U.S. Department of the Interior
U.S. Geological Survey

Numerical-Simulation and Conjunctive-Management Models of the Hunt–Annaquatucket–Pettaquamscutt Stream-Aquifer System, Rhode Island

By PAUL M. BARLOW and DAVID C. DICKERMAN

U.S. Geological Survey Professional Paper 1636

Prepared in cooperation with the
TOWN OF NORTH KINGSTOWN,
RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT,
RHODE ISLAND WATER RESOURCES BOARD, and the
RHODE ISLAND ECONOMIC DEVELOPMENT CORPORATION

2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

Subdistrict Chief
Massachusetts-Rhode Island District
U.S. Geological Survey
Water Resources Division
275 Promenade, Suite 150
Providence, RI 02908

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

or visit our web site at
http://ma.water.usgs.gov

Library of Congress Cataloging-in-Publication Data

Barlow, Paul M.

Numerical-simulation and conjunctive-management models of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island / by Paul M. Barlow and David C. Dickerman.

p. cm. -- (U.S. Geological survey professional paper ; 1636)

"Prepared in cooperation with the Town of North Kingstown; Rhode Island Department of Environmental Management; Rhode Island Water Resources Board; and the Rhode Island Economic Development Corporation."

Includes bibliographical references (p.).

ISBN 0-607-96440-5

1. Streamflow--Rhode Island--Hunt River--Mathematical models. 2. Streamflow--Rhode Island--Annaquatucket River--Mathematical models. 3. Streamflow--Rhode Island--Pettaquamscutt River--Mathematical models. I. Dickerman, David C. II. Rhode Island. Dept. of Environmental Management. III. Rhode Island. Water Resources Board. IV. Rhode Island Port Authority and Economic Development Corporation. V. Title. VI. Series.

GB1207 .B37 2001
551.48'09745--dc21 2001023208

CONTENTS

PLATE
(in back pocket)

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	by	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.02832	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.00006309	cubic meter per second
gallon per minute per foot (gal/min/ft)	0.0002070	cubic meter per second per meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Fahrenheit (˚F), which can be converted to degrees Celsius (˚C) by the following equation

$$^\circ C = (^\circ F - 32)/1.8$$

Transmissivity and Hydraulic Conductivity: In this report, the units of transmissivity and hydraulic conductivity are foot squared per day (ft^2/d) and foot per day (ft/d), respectively. These are the mathematically reduced forms of gallon per day per foot [(gal/d)/ft] and gallon per day per foot squared [$(gal/d)/ft^2$], respectively, used by previous authors such as Rosenshein and others (1968).

VERTICAL DATUM

Sea Level: In this report, sea level refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Numerical-Simulation and Conjunctive-Management Models of the Hunt–Annaquatucket–Pettaquamscutt Stream-Aquifer System, Rhode Island

By Paul M. Barlow *and* David C. Dickerman

Abstract

Numerical-simulation and optimization techniques were used to evaluate alternatives for the conjunctive management of ground- and surface-water resources of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system in central Rhode Island. Ground-water withdrawals from the Hunt–Annaquatucket–Pettaquamscutt aquifer exceeded 8 million gallons per day during months of peak water use during 1993–98, and additional withdrawals have been proposed to meet growing demands from within and outside of the system boundary. The system is defined by the Hunt–Annaquatucket–Pettaquamscutt aquifer, which is composed of glacial stratified deposits, and the network of rivers, brooks, and ponds that overlie and are in hydraulic connection with the aquifer. Nearly all of the water withdrawn, however, is derived from depletions of flow in the rivers, brooks, and ponds that overlie the aquifer. Streamflow depletions are of concern to environmental agencies because of the adverse effects that reductions in streamflow can have on aquatic and riparian ecosystems.

A conjunctive-management model of the stream-aquifer system was developed to simultaneously address the water-demand and streamflow-depletion issues. The objective of the model was to maximize total ground-water withdrawal from the aquifer during July, August, and September. These three months are generally the time of year when water-supply demands are largest and streamflows are simultaneously lowest. Total withdrawal from the aquifer was limited by a set of constraints specified in the model. These constraints were (1) maximum rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers; (2) minimum monthly water demands of each of three water-supply systems that withdraw water from the aquifer; and (3) minimum and maximum withdrawal rates at each supply well.

The conjunctive-management model was formulated mathematically as a linear program. The model was solved by a response-matrix technique that incorporates the results of transient, numerical simulation of the stream-aquifer system into the constraint set of the linear program. The basis of the technique was the assumption that streamflow-depletion rates in each river were a linear function of ground-water-withdrawal rates at each well. This assumption was shown to be valid for the conditions evaluated in this study, primarily because of the very high transmissivity of the aquifer near many of the wells pumped for water supply. A transient, numerical model of the system was developed to simulate an average annual cycle of monthly withdrawal and hydrologic conditions representative of the 56-year period 1941–96. The transient model was used to generate characteristic streamflow-depletion responses in each river to simulated withdrawals at each well; these characteristic responses, or response coefficients, were then incorporated directly into the streamflow-depletion constraints of the linear program.

Four sets of applications of the conjunctive-management model were made to determine whether total ground-water withdrawal from the aquifer during July, August, and September could be increased over the current total withdrawal for alternative definitions of the maximum rates of streamflow depletion allowed in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Current conditions were defined as the average monthly withdrawal rates at each supply well, water

demands of each of the three water-supply systems, and estimated streamflow-depletion rates during the 6-year period 1993–98. Total withdrawal from all wells in the system from July through September during 1993–98 was 506.5 million gallons. Estimated streamflow-depletion rates for 1993–98 were calculated by use of the transient model, with the 1993–98 average monthly withdrawal rates specified at each supply well. Streamflow-depletion rates calculated for July, August, and September averaged 25 percent of the model-calculated pre-withdrawal streamflow rates for the Hunt River, 19 percent for the Annaquatucket River, and 7 percent for the Pettaquamscutt River.

The first set of applications of the model were made with the current estimated rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Results of these applications indicated that total withdrawal from the aquifer during July, August, and September could be increased from about 8 to 18 percent (from 546.0 to 596.3 million gallons) over the current total withdrawal. The increased withdrawal would require modifications to the current annual withdrawal schedule of each supply well and, for the 18-percent increase, a modified network of supply wells that would include two new wells in the Annaquatucket River Basin. A second set of model applications then was made to determine if current estimated rates of streamflow depletion in the Hunt River could be reduced without increasing current estimated rates of streamflow depletion in the Annaquatucket or Pettaquamscutt Rivers. Decreases in the current rates of streamflow depletion in the Hunt River would result in increased streamflow in the river during these three months. Results showed that current rates of streamflow depletion in the Hunt River during July, August, and September could be decreased from 5 to 15 percent, depending on whether the existing or modified well network was used.

Subsequent model applications indicated that substantial increases in total ground-water withdrawal from the aquifer are possible, but would require increased rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers. Maximum increases in the July through September withdrawal from the aquifer of about 39 to 50 percent (from 705.1 to 760.3 million gallons) over the current total withdrawal were calculated when streamflow-depletion rates in the Annaquatucket and Pettaquamscutt Rivers were allowed to increase from current estimated rates to a maximum of 25 percent of the model-calculated pre-withdrawal streamflow for each river during July, August, and September. Alternatively, it was shown that current estimated rates of streamflow depletion in the Hunt River during July, August, and September could be reduced by as much as 35 percent for the maximum allowed increases in streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers; maximum increased withdrawal from the aquifer, however, would range from 8 to 18 percent over the current total withdrawal for the 35-percent reduction in streamflow-depletion rates in the Hunt River.

Results of the different applications of the model demonstrate the usefulness of coupling numerical-simulation and optimization techniques for regional-scale evaluation of water-resource management alternatives. The results of the evaluation must be viewed, however, within the limitations of the quality of data available for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system and representation of the system by a simulation model. An additional limitation of the analysis was the use of an average annual cycle of monthly withdrawal and hydrologic conditions. Ground-water withdrawal strategies may need to be modified to meet streamflow-depletion constraints during extreme hydrologic events, such as droughts.

Contributing areas and sources of water to the supply wells also were delineated by use of a steady-state model of the stream-aquifer system. The model was developed to simulate long-term-average ground-water flow and ground-water/ surface-water interactions in the system during the 56-year period 1941–96. Sources of water to the wells consisted of precipitation and wastewater recharge to the aquifer, streamflow leakage from natural stream-channel losses, streamflow leakage caused by induced infiltration, and lateral ground-water inflow from till and bedrock upland areas.

INTRODUCTION

The Hunt–Annaquatucket–Pettaquamscutt (HAP) aquifer in central Rhode Island is the source of water for the town of North Kingstown and parts of the towns of Warwick, East Greenwich, and Narragansett. Ground-water withdrawals from the HAP aquifer exceeded 8 Mgal/d during months of peak water use during 1993–98, and additional withdrawals have been proposed to meet growing demands from within and outside of the aquifer system boundary. Although the aquifer provides substantial amounts of high-quality water, these withdrawals cannot be sustained without causing depletions of flow in some of the streams that overlie the aquifer. Streamflow depletions caused by ground-water withdrawals can be an environmental problem when such depletions decrease the water available to aquatic communities below minimum levels required to sustain healthy aquatic and riparian ecosystems.

Concerns by the Rhode Island Department of Environmental Management (RIDEM) regarding the effects of ground-water withdrawals on streamflow depletions in the HAP stream-aquifer system prompted an investigation to better understand the water resources of the system and to evaluate alternatives for the conjunctive management of the ground- and surface-water resources of the system. The stream-aquifer system is defined by the HAP aquifer and the network of rivers, brooks, and ponds that overlie and are in hydraulic connection with the aquifer (fig. 1). The HAP aquifer is the principal water-bearing unit in the study area, and is composed of stratified sand-and-gravel sediments that were deposited by glacial melt-water. The investigation was done from 1995 to 2000 by the U.S. Geological Survey (USGS) in cooperation with the town of North Kingstown, RIDEM, Rhode Island Economic Development Corporation (RIEDC), and Rhode Island Water Resources Board (RIWRB).

The conflict between ground-water development and maintenance of streamflows for aquatic and riparian ecosystems is not unique to the towns of central Rhode Island. Many communities across the United States are seeking ways to develop sustainable ground-water supplies to meet growing demands, while simultaneously limiting the detrimental effects of such development on environmental resources. The methods of analysis used for the HAP stream-aquifer system are transferable to other areas where such competition is present between ground-water development and maintenance of streamflows.

Purpose and Scope

This report describes the development, application, and evaluation of numerical-simulation and conjunctive-management models of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system in central Rhode Island. Steady-state and transient numerical models were developed to improve the understanding of the hydrologic budget of the system, the interaction of ground-water and surface-water components of the system, and the contributing areas and sources of water to supply wells in the system. The numerical models were developed and calibrated on the basis of hydrologic data collected during this and previous investigations. These data include lithologic information for the aquifer; hydraulic properties of the aquifer and streambed materials; recharge to the aquifer; water levels measured in wells, ponds, and streambed piezometers; streamflow measurements for various streams within the system; and ground-water withdrawal rates from, and wastewater discharge to, the aquifer. The models are representative of average withdrawal and hydrologic conditions in the system for the 56-year period 1941–96. The U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), commonly known as MODFLOW, was used to numerically simulate the stream-aquifer system. Contributing areas and sources of water to supply wells were determined by tracking ground-water-flow paths with the computer program MODPATH (Pollock, 1994), a particle-tracking post-processor package for MODFLOW.

A conjunctive-management model[1] of the stream-aquifer system was developed to simultaneously address the water-demand and streamflow-depletion issues. The conjunctive-management model was formulated mathematically as a linear program. The model was solved by a response-matrix technique that incorporates the results of transient, numerical simulation of the stream-aquifer system directly into the constraint set of the linear program. Applications of the conjunctive-management model were made to determine whether total ground-water withdrawal from the aquifer during July, August, and September could be increased over the current total withdrawal for alternative definitions of the maximum rates of streamflow depletion allowed in the Hunt, Annaquatucket, and Pettaquamscutt Rivers.

[1]The term "conjunctive-management model" commonly is used in the hydrologic literature to refer to the combined use of numerical simulation and optimization to determine and evaluate alternative strategies for simultaneous management of stream-aquifer systems. Use of the term in this report does not imply that the U.S. Geological Survey recommends specific courses of action for management of the water resources of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system.

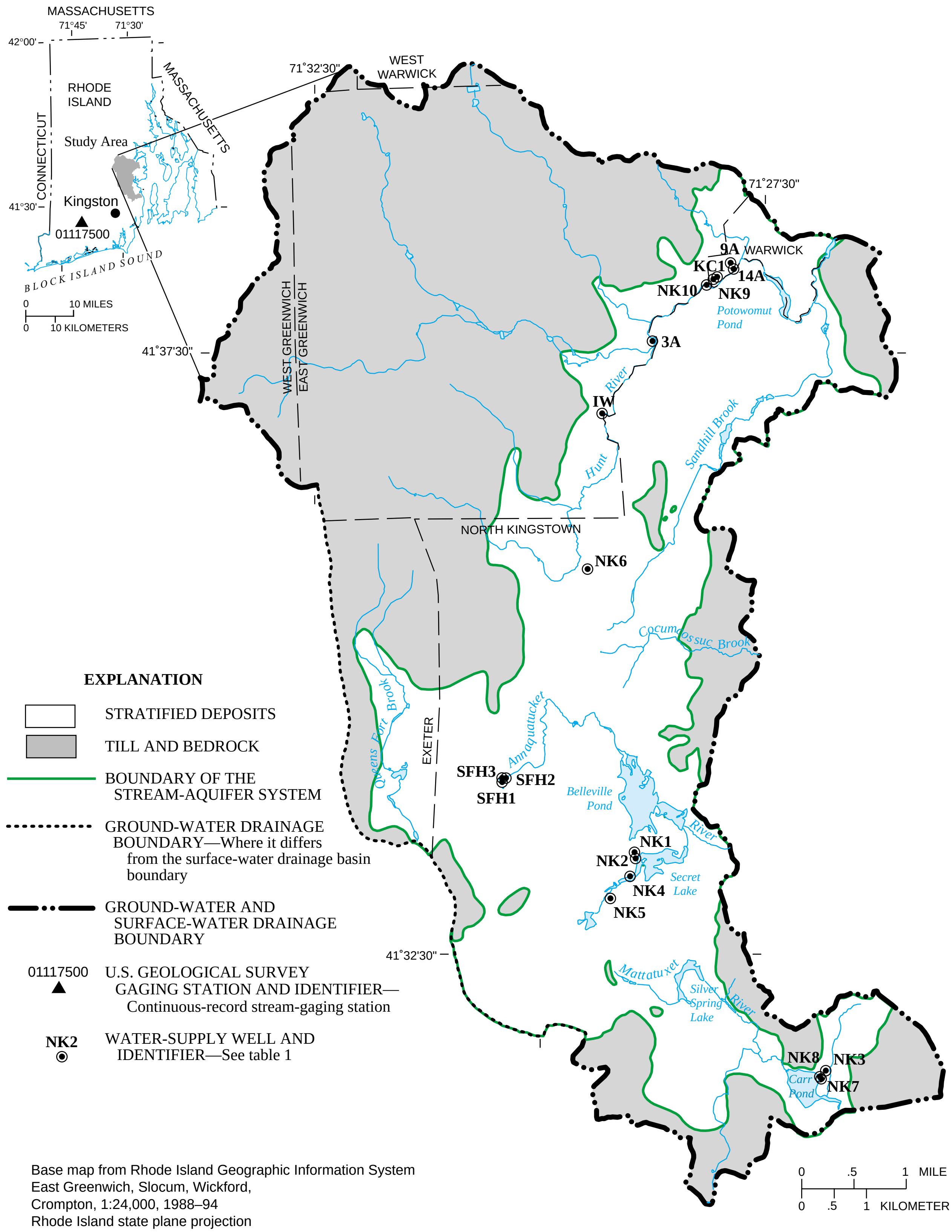


Figure 1. Location of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

Study Area

The HAP stream-aquifer system covers a 19.0-square-mile area in the towns of Warwick, East Greenwich, North Kingstown, and Exeter, Rhode Island (fig. 2). The system lies within parts of the Hunt, Annaquatucket, Cocumcossuc, Pettaquamscutt, Usquepaug–Queen, and Chipuxet River Basins. The Hunt River was called the Potowomut River by Rosenshein and others (1968) and the Pettaquamscutt River is called the Mattatuxet River in its headwater reaches. The surface-water drainage area of the system (35.6 mi^2) is smaller than the total drainage area of the system (39.6 mi^2), because ground-water and surface-water drainage boundaries are not coincident in the Chipuxet and Usquepaug–Queen River Basins (fig. 2). Surface-water runoff in these two basins drains to the west of the study area, whereas some of the ground water recharged within the basins flows eastward. In this report, the study area is defined as the entire 39.6-square-mile drainage area shown in figures 1 and 2, although most data were collected within the 19.0-square-mile area defined by the HAP stream-aquifer system. The remainder, 20.6 mi^2, is upland areas consisting of till, bedrock, and small amounts of sand-and-gravel deposits.

