Hydrogeology and Simulated Effects of Ground-Water Withdrawals in the Big River Area, Rhode Island

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ABSTRACT

The Rhode Island Water Resources Board is considering expanded use of ground-water resources from the Big River area because increasing water demands in Rhode Island may exceed the capacity of current sources. This report describes the hydrology of the area and numerical simulation models that were used to examine effects of ground-water withdrawals during 1964–98 and to describe potential effects of different withdrawal scenarios in the area.

The Big River study area covers 35.7 square miles (mi^2) and includes three primary surface-water drainage basins—the Mishnock River Basin above Route 3, the Big River Basin, and the Carr River Basin, which is a tributary to the Big River. The principal aquifer (referred to as the surficial aquifer) in the study area, which is defined as the area of stratified deposits with a saturated thickness estimated to be 10 feet or greater, covers an area of 10.9 mi^2. On average, an estimated 75 cubic feet per second (ft^3/s) of water flows through the study area and about 70 ft^3/s flows out of the area as streamflow in either the Big River (about 63 ft^3/s) or the Mishnock River (about 7 ft^3/s).

Numerical simulation models are used to describe the hydrology of the area under simulated predevelopment conditions, conditions during 1964–98, and conditions that might occur in 14 hypothetical ground-water withdrawal scenarios with total ground-water withdrawal rates in the area that range from 2 to 11 million gallons per day. Streamflow depletion caused by these hypothetical ground-water withdrawals is calculated by comparison with simulated flows for the predevelopment conditions, which are identical to simulated conditions during the 1964–98 period but without withdrawals at public-supply wells and wastewater recharge. Interpretation of numerical simulation results indicates that the three basins in the study area are in fact a single ground-water resource. For example, the Carr River Basin above Capwell Mill Pond is naturally losing water to the Mishnock River Basin. Withdrawals in the Carr River Basin can deplete streamflows in the Mishnock River Basin. Withdrawals in the Mishnock River Basin deplete streamflows in the Big River Basin and can intercept water flowing to the Flat River Reservoir North of Hill Farm Road in Coventry, Rhode Island. Withdrawals in the Big River Basin can deplete streamflows in the western unnamed tributary to the Carr River, but do not deplete streamflows in the Mishnock River Basin or in the Carr River upstream of Capwell Mill Pond. Because withdrawals deplete streamflows in the study area, the total amount of ground water that may be withdrawn for public supply depends on the minimum allowable streamflow criterion that is applied for each basin.

INTRODUCTION

The Rhode Island Water Resources Board (RIWRB) is responsible for developing and protecting the State's major water resources. Water demand in Rhode Island is increasing, and the RIWRB is concerned that this 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 an area of about 13.4 mi^2, was established under the responsibility of the Water Resources Coordinating Board, forerunner of the RIWRB. To date (2003), 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 1995, the U.S. Geological Survey (USGS) and RIWRB began a cooperative study of the hydrogeologic setting and water resources of the Big River area and the effects of ground-water withdrawals from water-supply wells on the hydrology of the area (fig. 1). Unconsolidated stratified sand-and-gravel deposits are capable of producing high yields (greater than 300 gal/min) from individual wells in the area. These coarse-grained deposits form the principal aquifer in the Big River Area, which is defined as the surficial aquifer. The aquifer is unconfined and is in hydraulic connection with rivers, brooks, lakes, ponds, and wetlands.

This report is the third in a series of reports produced from the cooperative study. Craft (2001) presented hydrogeologic data collected from July 1996 through October 1998; Stone and Dickerman (2002) characterized the glacial geology and hydraulic properties of the stratified deposits underlying the area.

Purpose and Scope

This report describes the hydrogeology of the Big River study area, the development and calibration of steady-state and transient numerical ground-water-flow models of the surficial aquifer of the study area, and an evaluation of the effects of 14 ground-water-withdrawal scenarios on the hydrologic system. The USGS finite-difference ground-water flow model (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), commonly referred to as MODFLOW, was used for numerical simulations of ground-water flow and ground-water/surface-water interactions. Reports by Craft (2001) and Stone and Dickerman (2002) provided much of the hydrogeologic data for this study on which the numerical models were developed and calibrated. The models are representative of average hydrologic conditions for the 35-year simulation period 1964–98. This simulation period was selected because it includes the full period of ground-water-supply withdrawals from the surficial aquifer for public supply and a large part of the most substantial recorded drought in Rhode Island history (Walker and Lautzenheiser, 1991).

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) and that part of the Mishnock River Drainage Basin (3.3 mi^2) that is upstream from a USGS partial-record streamflow measurement site at State Route 3 (station 01115970). The study area is part of the Seaboard Lowland section of the New England physiographic province (Fenneman, 1938, pl. 1). Landforms are characterized by a series of north- to northwest-trending hills and valleys. The highest point in the basin is on the southwestern boundary of the study area at an altitude of 600 ft on Raccoon Hill (pl. 1). Valley bottoms have altitudes that generally are below 300 ft; the lowest altitude in the study area is 240 ft along the Mishnock River where it leaves the study area near Route 3.

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 to 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, generally is less than 12 ft in depth (Guthrie and Stolgitis, 1977) and 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.

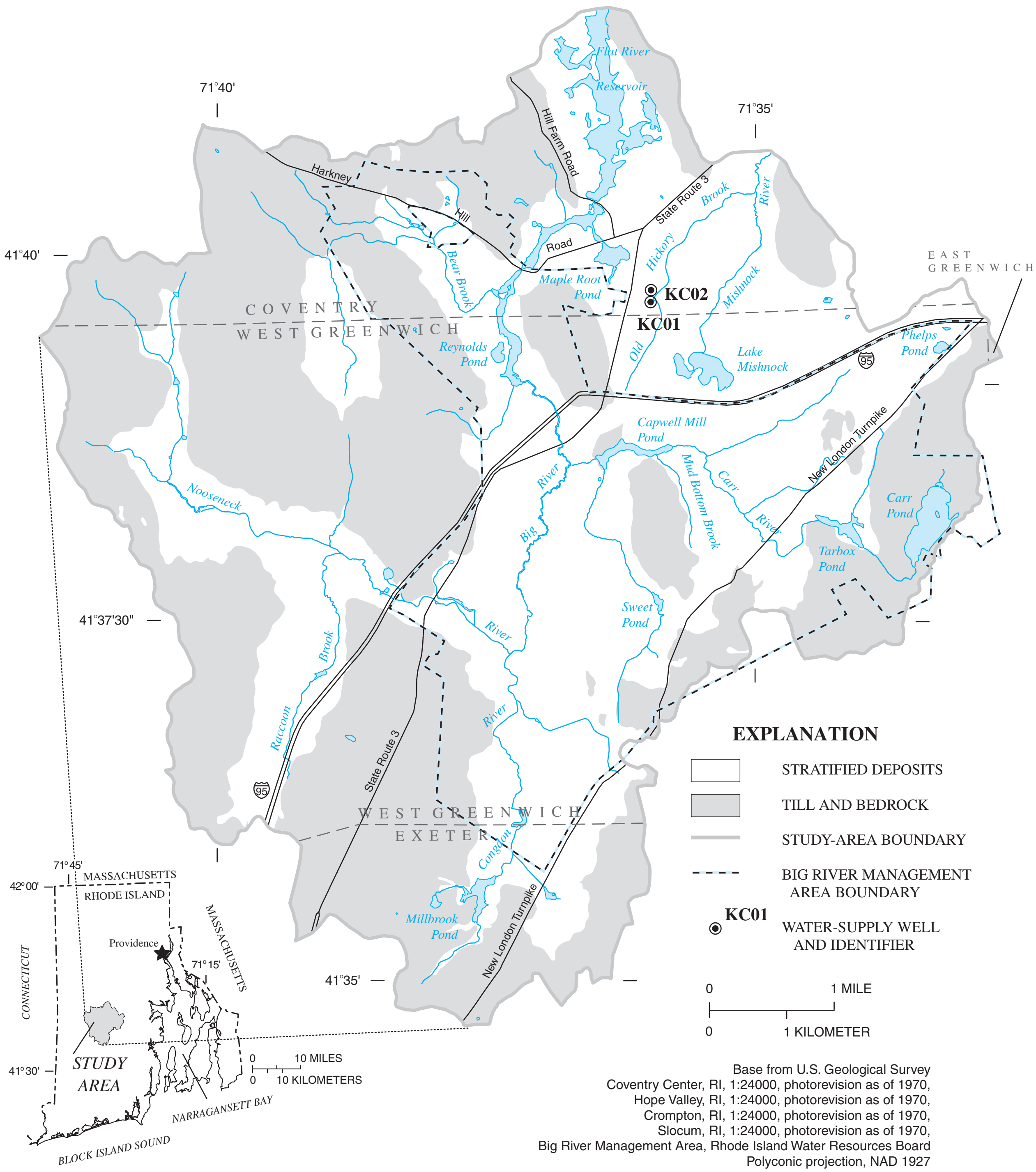


Figure 1. Location of the Big River study area, distribution of stratified sand-and-gravel deposits, and the boundary of the Big River Management Area, Rhode Island.

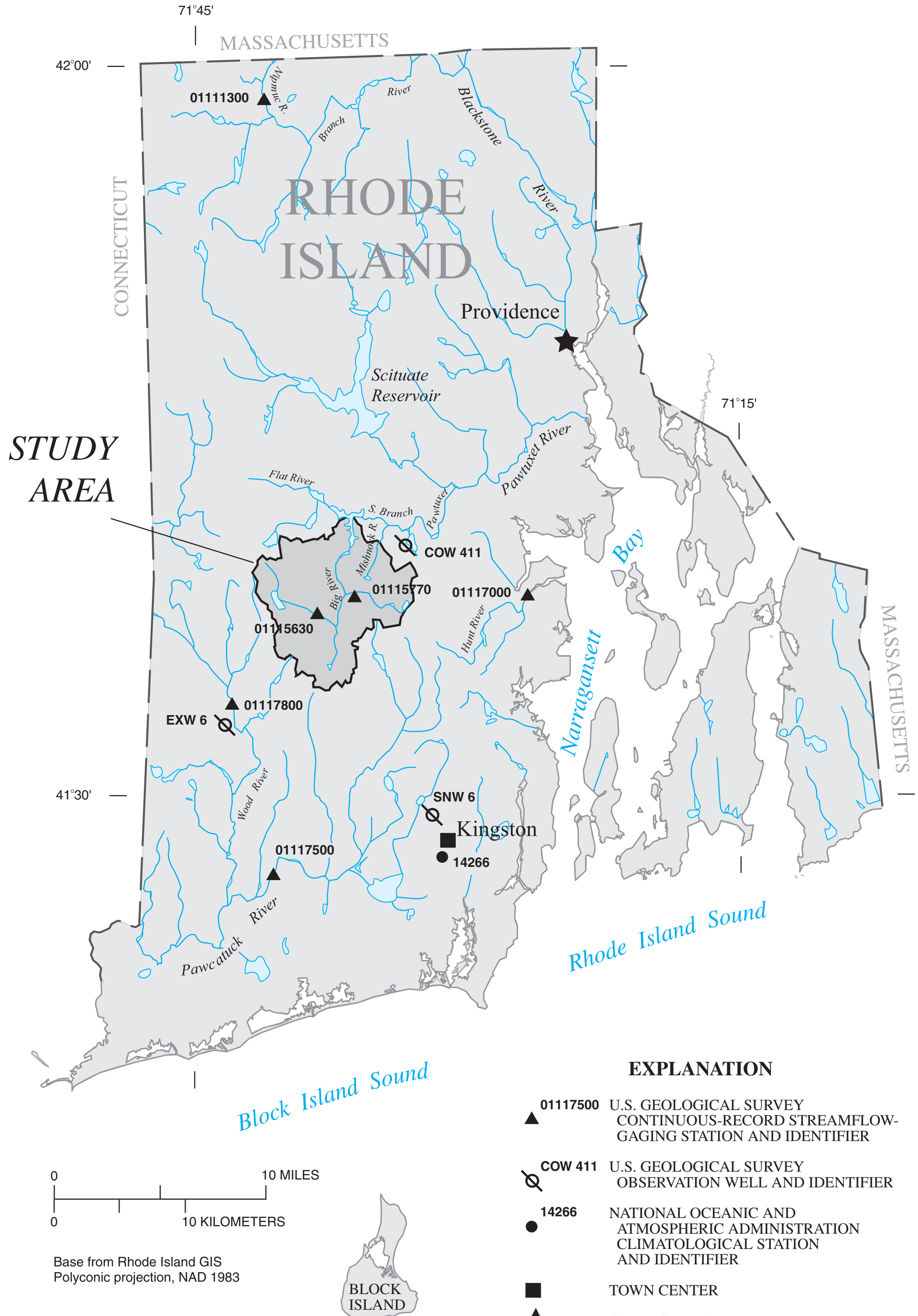


Figure 2. Location of U.S. Geological Survey continuous streamflow-gaging stations, observation wells, and National Oceanic and Atmospheric Administration climatological station used to estimate hydrologic conditions in the Big River study area, Rhode Island, 1964–98.

The Mishnock River originates at Lake Mishnock and flows northward through a large forested wetland called Mishnock Swamp. Old Hickory Brook is a tributary to the Mishnock River (fig. 1). The Mishnock River joins the South Branch of the Pawtuxet River about 1 mi north of the partial-record site at Route 3 and about a mile downstream of the Flat River Reservoir Dam.

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. The 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, Rhode Island, approximately 12 mi southeast of the center of the study area (fig. 2) was 50.3 in. during 1964–98, and varied from 30.8 to 70.4 in. (National Oceanic and Atmospheric Administration, 2002). Monthly total precipitation measurements ranged from 0.5 to 14.4 in. (fig. 3). The average monthly precipitation was 4.2 in. during the entire 1964–98 period and was fairly evenly distributed throughout the year, within a range of 3.3 to 5.1 in. of rain or snow each month. Average annual air temperature at the climatological station was 49.6°F during the 1964–98 period, and monthly average temperatures ranged from 28.4°F in January to 70.7°F during July.

Previous Studies and Data Networks

Prior to the report by Stone and Dickerman (2002), surficial geologic maps had been published for parts of the study area by Smith (1956), Feininger (1962), and Power (1957). Bedrock geology of the study area was mapped by Moore (1958, 1963), Power (1959), and Quinn (1963, 1971), and as part of a bedrock map of Rhode Island by Hermes and others (1994).

Hydrogeologic data and reconnaissance studies of ground-water availability in the study area are reported in Allen and others (1959), Bierschenk and Hahn (1959), Hahn (1959), Mason and Hahn (1960), Lang (1961), Gonthier (1966), and Craft (2001). Several additional studies were completed during the 1970s and 1980s in response to the proposal to construct a reservoir in the Big River Basin (Keyes and Associates and Metcalf and Eddy Inc., 1977; U.S. Army Corps of Engineers, 1979a-c, 1980a-c; Maguire and Goldberg, Zoino, and Associates, Inc., 1984; A.D. Little, Inc. 1989). More recently, Camp Dresser McKee, Inc. (1999, 2000, 2001) drilled test wells, conducted aquifer tests, and developed ground-water-flow models for the Mishnock River area as part of a water-supply study for the Kent County Water Authority.

Information about long-term average hydrologic conditions was necessary to simulate the effects of ground-water development. Streamflow measurements were made by the USGS at continuous-record streamflow-gaging stations on the Nooseneck River (station 01115630) during 1964–81 and Carr River (station 01115770) during 1964–80 (fig. 2). Continuous long-term records of streamflow and ground-water levels, however, are not available within the study area for the entire 35-year simulation period, 1964–98 (Socolow and others, 2001; U.S. Geological Survey, 2002). Six USGS streamflow-gaging stations and three USGS ground-water observation wells in similar hydrogeologic settings within Rhode Island (fig. 2) were selected to provide representative hydrologic data that are necessary to estimate long-term average conditions in the Big River area during 1964–98.

Acknowledgments

The authors thank Timothy Brown and Cindy Heard of the Kent County Water Authority for providing lithologic logs, aquifer-test data, ground-water-withdrawal records, and water-delivery records for the Mishnock River Basin. The authors also thank area residents who provided access to their property for the purpose of measuring water levels and streamflow during this investigation. Lance Ostiguy, USGS, provided support in the development of geographic-information-systems (GIS) datasets and maps. Janet Stone, USGS, provided detailed maps of sedimentary features within the stratified deposits.

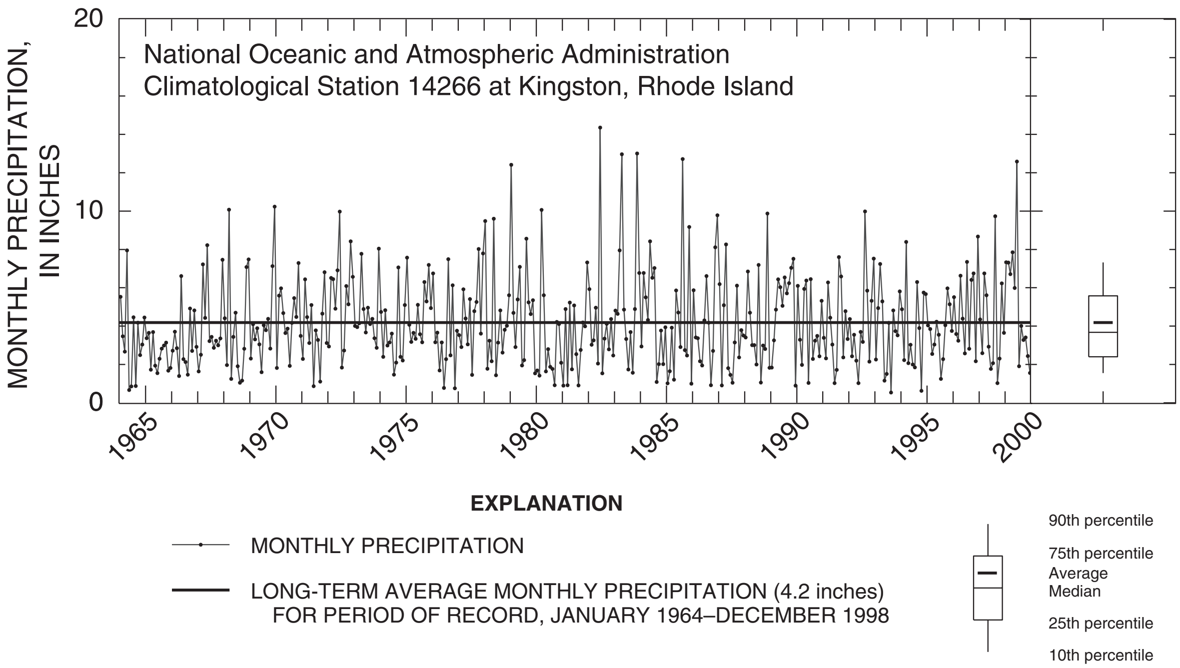


Figure 3. Record of total monthly precipitation and distribution of monthly precipitation measurements for the National Oceanic and Atmospheric Administration climatological station 14266, Kingston, Rhode Island, 1964–98. (Location of climatological station shown on fig. 2.)

HYDROGEOLOGY

This section describes the hydrogeology of the study area, which is necessary for development of the numerical models and the understanding of interactions between ground water and surface water in the Big River study area.

Hydrogeologic Units

The three major hydrogeologic units in the study area are glacial stratified deposits, glacial till, and bedrock (fig. 1). Stone and Dickerman (2002) provide detailed descriptions of these units, and the information that follows was drawn largely from their work.

Granitic bedrock that is cut by ubiquitous fractures and joints underlies the basin. Granitic bedrock in New England generally has extremely low primary porosity, and ground water commonly flows only through connecting fractures and joints. Reported yields of wells tapping bedrock in the study area range from less than 1 to 50 gal/min, with a median yield of 5 gal/min (Gonthier, 1966). Stone and Dickerman (2002) report that the depth to bedrock in the study area ranges from 0 to as much as 250 ft below land surface. The minimum bedrock altitude is about 100 ft above the National Vertical Geodetic Datum of 1929 (NVGD 1929; commonly referred to as "sea level") in a bedrock valley running north from the Carr River Basin, under Mishnock Lake and the Mishnock River and toward the northern edge of the study area. Hungry Hill and an area of till and bedrock uplands to the southeast of Hungry Hill overlie a bedrock ridge that separates the Big River Basin from the Mishnock River Basin south of Harkney Hill Road and separates the Big River Basin from the Carr River Basin above Capwell Mill Pond (Stone and Dickerman, 2002).

Glacial deposits overlie bedrock and range in thickness from a few feet to more than 200 ft. Glacial deposits consist of two broad types—till and meltwater (stratified) deposits. Till was deposited directly by glacial ice and generally is a compact, nonsorted mixture of sand, silt, and clay, with variable amounts of pebbles, cobbles, and large boulders (Stone and Dickerman, 2002). Till underlies most uplands in the study area and in many places extends beneath stratified deposits in the valleys. In most places, till is less than 10 to 15 ft thick. Glacial tills in New England commonly have low hydraulic conductivity (Melvin and others, 1992) and, therefore, even large-diameter wells tapping till have low yields. Hahn (1959) reports yields that generally are no more than

2 to 3 gal/min from wells completed in till within the study area. Although till generally is not considered a reliable water-bearing material, it is capable of yielding small amounts for domestic and agricultural uses.

Glacial stratified deposits are composed of gravel, sand, silt, and clay carried away from the ice front by meltwater streams, which commonly flowed directly or indirectly into glacial lakes (Stone and Dickerman, 2002). Stratified deposits underlie about 50 percent of the study area and reach a maximum known thickness of about 250 ft. The deposits were grouped by Stone and Dickerman (2002) into two broad categories of mappable units: coarse-grained and fine-grained sediments. Thick, coarse-grained, stratified sediments (coarse gravel to fine sand) have the highest transmissivity and the capacity to yield large quantities of water to wells. These coarse-grained sediments form the surficial aquifer. Fine-grained stratified sediments (very fine sand, silts, and clay) have the lowest transmissivity, and may produce local semiconfining conditions in the aquifer. Most stratified deposits occupy the three major preglacial bedrock valleys, the Big River Valley, the Carr River Valley, and the Mishnock River Valley. Small, isolated, or thin saturated areas of stratified coarse-grained deposits also are found within upland areas along Bear and Raccoon Brooks and the Nooseneck River (fig. 1).

Stone and Dickerman (2002) report results of six aquifer tests done in the study area to characterize the hydraulic properties of the surficial aquifer. The six tests were done at locations where the aquifer was thought to have the potential to yield 300 gal/min or more to individual supply wells. Test wells at the six sites were pumped at rates from 325 to 920 gal/min during the aquifer tests. Transmissivity of the aquifer at the six sites was estimated to range from 6,400 to 22,300 ft^2/d. Horizontal hydraulic conductivity of the total saturated thickness of the aquifer at the six sites ranged from 94 to 281 ft/d, but was estimated to be as high as 600 ft/d for a 30-ft basal unit of sand and gravel at a well site along a tributary to the Carr River near Capwell Mill Pond (fig. 1). Vertical hydraulic conductivity of the aquifer at the six sites ranged from 0.9 to 39.4 ft/d and ratios of horizontal to vertical hydraulic conductivity from 5:1 to 125:1. These estimates of transmissivity and hydraulic conductivity are similar to those reported for coarse-grained glacial stratified deposits of the nearby Hunt and Pawcatuck River Basins (Rosenshein and others, 1968; Dickerman, 1984; Dickerman and Ozbilgin, 1985; Dickerman and others, 1990 and 1997; Dickerman and Bell, 1993).

The storage properties of the surficial aquifer are assumed to be similar to those of other coarse-grained glacial stratified sediments. Allen and others (1963) report values of specific yield ranging from 0.16 to 0.39 for 18 relatively undisturbed samples of stratified sand-and-gravel deposits from the Pawcatuck River Basin. The mean and median values of specific yield for the samples were 0.30 and 0.28, respectively. Furthermore, Moench and others (2001) determined a specific yield of 0.26 for glacial stratified deposits of western Cape Cod, Massachusetts. Moench and others (2001) also report an estimate of 1.3×10^{-5} ft^{-1} for the specific storage of the Cape Cod stratified sediments. Porosity of the 18 sediment samples reported by Allen and others (1963) ranged from 0.25 to 0.50, with mean and median values of 0.34. These average values are close to the porosity of 0.39 determined for glacial stratified deposits of western Cape Cod, Massachusetts, by Garabedian and others (1991).

Postglacial materials locally overlie glacial deposits (Stone and Dickerman, 2002). Postglacial materials are thin (less than 10 ft) units that consist primarily of flood-plain alluvium and swamp deposits. Alluvium underlies the flood plains of most rivers and brooks and consists of sand, gravel, and silt with minor amounts of organic material. Swamp deposits cover many flood-plain surfaces and fill other poorly drained areas such as the Mud Bottom Brook area; these swamp deposits are composed of peat and muck with minor amounts of sand, silt, and clay. Although estimates of the hydraulic properties of these postglacial materials are unavailable, the vertical hydraulic conductivity of the materials can be assumed to be similar to that measured for streambed sediments underlying the adjoining Hunt River Basin. Rosenshein and others (1968) determined that the vertical hydraulic conductivity of streambed sediments at 11 sites on the Hunt River ranged from 0.1 ft/d for organically rich, fine sand and silt to 15.2 ft/d for medium to coarse sand.

Water-Supply Wells

The only large-scale ground-water withdrawals in the study area during the 1964–98 simulation period were from two wells in the Mishnock River Basin that are owned and operated by the Kent County Water Authority (KCWA). These wells, which are identified as KC01 and KC02 on figure 1, began operation in 1965 and 1966, respectively. The combined average annual rate of withdrawal from these two wells was 1.4 Mgal/d (2.15 ft^3/s) during the 1964–98 simulation period (monthly withdrawals from each well between 1965 and 1998 are given in table 1). The maximum combined average annual rate of withdrawal from these wells was 2.34 Mgal/d during 1986. Decreasing yield from the two wells and increased water demand within the KCWA supply area prompted several recent studies to evaluate the possibility for expansion of the KCWA supply-well system in the Mishnock River Basin (Timothy Brown, Kent County Water Authority, written commun., July 1996). Those studies propose future average annual withdrawals of about 3.4 Mgal/d (varying from 2.4 Mgal/d during the summer and early fall to 4.3 Mgal/d during the late fall, winter, and spring) from an expanded well field in the Mishnock River Basin (Camp Dresser McKee, Inc., 1999, 2000, 2001). The expanded well field would include one or more new wells in the vicinity of KC01 and KC02 and one or more new wells north of Lake Mishnock on the area of land between the wetlands along the Mishnock River and Old Hickory Brook.

Ground-Water Levels and Flow

Water levels in the surficial aquifer fluctuate in response to changes in the rates of ground-water recharge and discharge, which are mostly a function of seasonal changes in climatic conditions. Generally, water levels decline from mid-spring to mid-fall because most precipitation is returned to the atmosphere by evaporation and transpiration before it reaches the water table. From mid-fall to mid-spring, lower rates of evaporation and transpiration allow more precipitation to percolate through the soil to recharge the underlying water table, which commonly results in an increase in water levels. A total of 21 wells were selected to represent ground-water levels in the basin (fig. 4). Water-level fluctuations in the wells shown in figure 5 ranged from about 2.2 to 8.3 ft during the 28-month period. In comparison, water-level fluctuations in the three USGS observation wells ranged from 3.37 to 4.90 ft during the 28-month period and from 5.72 to 8.15 ft during the 35-year simulation period (fig. 6). Water-level fluctuations generally were largest in wells with the highest average water-level altitude, except where surface-water altitudes control local ground-water altitudes. At any given location, flows between the ground-water and surface-water systems commonly increase as the difference between the ground-water and surface-water elevations increases, thereby exerting a control on the magnitude of water-level fluctuations. For example, fluctuations in ground-water levels in wells WGW 294, WGW 312, and WGW 302, which are in the vicinity of Sweet Pond, Capwell Mill Pond, and Lake Mishnock, respectively (fig. 4), are less than variations at other wells in the area (for example, WGW 287). The damping effect of surface-water bodies on ground-water levels also is indicated by the narrow range of ground-water-level fluctuations in streambed piezometers (which are shallow wells driven into the bottom of the stream). Ground-water-level fluctuations measured in the streambed piezometers shown in figure 7 ranged from about 0.4 to 1.7 ft during the study period.

The effects of sustained drought conditions during the 1964–66 and 1980–81 periods are apparent as below-average precipitation and ground-water levels during these periods (figs. 3 and 6). Conversely, wet years in the late 1970s and 1982–83 produced higher-than-average ground-water levels. These records also indicate that the total amount of water in storage within the aquifer responds quickly (over the course of a few months) to the amount of available recharge.

A water-table map was prepared for areas of stratified deposits within the study area on the basis of water-level measurements made on December 9, 1997, in 34 observation wells, 7 ponds, and 15 streambed piezometers (pl. 1). This date was selected because ground-water levels measured in observation wells SNW 6, COW 411, and EXW 6 (fig. 2) were close to (but slightly lower than) average water levels measured in these wells during 1964–98 (fig. 6). In areas where observation wells were not available for the current study, supplemental water-level data were available from several wells measured as part of earlier studies; it was assumed that these measurements also reflect long-term-average conditions. Ground-water levels shown on plate 1 were measured in observation wells screened at or near the water table. Surface-water control points, such as locations at which streams cross topographic contours, also were used to construct the water-table map because pond and stream altitudes in the study area generally are equivalent or very close to the altitude of the underlying water table.

Table 1. Summary of monthly withdrawals from public water-supply wells in the Mishnock River Valley of the Big River study area, Rhode Island, 1964–98

[Withdrawals are the monthly average in million gallons per day. COW, Coventry well; KCWA, Kent County Water Authority; --, before pumping began]

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual average
KC01—COW 461 (well went online in June 1965)													
1964	--	--	--	--	--	--	--	--	--	--	--	--	--
1965	--	--	--	--	--	0.76	0.76	0.36	0.55	0.60	0.75	0.68	0.37
1966	0.64	0.73	0.93	0.69	0.91	1.05	.92	.80	.38	.29	.00	.77	.68
1967	1.31	.63	.24	.46	1.03	.56	.66	.92	.69	.21	.21	.42	.61
1968	.99	.81	.00	.00	1.19	.07	.24	.27	1.27	1.30	.99	.00	.59
1969	.00	.26	.58	.08	.77	1.30	1.32	.27	1.15	1.10	.27	.00	.59
1970	1.17	.77	.00	.25	1.30	1.19	.47	1.23	.49	.00	1.01	1.23	.76
1971	.52	.90	1.24	.46	.00	1.34	1.08	.79	1.05	1.08	1.06	1.12	.89
1972	1.18	.04	1.27	1.27	.87	.98	1.22	1.23	1.25	1.24	1.27	.44	1.02
1973	.67	1.08	.52	1.25	1.21	.79	.43	.50	.09	1.45	.00	.20	.68
1974	1.26	1.27	.46	1.14	.00	1.44	1.07	.90	.62	.90	.89	.71	.89
1975	.87	.92	.93	.81	.62	.29	.25	.69	1.03	.36	.02	1.10	.66
1976	1.09	1.12	.27	.54	.95	.97	.99	.91	.95	.90	.86	.83	.87
1977	.80	1.68	.75	.94	.93	.90	.90	.89	.93	.94	.94	.93	.96
1978	.85	.95	.98	1.01	1.05	1.02	1.01	.98	.98	.93	.70	.46	.91
1979	.70	.79	.92	.82	.58	.60	.88	.89	.86	.80	.82	.80	.79
1980	.80	.75	.79	.93	.91	.86	.80	.73	.71	.60	.54	.51	.74
1981	.54	.50	.57	.51	.63	.69	.71	.70	.61	.61	.63	.62	.61
1982	.68	.74	.75	.74	.74	.76	.87	.74	.73	.72	.68	.68	.74
1983	.70	.71	.78	.79	.78	.79	.79	.68	.67	.70	.72	.72	.74
1984	.59	.77	.39	.81	.91	.88	.89	.61	.77	.64	.59	.80	.72
1985	.10	.66	.72	.75	.80	.80	.79	.69	.67	.71	.72	.67	.67
1986	.71	.72	.73	.70	.77	.79	.82	.72	.73	.75	.75	.76	.75
1987	.76	.81	.84	.90	.87	.76	.79	.74	.60	.62	.63	.63	.75
1988	.64	.66	.65	.65	.77	.76	.72	.69	.66	.65	.65	.66	.68

Table 1. Summary of monthly withdrawals from public water-supply wells in the Mishnock River Valley of the Big River study area, Rhode Island, 1964–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual average
KC01—COW 461 (well went online in June 1965)—*Continued*													
1989	0.66	0.60	0.66	0.69	0.69	0.68	0.67	0.70	0.68	0.65	0.63	0.63	0.66
1990	.68	.70	.70	.72	.74	.71	.64	.65	.65	.65	.64	.66	.68
1991	.64	.64	.64	.65	.66	.58	.55	.58	.55	.56	.57	.60	.60
1992	.59	.58	.58	.58	.60	.60	.48	.57	.60	.60	.60	.59	.58
1993	.61	.61	.62	.63	.63	.64	.57	.50	.49	.48	.48	.48	.56
1994	.50	.48	.53	.59	.60	.61	.58	.56	.55	.55	.52	.30	.53
1995	.55	.53	.36	.82	.80	.25	.16	.56	.00	.00	.00	.00	.34
1996	.11	.56	.35	.45	.39	.00	.00	.00	.00	.00	.00	.00	.16
1997	.00	.00	.00	.00	.00	.01	.52	.45	.45	.49	.54	.53	.25
1998	.54	.54	.50	.54	.50	.40	.18	.37	.45	.45	.41	.44	.44
Average	0.64	0.67	0.58	0.63	0.69	0.71	0.68	0.65	0.65	0.64	0.57	0.57	0.64
KC02—COW 462 (well went online in July 1966)													
1964	--	--	--	--	--	--	--	--	--	--	--	--	--
1965	--	--	--	--	--	--	--	--	--	--	--	--	--
1966	--	--	--	--	--	--	1.11	0.76	0.94	1.11	1.17	0.74	0.49
1967	0.00	0.62	1.01	0.84	0.11	0.71	.41	.06	.22	.54	.63	.36	.46
1968	.00	.18	1.14	1.12	.43	1.09	.96	1.07	.08	.00	.18	1.08	.61
1969	1.07	.84	.33	1.05	.28	.18	.14	.78	.26	.12	.86	.88	.57
1970	.09	.39	.96	.78	.00	.02	.86	.00	.45	.96	.40	.00	.41
1971	.45	.09	.00	.36	.69	.44	.73	.43	.06	.24	.35	.12	.33
1972	.07	1.22	.00	.00	.94	.88	.75	.31	.00	.00	.00	1.26	.45
1973	.99	.57	1.05	.00	.00	1.72	1.28	1.25	1.22	1.32	1.29	.36	.92
1974	.00	.00	1.80	.56	1.16	.86	.88	.93	.87	.86	.83	.79	.80
1975	.20	.00	.66	.73	.68	.69	.66	.71	.73	1.01	1.06	.00	.59
1976	.00	.00	.78	.68	.62	2.17	.75	.70	.75	.72	.81	.76	.73
1977	.67	.73	.71	.79	.83	.77	.81	.79	.80	.78	.79	.82	.77
1978	.73	.75	.75	.77	.77	.77	.76	.72	.73	.75	.65	.76	.74

