fisheries Restoration Task Group; MMA, median of monthly average streamflows; MDEP, Massachusetts Department of Environmental Protection; MM, management model; MMM, median of monthly median streamflows; USFWS, U.S. Fish and Wildlife Service; $ft^3/s/mi^2$, cubic foot per second per square mile; Mgal/d, million gallons per day]

Management-model designation	Instream-flow criterion	Ground-water withdrawals by basin (Mgal/d)			
		Mishnock River	Carr River	Big River	Total
	Alternative Annual Instream-Flow Criteria				
MM01A	Hydrologic limit	4.24	3.55	8.40	16.2
MM01B	Connecticut standard	4.01	2.92	8.14	15.1
MM01C	Wetted-perimeter estimate	3.92	2.09	7.49	13.5
MM01D	Modified USFWS ABF	3.96	1.11	6.95	12.0
MM01E	R2Cross estimate	2.04	.00	3.06	5.10
	Alternative Seasonal or Monthly Instream-Flow Criteria				
MM01F	Saugus River IFIM	3.40	2.48	7.71	13.6
MM01G	MDEP Ipswich River diversion limit	3.24	1.84	7.45	12.5
MM01H	IRFRTG	1.73	.11	3.27	5.12
MM01I	USFWS ABF	.11	.00	.90	1.02
MM01J	MMM	.00	.00	.00	.00
MM01K	Hybrid Method	.00	.00	.00	.00
MM01L	MMA	.00	.00	.00	.00

Big River Basin for the period 1961–2000 (table 5). Results from the management models indicate that application of an instream-flow criteria may preclude ground-water withdrawals for a substantial period of time, even in an average year, if the criterion is high enough to approximate long-term average monthly flows.

The USFWS (1981) proposed seasonal instream-flow criteria to maintain seasonal variation in monthly average streamflows because surface-water diversions could reduce streamflows to the level of the annual criterion during each month of the year. The long streamflow-response times characteristic of ground-water systems in the Big River Area (figs. 20–23) and other valley aquifers in Rhode Island (Barlow and Dickerman, 2001a,b) and Massachusetts (DeSimone and others, 2002) indicate that a single annual instream-flow criterion may be sufficient to provide seasonal variability in monthly average streamflows. The maximum of monthly average streamflows commonly occurs during March and this value is commonly four to six times the minimum of monthly average streamflows, which commonly occurs during September at streamflow-gaging stations in Rhode Island. For example, the ratio of maximum to minimum estimated monthly average streamflows in the Big River at Hill Farm Road is about five in the absence of withdrawals (fig. 25). In comparison, the ratio of maximum to minimum estimated monthly average streamflows under management model MM01B is about 9. This occurs because ground-water withdrawals from the conjunctive-management model reduce streamflows in September to the specified criterion value under long-term monthly average conditions (fig. 25), but do not reduce flows in all months to the criterion value. Ground-water withdrawals throughout the year are limited by the depletions that they cause in September. The protective effect of the most con-straining month, however, may be limited by the response coefficients of potential well sites and the difference between the minimum and maximum monthly average streamflows. For example, monthly average streamflows in the Mishnock River Basin show seasonal variation under the proposed KCWA ground-water development scenarios, but the ratio between the maximum and minimum monthly average streamflow under these scenarios is not substantially increased relative to the ratio between the maximum and minimum monthly average streamflow without ground-water withdrawals (fig. 18*B* and 19*B*).

Alternative Seasonal or Monthly Instream-Flow Criteria: Seven seasonal or monthly instream-flow criteria (discussed in the instream-flow criteria section) were tested to examine the relation between these criteria and total ground-water withdrawals from the Big River Area under long-term monthly average conditions for the period 1961–2000 (table 15; Appendix 2). The minimum monthly instream-flow criterion for the Saugus River IFIM is 0.29 $ft^3/s/mi^2$ (table 1-6), which is comparable to the annual CT instream-flow criterion of 0.25 $ft^3/s/mi^2$. Use of the annual CT criterion (MM01B), however, yields an additional 1.5 Mgal/d of ground-water withdrawals (table 15) because the seasonal IFIM criteria (MM01F) further constrains ground-water withdrawals during

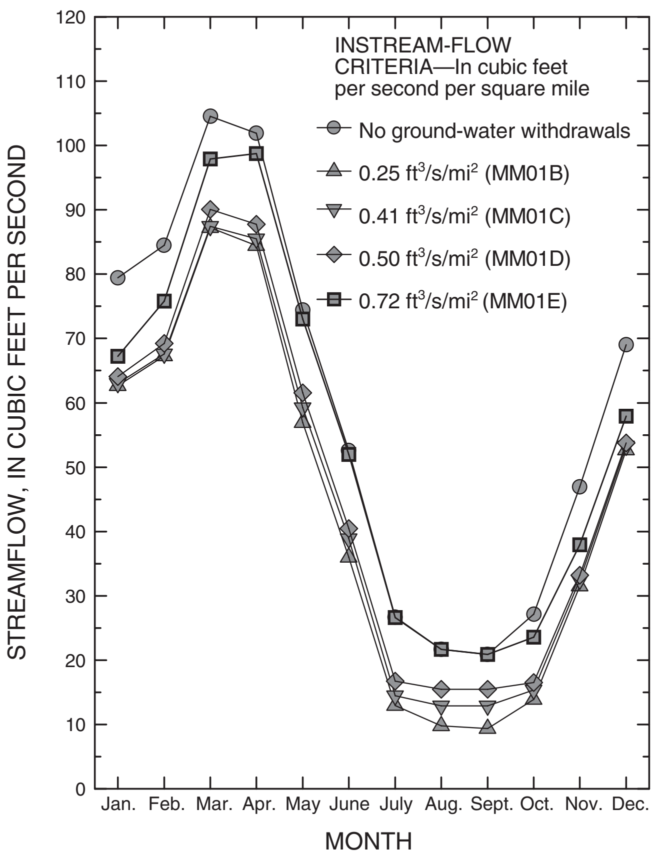

Figure 25. Seasonal variations in estimated average monthly streamflows at the Big River at Hill Farm Road (station 01115835), central Rhode Island, for alternative annual instream-flow criteria.

the high-flow months. The minimum monthly instream-flow criterion for the MDEP Ipswich River diversion limit is 0.42 $ft^3/s/mi^2$ (table 1-7), which is comparable to the wetted-perimeter criterion of 0.41 $ft^3/s/mi^2$. Use of the annual wetted-perimeter criterion (MM01C), however, yields an additional 1.0 Mgal/d of ground-water withdrawals in comparison to the MDEP Ipswich River diversion limit (MM01G) (table 15). The minimum IRFRTG Ipswich River monthly instream-flow criterion is 0.49 $ft^3/s/mi^2$ (table 1-8), which is comparable to the annual modified USFWS ABF criterion of 0.50 $ft^3/s/mi^2$. Use of the annual modified USFWS ABF criterion (MM01D), however, yields an additional 6.9 Mgal/d of ground-water withdrawals when compared to the IRFRTG Ipswich River monthly instream-flow criterion (MM01H) and 11.0 Mgal/d of ground-water withdrawals when compared to the unmodified USFWS seasonal criteria (MM01I) (table 15).

The minimum of monthly instream-flow criteria for the median of monthly median streamflows (table 1-9), the hybrid method (table 1-10), and the median of monthly average streamflows (table 1-11), are 0.50, 0.40, and 0.37 $ft^3/s/mi^2$, respectively. In each case, however, allowable depletions are calculated with a streamflow statistic other than the monthly average flow. Total simulated ground-water withdrawals are zero (MM01J, MM01K, and MM01L) (table 15) when these methods are applied because the applicable monthly flow statistic for the Big River at Hill Farm Road is less than or equal to the same statistic calculated for the continuous-record streamflow-gaging stations that were used as index sites for this area. Streamflow per unit area in the Big River Basin is slightly lower than in some nearby basins because the Carr River Basin, a tributary with about 24 percent of the total drainage area of the Big River Basin, (table 3) naturally loses water to the Mishnock River Basin (Granato and others, 2003).

Application of seasonal or monthly instream-flow criteria clearly has a substantial effect on total ground-water withdrawals from the Big River Area (table 15; tables 2-1 to 2-9 in Appendix 2). Additional instream-flow constraints substantially reduce total simulated ground-water withdrawals because of the long response times of streamflow to withdrawals in each basin. Seasonal or monthly constraints are designed to ensure that withdrawals do not severely reduce or eliminate seasonal variations in average monthly streamflows. The average ratio of maximum to minimum estimated average monthly streamflows in the Big River at Hill Farm Road is about 6.5 for scenarios with seasonal or monthly instream-flow criteria that allow ground-water withdrawals in the basin (fig. 26). Application of the conjunctive-management model in the Big River Area, however, indicates that although there is some attenuation in winter and spring streamflows, this attenuation is not substantial in comparison to average monthly streamflow variations within the annual cycle. For example, comparison of estimated average monthly streamflows with no ground-water withdrawals with streamflows calculated for the KCWA proposed annual criteria of 0.5 $ft^3/sec/mi^2$, and with streamflows calculated for the seasonal IRFRTG seasonal instream-flow criteria for the Big River at Hill Farm Road (fig. 27) indicates that average monthly streamflows would be attenuated by about 13 percent in March under the KCWA annual criteria. The ratio of March to September streamflows under the KCWA annual criteria, however, is about 6, which demonstrates that relative seasonal variation would be maintained. Therefore, implementation of seasonal or monthly instream-flow criteria may unnecessarily restrict total ground-water withdrawals without substantially increasing seasonal variability in average monthly streamflows.

Decisionmakers also are concerned about maintenance of short-term variability in streamflows to maintain aquatic and riparian habitat by periodic storm flushing. Simulation results indicate that streamflow-depletion response times for the simulated production-well sites in the Big River Area are on the scale of a few months to a year (figs. 20–23). In the northeastern United States, the average storm duration is about 11.5 hours (Driscoll and others, 1989). In comparison, Camp Dresser and McKee, Inc. (1999, 2000, 2001) simulated streamflow between the Lake Mishnock Outflow (USGS station 01115965) and the Mishnock River at State Route 3 (USGS station 01115970) during a series of short-term aquifer tests. They calculated that

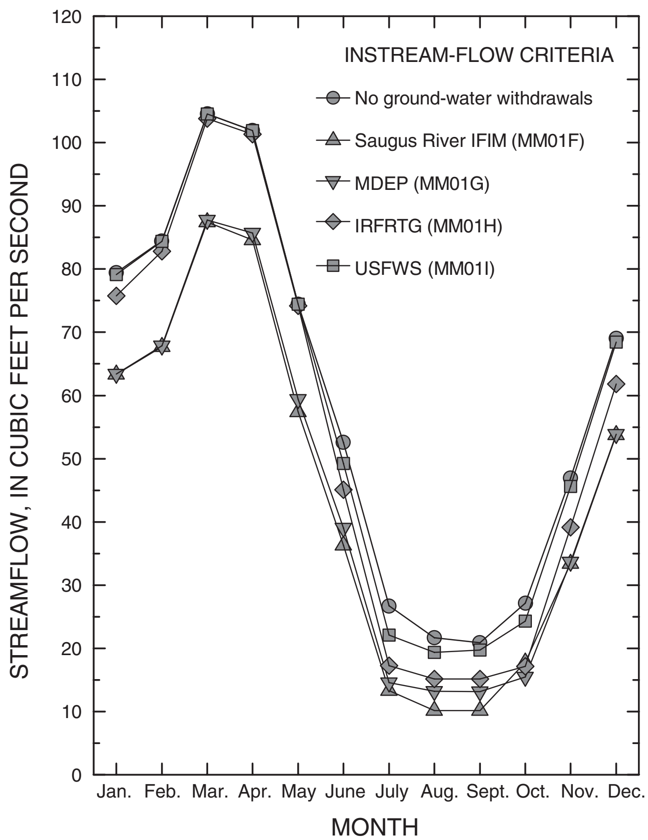

Figure 26. Seasonal variations in estimated average monthly streamflows in the Big River at Hill Farm Road (station 01115835), central Rhode Island, for alternative seasonal or monthly instream-flow criteria.

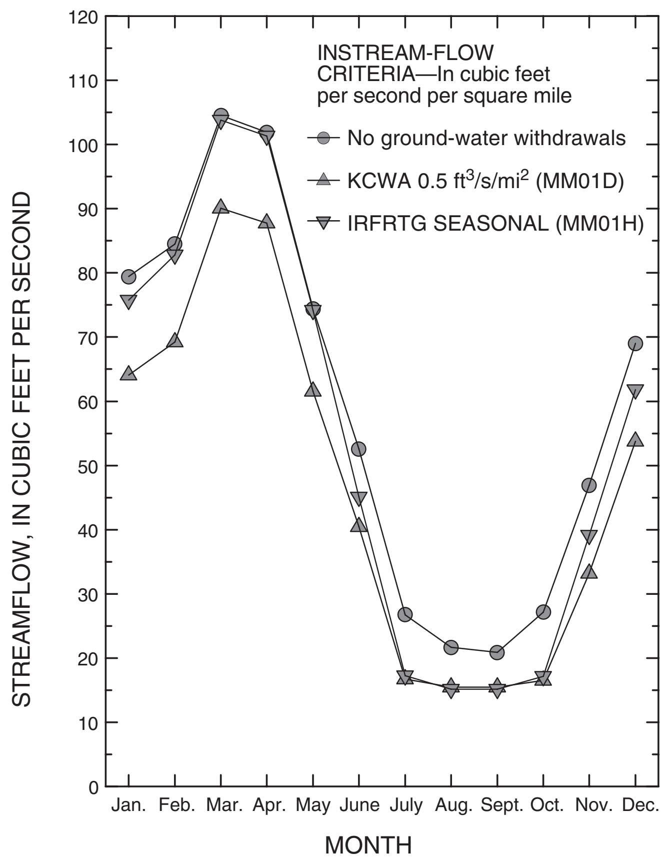

Figure 27. Seasonal variations in estimated average monthly streamflows in the BigRiver at Hill Farm Road (station 01115835), central Rhode Island, for the KCWA and the IRFRTG seasonal instream-flow criteria.

about 80 percent of increased withdrawals during the first 72 hours come from aquifer storage. Similarly, examination of estimated streamflows in the Mishnock River with and without documented monthly withdrawal rates for the period 1961–2000 (fig. 9; fig. 15) indicate that ground-water withdrawals during this period decrease base flow but do not substantially affect stormwater-runoff volumes. Barlow (1997) examined the effect of ground-water withdrawals on instorm bank storage by use of a ground-water model representing conditions in a typical valley aquifer in southeastern New England. Barlow (1997) concluded that short-term flood waves may not substantially affect the amount of streamflow captured by wells and that ground-water withdrawals do not substantially attenuate short-term runoff volumes. Seasonal or monthly instream-flow criteria were designed for and are applicable to surface-water withdrawals or diversions, which can instantaneously respond to variations in streamflow (U.S. Fish and Wildlife Service, 1981; Lang, 1994, 1999). Seasonal or monthly instream-flow criteria, however, may not be necessary for regulation of ground-water withdrawals because of the long response times of depletions to changes in ground-water-withdrawal rates.