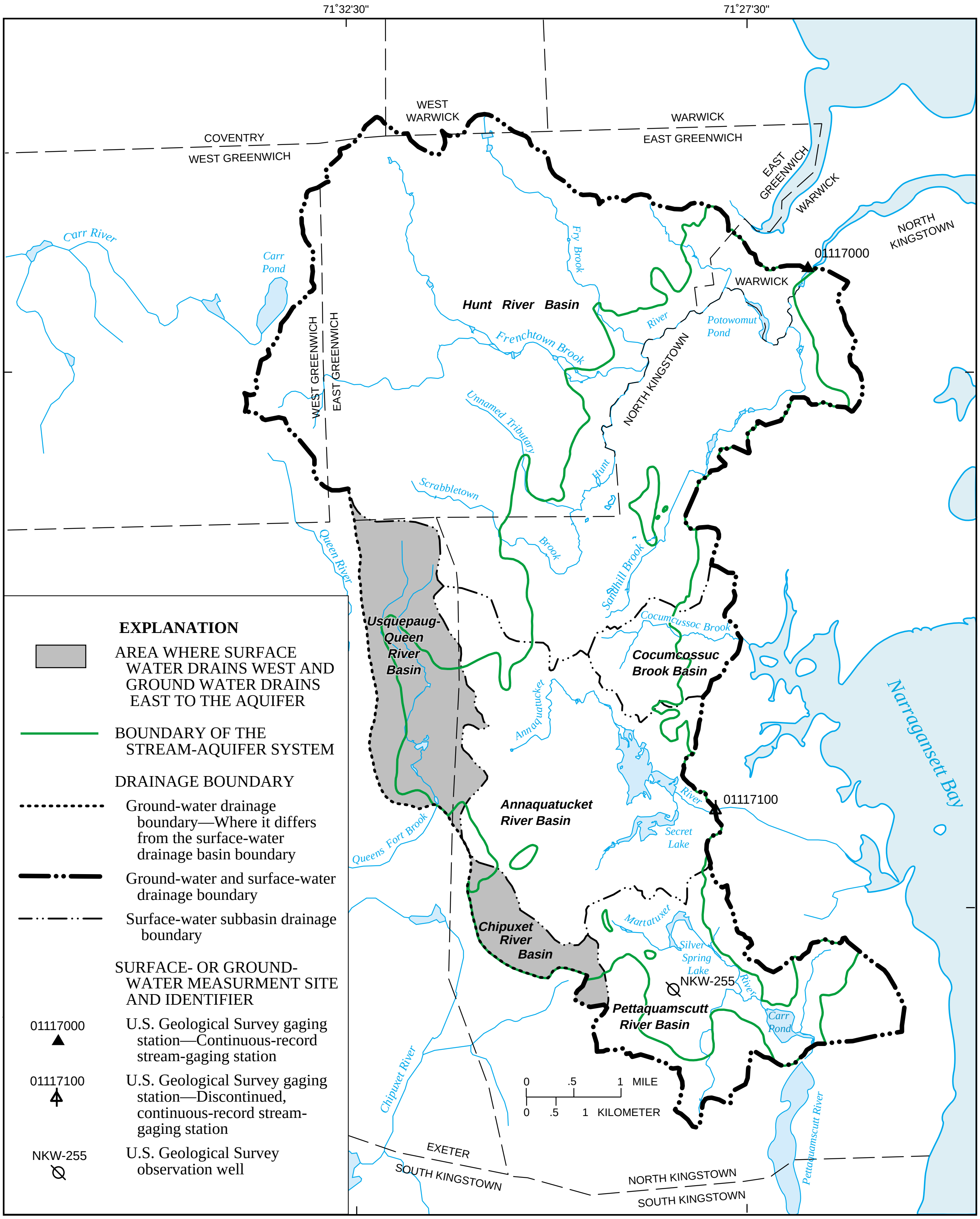
The study area consists of a relatively flat valley that contains several large but generally shallow ponds and lakes. Average depths of Belleville Pond, Carr (Pausacaco) Pond, and Silver Spring Lake were 8 ft or less during the period 1955–68 (Guthrie and Stolgitis, 1977). Land-surface altitudes in the valley range from about 5 ft above sea level at the downstream end of the Hunt and Pettaquamscutt River Basins to a maximum of about 250 ft in the headwaters of the Usquepaug–Queen River Basin. The valley is bounded by uplands where land-surface altitudes reach a maximum of about 480 ft.

Precipitation was measured during the 56-year period 1941–96 at a National Oceanic and Atmospheric Administration climatological station in Kingston, Rhode Island (fig. 1), approximately 6.5 mi southwest of the center of the study area (National Oceanic and Atmospheric Administration, 1998). Average annual total precipitation at the station for the period was 47.5 in. Monthly precipitation was fairly evenly distributed throughout the year, with 3.1 to 5.0 in. of rain or snow each month. Average annual air temperature at the Kingston station only is available for the 54-year period 1943–96. During that time, average annual air temperature was 49.3˚F and monthly average temperatures ranged from 28.4˚F in January to 70.4˚F in July (average annual total precipitation for the 54-year period was 47.8 in.).

Previous and Related Studies

Information on the geology and water resources of the study area is available from previous studies. Surficial and bedrock geology have been mapped by Power (1957, 1959), Quinn (1952, 1963), Schafer (1961), Smith (1955, 1956), and Williams (1964). Streamflow measurements for the Hunt River have been made by the USGS at a continuous-record streamflow-gaging station (USGS station number 01117000, fig. 2) since August 1940; these measurements are available in USGS publications [see Socolow and others (1998) for a complete listing of relevant citations]. Continuous-record streamflow measurements also were made at a site on the Annaquatucket River (USGS station number 01117100, fig. 2) during the period 1961–63 (Socolow and others, 1998). In addition, three low-flow partial-record streamflow sites in the Hunt River Basin were used by Cervione and others (1993) to evaluate low-flow characteristics of selected streams in Rhode Island. Ground-water levels have been measured monthly at well NKW-255 (fig. 2) since August 1954, with the exception of the 2-year period from January 1964 through December 1965; these measurements also are available in USGS publications (see Socolow and others, 1998). Reconnaissance studies on the availability of ground water were done by Allen (1956), Allen and others (1959), Hahn (1959), Johnson and Marks (1959), and Lang (1961).

A comprehensive study of the hydrologic characteristics and sustained yield of the HAP aquifer was done by Rosenshein and others (1968) as part of a larger study of the entire Potowomut–Wickford area, which includes the HAP basin and adjacent aquifer and upland areas that drain to Narragansett Bay. As part of that study, Rosenshein and others (1968) published maps of the transmissivity, saturated thickness, and water table of the aquifer.



Base map from Rhode Island Geographic Information System,
East Greenwich, Slocum, Wickford, Crompton, 1:24,000,
1988–94 Rhode Island state plane projection

Figure 2. Drainage boundaries to the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

They also prepared an unpublished map of the bedrock surface underlying the study area that is available at the USGS office in Providence, Rhode Island. Ground-water-level maps for smaller areas of the aquifer were made subsequent to that study by Heath (1991), GZA GeoEnvironmental (1992), and Fuss and O'Neill (1997). As part of this study, Dickerman and Barlow (1997) prepared a water-table map for the entire aquifer on the basis of water levels measured in October 1996. The map was used with streamflow measurements made during the same period to identify gaining and losing reaches of the major streams in the HAP system.

GZA GeoEnvironmental (1992) developed a ground-water-flow model of the Hunt River Basin for the purpose of delineating recharge areas and ground-water traveltimes to existing and proposed public water-supply wells in the basin. Heath (1991) discussed wellhead-protection areas for public water-supply wells in the Annaquatucket River Basin.

Conjunctive-management models for stream-aquifer systems of the northeastern United States that are similar in scope to the model presented in this report were developed by Male and Mueller (1992) and Mueller and Male (1993) for the Charles River Basin, Massachusetts, and by Barlow (1997a) for the Quashnet River Basin, Cape Cod, Massachusetts. Additional studies that use optimization techniques to address simultaneous management of ground-water withdrawals and streamflow depletions are described by Maddock (1974), Morel-Seytoux and Daly (1975), Morel-Seytoux (1975a, b), Illangasekare and Morel-Seytoux (1982), and Peralta and others (1988).

Acknowledgments

The authors express appreciation to area residents who provided access to their property for the purpose of measuring water levels and streamflow during this investigation. The authors also thank Susan Licardi and Michael Martin (North Kingstown Water Department), Peter Angelone (Office of Fish and Wildlife, RIDEM), William Harritos (RIEDC), and Timothy Brown (Kent County Water Authority) for providing information on ground-water withdrawals and to Galen McGovern (RIWRB and formerly of the RIDEM), Ernest Panciera (RIDEM), and Douglas Heath (U.S. Environmental Protection Agency) for assisting in the collection of water-level data.

HUNT–ANNAQUATUCKET–PETTAQUAMSCUTT STREAM-AQUIFER SYSTEM

Most of the hydrogeologic data that were used in the development of the numerical models of the HAP stream-aquifer system were available from previous investigations. In addition, water-level and streamflow measurements were made during this study to improve the understanding of ground-water flow and stream-aquifer interaction. A hydrologic budget also was estimated for the stream-aquifer system for the 1941–96 period.

Hydrogeologic Units

The three major hydrogeologic units in the study area are stratified sand and gravel, till, and crystalline and metamorphosed sedimentary bedrock. In addition, sediments composing the streambed and pond bottoms within the study area form a thin veneer over the major hydrogeologic units. Till and stratified sand and gravel are unconsolidated sediments deposited during Pleistocene glaciation. Small, isolated, and thinly saturated areas of stratified sand-and-gravel deposits are found within the upland areas shown as till and bedrock on figure 1 (Hahn, 1959; Allen and others, 1959). These areas of sand and gravel are not reliable sources of water for large public supplies because they are thinly saturated and have low transmissivity. Consequently, they are not considered part of the HAP stream-aquifer system. The properties and areal extent of the hydrogeologic units have been described by Quinn (1952, 1963), Smith (1955, 1956), Allen (1956), Power (1957, 1959), Allen and others (1959), Hahn (1959), Johnson and Marks (1959), Shafer (1961), Williams (1964), and Rosenshein and others (1968).

All large-capacity supply wells in the study area derive water from the sand-and-gravel deposits (the HAP aquifer). In some locations, the sand-and-gravel deposits are interbedded with very fine sand and silt (Rosenshein and others, 1968). Hahn (1959), Johnson and Marks (1959), and Rosenshein and others (1968) also describe small areas within the HAP aquifer where stratified sand and gravel is interbedded with till. In their analysis of the potential sustained yield of the aquifer, however, Rosenshein and others (1968) did not differentiate these small areas from other areas of the aquifer. Similarly, these areas were not differentiated in the present study.

Detailed maps of the transmissivity, bedrock altitude, and saturated thickness of the aquifer were prepared by Rosenshein and others (1968). They used aquifer and specific-capacity tests at 31 wells to estimate transmissivity (Rosenshein and others, 1968, table 1). In areas where aquifer tests had not been done, they calculated transmissivity from descriptions of the various materials penetrated by wells that were drilled in the aquifer. These calculations were based on the relation $T = K_h m$, where T is transmissivity of the aquifer, K_h is horizontal hydraulic conductivity of the aquifer, and m is saturated thickness of penetrated material. The values of K_h used in these calculations were determined from a multiple-regression analysis (Jenkins, 1963) of the results of the 31 aquifer and specific-capacity tests (Rosenshein and others, 1968, table 1), and ranged from 50 ft/d for fine sand to 470 ft/d for gravel. The largest value of K_h reported by Rosenshein and others (1968, table 1) was 680 ft/d near wells NK4 and NK5 (fig. 1).

As part of this study, transmissivity, bedrock altitude, and saturated thickness were modified in two areas of the aquifer. These modifications were based on hydrogeologic information made available since the 1960s, and provided to the authors by the town of North Kingstown and the Office of Fish and Wildlife, RIDEM. Modifications were made in the area of the Lafayette State Fish Hatchery (wells SFH1, SFH2, and SFH3 on fig. 1) and in the area of North Kingstown supply well NK6 (fig. 1). These modifications generally increased the transmissivity and saturated thickness values of the aquifer over those published by Rosenshein and others (1968).

Transmissivity ranges from zero at the boundary between the HAP aquifer and upland till and bedrock to a maximum reported value of 50,800 ft^2/d (Rosenshein and others, 1968, table 1). Transmissivity in the area of Sandhill and Cocumcossuc Brooks is less than 2,700 ft^2/d. Transmissivity is greater than or equal to 40,000 ft^2/d in the Hunt River Basin near wells 3A, 9A, 14A, KC1, NK9, and NK10 and in the Annaquatucket River Basin near wells NK1, NK2, NK4, and NK5. Saturated thickness ranges from zero at the boundary between the HAP aquifer and upland till and bedrock to about 120 ft in the area that parallels the Hunt River west of Potowomut Pond (Rosenshein and others, 1968, pl. 3). Saturated thickness generally is less than 20 ft in the area of Sandhill and Cocumcossuc Brooks and in the southwestern part of the Annaquatucket River Basin in the area between the Usquepaug–Queen and Chipuxet River Basins.

Rosenshein and others (1968, table 1) give 11 values of specific yield estimated for the HAP aquifer that range from 0.05 to 0.18. These values, determined from short-term aquifer tests, are low and likely do not reflect the true potential of the aquifer to store and release water in response to fluctuations of the water table. In contrast to these low estimates, 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 adjacent 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 (2000) determined a specific yield of 0.26 for glacial stratified deposits of western Cape Cod, Massachusetts. The values reported by Allen and others and by Moench and others are close to average values of specific yield compiled by Johnson (1966) for materials that are similar to those of the HAP aquifer.

Allen and others (1963) also determined the porosity of the 18 sediment samples from the Pawcatuck River Basin. The measured porosity ranged from 0.25 to 0.50, with mean and median values of 0.34. These average values are close to the value of 0.39 determined for glacial stratified deposits of western Cape Cod, Massachusetts, by Garabedian and others (1991).