Table 1. Summary of monthly withdrawals from public water-supply wells in the Mishnock River Valley of the Big River study area, Rhode Island, 1964–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual average
KC02—COW 462 (well went online in July 1966)—*Continued*													
1979	0.81	0.84	0.80	0.80	0.81	0.79	0.98	0.98	1.04	1.00	1.04	1.05	0.91
1980	1.03	.98	.98	1.03	1.07	1.09	1.07	1.04	1.02	.96	.98	.95	1.02
1981	.93	.97	1.00	1.08	1.02	1.01	1.10	1.10	1.18	1.12	1.16	1.12	1.07
1982	1.27	1.30	1.31	1.31	1.32	1.36	1.41	1.45	1.47	1.47	1.47	1.48	1.39
1983	1.40	1.31	1.32	1.31	1.32	1.34	1.34	1.34	1.34	1.30	1.26	1.37	1.33
1984	1.12	1.14	1.59	1.09	1.60	1.59	1.67	1.59	1.35	1.35	1.27	1.28	1.39
1985	1.31	1.18	1.20	1.23	1.36	1.41	1.44	1.46	1.36	1.49	1.51	1.53	1.37
1986	1.56	1.57	1.58	1.60	1.67	1.67	1.67	1.53	1.54	1.53	1.54	1.59	1.59
1987	1.62	1.82	1.87	1.92	1.99	1.41	1.27	1.29	1.37	1.38	1.41	1.37	1.56
1988	1.40	1.34	1.26	1.32	1.12	1.35	1.41	1.43	1.43	1.44	1.47	1.47	1.37
1989	1.47	1.50	1.53	1.55	1.58	1.17	.21	.51	.56	.56	.55	.51	.98
1990	.59	.59	.61	.61	.61	.53	.57	.55	.49	.50	.52	.51	.56
1991	.55	.54	.51	.58	.60	.53	.53	.35	.54	.54	.53	.51	.53
1992	.56	.58	.56	.54	.59	.59	.52	.54	.52	.55	.58	.57	.56
1993	.59	.60	.60	.62	.63	.64	.62	.64	.65	.62	.60	.59	.62
1994	.58	.49	.21	.34	.60	.60	.60	.60	.59	.60	.60	.54	.53
1995	.56	.56	.23	.00	.00	.92	.83	.10	.69	.70	.66	.62	.49
1996	.47	.02	.29	.17	.24	.65	.64	.62	.60	.60	.59	.57	.46
1997	.57	.57	.56	.58	.60	.58	.25	.52	.50	.02	.00	.00	.40
1998	.00	.00	.00	.00	.13	.14	.55	.52	.37	.43	.40	.41	.25
Average	0.65	0.67	0.78	0.72	0.72	0.85	0.82	0.76	0.73	0.76	0.78	0.74	0.75

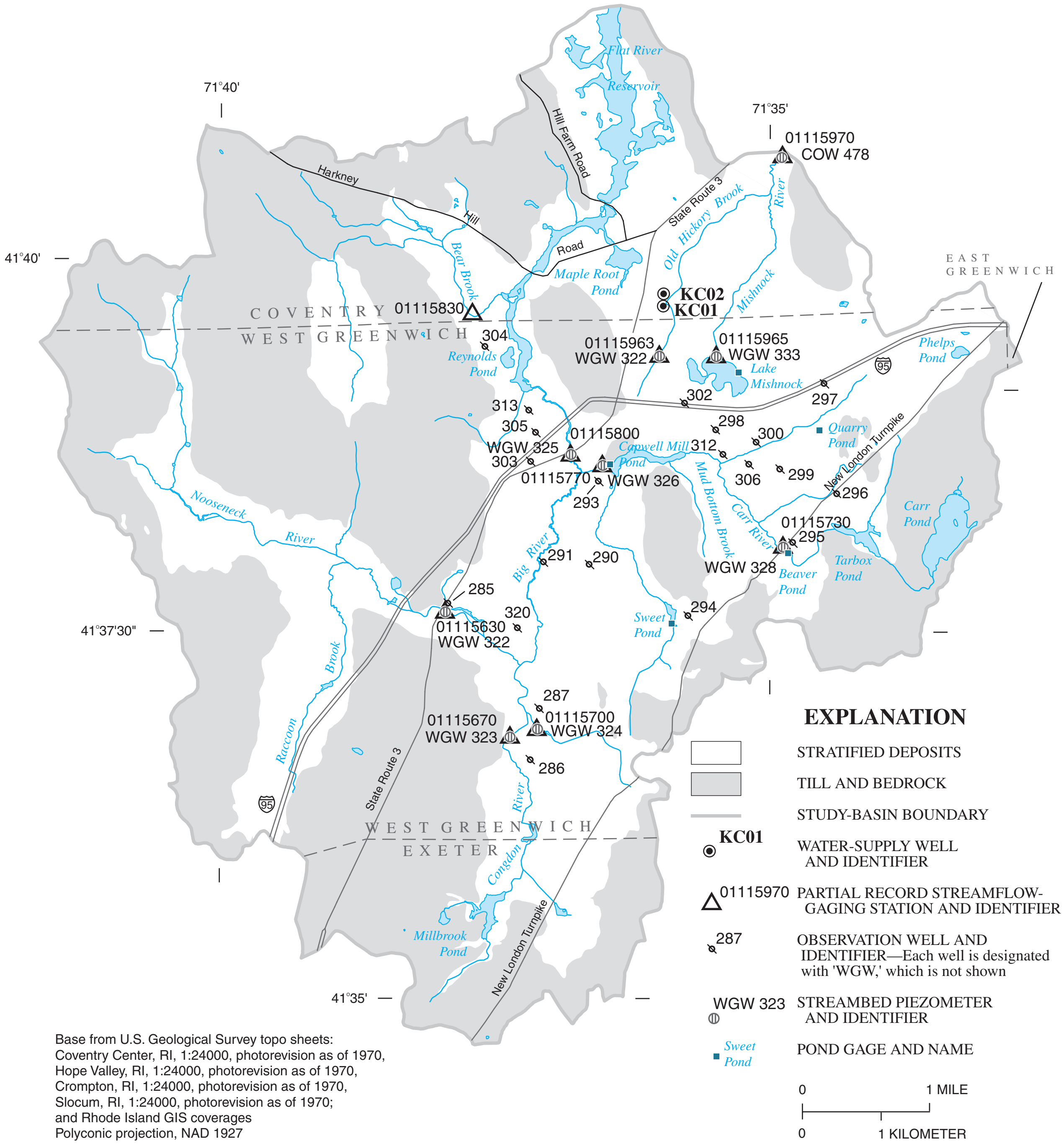


Figure 4. Location of selected partial-record streamflow-gaging stations, observation wells, and streambed piezometers used to collect hydrologic data to develop and calibrate simulation models of the Big River study area, Rhode Island.

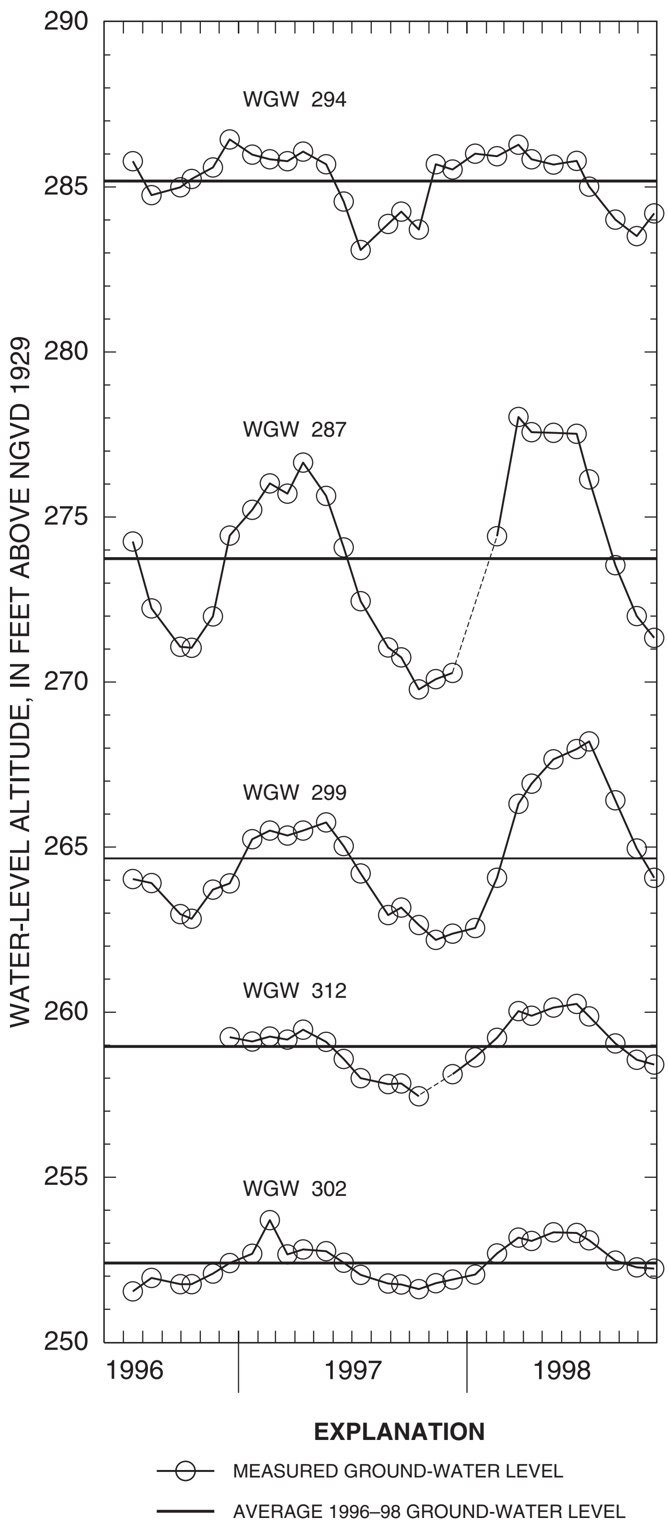


Figure 5. Water-level altitude measurements and the average of water-level altitudes measured in selected wells in the Big River study area, Rhode Island, 1996–98. (Well locations shown on fig. 4.)

Ground water moves through the surficial aquifer in the direction of lower water-level altitudes, which range from a maximum of about 416 ft above NVGD 1929 in the northwestern part of the study area to a minimum of about 240 ft above NVGD 1929 along the Mishnock River at State Route 3. The water-table contours indicate that ground-water flow in the Big River Valley largely is independent of flow in the Carr and Mishnock River Valleys; flow in the two ground-water systems underlying these areas is separated by a northwest-to-southeast-trending bedrock ridge that extends from Hungry Hill under Capwell Mill Pond and southward through the unnamed hill south of the pond (Stone and Dickerman, 2001). The water-table contours indicate that 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 northward to northeastward toward the Mishnock River outflow point on Route 3.

The surficial aquifer is recharged by precipitation, natural stream leakage, ground-water inflow from adjacent till and bedrock uplands, and locally by septic-system discharge. Under natural (predevelopment) conditions, ground water discharges to streams, ponds, and wetlands; by evapotranspiration; and by underflow to adjacent flow systems. During the December 1997 measurement period, water from supply well KC01 was withdrawn at a rate of 0.53 Mgal/d, which is close to the average withdrawal rate (0.64 Mgal/d) during 1964–98. Well KC02, however, was not in service in December 1997. Although withdrawals lower ground-water levels in and around public-supply wells, the localized cone of depression caused by withdrawals from KC01 was not measured in the vicinity of this well during December 1997.

Surface-Water Levels and Streamflow

In most places, ponds, rivers, streams, and riparian wetlands are hydraulically linked to the basin's ground-water system and are the principal areas of ground-water discharge. Locally, surface-water bodies also may be areas of ground-water recharge.

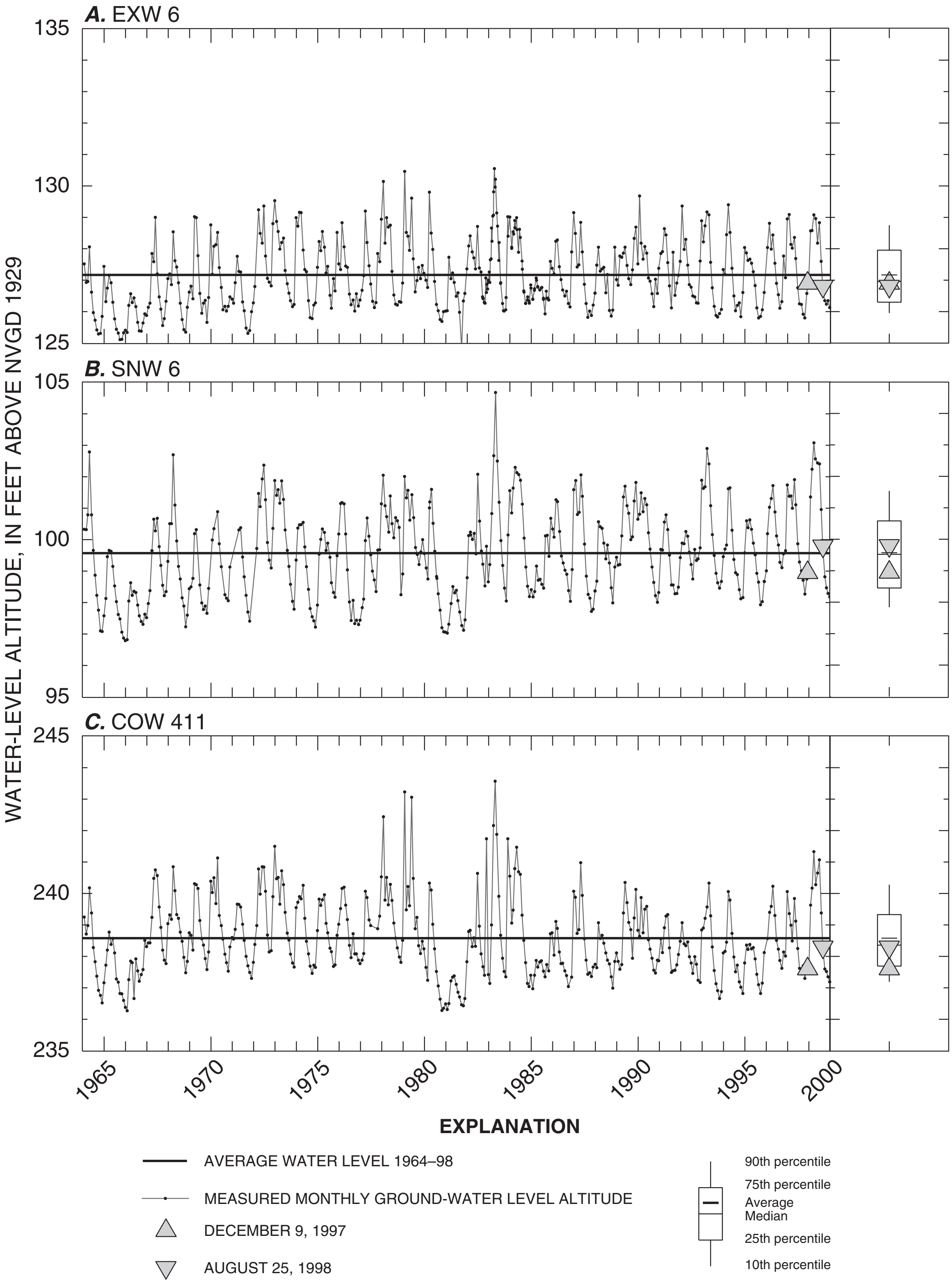


Figure 6. Record of monthly water-level altitudes and distribution of water-level altitudes recorded at wells (*A*) EXW 6, (*B*) SNW 6, and (*C*) COW 411, Big River study area, Rhode Island, 1964–98. (Locations of wells shown on fig. 2.)

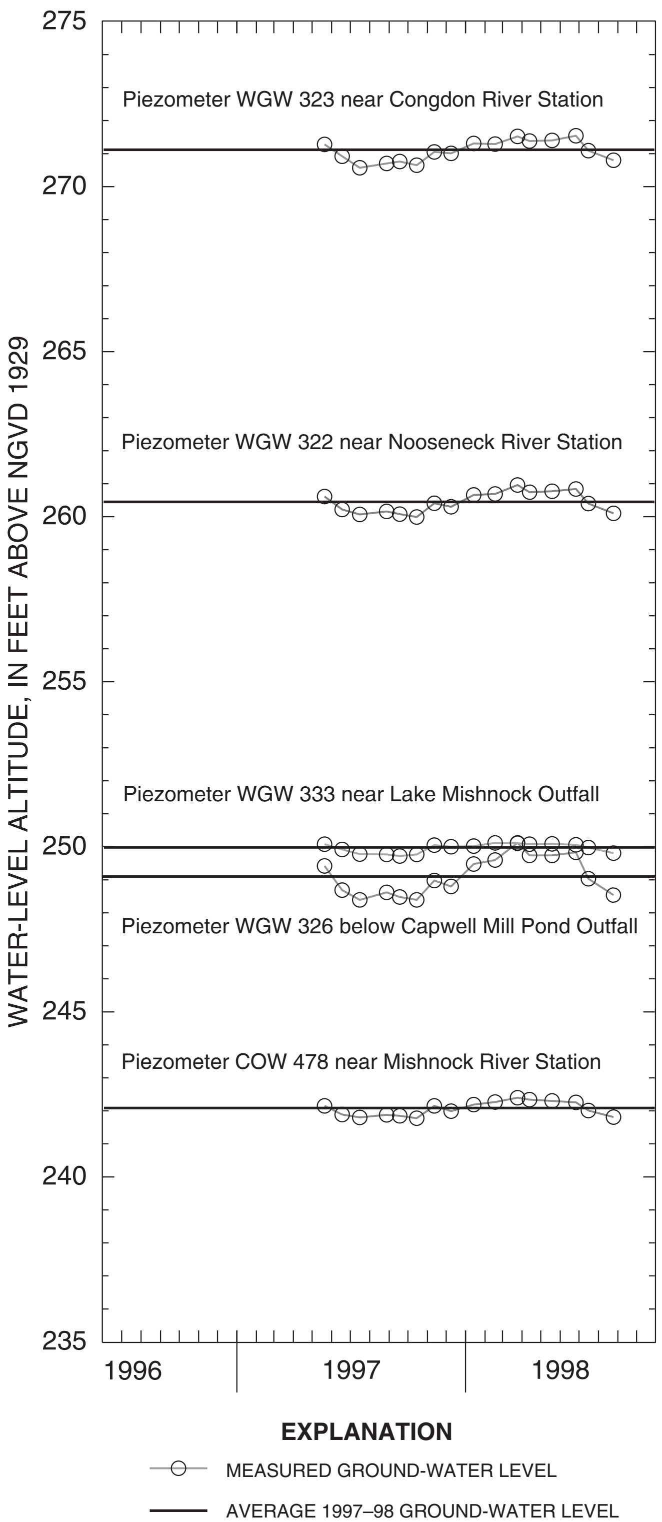


Figure 7. Water-level altitude measurements and the average of water-level altitudes measured in selected streambed piezometers in the Big River study area, Rhode Island, 1996–98. (Piezometer locations shown on fig. 4.)

Because of the importance of these surface waters to the hydrogeology of the study area, surface-water levels and streamflow were measured or estimated at several sites to better understand the interactions between the ground-water and surface-water systems.

Pond levels were measured monthly at eight sites from April 1997 through October 1998 (Craft, 2001). In general, the timing of the annual highs and lows in pond levels closely follows that of ground-water levels because of the hydraulic connection between ponds and the surrounding ground-water system. Seasonal pond-level fluctuations typically are not as large as ground-water level fluctuations, however, because ponds have greater storage capacity than aquifer materials per unit volume, and natural and man-made structural controls affect pond levels. Seasonal pond-water levels fluctuated by about 0.5 to 2.4 ft in Sweet Pond, Beaver Pond, Capwell Mill Pond, and Lake Mishnock (fig. 8) because streams flow from these ponds. Seasonal-water levels fluctuated by about 5.8 ft in Quarry Pond, which is a man-made pond with no stream outlet.

Paired measurements of ground-water and surface-water levels were made monthly at 15 streambed-piezometer sites during the 16-month period May 1997 through August 1998 (Craft, 2001). These measurements indicate the direction of flow between the aquifer and stream at each site. Most of the paired measurements made within the interior of the hydrologic system (that is, distant from the boundary between upland areas and valleys) indicated ground-water discharge to the streams (gaining streamflow conditions), such as along the Big River at WGW 325 (fig. 9*A*). There were several exceptions to this generalization, however. For example, three piezometers (WGW 330, WGW 331, and WGW 332) on the northern unnamed tributary of the Carr River (fig. 4) indicated consistently losing (or dry) conditions. The explanation for the losing conditions along this stream may be that the increase in hydraulic conductivity and saturated thickness of the aquifer that occurs in this area cause the water table to be lower than the streambed. Ground-water levels measured on the Mishnock River at the outfall of Mishnock Lake (site WGW 333, fig. 9*B*) also were consistently lower than surface-water levels; this difference indicates losing conditions on the downgradient end of the lake.

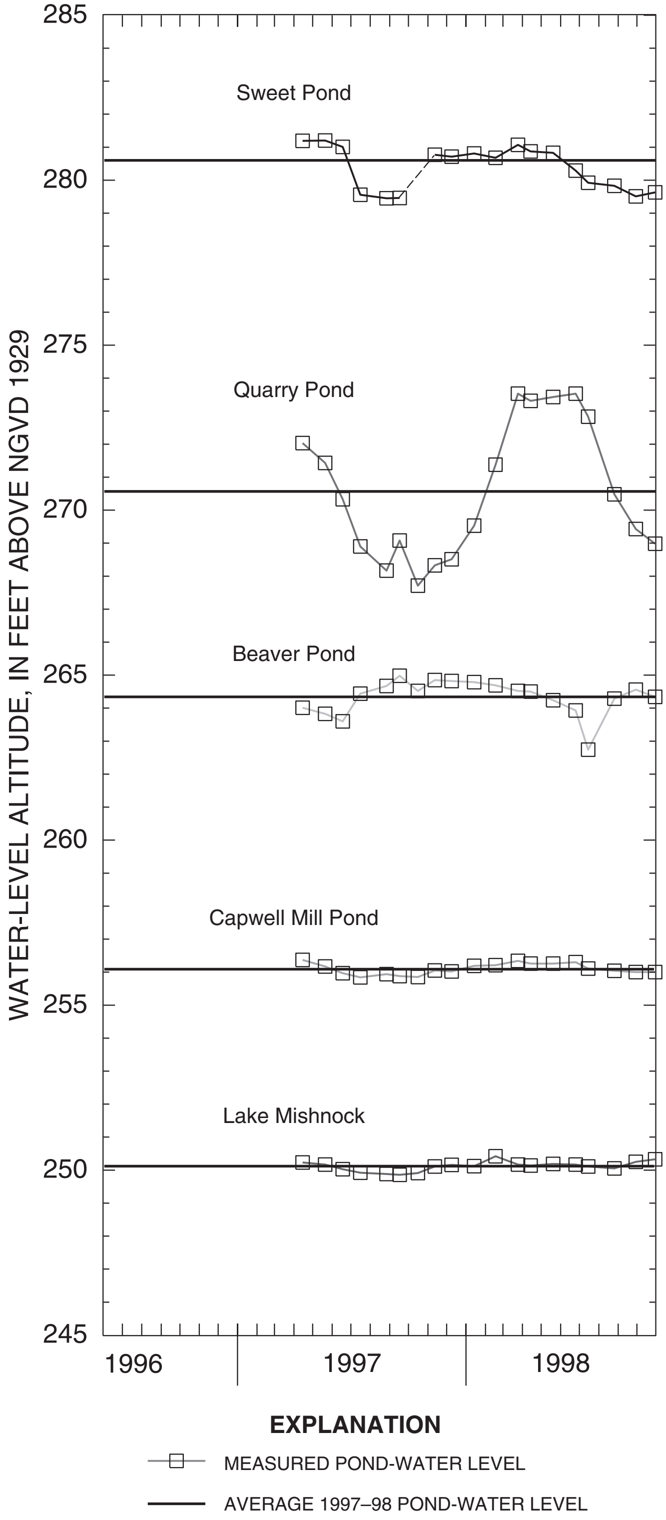


Figure 8. Water-level altitude measurements and the average of water-level altitudes measured at selected ponds in the Big River study area, Rhode Island, 1996–98. (Pond gage locations shown on fig. 4.)

Ground-water levels measured in piezometer WGW 322 near the Nooseneck River gage are consistently lower than surface-water levels at the site; this difference indicates losing conditions at the site as the stream flows out of the narrow Nooseneck River Valley and into the main aquifer area (pl. 1; fig. 9*C*).

Continuous streamflow measurements are available for two sites in the Big River study area, but these records do not include the entire 35-year simulation period. Streamflow was measured continuously between 1964 and the beginning of 1981 on the Nooseneck River (station 01115630, fig. 10*E*) and from 1964 to the beginning of 1980 on the Carr River (station 01115770, fig. 10*F*). These two streamflow-gaging stations were monitored as partial-record sites (about one measurement per month) during 1996–98. Comparison of streamflow statistics for the 1964–79 period and the entire 1964–98 period collected at the Hunt River (station 01117000, fig. 10*A*), Pawcatuck River (station 01117500, fig. 10*B*), Wood River (station 01117800), fig. 10*C*), and Nipmuc River (station 01111300, fig. 10*D*) streamflow-gaging stations indicates that the record for the 16-year period available for the Nooseneck River station and the Carr River station is representative of conditions for the entire 35-year simulation period. Records of daily streamflow for the 1964–98 period show the high variability in daily streamflows, the seasonal variation in runoff within each year, and the magnitude of floods and droughts. For example, daily streamflows can vary as much as two to four orders of magnitude in a given year (fig. 10). In comparison, summary statistics of daily streamflow as illustrated by boxplots (fig. 10) indicate a well-defined flow regime for each stream during the period of record, with the majority of daily streamflows (80 percent of daily values) falling within one or two orders of magnitude.

Data from long-term continuous-record streamflow-gaging stations near the study area (table 2, fig. 2) were correlated to streamflows measured at the partial-record streamflow-gaging stations during this study with the method of maintenance of variance extension, type 1 (MOVE.1) (Hirsch, 1982). These correlations were made for the purpose of estimating long-term-average streamflow, average monthly streamflow, and the 7-day 10-year (7Q10) streamflow at each partial-record station (table 3).

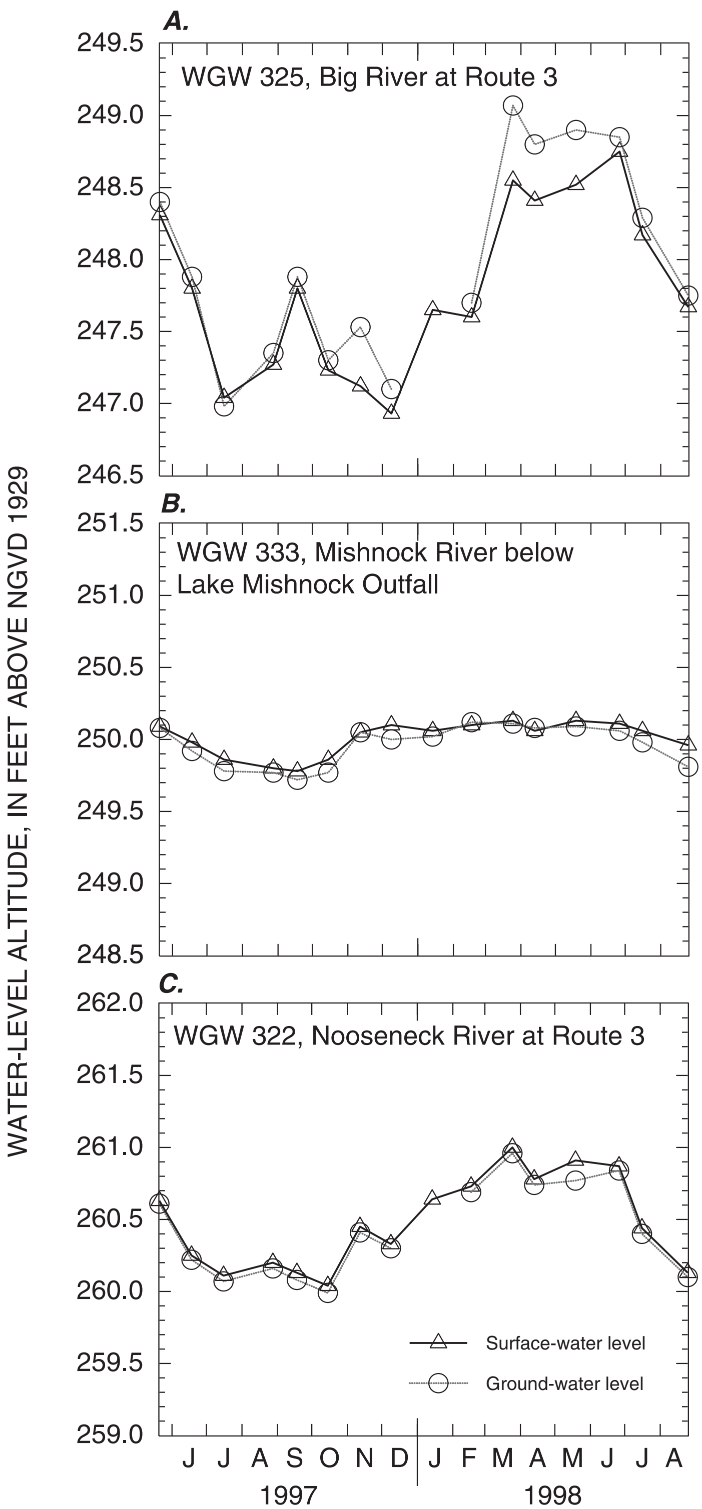


Figure 9. Paired surface-water-level altitudes and ground-water-level altitudes measured at selected streambed piezometers on the (*A*) Big River, (*B*) Mishnock River, and (*C*) Nooseneck River, Rhode Island, 1997–98. (Piezometer locations shown on fig. 4.)

The 7Q10 is the minimum 7-day-average flow that has a 10-percent chance of occurring in any given year; the 7Q10 flow has been used to regulate minimum allowable streamflows and wastewater discharges. MOVE.1 estimates of the average annual streamflow for the Carr River (station 01115770) and the Nooseneck River (station 01115630) during 1964–98 are within 9 percent (about 1.1 ft^3/s) of the average annual streamflow during 1964–79, and values of the 7Q10 during 1964–98 are within 8 percent (about 0.1 ft^3/s) of this statistic during 1964–79. MOVE.1 estimates of average monthly streamflow for the Carr River and the Nooseneck River stations also are comparable to monthly average streamflows measured during 1964–79 (fig. 11). An estimate of the long-term-monthly average streamflow for the Big River at Route 3 (station 01115800) was calculated by an area-weighted average of streamflow in the Nooseneck and Carr River tributaries. 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 (fig. 11).

Basin yields, which are the streamflow per unit surface-water drainage area (in cubic feet per second per square mile, $ft^3/s/mi^2$), for the partial-record stations (table 3) are similar to basin yields for the long-term streamflow-gaging stations (table 2) with the exception of the Lake Mishnock outflow (station 01115965) and the Carr River (station 01115770). The high basin yield for Lake Mishnock (about 13–15 $ft^3/s/mi^2$) indicates that the ground-water drainage area for the lake is much larger than the surface-water drainage area (table 3). If it were assumed that the basin yield for Lake Mishnock is similar to the other basins (about 2 $ft^3/s/mi^2$), then the estimated ground-water drainage area would need to be about seven times the surface-water drainage area (0.29 mi^2). Similarly, the Carr River streamflow statistics are among the lowest in the group because of natural ground-water underflows to Lake Mishnock, and natural streamflow losses from the western tributary to the Big River.

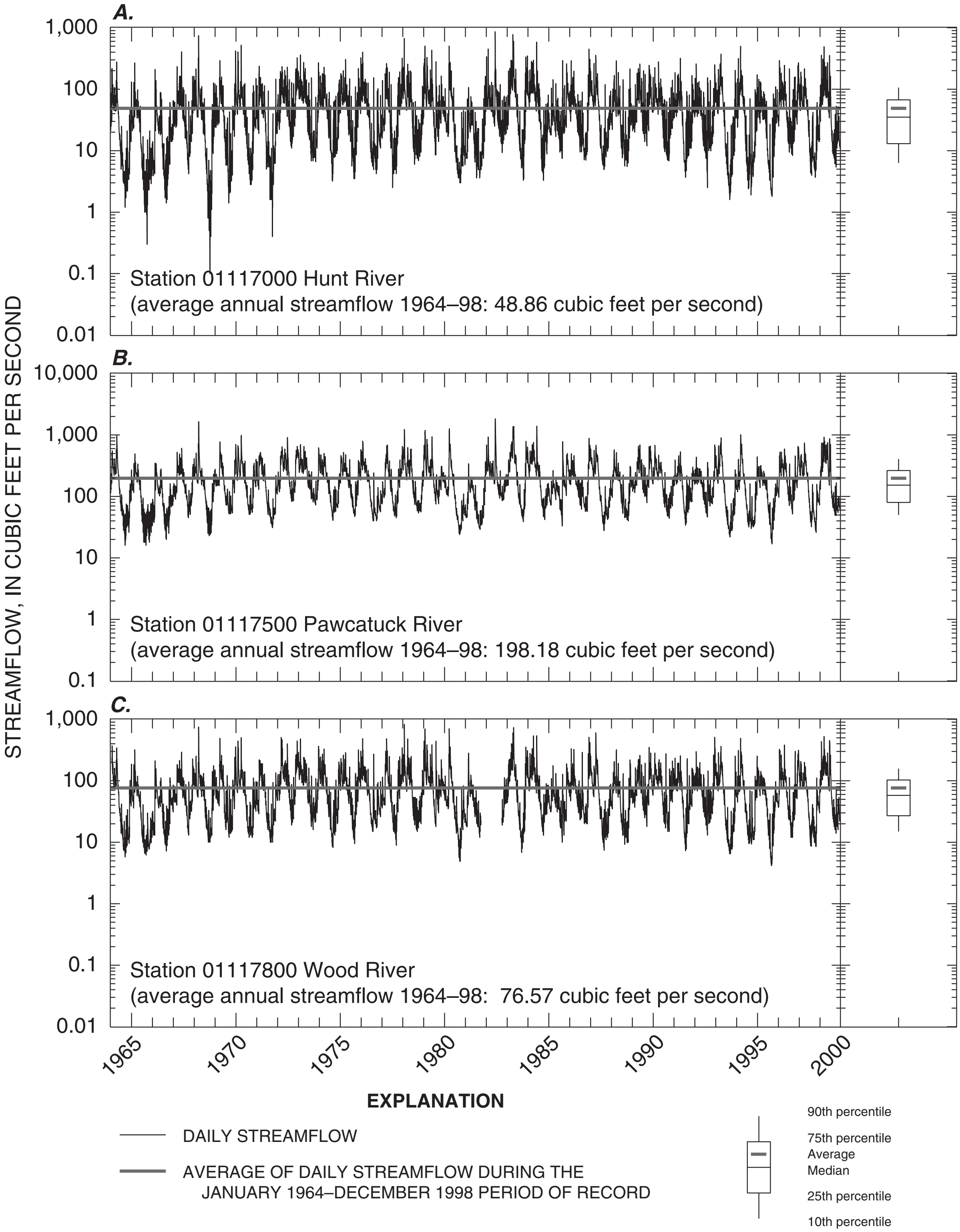


Figure 10. Record of daily streamflow and boxplot of streamflow statistics at gaging stations on the (*A*) Hunt River, (*B*) Pawcatuck River, (*C*) Wood River, (*D*) Nipmuc River, (*E*) Nooseneck River, and (*F*) Carr River, Rhode Island, 1964–98. (Gaging-station identification information listed in table 2. Locations of stations shown on fig. 2.)