Alternative Ground-Water-Demand Constraints

Conjunctive-management model formulations were examined to quantify relations between alternative ground-water-demand constraints and obtainable ground-water withdrawals from the entire Big River Area. The demand constraints that were considered include a seasonal ground-water-demand pattern for Rhode Island communities and two examples of withdrawal strategies proposed by the KCWA. Monthly ground-water-withdrawal rates were constrained by the allowable streamflow depletions calculated with equation 2 by use of the modified USFWS ABF instream-flow criterion of 0.50 $ft^3/s/mi^2$ in each month of the year (the same criterion used in management model MM01D in table 15). The monthly withdrawal rates calculated for each well (eq. 3) were constrained to be less than or equal to 1.4 Mgal/d at each of the 13 simulated production-well sites in the Big River Area (fig. 17). In these simulations, monthly withdrawal rates from the different basins were further constrained by alternative ground-water-demand patterns (eqs. 3, 4, and 5). The results of these scenarios can serve as examples indicating the maximum annual withdrawals that may be obtainable from the area under average monthly conditions for the period 1961–2000 as a function of different demand patterns.

Seasonal Ground-Water-Demand Pattern for Rhode Island: The seasonal ground-water-demand pattern averaged from six water-supply systems in Rhode Island (fig. 13) was tested to determine how this demand constraint would affect maximum ground-water withdrawals from the Big River Area under long-term average monthly conditions for the period 1961–2000. Simulated maximum ground-water withdrawals calculated with this management model are 0.92, 0.04, and 5.09 Mgal/d from the Mishnock River, the Carr River, and the Big River Basins, respectively (management model MM02 in table 16; table 2-10 in Appendix 2). Total simulated ground-water withdrawals from the basin (6.05 Mgal/d) for this seasonal ground-water-demand constraint (table 16) are about 50 percent of the total ground-water withdrawals from the area (12 Mgal/d) without this constraint (MM01D in table 15). By forcing the withdrawal pattern to match the seasonal demand pattern, there is, overall, a substantial reduction in total annual withdrawals that are possible from the aquifer. This is because peak demands coincide with the months of lowest average streamflow.

Kent County Water Authority Annual Average Withdrawals of 2.6 Mgal/d: The first development scenario proposed by the KCWA (fig. 18*A*) was tested as a hypothetical demand constraint to determine how independent management of water supplies in the Mishnock River Basin would affect maximum ground-water withdrawals from the entire Big River Area under long-term average-monthly conditions during the period 1961–2000. Two formulations of the management model were tested (MM03A and MM03B). (These formulations do not include any withdrawals from the simulated KCWA wells North-01 and South-01 (fig. 17; table 14) because the existing KCWA water-supply permit does not include use of the expanded well field.) The first formulation (MM03A) was specified to make the total estimated withdrawal rate in each month from the existing KCWA well field greater than or equal to the total monthly withdrawals depicted in figure 18*A*. Maximum ground-water withdrawals calculated with this management model are 2.62, 0.61, and 7.12 Mgal/d from the Mishnock River, the Carr River, and the Big River Basins, respectively (table 16; table 2-11 in Appendix 2). The second formulation (MM03B) was specified to make the total annual withdrawal rate from the existing KCWA well field greater than or equal to 2.6 Mgal/d. Maximum ground-water withdrawals calculated with management model MM03B are 2.65, 1.23, and 6.84 Mgal/d from the Mishnock River, the Carr River, and the

Table 16. Potential average annual ground-water withdrawal rates under average hydrologic conditions for the period 1961–2000 with alternative ground-water-demand constraints and water-supply networks for simulated production wells in the Mishnock, Carr, and Big River Basins, central Rhode Island.

[Well locations shown in figure 17. Values rounded to three significant figures. **Designation:** Management models MM02–MM09 meet the modified USFWS ABF instream-flow criteria of 0.50 $ft^3/s/mi^2$. ABF, aquatic base flow; KCWA, Kent County Water Authority; MM, Management model; USFWS, U.S. Fish and Wildlife Service; WGW, U.S. Geological Survey designation for a well in West Greenwich, RI; $ft^3/s/mi^2$, cubic foot per second per square mile; Mgal/d, million gallons per day.]

Management model		Ground-water withdrawals by basin, in Mgal/d			
Designation	**Description**	**Mishnock River**	**Carr River**	**Big River**	**Total**
	Alternative Ground-Water Demand Constraints				
MM02	Rhode Island Demand Pattern (fig. 13)	0.92	0.04	5.09	6.05
MM03A	KCWA 2.6 Mgal/d (monthly specification) (fig. 18)	2.62	.61	7.12	10.3
MM03B	KCWA 2.6 Mgal/d (annual specification)	2.65	1.23	6.84	10.7
MM04A	KCWA 3.37 Mgal/d (monthly specification) (fig. 19)	3.37	.14	7.20	10.7
MM04B	KCWA 3.37 Mgal/d (annual specification)	3.96	1.11	6.95	12.0
	Alternative Water-Supply Networks				
MM05	Eliminate Well WGW410	3.93	1.24	6.13	11.3
MM06	Eliminate Wells WGW410, WGW 354, and WGW 374 (Use well WGW355 in the Carr River Basin)	4.05	.62	6.22	10.9
MM07	Eliminate Wells WGW410, WGW 355, and WGW 374 (Use well WGW354 in the Carr River Basin)	4.05	.82	6.19	11.1
MM08	Eliminate Wells WGW410, WGW 354, and WGW 355 (Use well WGW374 in the Carr River Basin)	4.05	.70	6.17	10.9
MM09	Eliminate Wells WGW410, WGW 354, WGW 355, and WGW 374	4.16	.00	6.25	10.4

Big River Basins, respectively (table 16; table 2-12 in Appendix 2). There is a slight increase in total withdrawals from 10.3 Mgal/d to 10.7 Mgal/d as the constraint is relaxed from a monthly specification to a specified total annual average ground-water-withdrawal rate. Total ground-water withdrawals for both of these management-model formulations are substantially less (by 1.7 to 1.3 Mgal/d) than the basin-wide management model that meets the same streamflow constraint (MM01D, table 15). In part, this is because wells North-01 and South-01, in the expanded KCWA well field, are not included in this simulation and thus are not available for withdrawals.

Comparison of the monthly (MM03A) and annual formulation (MM03B) of this management model (table 2-11 and table 2-12 in Appendix 2) indicates the interdependence of ground-water withdrawals in the three river basins (table 16). Neither management model produces a substantial increase in ground-water-withdrawal rates from the Mishnock River when compared to KCWA proposals because Camp Dresser and McKee, Inc. (2001) used optimization methods to determine the withdrawal rates from the basin (R.P. Schreiber, Groundwater Subdiscipline Leader, Camp Dresser and McKee, Inc., Cambridge, MA, oral commun. 2003). The choice of monthly or annual constraints in the KCWA well field, however, has an effect on the balance of ground-water withdrawals between the Carr River and Big River Basins. The monthly withdrawal schedule favors withdrawals in the Big River Basin, whereas the less restrictive annual-constraint schedule favors increased withdrawals from both the Mishnock River and Carr River well fields. This is because the USGS management model for the entire Big River Area further optimizes withdrawals between wells in the Mishnock and Carr Basins to meet these instream-flow criteria.

Kent County Water Authority Annual Average Withdrawals of 3.37 Mgal/d: The second development scenario proposed by the KCWA (fig. 19*A*) was tested as a hypothetical demand constraint to further define how independent management of water supplies in the Mishnock River Basin would affect maximum ground-water withdrawals from the entire Big River Area under long-term average monthly conditions during the period 1961–2000. Two formulations of the management model were tested (MM04A and MM04B). The first formulation (MM04A) was specified to make the total estimated withdrawal rate in each month from the existing and expanded KCWA well field greater than or equal to the total monthly withdrawals depicted in figure 19*A*. Maximum ground-water withdrawals calculated with management model MM04A are 3.37, 0.14, and 7.20 Mgal/d from the Mishnock River, the Carr River, and the Big River Basins, respectively (table 16; table 2-13 in Appendix 2). The second formulation (MM04B) was specified to make the total annual withdrawal rate from the existing and expanded KCWA well field greater than or equal to 3.37 Mgal/d. Maximum ground-water withdrawals calculated with management model MM04B are 3.96, 1.11, and 6.95 Mgal/d from the Mishnock River, the Carr River, and the Big River Basins, respectively (table 16; table 2-14 in Appendix 2). The ground-water withdrawals for management model MM04B are identical to values for management model MM01D in table 15 because both models meet the modified annual USFWS ABF instream-flow criterion, both exceed proposed Kent County withdrawals, and because the same potential well sites are used in each model. The maximum ground-water withdrawals from management model MM04B are greater than the maximun calculated with MM04A by 1.3 Mgal/d because MM04B is less constrained and thus can better optimize the withdrawal pattern in the Mishnock River Basin (table 16). Comparison of values in tables 2-13 and 2-14 indicates the differences in monthly average ground-water withdrawal rates calculated with each constraint set. For example, management model MM04B has higher withdrawal rates for 10 months and lower withdrawal rates in July and August for wells in the Mishnock River Basin, higher withdrawal rates in the Carr River Basin, and slightly lower withdrawal rates in the Big River Basin.

Alternative Water-Supply-Network Constraints

In this section, five alternative formulations of the conjunctive-management model are run to evaluate how elimination of selected well sites from the conjunctive-management model affects total ground-water withdrawals from the basin. These runs were made in recognition of the fact that the costs of testing, permitting, installing, and connecting a production well necessitate that a water supplier obtain an average of about 1 Mgal/d from a production well to recoup the financial investment needed to bring a new well into operation (Timothy Brown, Kent County Water Authority, oral commun., 2004). Moreover, additional costs are incurred when the location of the production well is remote from available water-supply transmission lines and appropriate electrical connections. Therefore, the underlying assumption of these five alternative formulations is that the withdrawal rate of a well and the distance of a well from the available water-supply infrastructure can be used as surrogates for the economic cost associated with bringing a well into operation.

The management-model constraints used to evaluate alternative well networks are similar to constraints used in evaluating other management models; however, wells WGW 410, WGW 354, WGW 355, and WGW374 (fig. 17) were selectively eliminated in five formulations of the conjunctive-management model. Monthly ground-water-withdrawal rates were constrained by the modified USFWS ABF instream-flow criterion of 0.50 $ft^3/s/mi^2$ in each month of the year (the same criterion used in management model MM01D in table 15).

Evaluate Well WGW 410: A management model (MM05) that did not include use of well WGW 410 was tested to determine the maximum ground-water withdrawals from the Big River Area under long-term average monthly conditions during the period 1961–2000. Well WGW 410 was considered for elimination from the simulated well network for several reasons. In comparison to wells in the Mishnock River Basin, Carr River Basin, and the northern part of the Big River Basin, well WGW 410 is remote from existing infrastructure in the Mishnock Basin well field (fig. 17). Well WGW 410 produces only about 0.8 Mgal/d in management models constrained by the 0.50 $ft^3/s/mi^2$ instream-flow criterion because about 53 percent of withdrawals from this well are evident as streamflow depletions in the Carr River Basin (fig. 22; table 2-15 in Appendix 2). Furthermore, use of this site may be disadvantageous for several potential ecological reasons. In numerical simulations, Granato and others (2003) determined that steady-state withdrawals of one Mgal/d from this well caused substantial streamflow depletions in the western unnamed tributary to the Carr River that flows through Sweet Pond (fig. 1). Elimination of this well also would reduce or eliminate effects of ground-water withdrawals on aquatic and riparian habitat in the southern end of the Big River Management Area. In comparison to management model MM01D (table 15), elimination of this well reduces total ground-water withdrawals from the Big River Area by 0.7 Mgal/d to 11.3 Mgal/d (table 16; table 2-15 in Appendix 2).

Evaluate Simulated Production-Well Sites in the Carr River Basin: Well sites WGW 355, WGW 354, and WGW 374 (fig. 17) were tested individually (MM06, MM07, and MM08, respectively) to evaluate the possibility of obtaining ground-water withdrawals that are greater than or equal to 1.0 Mgal/d from a single well site in the Carr River Basin under long-term average monthly conditions during the period 1961–2000. These formulations of the conjunctive-management model did not include use of well WGW 410 in the Big River Basin. Maximum ground-water withdrawals calculated with these three management models average about 4.05, 0.71, and 6.19 Mgal/d from the Mishnock River, the Carr River, and the Big River Basins, respectively (table 16; tables 2-16 to 2-18 in Appendix 2). None of these simulated well sites in the Carr River Basin can produce ground-water withdrawals that are greater than or equal to 1.0 Mgal/d under the modified USFWS ABF instream-flow criterion of 0.50 $ft^3/s/mi^2$ (table 16). Elimination of well WGW 410 and all three wells in the Carr River Basin from the management model (MM09) increases total ground-water withdrawals to 4.16 Mgal/d from the Mishnock River Basin and 6.25 Mgal/d from the Big River Basin (table 16). The total ground-water withdrawals in MM09, however, are reduced by about 0.6 Mgal/d in comparison to total withdrawals calculated in management models MM06, MM07, and MM08, because the remaining wells cannot withdraw all the water that would be obtained by use of wells in the Carr River Basin (table 2-19 in Appendix 2). The alternative water-supply network defined by management model MM09 would not affect the natural streamflow regime in the Carr River upstream of Capwell Mill Pond and would minimize potential effects of water-supply development in the upper reaches of the Big River and its tributaries.