Rosenshein and others (1968) report that the veneer of streambed sediments of the Hunt River averages 2 ft thick, but is as much as 10 ft thick locally. These sediments range from organically rich, very fine sand and silt to boulders. Field measurements of the vertical hydraulic conductivity of streambed sediments at 11 sites on the Hunt River were made by Rosenshein and others (1968) with a variable-head permeameter. Vertical hydraulic conductivity of the streambed sediments 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

Ground water is withdrawn from the HAP aquifer from 18 large-capacity water-supply wells (fig. 1; table 1). These consist of 14 public water-supply wells,

Table 1. Characteristics of water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well locations are shown on figure 1. EGW, East Greenwich well; NKW, North Kingstown well; WCW, Warwick well; KCWA, Kent County Water Authority; NK, Town of North Kingstown; RIEDC, Rhode Island Economic Development Corporation; RIDEM, Rhode Island Department of Environmental Management, Office of Fish and Wildlife. **Specific capacity and well yield:** based on original aquifer test done when well was installed. USGS, U.S. Geological Survey; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; --, no data]

Water-supply well identifier	USGS well identifier	Water supplier	Well depth (feet)	Well-screen interval (feet below land surface)	Top of screen altitude (feet above or below (-) sea level)	Casing and screen diameter (inches)	Specific capacity (gal/min/ft)	Well yield (gal/min)
Hunt River Basin								
KC1	WCW-677	KCWA	118	88–118	-62.0	18	248	1,800
3A	EGW-180	RIEDC	98	68–98	-25.7	16	69	1,250
9A	WCW-39	RIEDC	61	36–61	-2.5	12	61	1,460
14A	WCW-40	RIEDC	80	50–80	-21.0	12	--	1,000
NK6	NKW-1299	NK	85	65–85	-10.0	18	22	950
NK9	WCW-33	NK	114	74–114	-46.0	[1]8	300	1,500
NK10	EGW-3	NK	107	72–107	-44.0	[1]8	140	1,500
IW	EGW-147	Industrial	77	57–77	-9.0	8	30	340
Annaquatucket River Basin								
SFH1	NKW-1323	RIDEM	49	39–49	71.0	16	14	280
SFH2	NKW-1345	RIDEM	49	37–49	73.0	18	17	395
SFH3	NKW-1346	RIDEM	71	51–71	74.0	18	22	728
NK1	NKW-26	NK	50	30–50	24.5	12	68	1,000
NK2	NKW-1156	NK	60	40–60	23.8	12	--	--
NK4	NKW-1297	NK	55	35–55	21.9	12	--	--
NK5	NKW-1298	NK	68	48–68	4.5	12	40	1,212
Pettaquamscutt River Basin								
NK3	NKW-1235	NK	67	47–67	-27.0	18	36	1,000
NK7	NKW-1347	NK	65	55–65	-40.0	12	17	325
NK8	NKW-1348	NK	55	45–55	-30.0	12	10	275

[1]Well was rehabilitated in 1984 and the original 12-inch well screen was replaced with 8-inch well screen.

an industrial well, and three fisheries wells. Three public-water suppliers withdraw water from the HAP aquifer—the town of North Kingstown (NK), Rhode Island Economic Development Corporation (RIEDC), and Kent County Water Authority (KCWA). The town of North Kingstown has 10 supply wells, RIEDC has 3 wells, and KCWA has a single well (table 1). Ground water also is withdrawn at a privately-owned industrial well (well IW, Hunt River Basin, fig. 1) and at three State-owned wells that provide water to the Lafayette State Fish Hatchery (wells SFH1—SFH3, Annaquatucket River Basin, fig. 1).

Ground-Water Levels and Ground-Water Flow

Monthly measurements of water levels were made at 14 observation wells distributed throughout the HAP aquifer during the 12-month period from November 1995 through November 1996 (with the exception of December 1995)[2]. Water-level hydrographs for several of these wells are shown in figure 3. Water-level fluctuations at the wells shown in figure 3 ranged from about 1.9 ft to 3.8 ft and were largest at wells with the highest mean water-level altitude. Water levels at NKW-255 for a representative 10-year period

[2]Ground-water-level measurements made at all observation wells during this investigation are given in appendix A.

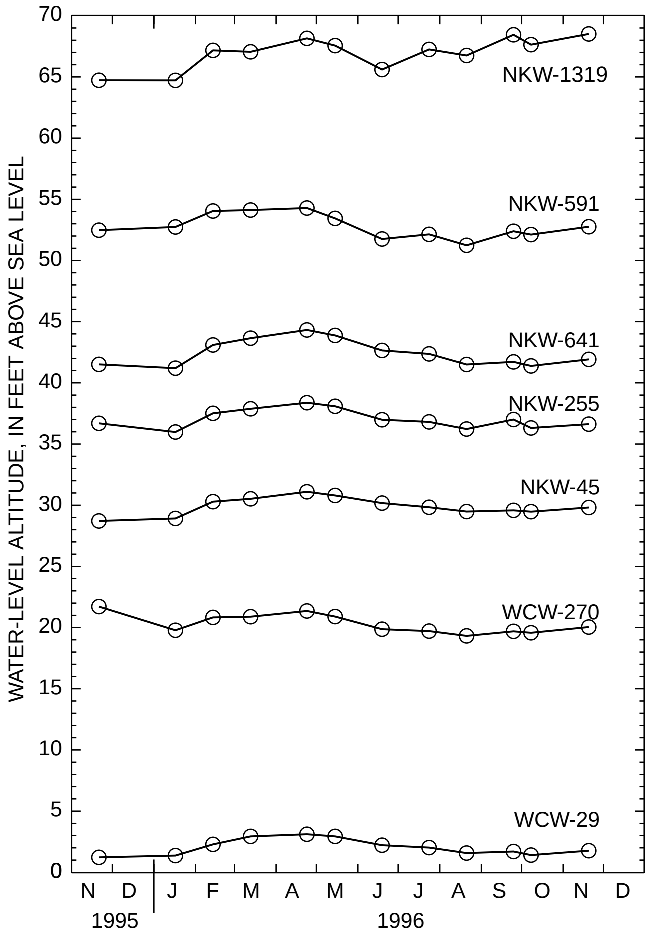


Figure 3. Water-level altitudes measured in selected wells in the Hunt–Annaquatucket–Pettaquamscutt aquifer, Rhode Island, 1995–96. (Well locations shown on figure 5.)

(January 1987 through December 1996) also are shown in figure 4A for the purpose of comparing hydrologic conditions during 1995–96 to those for a longer time period. Water levels in the aquifer fluctuate in response to changes in the rates of ground-water recharge and discharge, which are partly a function of 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 to the water table, which results in generally higher water levels.

A map of the water table was prepared for the HAP aquifer on the basis of water-level measurements made on October 7–9, 1996 (fig. 5). This period was selected because the water-level altitude at well NKW-255 measured on October 8, 1996 (36.31 ft above sea level), was close to the average water-level altitude at the well measured for the 40-year period 1955–63, 1966–96 (36.83 ft above sea level). On this basis, it was assumed that water-level altitudes shown on the map are representative of near-average conditions. Water levels were measured in 65 observation wells, 18 ponds, and 16 streambed piezometers (Dickerman and Barlow, 1997).

Ground water moves through the aquifer in the direction of lower water-level altitudes. The altitude and configuration of the water-table contours (fig. 5) indicate that the general direction of ground-water flow is from the western contact of the HAP aquifer with till and bedrock uplands toward the east, northeast, and southeast. The aquifer is recharged by precipitation, stream leakage, ground-water inflow from adjacent till-bedrock uplands, and by wastewater discharge. Under natural conditions, ground water discharges to streams, ponds, and wetlands; by evapotranspiration to the atmosphere; and by underflow to adjacent flow systems. Water-supply wells, however, intercept ground water that would have flowed to natural discharge areas. During the measurement period in October 1996, all but four of the water-supply wells were in operation; these four wells were KC1, NK10, 14A, and NK4. Although withdrawals lower ground-water levels in and around the wells, the scale of figure 5 is too small and the distances between observation wells were too large to show individual cones of depression.

Stream-Aquifer Interactions

The hydraulic interaction of the HAP aquifer with rivers, brooks, and ponds was inferred from downstream changes in streamflow at successive streamflow-measurement sites, and from paired measurements of ground-water and surface-water levels at streambed-piezometer sites. Gaining stream reaches are those in which net ground-water discharge to the stream is greater than net streamflow leakage to the aquifer, and, therefore, streamflow increases between two measurement sites. Conversely, losing stream reaches are those in which net streamflow leakage to the aquifer is greater than net ground-water discharge to the stream, and streamflow decreases between two measurement sites. Losing conditions result from natural

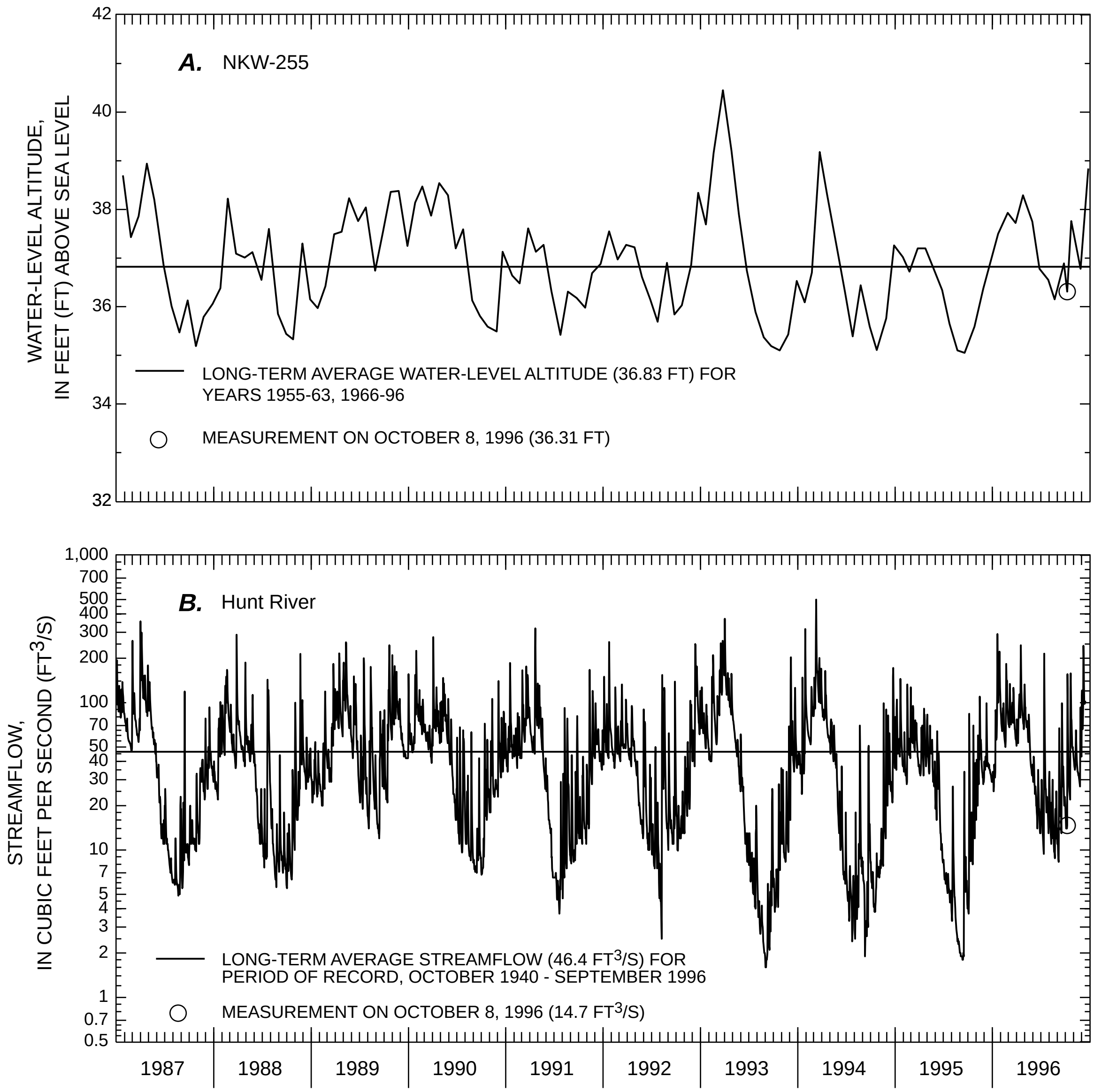


Figure 4. (*A*) Water-level altitudes at well NKW-255 and (*B*) streamflow for the Hunt River at the U.S. Geological Survey gaging station for the period January 1987 through December 1996, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island. (Locations of well and gaging station shown on fig. 2.)

stream-channel losses or from induced infiltration of streamflow caused by ground-water withdrawals. Paired measurements of ground- and surface-water levels at streambed-piezometer sites give the direction of flow between the aquifer and stream at each site.

Gaining and losing stream reaches were identified from streamflow measurements made at 19 to 22 sites in the study area on three dates (table 2). In calculating gains and losses of streamflow, tributary inflows between a pair of measurement sites were subtracted from the total gain or loss between the two sites (table 3). This likely resulted in some error in the gain/loss calculations because the measurement sites for some of the tributary streams were not immediately upstream of the tributary-mainstem confluence. Also, streamflow measurements typically have errors that affect the accuracy of the gain/loss calculations. As a result, where the gain or loss of streamflow in a reach is small, it may not be possible to accurately determine whether the reach is gaining or losing.

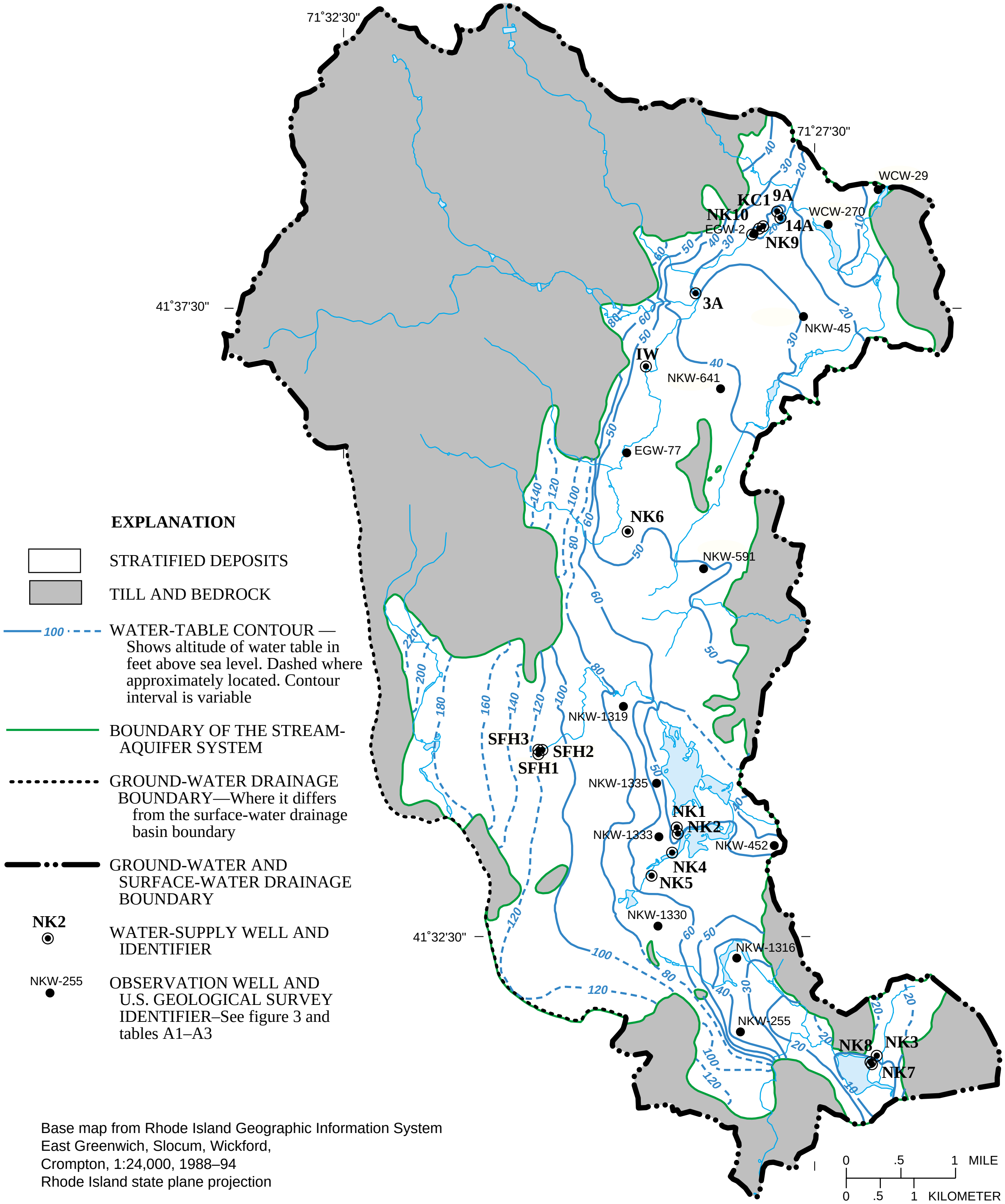


Figure 5. Altitude and configuration of the water table in the Hunt–Annaquatucket–Pettaquamscutt aquifer, Rhode Island, October 7–9, 1996. (Modified from Dickerman and Barlow, 1997; not all data points used to create the water-table map are shown in this figure.)