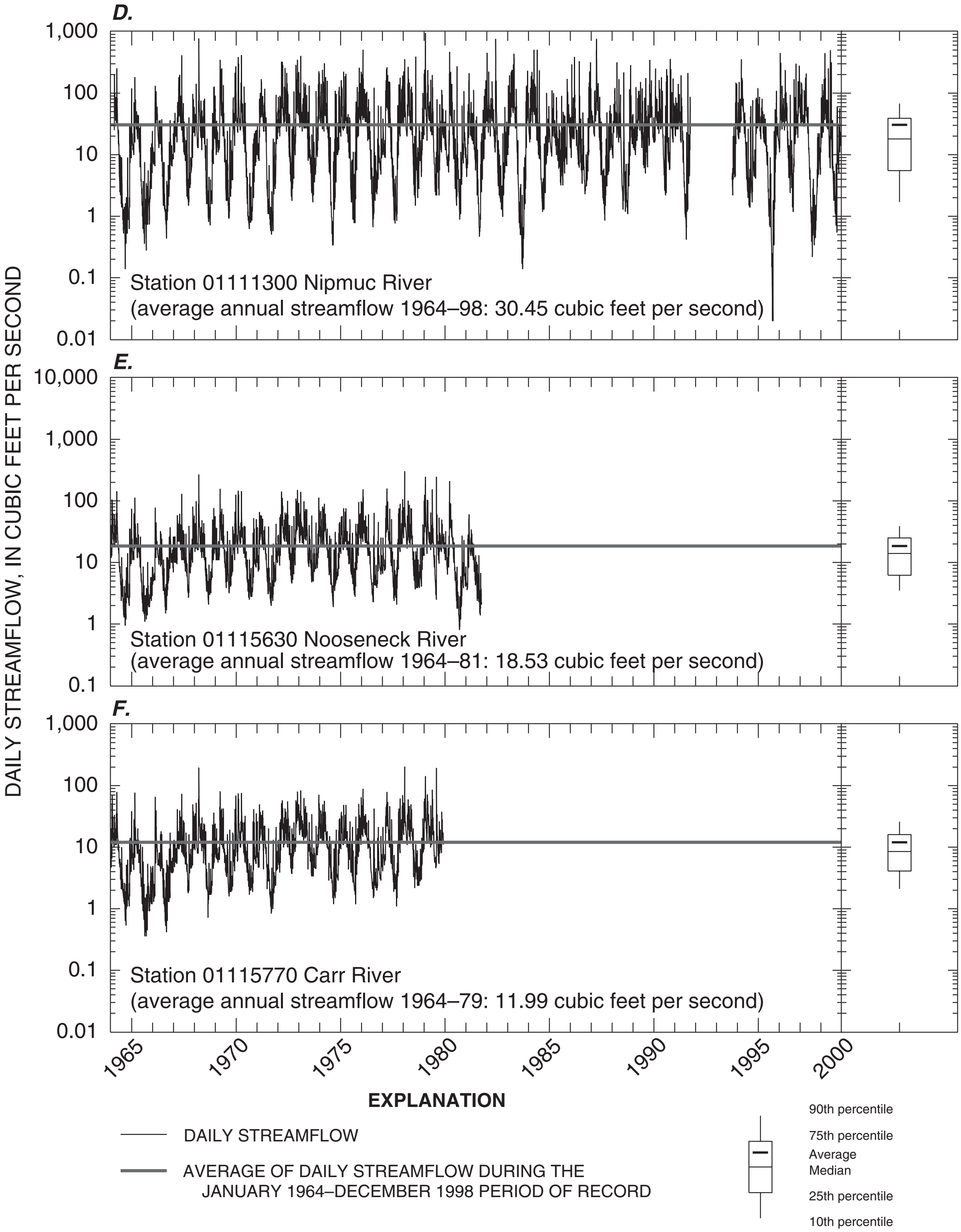


Figure 10—*Continued.* Record of daily streamflow and boxplot of streamflow statistics at gaging stations on the (*A*) Hunt River, (*B*) Pawcatuck River, (*C*) Wood River, (*D*) Nipmuc River, (*E*) Nooseneck River, and (*F*) Carr River, Rhode Island, 1964–98. (Gaging-station identification information listed in table 2. Locations of stations shown on fig. 2.)

Table 2. Continuous-record streamflow-gaging stations and summary statistics used to estimate long-term average streamflows in the Big River study area, Rhode Island

[Station locations shown on figure 2. Drainage areas from Socolow and others (2001) and Craft (2001). Percent stratified deposits from E.C. Wild, U.S. Geological Survey, written commun., 2002. The 7-day 10-year low flow (7Q10) is the minimum 7-day average flow that has a 10-percent chance of occurring in any given year. No., number; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; mi^2, square miles]

Station identification No.	Station name	Available record during the 1964–98 simulation period calendar years	Drainage area (mi^2)	Percent stratified deposits	Average annual flow		7Q10	
					(ft^3/s)	Per unit area ($ft^3/s/mi^2$)	(ft^3/s)	Per unit area ($ft^3/s/mi^2$)
01111300	Nipmuc River near Harrisville, RI	1964–91, 1993–98	16.0	29	30.4	1.90	0.26	0.02
01115630	Nooseneck River near Nooseneck, RI	1964–81	8.23	30	18.5	2.25	1.29	.16
01115770	Carr River near Nooseneck, RI	1964–80	7.33	63	12.0	1.64	.66	.09
01117000	Hunt River near East Greenwich, RI	1964–98	22.9	52	48.9	2.13	1.55	.07
01117500	Pawcatuck River at Wood River Junction, RI	1964–98	100	47	198	1.98	26.6	.27
01117800	Wood River near Arcadia, RI	1964–81, 1982–98	35.2	23	76.6	2.18	6.62	.19

Water Quality

Analysis of ground-water and surface-water samples was used to assess water quality in the Big River study area. Craft (2001) provides results of water-quality analysis of 48 ground-water samples collected from the stratified deposits between December 1996 and November 1999. Analytical results for ground-water samples include water-quality properties, major ions, and nutrients. Monthly specific-conductance measurements of the surface water were made concurrently with streamflow measurements at each of the 10 partial-record sites during the study period. Four synoptic studies were made during periods of expected base flow in April and October of 1997 and 1998, when there had been no precipitation for at least 5 consecutive days prior to the measurement. In these studies, temperature and specific conductance were measured at 41 surface-water sites across the study area. Water-quality data were collected and analyzed by use of standard methods as described by Craft (2001).

Specific-conductance measurements may be used to evaluate water quality in the basin and to assess possible land-use effects on water quality. Specific conductance is a direct measure of dissolved solids in surface and ground waters (Hem, 1992; Granato and Smith, 1999). Specific conductance values less than about 100 µS/cm generally indicate natural freshwater quality in streams and aquifers in central Rhode Island; conductances above this value commonly indicate anthropogenic influence on measured water quality (Dickerman and Ozbilgin, 1985; Dickerman and others, 1990; Dickerman and Bell, 1993; Dickerman and others, 1997). Potential sources of anthropogenic contaminants in the study area include highway runoff and wastewater recharge from septic systems. The specific conductance of highway runoff ranges from about 3 to 63,000 µS/cm (Granato and Smith, 1999) with conductances in downgradient ground water ranging from 100 to 2,500 µS/cm (Church and others, 1996). The specific conductance of residential septic effluent ranges from less than 500 to 3,500 µS/cm with conductances in downgradient ground water ranging from background values to 3,000 µS/cm (Morrill and Toler, 1973; Alhajjar and others, 1990; Weiskel and Howes, 1992; Robertson and Blowes, 1995).

Specific-conductance measurements for ground water (including 39 measurements from 22 wells), surface water (227 measurements from 10 partial-record streamflow stations and 145 measurements from 41 other surface-water-quality monitoring stations), and for the individual partial-record streamflow stations in the Big River study area are summarized in figure 12. Specific-conductance measurements in ground-water samples from the Big River Management Area generally indicate that water quality in the basin largely is unaffected by anthropogenic influences (73 percent of measured values are below 100 µS/cm). The highest measured ground-water conductance (354 µS/cm) was measured in a sample from well WGW 285 (fig. 4), which is downgradient of Interstate 95 and State Route 3 near the Nooseneck River station; the quality of water in this well may be affected by runoff from roads.

Table 3. Partial-record streamflow-gaging stations, streamflow statistics during the study period (1996–98), and estimates of associated streamflow statistics during the simulation period (1964–98) in the Big River study area, Rhode Island

[Station locations shown on figure 4. Drainage areas from Craft (2001). The 7-day 10-year low flow (7Q10) is the minimum 7-day average flow that has a 10-percent chance of occurring in any given year. No., number; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile; mi^2, square miles]

Station identification No.	Station name	Drainage area (mi^2)	Percent stratified deposits	Number of measurements during the study period	Flow during 1996–98 study period			Flow during the 1964–98 simulation period			
					Measured range (ft^3/s)	Average (ft^3/s)	Average per unit area ($ft^3/s/mi^2$)	Average (ft^3/s)	Average per unit area ($ft^3/s/mi^2$)	Estimated 7Q10 (ft^3/s)	7Q10 per unit area ($ft^3/s/mi^2$)
01115630	Nooseneck River near Nooseneck, RI	8.23	30	28	1.96–44.6	16.0	1.94	17.5	2.12	1.24	0.15
01115670	Congdon River near Nooseneck, RI	4.46	33	28	0.72–21.8	8.19	1.84	9.30	2.09	.72	.16
01115700	Unnamed tributary to Congdon River, RI	.5	81	28	0.30–2.63	1.07	2.14	1.26	2.52	.18	.36
01115730	Carr River, tributary to Capwell Mill Pond, RI	2.88	41	21	0.24–21.7	7.04	2.44	7.32	2.54	.21	.07
01115770	Carr River, near Nooseneck, RI	7.33	63	28	0.94–28.9	11.1	1.51	13.1	1.78	.71	.10
01115800	Big River at Route 3, RI	23.1	47	28	5.83–121	41.0	1.77	46.6	2.02	2.93	.13
01115830	Bear Brook, tributary to Big River, RI	3.98	28	28	0.45–17.7	5.95	1.49	7.23	1.82	.26	.07
01115963	Old Hickory Brook, tributary to Mishnock River, RI	.33	66	28	0.02–0.76	.25	.76	.30	.91	.01	.03
01115965	Outflow of Lake Mishnock near Washington, RI	.29	90	28	2.23–8.33	3.82	13.2	4.33	14.9	1.92	6.62
01115970	Mishnock River near Washington, RI	3.32	86	28	2.43–12.9	6.40	1.93	7.45	2.24	1.75	.53

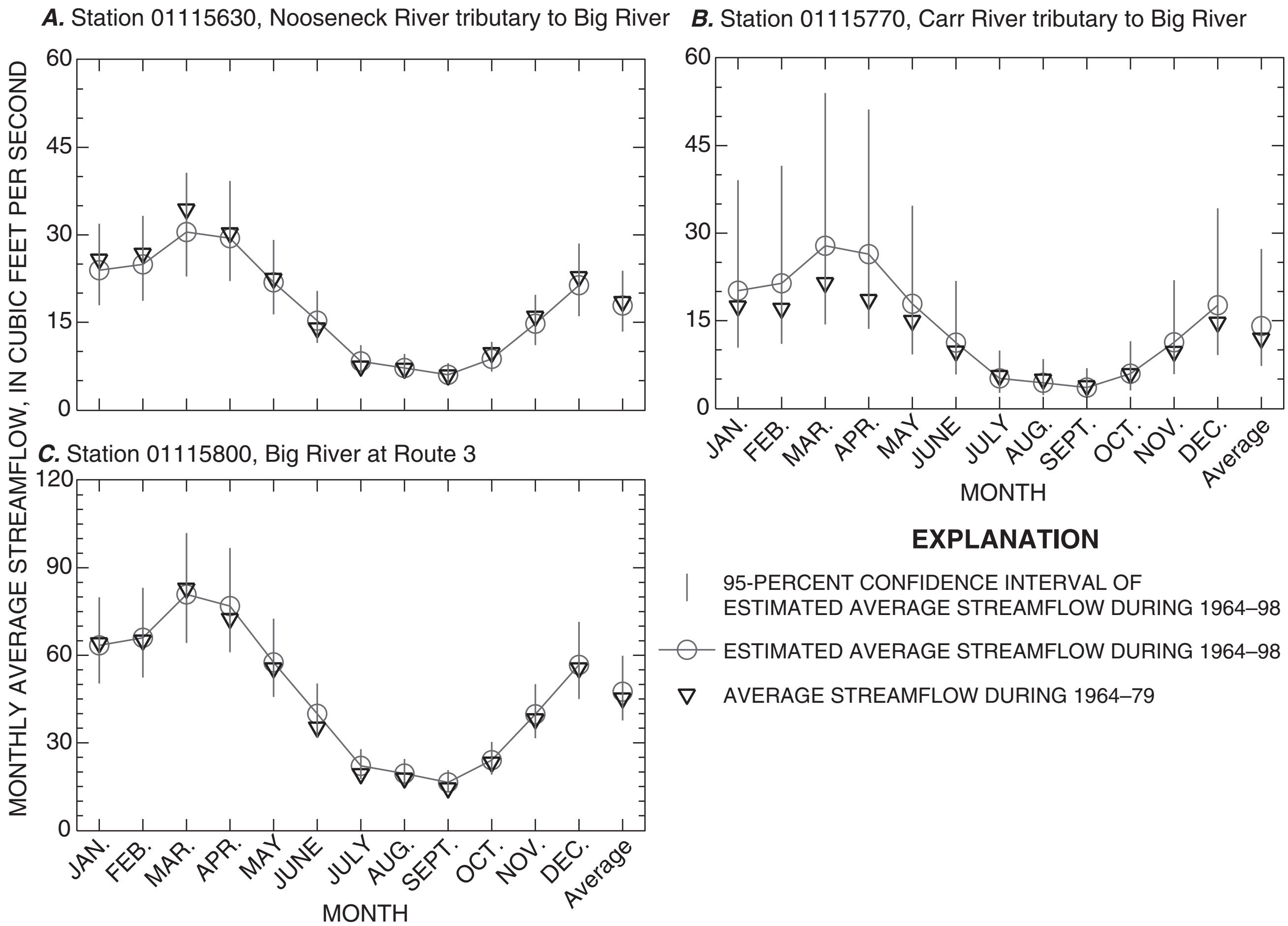


Figure 11. Estimated long-term average monthly streamflow at the Nooseneck River, Carr River, and Big River partial-record gaging stations compared to average monthly flows for the 1964–79 period of record for the Nooseneck River and Carr River gaging stations and an area-weighted estimate for the Big River from continuous-gage records at the Nooseneck River and Carr River tributaries, Rhode Island. (Gaging station identification information listed in tables 2 and 3. Locations of gages shown on figs. 2 and 4.)

Specific-conductance measurements for surface waters are more variable than those for ground water because there are more surface-water measurements and because these measurements more fully characterize the effects of different land uses in the study area. Specific-conductance measurements at partial-record measurement sites indicate that water quality in the Big River and Carr River Basins largely is unaffected by anthropogenic influences (fig. 12). Water quality in the Nooseneck River (station 01115630) probably is affected by road runoff from Interstate 95 and State Route 3, but this effect is minor. On the basis of specific-conductance values and land-use information, water quality in the Carr River and Big River Basins generally is better than water quality in the Mishnock River Basin. For example, samples from the Old Hickory Brook site (station 01115963) have the highest conductance values (610 µS/cm) among samples from the partial-record stations; water at this site probably is affected by runoff and recharge from the Interstate 95 right-of-way and (or) residential and commercial wastewater recharge from the till and bedrock uplands. Specific-conductance measurements at the Lake Mishnock outfall (station 01115965) also indicate effects of road runoff or residential development around the lake.

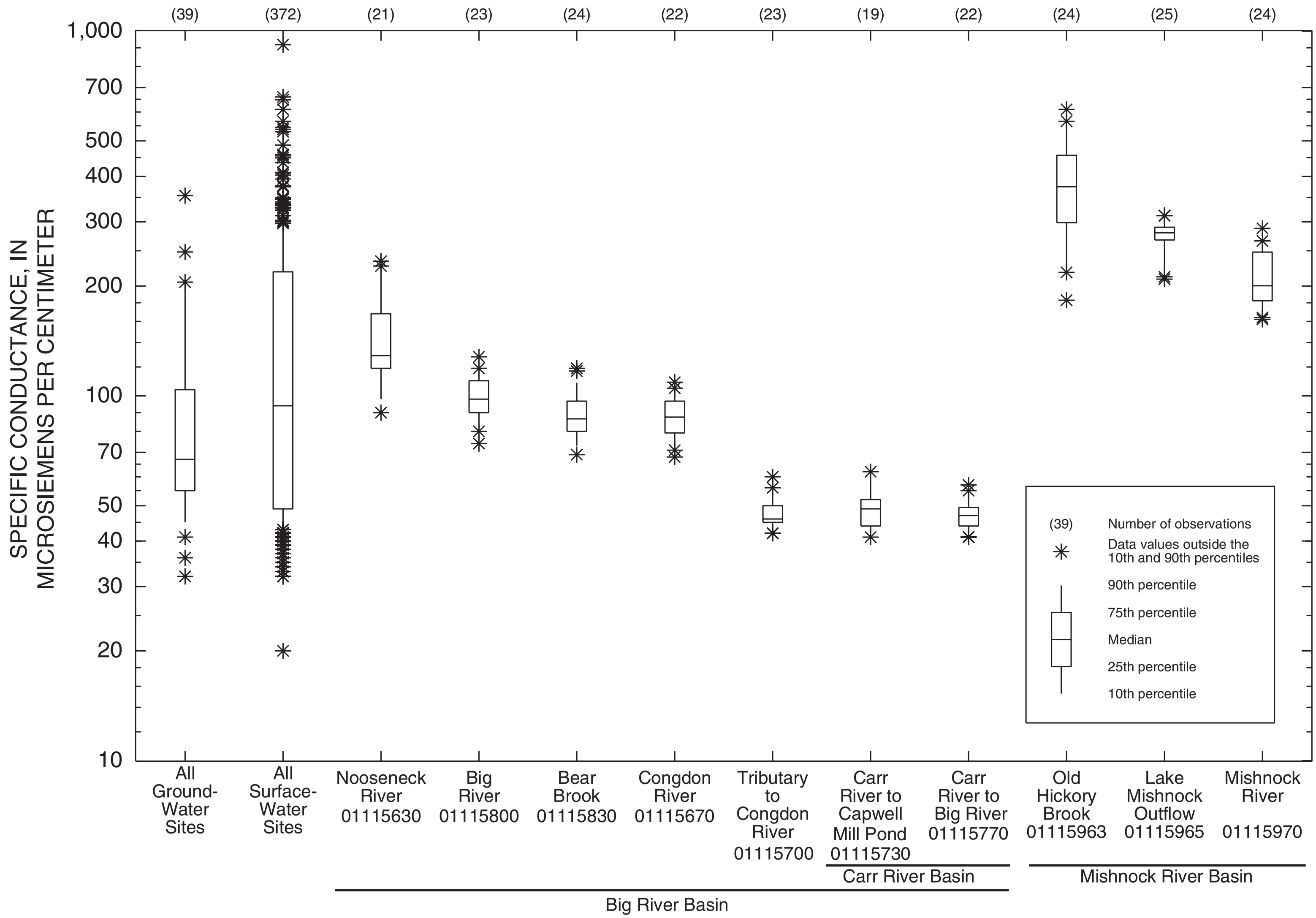


Figure 12. Distribution of specific-conductance measurements in samples of ground water and surface water in the Big River study area, Rhode Island, 1996–99.

Hydrologic Components and Budget

A hydrologic budget was estimated for part of the hydrogeologic system for the 35-year simulation period 1964–98. The budget quantifies the hydrologic inflow and outflow components along the boundary of the system and provides data that are used in the development and calibration of the numerical models of the system. The lateral boundary of the hydrogeologic system defined for the hydrologic budget is shown in figure 13, and is coincident with the boundary of the active area of the numerical models. The hydrologic-budget area encompasses 10.9 mi^2 and includes the most transmissive parts of the stratified sand-and-gravel deposits that compose the surficial aquifer in the study area. The saturated thickness of the aquifer within the hydrologic-budget area is estimated to be 10 ft or greater. Upland areas of till, bedrock, and thinly saturated areas of stratified deposits along Bear Brook, Raccoon Brook, and Nooseneck River are not included within the hydrologic-budget area. Water from these upland areas reaches the boundary of the hydrologic-budget area either as surface-water or ground-water inflow. The total upland area is 23.3 mi^2. Also excluded from the hydrologic budget is a small area (1.5 mi^2) that is northeast of Hill Farm Road and west of the Flat River Reservoir. This small area is not included because it drains to the reservoir and is downgradient of potential water-supply-development sites.

The components of the hydrologic budget are illustrated in figure 14. The budget is based on an assumption of steady-state conditions, that is that there are no net changes in water storage over the 35-year hydrologic budget period. Hydrologic inflow components are recharge from precipitation (R_{PR}) and wastewater discharge (R_{WW}), streamflow (SF_I) and ground-water inflow (GW_I) from upland areas, and direct runoff (DR). Hydrologic outflow components are streamflow (SF_O) from the Big and Mishnock River Basins, ground-water evapotranspiration where the water table is near land surface (ET_{GW}), ground-water withdrawals (Q_W), and ground-water underflow (GW_U).

The hydrologic budget is expressed mathematically as

$$R_{PR} + R_{WW} + SF_I + GW_I + DR = SF_O + ET_{GW} + Q_W + GW_U \pm \text{error} . \quad (1)$$

The error term is needed because each of the individual budget terms is an estimate based on available data. Each budget term is reported as a volumetric flow rate, in units of cubic feet per second (ft^3/s).

Precipitation and land-surface evapotranspiration are not directly included in the budget because they are not simulated by the numerical models. They are, however, important to the hydrology of the study area. Total annual precipitation is estimated to have averaged about 126 ft^3/s during the 1964–98 simulation period, on the basis of an average annual precipitation of about 50.3 in. measured at the Kingston climatological station and a basin area of 34.2 mi^2. Randall (1996) estimated an evapotranspiration rate of about 22 in/yr (plus or minus 1 in/yr) for Rhode Island for the period 1951–80; this estimate is consistent with those of Lyford and Cohen (1988) and Church and others (1995). On the basis of an assumed evapotranspiration rate of 22 in/yr, total evapotranspiration in the study area is estimated to have averaged about 55 ft^3/s during the simulation period; this rate leaves about 71 ft^3/s available in the budget area.

Inflow Components

Annual and monthly rates of ground-water recharge from precipitation (R_{PR}) were estimated from streamflow records by use of the computer program RORA (Rutledge, 1993). RORA has been used to estimate recharge in several basins in Rhode Island and southeastern Massachusetts (Bent, 1995; Barlow, 1997; Barlow and Dickerman, 2001). Use of the RORA program requires continuous streamflow records for the period of analysis. Because streamflow was not measured continuously in the study area during the 1964–98 period, it was necessary to use streamflow records from a long-term gaging station outside the study area for the analysis.

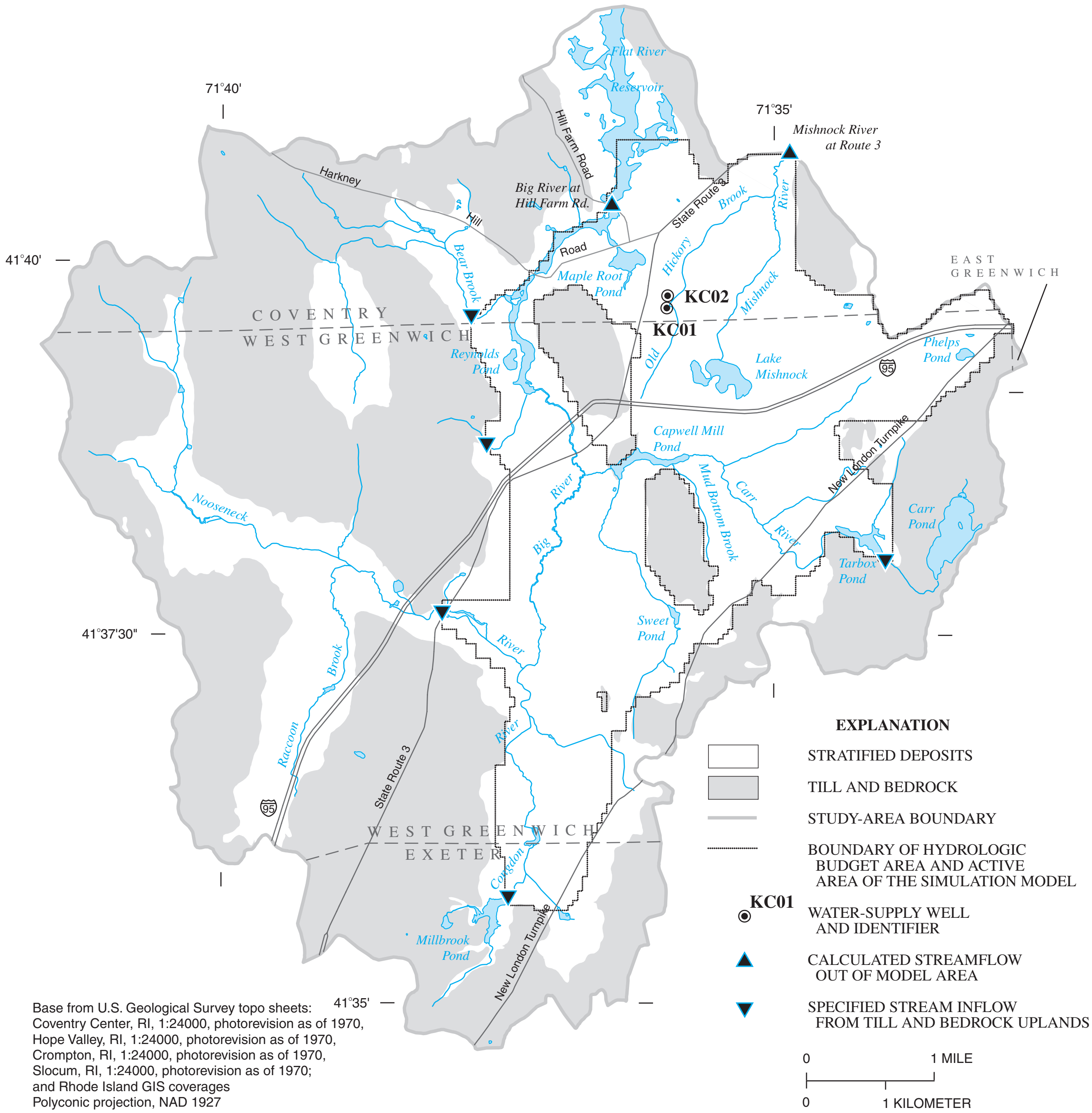
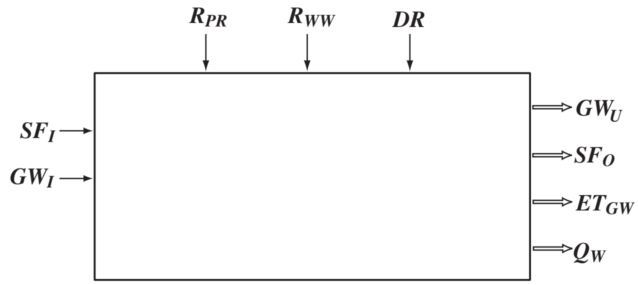


Figure 13. Spatial extent of the hydrologic-budget area, active area of simulation model, specified stream-inflow locations, and location of model-calculated streamflows out of the Big River study area, Rhode Island.



EXPLANATION

SOURCES		SINKS	
R_{PR}	Ground-water recharge from precipitation	GW_U	Ground-water underflow
R_{WW}	Ground-water recharge from wastewater discharge	SF_O	Streamflow out of basin
SF_I	Streamflow from till and bedrock upland	ET_{GW}	Ground-water evapotranspiration
GW_I	Lateral ground-water inflow from till and bedrock upland	Q_W	Ground-water withdrawal
DR	Direct runoff to surface water		

Figure 14. Sources and sinks of water along the boundaries of the numerical models of the Big River study area, Rhode Island.

Streamflow records from the Hunt River (station 01117000) (fig. 2) were selected for analysis from other nearby long-term continuous-record stations (table 2) because of the close proximity of the Hunt River Basin (fig. 2) and the similarity in the percentage of coarse-grained stratified deposits within the drainage area to the Hunt River station (52.0 percent) to that of the Big River study area (49.6 percent). Moreover, the estimated long-term runoff for the Hunt River [station 01117000, 2.13 $ft^3/s/mi^2$] is similar to the estimated runoff at partial-record stations in the Big River study area (table 3); these stations include those for the Nooseneck River [station 01115630, 2.12 $ft^3/s/mi^2$], the Congdon River [station 01115670, 2.09 $ft^3/s/mi^2$], the Big River at Route 3 [station 01115800, 2.02 $ft^3/s/mi^2$], and the Mishnock River [station 01115970, 2.24 $ft^3/s/mi^2$]. RORA requires specification of a recession index, which was estimated to be 20.2 days per log cycle of streamflow for the Hunt River Basin by use of the computer program RECESS (Rutledge, 1993).

Annual ground-water recharge rates estimated by use of the Hunt River streamflow records ranged from 11.5 in. for 1966 to 45.1 in. for 1983, with an average rate of 26.4 in. for the entire 1964–98 period. This average annual recharge rate is similar to those calculated for other basins of Rhode Island (Dickerman and others, 1990, 1997; Dickerman and Bell, 1993; Bent, 1995; Barlow, 1997; Barlow and Dickerman, 2001). R_{PR} for the hydrologic budget area during 1964–98 was estimated to be 21.2 ft^3/s by multiplying the estimated average recharge rate (26.4 in/yr) by the 10.9 mi^2 area of the budget area.

Average monthly recharge rates calculated for the 1964–98 period for the Hunt River Basin ranged from 0.6 in. for September to 4.2 in. for March (fig. 15). The variability of monthly recharge rates is smallest during July through October when recharge rates are lowest, as indicated by the small difference between the 10th and 90th percentile of recharge estimates for these months.

The second component of ground-water recharge consists of wastewater discharge (R_{WW}) to the aquifer from on-site facilities such as household septic systems. Water that is withdrawn at private wells or that is delivered to the basin by the Kent County Water Authority recharges the aquifer by on-site discharge facilities. It was assumed that the net wastewater discharge in areas with private wells is negligible. Therefore, the only areas for which R_{WW} was estimated are seven small areas that receive water from the KCWA; those areas are located near Lake Mishnock, Maple Root Pond, and the Flat River Reservoir (Cindy Heard, Kent County Water Authority, written commun., 2002). The amount of wastewater

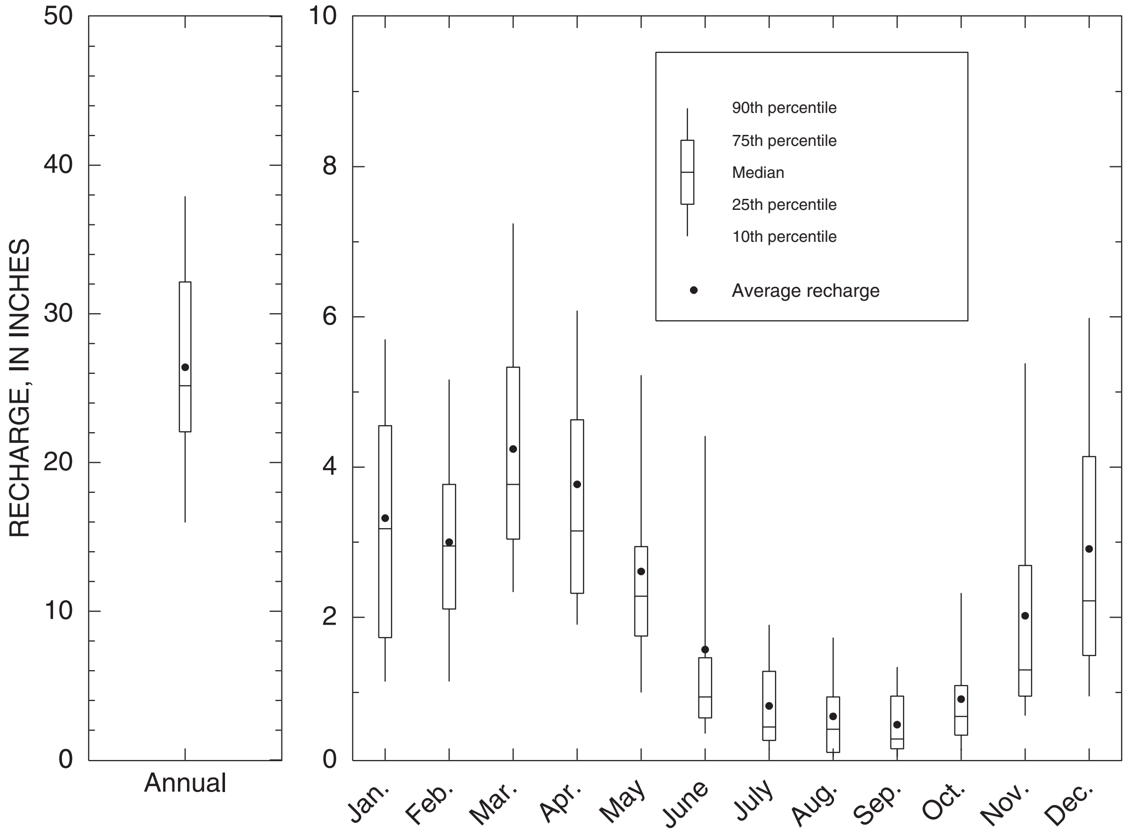


Figure 15. Distributions of annual and monthly recharge estimated from streamflow records for the Hunt River near East Greenwich, Rhode Island, 1964–98.

discharge in these areas during 1964–98 was estimated from information on the locations and rates of water-supply deliveries in the study area during 1998 provided by the KCWA. Wastewater discharge was assumed to be about 89 percent of water-delivery rates because consumptive losses are estimated to be about 11 percent of water deliveries (U.S. Geological Survey, 2002). Total average annual R_{WW} was estimated to be about 0.4 ft^3/s. Estimated quarterly rates of R_{WW} ranged from about 0.3 ft^3/s during the winter months to about 0.5 ft^3/s during the summer months.

Streamflow into the system (SF_I) was estimated for five streams that drain upland till and bedrock areas (locations shown on fig. 13). The total upland area drained by streams is 15.2 mi^2. In estimating streamflow from these upland areas, no attempt was made to separate the ground-water base flow and direct runoff components of total streamflow. Streamflow into the system from the Nooseneck River (station 01115630) and Bear Brook (station 01115830), which are the two largest streams that drain the upland area, was estimated by use of streamflow measurements made between 1996 and 1998 at the partial-record streamflow gaging stations on the two streams. Estimated streamflow rates from these two streams were determined to be 17.5 ft^3/s and 7.23 ft^3/s, respectively (table 3), by statistical correlation of streamflow measurements at each of the two partial-record stations to streamflow measurements at continuously gaged stations (table 2). Streamflows into the system from three additional streams, Carr River below Carr Pond, Congdon River below Millbrook Pond, and the unnamed tributary to the Big River, were estimated on the basis of the long-term runoff for the Hunt River station and basin characteristics. This estimation was necessary because streamflow measurements were not made on these three small streams. The estimated streamflow into the system from these streams was: 1.25 ft^3/s for the Carr River below Carr Pond (drainage area of 0.78 mi^2), 3.10 ft^3/s for the Congdon River below Millbrook Pond (drainage area of 1.46 mi^2), and 1.07 ft^3/s for the unnamed tributary to the Big River (drainage area of 0.5 mi^2). The total streamflow from the five upland streams (SF_I) was, therefore, estimated to be 30.1 ft^3/s, of which about 82 percent is from the Nooseneck River and Bear Brook.