Alternative Instream-Flow Criteria for Dry Periods

Formulations of the conjunctive-management model are examined to quantify relations between alternative instream-flow criteria for dry periods and potential ground-water withdrawals from the Big River Area. Estimates of average daily flows without ground-water withdrawals at the Lake Mishnock Outflow, Mishnock River at State Route 3, Carr River below Capwell Mill Pond, and Big River at Hill Farm Road all show substantial variations during the period 1961–2000 (fig. 11). For example, the ratio of the maximum to minimum estimated average daily streamflow for the 1961–2000 period is 5, 12, 355, and 183 for the Lake Mishnock Outflow, Mishnock River at State Route 3, Carr River below Capwell Mill Pond, and Big River at Hill Farm Road, respectively. As indicated in the section on streamflows and instream-flow criteria for the period 1961–2000, a substantial proportion of mean daily and mean monthly streamflows are below many of the proposed instream-flow criteria, even in the absence of ground-water withdrawals. Increases in ground-water withdrawals in a basin will increase the percentage of time that streamflows are below any given instream-flow criterion (Barlow and others, 2003). For example, estimated average daily streamflows for the Big River at Hill Farm Road under management model MM09 are lower than estimated streamflows without ground-water withdrawals because the remaining ground-water withdrawals deplete streamflow (fig. 28). Under the management model MM09, average daily streamflows during the 40-year period 1961–2000 are estimated to be less than or equal to 0.1 ft^3/s for about 15.3 percent of the time in the Mishnock River at State Route 3 and about 2.9 percent of the time in the Big River at Hill Farm Road (fig. 29). Streamflows at the Lake Mishnock Outflow and the Carr River below Capwell Mill Pond, however, are only minimally affected by ground-water withdrawals calculated in management model MM09 (fig. 29).

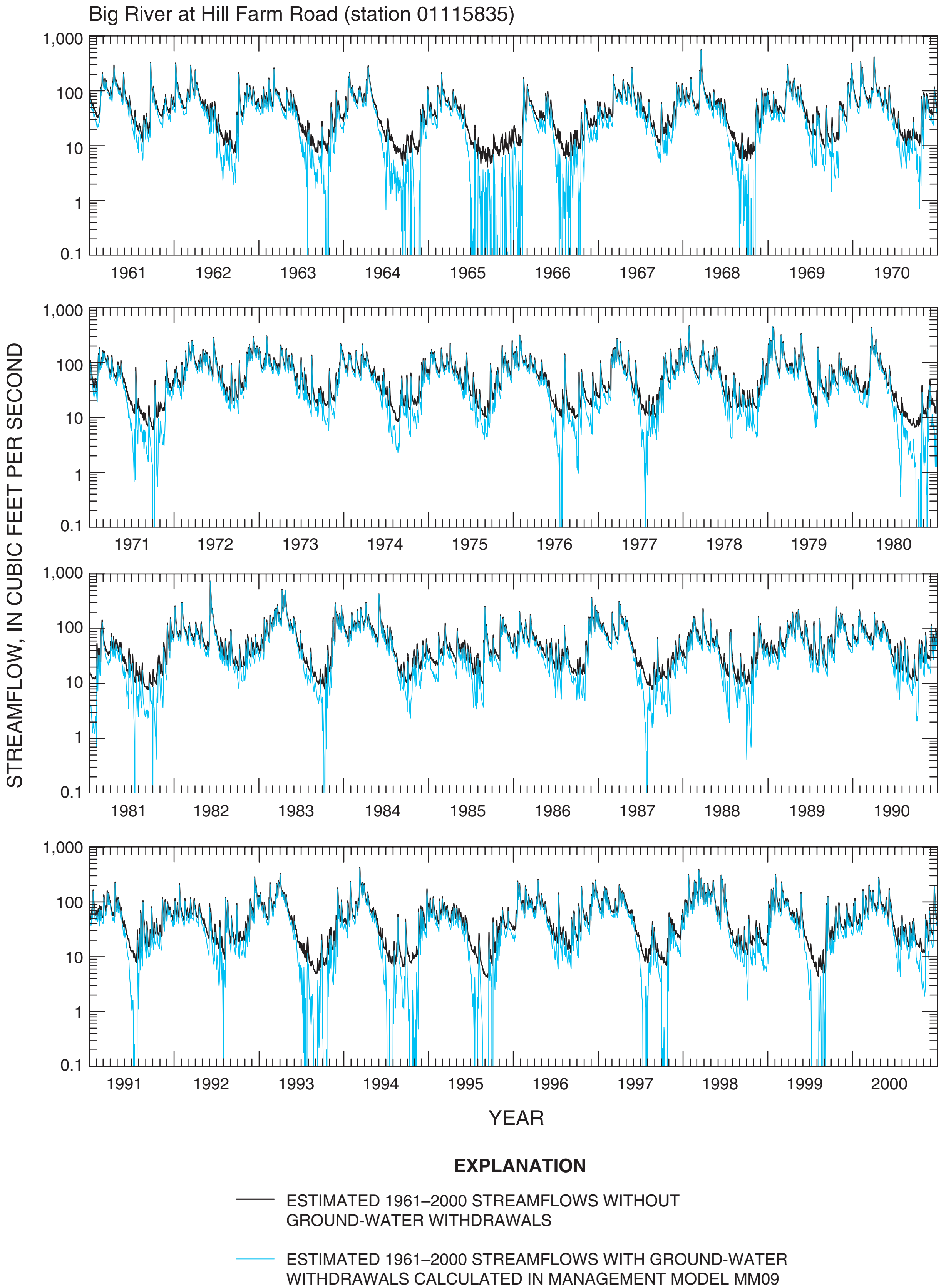

Figure 28. Estimated average daily streamflows at the Big River at Hill Farm Road (station 01115835), central Rhode Island, without ground-water withdrawals and with ground-water withdrawals calculated in management model MM09, 1961–2000.

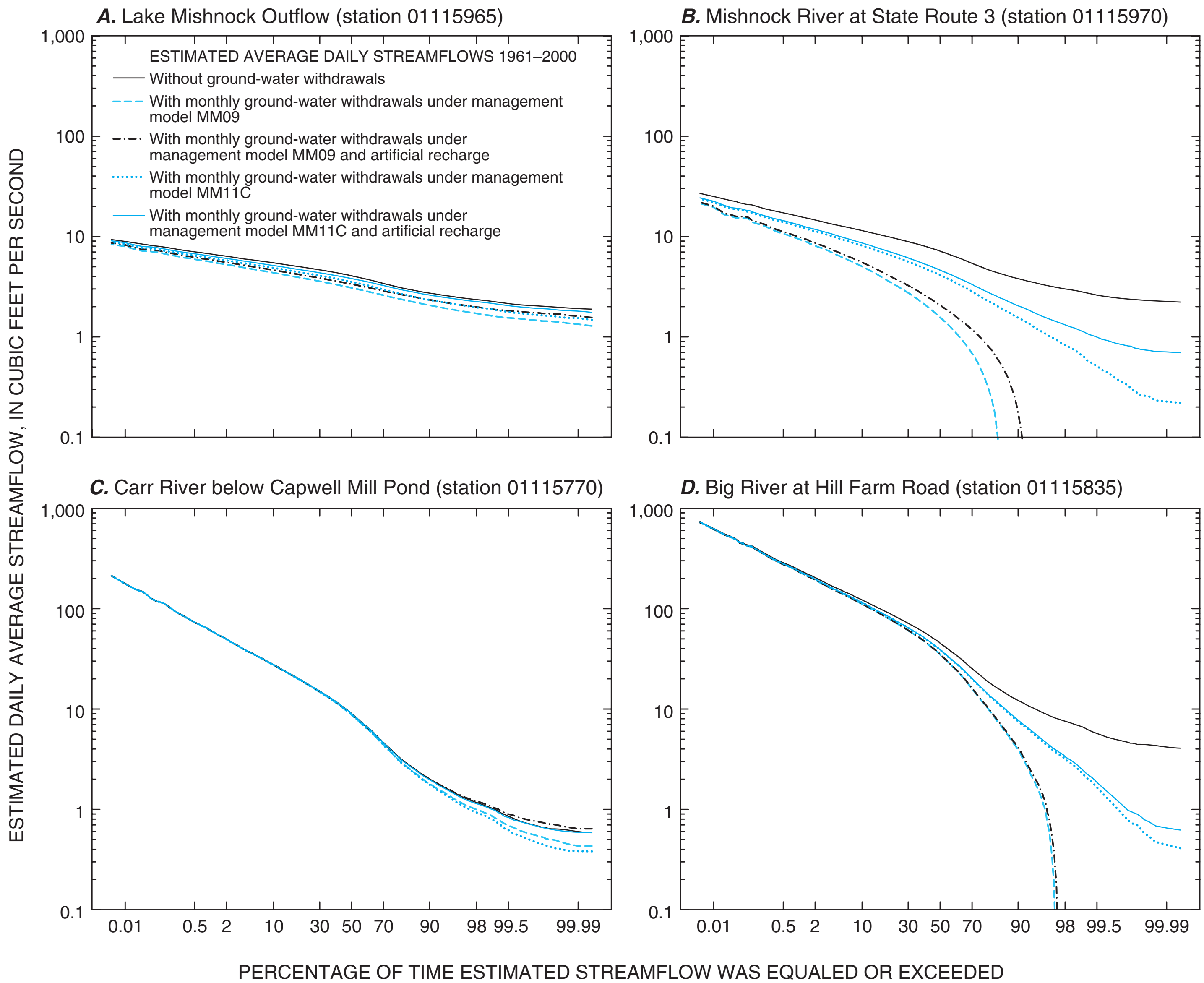

Figure 29. Daily streamflow-duration curves showing the percentage of time that the estimated streamflow would be equaled or exceeded in different ground-water withdrawal scenarios for *A*, the Lake Mishnock Outflow (station 01115965); *B*, the Mishnock River at State Route 3 (station 01115970); *C*, the Carr River below Capwell Mill Pond (station 01115770); and *D*, the Big River at Hill Farm Road (station 01115835), central Rhode Island, 1961–2000.

The management-model constraints used to evaluate alternative instream-flow criteria for dry periods are similar to constraints used in evaluating other management models. The formulations are designed to maximize withdrawals for the entire year (eq. 1). Monthly ground-water withdrawal rates are constrained by the allowable streamflow depletions (eq. 2). These depletions, however, are calculated as a function of the estimated 40-year minimum average daily streamflow in each basin without ground-water withdrawals. The monthly withdrawal rates at each well (eq. 3) are constrained to be less than or equal to 1.4 Mgal/d at each of the nine simulated well sites specified in management model MM09. If minimum flows are used to calculate potential allowable depletions, then use of a monthly rate is less constraining than an annual rate because the allowable depletion is a proportion of the monthly minimum streamflow (table 17). Use of the potential streamflow depletions as the basis for calculating ground-water withdrawal rates under dry-period conditions may be a conservative management plan, even during a dry period, because historically, no single year would include all monthly minimum streamflows (table 17). The monthly withdrawal rates at each well in the study area are not constrained by ground-water-withdrawal rates proposed by the KCWA in the following management models.

Evaluate a Hypothetical Allowable 40-Year Minimum Flow that is 0.1 ft^3/s: A management model (MM10A) based on a hypothetical minimum allowable streamflow of 0.1 ft^3/s for the period 1961–2000 was tested to determine the maximum ground-water withdrawals from the area during dry periods that would not cause a condition of zero streamflow (table 18). Hypothetical allowable depletions in this management-model scenario were calculated by subtracting 0.1 ft^3/s from the estimated minimum 40-year average daily flow that occurred each month during the period 1961–2000 (table 17). Maximum ground-water withdrawals calculated from this management model (MM10A) are 2.71 and 5.04 Mgal/d from the Mishnock River and the Big River Basins, respectively (table 18). Examination of monthly withdrawal rates from each basin, however, indicates that a combined minimum monthly ground-water-withdrawal rate of 1.34 Mgal/d would occur during July and a maximum of about 12.6 Mgal/d would occur during March (table 2-20 in Appendix 2).

Evaluate a Seasonal Withdrawal Pattern and a Hypothetical Allowable 40-Year Minimum Flow that is 0.1 ft^3/s: Management model MM10A was modified to produce a seasonal ground-water-withdrawal pattern rather than a widely varying monthly withdrawal pattern. A seasonal withdrawal pattern calculated with the management model was used to equalize total withdrawals in each month during the dry season (June through October) and to equalize total withdrawals in each month during the wet season (November through May). The seasonal ground-water-demand pattern for water-supply systems in Rhode Island was not used because this pattern, with a peak-withdrawal rate in June (fig. 13), heavily constrains total ground-water withdrawals, and because it is assumed that strict conservation measures would be enforced during these dry periods (Rhode Island Department of Administration, 2002). Two management models were formulated, one that maximizes ground-water withdrawals from the entire Big River Area (MM10B) and one that equalizes the daily ground-water-withdrawal rate for seasonal demand in each basin (MM10C). In comparison to management model MM10A, the penalty for equalizing ground-water withdrawals in this way is about 1 Mgal/d (table 18). The total minimum monthly withdrawal rates, however, are increased by about 3 Mgal/d to about 4.3 Mgal/d during the month of July (tables 2-20, 2-21, and 2-22 in Appendix 2). Average annual ground-water-withdrawal rates for management models MM10B and MM10C are essentially equivalent (table 18). Management model MM10C, however, increases and equalizes monthly ground-water withdrawals from the Mishnock River Basin, which is closer to the existing water-supply infrastructure.

Evaluate a Hypothetical Allowable 40-Year Minimum Flow that is 10 Percent of Minimum Flows Without Ground-Water Withdrawals: A management model (MM11A) based on an estimated minimum allowable depletion for the period 1961–2000 was tested to determine the maximum ground-water withdrawals that would not cause a condition of zero streamflow during dry periods. Hypothetical allowable depletions in this management-model scenario were calculated as being 90 percent of the estimated minimum 40-year average daily flows that occurred in each month during the period 1961–2000 (table 17). Maximum ground-water withdrawals calculated from management model MM11A are 2.53 and 4.78 Mgal/d from the Mishnock River and the Big River Basins, respectively (table 18). Examination of monthly withdrawal rates from each basin, however, indicates that the combined minimum monthly ground-water-withdrawal rate of 0.70 Mgal/d would occur during July and the maximum of about 10.8 Mgal/d would occur during April (table 2-23 in Appendix 2).

Table 17. Estimated minimum daily average streamflow without ground-water withdrawals and potential streamflow depletion in the Big River Area, central Rhode Island, under dry-period conditions, 1961–2000.