Table 2. Instantaneous streamflow in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Site identifiers are shown on figure 6. Streamflow is given in cubic feet per second and, in parentheses, million gallons per day. --, no data]

Site identi-fier	Instantaneous streamflow					
	September 20, 1995		April 24, 1996		October 8, 1996	
Hunt River Basin						
A	0.13	(0.08)	4.10	(2.65)	0.54	(0.35)
B	.24	(.16)	5.68	(3.67)	.98	(.63)
C	1.52	(.98)	16.6	(10.7)	3.07	(1.98)
D	4.73	(3.06)	23.8	(15.4)	4.81	(3.11)
E	1.24	(.80)	22.1	(14.3)	2.78	(1.80)
F	1.75	(1.13)	23.7	(15.3)	2.95	(1.91)
G	7.57	(4.89)	50.8	(32.8)	10.2	(6.59)
H	.04	(.03)	8.88	(5.74)	1.28	(.83)
I	5.65	(3.65)	64.5	(41.7)	7.13	(4.61)
J	5.43	(3.51)	62.7	(40.5)	7.71	(4.98)
K	5.14	(3.32)	61.3	(39.6)	10.6	(6.85)
L	--	--	1.29	(.83)	.18	(.12)
M	.08	(.05)	3.65	(2.36)	.90	(.58)
N	.78	(.50)	5.27	(3.41)	1.82	(1.18)
O	.71	(.46)	7.08	(4.58)	2.15	(1.39)
P	7.24	(4.68)	83.6	(54.0)	14.7	(9.50)
Cocumcussoc Brook Basin						
Q	.35	(.23)	4.37	(2.82)	1.14	(.74)
Annaquatucket River Basin						
R	--	--	2.68	(1.73)	1.95	(1.26)
S	--	--	3.84	(2.48)	1.36	(.88)
T	7.44	(4.81)	20.7	(13.4)	11.7	(7.56)
Pettaquamscutt River Basin						
U	1.36	(.88)	4.75	(3.07)	2.39	(1.55)
V	2.68	(1.73)	12.0	(7.76)	4.0	(2.59)

Table 3. Gains and losses of streamflow in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Stream reaches are shown on figure 6. Streamflow is given in cubic feet per second and, in parentheses, million gallons per day. --, no data]

Stream reach	Gain or loss (-) in streamflow					
	September 20, 1995		April 24, 1996		October 8, 1996	
Hunt River Basin						
A–C	1.15	(0.74)	6.82	(4.41)	1.55	(1.00)
C–D	3.21	(2.08)	7.20	(4.65)	1.74	(1.12)
E–F	.51	(.33)	1.60	(1.03)	.17	(.11)
D–G	1.09	(.70)	3.30	(2.13)	2.44	(1.58)
G–I	-1.96	(-1.27)	4.82	(3.12)	-4.35	(-2.81)
J–K	-.29	(-.19)	-1.40	(-.91)	2.89	(1.87)
L–M	--	--	2.36	(1.53)	.72	(.47)
M–N	.70	(.45)	1.62	(1.05)	.92	(.59)
N–O	-.07	(-.05)	1.81	(1.17)	.33	(.21)
K–P	1.39	(.90)	15.2	(9.82)	1.95	(1.26)
Annaquatucket River Basin						
R–S	--	--	1.16	(.75)	-.59	(-.38)
S–T	--	--	16.9	(10.90)	10.3	(6.68)

The distribution and rates of streamflow gains and losses shown in table 3 vary in response to changing climatic conditions and changes in the locations and rates of withdrawals at supply wells. This result is particularly evident for the Hunt River, where losing reaches migrated between sites G and K on the three measurement dates (table 3). Streamflow losses between sites G and K on the Hunt River are caused, in part, by withdrawals from supply wells near the river. Reach R-S on the Annaquatucket River was losing on October 8, 1996, but was gaining on April 24, 1996, when streamflows were higher throughout the system (table 2). The large increases in streamflow on the Annaquatucket River measured between sites S and T on April 24 and October 8, 1996, are the result of the large ground-water drainage area west of Belleville Pond and upgradient of site T.

Streamflow gains and losses on October 8, 1996, when water levels were measured throughout the HAP aquifer, are shown on figure 6. Gaining conditions were measured on this date on all reaches with the exception of reach G-I on the Hunt River and reach R-S on the Annaquatucket River (fig. 6 and table 3). Instantaneous streamflow at the gaging station on the Hunt River (site P, fig. 6) on this date (14.7 ft^3/s) was lower than average streamflow measured at the gage for the 56-year period from October 1940 through September 1996 (46.4 ft^3/s, fig. 4*B*). The low streamflow measured on this date is typical of flow in the river during early autumn (fig. 4*B*). Flow in other streams in the study area on October 8, 1996, also was likely to be lower than average.

The direction of flow between the aquifer and adjoining streams determined from water levels measured at the 16 streambed-piezometer sites on October 8, 1996, was generally consistent with the gaining and losing reaches identified from streamflow measurements on that date.

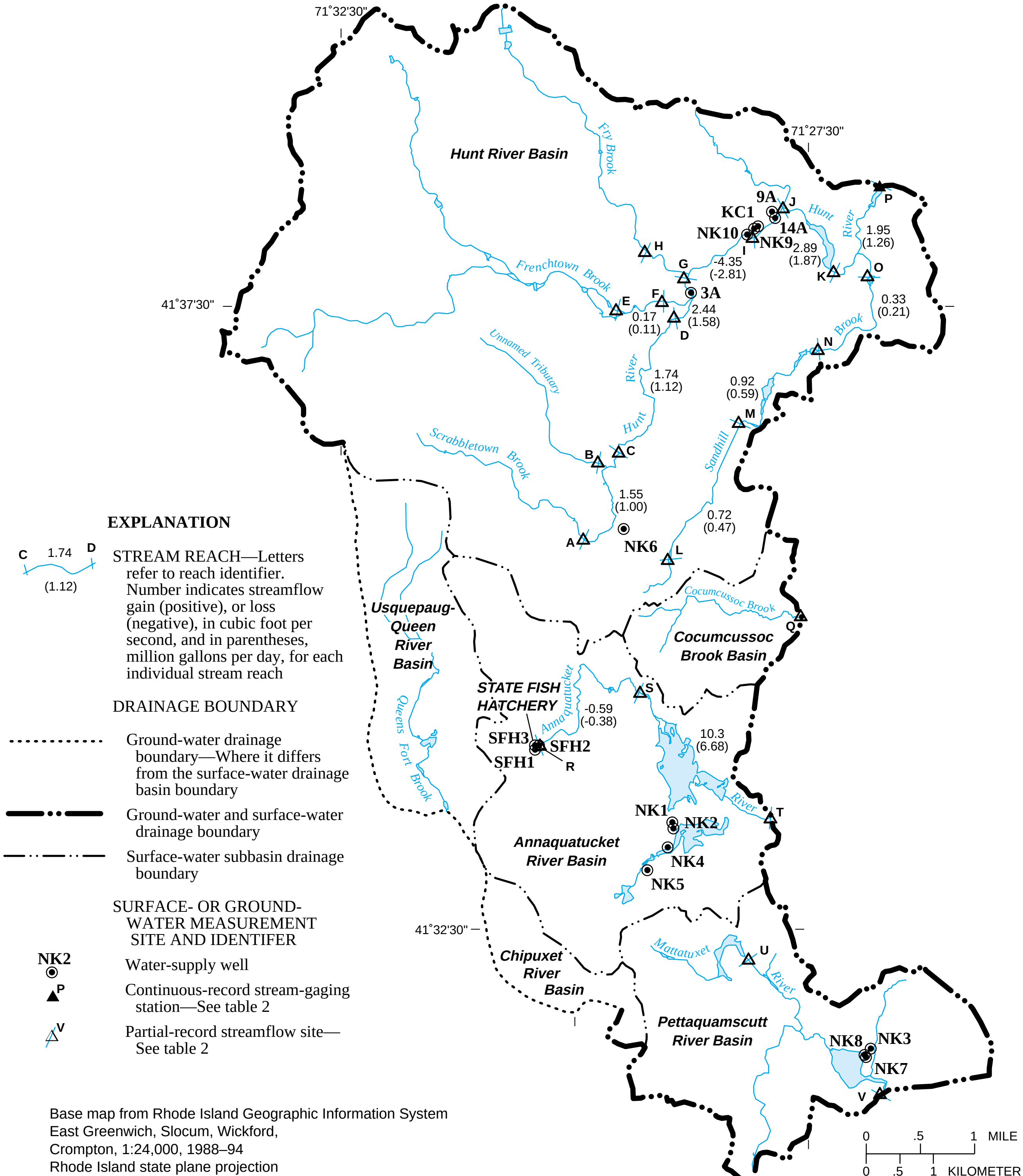


Figure 6. Streamflow measurement sites and distribution of gaining and losing stream reaches in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, October 8, 1996.

At four sites, however, the direction of flow was downward even though a streamflow gain was measured in the reach above or below the site. At two of these four sites (site F on Frenchtown Brook and site S on the Annaquatucket River), the water table was more than 4.5 ft below the streambed. The discrepancy between the downward water-level measurements at the piezometer sites and the gaining conditions measured in reaches above or below the piezometer sites may have resulted because water levels measured at the piezometer sites provide a measurement of stream-aquifer interaction at a single point along a stream reach, whereas changes in streamflow measured between two sites give net gains or losses of flow over an entire stream reach. Some of the discrepancy between the two types of measurements also may have been caused by measurement errors, particularly those for streamflow.

Hydrologic Components and Budget

A hydrologic budget was estimated for the HAP stream-aquifer system for the 56-year period 1941–96. The budget identifies and quantifies the hydrologic inflow and outflow components of the stream-aquifer system and provides data that are used in the development and calibration of the numerical models of the system. The hydrologic components of the system are illustrated in figure 7. The system shown in figure 7 is assumed to be in a steady-state condition (that is, there are no changes in water storage in the system); as a consequence, storage changes are not identified.

Precipitation (*PR*) is the ultimate source of water to the study area. Some of this precipitation is returned to the atmosphere by evaporation and transpiration at or near land surface (ET_S). Precipitation that is not returned to the atmosphere either flows directly to the surface-water drainage system as direct runoff (*DR*) or is recharged to the ground-water system (R_{PR}). Direct runoff and ground-water recharge that occur in the till and bedrock uplands enter the stream-aquifer system as streamflow (SF_I) or lateral ground-water inflow (GW_I).

Within the stream-aquifer system, some water is recharged to the aquifer by streamflow leakage that results from natural stream-channel losses (SL_N) or induced infiltration caused by ground-water withdrawal (SL_I). Ground water is discharged from the HAP aquifer to the rivers, brooks, and ponds that make up the surface-water network (GW_D); this discharge is referred to as the base flow of streams. Ground water also discharges by evapotranspiration where the water table is near land surface (ET_{GW}), such as along streams and in wetlands; by ground-water withdrawal (Q_W); and by underflow out of the basin at the downgradient boundary of the stream-aquifer system (GW_U). Of the water that is withdrawn from the aquifer (Q_W), some is exported out of the basin (Q_E), some is used consumptively within the basin (Q_C), some is discharged to the headwaters of the Annaquatucket River at the Lafayette State Fish Hatchery (Q_{AR}), and some is returned to the aquifer by wastewater discharge (R_{WW}). Streamflow leaves the system at the downgradient boundaries of each of the river basins (SF_O).

The following two sections describe methods used to quantity each of the inflow and outflow components of the hydrologic budget for the 1941–96 period. Only those components that are sources and sinks along the boundaries of the stream-aquifer system were included in the hydrologic budget (fig. 8). Inflow components (sources) along the boundaries of the system are R_{PR}, R_{WW}, GW_I, SF_I, Q_{AR}, and *DR*; outflow components (sinks) are SF_O, ET_{GW}, GW_U, and Q_W. Precipitation (*PR*), near-surface evapotranspiration (ET_S), internal flows (SL_N, SL_I, and GW_D), and two of the subcomponents of ground-water withdrawal (Q_E and Q_C) are not needed, or included, in the budget.

R_{PR}, *DR*, and ET_{GW} were estimated with analysis techniques that are based on streamflow records at continuous-record gaging stations. These techniques require that various assumptions be made with respect to the streamflow record and hydrologic conditions in the basin; these assumptions are discussed in detail by Rutledge (1993 and 2000). One of these assumptions is that there are no ground-water withdrawals within the basin from which the streamflow record is derived. Because there have been withdrawals from the Hunt River Basin throughout the 1941–96 period, the streamflow record of a nearby basin where much less ground water has been withdrawn also was used to estimate R_{PR}, *DR*, and ET_{GW}, for comparison to the values of these three variables determined for the Hunt River Basin.

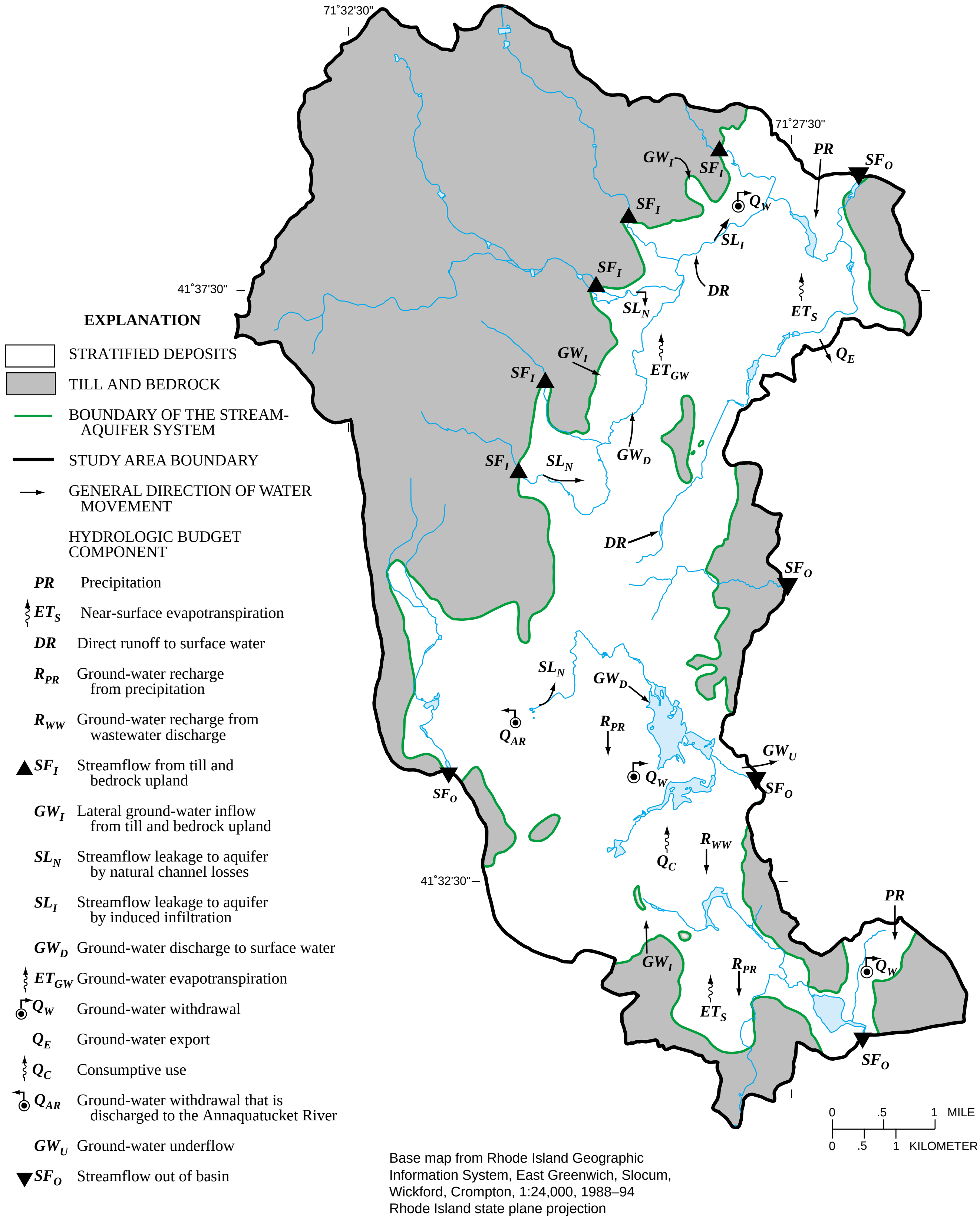
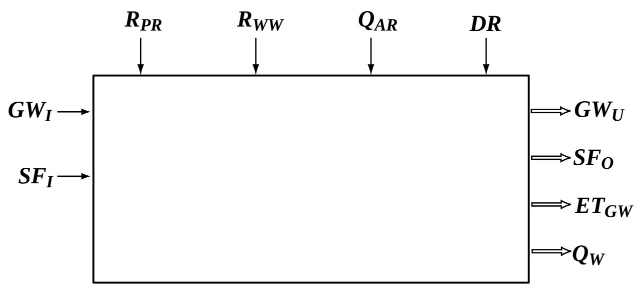


Figure 7. Steady-state hydrologic budget components of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.