Ground-water recharge in the undrained parts of the upland areas of till, bedrock and thinly saturated stratified deposits (8.1 mi^2) reaches the aquifer by lateral ground-water inflow (GW_I) at the boundary between the upland areas and the aquifer. An inflow of 15.7 ft^3/s was estimated by multiplying the average precipitation recharge rate estimated for the study area (26.4 in/yr) by the total upland area that is not drained by streams.

Direct runoff (DR) was estimated from streamflow records for the Hunt River Basin for the period 1964–98. Direct runoff is calculated by subtracting the ground-water base-flow component of streamflow from total streamflow. Ground-water base flow was estimated by use of a hydrograph-separation technique described in Rutledge (1993). On an areal basis, total streamflow and ground-water base flow at the Hunt River (station 01117000) were about 29 in/yr and 23 in/yr, respectively, during 1964–98. Direct runoff, therefore, is estimated to have been about 6 in/yr during 1964-98. This is equivalent to 8.3 ft^3/s of direct runoff (DR) from both the area of the hydrologic budget (also the model area, 10.9 mi^2) and from the undrained upland areas (8.1 mi^2).

Outflow Components

Streamflow (SF_O) is the major outflow component from the hydrologic system. The two locations of outflow are the Big River into the Flat River Reservoir and the Mishnock River at the Route 3 partial-record gaging station (station 01115970). It was not possible to measure streamflow from the Big River into the Flat River Reservoir because the reservoir causes backwater in the Big River to a point that is about 3,000 ft downstream of the partial-record measurement site (station 01115800) on the river at Route 3 (fig. 4). Therefore, an estimate of outflow to the Flat River Reservoir was made on the basis of the estimated streamflow at the partial-record station on the Big River at Route 3 (2.02 $ft^3/s/mi^2$, table 3). The total drainage area of the Big River at the outflow point of the system at Hill Farm Road is 30.9 mi^2, which results in an estimated outflow of 62.4 ft^3/s. The long-term average discharge of the Mishnock River from the system, 7.45 ft^3/s (table 3), was estimated on the basis of statistical correlations between streamflow in the Mishnock River at the Route 3 partial-record gaging station (station 01115970) and long-term records from continuously gaged streams (table 2). Total streamflow out of the system (SF_O), therefore, was estimated to be 69.9 ft^3/s.

The average annual rate of evapotranspiration from the water table (ET_{GW}), which sometimes is referred to as riparian evapotranspiration (Rutledge, 1993), is assumed to be the difference between the average ground-water recharge rate (R_{PR}) to an aquifer and average ground-water base-flow rate out of the aquifer. The average rate of ground-water evapotranspiration for the system (3.4 in/yr) was estimated by subtracting the ground-water base-flow rate (23.0 in/yr) from the ground-water recharge rate (26.4 in/yr) determined from the 1964–98 streamflow records of the Hunt River (station 01117000). This value, which is similar to estimates of ground-water evapotranspiration determined for other river basins of Rhode Island and southeastern Massachusetts (Bent, 1995; Dickerman and others, 1997; Barlow, 1997; Barlow and Dickerman, 2001), is an average evapotranspiration rate over the entire areal extent of the basin. In areas where evapotranspiration actually occurs, the rate of evapotranspiration is likely much higher. Based on the rate of 3.4 in/yr, ET_{GW} over the entire 10.9 mi^2 budget area is estimated to have been 2.7 ft^3/s.

Ground water has been withdrawn at two public water-supply wells in the Mishnock River Basin since June of 1965. Monthly withdrawal records (table 1) indicate that the average rate of withdrawal (Q_W) from the two wells during 1964–98 was 2.2 ft^3/s (or 1.4 Mgal/d).

Small amounts of ground water may flow out of the system as ground-water underflow (GW_U) along the northern boundary in the Mishnock River Valley (fig. 13). The rate of underflow in this area was determined by use of Darcy's law and estimates of aquifer transmissivity and the hydrologic gradient. Transmissivity of the aquifer was estimated from the geology map by Stone and Dickerman (2002). The hydraulic gradient of the water table was estimated by comparing the difference between average ground-water altitudes measured in streambed piezometers WGW 333—located at the Lake Mishnock outflow, and COW 478—located in the Mishnock River near Route 3 (fig. 4). The average annual underflow rate (GW_U) estimated for this area is about 0.1 ft^3/s, which is less than 1 percent of all the estimated outflow.

Hydrologic Budget

The estimated hydrologic budget is summarized in table 4. As shown in the table, there is an error between inflows and outflows in the estimated budget of 0.8 ft^3/s. This error, which is about 1 percent of the average of the total inflow and outflow components (75.3 ft^3/s), is the result of various factors, which include (1) use of the streamflow record of the Hunt River to estimate some of the budget components (R_{PR}, DR, and ET_{GW}), (2) the assumption that the average annual wastewater-recharge rate for the 35-year period is equal to that estimated for 1998, (3) use of a uniform recharge rate in the upland areas equal to the estimated rate of precipitation recharge to the stratified deposits, (4) inaccuracies in the estimates of long-term-average streamflows in the basin from short term 1996–98 partial-record data, and (5) the assumption that the system is at steady state (no net change in storage).

Although not included in the hydrologic budget, an estimate of the rate of ground-water export from the system can be made from the budget components (table 4). This rate is equal to the difference between the rate of ground-water withdrawal from the aquifer (2.2 ft^3/s) and the rate at which this water is returned to the system as wastewater recharge (0.4 ft^3/s). Therefore, the estimated rate of ground-water export from the system during the 35-year period is about 1.8 ft^3/s, or about 81 percent of the estimated total ground-water-withdrawal rate.

Table 4. Estimated average annual hydrologic budget for the Big River model area, Rhode Island, 1964–98

[Budget components shown schematically on figure 14]

Hydrologic budget component	Rate of flow	
	Cubic feet per second	Million gallons per day
Estimated inflow		
Ground-water recharge from		
Precipitation (R_{PR})	21.2	13.7
Wastewater-return flow (R_{WW})	.4	.3
Streamflow from uplands (SF_I)	30.1	19.5
Lateral ground-water inflow (GW_I)	15.7	10.1
Direct runoff (DR)	8.3	5.4
Total inflow	75.7	48.9
Estimated outflow		
Streamflow (SF_O)	69.9	45.2
Evapotranspiration (ET_{GW})	2.7	1.7
Ground-water withdrawal (Q_W)	2.2	1.4
Ground-water underflow (GW_U)	.1	.1
Total outflow	74.9	48.4
Budget error (inflow-outflow)	.8	.5

DEVELOPMENT OF STEADY-STATE AND TRANSIENT NUMERICAL MODELS

Steady-state and transient numerical models of the Big River study area were developed to better describe ground-water flow, interactions between ground water and surface water, and potential effects of ground-water development on the water resources of the area. Ground-water flow was simulated with MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The spatial extent of the active area of the model—that is, the area of the model in which ground-water heads were simulated—is shown in figure 13. The full lateral extent of the model domain (63.2 mi^2) is much larger than the active model area (10.9 mi^2) so that it would include all of the irregularly shaped 35.7 mi^2 Big River study area. The larger model domain was established to allow expansion of the active model area from stratified deposits into the surrounding upland areas if this is deemed necessary for future water-resources studies. The steady-state and transient models were developed and calibrated iteratively and are consistent in their numerical representation of the hydrogeology of the study area.

Steady-State Model

The steady-state model is representative of average annual hydrologic conditions in the Big River study area during 1964–98. Information about the study area was discretized so that the model would represent the hydrogeology of the aquifer. Boundary conditions and hydrologic stresses, including recharge, water use, and wastewater-return flows were specified to represent average annual conditions. The areal distribution of aquifer characteristics incorporated into the model was derived from available information and data (Craft, 2001; Stone and Dickerman 2002). The model was then calibrated to estimates of ground-water levels and streamflows that are representative of the 1964–98 period. A budget was developed to quantify the water entering and leaving the system under long-term average, steady-state conditions with no net change in storage within the system.

Spatial Discretization

The Big River study area was discretized into a model grid of 216 rows by 204 columns of square cells with a uniform size of 200 ft on each side. The model grid was aligned with a north-south orientation to be parallel to the north-trending valleys of the Congdon River, the Big River, and the Mishnock River. The active area of the model (fig. 16) includes the stratified-deposit areas that have an estimated saturated thickness of at least 10 ft within the Big River and Mishnock River Basins; this area is about 30 percent of the total Big River study area (35.7 mi^2).

The model consists of a maximum of five layers and extends vertically from the water table to the intersection of the surficial aquifer with underlying bedrock (fig. 17). The model layers were discretized with reference to the water-table map of December 1997 (pl. 1); the bedrock-elevation contours on the geologic map by Stone and Dickerman (2002); and the screened intervals of existing, proposed, and hypothetical public-supply wells. An initial water-table elevation was calculated for each cell of the top model layer (layer 1) by overlaying a geographically referenced digital coverage of the water-table map onto a coverage of the model grid. The bottom elevation of the aquifer was defined as the bedrock contact and was calculated for each vertical stack of cells by overlaying a geographically referenced digital coverage of the bedrock-elevation map onto the model-grid coverage. The thickness of each active layer was truncated where the elevation of the underlying bedrock is greater than the bottom of the layer; underlying layers are inactive. It was assumed that flow within the bedrock is negligible and any flows that may occur below the aquifer-bedrock contact are constrained within and accounted for in the active model. The top layer of each stack of cells (layer 1) extends from the water table down to an altitude of 230 ft (except where bedrock elevations are higher than 230 ft). The 230-ft altitude corresponds to an average saturated thickness of about 21 ft and a maximum saturated thickness of about 72 ft for layer 1. The bottom elevations of the remaining four layers (layers 2–5) are 200, 160, 130, and 100 ft (fig. 17). The bottom elevation of the model (100 ft) corresponds with the deepest bedrock altitude in the Big River and Mishnock River Valleys as delineated by Stone and Dickerman (2002). To ensure numerical stability of the model, active cells in layers 2–5 were made inactive if they were surrounded by inactive cells or were on the edge of the active layer and were less than 3 ft thick. The thickness of the bottom cells within the active area that were less than three 3 ft thick was changed to a thickness of 3 ft for the same reason. Because the thickness of the surficial aquifer varies laterally, the number of active layers within each vertical stack of cells varies laterally as well. The active areas of the model layers are, from top to bottom (layers 1–5), 10.9, 5.4, 4.1 2.7, and 1.5 mi^2, respectively.

Hydrologic Boundary Conditions and Stresses

Hydrologic boundary conditions and stresses represent physical features of the study area and define how and where water enters and leaves the modeled area (Reilly, 2001). The boundaries were based on the water-table map of the aquifer (pl. 1), topographic maps of the area, geologic information provided by Stone and Dickerman (2002), and hydrologic information provided by Craft (2001). The lower model boundary is the contact between the stratified deposits (the bottom of the surficial aquifer) and the underlying bedrock. This boundary was set as a no-flow boundary because the bedrock and the thin layer of basal till separating stratified deposits and bedrock were assumed to be impermeable.

No-flow boundaries were specified along ground-water divides and along ground-water-flow lines that separate the modeled area from adjacent areas that were not simulated. A ground-water divide was assumed to coincide with the surface-water drainage divide in the northeast corner of the study area near the border between West Greenwich, East Greenwich, and Coventry (fig. 13, pl. 1). This assumption is supported by pond levels published on the USGS 7.5-minute topographic map for Crompton, Rhode Island, and by water-level measurements at the well COW-411 (fig. 2) on the northern side of the ground-water divide near Tiogue Lake. Changes in the natural hydrologic system of the area (such as by pumping from a high-capacity well), however, could affect the location of the ground-water divide and thereby affect the accuracy of the model-simulated hydrologic budget. No-flow boundaries were specified along ground-water flow lines at the Flat River Reservoir and the Mishnock River outflow (fig. 13).

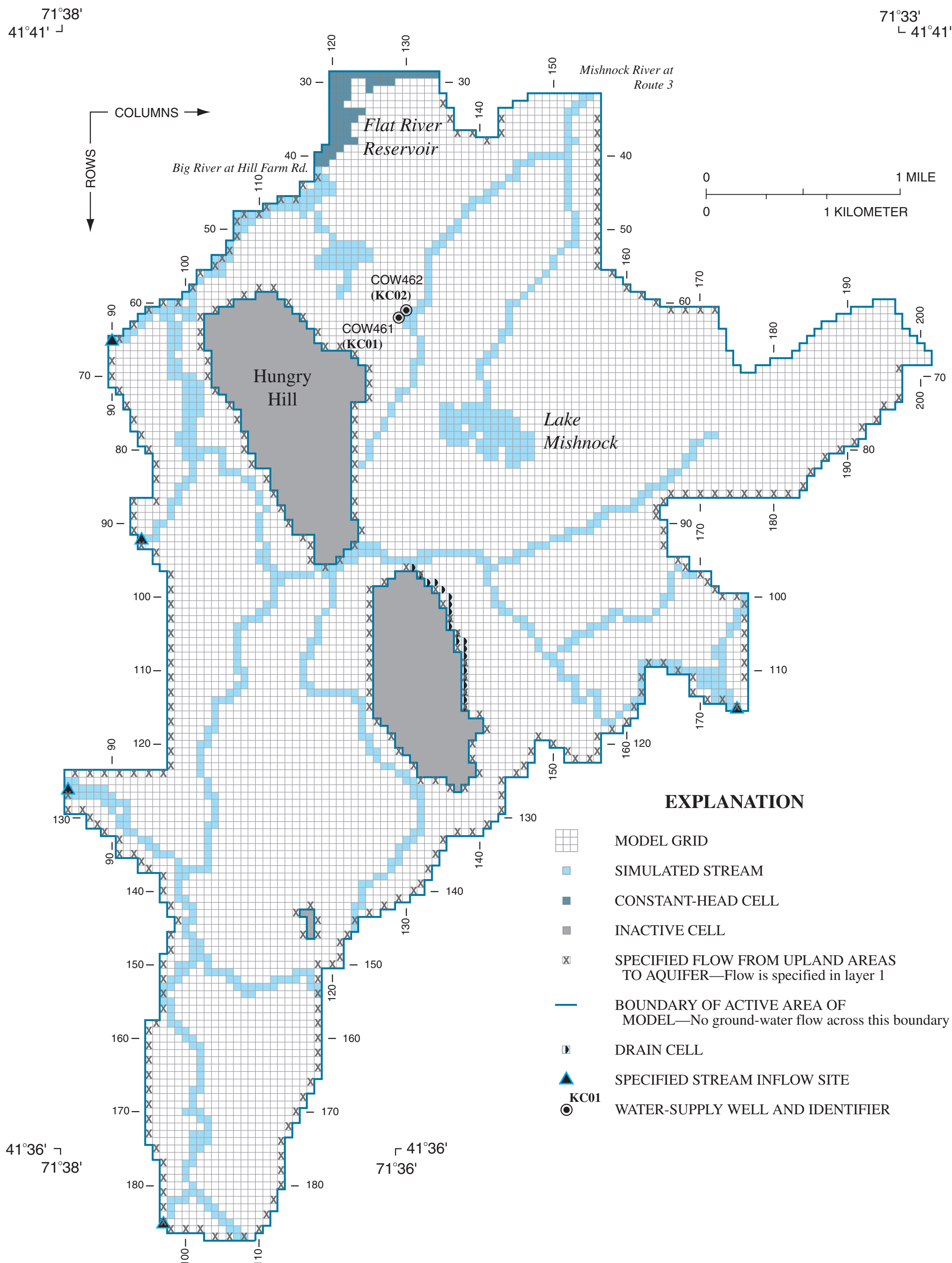


Figure 16. Grid and boundary conditions of the active model cells for the simulation model of the Big River study area, Rhode Island.

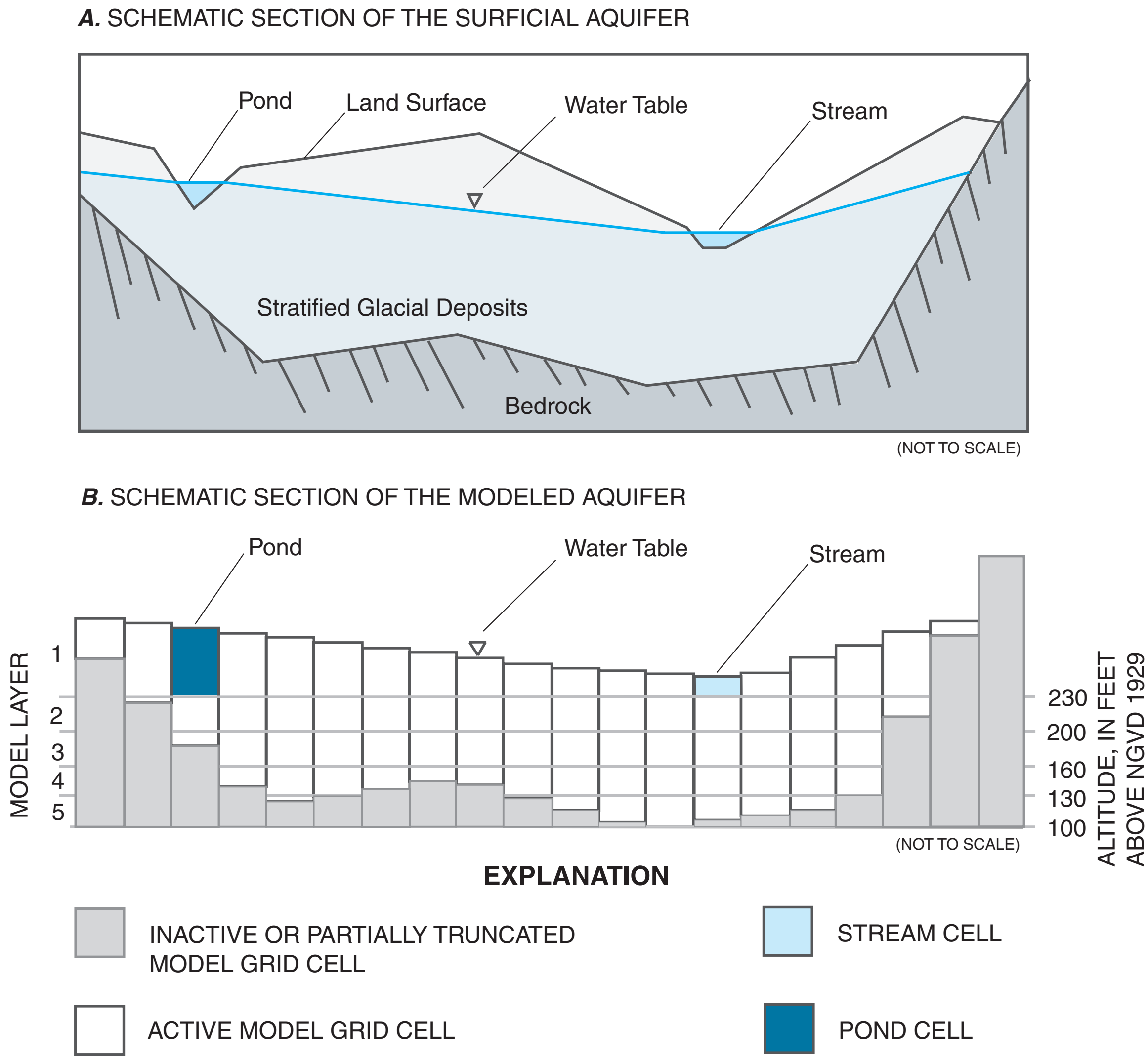


Figure 17. Schematic section showing active model cells and model layers for the simulation model of the Big River study area, Rhode Island.

In these areas, water-table gradients generally are flat, and the predominant ground-water-flow direction is parallel to the boundary from the surrounding uplands toward the river. The small amount of ground-water underflow that may occur in these areas is accounted for in the model as discharge to the Flat River Reservoir or streamflow in the Mishnock River. For example, the estimated ground-water underflow at the northern boundary in the Mishnock River Basin is about 0.1 ft^3/s (table 4), which represents less than 2 percent of the estimated long-term average streamflow in the Mishnock River (7.45 ft^3/s) at the model boundary.

The remaining lateral model boundaries are between stratified deposits and adjacent upland areas of till, bedrock, and thinly saturated stratified deposits. The locations of these boundaries were specified to include only those areas of the surficial aquifer where the saturated thickness is estimated to be at least 10 ft thick. This minimum thickness was specified to ensure numerical stability of the model.

Surface-water inflows from upland areas (SF_I) drained by streams were specified at the first boundary cell of each tributary stream of the MODFLOW stream package (Prudic, 1989). Specified streamflow sites at the edge of the model are indicated as triangles in the model grid on figure 16. Flow rates for these streams were specified by either partial-record streamflow estimates (table 3) or areal estimates from the statistics from the Hunt River (station 01117000) (table 2). Total specified inflows to these five tributaries are 30.1 ft^3/s (table 4).

Underflow from upland areas drained by streams was assumed to be negligible because of the small saturated thickness (less than 10 ft thick) at the model boundary and because ground water generally flows toward the stream rather than across the model boundary in these areas.

Lateral ground-water inflow from upland areas not drained by streams (GW_I) was accounted for by injecting water at wells that are simulated with the MODFLOW well package (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The simulated wells were located in the first layer of the model just inside the boundary between the aquifer and adjoining till and bedrock (or just inside the boundary between the simulated area of the aquifer and adjoining areas where saturated thickness was less than 10 ft). The locations of injection wells that simulate ground-water inflows at the edge of the model are indicated as an "x" in the model grid on figure 16. Total inflow along these boundaries was calculated by multiplying the estimated effective recharge rate of 26.4 in/yr for the basin by the total undrained area adjacent to the boundaries. Total GW_I from upland areas not drained by streams is 15.7 ft^3/s (table 4).

The Flat River Reservoir north of Hill Farm Road in Coventry was simulated as a constant-head boundary to account for potential inflows from, or outflows to, the reservoir (fig. 13). The Flat River Reservoir was defined as a constant-head boundary because water levels are controlled at the dam and because the reservoir has a large storage capacity (about 244 million cubic feet (Guthrie and Stolgitis, 1977)), which is equivalent to more than 40 days of long-term-average streamflow from the Big and Mishnock Rivers. Locations of the constant-head cells in the Flat River Reservoir are shown in figure 16. Long-term records of reservoir levels were not available during this study. Therefore, the median reservoir stage (247.8 ft) measured at the wire-weight gage on Hill Farm Road during 1997–98 (Craft, 2001) was used as the constant-head boundary condition.

The model is bounded on top by the water table, which is a free-surface boundary that receives spatially variable rates of recharge. During the steady-state model simulation, recharge was specified as the long-term average annual recharge rate for the basin (26.4 in.). The position of the water table was not specified, but was calculated during the simulation. If the elevation of the calculated water table falls below the bottom elevation of one or more of the model layers within a vertical stack of cells, then those cells above the water table become inactive. Model cells that contained or were below the water table remain active in the simulation.

Recharge to the water table was specified as a flow rate applied to the uppermost active cell in each vertical stack of cells. Recharge from precipitation (R_{PR}) was specified at a rate of 26.4 in/yr to all areas of the model except those overlain by ponds and lakes. Recharge to ponds and lakes was specified at a rate of 22.3 in/yr, which is equal to the difference between the 1964–98 average annual precipitation rate of 50.3 in. and the estimated average annual rate of free-water-surface evaporation of 28 in. from shallow lakes in the area (Farnsworth and others, 1982, map 3). Recharge to the water table from wastewater (R_{WW}) was simulated in seven small areas that receive public-water supplies from the KCWA but are unsewered. These seven areas, totaling about 0.85 mi^2, are in residential and commercial developments around Lake Mishnock, Maple Root Pond, the Flat River Reservoir, and along State Route 3 north of Interstate 95. The total estimated wastewater-recharge rate to these areas is 0.4 ft^3/s, which is about 0.5 percent of the total inflows (table 4).

Evapotranspiration from the water table (ET_{GW}) was simulated with the evapotranspiration package of MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). Measurements of the maximum rate and maximum depth of evapotranspiration from the water table are not available for the aquifer. Consequently, it was necessary to assume values for these variables. A maximum evapotranspiration rate from the water table of 21.0 in/yr (table 4) was assumed; this value is equal to the estimated average growing-season (May through October) rate of free-water-surface evaporation from shallow lakes in the study area (Farnsworth and others, 1982, map 2). This rate also is similar to the average annual near-surface evapotranspiration rate (ET_S) determined for the Hunt River Basin for 1964–98 (21.3 in/yr). The maximum depth of evapotranspiration from the water table was assumed to equal 4 ft below land surface.

Ground-water withdrawals (Q_W) equal to the 35-year average withdrawal rate (table 1) for the 1964–98 period were simulated at KC01 and KC02. The long-term average annual withdrawal rates for KC01 (0.99 ft^3/s) and KC02 (1.16 ft^3/s) were assigned to the cells and model layers representing the location of the screens for each well (fig. 16).

Streams were simulated in the model by use of the stream-routing package developed for MODFLOW (Prudic, 1989). This package simulates hydraulic interactions between an aquifer and adjoining streams, and tracks cumulative streamflow within each simulated stream. All streams were simulated in the top layer (layer 1) of the model, and each stream was divided into reaches that corresponded to individual model cells (fig. 16). Most of the simulated streams flow through ponds and lakes that are in hydraulic connection with the aquifer. Flows between the aquifer and these ponds and lakes also were simulated with the stream-routing package.

The rate of flow between each stream reach and ground water in the corresponding model cell was calculated as the product of the streambed conductance and the difference between stream stage and ground-water level in the model cell (eq. 1 in Prudic, 1989). The streambed-conductance term, in units of feet squared per day, was calculated as the product of the hydraulic conductivity of streambed materials, stream width, and stream-reach length divided by the thickness of streambed materials (Prudic, 1989). Measurements of the hydraulic conductivity and thickness of streambed materials in similar streams in the neighboring Hunt River Basin (Rosenshein and others, 1968) were used to estimate the streambed conductance of streams in the Big River area. Generally, it was assumed that fine-grained sediments may accumulate to substantial thickness in low-slope depositional areas and that coarse sediments would be of minimal thickness in high-slope reaches. Estimates of the hydraulic conductivity of streambed sediments ranged from 0.5 ft/d for pond-bottom sediments to 6 ft/d in relatively high-slope streams. The width of each stream reach was determined from field measurements or estimated on the basis of the width of streams at nearby streamflow-measurement sites. The length of each stream reach was estimated by overlaying a geographically referenced digital coverage of the stream channels onto the model-grid coverage. The thickness of the streambed of each reach was assumed to equal 1 ft, except in ponds and lakes, where it was assumed to be up to 5 ft. Streambed conductances ranged from 120 ft^2/d in a small tributary to the Nooseneck River to 20,000 ft^2/d in ponded reaches that cover a whole model grid cell.

Specified stream stages substantially influence calculated aquifer heads and flows in river-valley areas near stream cells. If the calculated head in the aquifer is higher than the water level in the stream, ground water discharges to the stream reach; if the calculated aquifer head falls below stream levels, the stream leaks to the aquifer. After the net flow into or out of the stream is calculated for a reach, it is added to or subtracted from the streamflow of the upstream reach, and the resulting streamflow is routed to the adjacent downstream reach. When stream leakage to the aquifer exceeds inflows from upstream areas, the stream-routing package allows individual stream reaches to go dry.

The average stream stage and streambed elevation specified for each stream reach were determined from surface-water levels and streambed elevations measured at streambed piezometers and pond gages and from estimates based on the altitude of land-surface-contour intersections with streams from USGS 7.5-minute topographic maps. Stream levels initially were assigned by linear interpolation between control points where average stream stage was known, or could be estimated from a topographic contour. The initial estimates, between control points, were adjusted to reflect physical features in the watershed. For example, the presence of a riparian wetland between two known points would suggest an area of low slope along the stream.

One stream in the model area, Mud Bottom Brook, which is in a wetland west of the Carr River, was simulated using the MODFLOW drain package (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). Mud Bottom Brook was simulated as a drain (fig. 16) because field studies indicated that the brook may flow intermittently during runoff events, but does not have an established stream channel with a measurable base flow.

Hydraulic Conductivity

Values of horizontal and vertical hydraulic conductivity were assigned to each of the four textural units of stratified deposits identified in the study area by Stone and Dickerman (2002)—sand and gravel, sand, fine, and sand and gravel underlying sand or fine (referred to here as buried sand and gravel). Maps of the distribution of these sediments within the study area are provided in Stone and Dickerman (2002) and in the files of the U.S. Geological Survey Providence, RI, office. Uniform values of hydraulic conductivity were assigned to each type of deposit on the basis of existing information and the results of six aquifer tests in the study area reported in Stone and Dickerman (2002): 250 ft/d for sand and gravel, 105 ft/d for sand, 15 ft/d for fine, and 600 ft/d for buried sand and gravel. Uniform values of the ratio of horizontal to vertical hydraulic conductivity of 5:1 for sand and gravel, sand, and buried sand and gravel, and of 50:1 for fine deposits also were used. If more than one of the four textural units were present in a model grid cell, average (also referred to as equivalent) values of horizontal and vertical hydraulic conductivity were determined for the cell by use of averaging methods described in Freeze and Cherry (1979, equations. 2.31 and 2.32) and McDonald and Harbaugh (1988, chap. 5). Small areas of alluvium, artificial fill, and swamp deposits mapped by Stone and Dickerman (2002) were assigned values of hydraulic conductivity equal to those of adjoining stratified deposits. Model cells that contain ponds or lakes were assigned a horizontal hydraulic conductivity of 50,000 ft/d; this large value was used to simulate the lack of resistance to flow through these surface-water bodies.

Calibration

The model was calibrated to estimates of long-term average annual water levels at 21 observation wells and to streamflows at eight partial-record stations (tables 5 and 6, fig. 4). Initial values of several model parameters were adjusted on a trial-and-error basis during model calibration to improve the match between model calculated and estimated water levels and streamflows. Initial estimates of the horizontal hydraulic conductivity of the sand and gravel and buried sand and gravel were lowered to 200 and 300 ft/d, respectively, and the ratio of horizontal to vertical hydraulic conductivity for sand and gravel, sand, and buried sand and gravel was increased from an initial estimate of 5:1 to a final estimate of 10:1. Small changes also were made during the calibration process to the bedrock elevation and (or) the type of stratified deposit simulated within a model cell; however, these changes were made only in areas where lithologic logs were unavailable. Finally, initial estimates of streambed conductance and stream stage also were adjusted for several of the simulated streams. Generally,

Table 5. Model-calculated steady-state water-level altitudes, statistical estimates of long-term mean water-level altitudes, and measured water-level altitudes in August 1998 and December 1997 at observation wells in the Big River study area, Rhode Island

[Well locations are shown in figure 4. Water-level altitudes are in feet above NGVD 1929 (formerly called the Sea-Level Datum of 1929). Differences between estimated or measured altitudes and model-calculated altitudes are in feet. **USGS well identifier:** WGW, West Greenwich well. USGS, U.S. Geological Survey. --, not applicable]

USGS well identifier	Model location			Model-calculated altitude	Estimated long-term water-level		August 1998 measurement		December 1997 measurement	
	Layer	Row	Column		Altitude	Difference	Altitude	Difference	Altitude	Difference
WGW 286	1	157	102	284.95	286.04	1.09	286.68	1.73	284.88	-0.07
WGW 287	1	147	104	272.69	272.91	.22	273.54	.85	270.28	-2.41
WGW 320	1	130	99	262.50	264.38	1.88	262.06	-.44	265.16	2.66
WGW 285	1	125	85	264.83	264.43	-.40	263.79	-1.04	264.35	-.48
WGW 294	1	127	135	286.83	284.89	-1.94	284.01	-2.82	285.53	-1.30
WGW 290	1	117	114	260.84	262.76	1.92	263.26	2.42	261.83	.99
WGW 291	2	116	105	253.55	253.88	.33	253.70	.15	253.68	.13
WGW 293	1	100	116	252.55	252.09	-.46	251.60	-.95	252.06	-.49
WGW 303	2	95	102	257.64	257.97	.33	259.19	1.55	255.98	-1.66
WGW 305	1	89	103	254.71	257.23	2.52	257.97	3.26	255.71	1.00
WGW 313	4	85	102	252.82	253.11	.29	253.11	.29	252.79	-.03
WGW 304	1	72	92	251.63	252.93	1.30	253.18	1.55	250.97	-.66
WGW 297	1	79	163	286.89	285.92	-.97	287.68	.79	284.95	-1.94
WGW 296	1	102	166	276.03	274.19	-1.84	277.54	1.51	271.10	-4.93
WGW 295	1	112	156	263.68	263.57	-.11	262.89	-.79	263.64	-.04
WGW 299	1	97	154	264.57	264.10	-.47	266.42	1.85	262.38	-2.19
WGW 300	1	91	149	260.09	260.62	.53	260.50	.41	259.55	-.54
WGW 306	5	96	147	260.00	260.28	.28	260.28	.28	259.01	-.99
WGW 312	4	94	142	258.37	259.76	1.39	259.05	.68	258.12	-.25
WGW 302	2	83	134	252.52	252.20	-.32	252.47	-.05	251.90	-.62
WGW 298	1	89	140	257.40	258.10	.70	258.79	1.39	257.20	-.20
Average of differences	--	--	--	--	--	0.30	--	0.60	--	-0.67
Average of absolute values of differences	--	--	--	--	--	0.92	--	1.18	--	1.12

Table 6. Model-calculated steady-state streamflows and statistical estimates of long-term average streamflow at partial-record stations in the Big River study area, Rhode Island

[Model-calculated streamflow does not include direct runoff in the model area. Streamflows are in cubic feet per second. The lower and upper 95th-percentile confidence bounds reflect the accuracy of the predicted average streamflow, not the variability of flow in the stream. No., number]

Station identification No.	Station name	Model location				Estimated long-term average streamflow			Model-calculated streamflow
		Segment	Reach	Row	Column	Lower 95%	Average	Upper 95%	
01115670	Congdon River near Nooseneck, RI	3	43	153	97	7.4	9.3	11.6	8.1
01115700	Unnamed tributary to Congdon River, RI	4	24	151	104	.9	1.3	1.8	.7
01115730	Carr River, tributary to Capwell Mill Pond, RI	12	40	114	154	4.9	7.3	10.9	4.4
01115770	Carr River, near Nooseneck, RI	18	4	96	118	9.1	13.0	18.6	9.0
01115800	Big River at Route 3, RI	19	10	93	111	38.0	46.5	57.0	42.6
01115963	Old Hickory Brook tributary to Mishnock River, RI	27	11	72	129	.2	.3	.5	.0
01115965	Outflow of Lake Mishnock near Washington, RI	26	75	74	141	3.6	4.3	5.2	3.3
01115970	Mishnock River near Washington, RI	28	13	32	155	6.6	7.5	8.5	6.2

initial estimates of streambed conductance were lowered during model calibration in areas where model-calculated streamflows and water levels did not match observed values. Final estimates of streambed conductance ranged from 120 to 20,000 ft^2/d. All of the changes made to the model during calibration are considered to be acceptable within the limitations of available data.