[**Hypothetical value-based criterion:** Minimum allowable average daily streamflow for 1 day each month (ft^3/s). **Hypothetical percentage-based criterion:** Minimum allowable average daily streamflow for 1 day each month as a percentage of the estimated minimum average daily streamflow without withdrawals. Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, are shown in figure 17. Potential streamflow depletions are calculated by subtracting the hypothetical allowable minimum average daily streamflow from the estimated minimum of average daily streamflows without ground-water withdrawals in each month during the period 1961–2000. ft^3/s, cubic foot per second]

Month	Date of estimated minimum average daily streamflow	Lake Mishnock Outflow near Washington (01115965)		Mishnock River at State Route 3 (01115970)		Carr River below Capwell Mill Pond (01115770)		Big River at Hill Farm Road (01115835)	
		Minimum streamflow (ft^3/s)	Potential depletion (ft^3/s)	Minimum streamflow (ft^3/s)	Potential depletion (ft^3/s)	Minimum streamflow (ft^3/s)	Potential depletion (ft^3/s)	Minimum streamflow (ft^3/s)	Potential depletion (ft^3/s)
		Hypothetical value-based criterion (0.1 ft^3/s)							
January	1-29-1966	2.57	2.47	3.46	3.36	1.60	1.50	9.95	9.85
February	2-09-1966	2.60	2.50	3.51	3.41	1.67	1.57	10.33	10.23
March	3-05-1980	3.45	3.35	5.51	5.41	4.81	4.71	26.24	26.14
April	4-30-1985	3.38	3.28	5.34	5.24	4.47	4.37	24.54	24.44
May	5-30-1992	3.25	3.15	5.02	4.92	3.86	3.76	21.68	21.58
June	6-30-1964	2.75	2.65	3.83	3.73	2.07	1.97	12.55	12.45
July	7-31-1999	2.15	2.05	2.60	2.50	.81	.71	5.45	5.35
August	8-06-1999	2.03	1.93	2.36	2.26	.64	.54	4.44	4.34
September	9-11-1965	1.93	1.83	2.22	2.12	.59	.49	4.07	3.97
October	10-02-1968	1.89	1.79	2.28	2.18	.82	.72	5.38	5.28
November	11-20-1965	2.31	2.21	2.93	2.83	1.08	.98	6.96	6.86
December	12-11-1965	2.33	2.23	2.97	2.87	1.11	1.01	7.20	7.10
		Hypothetical percentage-based criterion (10 percent of minimum streamflow)							
January	1-29-1966	2.57	2.31	3.46	3.12	1.60	1.44	9.95	8.95
February	2-09-1966	2.60	2.34	3.51	3.16	1.67	1.50	10.33	9.30
March	3-05-1980	3.45	3.11	5.51	4.96	4.81	4.33	26.24	23.61
April	4-30-1985	3.38	3.04	5.34	4.81	4.47	4.03	24.54	22.09
May	5-30-1992	3.25	2.93	5.02	4.52	3.86	3.47	21.68	19.51
June	6-30-1964	2.75	2.47	3.83	3.45	2.07	1.86	12.55	11.29
July	7-31-1999	2.15	1.94	2.60	2.34	.81	.73	5.45	4.91
August	8-06-1999	2.03	1.82	2.36	2.13	.64	.58	4.44	3.99
September	9-11-1965	1.93	1.74	2.22	2.00	.59	.53	4.07	3.66
October	10-02-1968	1.89	1.70	2.28	2.05	.82	.74	5.38	4.84
November	11-20-1965	2.31	2.08	2.93	2.64	1.08	.97	6.96	6.26
December	12-11-1965	2.33	2.10	2.97	2.68	1.11	1.00	7.20	6.48

Table 18. Potential average annual ground-water withdrawal rates under dry-period conditions during the period 1961–2000 with alternative ground-water-demand constraints and alternative water-supply networks for simulated production wells in the Mishnock, Carr, and Big River Basins, central Rhode Island.

[Seasonal withdrawal patterns equalize average daily withdrawals in two seasons: A dry season that includes June, July, August, September, and October, and a wet season that includes November, December, January, Feburary, March, April, and May. MM, Management model; ft^3/s, cubic foot per second; Mgal/d, million gallons per day]

Management model		Ground-water withdrawals by basin (Mgal/d)			
Designation	Description	Mishnock River	Carr River	Big River	Total
Hypothetical allowable 40-year minimum flows of 0.1 ft^3/s					
MM10A	Maximize withdrawals	2.71	0.00	5.04	7.7
MM10B	Seasonal withdrawals	1.71	.00	5.01	6.7
MM10C	Seasonal withdrawals by basin	2.30	.00	4.32	6.6
Hypothetical allowable 40-year minimum flows of 10 percent of the minimum flow without ground-water withdrawals					
MM11A	Maximize withdrawals	2.53	0.00	4.78	7.3
MM11B	Seasonal withdrawals	1.60	.00	4.63	6.2
MM11C	Seasonal withdrawals by basin	2.17	.00	3.99	6.2

Evaluate a Seasonal Withdrawal Pattern and a Hypothetical Allowable 40-Year Minimum Flow that is 10 Percent of Minimum Flows Without Ground-Water Withdrawals: Management model MM11A was modified to produce a seasonal ground-water-withdrawal pattern rather than a widely varying monthly withdrawal pattern. The seasonal ground-water-demand pattern for ground-water supply systems in Rhode Island (fig. 13) was not used for management models MM11B and MM11C. A seasonal-withdrawal pattern, however, was used to equalize total withdrawals in each month during the dry season (June through October) and the wet season (November through May). Management model MM11B is used to maximize ground-water withdrawals from the entire Big River Area. MM11C is used to equalize the seasonal demand in each basin (table 18). The penalty for equalizing ground-water withdrawals in both of these ways is about 1 Mgal/d in comparison to management model MM11A, but the total minimum monthly withdrawal rates are increased by about 3 Mgal/d to about 4.1 Mgal/d during the month of July (tables 2-24 and 2-25 in Appendix 2). Average annual ground-water-withdrawal rates for management models MM11B and MM11C are equivalent (table 18). Management model MM11C, however, increases and equalizes monthly ground-water withdrawals from the Mishnock River Basin, which is closer to the existing water-supply infrastructure.

Alternative Management Option: Artificial Recharge

Potential gains in streamflows by use of artificial recharge in the Big River Area are examined through three formulations of the conjunctive-management model as hypothetical examples of the potential benefits of this alternative-management method. Artificial recharge has not been used extensively in combination with ground-water-based water-supply systems in the northeastern United States (Barlow, 1997). Artificial recharge may be used to augment streamflows in a basin with fixed ground-water-withdrawal rates, to increase ground-water withdrawals from the basin without regard to streamflow augmentation, or to combine these approaches as part of a plan for limited increases in streamflows and ground-water withdrawals. There are, however, potential concerns about recharge of water that may affect aquifer and stream water quality or the temperature of ground-water discharge to streams in Rhode Island (Alisa Richardson, Rhode Island Department of Environmental Management, written commun., 2004). Artificial recharge is a consideration in the Big River Area because there is an industrial complex in the Mishnock River Basin that may use about 0.5 Mgal/d of public-water supply for noncontact cooling water and may discharge this high-quality water to a regional wastewater-treatment plant outside of the Big River Area (Timothy Brown, Kent County Water Authority, oral commun., 2004). To explore the potential advantages of retaining this water within the Big River Area, three hypothetical conjunctive-management models were formulated to quantify potential increases in ground-water withdrawals caused by this type of wastewater-return flow at a hypothetical infiltration facility in the Mishnock River Basin. Neither the monthly return-flow recharge pattern nor the location of the return-flow recharge was optimized in this study because determination of the location and availability of this potential wastewater recharge is beyond the scope of these hypothetical-management models.

The calibrated numerical model described by Granato and others (2003) was modified to include an artificial-recharge site in layer 1 of the model at row 70 and column 165 (fig. 17) to receive 0.5 Mgal/d (0.77 ft^3/s) of recycled cooling water. This site, which is north of Interstate 95 and east of Hopkins Hill Road, was selected because it is a depression in an area of high ground characterized by sand and gravel over sand (Stone and Dickerman, 2002). This hypothetical site was chosen as an example and may not represent the optimum recharge site in the basin. Furthermore, the recharge was simulated in a simplified manner by use of the MODFLOW well package (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) because a detailed geotechnical recharge-facility design has not been completed for this area. These simulation results indicate that, on average, about 91 percent of the artificially recharged cooling water would be manifest as an increase in streamflows from the basin and about 9 percent would be lost to riparian evapotranspiration during the growing season (May–October) if ground-water-withdrawal rates in the area are held constant. Streamflows are augmented by about 0.3, 0.5, 0.2, and 0.2 ft^3/s in the Lake Mishnock Outflow, Mishnock River at State Route 3, Carr River below Capwell Mill Pond, and Big River at Hill Farm Road, respectively (table 19). Streamflows in the Carr River Basin (and, therefore, the Big River Basin) increase because the artificial recharge changes the slope of the water table and decreases the natural ground-water underflow from the Carr River Basin to the Mishnock River Basin.

Management models MM01D, MM09, and MM11C were modified to quantify relations between potential increases in allowable depletions and resultant increases in total ground-water withdrawals from the entire Big River Area under this hypothetical wastewater-recharge scenario. Management model MM01D (table 15) was selected to quantify the potential increase in total ground-water withdrawals caused by this wastewater recharge. Management model MM09 (table 16) was selected to quantify the potential increase in total ground-water withdrawals facilitated by this wastewater recharge without use of wells in the Carr River Basin and well WGW 410. Management model MM11C (table 18) was selected to quantify the potential increase in total ground-water withdrawals facilitated by this wastewater recharge under an alternative dry-period instream-flow criterion. The total allowable depletion in each month was increased in all three management models by the model-calculated increase in streamflows caused by wastewater recharge (table 19).

Example, Instream-Flow Augmentation by Use of Artificial Recharge in the Mishnock River Basin: Two examples of the potential benefits of artificial recharge on instream flows in the Big River Area are examined by comparing estimated streamflow statistics for management models MM09 and MM11C with and without flow augmentation caused by the artificial recharge. The amount of streamflow augmentation (table 19) is about 19 percent of the estimated 7Q10 (table 7) in the absence of ground-water withdrawals in the Mishnock River Basin, and about 3 percent of the estimated 7Q10 (table 7) in the absence of ground-water withdrawals in the Big River Area for the period 1961–2000. The model-calculated increases in available streamflow (table 19) were added to estimates of streamflow under MM09 and MM11C to examine changes in low-flow statistics in the basin. Under management-model MM09, without artificial recharge, estimated average daily streamflows would be less than or equal to 0.1 ft^3/s for 17.2 and 3.00 percent of the time in the Mishnock River at State Route 3 and the Big River at Hill Farm Road, respectively (fig. 29). The use of artificial recharge reduces the frequency of average daily streamflows that are less than or equal to 0.1 ft^3/s to 7.85 and 2.75 percent of the time in the Mishnock River at State Route 3 and the Big River at Hill Farm Road, respectively.

Table 19. Simulated increases in available streamflow caused by artificial recharge of 0.5 million gallons per day (0.77 cubic foot per second) applied in the calibrated ground-water model within the Mishnock River Basin, central Rhode Island.

[Hypothetical artificial recharge site in model cell row 70 column 165 shown on figure 17. Mgal/d, million gallons per day]

Month	Increases in available streamflow, in cubic foot per second					
	Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)	Entire Big River Area	Entire Big River Area (Mgal/d)
January	0.27	0.48	0.19	0.19	0.67	0.43
February	.27	.50	.21	.21	.71	.46
March	.28	.51	.21	.21	.72	.47
April	.28	.52	.21	.21	.73	.47
May	.28	.52	.21	.21	.73	.47
June	.28	.51	.22	.22	.73	.47
July	.28	.51	.21	.21	.73	.47
August	.28	.48	.21	.21	.69	.45
September	.27	.48	.21	.21	.69	.44
October	.27	.48	.20	.20	.68	.44
November	.27	.47	.20	.20	.66	.43
December	.27	.52	.20	.20	.73	.47

In the dry-period management model MM11C, however, artificial recharge may cause substantial increases in minimum streamflows (fig. 29). The flow-duration curves for both management models with and without artificial recharge converge as streamflow increases because the amount of streamflow augmentation is a smaller fraction of total streamflows as these flows increase. These results indicate that artificial recharge may be an important source of streamflow, especially during dry periods.

Example, Maximize Total Annual Withdrawals (Management Model MM01D) with Artificial Recharge: The increased allowable depletions from the artificial recharge applied to management model MM01D increased total ground-water withdrawals in the Big River Area by 0.7 Mgal/d in management model MM12 (table 20). The increase in ground-water withdrawals is greater than the streamflow augmentation caused by artificial recharge because the increase in allowable depletion in the most constraining month (September) compounds the total amount of ground-water withdrawals in other months (table 2-26 in Appendix 2). In this example, withdrawals from the simulated production-well sites in the Carr River Basin increase to utilize almost all of the increase in allowable depletions. Well WGW 410 in the Big River Basin and all three individual simulated production-well sites in the Carr River Basin (table 20), however, do not produce 1 Mgal/d even with this artificial recharge. These results indicate that these well sites may not be feasible for water-supply development.

Example, Maximize Total Annual Withdrawals From Nine Well Sites (Management Model MM09) with Artificial Recharge: The increased allowable depletions from the artificial recharge applied to management model MM09 increased total ground-water withdrawals in the Big River Area by 0.3 Mgal/d in management model MM13 (table 20); this increase is only about 66 percent of the amount of artificial recharge that would otherwise discharge to streams in the basin. The reduced return in this management model is caused by the reduced withdrawal capacity of the 9-well network in comparison to the 13-well network in management model MM12 (tables 2-26 and 2-27 in Appendix 2). In management model MM09 (table 2-19), each well in the Big River Basin is operating at design capacity (1.4 Mgal/d) for 10 months of the year and each well in the Mishnock River Basin is operating at design capacity for 5 months of the year. In management model MM13 (table 2-27), each well in the Big River Basin is operating at design capacity for 10 months of the year and each well in the Mishnock River Basin is operating at design capacity for 6 months of the year. In this case, excess recharge will be discharged from the area as streamflow.

Example, Alternative Dry-Period Management Model with Nine Well Sites on a Seasonal Demand Pattern (Management Model MM11C) with Artificial Recharge: The increased allowable depletions from the artificial recharge applied to management model MM11C increased total ground-water withdrawals in the Big River Basin by 0.4 Mgal/d in management model MM14 (table 20; table 2-28 in Appendix 2); this increase is about 88 percent of the amount of artificial recharge that would otherwise discharge to streams in the basin. In this case, the seasonal-demand constraint limits the capacity of the management model to maximize withdrawals to capture all of the artificial recharge. Excess recharge will be discharged from the area as streamflow.