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
Q_{AR}	Ground-water withdrawal that is discharged to the Annaquatucket River	ET_{GW}	Ground-water evapotranspiration
DR	Direct runoff to surface water	Q_W	Ground-water withdrawal
GW_I	Lateral ground-water inflow from till and bedrock upland		
SF_I	Streamflow from till and bedrock upland		

Figure 8. Sources and sinks of water along the boundaries of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

The record of the Pawcatuck River at Wood River Junction, Rhode Island (USGS gaging station 01117500, fig. 1), was selected because (1) the gaging station is relatively close to the HAP study area (about 18.3 mi southwest of the Hunt River gaging station); (2) the record includes the entire 1941-96 period; and (3) the percentage of stratified deposits within the drainage area of the gaging station (47 percent) is similar to that within the drainage area of the Hunt River gaging station (52 percent). This similarity is important because geology affects the flow and storage of water within a basin.

On an areal basis, average annual streamflow at the Hunt and Pawcatuck River gaging stations during the 1941–96 period was very similar, with 27.6 in. for the Hunt River and 26.4 in. for the Pawcatuck River. Average annual near-surface evapotranspiration (ET_S) can be estimated for each basin by subtracting average annual streamflow from the average annual precipitation to each basin, which was estimated to have been 47.5 in/yr for the 1941–96 period. Therefore, average annual ET_S is estimated to have been 19.9 in/yr for the Hunt River Basin and 21.1 in/yr for the Pawcatuck River Basin for the 56-year period.

Inflow Components

Ground-water recharge from precipitation (R_{PR}) is the major source of water to the HAP stream-aquifer system. Annual and monthly precipitation recharge rates were estimated by analysis of streamflow records for the Hunt and Pawcatuck Rivers with the computer program RORA (Rutledge, 1993). RORA is based on a method that estimates recharge from vertical displacements in a streamflow record. The program requires that a recession index be specified for each basin for which recharge is estimated. The recession index is the time required for streamflow during periods of base-flow recession to decline through one logarithmic (log) cycle on a semi-logarithmic plot of streamflow (on the log axis) and time (on the linear axis). The recession index was determined for each basin with the computer program RECESS (Rutledge, 1993). Recession periods during December through March were used in the analysis because ET_{GW} can be assumed to be negligible during these winter months. The recession index determined for the Hunt River Basin was 20.2 days per log cycle and for the Pawcatuck River Basin was 29.8 days per log cycle.

Average annual ground-water recharge rates calculated from streamflow records for the Hunt and Pawcatuck River gaging stations for the 1941–96 period were 25.4 in. and 25.5 in., respectively. These are effective recharge rates over the entire basin, including areas of stratified sand and gravel, till, bedrock, wetlands, and ponds. These average annual recharge rates are similar to those calculated for other basins of Rhode Island (Dickerman and others, 1990, 1997; Dickerman and Bell, 1993; Bent, 1995; Barlow, 1997a). The total average annual volumetric recharge rate to the HAP stream-aquifer system for the 1941–96 period was estimated at 35.5 ft^3/s, and was calculated by multiplying the recharge rate of 25.4 in/yr estimated for the Hunt River Basin by the 19.0 mi^2 area of the HAP system.

The variability of annual ground-water recharge within the two river basins for the 1941–96 period is shown by the graphs in figure 9. The maximum estimated annual recharge rate for the Hunt River Basin (45.1 in.) occurred in 1983 and the minimum estimated annual recharge rate (11.5 in.) in 1966 (fig. 9*A*). The graphs clearly indicate a period of very low recharge during the mid 1960s that is coincident with a period of severe drought throughout the northeastern United States. Average monthly recharge rates calculated for the 1941–96 period for the Hunt River Basin range from 0.6 in. for September to 4.3 in. for March (fig. 10*A*); a similar range was calculated for the Pawcatuck River Basin (0.9 in. for August to 4.0 in. for March; fig. 10*B*). For both basins, the variability of monthly recharge rates is smallest during July through October when recharge rates are lowest, as indicated by the standard deviation of calculated monthly recharge rates during the 56-year period (fig. 10).

The second component of ground-water recharge is wastewater discharge to the aquifer (R_{WW}), such as produced by septic systems. Very few sewered areas are present within the HAP stream-aquifer system; most water delivered for domestic and other uses is returned to the aquifer by on-site discharge facilities. The amount of wastewater discharge to the aquifer during the 1941–96 period was estimated from information on the locations and rates of water-supply deliveries for the town of North Kingstown available for 1996. For this analysis, it was assumed that the rate of wastewater discharge is constant throughout the year. It also was assumed that wastewater recharged to the aquifer does not cause vertical displacements in the streamflow record of the Hunt River, and, as a consequence, that wastewater recharge is not included in the estimate of R_{PR}.

Unsewered areas that receive town water were identified by overlaying a map of the town's water-distribution system onto a map of the HAP stream-aquifer system. The town's water-distribution system consists of several zones in which water-delivery rates are reported quarterly. From the water-delivery data, a total wastewater recharge rate of 1.2 ft^3/s was estimated. This estimate may be high because no reduction was made to account for consumptive losses, which are usually estimated to be about 10 percent of water deliveries.

Part of the ground water that is recharged in the till and bedrock upland areas reaches the HAP stream-aquifer system by lateral ground-water inflow at the boundary between the upland areas and HAP aquifer (GW_I). An estimate of GW_I was determined by multiplying the effective average-annual recharge rate estimated for the Hunt River Basin (25.4 in/yr) by the amount of upland area that is not drained by streams (6.8 mi^2). The total average annual rate of lateral ground-water inflow for the period 1941–96 was estimated at 12.7 ft^3/s.

Streamflow from till and bedrock upland areas (SF_I) was estimated from streamflow measurements made at four partial-record gaging sites established on the four largest streams draining the upland area (fig. 6): Scrabbletown Brook (site A), unnamed tributary to the Hunt River (site B), Frenchtown Brook (site E), and Fry Brook (site H). Measurements were made once each month during the 16-month period from August 1995 through November 1996 (with the exception of December 1995). These four streams have a total drainage area within the till and bedrock uplands of 12.1 mi^2, which is 91.7 percent of the total upland area that is drained by streams that flow to the HAP stream-aquifer system (13.2 mi^2) (0.6 mi^2 of upland area drains away from the stream-aquifer system to Cocumcossuc Brook). Streamflow measurements were made as close as possible to the boundary between the till and bedrock upland areas and the HAP system. The total drainage area to the four partial-record sites is 12.4 mi^2, which includes 0.3 mi^2 of the HAP system. All streamflow measurements made at these sites are given in appendix B.

Streamflow measurements made at each of the partial-record sites on each of the measurement dates were graphically correlated (by use of logarithmic plots) to the average daily streamflow on the same dates at the continuous-record streamflow-gaging station on the Pawcatuck River at Wood River Junction. From these correlation graphs, an average annual streamflow was determined for each of the four streams for the 1941–96 period that corresponds to the average annual streamflow for the same period for the Pawcatuck River at Wood River Junction (194 ft^3/s). The resulting combined average annual streamflow for these four streams is 23.9 ft^3/s, of which more than 50 percent is for Frenchtown Brook (13.5 ft^3/s). The total streamflow originating within the till and bedrock upland drainage areas of these four streams is slightly

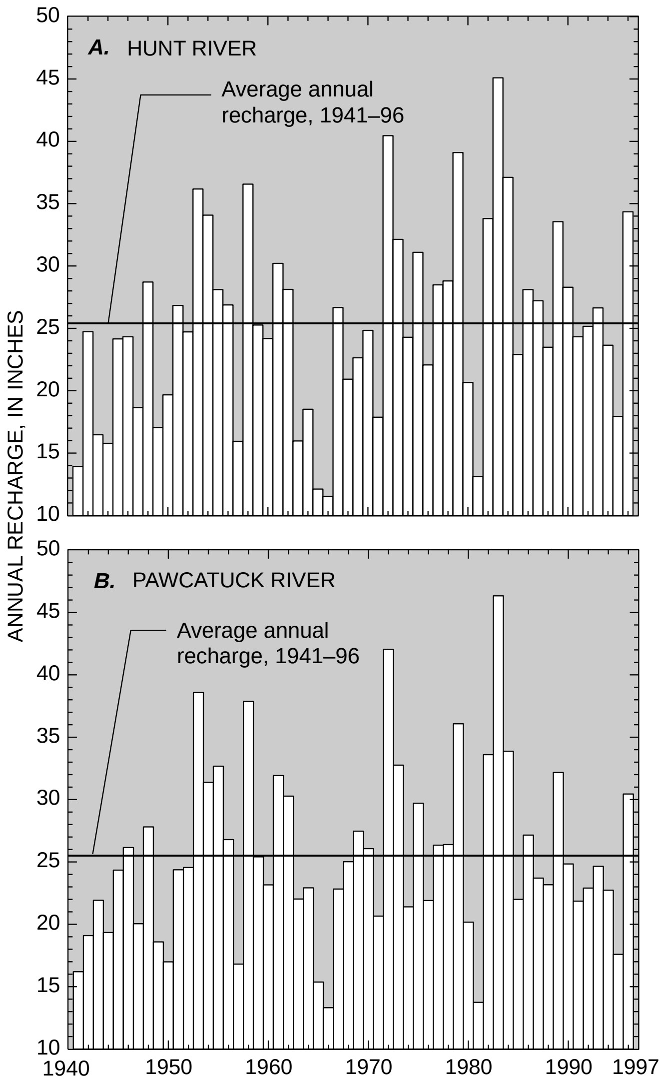


Figure 9. Annual ground-water recharge estimated from streamflow records for (*A*) Hunt River near East Greenwich and (*B*) Pawcatuck River at Wood River Junction, Rhode Island, 1941–96.

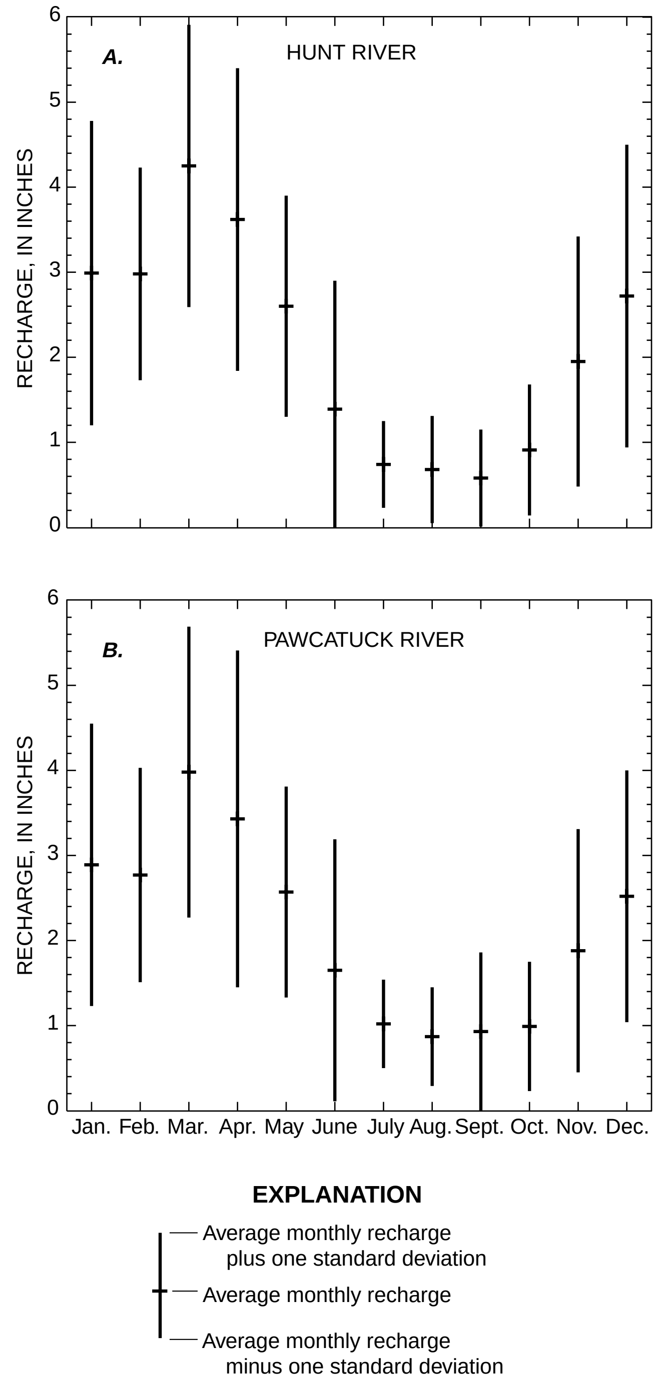


Figure 10. Monthly recharge rates estimated from streamflow records for (*A*) Hunt River near East Greenwich and (*B*) Pawcatuck River at Wood River Junction, Rhode Island, 1941–96.

less than 23.9 ft^3/s because of the small area (0.3 mi^2) within the HAP system that is drained by the streams. If it is assumed that the rate of runoff per square mile of drainage area for the entire 13.2 mi^2 till and bedrock upland area drained by streams that flow to the HAP system is the same as the 12.4 mi^2 drained by the four measured streams [1.93 $(ft^3/s)/mi^2$], then the total average annual streamflow from the entire 13.2-square-mile upland area is estimated to have been 25.5 ft^3/s during the 1941–96 period. The correlation graphs also were used to estimate average monthly streamflows for each of the four streams for the 1941–96 period. The estimated combined average monthly streamflows for all four streams range from a minimum of 4.5 ft^3/s in September to a maximum of 48.5 ft^3/s in March.

An additional source of streamflow to the HAP system is ground water that is withdrawn at the Lafayette State Fish Hatchery (wells SFH1, SFH2, and SFH3 on fig. 1) and then discharged to the Annaquatucket River after use in the hatchery (Q_{AR}, fig. 7). Average annual discharge from the hatchery is estimated to have been 2.0 ft^3/s during 1941–96, on the basis of measurements made in 1995–96 and discussions with hatchery personnel (Peter Angelone, Rhode Island Department of Environmental Management, oral commun., 1996).

Direct runoff (*DR*) to a stream can be calculated by subtracting ground-water base flow from total flow in the stream. Ground-water base flow in the Hunt and Pawcatuck Rivers was estimated with the hydrograph-separation computer program PART (Rutledge, 1993). The theoretical basis of the program is described by Rutledge (1993). The average annual base flow calculated for the 1941–96 period was 22.3 in. for the Hunt River and 23.8 in. for the Pawcatuck River. Because average annual streamflow for each river during the same period was 27.6 in. and 26.4 in., respectively, average annual direct runoff for the period (streamflow minus base flow) is estimated to have been 5.3 in. for the Hunt River Basin and 2.6 in. for the Pawcatuck River Basin. Differences between the two values likely are caused by physical differences between the two basins, including the amount of stratified sand and gravel and wetlands in each basin and the topographic slope of each basin, and by errors introduced into the estimate of base flow for each basin as a result of ground-water withdrawals. Based on the estimate of direct runoff for the Hunt River Basin (5.3 in/yr), the total average annual rate of direct runoff from within the HAP stream-aquifer system and from the undrained upland areas (a total area of 25.8 mi^2) for the 1941–96 period was estimated at 10.1 ft^3/s.