The water-level altitude calculated in the calibrated model at each of the 21 observation wells is reported with the estimate of the long-term average annual water-level altitude for that well in table 5. The estimated long-term average annual water-level altitude for each well was calculated by use of the MOVE.1 method (Hirsch, 1982) to relate water-level measurements at each observation well made between 1996 and 1998 (reported in Craft, 2001) to equivalent measurements made at wells COW 411, EXW 6, and SNW 6, each of which has more than 35 years of monthly water-level record. The mean difference between the model-calculated and estimated long-term water-level altitudes for the 21 wells is 0.30 ft, which indicates that, on average, the calibrated model overestimates water levels at the observation wells. The mean of the absolute value of the difference between calculated and estimated long-term water-level altitudes is 0.92 ft, which is less than 3 percent of the total estimated relief of the water table (33.95 ft) at the 21 observation wells used for model calibration. Also shown in table 5 are water-level altitudes measured at the 21 observation wells during two representative periods during the study (December 1997 and August 1998). Model-calculated water levels are systematically higher than those measured in December 1997, which was a period of below-average water-level conditions in central Rhode Island. The small differences between the December 1997 measurements and the long-term-average estimates, however, suggest that the water-level contours and ground-water flow directions shown on plate 1 for December 1997 are representative of typical conditions in the aquifer. A map of the simulated water table for steady-state conditions is shown in figure 18. Overall, there is good agreement between the configuration of the simulated water table as shown in figure 18 and the water table shown on plate 1.

The streamflow calculated with the calibrated model at each of the eight partial-record streamflow-gaging stations is shown with estimates of long-term average annual streamflows at each station in table 6. Model-calculated average annual streamflows at the Congdon River and the Big River streamflow-gaging stations (stations 01115670 and 01115800, respectively) are below the estimated average annual streamflow, but are within the 95-percent confidence limit of this estimate. Model-calculated average annual streamflows are below the 95-percent confidence limit of the long-term average annual streamflow for the other six stations. The calibrated model generally underestimates streamflow because direct runoff from within the stratified deposits is not accounted for in model-calculated streamflows.

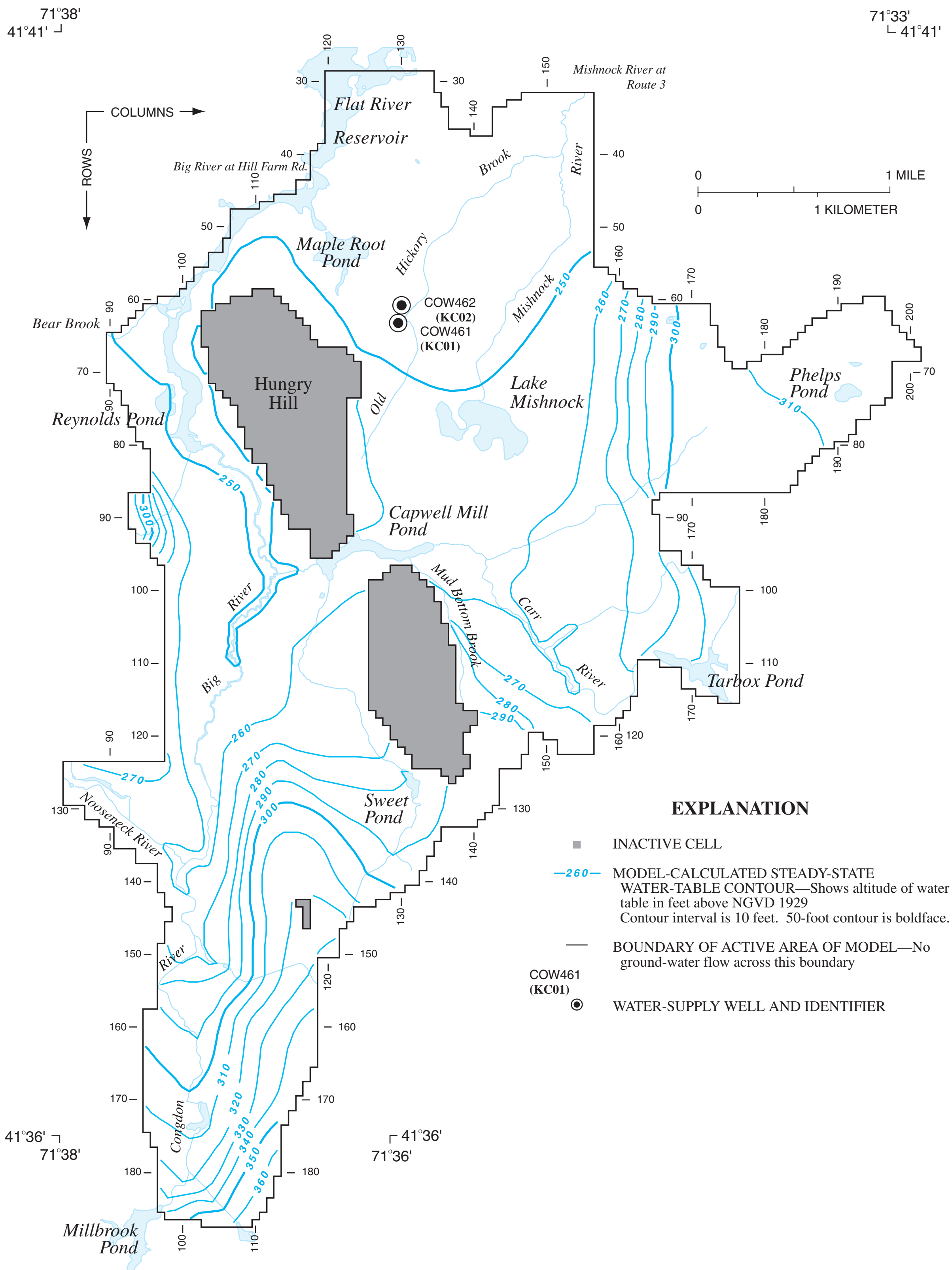


Figure 18. Model-calculated steady-state water table, Big River study area, Rhode Island.

The steady-state, average annual hydrologic budget of the model area calculated with the calibrated model is shown in table 7. The model-calculated total flow rate through the system (table 7), about 67.1 ft^3/s, is similar to the flow rate estimated for the system for the 1964–98 period (about 75 ft^3/s, table 4). There are, however, a few differences between the model-calculated hydrologic budget and the estimated hydrologic budget. For example, total streamflow calculated by the model at the outflow sites (61.5 ft^3/s) is less than the total estimated streamflow for these sites during 1964–98 (69.9 ft^3/s; table 4). This results in part because direct runoff is not simulated within the modeled area. Consequently, total inflow and outflow are somewhat less for the ground-water-model budget than for the estimated budget.

A sensitivity analysis of the steady-state model was done as part of the model-calibration process to determine the relative response of calculated water levels and streamflow to uniform changes in the simulated values of recharge, horizontal and vertical hydraulic conductivity, and streambed conductance. Each variable was increased and decreased individually by 10 percent of its calibrated value in a series of eight simulations. Results of the sensitivity analysis indicate that model-calculated ground-water level altitudes were most sensitive to variations in the values specified for recharge and horizontal hydraulic conductivity, and least sensitive to changes in the values specified for vertical hydraulic conductivity and streambed conductance. Model-calculated streamflows for the three largest rivers with measurement data within the modeled area (the Big, Carr, and Mishnock Rivers) were most sensitive to increases and decreases in the values specified for recharge, and least sensitive to changes in the values specified for vertical hydraulic conductivity.

Table 7. Model-calculated steady-state average annual hydrologic budget for the Big River study area, Rhode Island

[Does not include direct runoff (about 8.3 cubic feet per second) in model area. Budget components shown schematically on figure 14]

Hydrologic budget component	Rate of flow: Cubic feet per second	Rate of flow: Million gallons per day
Estimated inflow		
Ground-water recharge from		
Precipitation (R_{PR})	20.9	13.5
Wastewater-return flow (R_{WW})	.4	.3
Streamflow from uplands (SF_I)	30.1	19.5
Lateral ground-water inflow (GW_I)	15.7	10.1
Total inflow	67.1	43.4
Estimated outflow		
Streamflow (SF_O)	61.5	39.7
Evapotranspiration (ET_{GW})	3.4	2.2
Ground-water withdrawal (Q_W)	2.2	1.4
Total outflow	67.1	43.4
Budget error (inflow-outflow)	0.0	0.0

Transient Model

A transient model was developed to simulate the average annual hydrologic cycle in the model area. Average annual hydrologic conditions are defined as the average conditions during each of the 12 months of the 35-year simulation period 1964–98. The transient model has the same areal and vertical extent as the steady-state model. Several of the data sets developed for the steady-state model also were used for the development of the transient model; these data sets included those for hydraulic conductivity and the top and bottom elevations of each cell. The primary purpose of simulating transient conditions was to quantify the effect of monthly average ground-water withdrawal rates on monthly streamflow depletions from the Lake Mishnock outfall, the Big River, the Carr River, and the Mishnock River in the context of seasonal variations in recharge. The transient model was designed to simulate dynamic equilibrium, which is defined here as the condition in which there is no net change in storage in the simulated flow system over the average annual hydrologic cycle. Calculated water-level altitudes and streamflows vary over the annual cycle, but at the end of the cycle the system returns to the condition that existed at the beginning of the cycle.

Temporal Discretization and Initial Conditions

The annual hydrologic cycle was divided into 12 monthly time periods. The length of each period was the number of days in the month. In MODFLOW, these 12 periods are referred to as stress periods, because specified hydrologic stresses change from one period to the next. Within each period, however, stress rates were constant. Thirty time steps were used for each stress period, regardless of the particular month. Time steps were increased in length during each stress period to ensure numerical stability of the model. The first time step in each stress period was less than 0.2 day, and the last time step in each stress period was about 3.0 days. Water-level altitudes specified for each model cell at the beginning of the transient simulation were those determined by the calibrated, steady-state model. Stress conditions specified for the initial conditions were those for the month of January, which are described in detail in the next section. Because the initial conditions affect the transient response of the simulated system, it was necessary to repeat the 1-year cycle of transient stresses until there was no change in storage over a 1-year cycle (that is, until dynamic equilibrium was attained). It was found that five annual cycles, a total of 60 monthly stress periods, were adequate to produce dynamic equilibrium. The net change in storage during the fifth year of simulation was 0.1 percent, which was close to the desired value of zero. At dynamic equilibrium, simulation results on the first day of the year were equal to those on the first day of the previous year.

Storage Properties of Aquifer

A uniform value of specific yield of 0.28 was specified for the stratified deposits simulated in the model. A specific yield equal to 1.0 was specified for the simulated ponds and lakes. In model layers 2–5 a uniform value of 3.0×10^{-4} was specified for the storage coefficient of the aquifer in each cell. These storage values are considered to be characteristic of stratified surficial aquifers in southeastern New England (Barlow and Dickerman, 2001).

Hydrologic Boundary Conditions and Stresses

The types of boundary conditions and stresses specified in the transient model were equivalent to those used for the steady-state model (fig. 16). In the transient model, however, stress rates vary by month over the annual cycle.

Average monthly precipitation recharge rates estimated for the Hunt River Basin for the 1964–98 period (fig. 15) were used for the transient model. For all areas of the model except ponds and lakes, the rates ranged from 0.6 in. for September to 4.2 in. for March, with a total annual recharge of 26.4 in. Monthly recharge rates to ponds and lakes were calculated by subtracting average monthly free-water-surface evaporation rates from average monthly precipitation rates measured in 1964–98 at the Kingston climatological station. Total free-water-surface evaporation during the May through October growing season was estimated to be 21.0 in. (Farnsworth and others, 1982, map 2). The total annual free-water-surface evaporation of 28.0 in. (Farnsworth and others, 1982, map 3) gave a total of 7.0 in. of free-water-surface evaporation for the months of November through April. Average monthly free-water-surface evaporation rates were, therefore, about 3.50 in. during May through October and 1.17 in. during November through April. Net monthly recharge rates specified to ponds ranged from -0.24 in. for July to 3.66 in. for November, with a total annual recharge rate to ponds and lakes that is slightly lower (by 0.02 in.) than the value of about 22.3 in. specified in the steady-state model.

In addition to precipitation recharge, some areas also receive recharge from wastewater disposal. Quarterly water-delivery rates were used to estimate monthly wastewater-discharge rates. The total average annual recharge rate from wastewater disposal over the entire model area was about 0.4 ft^3/s, as in the steady-state model. The spatial distribution of wastewater recharge was identical to the distribution described for the steady-state model.

Monthly streamflow rates were specified for the first reach of each of the five streams that enter the model area from till and bedrock uplands (fig. 13). Specified inflows for the Congdon River from Millbrook Pond, the Carr River from Carr Pond, and the unnamed tributary to the Big River were determined on the basis of the long-term Hunt River streamflow records. These streamflow estimates were proportioned by month according to the annual distribution of estimated monthly average streamflow in Fry Brook, a tributary to the Hunt River that drains an upland basin (fig. 2) (Barlow and Dickerman, 2001). The seasonal pattern of streamflows from Fry Brook was used to estimate the seasonal pattern of streamflow from upland areas because the watershed is small, adjacent to the Carr River Basin, and is composed of till and bedrock uplands. The Fry Brook Basin is expected to better represent the seasonal pattern of recharge from till areas than would the basin that drains to the Hunt River streamflow-gaging station, because the latter basin includes substantial areas of stratified deposits. The specified monthly inflows for the Nooseneck River and Bear Brook were estimated with the Maintenance of Variance Extension, type 1 (MOVE.1) method (Hirsch, 1982) from the partial-record data available for these streams. Physical characteristics of the simulated streams, such as streambed conductance, and streambed elevation were equivalent to those specified in the steady-state model.

Monthly rates of lateral ground-water inflow from upland areas not drained by streams were determined by proportioning the amount of annual inflow at each boundary cell among the 12 months on the basis of the percentage of annual precipitation recharge for each month. The percentage of annual precipitation recharge for each month was determined by use of the estimated Fry Brook recharge pattern because the Fry Brook Basin is composed of till and bedrock uplands that are characteristic of the upland areas that produce lateral ground-water inflow in the Big River study area.

Monthly evapotranspiration rates from the water table were based on the assumption that the total average annual amount of water-table evapotranspiration (21.0 in.) occurs at an equal rate throughout the growing-season months of May through October. Consequently, maximum water-table evapotranspiration rates, averaging 3.5 inches per month, were specified for May through October; rates of zero inches per month were specified for the remaining months of the year. As in the steady-state model, the maximum depth of evapotranspiration from the water table was assumed to equal 4 ft below land surface.

Monthly withdrawal rates at each public water-supply well were set equal to the average monthly withdrawal rates provided by the KCWA (table 1). Total monthly withdrawal rates simulated for both wells ranged from 2.0 ft^3/s to 2.4 ft^3/s, and averaged 2.2 ft^3/s.

Calibration

The transient model was calibrated to estimates of long-term average monthly water levels at 21 observation wells and to streamflows at eight partial-record streamflow-gaging stations. Model-calculated water levels are within the 95-percent confidence interval of estimated average monthly ground-water levels for 13 of the 21 observation wells (fig. 29, at back of report). Moreover, the model accurately represents the magnitude of annual fluctuations in five of the remaining wells (WGW 286, WGW 290, WGW 303, WGW 313, and WGW 320), although many of the model-calculated mid-monthly values are outside the 95-percent confidence interval of the monthly average estimates. The model does not fully account for hydrologic and hydrogeologic processes that affect ground-water levels at the three remaining wells (WGW 285, WGW 294, and WGW 305). For example, wells WGW 285 and WGW 294 are in thinly saturated areas near boundaries between the stratified deposits and uplands (fig. 4); model-calculated hydrographs for these wells may be affected by uncertainty in the specified values of ground-water inflow from upland areas at the model boundary. The cause of the differences between model-calculated and estimated water levels at well WGW 305 (fig. 29) is not clear, but may be related to uncertainty in the value of hydraulic conductivity of the stratified deposits near the well.

A statistical summary of the differences between the estimated and model-calculated water levels for all 21 wells is shown on figure 19. The plots on figure 19 indicate an annual pattern in the median difference between the estimated and model-calculated water levels, with model-calculated water levels generally greater than estimated water levels from April through August and estimated water levels greater than model-calculated water levels from September through March. This pattern likely results from uncertainties in the annual patterns of recharge and of ground-water inflow from upland areas specified in the model.

Estimated average monthly streamflows and model-calculated, mid-monthly streamflows at six selected partial-record streamflow-gaging stations are shown in figure 20. Streamflows at the Old Hickory Brook site (station 01115963) are not included in figure 20 because model calculations indicate that this reach was dry throughout the year. Model-calculated streamflows at the Carr River site (station 01115730), between Tarbox Pond and Capwell Mill Pond (fig. 4), are not included in figure 20 because they are influenced by boundary conditions similar to those described for wells WGW 285 and WGW 294. Model-calculated streamflows at the six sites that are shown in figure 20 indicate that the calibrated transient model generally represents the magnitude and timing of streamflow within the model area. As was the case with the steady-state model, the transient model does not simulate the direct-runoff component of streamflow in the aquifer area, and therefore, model-calculated streamflows are less than streamflow estimates.

The maximum and minimum estimated streamflows are in March and September, respectively, yet the maximum and minimum model-calculated streamflows are in April and October, respectively. The model-calculated streamflows are fairly representative of the estimated annual hydrograph for all six sites despite this small phase shift in the annual cycle. The timing of the streamflow extremes may differ, in part, because the ground-water model does not fully account for runoff

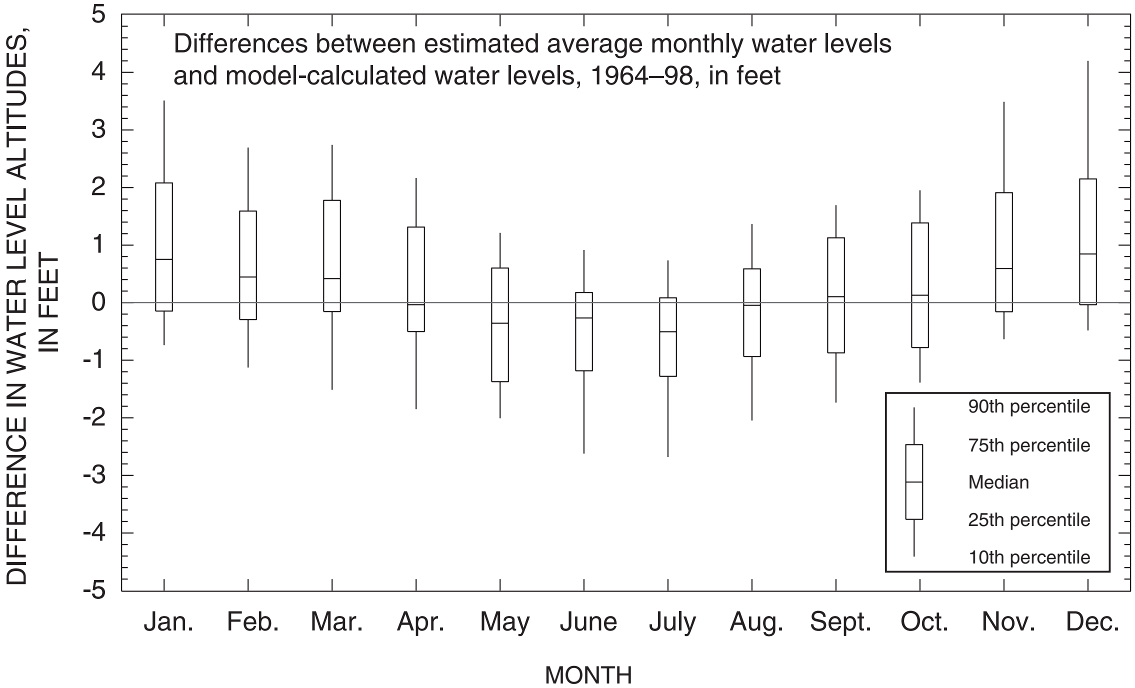


Figure 19. Distribution of differences between estimates of average monthly water levels during 1964–98 and model-calculated water levels, in feet, at the 21 well sites used for model calibration in the Big River study area, Rhode Island. (Well locations shown on fig. 4.)

from the aquifer area, which is included in the average monthly streamflows. This slight phase shift also may be caused, in part, by the use of the Hunt River streamflow record to calculate monthly recharge, whereas the streamflow estimates were developed with data from six continuous-record streamflow-gaging stations (table 2). Also, recharge estimates are applied in the model as water entering the aquifer, whereas streamflow records are indicative of water leaving the aquifer. Despite these limitations, the model accurately simulates low streamflows during the late summer and early fall when monthly recharge rates and streamflow are close to annual minimums (fig. 20).

Modifying the specified rates of recharge, streamflow from upland areas, or lateral ground-water inflow from upland areas might have further minimized the differences between measured and calculated water-level altitudes and streamflows. Modifying these variables for this purpose, however, was judged to be inappropriate given the limited availability of data for these variables.

The average annual hydrologic budget for the modeled system calculated with the calibrated transient model is compared to the steady-state budget in table 8. Overall, good agreement was found between hydrologic components of the two models. The transient model also calculates changes in aquifer storage that occur in response to the annual cycle of recharge. The average rate of inflow to and outflow from aquifer storage is about 9.1 ft^3/s.

During the calibration process, both uniform and non-uniform specific-yield scenarios were tested. Four uniform values of specific yield were tested (0.15, 0.25, 0.28, and 0.30). As the value of specific yield was increased, the range of calculated water-level altitudes for the well decreased. Because a storage coefficient of 0.28 provided the best match for the majority of wells, this value was retained from among the uniform specific-yield trials. Non-uniform specific-yield scenarios, based on different values for different sediment types, also were tested, but this approach did not improve the match. In addition, specific-yield data from field measurements are not available for sediments in the Big River study area, and there is no clear relation between specific yield and grain size (Johnson, 1966). In the absence of more data on the specific yield of the aquifer, therefore, a value of 0.28 was retained.

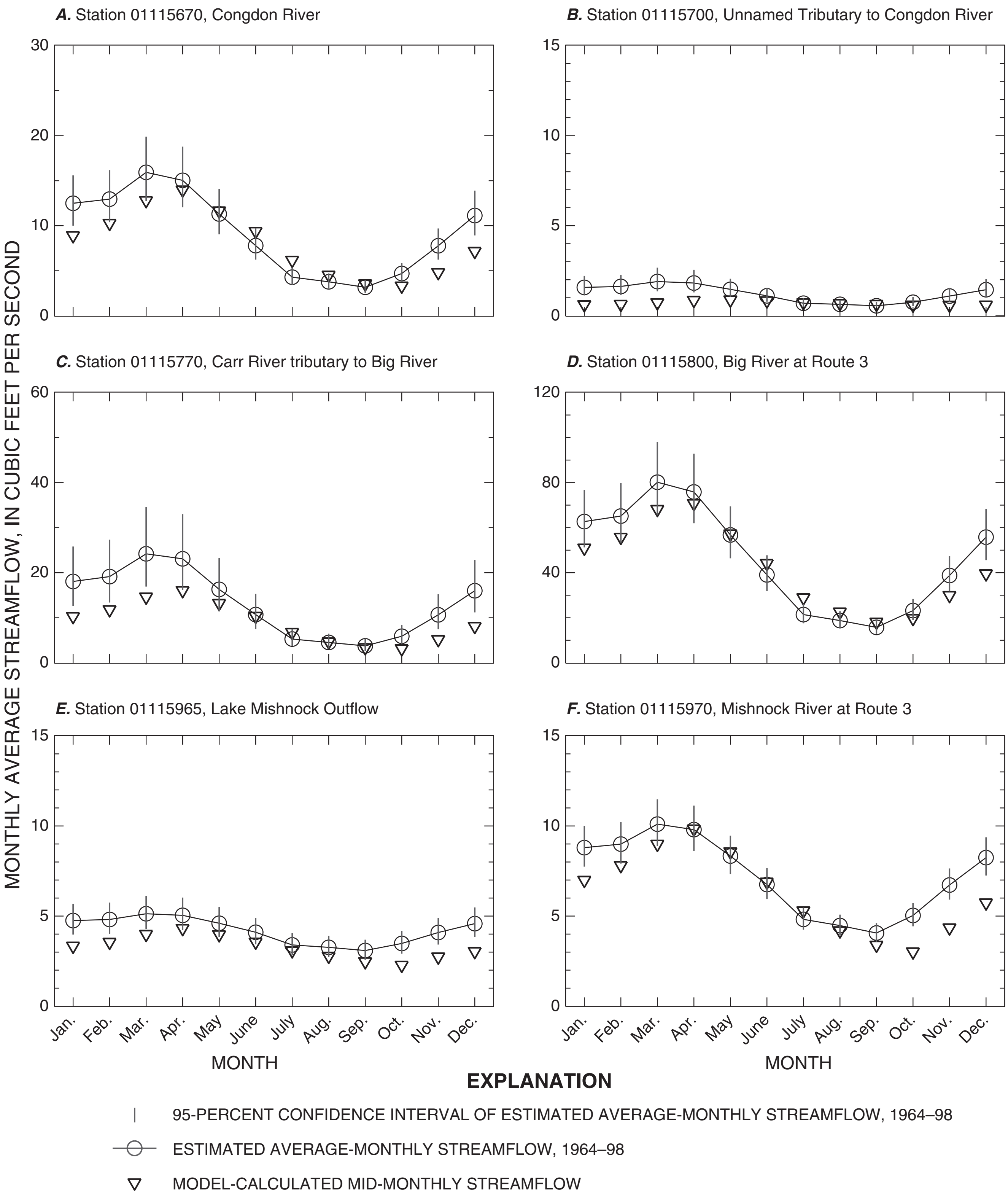


Figure 20. Estimated average monthly and model-calculated streamflows at six partial-record streamflow-gaging stations within the Big River study area, Rhode Island. (Locations of streamflow-gaging stations shown on fig. 4.)

Table 8. Model-calculated steady-state and transient average annual hydrologic budgets for the Big River study area, Rhode Island

[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; budget components shown schematically on figure 14]

Hydrologic budget component	Steady-state model budget		Transient-model budget	
Estimated inflow				
Ground-water recharge from				
Precipitation (RP_R)	20.9	(13.5)	20.9	(13.5)
Wastewater-return flow (R_{WW})	.4	(.3)	.4	(.3)
Streamflow from uplands (SF_I)	30.1	(19.5)	30.1	(19.5)
Lateral ground-water inflow (GW_I)	15.7	(10.1)	15.7	(10.1)
Total inflow	67.1	(43.4)	67.1	(43.4)
Estimated outflow				
Streamflow (SF_O)	61.5	(39.7)	61.2	(39.6)
Evapotranspiration (ET_{GW})	3.4	(2.2)	3.4	(2.2)
Ground-water withdrawal (Q_W)	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)

A sensitivity analysis of the transient model was done to determine the relative response of calculated water levels and streamflow to variations in monthly recharge and the specific yield of aquifer materials. As with the steady-state model, results of the sensitivity analysis indicate that model-calculated ground-water levels and streamflows were most sensitive to variations in the values specified for recharge.

SIMULATED EFFECTS OF GROUND-WATER WITHDRAWALS

The calibrated steady-state and transient numerical models were used to evaluate the effects of ground-water withdrawals for average annual hydrologic conditions during 1964–98 and for hypothetical future conditions. The effects of the simulated withdrawals are reported primarily in terms of changes in streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road. An initial simulation was made for a condition of no ground-water withdrawals in the basin to provide a basis for evaluating the effects of alternative ground-water-withdrawal scenarios on the hydrologic system; this initial simulation is referred to as the predevelopment scenario. All of the following simulations were based on long-term average recharge rates estimated for 1964–98.

Predevelopment Conditions

The predevelopment scenario simulates hydrologic conditions that might have occurred in the absence of ground-water withdrawals and wastewater-return flow. The conditions were modeled by removing simulated withdrawals (2.2 ft^3/s, Q_W) at wells KC01 and KC02 and simulated recharge from wastewater-return flow in developed areas (0.4 ft^3/s, R_{WW}) (table 9); all of the other stresses were equivalent to the 1964–98 simulated conditions. The net water exported from the basin by the KCWA (that is, withdrawals minus wastewater-return flow) under the 1964–98 simulated conditions was 1.8 ft^3/s. Results of this simulation indicate an increase of about 1.4 ft^3/s in streamflow out of the Mishnock River Basin, an increase of about 0.2 ft^3/s in streamflow out of the Big River Basin into the Flat River Reservoir, and an increase of about 0.2 ft^3/s in the rate of evapotranspiration. The net difference between hydrologic budgets for the simulated 1964–98 and for the simulated predevelopment conditions is 0.4 ft^3/s; this value is equal to the rate of wastewater-return flow that is simulated for the 1964–98 conditions but is not simulated for the predevelopment conditions.

Results of the transient simulation indicate that several stream reaches within the study area may go dry even in the absence of ground-water withdrawals. For example, results for Mud Bottom Brook indicate that the stream is completely dry 5 months of the year and is only active in a few isolated cells even in the wettest months (March and April). Some streams, such as the unnamed tributary to the Big River north of Interstate 95, have substantial flows originating in upland bedrock and till areas, but become losing streams and go dry as they enter the stratified-deposits. A number of small streams, such as the unnamed tributaries to the Congdon River and the unnamed tributaries to the Carr River, originate in thinly saturated stratified-deposit areas, but are dry in the upper reaches for most of the year. For example, streambed-piezometer data and model-calculated results indicate that the northern tributary to the Carr River along Division Road in the Management Area (pl. 1) is naturally dry most

Table 9. Model-calculated hydrologic budget for predevelopment and conditions for 1964–98 in the Big River study area, Rhode Island

[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; budget components shown schematically on figure 14]

Hydrologic budget component	Predevelopment conditions		Conditions for 1964–98	
Estimated inflow				
Ground-water recharge from				
Precipitation (RP_R)	20.9	(13.5)	20.9	(13.5)
Wastewater-return flow (R_{WW})	0.0	(.0)	0.4	(.3)
Streamflow from uplands (SF_I)	30.1	(19.5)	30.1	(19.5)
Lateral ground-water inflow (GW_I)	15.7	(10.1)	15.7	(10.1)
Total inflow	66.7	(43.1)	67.1	(43.4)
Estimated outflow				
Streamflow (SF_O)	63.1	(40.8)	61.5	(39.7)
Evapotranspiration (ET_{GW})	3.6	(2.3)	3.4	(2.2)
Ground-water withdrawal (Q_W)	.0	(.0)	2.2	(1.4)
Total outflow	66.7	(43.1)	67.1	(43.4)
Budget error (inflow-outflow)	0.0	(0.0)	0.0	(0.0)

of the year. Model calculations, however, do not include direct runoff, which may be a source of water to the stream during and shortly after precipitation. For example, data from the Old Hickory Brook partial-record streamflow-gaging station indicate that streamflows ranged from 0.02 to 0.76 ft^3/s during 1996–98 (table 3). Model simulation results, however, indicate that the brook was dry throughout the year for about a half a mile downstream from the streamflow-gaging station (including the Kent County well-field area, fig. 4), even under the predevelopment condition. Specific-conductance measurements from the Old Hickory Brook partial-record streamflow-gaging station are among the highest from all surface-water measurement stations (fig. 12); this result suggests that measured streamflows may be influenced by anthropogenic factors such as flow from highway underdrains and wastewater recharge from developed areas in the adjacent till and bedrock uplands, which are not characterized in detail within the ground-water model.

Conditions for 1964–98

The calibrated steady-state and transient models were used to evaluate streamflows and streamflow depletions along several of the streams in the basin for annual hydrologic conditions simulated for 1964–98. The steady-state model also was used to examine contributing areas and the sources of water to Mishnock Lake and the two public-supply wells active during the 1964–98 period.

Model-calculated streamflows and streamflow depletions for the Congdon, Big, and Carr Rivers, the western unnamed tributary to the Carr River, the Mishnock River, and Old Hickory Brook as a function of distance along each stream are shown in figure 21. River mile 0.0 on each figure is the uppermost reach (model cell) of each of the simulated streams in the modeled area (fig. 13). Calculated streamflows are shown for the 1964–98 conditions and for the estimated predevelopment conditions. Tributary inflows to the streams are apparent as sharp increases in streamflow plotted on each graph. For example, the unnamed tributary to the Congdon River increases streamflow in the main stem by 1.12 ft^3/s at about 1.6 river miles, and the Nooseneck River contributes 18.8 ft^3/s at the confluence with the Big River at about 1.9 river miles (fig. 21*A*). The streamflow depletions caused by ground-water withdrawals at KC01 and KC02 (shown on fig. 21) are equal to the difference between the model-calculated streamflows (that is, those calculated for the 1964–98 withdrawal conditions and those for predevelopment conditions).

The total streamflow depletion caused by ground-water withdrawals at the Kent County wells during the 1964–98 simulation is 1.65 ft^3/s. The total streamflow depletion in the Big River Basin south of Hill Farm Road is 0.24 ft^3/s; 0.23 ft^3/s of the water is depleted in the Maple Root Pond stream reach, which joins the Big River at 6.8 river miles (fig. 21*A*). The model-calculated streamflow depletion in the Carr River (fig. 21*B*) is about 0.01 ft^3/s, which is about 0.1 percent of the average annual streamflow and probably is attributable to numerical-simulation error. There was no depletion in the western unnamed tributary to the Carr River, which is in the Big River Valley (fig. 21*C*). Therefore, the Carr River and its tributaries are not affected by withdrawals at the Kent County wells. The streamflow depletion at the outfall of Lake Mishnock (river mile 0.3) is 0.21 ft^3/s (fig. 21*D*).

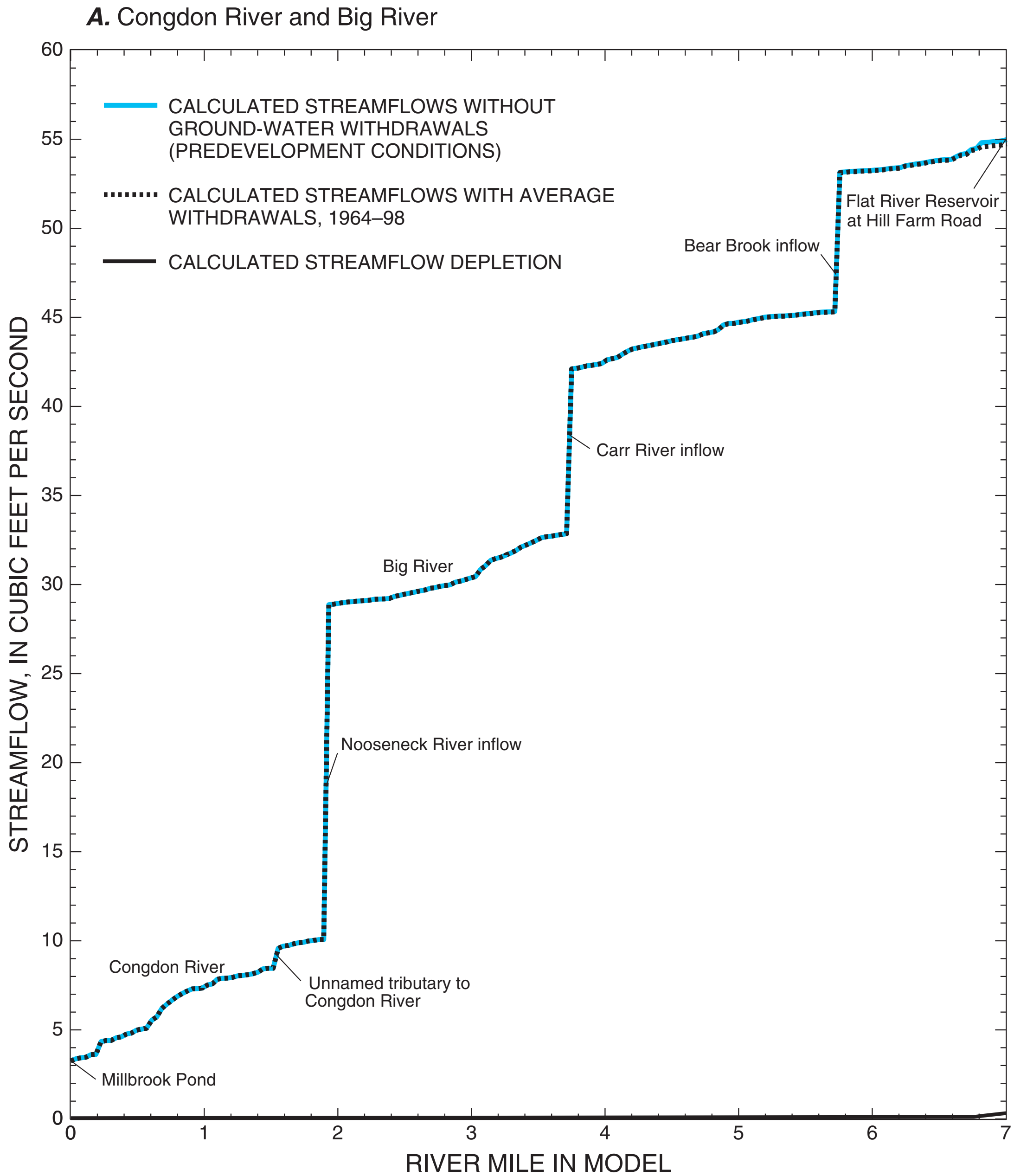


Figure 21. Model-calculated steady-state streamflows and streamflow depletions for the 1964–98 period in the (*A*) Congdon and Big Rivers, (*B*) Carr River, (*C*) westerm unnamed tributary to the Carr River, (*D*) Mishnock River, and (*E*) Old Hickory Brook, Rhode Island. (For on-stream ponds, streamflows were calculated for model cells along the centerline of the ponds.)