Table 20. Examples of potential average annual ground-water withdrawal rates with an artificial recharge rate of 0.5 million gallons per day under different hydrologic conditions during the period 1961–2000 with alternative ground-water-demand constraints and alternative water-supply networks for hypothetical production wells in the Mishnock, Carr, and Big River Basins, central Rhode Island.

[MM, Management model; Mgal/d, million gallons per day]

Management model		Ground-water withdrawals by basin (Mgal/d)			
Designation	Description	Mishnock River	Carr River	Big River	Total
Alternative Ground-Water-Demand Constraints					
MM01D	Maximize withdrawals	3.96	1.11	6.95	12.0
MM12	MM01D with artificial recharge	4.15	1.62	6.95	12.7
Alternative Water-Supply Network					
MM09	Reduced well network	4.16	0.00	6.25	10.4
MM13	MM09 with artificial recharge	4.40	.00	6.28	10.7
40-Year Minimum Flows are 10 Percent of the Minimum Flow Without Ground-Water Withdrawals					
MM11C	Reduced well network and seasonal withdrawals	2.17	0.00	3.99	6.2
MM14	MM11C with artificial recharge	2.53	.00	4.11	6.6

Summary and Conclusions

Water demand is increasing throughout Rhode Island, and the Rhode Island Water Resources Board (RIWRB), which is responsible for developing and protecting the State's major water resources, is concerned that increasing demand may exceed the capacity of current sources. In the early 1960s, the State proposed construction of a surface-water reservoir in the Big River Basin in central Rhode Island to meet these growing demands. The RIWRB would like to develop the largely untapped ground-water resources of the basin as a temporary alternative to a surface-water reservoir. The U.S. Geological Survey (USGS), in cooperation with the RIWRB, conducted a cooperative study of the area to understand the hydrogeology and ground-water-development options for the Big River Area.

In this study, conjunctive-management models of the Big River Area were formulated to address water-demand and streamflow-depletion issues simultaneously. The objectives of the models were to maximize ground-water withdrawals from the area while meeting different sets of alternative constraints. Total ground-water withdrawals were calculated under alternative constraints for instream-flow criteria, ground-water-demand constraints, water-supply-network constraints, dry-period instream-flow criteria, and artificial recharge to provide information about the potential benefits and limitations for management of streamflow depletion and associated ground-water withdrawals in the Big River Area. Results of the study could help decisionmakers evaluate strategies for balancing ground-water development and streamflow reductions. Results of this analysis should be transferable to similar basins in southern New England.

The conjunctive-management model was formulated mathematically as a linear program. The model was solved by a response-matrix technique that incorporates the results of a transient numerical simulation of the Big River Area in the constraint set of the linear program. The basis of the technique was the assumption that streamflow-depletion rates in each river were a linear function of ground-water-withdrawal rates at each well. This assumption was shown to be valid for the conditions evaluated in this study, primarily because of the high transmissivity of the surficial aquifer near many of the wells. The transient model was used to generate characteristic streamflow-depletion responses in each river to simulated unit withdrawals at each well. These characteristic responses, or response coefficients, were then incorporated directly into the streamflow-depletion constraints of the linear program.

Thirty-one conjunctive-management models were examined to evaluate the effects of alternative definitions of instream-flow criteria and water-supply demands on ground-water-development options in the Big River Area. Total withdrawals calculated with the model ranged from 0 to about 16 Mgal/d, depending on the instream-flow criterion, water demand, or water-supply network specified in the models. Results indicate that maximum withdrawals of about 10–12 Mgal/d are possible from the basin for typical conditions under an annual instream-flow criterion of 0.5 $ft^3/s/mi^2$. An average withdrawal of 10 Mgal/d is consistent with the 2020 water-supply needs estimated for central Rhode Island in a recent study commissioned by the Rhode Island Water Resources Board. An average withdrawal of 10 Mgal/d also represents an increase in water supply for the State that is about 13 percent of the average 2002 daily withdrawal of 76 Mgal from the Scituate Reservoir, the State's largest water supply. Furthermore, an average withdrawal of 10 Mgal/d is estimated to be sufficient to supply water to an estimated 60,000 households in Rhode Island. Although the surface-water reservoir that was proposed by the State for the Big River Area has not yet been approved for construction, the foresight of State planners in the 1960s to set aside land for long-term water supply has given the State a protected area for development of a substantial quantity of water to meet future increases in water demands.

Management-model results indicate that annual instream-flow criteria may be sufficient to preserve seasonal variations in monthly average streamflows while meeting water-supply demands in the Big River Area. Annual criteria may be sufficient because ground-water withdrawals from all of the wells in the Big River Area cause streamflow depletions for 6 months to a year. An annual instream-flow criterion that is binding in a low-flow month like September will limit withdrawals throughout the year. In comparison, monthly or seasonal instream-flow criteria cause substantial reductions in total allowable ground-water withdrawals but do not increase seasonal variability in long-term average monthly streamflows. Furthermore, results of the management models indicate that application of a seasonal or monthly instream-flow criterion that is based on streamflow statistics such as the average monthly streamflow, the median of monthly average streamflows, or the median monthly streamflows from one or more large drainage basins may preclude ground-water withdrawals in smaller basins when there is one or more months in which the streamflow statistic is below the regional instream-flow criterion. Instream-flow criteria that are based on these statistics also are restrictive in the context of hydrologic variability from year to year because, by definition, about 50 percent or more of the flows are less than these statistics.

Ground-water withdrawals from basins in Rhode Island typically increase during the months of May through October to meet increased water demands during the summer. Simulations that mimicked typical patterns of increased summer demands resulted in rates of average annual ground-water withdrawals from the basin that were about one-half of withdrawal rates without the seasonal constraint because peak water use during the summer season coincides with the period of lowest annual streamflows. Average annual withdrawals of about 6 Mgal/d from the network of 13 ground-water wells were determined for these seasonal-demand patterns under an annually constant instream-flow criterion of 0.5 $ft^3/s/mi^2$.

Four management models were tested to examine whether it was more advantageous to develop ground-water withdrawals in the area as separate or combined systems. This analysis indicates that ground-water withdrawals may be reduced by 1.3 to 1.7 Mgal/d if the well network is not managed as a single resource. Separate systems, however, may produce equivalent ground-water-withrawal rates if individual systems are each run in the most optimal manner.

Five alternative formulations of the conjunctive-management model were used to determine how elimination of selected wells from the well network affects total ground-water withdrawals from the basin. If the well network is reduced to nine wells by eliminating three hypothetical wells in the Carr River Basin and one hypothetical well in the Big River Basin, the ground-water withdrawals are reduced by about 13 percent, from 12 Mgal/d to 10.4 Mgal/d. These four wells were eliminated in the scenarios because results of previous simulations indicated that for the condition of an annually constant instream-flow criterion of 0.5 $ft^3/s/mi^2$, none of these wells would produce the 1 Mgal/d that is considered necessary to recover the cost of installing and operating a production well. This alternative well network would not affect the natural streamflow regime in the Carr River upstream of Capwell Mill Pond and would minimize the potential effects of water-supply development in the upper reaches of the Big River and its tributaries.

Examination of estimated hydrologic variability in the Big River Area indicated the need for an alternative dry-period withdrawal plan. Management models based on allowable depletions estimated from long-term average streamflows would cause streamflows to be less than or equal to 0.1 ft^3/s for a substantial percentage of time during dry periods. Two different alternative dry-period instream-flow criteria, based on the lowest estimated average daily flow during the period 1961–2000, were tested in six management models. Total dry-period annual average ground-water withdrawals under these criteria ranged from 6.2 to 7.7 Mgal/d. Management models with an alternate seasonal-withdrawal pattern, which equalized monthly average ground-water withdrawals during the dry season (June through October) and the wet season (November through May), smoothed out monthly variations in withdrawal rates without a substantial decrease in the total annual average withdrawal rate.

Finally, a potential source of 0.5 Mgal/d of high-quality industrial cooling water could hypothetically be available for artificial recharge in the Mishnock River Basin. The potential effect of this recharge was evaluated in terms of potential increases in streamflows and ground-water withdrawals. A hypothetical recharge site in the Mishnock River Basin was simulated with the numerical model to determine the potential effect on streamflows in the basin. Results of model simulations indicate that about 91 percent of the recharged water would be manifest as an increase in streamflow from the basin and about 9 percent would be lost to riparian evapotranspiration during the growing season (May–October) if ground-water-withdrawal rates were held constant. The hypothetical artificial recharge is not a large percentage of total streamflows, except during dry periods when the use of artificial recharge may make critical differences in aquatic and riparian ecosystems. Three management models were tested to quantify potential gains in total ground-water withdrawals. Increases in withdrawals ranged from 0.3 to 0.7 Mgal/d and depended on well-network configuration, instream-flow criteria, and hydrologic conditions.

Results of the different applications of the model demonstrate the usefulness of coupling numerical simulation and optimization for regional-scale evaluation of water-resource-management alternatives. The results of the evaluation must be viewed, however, within the limitations of the quality of data available for the Big River Area and representation of the system with a simulation model. For example, all the streamflow and streamflow-depletion data used in the analysis are based on statistical extrapolation from short-term partial-record measurements in the basin and on data from three surrounding long-term (1961–2000) continuous streamflow-gaging stations. Actual streamflow statistics for the area and, therefore, allowable streamflow depletions and total ground-water withdrawals may vary in the future. Although there is uncertainty about the total magnitude of streamflows, depletions, and withdrawals, the results of the study nevertheless provide information about the relative merit of different water-resource-management alternatives.

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APPENDIX 1

Potential Streamflow Depletions in the Big River Area under Alternative Instream-Flow Criteria

Tables

Table 1-1. Potential streamflow depletion in the Big River Area, central Rhode Island, under the U.S. Fish and Wildlife Service instream-flow criterion.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the USFWS recommendations (U.S. Fish and Wildlife Service, 1981) from estimated medians of monthly average streamflows without ground-water withdrawals at stations in the Big River Area. Potential streamflow depletions are set to zero when median of monthly average predevelopment streamflow is less than the USFWS recommendation. USFWS, U.S. Fish and Wildlife Service; ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criterion ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.00	4.40	5.75	9.27	46.40
February	1.00	4.51	6.03	10.51	51.26
March	4.00	3.87	.00	.00	.00
April	4.00	3.92	.00	.00	.00
May	4.00	3.39	.00	.00	.00
June	.50	3.69	4.90	4.09	24.03
July	.50	3.09	3.31	.27	6.32
August	.50	2.90	2.93	.00	3.38
September	.50	2.79	2.62	.00	1.19
October	.50	3.01	3.17	.13	5.25
November	1.00	3.42	2.94	.00	4.56
December	1.00	4.07	4.76	5.19	28.99

Table 1-2. Potential streamflow depletion in the Big River Area, central Rhode Island, under the 1977 Connecticut instream-flow criterion of 0.25 cubic foot per second per square mile.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the 1977 Connecticut (Connecticut General Assembly, 2003) minimum streamflow limit of 0.25 $ft^3/s/mi^2$ from the estimated average monthly streamflows without ground-water withdrawals at stations in the Big River Area. USFWS, U.S. Fish and Wildlife Service; ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criterion ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.25	4.54	8.06	15.69	71.70
February	.25	4.68	8.45	16.79	76.76
March	.25	5.02	9.50	21.80	96.83
April	.25	4.97	9.36	21.12	94.17
May	.25	4.54	7.99	14.19	66.72
June	.25	3.95	6.33	9.28	44.82
July	.25	3.24	4.43	3.27	19.01
August	.25	3.01	3.87	2.24	13.96
September	.25	2.95	3.74	2.10	13.18
October	.25	3.20	4.37	3.46	19.45
November	.25	3.80	5.95	7.95	39.21
December	.25	4.32	7.44	13.17	61.30

Table 1-3. Potential streamflow depletion in the Big River Area, central Rhode Island, under the estimated Usquepaug–Queen River Basin wetted-perimeter instream-flow criterion of 0.41 cubic foot per second per square mile.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the Usquepaug–Queen River Basin wetted-perimeter instream-flow criterion of 0.41 $ft^3/s/mi^2$ (Armstrong and Parker, 2003) from the estimated average monthly streamflows without ground-water withdrawals at stations in the Big River Area. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criterion ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.41	4.49	7.53	14.51	66.76
February	.41	4.63	7.92	15.61	71.82
March	.41	4.97	8.97	20.62	91.89
April	.41	4.92	8.83	19.94	89.23
May	.41	4.49	7.46	13.01	61.78
June	.41	3.90	5.80	8.10	39.88
July	.41	3.19	3.90	2.09	14.07
August	.41	2.96	3.34	1.06	9.02
September	.41	2.90	3.21	.92	8.24
October	.41	3.15	3.84	2.28	14.51
November	.41	3.75	5.42	6.77	34.27
December	.41	4.27	6.91	11.99	56.36

Table 1-4. Potential streamflow depletion in the Big River Area, central Rhode Island, under the modified U.S. Fish and Wildlife Service aquatic base flow instream-flow criterion, 0.50 cubic foot per second per square mile, specified for application to KCWA wells in the Mishnock Basin.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the instream-flow criterion of 0.50 $ft^3/s/mi^2$ (Camp Dresser McKee, Inc., 1999, 2000, 2001) from the estimated average monthly streamflows without ground-water withdrawals at stations in the Big River Area. KCWA, Kent County Water Authority; ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criterion ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.50	4.47	7.23	13.86	63.98
February	.50	4.61	7.62	14.96	69.04
March	.50	4.95	8.67	19.97	89.11
April	.50	4.90	8.53	19.29	86.45
May	.50	4.47	7.16	12.36	59.00
June	.50	3.88	5.50	7.45	37.10
July	.50	3.17	3.60	1.44	11.29
August	.50	2.94	3.04	.41	6.24
September	.50	2.88	2.91	.27	5.46
October	.50	3.13	3.54	1.63	11.73
November	.50	3.73	5.12	6.12	31.49
December	.50	4.25	6.61	11.34	53.58