Outflow Components

Streamflow (SF_O) is the major outflow component from the HAP stream-aquifer system. Rates of outflow were estimated for five streams: the Hunt River, Cocumcossuc Brook, Annaquatucket River, Pettaquamscutt River, and Queens Fort Brook. Continuous streamflow measurements for the 1941–96 period of analysis only are available for the Hunt River, during which time the average annual streamflow at the point at which the river leaves the basin (site P, fig. 6) was 46.4 ft^3/s. Queens Fort Brook is a naturally losing stream that is dry over most of its length during most of the year (Kliever, 1995). Average annual streamflow for the brook is assumed to be zero. Average annual streamflows for Cocumcossuc Brook, Annaquatucket River, and Pettaquamscutt River were estimated in the same manner as was done for the four streams that flow into the stream-aquifer system from upland areas. Partial-record streamflow-gaging sites were established on Cocumcossuc Brook, Annaquatucket River, and Pettaquamscutt River, where these rivers leave the basin (sites Q, T, and V). Streamflow was measured at each site once each month during the 16-month period from August 1995 through November 1996 (with the exception of December 1995). From these measurements, logarithmic correlation graphs were developed between flow in each of the streams on each of the measurement dates and the average daily streamflow on the same dates at the continuous-record streamflow gaging station on the Pawcatuck River at Wood River Junction. The average annual streamflow determined from the correlation graphs for the 1941–96 period was 4.0 ft^3/s for Cocumcossuc Brook, 17.0 ft^3/s for Annaquatucket River, and 9.5 ft^3/s for Pettaquamscutt River. Therefore, total average annual streamflow out of the basin in the five streams was estimated at 76.9 ft^3/s.

The average annual rate of evapotranspiration from the water table (ET_{GW}), which is sometimes referred to as riparian evapotranspiration (Rutledge, 1993), is equal to the difference between the average annual ground-water recharge rate (R_{PR}) to an aquifer and average annual base-flow rate out of the aquifer (which, as described previously, is equal to the ground-water discharge rate, GW_D). ET_{GW} was estimated for the Hunt and Pawcatuck River Basins from the values of precipitation recharge and ground-water base flow for each basin determined with programs RORA and PART for the 1941–96 period (described previously). The resulting estimates of ET_{GW} are 3.1 in/yr for the Hunt River Basin and 1.7 in/yr for the Pawcatuck River Basin. These estimates are average rates over the entire areal extent of each basin; in areas where evapotranspiration actually occurs, the rate of evapotranspiration is likely to be much higher than these basin-wide averages. These estimated rates of ET_{GW} are similar to those determined by means of the same estimation methods for other river basins of southern Rhode Island (Dickerman and others, 1997; Barlow, 1997a) and for the Buzzards Bay Basin in southeastern Massachusetts (Bent, 1995). Based on the estimate of 3.1 in/yr determined for the Hunt River Basin, the total average annual rate of evapotranspiration from the water table within the 19.0 mi^2 stream-aquifer system was estimated at 4.3 ft^3/s for the 1941–96 period.

Small amounts of ground water flow out of the stream-aquifer system as ground-water underflow (GW_U) where Cocumcussoc Brook and the Hunt, Annaquatucket, and Pettaquamscutt Rivers leave the stream-aquifer system. The only location of substantial underflow is across a 0.5-mile width of aquifer near the outflow point of the Annaquatucket River (site T, fig. 6). The rate of underflow in this area was determined from Darcy's law. Transmissivity of the aquifer was estimated from plate 2 of Rosenshein and others (1968), and the hydraulic gradient of the water table was estimated from the water-table map of the area given in Dickerman and Barlow (1997). The average annual underflow rate estimated for this area is 1.0 ft^3/s.

Ground water has been withdrawn at public water-supply wells in the HAP aquifer throughout the 56-year period of analysis. During that time, the number of wells in use, the locations of withdrawal, and the rates of withdrawal have changed. Because there are 14 public water-supply wells in the aquifer and 56 years of analysis, a total of 784 record-years of withdrawal data are needed for the analysis. Included in this total are years in which withdrawal at a particular well was zero because the well was not yet installed or was not operated. These years of zero withdrawal are necessary because streamflow data for the same period reflect both withdrawal and non-withdrawal conditions. Unfortunately, withdrawal records for public water-supply wells in the basin are incomplete. Of the 784 record-years needed, only 551 record-years, or 70 percent of the total, were found to have been archived and available. Most or all of the withdrawal records were available for 1941–61, 1970–75, and 1990–96, but many records were unavailable for 1962–69 and 1976–89. Monthly withdrawals for each public water-supply well in the system for the 1941–96 period are given in appendix C.

Because the withdrawal record for the system is incomplete, it was not possible to determine the actual average annual withdrawal rates for each well. Instead, an estimate of the average annual withdrawal rate in each basin during the 56-year period was made from the available record, under the assumption that the average of the known record would approximately equal the average of the true record. This assumption is supported by the fact that withdrawal records were available for different time periods throughout the total 56-year period of analysis (1941–61, 1970–75, and 1990–96) and were not concentrated at either the beginning or end of the analysis period. The resulting average annual withdrawal rates at public water-supply wells for the 1941–96 period was estimated at 4.4 ft^3/s for the Hunt River Basin, 1.0 ft^3/s for the Annaquatucket River Basin, and <0.1 ft^3/s for the Pettaquamscutt River Basin; total average annual withdrawal from these wells, therefore, was estimated at 5.4 ft^3/s.

Ground water also has been withdrawn at an industrial facility in the Hunt River Basin and at the Lafayette State Fish Hatchery in the Annaquatucket River Basin. Although withdrawal rates at these two facilities are not available for the entire 1941–96 period, estimated average rates of withdrawal for 1996 were provided by personnel at each facility. These rates were 0.4 ft^3/s at the industrial facility and 2.0 ft^3/s at the fish hatchery. Assuming that the average withdrawal rates at these wells for the 1941–96 period were the same as the 1996 average withdrawal rates, these additional withdrawals increase the total estimated average annual withdrawal rates from the Hunt and Annaquatucket River Basins to 4.8 ft^3/s and 3.0 ft^3/s, respectively. Total average annual withdrawal from all wells in the stream-aquifer system (Q_W) during the 1941–96 period, therefore, was estimated at 7.8 ft^3/s.

Hydrologic Budget

An average annual hydrologic budget for the HAP stream-aquifer system for the 1941–96 period can be determined on the basis of the inflow and outflow components estimated in the preceding two sections. The steady-state average annual budget for the system is

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

The estimated average annual hydrologic budget for the system is summarized in table 4.

As shown in the table, there is an error in the estimated budget of -3.0 ft^3/s. This error, which is about 3.4 percent of the average of the total inflow and outflow components (88.5 ft^3/s), is the result of various factors. These include (1) use of the streamflow record of the Hunt River to estimate some of the budget

Table 4. Estimated average annual hydrologic budget for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1941–96

[Budget components shown schematically on figure 7]

Hydrologic budget component	Rate of flow	
	Cubic feet per second	Million gallons per day
Estimated inflow		
Recharge		
Precipitation (R_{PR})	35.5	23.0
Wastewater return flow (R_{WW})	1.2	.8
Lateral ground-water inflow (GW_I)	12.7	8.2
Streamflow from uplands (SF_I)	25.5	16.5
Ground water discharged to Annaquatucket River (Q_{AR})	2.0	1.3
Direct runoff (DR)	10.1	6.5
Total inflow	87.0	56.3
Estimated outflow		
Streamflow (SF_O)	76.9	49.7
Evapotranspiration (ET_{GW})	4.3	2.8
Ground-water underflow (GW_U)	1.0	.7
Ground-water withdrawal (Q_W)	7.8	5.0
Total outflow	90.0	58.2
Budget error (inflow-outflow)	-3.0	-1.9

components (R_{PR}, DR, and ET_{GW}), even though ground-water withdrawals have affected the record; (2) the assumption that the average annual wastewater recharge rate for the 56-year period is equal to that estimated for 1996; (3) use of a uniform recharge rate in the upland areas equal to the estimated rate of precipitation recharge to the HAP stream-aquifer system; (4) inaccuracies in the correlation graphs developed between streamflow in the HAP stream-aquifer system with streamflow in the Pawcatuck River Basin; (5) an incomplete record of ground-water withdrawal rates from the system; and (6) the assumption that the system is at steady state.

Although not included in the hydrologic budget, an estimate of the rate of ground-water export from the HAP stream-aquifer system (Q_E) can be made from the budget components. This rate is equal to the difference between the rate of ground-water withdrawal from the aquifer (Q_W; 7.8 ft^3/s) and the rate at which this water is returned to the stream-aquifer system. The total rate at which water is returned to the system is equal to the sum of the rate of discharge to the headwaters of the Annaquatucket River at the Lafayette State Fish Hatchery (Q_{AR}; 2.0 ft^3/s) and the rate of wastewater discharge (R_{WW}; 1.2 ft^3/s). Therefore, the estimated rate of ground-water export from the system during the 56-year period is 4.6 ft^3/s, or about 59 percent of the estimated total ground-water-withdrawal rate.

STEADY-STATE NUMERICAL MODEL

Ground-water flow in the HAP aquifer was simulated with the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), commonly known as MODFLOW. 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 11. As shown in the figure, ground-water flow was only simulated within the stratified deposits. The active area of the model is much smaller than the full lateral extent of the model domain, which is 57.9 mi^2. The model grid was aligned approximately parallel to the northeast-trending valleys of the Hunt River and Sandhill Brook and southeast-trending valley of the Pettaquamscutt River. The steady-state model simulated average flow conditions that are presumed to represent the 56-year period 1941–96.

Development

Spatial Discretization

The model domain was discretized into a grid of 205 rows by 197 columns of square cells that are a uniform size of 200 ft on each side (fig. 12). In the vertical dimension, the model domain consists of a maximum of four layers and extends from the water table to the intersection of the HAP aquifer with underlying bedrock. The layers were discretized with reference to the water-table map of October 1996 (Dickerman and Barlow, 1997) and the bedrock-elevation map prepared by Rosenshein and others (1968) and modified during this study. A water-table elevation was calculated for each cell of the top layer of the model by overlaying a geographically referenced digital coverage of the

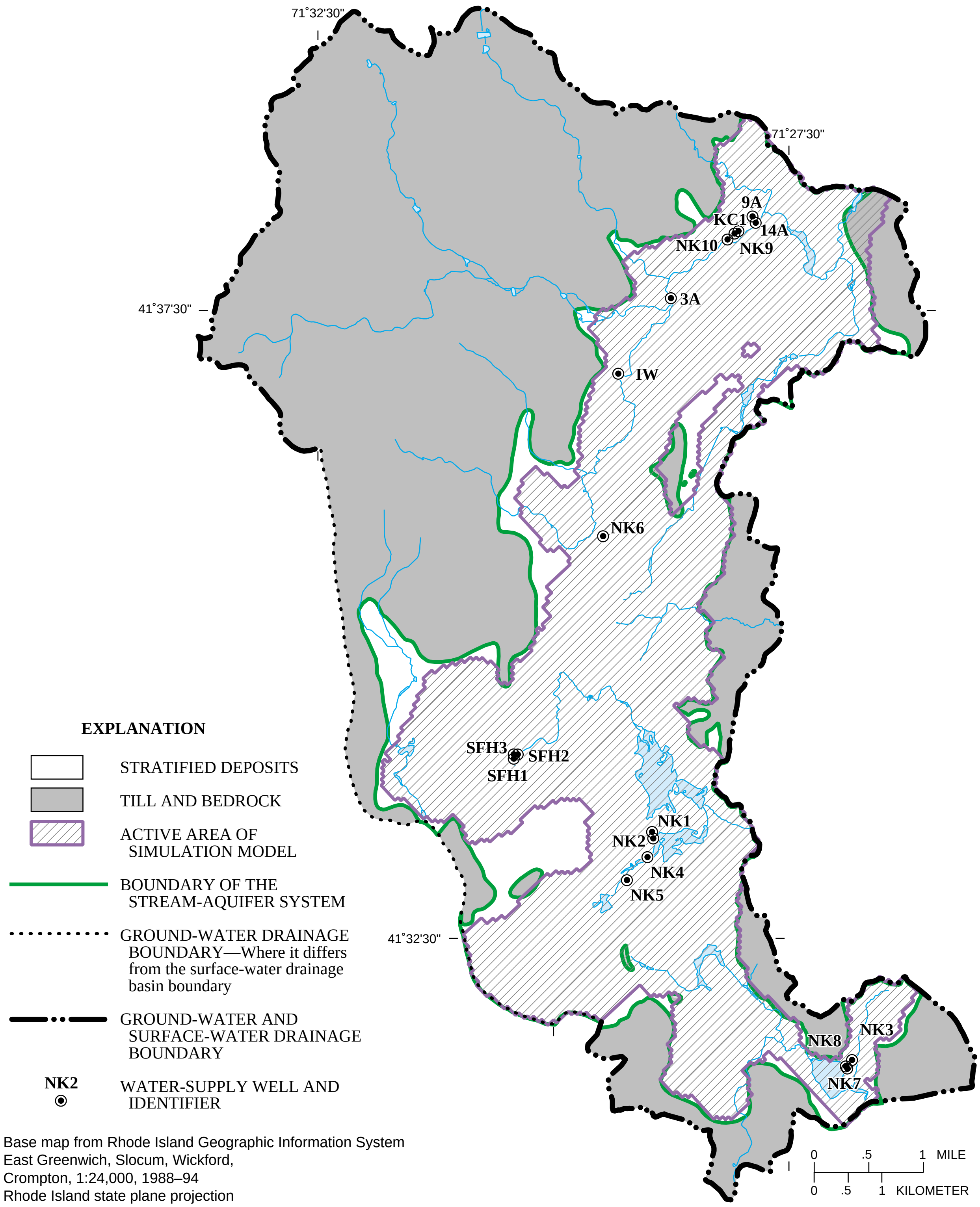


Figure 11. Spatial extent of active area of simulation model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

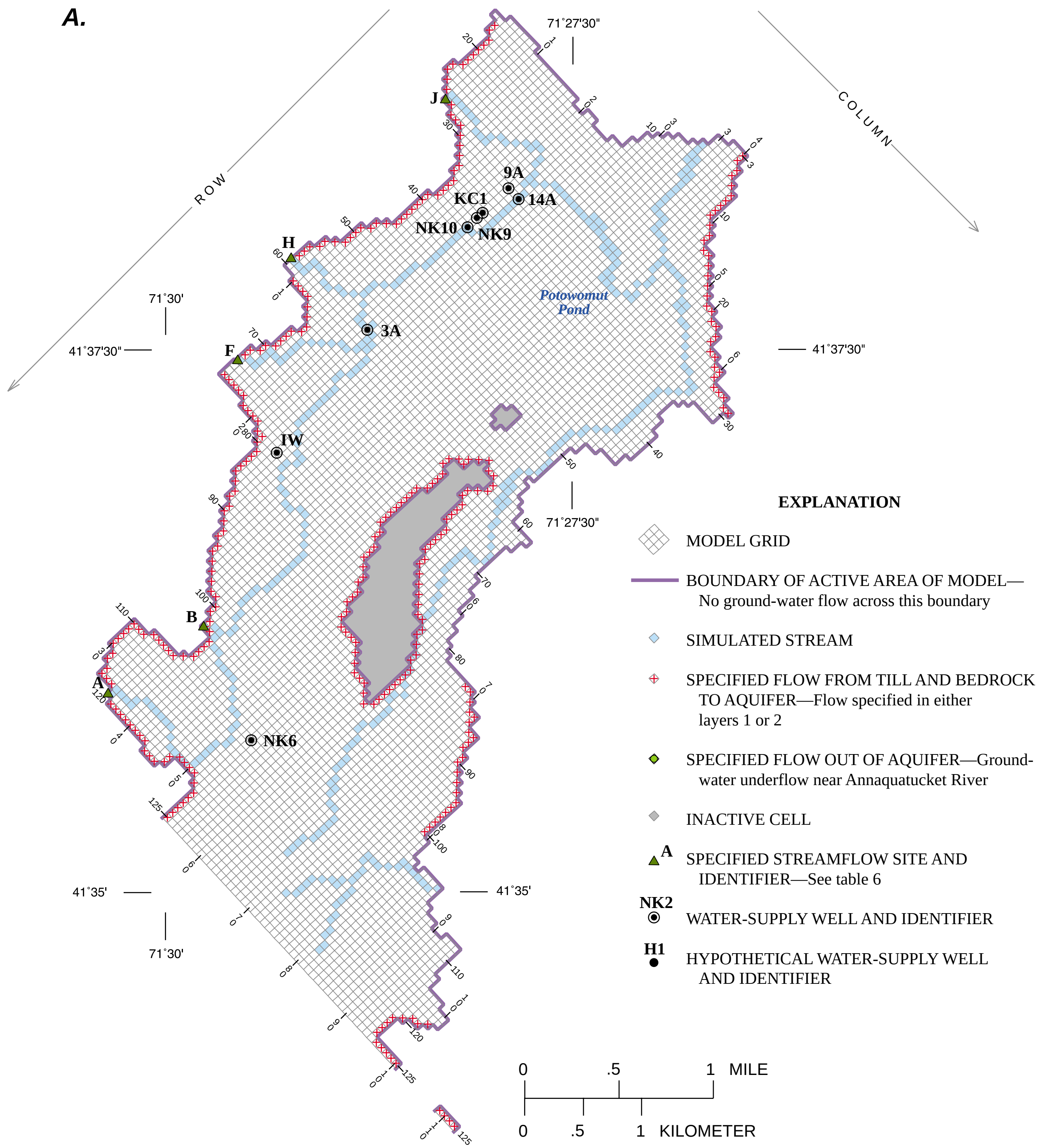


Figure 12. Grid and boundary conditions of the simulation model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, (*A*) rows 3–125 and (*B*) rows 126–205.