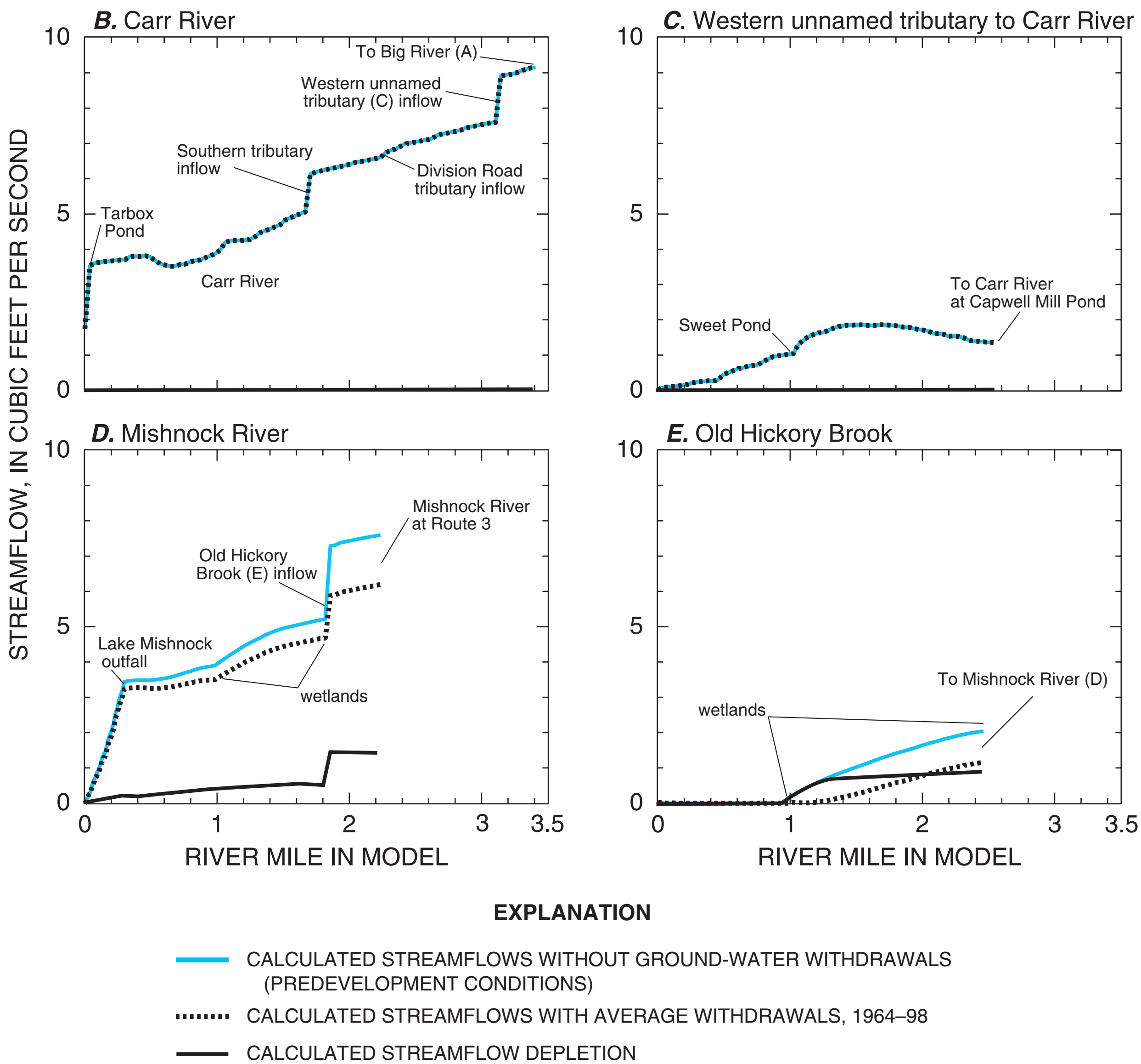


Figure 21—*Continued.* Model-calculated steady-state streamflows and streamflow depletions for the 1964–98 period in the (*A*) Congdon and Big Rivers, (*B*) Carr River, (*C*) westerm unnamed tributary to the Carr River, (*D*) Mishnock River, and (*E*) Old Hickory Brook, Rhode Island. (For on-stream ponds, streamflows were calculated for model cells along the centerline of the ponds.)

The streamflow depletion at river mile 1.8 of the Mishnock River upstream of the confluence with Old Hickory Brook is 0.53 ft^3/s (fig. 21*D*). The total depletion in Old Hickory Brook is 0.88 ft^3/s (fig. 21*E*). Tghe combined depletion of Old Hickory Brook and the Mishnock River at their confluence is equivalent to the total depletion in the Mishnock River Basin (1.41 ft^3/s) south of Route 3.

Natural stream-channel losses were calculated for several stream reaches in the model area. The comparison of calculated streamflows for the predevelopment conditions and 1964–98 conditions indicates whether a loss in streamflow along a reach is natural (a condition of stream loss with no depletion) or induced. For example, the Carr River graph (fig. 21*B*) indicates natural streamflow losses at the downgradient end of Tarbox Pond (between river mile 0.5 and 0.7). Streamflow in the Carr River then increases in the area downgradient of the pond outfall. The western unnamed tributary to the Carr River naturally loses water to the aquifer in the reach below Sweet Pond (fig. 21*C*); streamflow decreases from 1.86 ft^3/s at river mile 1.6 to 1.36 ft^3/s where it joins Capwell Mill Pond (river mile 2.5).

Contributing areas and sources of water were delineated for the public-water-supply wells and Lake Mishnock by use of the calibrated steady-state model. The contributing area of a well is the surface area of the water table where water entering the ground-water system eventually flows to the well (Franke and others, 1998). Potential sources of water to wells in the model area are precipitation and wastewater recharge, streamflow leakage from natural channel losses, streamflow leakage caused by induced infiltration, and lateral ground-water inflow from upland areas.

Contributing areas and sources of water were delineated with the computer program MODPATH (Pollock, 1994), which calculates three-dimensional flow paths from the results of the MODFLOW steady-state simulation. MODPATH uses a semi-analytical particle-tracking scheme to track the movement of hypothetical particles of water through the simulated ground-water-flow system from points of recharge to points of discharge (Pollock, 1994). MODPATH requires specification of the porosity of the aquifer for each cell of the model grid. A uniform porosity of 0.35 was specified for the stratified deposits simulated with the model. This value is based on porosity measurements made on sediment samples from the adjoining Pawcatuck River Basin (Allen and others, 1963) and for similar sediments on western Cape Cod, Massachusetts (Garabedian and others, 1991). A porosity of 1.0 was specified for the simulated ponds and lakes.

The contributing area to each well and to Lake Mishnock was delineated by overlaying an array of particles onto the simulated water table at a uniform density of four particles per model cell. Particles then were tracked from the water table to the wells and to the lake. The starting locations of those particles that reached the wells and the lake define the contributing area to these features. The combined contributing area to wells KC01 and KC02 shown in figure 22 reflects the complex hydrogeology of the flow system. These wells draw water from the till and bedrock uplands on Hungry Hill, the area around Maple Root Pond, areas near Old Hickory Brook and the Mishnock River, and an area stretching east from the northern edge of Lake Mishnock along and north of Interstate 95. Contributing areas include developed areas of the Mishnock Basin, State Route 3, and a small portion of the Interstate 95 right-of-way. The analysis of calculated streamflow depletions supports particle-tracking results because most streamflow depletions occur in areas along Old Hickory Brook, the upper reaches of the Mishnock River, and Maple Root Pond (fig. 21). These results indicate that the primary source of water to the public-supply wells in the basin largely is intercepted ground water from these areas that otherwise would flow to the streams.

The contributing area to Lake Mishnock was delineated because potential effects of different withdrawal scenarios on streamflows from the lake are an important consideration for water-supply development and because measured outflows from the lake indicates that the ground-water contributing area for the lake is much larger than the surface-water drainage area (table 3). The average measured streamflow from Lake Mishnock during the 1996–98 study period is 3.82 ft^3/s, which represents a streamflow per unit drainage area of 13.2 $ft^3/s/mi^2$ from the lake's surface-water basin (table 3). If, however, the Lake Mishnock outflow is divided by the lake's model-calculated ground-water contributing area (about 1.6 mi^2), then the resulting streamflow per unit drainage area of about 2.4 $ft^3/s/mi^2$ is much more comparable with the estimated streamflow per unit drainage area for partial-record stations in the basin (table 3) and measured streamflow per unit drainage area at streamflow-gaging stations in the study area and in nearby basins (table 2). Water from the till and bedrock uplands on Hungry Hill, the upstream end of Old Hickory Brook, and the Carr River Basin contribute ground-water discharge to the lake (fig. 22). The contributing area to the lake includes areas of the Interstate 95 right-of-way and areas where residential and commercial land uses contribute wastewater-return flow to the aquifer. Comparisons of specific-conductance data from different water-quality monitoring sites in the basin also support results of the particle-tracking analysis. Specific-conductance measurements at the Lake Mishnock outfall are three to five times higher than natural background conductance values measured at water-quality monitoring sites within the relatively pristine Big River Management Area (fig. 12).

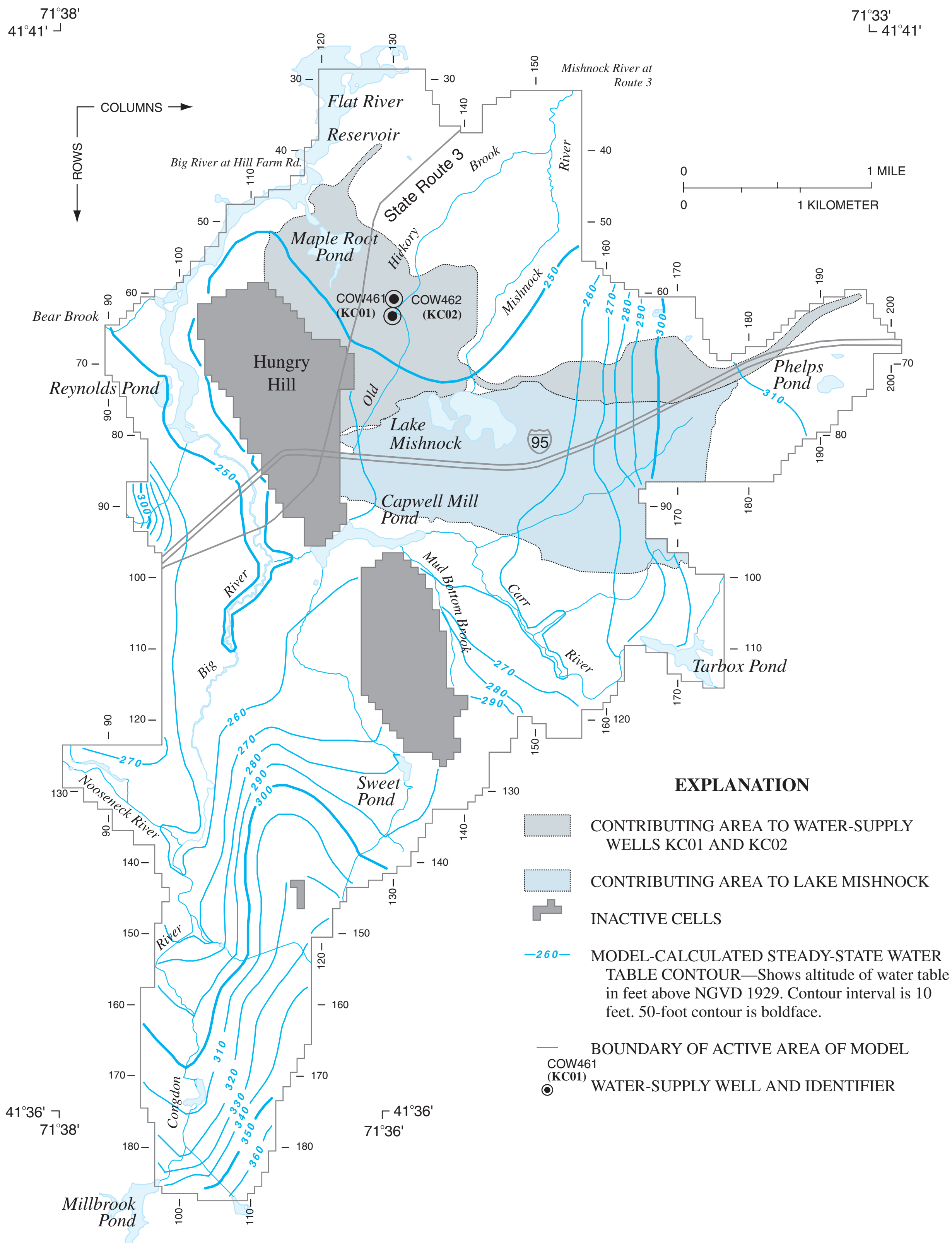


Figure 22. Model-calculated steady-state contributing areas for Lake Mishnock, Rhode Island, and for public-water-supply wells KC01 and KC02 for simulated conditions during 1964–98.

These large differences in specific conductance indicate that the water quality of the lake may be affected by runoff and recharge from areas of the Interstate 95 right-of-way and areas where residential and commercial land uses contribute wastewater-return flow to the aquifer.

Hypothetical Ground-Water Withdrawal Scenarios

Fourteen hypothetical ground-water-withdrawal scenarios were simulated to assess potential effects of different withdrawal patterns on streamflow and streamflow depletion in the Big River study area (table 10). Public water-supply withdrawals at a subset of 12 potential ground-water development sites (fig. 23) in the basin were simulated in these scenarios. The KCWA has operated or is evaluating the potential for operation of wells COW 461, COW 477, COW 482 (which is a replacement for COW 462), and (or) COW 483 in the Mishnock River Basin (Timothy Brown, Kent County Water Authority, written commun., 1999). The Rhode Island Water Supply Board is evaluating the potential for operation of wells in the Carr River Basin and the Big River Basin; these wells include three in the Carr River Basin (WGW 354, WGW 355, and WGW 374) and three wells (WGW 356, WGW 410, and WGW 411) in the Big River Basin that have been installed and tested (Craft, 2001; Stone and Dickerman, 2002). Two additional potential sites were identified from the analysis of lithologic logs taken during the drilling of observation wells (WGW 363 and WGW 366) in the Big River Basin.

Ground-water withdrawals in the Big River study area were simulated by modifying the calibrated steady-state and transient models to reflect different withdrawal scenarios. All scenarios included water-supply withdrawals at each active well at a constant rate of 1 Mgal/d throughout the year. The rate of 1 Mgal/d was assumed to be an attainable withdrawal rate from the aquifer at each site in the study area, but further testing of these sites would be required to determine the maximum sustainable withdrawal rate for an actual withdrawal well at each site. Constant withdrawal rates for each well were used in the transient scenarios for comparison of the effects of withdrawals at the well sites without dynamics induced by variable withdrawal rates at different distances from the stream. Withdrawals were simulated with the transient model for a cycle of 5 years to ensure that dynamic equilibrium was obtained in the fifth year; the results reported here are from the fifth year of simulation. Streamflows calculated for each scenario were subtracted from model-calculated predevelopment streamflows to estimate potential streamflow depletions caused by each withdrawal scenario. Wastewater-return flows simulated for the withdrawal scenarios were held constant at the rate used for simulating the 1964–98 conditions (0.4 ft^3/s) in all of the hypothetical ground-water withdrawal scenarios because it was assumed that any additional withdrawals would be exported from the basin. The application of wastewater-return flow in the study area would moderate the effect of withdrawals on streamflow depletion, but as the elevated specific-conductance values in the Mishnock River Basin (fig. 12) indicate, this return flow may reduce the quality of water in parts of the basin where return flow is applied.

Four sites were selected for the evaluation of potential streamflow depletion in each basin (fig. 23). These sites are the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River upstream of Capwell Mill Pond, and the Big River at Hill Farm Road. Streamflows out of Lake Mishnock were of interest because the lake is considered a local resource and because these streamflows help sustain habitat in the wetlands along the Mishnock River downstream of the lake. The Mishnock River site was evaluated because of the potential for adverse ecological effects from water-supply development along the reach between Lake Mishnock and the streamflow-gaging station (Camp Dresser McKee, Inc., 1999; 2000; 2001). The Carr River upstream of Capwell Mill Pond was evaluated because it is the last point along the Carr River where streamflow could be measured in a location that is east of the bedrock divide separating the Carr River Valley from the Big River Valley. The Big River at Hill Farm Road was evaluated because it represents a distinct surface-water divide between the Big River and the Flat River Reservoir, and could be affected by withdrawals in both the Big River Basin and in the Mishnock River Basin.

The steady-state model was used to calculate long-term average depletions at the four streamflow sites (fig. 24) and the total basin-wide depletion in the Big River and Mishnock River Basins (fig. 25). The transient model was used to calculate the effect of withdrawals on streamflows throughout the year (fig. 30, at back of report) and to compare the relative effect of the different scenarios on August streamflows at these four sites (fig. 26).

Table 10. Hypothetical ground-water withdrawal scenarios in the Big River study area, Rhode Island

[Wells WGW 363 and WGW 366 are small-diameter monitoring wells, not aquifer-test wells. COW, Coventry well; WGW, West Greenwich well; X, designates an active well in the scenario. ft^3/s, cubic feet per second; Mgal/d, million gallons per day]

Scenario	Mishnock River Valley wells				Carr River Valley wells			Big River Valley wells					Total withdrawal	
	COW 461	COW 477	COW 482	COW 483	WGW 354	WGW 355	WGW 374	WGW 356	WGW 363	WGW 366	WGW 410	WGW 411	Mgal/d	ft^3/s
1	X		X										2.0	3.1
2	X	X	X	X									4.0	6.2
3a	X		X	X									3.0	4.6
3b	X	X	X										3.0	4.6
4					X	X	X	X			X	X	6.0	9.3
5	X		X		X	X	X	X			X	X	8.0	12.4
6a	X		X		X	X	X	X		X	X	X	9.0	13.9
6b	X		X		X	X	X	X	X		X	X	9.0	13.9
7a	X		X	X	X	X	X	X		X	X	X	10.0	15.5
7b	X		X	X	X	X	X	X	X		X	X	10.0	15.5
8	X	X	X	X		X	X	X	X	X	X	X	11.0	17.0
9a	X		X	X			X	X	X	X	X	X	9.0	13.9
9b	X			X		X	X	X	X	X	X	X	9.0	13.9
10	X			X			X	X	X	X		X	7.0	10.8

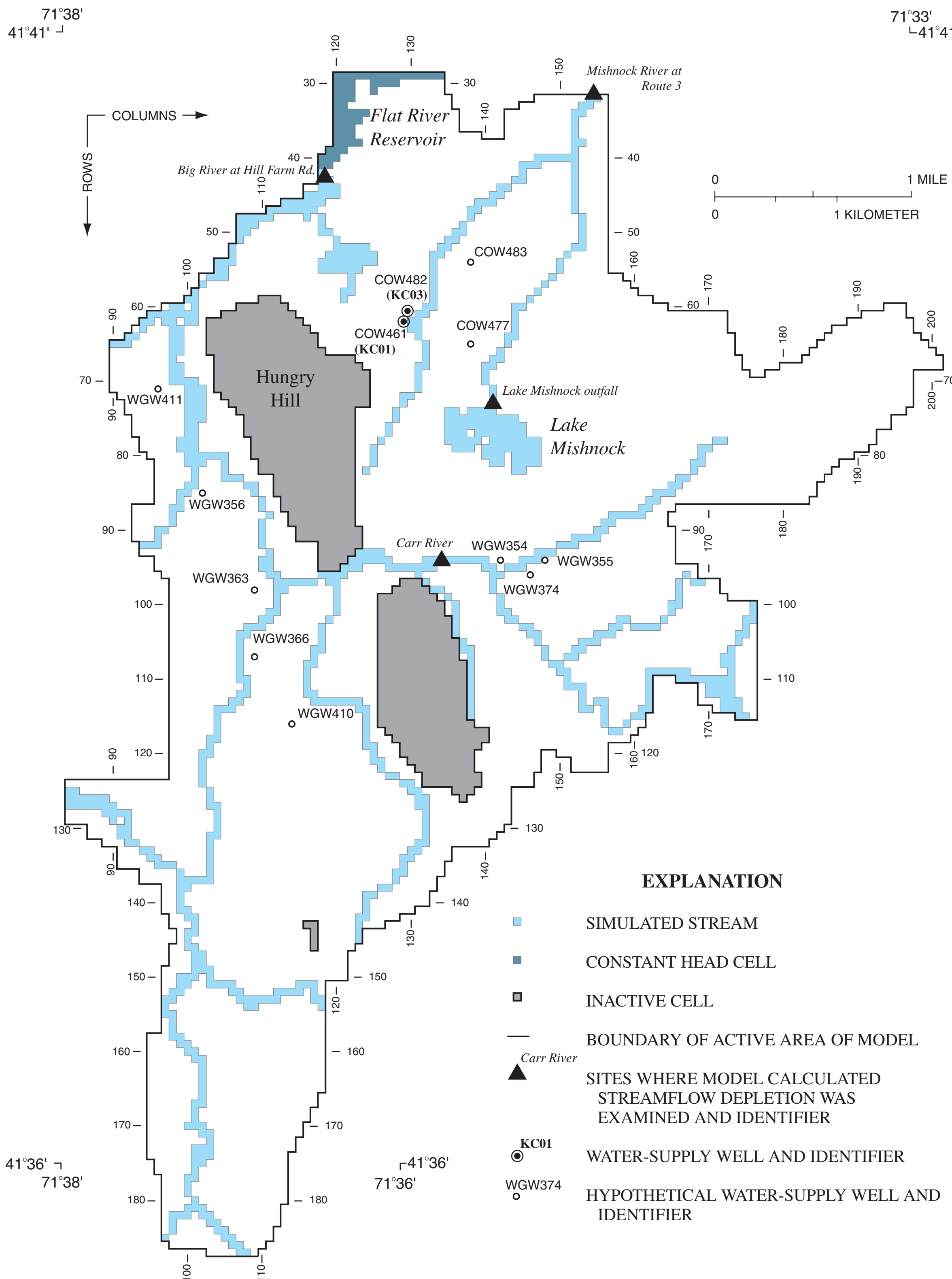


Figure 23. Location of current and hypothetical ground-water-development sites and streamflow sites selected for examination of streamflow depletion in the Big River study area, Rhode Island.

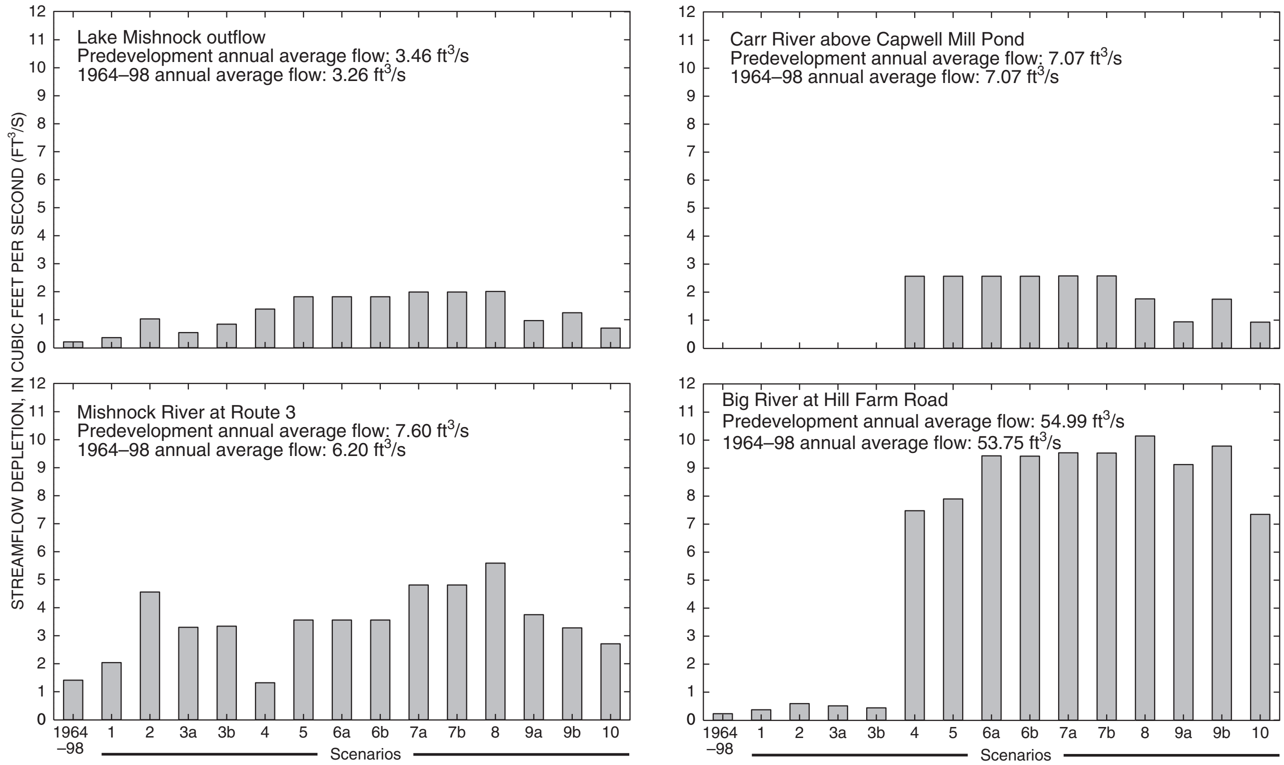


Figure 24. Model-calculated steady-state streamflow depletion at the Lake Mishnock outfall, Mishnock River Basin (at Route 3), Carr River above Capwell Mill Pond, and the Big River Basin (at Hill Farm Road) for conditions during 1964–98 and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)

Model-calculated transient results indicate a nearly constant rate of streamflow depletion at each site throughout the year for each scenario (fig. 30); however, during the period from May through October, drawdown caused by withdrawals at the wells resulted in decreased rates of evapotranspiration and, therefore, slightly smaller amounts of streamflow depletion than from November through April.

Model-calculated streamflows were compared to estimates of the U.S. Fish and Wildlife Service (1981) aquatic base-flow (ABF) criterion for August. The U.S. Fish and Wildlife Service averaged data from 48 selected USGS streamflow-gaging stations throughout New England that have at least 50 mi^2 of drainage area and 25 years of streamflow records to estimate the median of monthly average flows per unit surface-water drainage area (in cubic feet per second per square mile, $ft^3/s/mi^2$) at any ungaged site in New England. These monthly ABF criteria are used to determine the minimum allowable reservoir outflow when streamflows into the reservoir equal or exceed the calculated ABF. The August ABF criterion, which is 0.5 $ft^3/s/mi^2$, was chosen for evaluation of model results for the Big River area because high water temperatures, diminished living space, low dissolved oxygen, and reduced food supplies put substantial stresses on aquatic communities during this time of the year (U.S. Fish and Wildlife Service, 1981). Table 11 shows the August ABF, which is calculated by multiplying the value of 0.5 $ft^3/s/mi^2$ by the estimated surface-water drainage area to each site of interest. In theory, the model-calculated average August streamflow should be comparable to the August ABF because the model developed for the study area represents long-term average conditions.

Model-calculated streamflows also were compared to estimates of the 7Q10 streamflow at each site (table 11). The 7Q10 streamflow was estimated by record extension for Lake Mishnock and the Mishnock River at Route 3, and by areal extrapolation from partial-record sites (table 2) for the streamflow sites located on the Carr River above Capwell Mill Pond and on the Big River at Hill Farm Road. The 7Q10 is a 7-day drought-flow condition that has a 10-percent chance of occurring in any given year and commonly is expected to occur, on

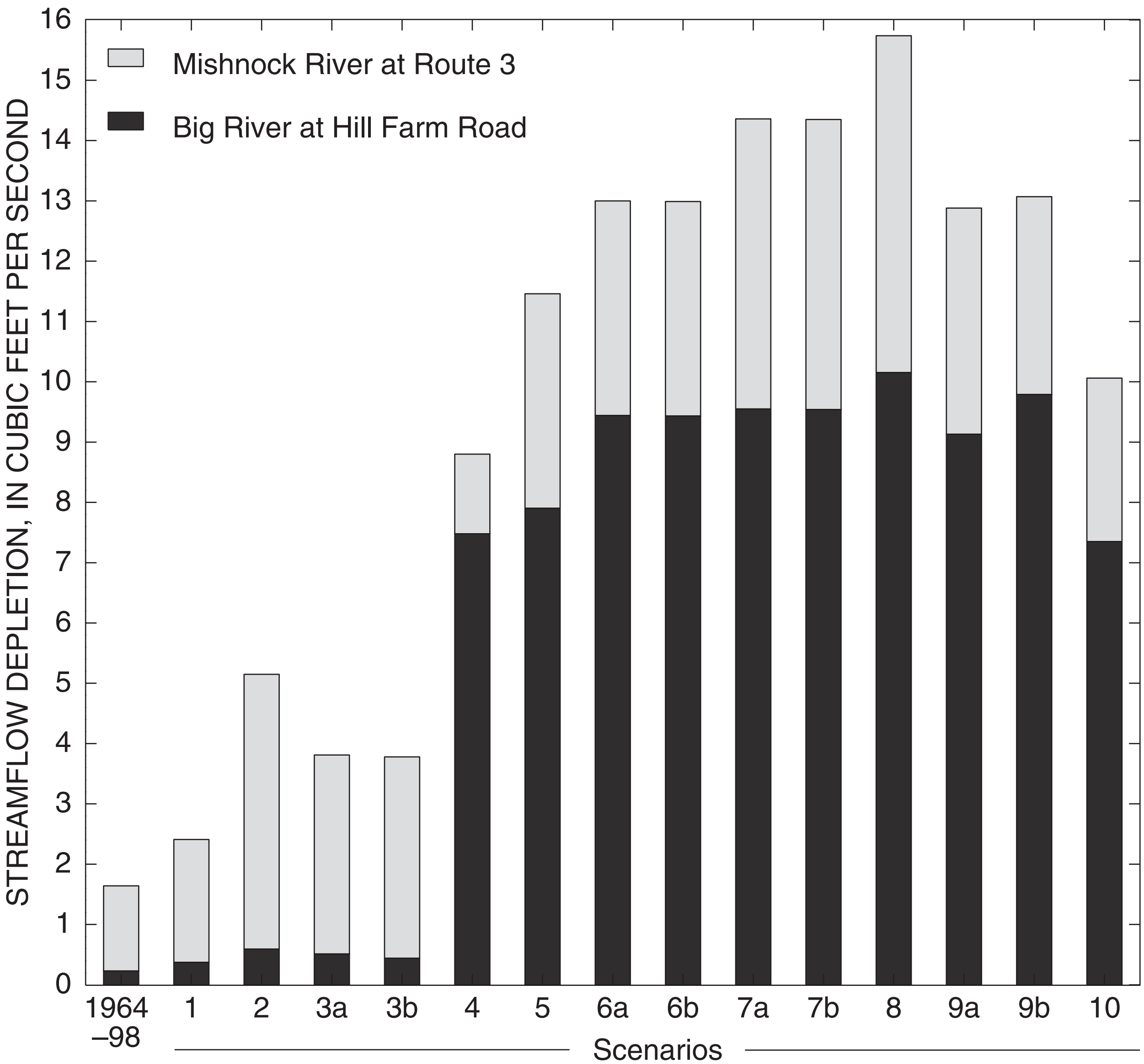


Figure 25. Total model-calculated steady-state streamflow depletion for the Mishnock River Basin (at Route 3), and the Big River Basin (at Hill Farm Road) for conditions during 1964–98 and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)

average, once every 10 years for a natural stream. Therefore, comparisons between the results of model simulations and the estimated 7Q10 streamflows indicate the likelihood that withdrawals may cause drought-like streamflows in the "normal year."

Standard analysis with either the ABF or the 7Q10 does not readily apply to the hydrology of Lake Mishnock. The U.S. Fish and Wildlife Service (1981) August ABF criterion is based on the surface-water drainage area, which for Lake Mishnock is substantially smaller than the ground-water contributing area. Therefore, the estimated ABF for this site (0.15 ft^3/s) does not reflect the historical median of average August streamflows. If an ABF based on the estimated ground-water contributing area (1.6 mi^2, which includes part of the surface-water drainage area of the Carr River Basin) is used, then this estimated value (0.8 ft^3/s) still is less than half of the estimated 7Q10 streamflow (estimated with the MOVE.1 method) for the lake (1.92 ft^3/s; table 10).