Table 1-5. Potential streamflow depletion in the Big River Area, central Rhode Island, under the estimated Usquepaug–Queen River Basin R2Cross instream-flow criterion of 0.72 cubic foot per second per square mile.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the Usquepaug–Queen River Basin R2Cross instream-flow criterion of 0.72 $ft^3/s/mi^2$ (Armstrong and Parker, 2003) from the estimated average monthly streamflows without ground-water withdrawals at stations in the Big River Area. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criterion ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.72	4.40	6.50	12.24	57.19
February	.72	4.54	6.89	13.34	62.25
March	.72	4.88	7.94	18.35	82.32
April	.72	4.83	7.80	17.67	79.66
May	.72	4.40	6.43	10.74	52.21
June	.72	3.81	4.77	5.83	30.31
July	.72	3.10	2.87	.00	4.50
August	.72	2.87	2.31	.00	.00
September	.72	2.81	2.18	.00	.00
October	.72	3.06	2.81	.01	4.94
November	.72	3.66	4.39	4.50	24.70
December	.72	4.18	5.88	9.72	46.79

Table 1-6. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Instream Flow Incremental Methodology instream-flow criteria for the Saugus River, Massachusetts.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the Gomez and Sullivan Engineers (2002) IFIM instream-flow criteria from average monthly streamflows without ground-water withdrawals at stations in the Big River Area. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	0.57	4.44	7.00	13.34	61.82
February	.57	4.58	7.39	14.44	66.88
March	1.14	4.76	6.55	15.27	69.35
April	1.14	4.71	6.41	14.59	66.69
May	.95	4.33	5.67	9.06	45.10
June	.29	3.94	6.20	8.98	43.58
July	.29	3.23	4.30	2.97	17.77
August	.29	3.00	3.74	1.94	12.72
September	.29	2.94	3.61	1.80	11.94
October	.57	3.10	3.31	1.11	9.57
November	.57	3.70	4.89	5.60	29.33
December	.57	4.22	6.38	10.82	51.42

Table 1-7. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Massachusetts Department of Environmental Protection streamflow-diversion limits for the Ipswich River, Massachusetts.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the Massachusetts Department of Environmental Protection (2003) streamflow-diversion limits for the Ipswich River from average monthly streamflows without ground-water withdrawals at stations in the Big River Area. ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.00	4.32	5.57	10.19	48.54
February	1.00	4.46	5.96	11.29	53.60
March	1.00	4.80	7.01	16.30	73.67
April	1.00	4.75	6.87	15.62	71.01
May	1.00	4.32	5.50	8.69	43.56
June	.42	3.90	5.77	8.03	39.57
July	.42	3.19	3.87	2.02	13.76
August	.42	2.96	3.31	.99	8.71
September	.42	2.90	3.18	.85	7.93
October	.42	3.15	3.81	2.21	14.20
November	1.00	3.58	3.46	2.45	16.05
December	1.00	4.10	4.95	7.67	38.14

Table 1-8. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Ipswich River Fisheries Restoration Task Group (IRFRTG) instream-flow criteria for the Ipswich River, Massachusetts.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the IRFRTG (2002) instream-flow criteria for the Ipswich River from average monthly streamflows without ground-water withdrawals at stations in the Big River Area. Potential streamflow depletions were set to zero if the average monthly streamflows without ground-water withdrawals were less than the IRFRTG instream-flow criteria. IRFRTG Ipswich River Fisheries Restoration Task Group; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.00	4.32	5.57	10.19	48.54
February	1.00	4.46	5.96	11.29	53.60
March	2.50	4.37	2.03	5.31	27.35
April	2.50	4.32	1.89	4.63	24.69
May	2.50	3.89	.52	.00	.00
June	.49	3.88	5.53	7.52	37.41
July	.49	3.17	3.63	1.51	11.60
August	.49	2.94	3.07	.48	6.55
September	.49	2.88	2.94	.34	5.77
October	.49	3.13	3.57	1.70	12.04
November	1.00	3.58	3.46	2.45	16.05
December	1.00	4.10	4.95	7.67	38.14

Table 1-9. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Apse median of monthly median streamflows instream-flow criteria from three selected Rhode Island streamflow-gaging stations.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the median of monthly median flows (Apse, 2000) at selected Rhode Island streamflow-gaging stations from estimates of median of monthly median streamflows for stations in the Big River Area without ground-water withdrawals. Potential streamflow depletion was set to zero if the median of monthly median streamflows without ground-water withdrawals was less than this instream-flow criterion. Selected streams are the Hunt River (station 01117000), the Pawcatuck River at Wood River Junction (station 01117500), and the Wood River at Hope Valley (station 01118000). ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	2.20	3.88	1.20	0.00	0.00
February	2.68	3.98	.31	.00	.00
March	3.09	4.05	.00	.00	.00
April	3.27	4.05	.00	.00	.00
May	2.28	3.84	.83	.00	.00
June	1.27	3.42	2.18	.00	.00
July	.68	2.92	2.43	.00	.00
August	.53	2.78	2.50	.00	.00
September	.50	2.73	2.46	.00	.00
October	.61	2.89	2.56	.00	.00
November	1.13	3.30	2.27	.00	.00
December	1.81	3.77	1.80	.00	.00

Table 1-10. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Apse hybrid instream-flow criteria from three selected Rhode Island streamflow-gaging stations.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting hybrid instream-flow criteria (Apse, 2000) at selected Rhode Island streamflow-gaging stations (rounded values of the median of monthly average streamflows in July, August, and September and median of monthly median streamflows in other months) from estimates of the median of monthly median streamflows without ground-water withdrawals at stations in the Big River Area. Potential streamflow depletion was set to zero if the median of monthly median streamflows without ground-water withdrawals was less than the hybrid instream-flow criterion. Selected streams are the Hunt River (station 01117000), the Pawcatuck River at Wood River Junction (station 01117500), and the Wood River at Hope Valley (station 01118000). ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	1.50	3.88	1.20	0.00	0.00
February	1.80	3.98	.25	.00	.00
March	2.60	4.05	.00	.00	.00
April	2.50	4.04	.00	.00	.00
May	1.60	3.83	.76	.00	.00
June	.80	3.41	2.08	.00	.00
July	.50	2.89	2.03	.00	.00
August	.40	2.76	2.27	.00	.00
September	.40	2.70	2.13	.00	.00
October	.50	2.90	2.60	.00	.00
November	1.10	3.31	2.37	.00	.00
December	1.50	3.77	1.83	.00	.00

Table 1-11. Potential streamflow depletion in the Big River Area, central Rhode Island, under the Apse median of monthly average streamflows instream-flow criteria from three selected Rhode Island streamflow-gaging stations.

[Stations selected for analysis of streamflow depletion in the Big River Area, Rhode Island, shown in figure 1. Potential streamflow depletions calculated by subtracting the average of the median of monthly average flows (Apse, 2000) at selected Rhode Island streamflow-gaging stations from estimates of median of monthly average streamflows without ground-water withdrawals at stations in the Big River Area. Potential streamflow depletion was set to zero if the median of monthly average streamflows without ground-water withdrawals was less than this instream-flow criterion. Selected streams are the Hunt River (station 01117000), the Pawcatuck River at Wood River Junction (station 01117500), and the Wood River at Hope Valley (station 01118000). ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile]

Month	Instream-flow criteria ($ft^3/s/mi^2$)	Potential streamflow depletion (ft^3/s)			
		Lake Mishnock Outflow near Washington (01115965)	Mishnock River at State Route 3 (01115970)	Carr River below Capwell Mill Pond (01115770)	Big River at Hill Farm Road (01115835)
January	2.08	3.90	0.07	0.00	0.00
February	2.23	3.92	.00	.00	.00
March	3.35	4.05	.00	.00	.00
April	3.26	4.07	.00	.00	.00
May	2.07	3.87	.76	.00	.00
June	.91	3.41	1.78	.00	.00
July	.51	3.01	2.41	.00	.00
August	.37	2.86	2.55	.00	.00
September	.38	2.76	2.34	.00	.00
October	.62	2.94	2.47	.00	.00
November	1.45	3.33	1.94	.00	.00
December	1.95	3.76	1.25	.00	.00

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APPENDIX 2

Monthly Ground-Water Withdrawal Rates for Each Alternative Conjunctive-Management Model

Tables

Table 2-1. Monthly ground-water withdrawal rates calculated for management model MM-01A for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.35	0.00	0.98	1.36	1.40	1.40	1.40	453
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	1.11	1.40	1.40	1.40	1.40	1.40	503
3	South-01	1.40	1.40	1.40	1.40	.97	.00	.00	.00	.00	.66	1.40	1.40	304
4	North-01	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	1.10	1.40	288
	Total	5.60	5.60	5.60	5.60	5.17	2.75	1.11	2.38	2.76	3.46	5.30	5.60	1,548
							Carr River Basin							
5	WGW 354	1.40	1.40	1.40	1.40	1.40	1.40	0.65	0.00	0.00	1.40	1.40	1.40	402
6	WGW 355	1.40	1.40	1.40	1.40	1.40	1.40	.00	.89	1.40	1.40	1.40	1.40	453
7	WGW 374	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.53	1.40	1.40	1.40	441
	Total	4.20	4.20	4.20	4.20	4.20	4.20	2.05	0.89	1.93	4.20	4.20	4.20	1,296
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
11	WGW 410	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
	Total	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40	8.40	3,068
							Total for Big River Area							
		18.20	18.20	18.20	18.20	17.77	15.35	11.56	11.67	13.08	16.06	17.90	18.20	5,912

Table 2-2. Monthly ground-water withdrawal rates calculated for management model MM-01B for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.24	0.00	0.76	1.10	1.40	1.40	1.40	435
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.99	1.40	1.40	1.40	1.40	1.40	499
3	South-01	1.40	1.40	1.40	1.40	1.27	.00	.00	.00	.00	.40	1.40	1.40	305
4	North-01	1.34	1.25	1.40	1.40	.00	.00	.00	.00	.00	.00	.65	1.40	225
	Total	5.54	5.45	5.60	5.60	4.07	2.64	0.99	2.16	2.50	3.20	4.85	5.60	1,465
							Carr River Basin							
5	WGW 354	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.86	1.40	1.40	366
6	WGW 355	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.66	1.40	1.40	1.40	359
7	WGW 374	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	1.40	1.40	1.40	339
	Total	4.20	4.20	4.20	4.20	4.20	1.40	0.00	0.00	0.66	3.66	4.20	4.20	1,065
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
11	WGW 410	1.40	1.40	1.40	1.40	1.40	1.40	.36	.00	.78	1.40	1.40	1.40	417
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
	Total	8.40	8.40	8.40	8.40	8.40	8.40	7.36	7.00	7.78	8.40	8.40	8.40	2,974
							Total for Big River Area							
		18.14	18.05	18.20	18.20	16.67	12.44	8.35	9.16	10.93	15.26	17.45	18.20	5,504

Table 2-3. Monthly ground-water withdrawal rates calculated for management model MM-01C for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
								Mishnock River Basin						
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.51	0.95	1.40	1.40	1.40	428
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.79	1.40	1.40	1.40	1.40	1.40	493
3	South-01	1.40	1.40	1.40	1.40	1.40	.02	.00	.00	.00	.27	1.40	1.40	306
4	North-01	.96	.95	1.40	1.40	.32	.00	.00	.00	.00	.00	.41	1.31	204
	Total	5.16	5.15	5.60	5.60	4.52	2.82	0.79	1.91	2.35	3.07	4.61	5.51	1,431
								Carr River Basin						
5	WGW 354	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.00	0.20	1.40	1.40	261
6	WGW 355	1.40	1.40	1.14	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	246
7	WGW 374	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	254
	Total	4.20	4.20	3.94	1.40	0.00	0.00	0.00	0.00	0.00	3.00	4.20	4.20	761
								Big River Basin						
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
11	WGW 410	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.60	1.40	1.40	1.40	358
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.34	1.23	1.40	1.40	1.40	504
	Total	8.40	8.40	8.40	8.40	8.40	7.00	7.00	4.14	4.63	8.40	8.40	8.40	2,734
								Total for Big River Area						
		17.76	17.75	17.94	15.40	12.92	9.82	7.79	6.05	6.98	14.47	17.21	18.11	4,925

Table 2-4. Monthly ground-water withdrawal rates calculated for management model MM-01D for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.38	0.83	1.40	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.69	1.40	1.40	1.40	1.40	1.40	490
3	South-01	1.40	1.40	1.40	1.40	1.40	.05	.00	.00	.00	.25	1.40	1.40	306
4	North-01	1.23	1.40	1.40	1.40	.75	.00	.00	.00	.00	.00	.32	1.19	233
	Total	5.43	5.60	5.60	5.60	4.95	2.85	0.69	1.78	2.23	3.05	4.52	5.39	1,449
							Carr River Basin							
5	WGW 354	1.40	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	1.40	1.40	185
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	127
7	WGW 374	.23	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	93
	Total	1.63	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	4.20	4.20	405
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	1.40	383
11	WGW 410	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.06	1.40	1.40	1.40	299
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.66	1.40	1.40	1.40	1.40	488
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.16	1.40	1.40	1.40	429
	Total	8.40	8.40	8.40	8.40	7.00	7.00	5.60	2.06	3.02	8.40	8.40	8.40	2,535
							Total for Big River Area							
		15.46	15.15	14.00	14.00	11.95	9.85	6.29	3.83	5.25	13.56	17.12	17.99	4,390

Table 2-5. Monthly ground-water withdrawal rates calculated for management model MM-01E for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
2	KC04	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	.00	.00	42
3	South-01	1.40	1.40	.00	.00	.00	.00	.00	1.40	1.40	1.40	1.40	1.40	301
4	North-01	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.39	.12	.25	1.40	1.40	406
	Total	2.80	2.80	1.40	1.40	1.40	1.40	1.40	1.79	1.52	3.05	2.80	2.80	749
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	1.40	171
9	WGW 363	1.40	.00	.00	.00	.00	.00	.00	.00	.00	.29	1.40	1.40	138
10	WGW 366	1.40	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	129
11	WGW 410	1.40	1.40	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	172
12	WGW 411	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	254
13	H3	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	254
	Total	8.40	4.20	2.80	0.00	0.00	0.00	0.00	0.00	0.00	4.49	8.40	8.40	1,117
							Total for Big River Area							
		11.20	7.00	4.20	1.40	1.40	1.40	1.40	1.79	1.52	7.54	11.20	11.20	1,866