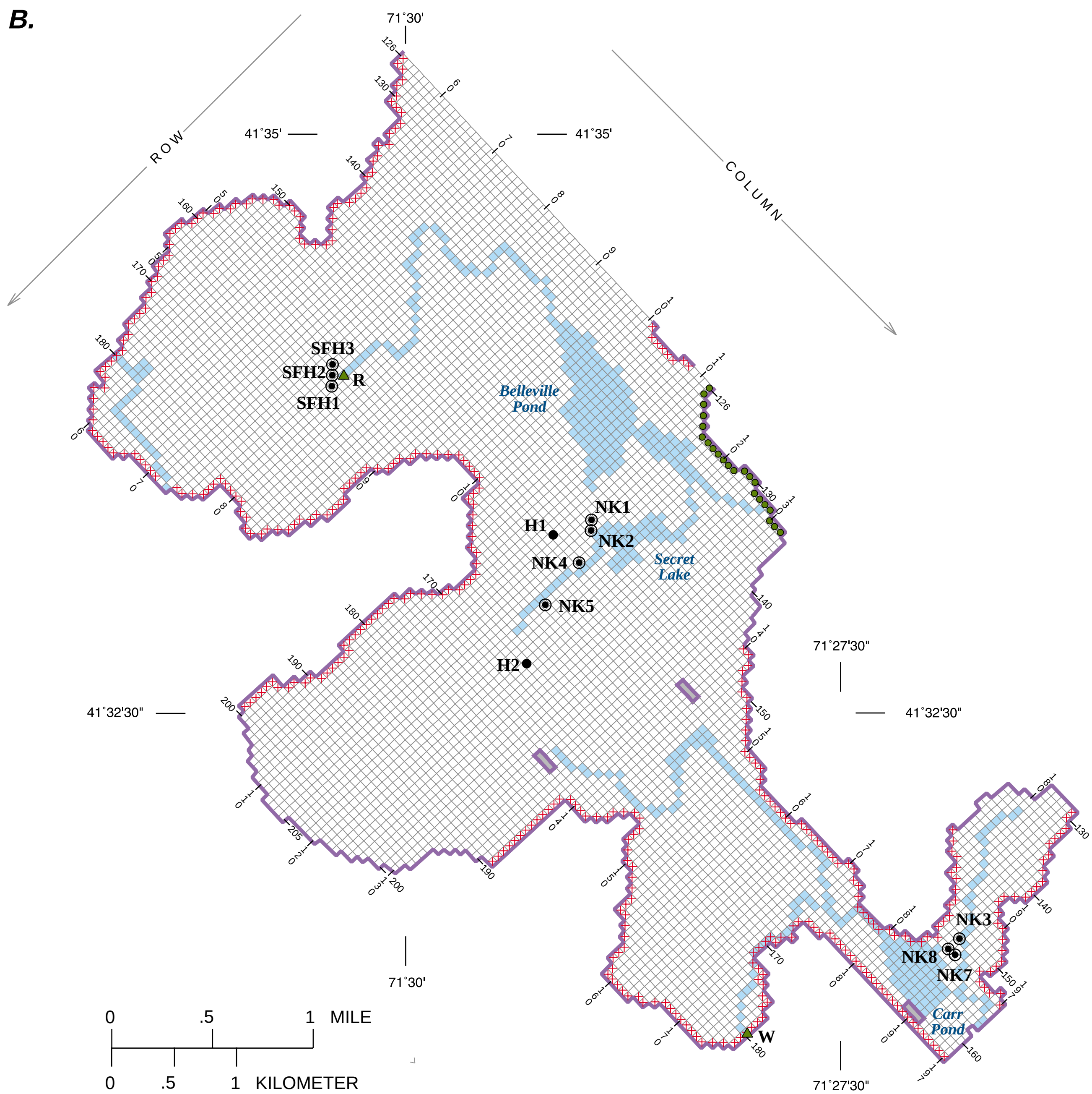


Figure 12. Grid and boundary conditions of the simulation model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, (*A*) rows 3–125 and (*B*) rows 126–205—*Continued*.

water-table map onto a geographically referenced coverage of the model grid. The elevation at which the HAP aquifer intersects bedrock 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 top layer of each stack of cells extends to a maximum depth of 10 ft below the water table. This uppermost layer is relatively thin in order to simulate shallow ground-water flow near surface-water bodies as accurately as possible. The maximum thickness of the second and third layers is 30 ft thick; layer 2 extends from 10 ft to a maximum of 40 ft below the water table and layer 3 extends from 40 ft to a maximum of 70 ft below the water table. Layers 2 and 3 are less than 30 ft thick where the HAP aquifer is truncated by underlying bedrock. The fourth layer extends from the bottom of the third layer to the HAP aquifer/bedrock contact. Because the thickness of the aquifer varies laterally, the number of active layers within each vertical stack of cells varied laterally as well. The active area of each model layer decreased in size from the top to the bottom layer.

Areas of the HAP aquifer where saturated thickness was less than 5 ft were made inactive to ensure numerical stability of the model. This criterion resulted in many cells near the boundary between the HAP aquifer and adjoining till and bedrock uplands being made inactive, and a modeled area that was smaller than the measured extent of the HAP aquifer (compare boundary of HAP stream-aquifer system to active area of model in fig. 11).

Boundary Conditions and Stresses

The active area of the model was surrounded laterally by no-flow boundaries (fig. 12). The boundaries were based on the water-table map of the HAP aquifer developed by Dickerman and Barlow (1997) and hydrogeologic information provided in Rosenshein and others (1968). No-flow boundaries were specified along ground-water-flow lines that separate the modeled area from adjacent aquifer areas that were not simulated. These flow lines were located along the northern end of the model above the Hunt River and Potowomut Pond, along the eastern boundary of the model, and in the Pettaquamscutt River Basin. A no-flow boundary condition also was specified along the ground-water drainage divide between the HAP aquifer and adjoining Chipuxet River Basin ground-water-flow system (fig. 12*B*).

Ground-water inflow from upland areas not drained by streams (GW_I) was accounted for by injecting water into simulated wells located in the first or second layer of the model just inside the boundary between the HAP aquifer and adjoining till and bedrock (or just inside the boundary between the simulated area of the HAP aquifer and adjoining areas where saturated thickness was less than 5 ft). Total inflow along these boundaries was calculated by multiplying the estimated effective recharge rate of 25.4 in/yr for the Hunt River Basin by the total area of undrained till and bedrock uplands and unsimulated aquifer areas adjacent to the boundaries. Ground-water underflow (GW_U) near the Annaquatucket River where it leaves the system was accounted for by withdrawing 1.0 ft^3/s of water from simulated wells in the top layer of the model in that area (fig. 12*B*).

The position of the water table was not specified, but was calculated during the simulation. If the elevation of the calculated water table fell 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 became inactive. Model cells that contained or were below the water table remained active in the simulation.

Recharge to the water table was represented as a specified 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 25.4 in/yr to all areas of the HAP aquifer except those overlain by ponds and lakes. Recharge to ponds and lakes was specified at a rate of 19.5 in/yr, which equalled the difference between the 1941–96 average annual precipitation rate of 47.5 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 from wastewater (R_{WW}) was specified in those areas of the model that receive public-water supplies but are unsewered. Recharge rates from wastewater specified in the model ranged from 1.6 to 4.6 in/yr, and the total amount of wastewater applied to the model was 1.2 ft^3/s.

Evapotranspiration from the water table (ET_{GW}) was simulated with the evapotranspiration package of MODFLOW. Measurements of the maximum rate and maximum depth of evapotranspiration from the water table are not available for the HAP aquifer. Consequently, it was necessary to assume values for these variables. A maximum evapotranspiration rate from the water table of 21.0 in/yr 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 and Pawcatuck River Basins for 1941–96 (19.9 and 21.1 in/yr, respectively).

The maximum depth of evapotranspiration from the water table was assumed to equal 4 ft below land surface.

As described in the section on hydrologic outflow components, withdrawal records for supply wells in the HAP aquifer are incomplete for the 1941–96 period. Because of this incomplete record, average annual withdrawal rates for each well could not be determined accurately for the period. Instead, the average annual withdrawal rate at each well during 1996 was specified in the model (table 5). These withdrawal rates were used because withdrawal records for each well are complete for 1996 and because the total withdrawal rates from each basin during 1996 are very close to the total withdrawal rates from each basin estimated for 1941–96 (see values given in discussion on hydrologic outflow components). Differences between the total 1996 average annual withdrawal rates and estimated average annual withdrawal rates for 1941–96 are about 0.5 ft^3/s for each of the Hunt and Annaquatucket River Basins and about 0.2 ft^3/s for the Pettaquamscutt River Basin. These differences are small, particularly when compared to the measured (or estimated) 1941–96 average flows of the three major rivers at their locations of outflow from the stream-aquifer system—46.4 ft^3/s for the Hunt River, 17.0 ft^3/s for the Annaquatucket River, and 9.5 ft^3/s for the Pettaquamscutt River.

Table 5. Withdrawal rates (1996) specified for water-supply wells in the steady-state model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well locations are shown on figure 1]

Water-supply well identifier	Model cell			Withdrawal rate	
	Layer	Row	Column	Cubic feet per second	Million gallons per day
Hunt River Basin					
KC1	4	35	21	0.50	0.32
3A	4	58	22	.35	.23
9A	2	30	21	.25	.16
14A	3	30	23	.61	.39
NK6	3	109	53	.38	.25
NK9	4	36	21	1.82	1.18
NK10	4	38	21	0	0
IW	3	79	26	.39	.25
Total for basin				4.30	2.78
Annaquatucket River Basin					
SFH1	3	162	78	.98	.63
SFH2	3	161	77	.98	.63
SFH3	3	160	76	0	0
NK1	2	149	114	.28	.18
NK2	2	150	115	.21	.14
NK4	2	154	117	.27	.18
NK5	3	161	118	.76	.49
Total for basin				3.48	2.25
Pettaquamscutt River Basin					
NK3	3	151	187	.28	.18
NK7	3	153	188	.03	.02
NK8	3	153	187	.01	.01
Total for basin				0.32	0.21
Total for all basins				8.10	5.24

Streams were simulated in the model with the stream-routing package developed for MODFLOW by Prudic (1989). This package simulates hydraulic interaction between an aquifer and adjoining streams, and tracks the amount of water within each simulated stream. All streams were simulated in the top layer of the model, and each stream was divided into reaches that corresponded to individual model cells (fig. 12). Most of the simulated streams flow through ponds and lakes that are in hydraulic connection with the HAP aquifer. Flow between the HAP aquifer and these ponds and lakes also was simulated with the stream-routing package.

Flow between each stream reach and corresponding model cell is calculated by the stream-routing package from the equation

$$Q_s = C_s(H_s - h) \ , \qquad (2)$$

where

Q_s is flow rate between each stream reach and model cell (L^3/T),

C_s is streambed conductance (L^2/T),

H_s is average water level specified for the stream reach (L), and

h is ground-water level calculated for the model cell (L).

Ground water discharges to the simulated stream if $h > H_s$; streamflow recharges the aquifer when $H_s > h$ (provided there is streamflow in the reach). If, however, the calculated ground-water level (h) falls below the specified elevation of the bottom of the streambed in the reach (H_{sbot}), then the calculated flow rate between the stream reach and corresponding model cell is a constant value equal to

$$Q_s = C_s(H_s - H_{sbot}). \qquad (3)$$

After Q_s 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.

Streamflow must be specified in the first reach of each stream. Streamflow values greater than zero were specified for those streams that enter the HAP stream-aquifer system from upland areas (sites A, B, F, H, and J in fig. 12*A* and site W in fig. 12*B*) and at the headwater of the Annaquatucket River (site R, fig. 12*B*) where ground water is discharged to the stream at the Lafayette State Fish Hatchery. Streamflows specified in the model are given in table 6. The total streamflow specified at streams that enter the system from upland areas (26.5 ft^3/s; table 6) was slightly larger than that estimated for the 1941–96 period (25.5 ft^3/s; table 4) to account for areas of the HAP aquifer with a saturated thickness less than 5 ft that were made inactive.

The average head and streambed elevation specified for each stream reach were determined from field measurements or estimated from topographic maps of the area. The thickness of the streambed of each reach was assumed to equal 1 ft, except in ponds and lakes where it was assumed to equal 2 ft. Therefore, the elevation of the bottom of the streambed of each reach was either 1 ft or 2 ft below the measured or estimated streambed (or pond bottom) elevation.

The streambed conductance specified for each reach was determined from the equation (Prudic, 1989, p. 7)

$$C_s = \frac{K_s W_s L_s}{b_s}, \qquad (4)$$

where

C_s is the streambed conductance of the reach (ft^2/d),
K_s is the hydraulic conductivity of the streambed in the reach (ft/d),
W_s is the width of the stream reach (ft),
L_s is the length of the stream reach (ft), and
b_s is the thickness of the streambed in the reach (ft).

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 taken to be 200 ft, which is the length of the side of each model cell. Hydraulic conductivity of streambed sediments was measured at 11 sites in the Hunt River by Rosenshein and others (1968). These estimated values (0.1 to 15.2 ft/d) were applied to the different reaches based on field observations of the streambed sediments or the proximity of the reaches to streams where the streambed sediments were known. The resulting streambed conductances estimated for the model ranged from a minimum of 500 ft^2/d along the upper reaches of the Annaquatucket River to a maximum of about 30,000 ft^2/d along Sandhill Brook and the lower reaches of the Annaquatucket River. Streambed conductances specified for ponds and lakes ranged from 1,000–20,000 ft^2/d. Sixty-six percent of the reaches (including those lying within simulated ponds and lakes) had an estimated conductance of 20,000–30,400 ft^2/d.