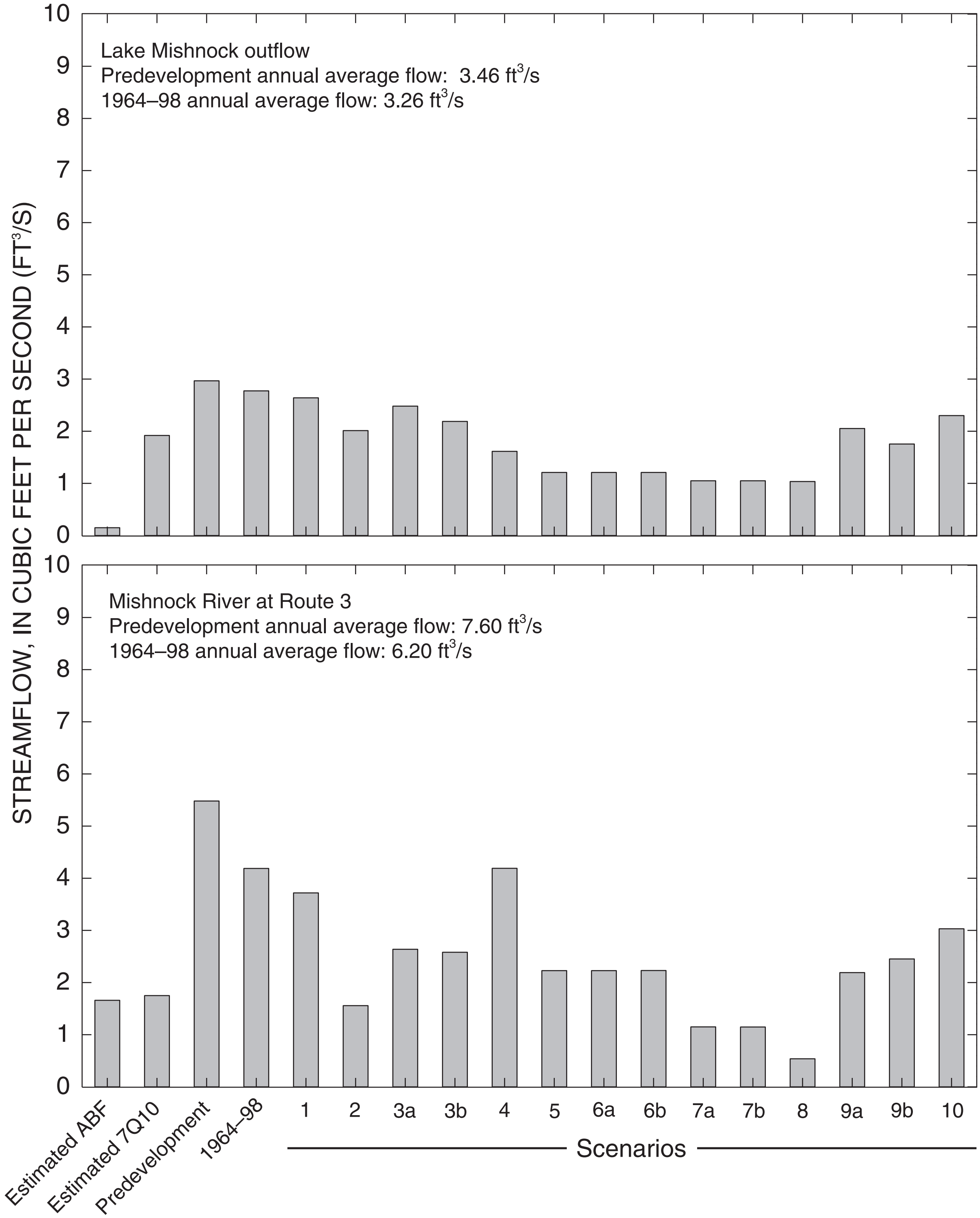


Figure 26. Model-calculated monthly average August streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow sites shown on fig. 23; withdrawal scenarios described in table 10.)

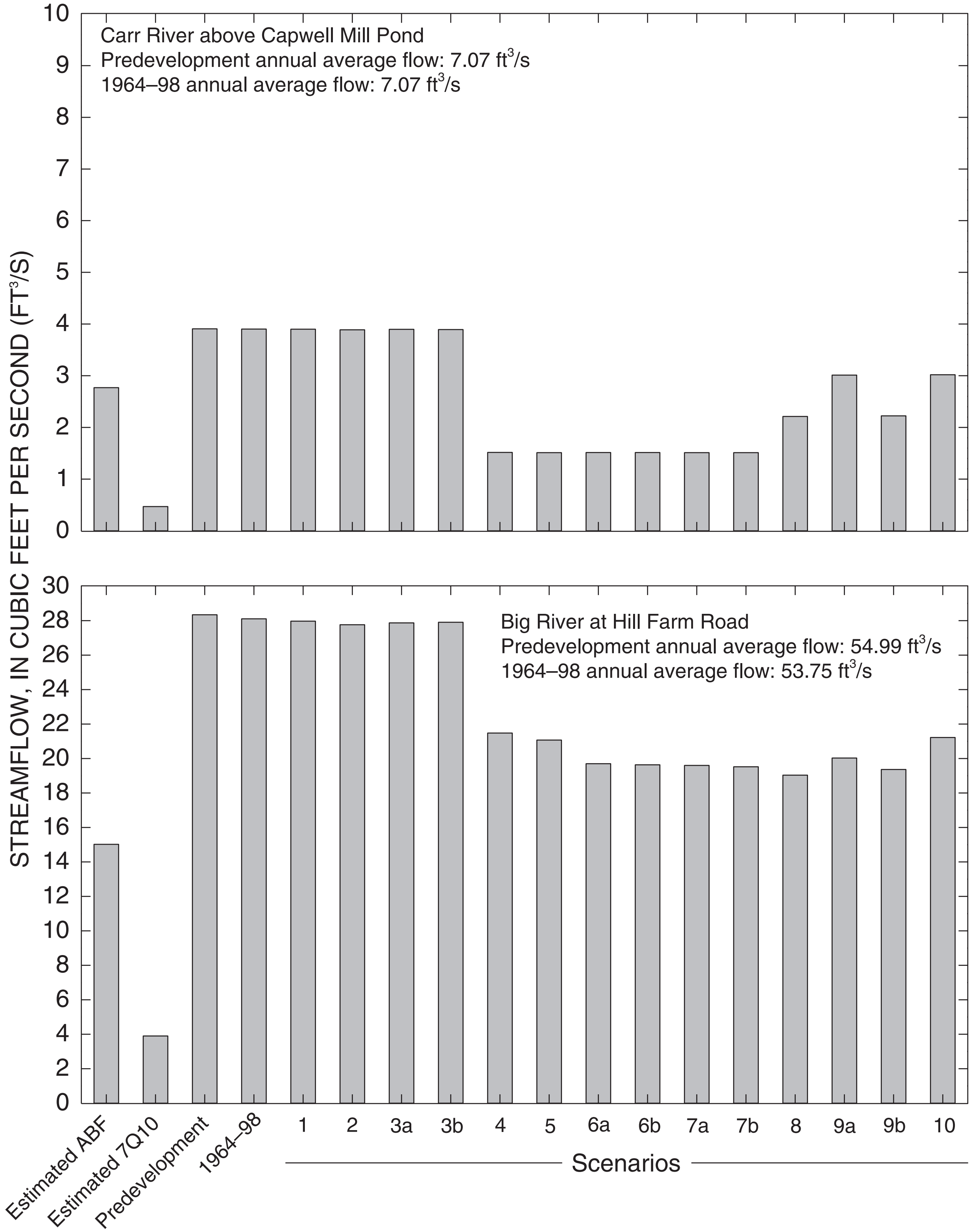


Figure 26—*Continued.* Model-calculated monthly average August streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow sites shown on fig. 23; withdrawal scenarios described in table 10.)

Table 11. Estimated aquatic base flow, 7-day 10-year low flow, and model-calculated transient streamflows for August for withdrawal scenario evaluation in the Big River study area, Rhode Island

[ABF, Aquatic Base Flow, U.S. Fish and Wildlife Service (1981) New England minimum August streamflow of 0.5 $ft^3/s/mi^2$; 7Q10, the 7-day 10-year low flow (7Q10) is the minimum 7-day average flow that has a 10-percent chance of occurring in any given year. Estimated by record extension for Lake Mishnock and the Mishnock River at Route 3, estimated by areal extrapolation from partial-record sites (table 2) for the Carr River above Capwell Mill Pond and the Big River at Hill Farm Road; CI, 95-percent confidence interval of the estimate. All flows are in cubic feet per second]

Site	Estimated low-flow criteria			Model-calculated long-term average August flow	
	ABF	7Q10	CI for 7Q10	Predevelopment	1964–98
Lake Mishnock outfall	0.15	1.92	1.61–2.30	2.97	2.77
Mishnock River	1.66	1.75	1.54–1.99	5.48	4.19
Carr River	2.77	.47	0.3–0.7	3.91	3.90
Big River	15.44	3.90	3.1–4.7	28.35	28.11

Similarly, the surface-water drainage-area-based ABF for the Mishnock River streamflow-gaging station (1.66 ft^3/s) is less than the estimated 7Q10 (1.75 ft^3/s) because the estimated ABF does not account for the substantial ground-water drainage to this basin from the Carr River Basin. The estimated 7Q10 streamflow for the partial-record streamflow-gaging station at the Lake Mishnock outfall is greater than the estimated 7Q10 streamflow for the downstream partial-record streamflow-gaging station on the Mishnock River at Route 3; this indicates that the characteristics of the long-term-record streamflow-gaging stations (table 2) that were used to estimate streamflow statistics for the partial-record sites in the study area (table 3) are not representative of the unique hydrologic characteristics of Lake Mishnock. Comparisons of long-term and partial-record estimates for the Carr River and Nooseneck River streamflow-gaging stations, however, indicate that 7Q10 estimates for the other partial-record sites are reasonable for streams in the study area.

The following paragraphs describe the effects of each particular withdrawal scenario on streamflows in each basin. Table 10, which is organized by river basin, is a list of withdrawal-well sites used in each scenario and the total withdrawal rate for each scenario. Figure 23 indicates the locations of these withdrawal-well sites within the model area. The effects of withdrawals in each basin are evaluated in relation to the August ABF and the 7Q10, but these evaluations must be considered in light of the limitations of the area-based ABF and the fact that the 7Q10 streamflows represent drought conditions, whereas the models simulate average hydrologic conditions.

Scenario 1: This scenario is similar to, but more intensive than, the 1964–98 withdrawal pattern in that a total of 2 Mgal/d (3.1 ft^3/s) was withdrawn from wells in the Mishnock River Basin (table 10, fig. 23). Model-calculated steady-state results indicate depletions of 0.36 ft^3/s at the Lake Mishnock outfall, 2.04 ft^3/s in the Mishnock River at Route 3, and 0.37 ft^3/s in the Big River at Hill Farm Road (fig. 24). This scenario also indicates that withdrawals totaling 2 Mgal/d in the Mishnock Basin do not affect streamflow in the Carr River Basin (figs. 24 and 30). Model-calculated transient streamflows for August indicate that withdrawals in the Mishnock Basin do not deplete these simulated streamflows below either the estimated ABF or the estimated 7Q10 at the four sites (fig. 26).

Scenario 2: This scenario was used to evaluate potential effects of a total withdrawal rate of 4 Mgal/d (6.2 ft^3/s) from the four KCWA wells in the Mishnock River Basin (table 10, fig. 23). Model-calculated steady-state results indicate depletions of 1.03 ft^3/s at the Lake Mishnock outfall, 4.56 ft^3/s in the Mishnock River at Route 3, and 0.59 ft^3/s in the Big River at Hill Farm Road (fig. 24). This scenario also indicates that withdrawals totaling 4 Mgal/d in the Mishnock Basin do not affect streamflow in the Carr River Basin (figs. 24 and 30). This level of water-supply development does not deplete model-calculated transient streamflows for August below either the estimated ABF or the estimated 7Q10 for the Carr River, the Big River, or Lake Mishnock outflow (fig. 26). The model-calculated transient streamflow in the Mishnock River at Route 3 (1.6 ft^3/s), however, is slightly below both the estimated 7Q10 (1.75 ft^3/s) and the estimated ABF (1.66 ft^3/s).

Scenarios 3A and 3B: These two scenarios were used to evaluate the effect of withdrawal-well location on streamflow depletions with a total withdrawal rate of 3 Mgal/d (4.6 ft^3/s) in the Mishnock River Basin (table 10, fig. 23). Withdrawals in scenario 3A (with COW 483) and 3B (with COW 477) result in steady-state depletions of 0.54 and 0.84 ft^3/s at the Lake Mishnock outfall, respectively. The primary effect of both withdrawal scenarios is observed as a depletion of about 3.3 ft^3/s in the Mishnock River at Route 3 (fig. 24). COW 483 is farther away from Lake Mishnock and closer to the Big River and the Flat River Reservoir north of Hill Farm Road than COW 477; therefore, withdrawals from COW 483 have less effect on Lake Mishnock and more effect on the Big River and the Flat River Reservoir than withdrawals from COW 477 (fig. 24). Neither of these ground-water withdrawal scenarios depletes model-calculated transient streamflows for August below the estimated ABF or the estimated 7Q10 for any of the four sites (fig. 26).

Scenario 4: This scenario was used to evaluate the potential for withdrawals of 3 Mgal/d (4.6 ft^3/s) in the Carr River Basin and 3 Mgal/d (4.6 ft^3/s) in the Big River Basin (table 10, fig. 23). Model-calculated steady-state results indicate streamflow depletions of 1.38 ft^3/s at the Lake Mishnock outfall, 1.32 ft^3/s in the Mishnock River at Route 3, 2.57 ft^3/s at the Carr River site, and 7.48 ft^3/s in the Big River at Hill Farm Road (fig. 24). These withdrawals do not deplete model-calculated transient streamflows for August below the estimated ABF for the Lake Mishnock outfall, the Mishnock River, or the Big River (fig. 26). The model-calculated transient streamflow (1.52 ft^3/s) for the Carr River, however, is below the estimated ABF of 2.77 ft^3/s. Ground-water withdrawals simulated in scenario 4 do not deplete August streamflows below estimated 7Q10 flows for the Carr, the Big, or the Mishnock Rivers (fig. 26). The model-calculated streamflow for August (1.62 ft^3/s) at the Lake Mishnock outfall is below the estimated 7Q10 for this site (table 11). Results of scenario 4, therefore, indicate that withdrawals of 3 Mgal/d (4.6 ft^3/s) in the Carr River Basin intercept ground water that otherwise would discharge to Lake Mishnock. Streamflows in the Big River, however, are sufficient to support upstream withdrawals of 6 Mgal/d (4.6 ft^3/s) even as streamflow from the Carr River is depleted.

Scenario 5: This scenario was used to evaluate the potential for withdrawals of 2 Mgal/d (3.1 ft^3/s) in the Mishnock River Basin, 3 Mgal/d (4.6 ft^3/s) in the Carr River Basin, and 3 Mgal/d (4.6 ft^3/s) in the Big River Basin (table 10, fig. 23). Model-calculated steady-state results indicate streamflow depletions of 1.82 ft^3/s at the Lake Mishnock outfall, 3.56 ft^3/s in the Mishnock River at Route 3, 2.57 ft^3/s at the Carr River site, and 7.90 ft^3/s in the Big River at Hill Farm Road (fig. 24). These withdrawals deplete model-calculated transient streamflows for August below the estimated ABF for the Carr River site and below the estimated 7Q10 flow requirement for the Lake Mishnock outflow (fig. 26). Therefore, withdrawals in the Carr River Basin intercept ground water that otherwise would discharge to Lake Mishnock, but the combined withdrawals do not deplete model-calculated transient streamflows for August below the ABF or the 7Q10 in the Mishnock River at Route 3.

Scenarios 6A and 6B: These scenarios are identical to scenario 5 except that an additional well site was used for public water-supply withdrawals in the Big River Basin. Total withdrawal rates of 2 Mgal/d (3.1 ft^3/s) in the Mishnock River Basin, 3 Mgal/d (4.6 ft^3/s) in the Carr River Basin, and 4 Mgal/d (6.2 ft^3/s) in the Big River Basin were specified (table 10, fig. 23). Scenarios 6A and 6B include withdrawals at well sites WGW 366 and WGW 363, respectively. The results for the Carr River above Capwell Mill Pond and the Mishnock River Basin are identical to results for scenario 5; these results indicate that the increased withdrawal in the Big River Valley does not affect streamflows in the Mishnock River Basin or the Carr River Basin in the area east of Capwell Mill

Pond. Model-calculated steady-state results indicate that withdrawals from either well site WGW 366 or WGW 363 generate a model-calculated long-term-average depletion of about 9.43 ft^3/s in the Big River at Hill Farm Road (fig. 24). Neither of these ground-water withdrawal scenarios, however, depletes model-calculated transient streamflows for August below the estimated ABF or the estimated 7Q10 in the Big River at Hill Farm Road (fig. 26).

Scenarios 7A and 7B: These scenarios are identical to scenarios 6A and 6B, except that an additional well site (COW 483) was utilized for public water-supply withdrawals in the Mishnock River Basin. Total withdrawal rates of 3 Mgal/d (4.6 ft^3/s) in the Mishnock River Basin, 3 Mgal/d (4.6 ft^3/s) in the Carr River Basin, and 4 Mgal/d (6.2 ft^3/s) in the Big River Basin were specified (table 10, fig. 23). Scenarios 7A and 7B were done to examine the effect of withdrawals from COW 483, which is nearest to Hill Farm Road, on streamflow depletions in the Big River Basin. Scenarios 7A and 7B include withdrawals at well sites WGW 366 and WGW 363, respectively (fig. 23). Model-calculated steady-state results indicate depletions of 2.58 ft^3/s at the Carr River site, about 9.55 ft^3/s in the Big River at Hill Farm Road, 1.99 ft^3/s at the Lake Mishnock outfall, and 4.81 ft^3/s in the Mishnock River at Route 3 (fig. 24). The model-calculated transient streamflow for August is above the estimated 7Q10, but below the estimated ABF at the Carr River site. Model-calculated transient streamflow for August is well above these limits at the Big River site. It is above the ABF but below the 7Q10 at the Lake Mishnock outfall and is below both minimum streamflow requirements in the Mishnock River at Route 3 (fig. 26). Furthermore, flows are below the estimated 7Q10 streamflows for Lake Mishnock, the Mishnock River, and the Carr River for much of the summer and early fall (fig. 30). Therefore, the choice of the development site in the Big River Basin is of little consequence to streamflow requirements at Farm Hill Road.

Scenario 8: This scenario had the maximum withdrawal rate that was tested (11.0 Mgal/d), which included withdrawals of 4 Mgal/d (6.2 ft^3/s) in the Mishnock River Basin, 2 Mgal/d (3.1 ft^3/s) in the Carr River Basin, and 5 Mgal/d (7.7 ft^3/s) in the Big River Basin (table 10, fig. 23). Model-calculated steady-state results indicate a depletion of 1.76 ft^3/s at the Carr River site, 10.15 ft^3/s in the Big River at Hill Farm Road, 2.01 ft^3/s at the Lake Mishnock outfall, and 5.59 ft^3/s in the Mishnock River at Route 3 (fig. 24). Model-calculated transient streamflow for August is above the estimated 7Q10, but below the estimated ABF at the Carr River site. Model-calculated transient streamflow for August is well above these limits at the Big River site. It is above the ABF, but below the 7Q10 at the Lake Mishnock outfall, and is below both minimum streamflow requirements in the Mishnock River at Route 3 (fig. 26). Furthermore, model-calculated transient streamflows in scenario 8 are below estimated 7Q10 estimates for Lake Mishnock and the Mishnock River sites for much of the summer and early fall (fig. 30). Depletions below the ABF and 7Q10 indicate that withdrawals of 2 Mgal/d (3.1 ft^3/s) from wells in the Carr River Basin deplete the Carr River and intercept water that would flow to Lake Mishnock.

Scenarios 9A and 9B: These two scenarios were used to simulate a total of 4 Mgal/d (6.2 ft^3/s) from the combined Carr River and Mishnock River Basins and 5 Mgal/d (7.7 ft^3/s) from the Big River Basin (table 10, fig. 23). Scenario 9A includes a total withdrawal rate of 3 Mgal/d (4.6 ft^3/s) in the Mishnock River Basin and 1 Mgal/d (1.5 ft^3/s) in the Carr River Basin, whereas scenario 9B includes a total withdrawal rate of 2 Mgal/d (3.1 ft^3/s) in the Mishnock River Basin and 2 Mgal/d (4.6 ft^3/s) in the Carr River Basin. Results of these withdrawal scenarios indicate moderate levels of model-calculated steady-state streamflow depletion at the selected sites (fig. 24). Model-calculated transient streamflow for August at the Carr River site is above the ABF for scenario 9A, but below the ABF for 9B (fig. 26); this result indicates that the development potential in the Carr River Basin is limited. Model-calculated transient streamflows for August are above the ABF at the other three sites (fig. 26). This result indicates that the Mishnock River Basin, which receives underflow from the Carr River Basin, has more potential for development. Model-calculated transient streamflows for August at the Big

River at Hill Farm Road are above both the ABF and the 7Q10 in scenarios 9A and 9B; these results indicate that 5 Mgal/d can be withdrawn from the Big River Basin.

More detailed analysis, however, indicates that scenarios 9A and 9B may cause streamflow depletions at other sites within each basin. Withdrawals of 5 Mgal/d all year in the Big River Basin may cause depletions in the western unnamed tributary to the Carr River (fig. 27*A*); this tributary flows through Sweet Pond and into Capwell Mill Pond. These depletions may reduce streamflow measured at the Carr River streamflow-gaging station (station 01115770) below the ABF. Withdrawals in the Mishnock River Basin affect streamflow in Old Hickory Brook wetland area (fig. 27*B*) by reducing total streamflows and decreasing the length of the active stream channel. It should be noted, however, that transient model runs indicate that some tributary streams in the basin may be naturally intermittent or discontinuous during dry months, even under predevelopment conditions.

Scenario 10: This scenario was used to simulate withdrawals of 2 Mgal/d (3.1 ft^3/s) in the Mishnock River Basin, 1 Mgal/d (1.5 ft^3/s) in the Carr River Basin, and 4 Mgal/d (6.2 ft^3/s) in the Big River Basin (table 10, fig. 23). Scenario 10 is based on the assumption that at least one well would be located in each of the three basins and was used to evaluate effects of withdrawals in light of potential concerns identified in scenarios 9A and 9B. Model-calculated steady-state results indicate a depletion of 0.93 ft^3/s at the Carr River site, about 7.35 ft^3/s in the Big River at Hill Farm Road, 0.7 ft^3/s at the Lake Mishnock outfall, and 2.71 ft^3/s in the Mishnock River at Route 3 (fig. 24). Model-calculated transient streamflow for August is above the estimated ABF and 7Q10 for all four sites (fig. 26). Further investigation reveals that substantial streamflows are maintained in the principal streams (those that are not intermittent or discontinuous in the predevelopment scenario) throughout the basin (fig. 28). Withdrawals from WGW 410 in scenarios 9A and 9B cause substantial streamflow depletion in the western unnamed tributary to the Carr River (fig. 27*A*) and, therefore, cause streamflow depletion in the Carr River downstream of Capwell Mill Pond. Results of scenario 10, which do not include withdrawals from WGW 410, indicate that the other wells in the Big River Valley do not have a substantial effect on streamflow in the western unnamed tributary to the Carr River (fig. 28*C*) or in the Carr River downstream of Capwell Mill Pond (fig. 28*B*).

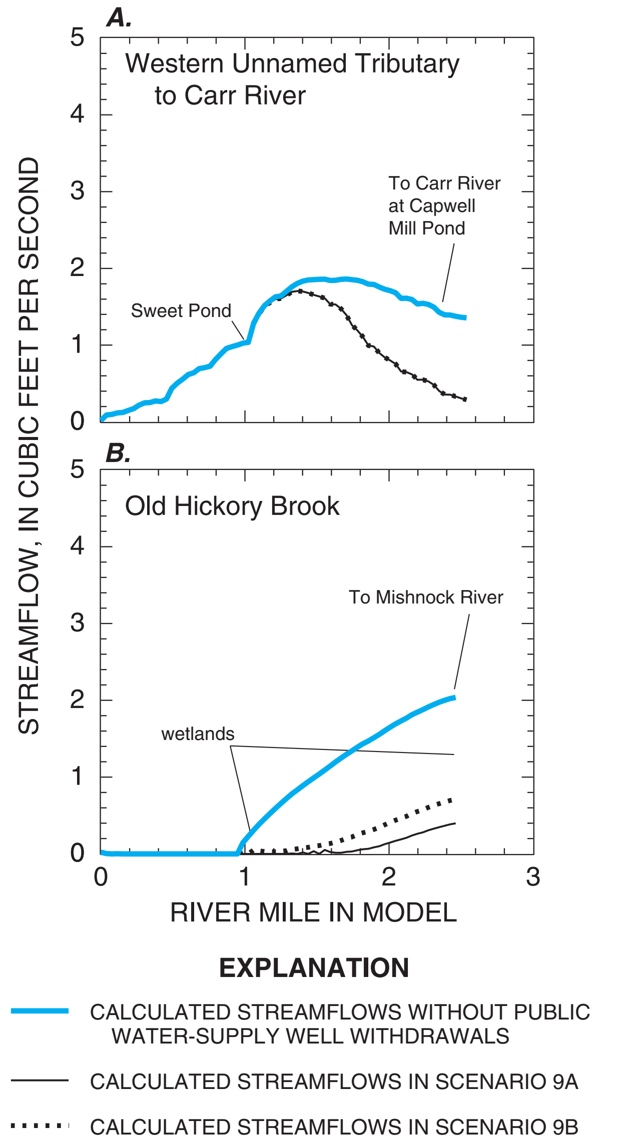


Figure 27. Model-calculated steady-state streamflows and streamflow depletions in scenarios 9A and 9B for the (*A*) western unnamed tributary to the Carr River and (*B*) Old Hickory Brook, Rhode Island. (Streamflows calculated for model cells along the centerlines of on-stream ponds were used.)

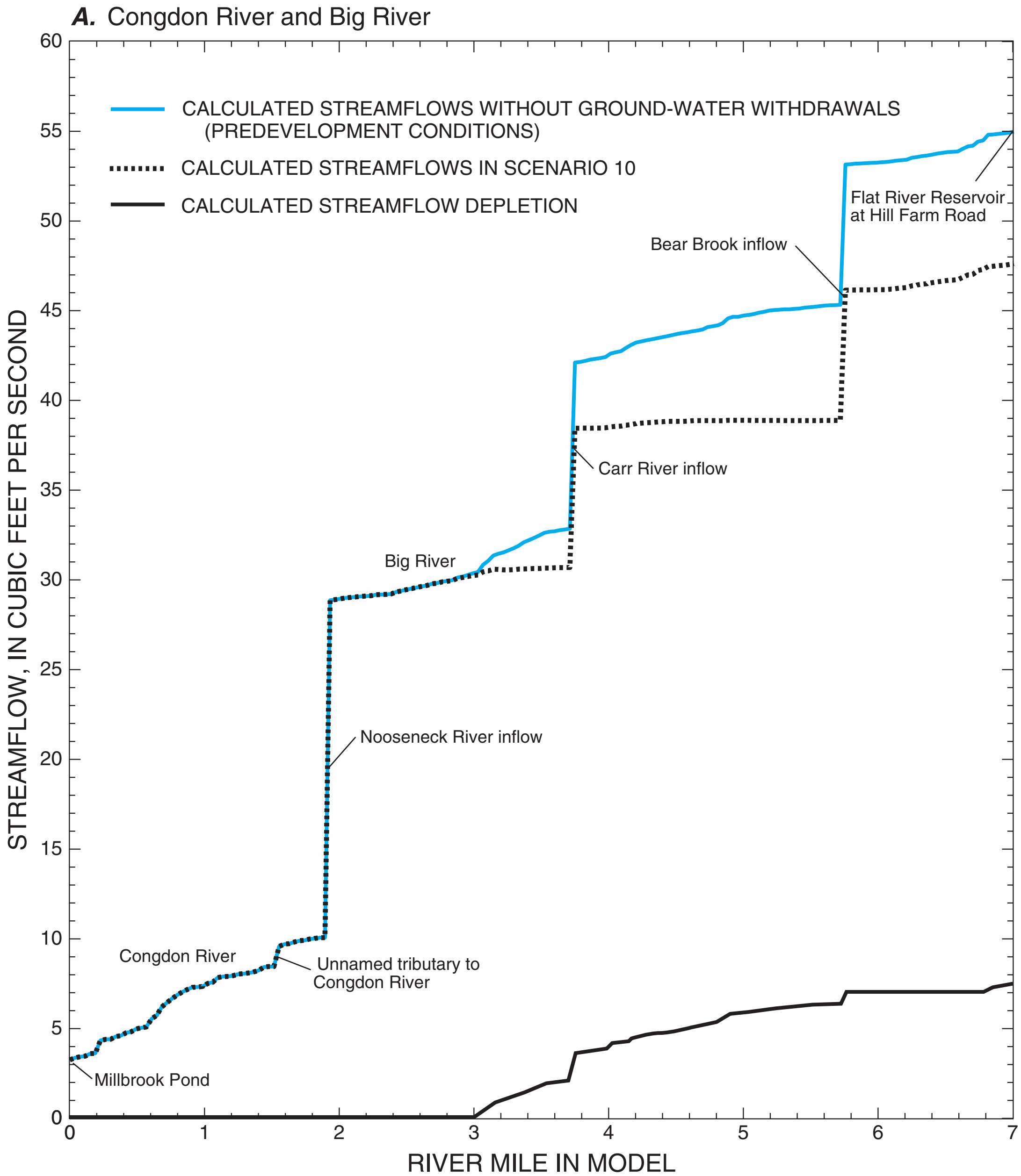


Figure 28. Model-calculated steady-state streamflows and streamflow depletions for scenario 10 in the (*A*) Congdon and Big Rivers, (*B*) Carr River, (*C*) western unnamed tributary to the Carr River, (*D*) Mishnock River, and (*E*) Old Hickory Brook, Rhode Island. (Streamflows calculated for model cells along the centerline of on-stream ponds were used.)

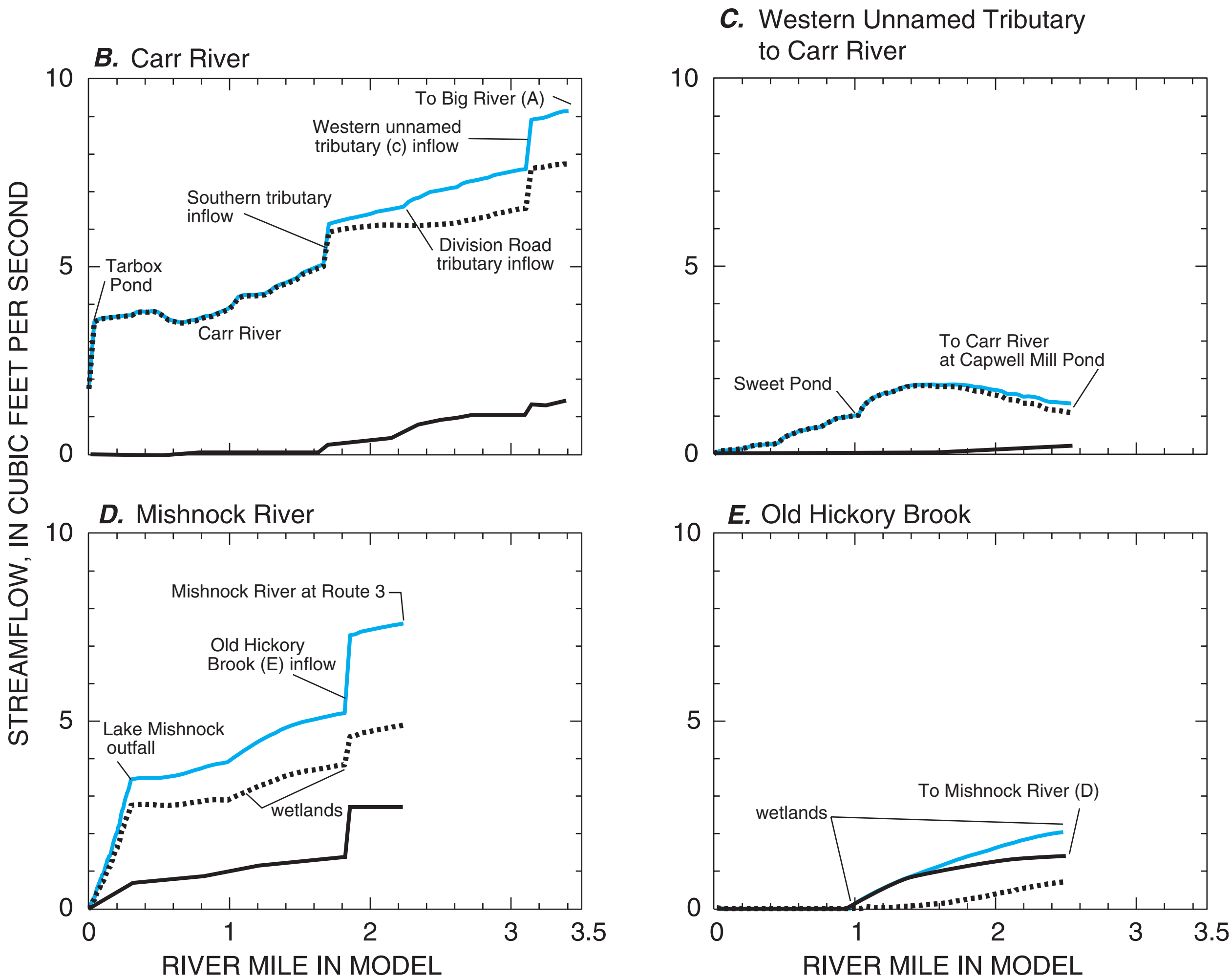


Figure 28—*Continued.* Model-calculated steady-state streamflows and streamflow depletions for scenario 10 in the (*A*) Congdon and Big Rivers, (*B*) Carr River, (*C*) western unnamed tributary to the Carr River, (*D*) Mishnock River, and (*E*) Old Hickory Brook, Rhode Island. (Streamflows calculated for model cells along the centerline of on-stream ponds were used.)

SUMMARY AND CONCLUSIONS

The Rhode Island Water Resources Board (RIWRB) is responsible for developing and protecting the State's major water resources. Water demand in Rhode Island is increasing and the RIWRB is concerned that this continued demand may exceed the capacity of current water supplies. Ground-water withdrawals from the Big River study area averaged about 1.4 Mgal/d during the 1964–98 period, and additional withdrawals have been proposed to meet growing demands in central Rhode Island. Nearly all of the ground water withdrawn is derived from depletion of streamflow in the rivers, brooks, and ponds that overlie the surficial aquifer. Concerns regarding the effects of additional ground-water withdrawals on streamflow depletions prompted an investigation to better describe water resources in the area. The U.S. Geological Survey, in cooperation with the RIWRB, has characterized the hydrogeology of the basin and simulated potential effects of water-supply development in the basin.

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. The area includes the Big River drainage basin upstream (south) of Hill Farm Road (30.9 mi^2). The Carr River, the Congdon River, and the Nooseneck River are tributaries to the Big River. The Big River study area also includes the part of the Mishnock River drainage basin that is upstream from a USGS partial-record-gaging station at State Route 3 (3.3 mi^2) and uplands and stratified deposits contributing to the Flat River Reservoir north of Hill Farm Road (1.5 mi^2). The basin includes upland areas composed of till, bedrock, and thinly saturated stratified deposits. Within the Big River and Mishnock River Basins, upland areas that are drained by rivers and streams cover an area of 15.2 mi^2 and upland areas drained by subsurface flow or overland runoff cover an area of 8.1 mi^2. The surficial aquifer (where stratified deposits have a saturated thickness of more than 10 ft) covers about 10.9 mi^2.

During 1964–98 the total annual precipitation to the 34.2 mi^2 area of the Big River and Mishnock River Basins is estimated to have been about 126 ft^3/s, based on the average annual precipitation rate of 50.3 in/yr measured at the Kingston climatological station. In comparison, the total average annual streamflow for the period is estimated to have been about 70 ft^3/s, with ground-water withdrawals averaging 2.2 ft^3/s and wastewater-return flows estimated as averaging 0.4 ft^3/s during this period.

Steady-state and transient numerical models were developed to simulate ground-water flow and interactions between ground-water and surface-water bodies in the study area. The models are representative of average withdrawal and hydrologic conditions during 1964–98. The steady-state model simulates long-term-average hydrologic stresses, whereas the transient model simulates an average annual cycle of monthly hydrologic stresses. The long-term-average total-flow rate through the system calculated with the steady-state model was about 67 ft^3/s, which is close to the flow rate of about 75 ft^3/s estimated independently from hydrologic and water-use data. The models, however, do not simulate direct runoff within the modeled area (about 8 ft^3/s), which partly explains the lower flow rate calculated by the steady-state model. The models were used to estimate rates of streamflow depletion caused by ground-water withdrawals at two public water-supply wells during 1964–98. Streamflow-depletion rates (about 1.6 ft^3/s for the combined Mishnock and Big River Basins) calculated by the steady-state model for the long-term-average conditions were nearly equal to the average annual rates calculated with the transient model and were about 70 percent of withdrawals during the 1964–98 period. These withdrawals are offset by the wastewater-return flows (about 18 percent of withdrawals) and reductions in evapotranspiration from riparian wetland areas (about 12 percent of withdrawals).