Table 2-6. Monthly ground-water withdrawal rates calculated for management model MM-01F for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.65	1.16	0.77	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	1.04	1.40	1.40	1.40	1.40	1.40	501
3	South-01	1.40	1.40	.39	.80	.02	1.40	.00	.00	.00	.00	1.40	1.40	252
4	North-01	.65	.58	.00	.00	.00	.27	.00	.00	.00	.00	.09	.99	79
	Total	4.85	4.78	3.19	3.60	2.82	4.47	1.04	2.05	2.56	2.17	4.29	5.19	1,251
							Carr River Basin							
5	WGW 354	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.00	1.40	1.40	341
6	WGW 355	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	.52	1.40	1.40	271
7	WGW 374	1.40	1.40	1.40	1.40	1.39	.00	.00	.00	.00	.00	1.40	1.40	297
	Total	4.20	4.20	4.20	4.20	2.79	1.40	0.00	0.00	0.00	0.52	4.20	4.20	908
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.67	1.40	1.40	489
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.22	1.16	.00	1.40	1.40	456
11	WGW 410	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	1.40	1.40	341
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
	Total	8.40	8.40	8.40	8.40	8.40	8.40	7.00	6.82	6.76	4.87	8.40	8.40	2,820
							Total for Big River Area							
		17.44	17.38	15.79	16.20	14.02	14.27	8.04	8.87	9.32	7.56	16.89	17.79	4,980

Table 2-7. Monthly ground-water withdrawal rates calculated for management model MM-01G for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
Mishnock River Basin														
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.47	0.90	1.40	0.45	1.40	395
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.97	1.40	1.40	1.40	1.40	1.40	498
3	South-01	1.13	1.10	1.40	1.40	.01	1.40	.00	.00	.00	.33	.00	1.40	247
4	North-01	.00	.00	.94	.30	.00	.14	.00	.00	.00	.00	.00	.02	41
	Total	3.93	3.90	5.14	4.50	2.81	4.34	0.97	1.87	2.30	3.13	1.85	4.22	1,182
Carr River Basin														
5	WGW 354	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.00	1.30	0.00	1.40	251
6	WGW 355	1.40	1.40	.77	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	236
7	WGW 374	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	.00	.46	1.40	183
	Total	4.20	4.20	3.57	1.40	0.00	0.00	0.00	0.00	0.00	2.70	1.86	4.20	669
Big River Basin														
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.07	1.40	1.40	1.40	427
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
11	WGW 410	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	1.40	1.40	1.40	339
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.12	1.40	1.40	1.40	1.40	503
	Total	8.40	8.40	8.40	8.40	8.40	7.00	7.00	3.92	4.27	8.40	8.40	8.40	2,716
Total for Big River Area														
		16.53	16.50	17.11	14.30	11.21	11.34	7.97	5.79	6.57	14.22	12.11	16.82	4,567

Table 2-8. Monthly ground-water withdrawal rates calculated for management model MM-01H for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
2	KC04	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	.00	.00	.00	85
3	South-01	.00	.00	.00	.00	.00	1.40	1.40	1.40	1.40	1.40	1.40	.00	258
4	North-01	1.40	1.40	.08	.00	.00	1.40	.90	.21	.39	1.40	1.05	1.40	295
	Total	1.40	1.40	0.08	0.00	0.00	4.20	3.70	1.61	1.79	2.80	2.45	1.40	638
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	1.40	.00	.00	.00	.00	.00	.00	.00	.00	43
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43
							Big River Basin							
8	WGW 356	0.00	0.00	0.00	0.00	0.00	1.40	1.40	1.40	1.40	1.40	0.00	0.00	214
9	WGW 363	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	1.40	.00	.00	127
10	WGW 366	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	1.40	.00	.00	127
11	WGW 410	.00	.00	.00	.00	.00	1.40	.21	.00	.17	1.40	1.40	1.40	182
12	WGW 411	.00	.00	.00	.00	.00	1.40	1.40	1.40	1.40	1.40	1.40	1.40	300
13	H3	.00	.00	.00	.00	.00	1.40	1.40	.61	.22	1.40	1.40	1.40	239
	Total	0.00	0.00	0.00	0.00	0.00	8.40	7.21	3.41	3.19	8.40	4.20	4.20	1,189
							Total for Big River Area							
		1.40	1.40	0.08	1.40	0.00	12.60	10.92	5.02	4.97	11.20	6.65	5.60	1,870

Table 2-9. Monthly ground-water withdrawal rates calculated for management model MM-01I for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
2	KC04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
3	South-01	.00	.00	.00	.00	.00	1.40	.00	.00	.00	.00	.00	.00	43
4	North-01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	1.40	0.00	0.00	0.00	0.00	0.00	0.00	43
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	0.00	0.00	0.00	0.00	0.00	1.40	1.00	0.00	0.00	0.00	0.00	0.00	73
9	WGW 363	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
10	WGW 366	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	1.40	.00	.00	127
13	H3	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	1.40	.00	.00	127
	Total	0.00	0.00	0.00	0.00	0.00	4.20	3.80	0.00	0.00	2.80	0.00	0.00	328
							Total for Big River Area							
		0.00	0.00	0.00	0.00	0.00	5.60	3.80	0.00	0.00	2.80	0.00	0.00	371

Table 2-10. Monthly ground-water withdrawal rates calculated for management model MM-02 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	1.17	0.00	0.00	0.00	122
2	KC04	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	.00	.00	.00	87
3	South-01	.00	.00	.00	.00	.00	.00	1.26	1.03	.00	.00	.00	.00	70
4	North-01	.00	.00	.00	.00	1.40	.46	.00	.00	.00	.00	.00	.00	56
	Total	0.00	0.00	0.00	0.00	1.40	0.46	2.66	3.83	2.57	0.00	0.00	0.00	335
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.53	.00	.00	.00	16
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	16
							Big River Basin							
8	WGW 356	0.96	0.14	0.00	0.00	0.00	1.40	1.40	1.40	1.40	1.40	1.40	1.40	334
9	WGW 363	1.40	1.40	.96	1.14	1.40	1.40	1.40	1.40	.00	.96	.00	.96	378
10	WGW 366	1.40	1.40	.00	.00	1.40	1.40	1.40	.00	.00	.00	.00	.00	214
11	WGW 410	.00	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.14	.00	162
12	WGW 411	.00	1.40	1.40	1.40	.60	1.40	.00	.61	1.40	1.40	1.40	1.40	377
13	H3	1.40	.00	1.40	1.40	1.40	1.40	1.40	.00	.53	1.40	1.40	1.40	397
	Total	5.16	5.74	5.16	5.34	4.80	7.00	5.60	3.40	3.33	5.16	5.34	5.16	1,862
							Total for Big River Area							
		5.16	5.74	5.16	5.34	6.20	7.46	8.26	7.23	6.43	5.16	5.34	5.16	2,213

Table 2-11. Monthly ground-water withdrawal rates calculated for management model MM-03A for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.38	1.40	1.40	0.98	0.86	0.78	1.40	1.40	1.40	462
2	KC04	1.33	1.32	1.32	1.40	1.34	1.19	1.40	1.40	1.40	1.40	1.40	1.33	494
3	South-01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
4	North-01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	2.73	2.72	2.72	2.78	2.74	2.59	2.38	2.26	2.18	2.80	2.80	2.73	956
							Carr River Basin							
5	WGW 354	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.79	1.40	1.40	154
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	.00	.00	42
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.86	.00	27
	Total	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	2.19	2.26	1.40	222
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.89	.00	.00	1.40	1.40	1.40	409
11	WGW 410	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.13	1.40	1.40	1.40	343
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.29	1.40	1.40	1.40	1.40	477
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.19	1.40	1.40	1.40	430
	Total	8.40	8.40	8.40	8.40	8.40	7.00	6.48	1.69	3.11	8.40	8.40	8.40	2,595
							Total for Big River Area							
		12.53	11.12	11.12	11.18	11.14	9.59	8.86	3.95	5.32	13.39	13.46	12.53	3,773

Table 2-12. Monthly ground-water withdrawal rates calculated for management model MM-03B for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	1.34	0.36	0.70	1.40	1.40	1.40	456
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
3	South-01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
4	North-01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	2.80	2.80	2.80	2.80	2.80	2.80	2.74	1.76	2.10	2.80	2.80	2.80	967
							Carr River Basin							
5	WGW 354	1.40	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	1.40	1.40	193
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	127
7	WGW 374	1.40	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	129
	Total	2.80	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	4.20	4.20	449
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	.06	.00	.00	.00	1.40	1.40	1.40	341
11	WGW 410	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	1.40	1.40	1.40	297
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.76	1.40	1.40	1.40	1.40	491
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.14	1.40	1.40	1.40	429
	Total	8.40	8.40	8.40	8.40	7.00	5.66	5.60	2.16	2.94	8.40	8.40	8.40	2,494
							Total for Big River Area							
		14.00	12.60	11.20	11.20	9.80	8.46	8.34	3.92	5.04	13.30	15.40	15.40	3,910

Table 2-13. Monthly ground-water withdrawal rates calculated for management model MM-04A for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	0.00	1.40	1.40	0.80	0.80	0.24	0.00	0.00	1.40	310
2	KC04	.32	.32	.00	1.40	.00	.80	1.40	1.40	1.40	.64	.00	.32	246
3	South-01	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.56	1.40	1.40	1.40	357
4	North-01	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.62	1.40	1.40	316
	Total:	4.52	4.52	4.20	4.20	4.20	2.20	2.20	2.20	2.20	2.66	2.80	4.52	1,229
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.27	0.00	50
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.27	0.00	50
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.85	.00	.00	1.40	1.40	1.40	408
11	WGW 410	1.40	1.40	1.40	1.40	1.40	.84	.00	.00	.24	1.40	1.40	1.40	372
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.36	1.40	1.40	1.40	1.40	479
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.15	1.40	1.40	1.40	429
	Total:	8.40	8.40	8.40	8.40	8.40	7.84	6.45	1.76	3.19	8.40	8.40	8.40	2,625
							Total for Big River Area							
		12.92	12.92	12.60	12.60	12.60	10.04	8.65	3.97	5.39	12.46	11.47	12.92	3,904

Table 2-14. Monthly ground-water withdrawal rates calculated for management model MM-04B for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.38	0.83	1.40	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.69	1.40	1.40	1.40	1.40	1.40	490
3	South-01	1.40	1.40	1.40	1.40	1.40	.05	.00	.00	.00	.25	1.40	1.40	306
4	North-01	1.23	1.40	1.40	1.40	.75	.00	.00	.00	.00	.00	.32	1.19	233
	Total	5.43	5.60	5.60	5.60	4.95	2.85	0.69	1.78	2.23	3.05	4.52	5.39	1,449
							Carr River Basin							
5	WGW 354	1.40	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	1.40	1.40	185
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	127
7	WGW 374	.23	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	93
	Total	1.63	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	4.20	4.20	405
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	1.40	383
11	WGW 410	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.06	1.40	1.40	1.40	299
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.66	1.40	1.40	1.40	1.40	488
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.16	1.40	1.40	1.40	429
	Total	8.40	8.40	8.40	8.40	7.00	7.00	5.60	2.06	3.02	8.40	8.40	8.40	2,535
							Total for Big River Area							
		15.46	15.15	14.00	14.00	11.95	9.85	6.29	3.83	5.25	13.56	17.12	17.99	4,390

Table 2-15. Monthly ground-water withdrawal rates calculated for management model MM-05 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.37	0.83	1.40	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.66	1.40	1.40	1.40	1.40	1.40	489
3	South-01	1.40	1.40	1.40	1.40	1.40	.03	.00	.00	.00	.09	1.40	1.40	301
4	North-01	1.24	1.36	1.40	1.40	0.70	0.00	0.00	0.00	0.00	0.00	0.27	1.17	228
	Total	5.44	5.56	5.60	5.60	4.89	2.83	0.66	1.77	2.23	2.89	4.47	5.37	1,438
							Carr River Basin							
5	WGW 354	1.40	1.40	0.58	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	1.40	231
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	127
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.33	1.40	1.40	95
	Total	1.40	1.40	0.58	0.00	0.00	0.00	0.00	0.00	0.00	3.13	4.20	4.20	454
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	1.40	383
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.73	1.40	1.40	1.40	1.40	490
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.15	1.40	1.40	1.40	429
	Total	7.00	7.00	7.00	7.00	7.00	7.00	5.60	2.13	2.95	7.00	7.00	7.00	2,238
							Total for Big River Area							
		13.84	13.96	13.18	12.60	11.89	9.83	6.26	3.90	5.18	13.03	15.67	16.57	4,130

Table 2-16. Monthly ground-water withdrawal rates calculated for management model MM-06 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.39	0.82	1.40	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.70	1.40	1.40	1.40	1.40	1.40	490
3	South-01	1.40	1.40	1.40	1.40	1.40	.06	.00	.00	.00	.36	1.40	1.40	310
4	North-01	1.40	1.40	1.40	1.40	.80	.00	.00	.00	.00	.00	.74	1.40	259
	Total	5.60	5.60	5.60	5.60	5.00	2.86	0.70	1.79	2.22	3.16	4.94	5.60	1,479
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	1.40	1.40	.35	.00	.00	.00	.00	.00	.07	1.40	1.40	1.40	226
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	1.40	1.40	0.35	0.00	0.00	0.00	0.00	0.00	0.07	1.40	1.40	1.40	226
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.29	.00	.00	1.40	1.40	1.40	421
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.33	1.40	1.40	1.40	1.40	478
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.24	1.40	1.40	1.40	432
	Total	7.00	7.00	7.00	7.00	7.00	7.00	6.89	1.73	3.04	7.00	7.00	7.00	2,267
							Total for Big River Area							
		14.00	14.00	12.95	12.60	12.00	9.86	7.59	3.52	5.33	11.56	13.34	14.00	3,973

Table 2-17. Monthly ground-water withdrawal rates calculated for management model MM-07 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.39	0.85	1.40	1.40	1.40	421
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.70	1.40	1.40	1.40	1.40	1.40	490
3	South-01	1.40	1.40	1.40	1.40	1.40	.05	.00	.00	.00	.43	1.40	1.40	311
4	North-01	1.40	1.40	1.40	1.40	.69	.00	.00	.00	.00	.00	.83	1.40	258
	Total	5.60	5.60	5.60	5.60	4.89	2.85	0.70	1.79	2.25	3.23	5.03	5.60	1,481
							Carr River Basin							
5	WGW 354	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.02	1.40	1.40	1.40	298
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	1.40	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.02	1.40	1.40	1.40	298
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.82	.00	.00	1.40	1.40	1.40	407
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.48	1.40	1.40	1.40	1.40	483
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.24	1.40	1.40	1.40	432
	Total	7.00	7.00	7.00	7.00	7.00	7.00	6.42	1.88	3.04	7.00	7.00	7.00	2,257
							Total for Big River Area							
		14.00	14.00	14.00	14.00	11.89	9.85	7.11	3.67	5.30	11.63	13.43	14.00	4,036