Contributing areas to the two supply wells and Lake Mishnock were delineated by use of the steady-state model. The Kent County water-supply wells draw water from the till and bedrock uplands on Hungry Hill, the area around Maple Root Pond, areas near Old Hickory Brook and the Mishnock River, and an area stretching east from the northern edge of Lake Mishnock along and north of Interstate 95. Contributing areas include developed areas of the Mishnock Basin, State Route 3, and a small portion of the Interstate 95 right-of-way. Water from the till and bedrock uplands on Hungry Hill, the upstream end of Old Hickory Brook, and the Carr River Basin contribute ground-water discharge to the Lake Mishnock. The contributing area to the lake includes areas of the Interstate 95 right-of-way and areas where residential and commercial land uses contribute wastewater-return flow to the aquifer.

Fourteen hypothetical ground-water withdrawal scenarios with total ground-water withdrawal rates that ranged from 2 to 11 Mgal/d were simulated to assess potential effects of withdrawals on streamflows in the study area. Ground-water withdrawals in the Big River study area were simulated by modifying the calibrated steady-state and transient models to reflect different withdrawal scenarios. To give the different withdrawal scenarios a common basis for comparison, it was necessary to simulate predevelopment conditions, in which there were no withdrawals or wastewater recharge. All scenarios included water-supply withdrawals at each simulated well at a constant rate of 1 Mgal/d. Streamflows at the selected sites are compared to the U.S. Fish and Wildlife Service New England aquatic base flow (ABF) criterion of 0.5 $ft^3/s/mi^2$ in August. August streamflows from the transient model are examined because high water temperatures, diminished living space, low dissolved oxygen, and reduced food supplies represent substantial stress on aquatic communities. Effects of withdrawals on streamflows in August also are evaluated by comparing these scenarios to estimates of the 7-day 10-year low flow (7Q10), which indicates the likelihood that withdrawals may cause drought-like streamflow conditions in the "normal year."

Examination of the simulation results indicates that the surficial aquifer is a single ground-water resource in the Big River area, and that development in one river basin can affect the hydrology of the other river basins in the Big River area. For example, precipitation recharge in the Carr River Basin naturally flows through the surficial aquifer to discharge in the Mishnock River Basin. A till-and-bedrock ridge separates the Big River aquifer from the Mishnock River Basin south of Harkney Hill Road and separates the Big River aquifer from the Carr River Basin upstream of Capwell Mill Pond. The western unnamed tributary to the Carr, however, is in the Big River Valley and naturally loses water to the Big River aquifer. Withdrawals from the Big River aquifer, therefore, do not affect streamflows in the Mishnock River Basin or the Carr River Basin upstream of Capwell Mill Pond. Withdrawals from wells in the Mishnock basin, however, have a limited effect on the Big River outflow at Hill Farm Road because these wells intercept water that otherwise would flow to Maple Root Pond and the Big River in the area north of Hungry Hill.

There are many potentially viable options for developing ground-water supplies in the Mishnock River, Carr River, and Big River Basins. Examination of the constant-rate withdrawal scenarios provides insight about the potential magnitude of withdrawal effects in each basin. Model-calculated streamflow depletions indicate total limits on ground-water withdrawals and potential problem areas within each of the surface-water basins. For example, maximum annual public water-supply demand generally occurs during the dry summer months. Dry-period (July through September) streamflow criteria limit ground-water withdrawals in all three surface-water basins. Streamflow limits in the Big River study area, however, are based on estimates from partial-record data because long-term streamflow data are currently (2003) not available in the study area. Therefore, establishing continuous-record gaging stations on the Big River, the Mishnock River, and the Carr River would provide data that would be helpful in the management of the ground-water resources in these basins.

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Figures 29 and 30

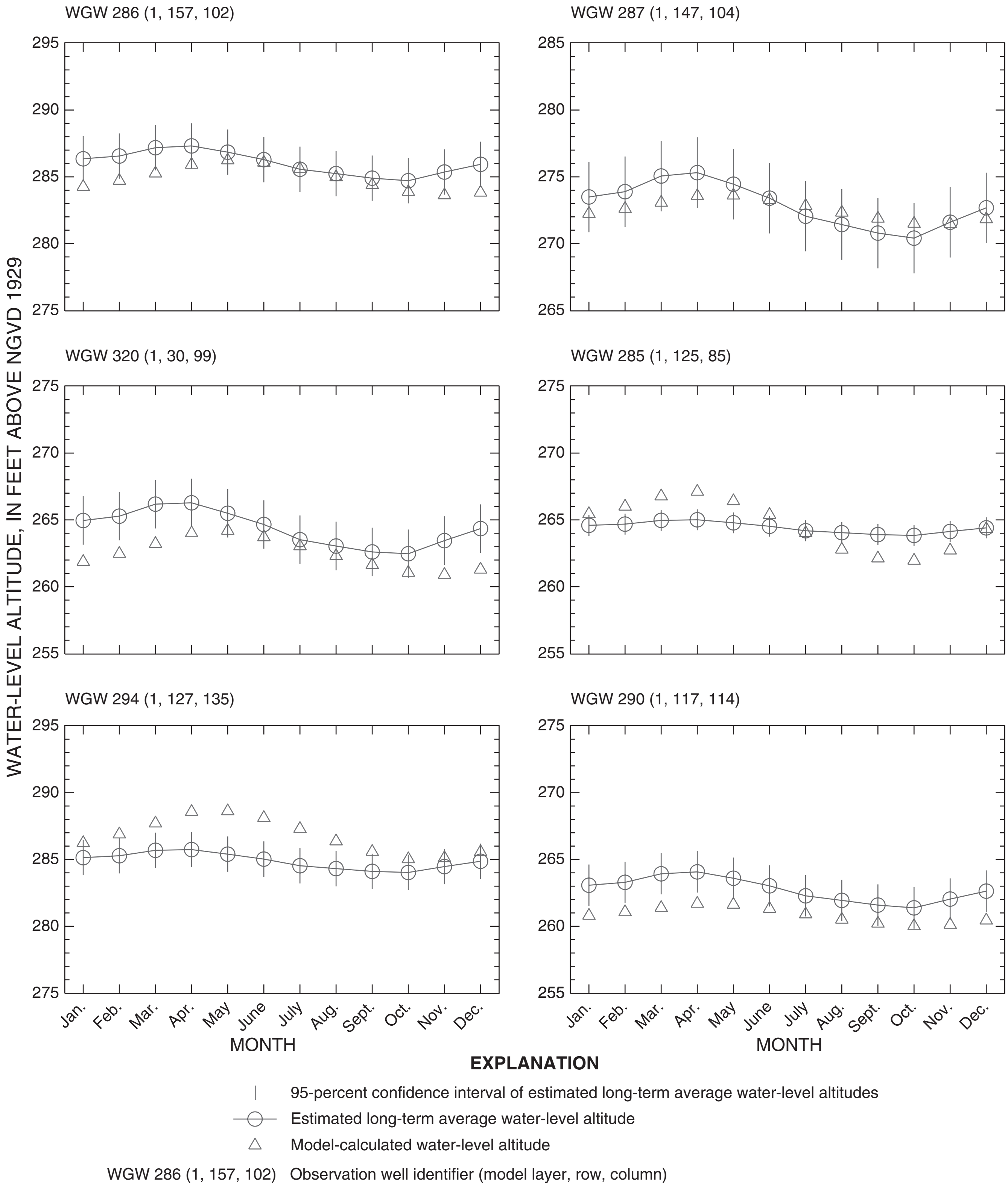

Figure 29. Estimated monthly average and model-calculated ground-water altitudes at 21 observation wells within the Big River study area, Rhode Island. (Locations of wells shown on fig. 4.)

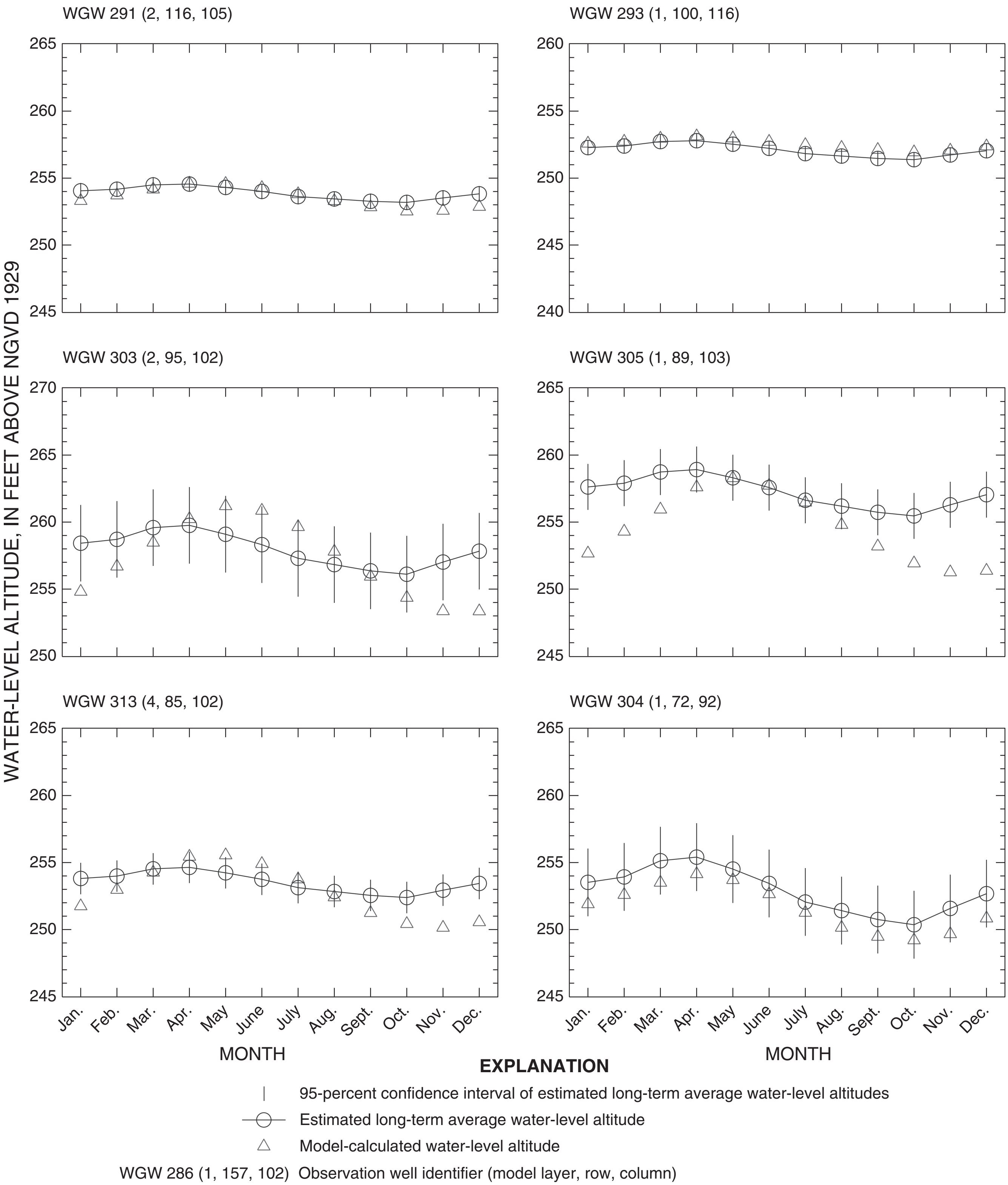

Figure 29 —*Continued*. Estimated monthly average and model-calculated ground-water altitudes at 21 observation wells within the Big River study area, Rhode Island. (Locations of wells shown on fig. 4.)

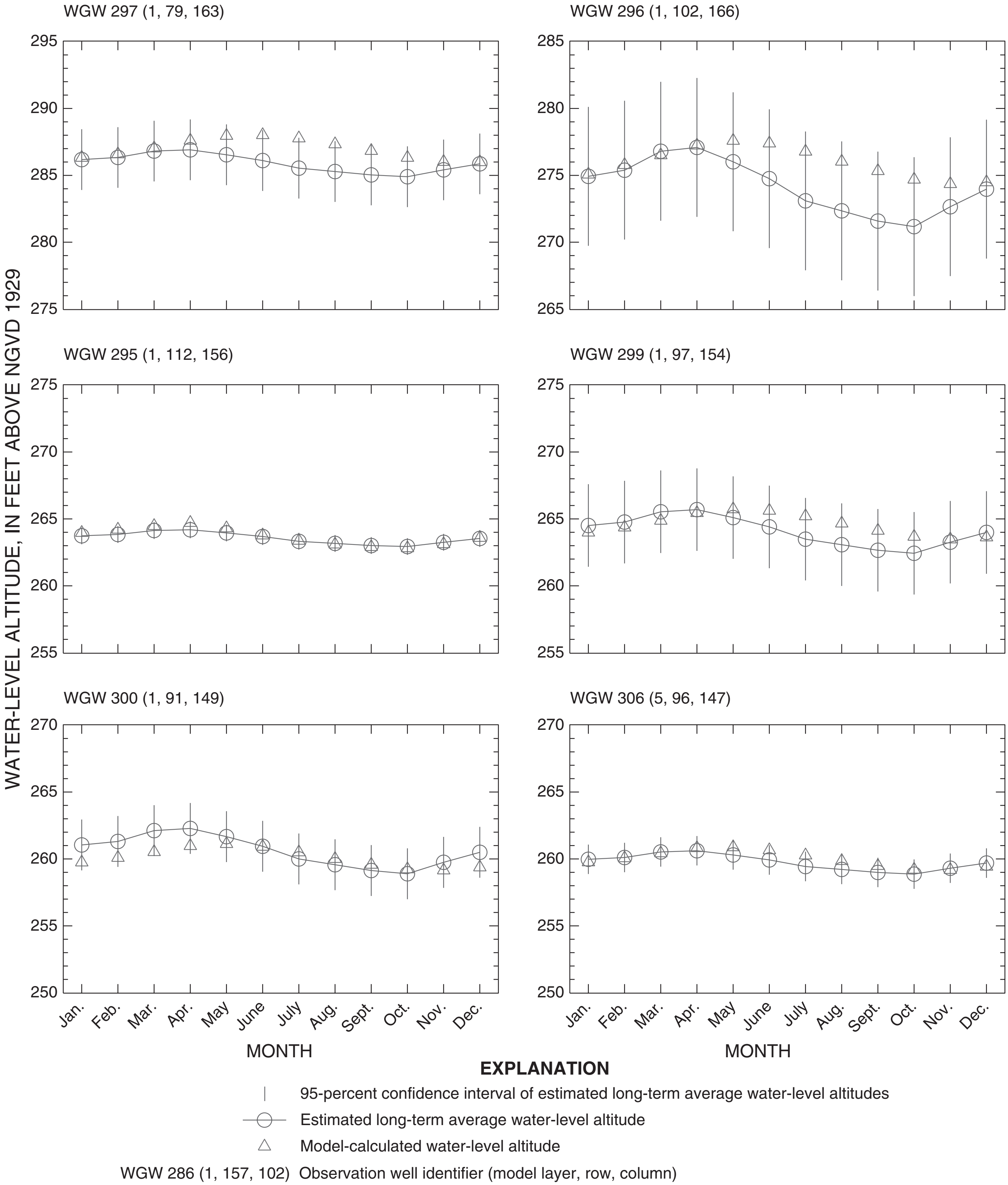

Figure 29 —*Continued*. Estimated monthly average and model-calculated ground-water altitudes at 21 observation wells within the Big River study area, Rhode Island. (Locations of wells shown on fig. 4.)

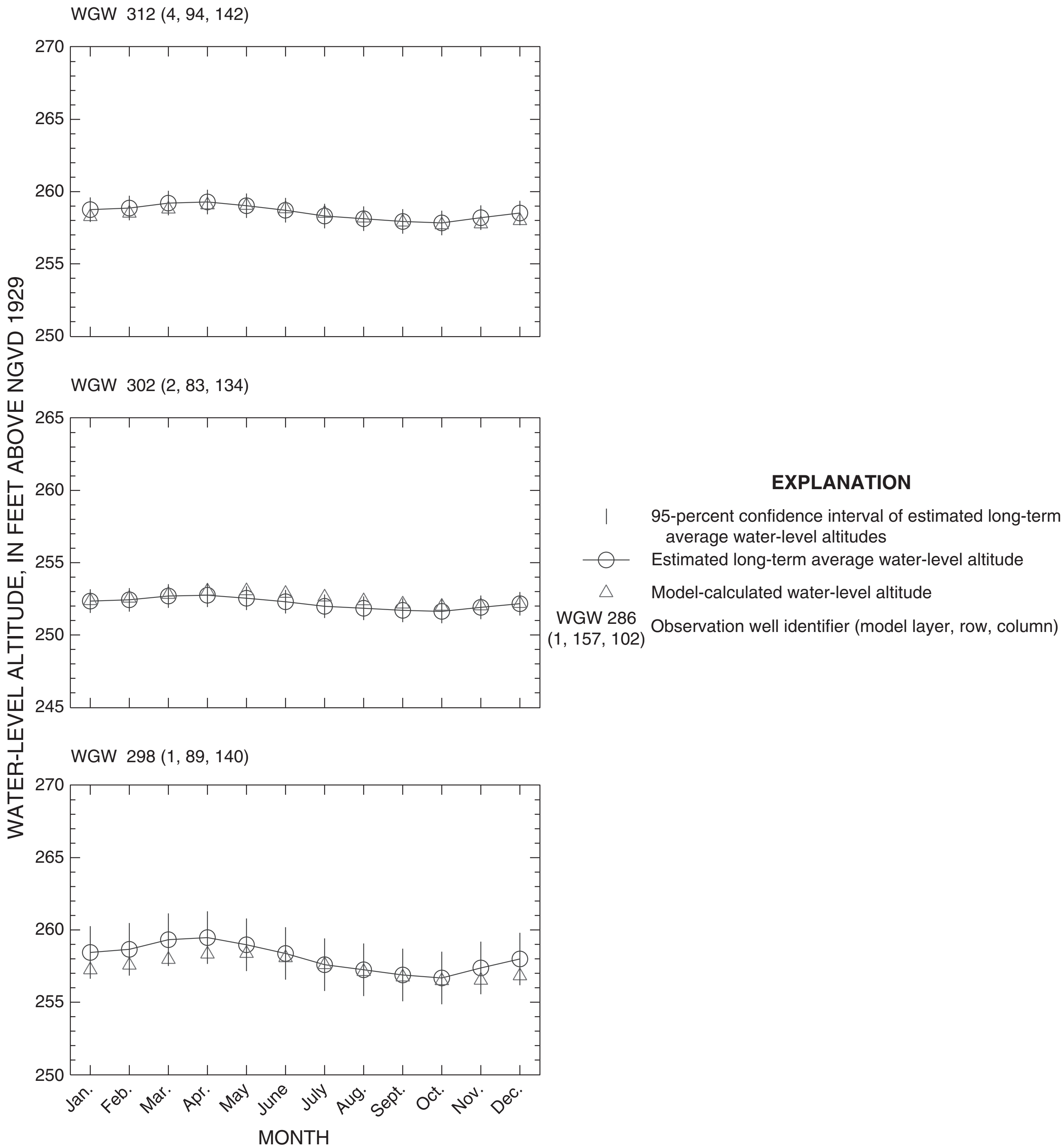

Figure 29 —*Continued*. Estimated monthly average and model-calculated ground-water altitudes at 21 observation wells within the Big River study area, Rhode Island. (Locations of wells shown on fig. 4.)

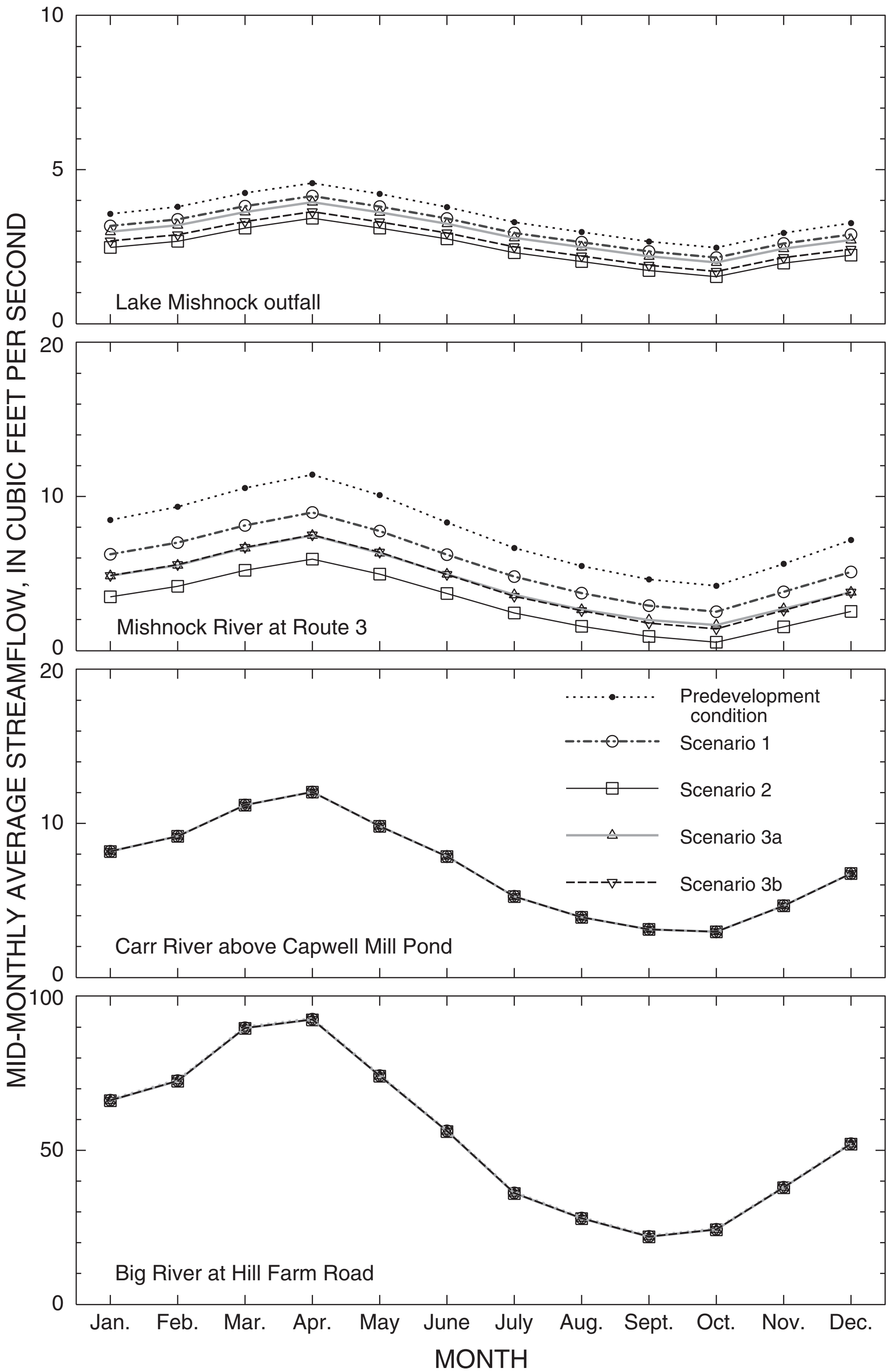

Figure 30. Model-calculated monthly average streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)

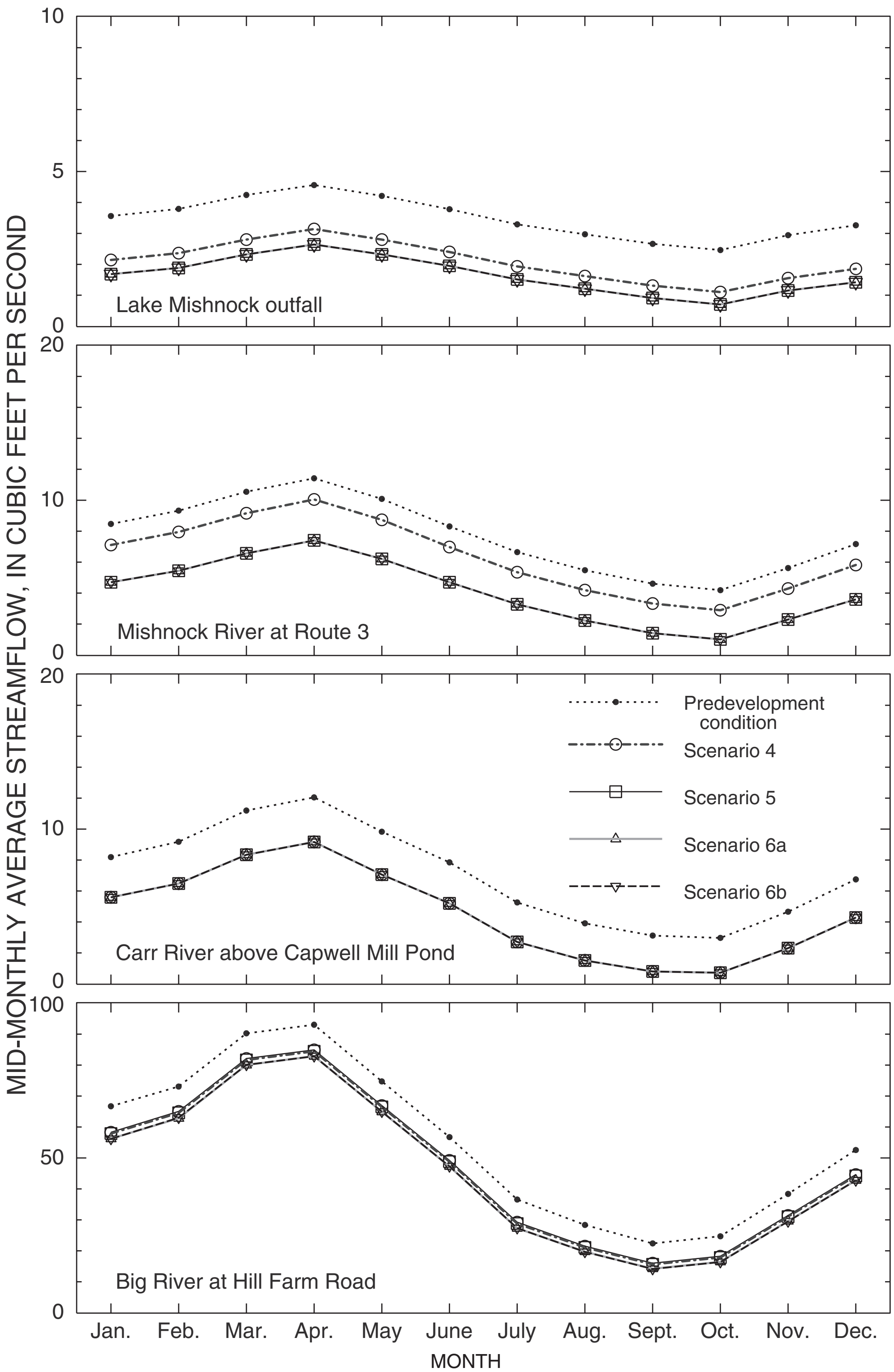

Figure 30—*Continued.* Model-calculated monthly average streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)

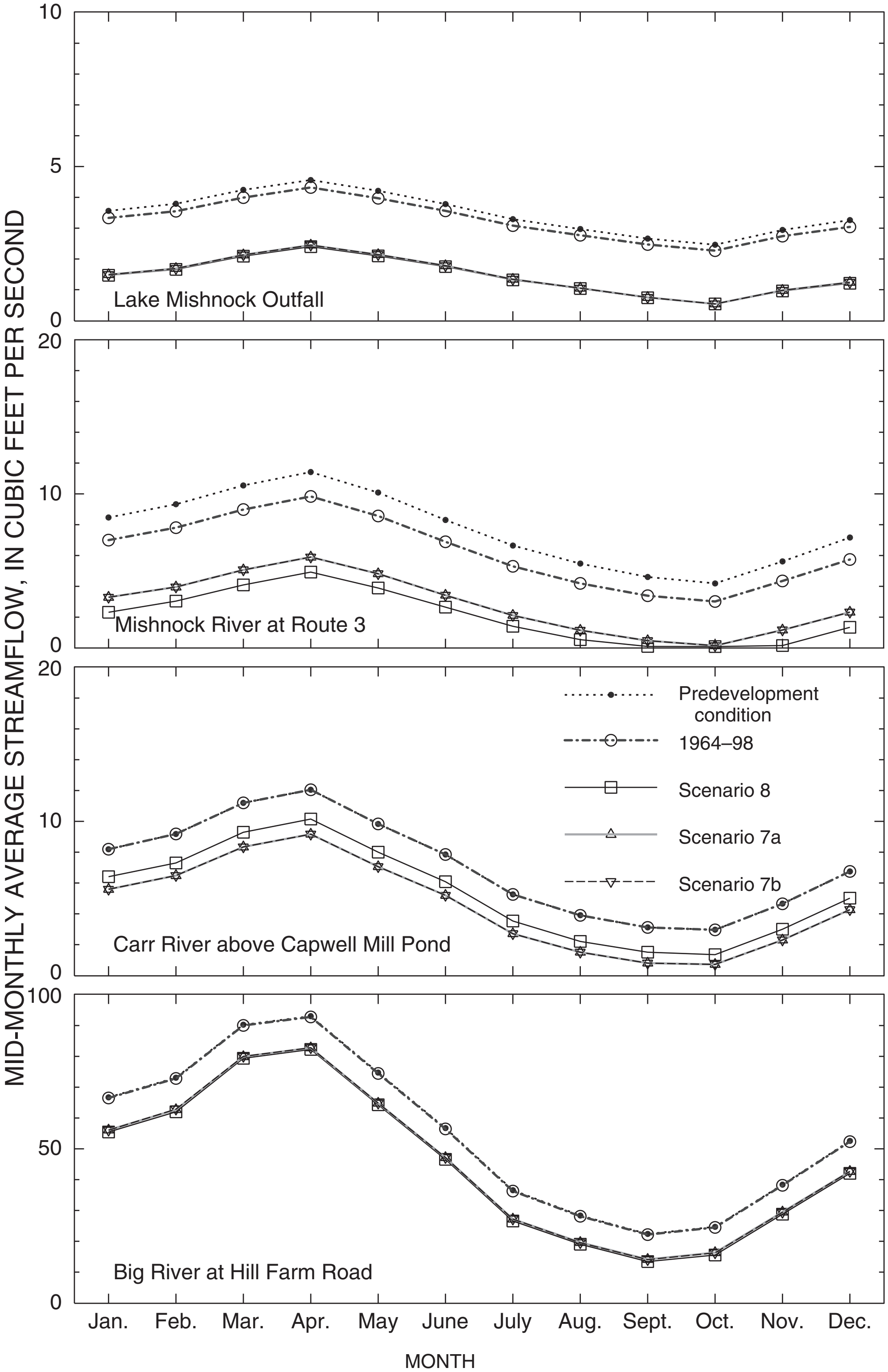

Figure 30—*Continued.* Model-calculated monthly average streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)

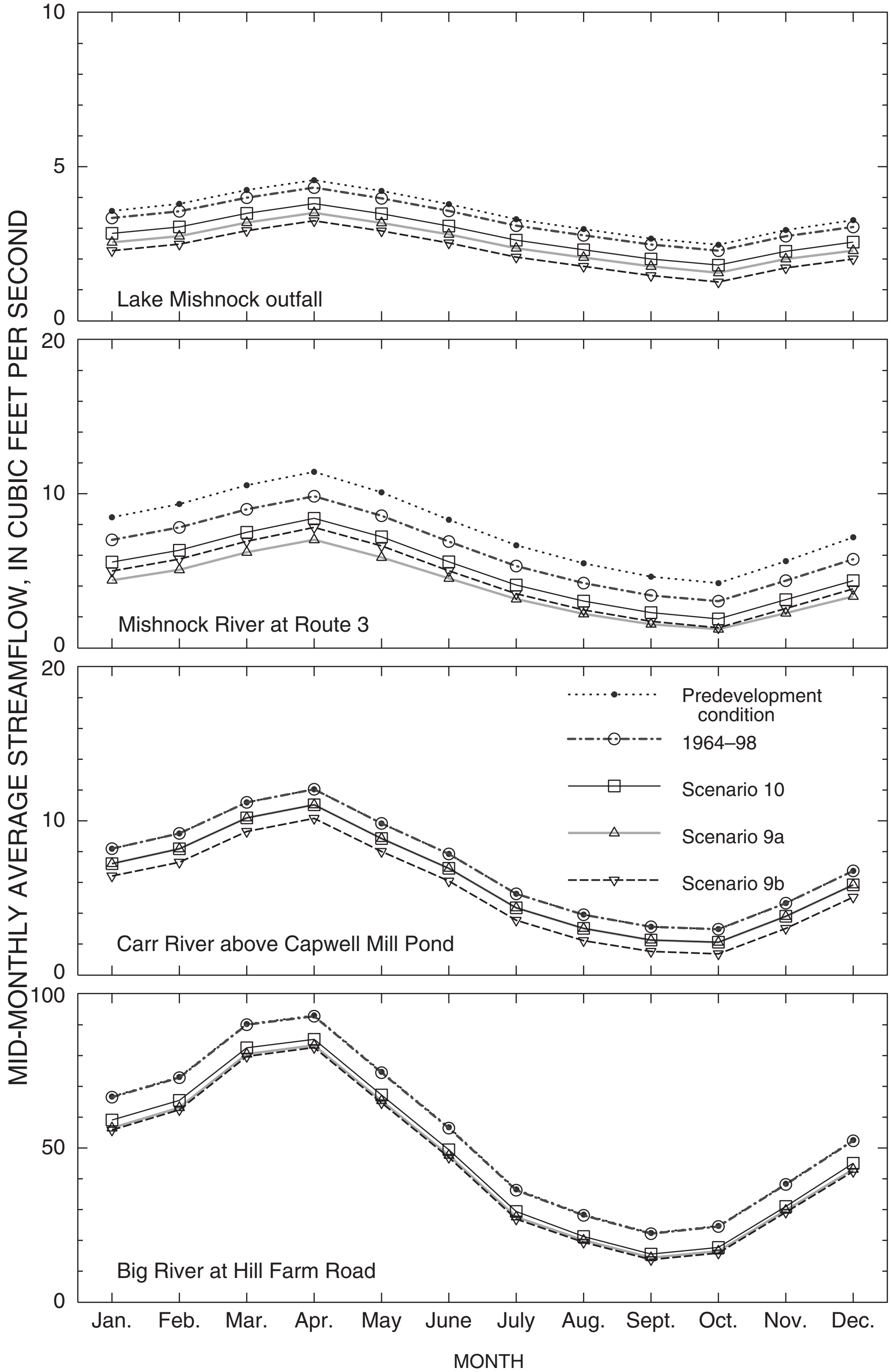

Figure 30—*Continued.* Model-calculated monthly average streamflow at the Lake Mishnock outfall, the Mishnock River at Route 3, the Carr River above Capwell Mill Pond, and the Big River at Hill Farm Road for the predevelopment conditions, conditions during 1964–98, and 14 withdrawal scenarios, Big River study area, Rhode Island. (Location of streamflow index sites shown on fig. 23; withdrawal scenarios described in table 10.)