Table 2-18. Monthly ground-water withdrawal rates calculated for management model MM-08 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.38	0.82	1.40	1.40	1.40	420
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.70	1.40	1.40	1.40	1.40	1.40	490
3	South-01	1.40	1.40	1.40	1.40	1.40	.05	.00	.00	.00	.42	1.40	1.40	311
4	North-01	1.40	1.40	1.40	1.40	.75	.00	.00	.00	.00	.00	.80	1.40	259
	Total	5.60	5.60	5.60	5.60	4.95	2.85	0.70	1.78	2.22	3.22	5.00	5.60	1,481
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	254
	Total	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	1.40	254
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.67	.00	.00	1.40	1.40	1.40	403
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.49	1.40	1.40	1.40	1.40	483
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.17	1.40	1.40	1.40	430
	Total	7.00	7.00	7.00	7.00	7.00	7.00	6.27	1.89	2.97	7.00	7.00	7.00	2,252
							Total for Big River Area							
		14.00	14.00	14.00	12.60	11.95	9.85	6.97	3.67	5.19	11.62	13.40	14.00	3,986

Table 2-19. Monthly ground-water withdrawal rates calculated for management model MM-09 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.44	0.90	1.40	1.40	1.40	424
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.82	1.40	1.40	1.40	1.40	1.40	494
3	South-01	1.40	1.40	1.40	1.40	1.40	.16	.00	.00	.00	.67	1.40	1.40	322
4	North-01	1.40	1.40	1.40	1.40	1.18	.00	.00	.00	.00	.00	1.10	1.40	281
	Total	5.60	5.60	5.60	5.60	5.38	2.96	0.82	1.84	2.30	3.46	5.30	5.60	1,521
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.57	1.40	1.40	1.40	1.40	486
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.27	1.40	1.40	1.40	433
	Total	7.00	7.00	7.00	7.00	7.00	7.00	7.00	1.97	3.07	7.00	7.00	7.00	2,279
							Total for Big River Area							
		12.60	12.60	12.60	12.60	12.38	9.96	7.82	3.81	5.37	10.46	12.30	12.60	3,800

Table 2-20. Monthly ground-water withdrawal rates calculated for management model MM-10A for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
Mishnock River Basin														
1	KC03	1.40	1.40	1.40	1.40	1.40	0.41	0.00	0.13	0.20	0.46	1.40	1.12	325
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.58	1.40	1.40	1.40	1.40	1.40	487
3	South-01	.42	.11	1.40	1.40	.87	.00	.00	.00	.00	.00	.18	.00	131
4	North-01	.00	.00	1.40	.00	.00	.00	.00	.00	.00	.00	.00	.00	40
	Total	3.22	2.91	5.60	4.20	3.67	1.81	0.58	1.53	1.60	1.86	2.98	2.52	983
Carr River Basin														
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Big River Basin														
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.85	0.00	1.40	1.40	1.40	409
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	.79	364
10	WGW 366	1.40	1.09	1.40	1.40	1.40	1.40	.00	.00	1.38	.34	.92	.00	327
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	.76	1.40	.00	1.40	1.40	1.40	449
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	1.29	294
	Total	7.00	6.69	7.00	7.00	7.00	7.00	0.76	2.25	1.38	4.54	5.12	4.88	1,843
Total for Big River Area														
		10.22	9.60	12.60	11.20	10.67	8.81	1.34	3.78	2.97	6.40	8.10	7.40	2,826

Table 2-21. Monthly ground-water withdrawal rates calculated for management model MM-10B for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	85
2	KC04	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	.00	1.40	1.40	172
3	South-01	.31	1.15	1.40	.06	.31	.00	.92	.00	.42	.37	.21	.39	166
4	North-01	1.40	.00	.31	1.40	1.40	.00	1.40	.63	.00	.00	.00	.00	199
	Total	1.71	1.15	1.71	1.46	1.71	0.00	2.32	2.03	1.82	0.37	3.01	3.19	623
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.40	1.20	1.40	1.40	1.40	0.00	0.00	0.13	0.00	0.00	1.40	1.40	295
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.33	.00	.00	.91	1.40	1.40	1.32	406
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	469
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	1.40	254
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	.53	.69	.00	1.09	1.24	1.40	406
	Total	7.00	6.80	7.00	7.00	7.00	4.13	1.93	2.22	2.31	3.89	5.44	5.52	1,829
							Total for Big River Area							
		8.71	7.95	8.71	8.46	8.71	4.13	4.25	4.25	4.13	4.25	8.46	8.71	2,452

Table 2-22. Monthly ground-water withdrawal rates calculated for management model MM-10C for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.07	0.16	0.00	0.00	0.00	0.00	0.00	1.40	1.40	92
2	KC04	1.26	1.40	.16	.00	.00	.00	1.31	.79	.53	.00	1.40	1.40	253
3	South-01	1.40	1.30	1.40	1.40	1.40	.05	.00	.00	.92	1.40	.07	.16	287
4	North-01	.30	.00	1.40	1.40	1.40	1.40	.18	.70	.00	.09	.00	.00	207
	Total	2.96	2.70	2.96	2.87	2.96	1.45	1.49	1.49	1.45	1.49	2.87	2.96	840
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.90	0.00	1.40	1.40	157
9	WGW 363	1.40	1.40	1.40	1.10	1.40	1.01	1.40	.00	.00	1.40	1.40	1.26	399
10	WGW 366	1.26	.78	1.26	1.40	1.40	1.40	1.40	1.18	.55	1.40	1.40	.00	409
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.26	.00	.00	.35	1.40	.00	.00	1.40	304
13	H3	1.40	1.40	1.40	1.40	1.40	.44	.13	.00	.00	.13	1.10	1.40	309
	Total	5.46	4.98	5.46	5.30	5.46	2.85	2.93	2.93	2.85	2.93	5.30	5.46	1,577
							Total for Big River Area							
		8.41	7.68	8.41	8.17	8.41	4.29	4.42	4.42	4.29	4.42	8.17	8.41	2,417

Table 2-23. Monthly ground-water withdrawal rates calculated for management model MM-11A for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.30	1.40	1.40	1.40	0.29	0.00	0.06	0.11	0.34	1.40	0.95	305
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	.56	1.40	1.40	1.40	1.40	1.40	486
3	South-01	.22	.00	1.40	.99	.60	.00	.00	.00	.00	.00	.01	.00	95
4	North-01	.00	.00	1.16	.00	.00	.00	.00	.00	.00	.00	.00	.00	33
	Total	3.02	2.70	5.36	3.79	3.40	1.69	0.56	1.46	1.51	1.74	2.81	2.35	919
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.00	0.00	1.40	1.40	1.40	383
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	.00	.55	.00	1.40	1.40	1.40	400
10	WGW 366	1.01	.53	1.40	1.40	1.40	1.40	.00	.00	1.39	.21	1.40	.58	326
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	.14	1.40	.00	1.27	.00	1.40	383
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	.00	255
	Total	6.61	6.13	7.00	7.00	7.00	7.00	0.14	1.95	1.39	4.28	4.20	4.78	1,746
							Total for Big River Area							
		9.63	8.83	12.36	10.79	10.40	8.69	0.70	3.42	2.90	6.02	7.00	7.13	2,666

Table 2-24. Monthly ground-water withdrawal rates calculated for management model MM-11B for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	85
2	KC04	.00	.00	.00	.00	.00	.00	.00	1.40	1.22	.00	1.40	1.40	167
3	South-01	.02	1.40	.92	.00	.00	.00	.99	.00	.46	.96	.00	.08	145
4	North-01	1.40	.00	.00	1.40	1.40	.00	1.40	.50	.00	.00	.00	.00	186
	Total	1.42	1.40	0.92	1.40	1.40	0.00	2.39	1.90	1.68	0.96	2.80	2.88	584
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.12	0.23	1.40	0.69	0.92	0.00	0.00	0.86	0.00	0.00	1.40	1.40	242
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	.84	366
10	WGW 366	1.17	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	462
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.96	.00	.69	1.40	305
13	H3	1.40	1.40	1.40	1.40	1.40	1.24	.37	.00	.00	.40	.00	1.40	315
	Total	6.49	5.83	7.00	6.29	6.52	4.04	1.77	2.26	2.36	3.20	4.89	5.04	1,690
							Total for Big River Area							
		7.92	7.22	7.92	7.69	7.92	4.04	4.16	4.16	4.04	4.16	7.69	7.92	2,274

Table 2-25. Monthly ground-water withdrawal rates calculated for management model MM-11C for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	1.40	89
2	KC04	1.40	1.40	.00	.00	.00	.00	1.30	.68	.44	.00	1.40	1.40	246
3	South-01	1.40	.95	1.40	1.32	1.40	.00	.00	.00	.92	1.39	.00	.00	265
4	North-01	.00	.00	1.40	1.40	1.40	1.35	.09	.71	.00	.00	.00	.00	192
	Total	2.80	2.56	2.80	2.72	2.80	1.35	1.39	1.39	1.35	1.39	2.72	2.80	792
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.36	0.00	1.40	1.40	140
9	WGW 363	1.40	1.40	1.40	.74	1.40	.22	1.25	.00	.00	1.25	1.40	.88	343
10	WGW 366	.88	.44	.88	1.40	1.40	1.40	1.40	1.22	.81	1.40	1.40	.00	385
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	.88	.00	.00	.04	1.40	.00	.00	1.40	283
13	H3	1.40	1.40	1.40	1.40	1.40	.95	.00	.00	.00	.00	.74	1.40	306
	Total	5.08	4.64	5.08	4.94	5.08	2.58	2.65	2.65	2.58	2.65	4.94	5.08	1,457
							Total for Big River Area							
		7.88	7.19	7.88	7.65	7.88	3.93	4.05	4.05	3.93	4.05	7.65	7.88	2,249

Table 2-26. Monthly ground-water withdrawal rates calculated for management model MM-12 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.00	0.67	1.17	1.40	1.40	1.40	440
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	1.17	1.40	1.40	1.40	1.40	1.40	504
3	South-01	1.40	1.40	1.40	1.40	1.40	.31	.00	.00	.00	.47	1.40	1.40	321
4	North-01	1.13	1.37	1.40	1.40	1.07	.00	.00	.00	.00	.00	.55	1.40	251
	Total	5.33	5.57	5.60	5.60	5.27	3.11	1.17	2.07	2.57	3.27	4.75	5.60	1,516
							Carr River Basin							
5	WGW 354	1.40	1.40	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	1.40	212
6	WGW 355	1.40	.00	.00	.00	.00	.00	.00	.00	.00	1.40	1.40	1.40	171
7	WGW 374	1.40	1.40	.00	.00	.00	.00	.00	.00	.00	1.29	1.40	1.40	211
	Total	4.20	2.80	1.40	0.00	0.00	0.00	0.00	0.00	0.00	2.69	4.20	4.20	594
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	1.40	1.40	1.40	383
11	WGW 410	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.05	1.40	1.40	1.40	299
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.64	1.40	1.40	1.40	1.40	488
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.20	1.40	1.40	1.40	431
	Total	8.40	8.40	8.40	8.40	7.00	7.00	5.60	2.04	3.06	8.40	8.40	8.40	2,536
							Total for Big River Area							
		17.92	16.76	15.40	14.00	12.27	10.11	6.77	4.11	5.62	14.36	17.35	18.20	4,645

Table 2-27. Monthly ground-water withdrawal rates calculated for management model MM-13 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	1.40	1.40	1.40	1.40	1.40	1.40	0.02	0.79	1.28	1.40	1.40	1.40	447
2	KC04	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
3	South-01	1.40	1.40	1.40	1.40	1.40	.79	.00	.00	.00	.99	1.40	1.40	351
4	North-01	1.40	1.40	1.40	1.40	1.40	.00	.00	.00	.00	.00	1.39	1.40	297
	Total	5.60	5.60	5.60	5.60	5.60	3.59	1.42	2.19	2.68	3.79	5.59	5.60	1,607
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	511
9	WGW 363	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
10	WGW 366	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.00	1.40	1.40	1.40	425
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.85	1.40	1.40	1.40	1.40	494
13	H3	1.40	1.40	1.40	1.40	1.40	1.40	1.40	.00	.31	1.40	1.40	1.40	434
	Total	7.00	7.00	7.00	7.00	7.00	7.00	7.00	2.25	3.11	7.00	7.00	7.00	2,289
							Total for Big River Area							
		12.60	12.60	12.60	12.60	12.60	10.59	8.42	4.44	5.79	10.79	12.59	12.60	3,895

Table 2-28. Monthly ground-water withdrawal rates calculated for management model MM-14 for each well in the Big River Area, Rhode Island.

[Withdrawal rates are in million gallons per day. Well locations are shown on figure 17. Mgal, million gallons]

Well number	Well name	January	February	March	April	May	June	July	August	September	October	November	December	Annual total (Mgal)
							Mishnock River Basin							
1	KC03	0.25	0.19	0.00	0.29	0.38	0.00	0.00	0.00	0.00	0.00	1.40	1.40	120
2	KC04	1.40	1.40	.38	.00	.00	.00	1.27	.86	.46	.00	1.40	1.40	262
3	South-01	1.40	1.31	1.40	1.40	1.40	.28	.00	.00	1.21	1.40	.29	.38	318
4	North-01	.14	.00	1.40	1.40	1.40	1.40	.46	.87	.00	.33	.00	.00	223
	Total	3.18	2.91	3.18	3.09	3.18	1.68	1.73	1.73	1.68	1.73	3.09	3.18	923
							Carr River Basin							
5	WGW 354	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	WGW 355	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
7	WGW 374	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
	Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
							Big River Basin							
8	WGW 356	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.37	0.00	1.40	1.40	140
9	WGW 363	1.40	1.40	1.40	.85	1.40	.39	1.37	.00	.00	1.37	1.40	1.00	362
10	WGW 366	1.00	.55	1.00	1.40	1.40	1.40	1.40	1.31	.92	1.40	1.40	.00	402
11	WGW 410	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	0
12	WGW 411	1.40	1.40	1.40	1.40	1.00	.00	.00	.06	1.40	.00	.00	1.40	287
13	H3	1.40	1.40	1.40	1.40	1.40	.90	.00	.00	.00	.00	.85	1.40	308
	Total	5.20	4.75	5.20	5.05	5.20	2.69	2.77	2.77	2.69	2.77	5.05	5.20	1,499
							Total for Big River Area							
		8.39	7.65	8.39	8.14	8.39	4.36	4.50	4.50	4.36	4.50	8.14	8.39	2,422