Table 6. Streamflows specified in the steady-state model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Site identifiers are shown on figure 12]

Site identifier	Stream name	Model cell			Streamflow	
		Layer	Row	Column	Cubic-feet per second	Million gallons per day
	Hunt River Basin					
A	Scrabbletown Brook	1	119	35	2.25	1.45
B	Unnamed tributary #1 to Hunt River	1	103	37	2.95	1.91
F	Frenchtown Brook	1	74	13	13.50	8.73
H	Fry Brook	1	59	8	6.40	4.14
J	Unnamed tributary #2 to Hunt River	1	28	6	.80	.52
	Annaquatucket River Basin					
R	Annaquatucket River	1	160	78	1.95	1.26
	Pettaquamscutt River Basin					
W	Unnamed tributary to Pettaquamscutt River	1	180	177	.62	.40

Hydraulic Conductivity

The horizontal hydraulic conductivity of the HAP aquifer (K_h) was determined for each vertical stack of cells by dividing the transmissivity by the total saturated thickness of the stack of cells. Transmissivity values were determined by overlaying a geographically referenced digital coverage of the transmissivity map of the HAP aquifer, which was prepared by Rosenshein and others (1968) and modified during this study, onto the model-grid coverage. Saturated thickness values were calculated by subtracting the bedrock elevation estimated for the bottom layer of each stack of cells from the water-table elevation of the top layer of the stack of cells. Uniform values of horizontal hydraulic conductivity were used in each layer of each stack, with the exception that a horizontal hydraulic conductivity of 50,000 ft/d was assigned to grid cells in the top layer of the model that were coincident with large ponds and lakes (fig. 12). The large value of hydraulic conductivity was used to simulate the lack of resistance to flow through the ponds and lakes.

A uniform anisotropic ratio of vertical to horizontal hydraulic conductivity of 1:5 was used throughout the model grid. This ratio is similar to that determined for stratified deposits of sand and gravel in Rhode Island and Cape Cod, Massachusetts (Dickerman and others, 1990; Masterson and Barlow, 1997; Barlow, 1997b).

Calibration and Sensitivity Analysis

The model was calibrated to water-level altitudes measured on October 8, 1996, at 23 observation wells distributed throughout the stream-aquifer system (fig. 13); average annual streamflow measured on the Hunt River at the USGS gaging station; and estimated average annual streamflows for Cocumcossuc Brook, Annaquatucket River, Queens Fort Brook, and Pettaquamscutt Brook. Water-level altitudes measured at the 23 observation wells were assumed to be representative of average annual conditions, based on the measured water-level altitude at observation well NKW-255 on October 8, 1996, which was near its 40-year average level (fig. 4*A*). The values of various model variables were adjusted during the calibration process. First, the rate of precipitation recharge was increased by 10 percent from the initial estimate of 25.4 in/yr, to 28.0 in/yr. This increase was done because simulated streamflows were lower than the measured (or estimated) average annual streamflows at the five measurement sites. Rates of ground-water inflow at the boundaries between the HAP aquifer and adjoining till and bedrock upland areas also were increased by 10 percent for consistency with the increased recharge rate. An average annual precipitation recharge rate of 28.0 in/yr is consistent with previous estimates determined for aquifers of central and southern Rhode Island (Dickerman and others, 1990, 1997; Dickerman and Bell, 1993; Barlow, 1997a).

Estimates of the horizontal hydraulic conductivity of the aquifer were modified to produce improved matches between measured and calculated water levels. Most of the modifications were increases to the initial estimates of K_h, particularly in areas close to the boundary between the HAP aquifer and till and bedrock uplands. The average K_h of each layer of the calibrated model (excluding areas of ponds and lakes in layer 1) ranges from 169 ft/d to 191 ft/d, which is close to the 200 ft/d estimated for sand-and-gravel deposits of the HAP aquifer by Rosenshein and others (1968). The minimum K_h of each layer is 25 ft/d and the maximum K_h of each layer ranges from 531 ft/d to 587 ft/d. The value specified for the anisotropic ratio of vertical to horizontal hydraulic conductivity was not changed during model calibration.

Finally, adjustments were made to some of the initial estimates of streambed conductance specified for the stream reaches. The adjustments included decreasing the largest estimate of streambed conductance from 30,400 ft^2/d to 20,000 ft^2/d, and increasing the initial estimates specified for the upper reaches of the Annaquatucket and Pettaquamscutt River Basins. Streambed conductances of the calibrated model range from 1,000 ft^2/d to 20,000 ft^2/d; 67 percent of the reaches have a conductance of 20,000 ft^2/d. The changes made to streambed conductances were judged to be reasonable, given the large number of variables (K_s, W_s, L_s, b_s) that must be estimated to calculate the streambed conductance of each reach.

Calculated water-level altitudes at each of the 23 observation wells for the calibrated model are shown with the measured values in table 7. The mean of the absolute value of the difference between calculated and measured water-level altitudes (referred to as the mean water-level residual) is 2.97 ft, which is less than 2 percent of the total relief of the water table (170.98 ft) measured at the observation wells on October 8, 1996.

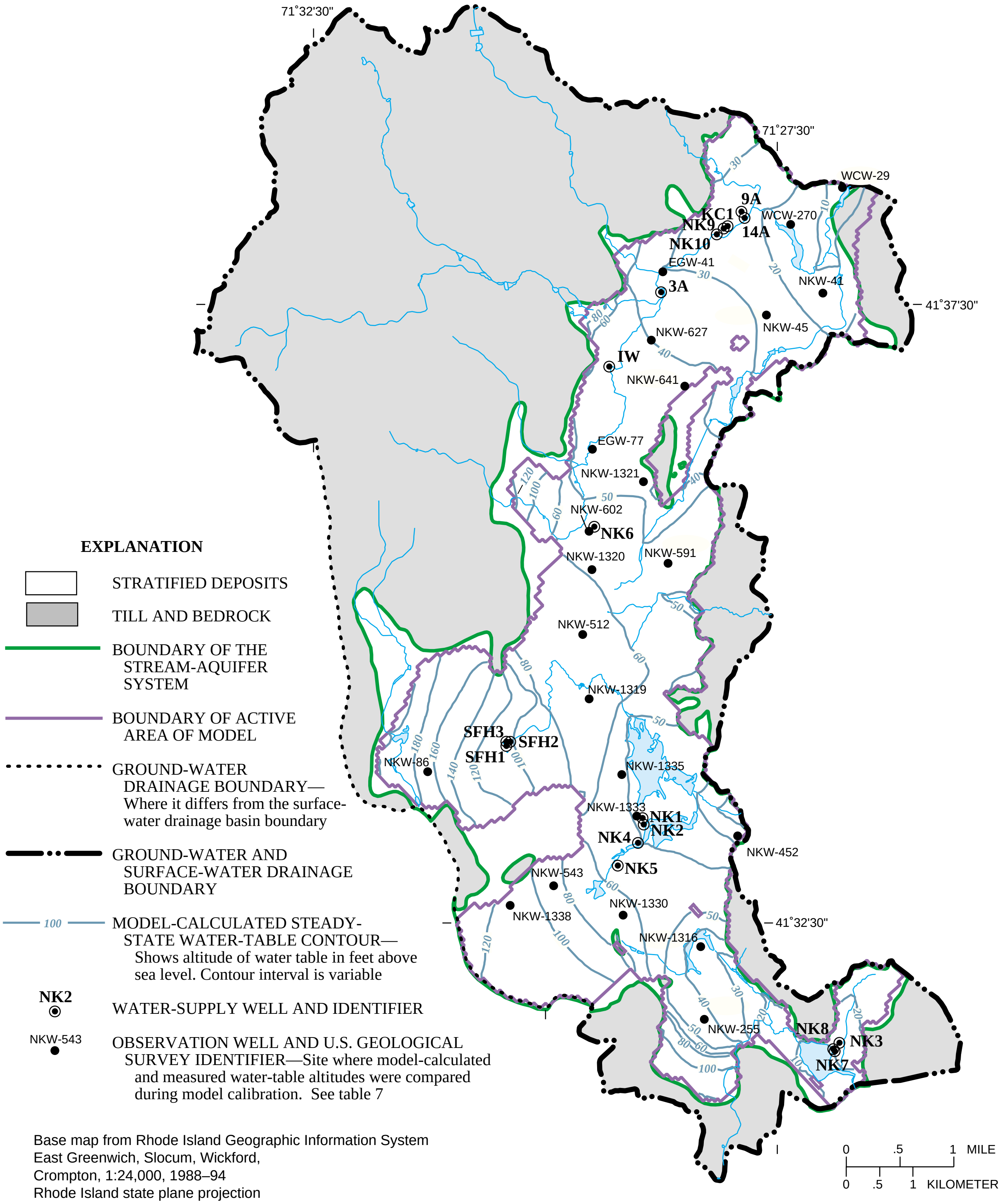


Figure 13. Model-calculated steady-state water table, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

Table 7. Model-calculated steady-state water-level altitudes and measured water-level altitudes on October 8, 1996, at observation wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well locations are shown in figure 13. **USGS well identifier:** EGW, East Greenwich well; NKW, North Kingstown well; WCW, Warwick well. USGS, U.S. Geological Survey]

USGS well identifier	Model location (layer, row, column)	Water-level altitude		
		Calculated (feet above sea level)	Measured (feet above sea level)	Difference (feet)
WCW-29	1, 8, 33	6.86	1.41	5.45
WCW-270	1, 23, 31	16.02	19.58	-3.56
NKW-41	1, 29, 49	15.12	14.05	1.07
NKW-45	1, 43, 43	28.47	29.47	-1.00
EGW-41	1, 54, 19	30.76	31.23	-.47
NKW-627	1, 66, 28	39.45	38.66	.79
NKW-641	1, 69, 43	41.91	41.38	.53
NKW-1321	1, 93, 53	49.53	45.28	4.25
EGW-77	1, 96, 39	42.98	43.16	-.18
NKW-591	1, 102, 72	53.30	52.12	1.18
NKW-602	1, 111, 53	53.82	47.32	6.50
NKW-1320	1, 117, 60	59.38	52.04	7.34
NKW-512	1, 130, 71	66.41	63.10	3.31
NKW-1319	1, 139, 83	69.04	67.64	1.40
NKW-452	1, 135, 133	43.39	44.01	-.62
NKW-1335	2, 146, 102	52.38	57.91	-5.53
NKW-1333	3, 150, 112	49.73	50.08	-.35
NKW-1316	1, 160, 148	37.84	37.13	.71
NKW-1330	2, 170, 128	65.87	68.36	-2.49
NKW-255	1, 170, 159	40.74	36.31	4.43
NKW-543	2, 177, 111	89.53	93.71	-4.18
NKW-86	2, 180, 69	169.19	172.39	-3.20
NKW-1338	2, 188, 107	113.80	104.36	9.44

A map of the simulated water table for steady-state conditions is shown in figure 13. Overall, there is good agreement between the configuration of the simulated water table and the measured water table shown in figure 5. Calculated streamflows at the five measurement sites are 42.3 ft^3/s for the Hunt River, 2.9 ft^3/s for Cocumcossuc Brook, 0.6 ft^3/s for Queens Fort Brook, 13.8 ft^3/s for Annaquatucket River, and 9.7 ft^3/s for Pettaquamscutt River. Total calculated streamflow out of the simulated stream-aquifer system, therefore, is 69.3 ft^3/s.

A sensitivity analysis was done 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 individually increased and decreased by 10 percent of its calibrated value in a series of eight simulations. Results of the sensitivity analysis indicate that model-calculated water levels 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 streamflow for the three largest rivers (the Hunt, Annaquatucket, and Pettaquamscutt) were most sensitive to increases and decreases in the values specified for recharge.

Hydrologic Budget

The steady-state, average annual hydrologic budget of the stream-aquifer system calculated with the calibrated model is shown in table 8. Recharge from precipitation is the largest component of inflow to the system and streamflow is the largest component of outflow from the system. The calculated total flow rate through the system, about 83 ft^3/s, is similar to the flow rate estimated for the system for the 1941–96 period (about 88.5 ft^3/s, table 4). There are, however, a few differences between the model-calculated hydrologic budget and the estimated hydrologic budget. First, direct runoff is not simulated within the modeled area. Consequently, total inflow and outflow rates should be, and are, somewhat less for the model budget than for the estimated budget. This result may be one reason why total streamflow calculated by the model at the five outflow measurement sites (69.3 ft^3/s) is less than the total streamflow measured (or estimated) at these sites during 1941–96 (76.9 ft^3/s; table 4). Second, because the precipitation recharge rate specified in the model (28.0 in/yr) is larger than that for the estimated budget (25.4 in/yr), the rates of precipitation recharge and lateral ground-water inflow are larger for the model budget (53.8 ft^3/s; table 8) than for the estimated budget (48.2 ft^3/s; table 4). Finally, because the areal extent of the active area of the model is smaller than the areal extent of the stream-aquifer system (fig. 11),

Table 8. Model-calculated steady-state average annual hydrologic budget for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Budget components shown schematically in figure 7]

Hydrologic budget component	Rate of flow	
	Cubic feet per second	Million gallons per day
Inflow		
Recharge		
Precipitation (R_{PR})	34.3	22.2
Wastewater return flow (R_{WW})	1.2	.8
Lateral ground-water inflow (GW_I)	19.5	12.6
Streamflow from uplands (SF_I)	26.5	17.1
Ground water discharged to Annaquatucket River (Q_{AR})	2.0	1.3
Total inflow	83.5	54.0
Outflow		
Streamflow (SF_O)	69.3	44.8
Evapotranspiration (ET_{GW})	4.6	3.0
Ground-water underflow (GW_U)	1.0	.6
Ground-water withdrawal (Q_W)	8.1	5.2
Total outflow	83.0	53.6
Budget error (inflow-outflow)	0.5	0.4

the relative amounts of precipitation recharge and lateral ground-water inflow to the total inflow of each budget differ.

Stream-Aquifer Interactions

The calibrated model provides information on stream-aquifer interactions that supplements data collected in the field. This information includes the locations and rates of ground-water discharge to streams, streamflow leakage to the aquifer, and streamflow depletions caused by ground-water withdrawals. The model also can be used to estimate streamflow conditions before withdrawals began.

Total ground-water discharge to the simulated surface-water network for the average hydrologic conditions simulated by the model is 52.0 ft^3/s, whereas total streamflow leakage to the HAP aquifer calculated by the model is 11.2 ft^3/s. Streamflow leakage consists of both natural stream-channel losses (SL_N) and induced infiltration (SL_I). To determine the locations and rates of natural stream-channel losses and induced infiltration, it was necessary to compare streamflow-leakage rates calculated for each simulated stream cell with the calibrated model to those calculated for conditions of no withdrawals at the simulated wells. Two such conditions were simulated: in a first simulation, withdrawals were eliminated at all of the wells; in a second simulation, withdrawals were eliminated at all wells except those at the Lafayette State Fish Hatchery. The second simulation was necessary to isolate the effects of ground-water withdrawals at the fish hatchery.

Streamflow-leakage rates calculated for these two simulations indicate that the average annual rate of induced infiltration caused by ground-water withdrawals is 1.2 ft^3/s of the total 11.2 ft^3/s of streamflow leakage to the HAP aquifer. Total average annual induced infiltration for the Hunt River Basin is 0.7 ft^3/s; for the Annaquatucket River Basin is 0.3 ft^3/s; and for the Pettaquamscutt River Basin is 0.2 ft^3/s. The remaining streamflow leakage to the HAP aquifer, 10.0 ft^3/s, is the average annual rate of natural stream-channel losses. These losses take place primarily along stream reaches that are close to the boundary of the HAP aquifer with upland areas of till and bedrock, and at stream reaches on the downgradient ends of the larger ponds. Some of the locations of the largest natural stream-channel losses are Frenchtown Brook above its confluence with the Hunt River (3.8 ft^3/s); the downgradient end of Belleville Pond (1.0 ft^3/s); the upper reach of Scrabbletown Brook (0.9 ft^3/s); the upper reach of the Annaquatucket River (0.8 ft^3/s); and the downgradient end of Potowomut Pond (0.7 ft^3/s). Streamflow leakage calculated along the upper reach of the Annaquatucket River consists of water that is withdrawn from the HAP aquifer and discharged to the headwaters of the river; when that water is no longer discharged, the river goes dry along this reach, and leakage to the underlying aquifer ceases. The calculated losses of water along Frenchtown Brook and the Annaquatucket River are supported by water-level altitudes measured beneath the two streams on October 8, 1996, which indicated that the water table was at least 4.5 ft beneath the streambeds at that time.

Total streamflow depletion caused by withdrawals at all wells except those at the hatchery is 5.9 ft^3/s, which is all but 0.3 ft^3/s of the total simulated withdrawals at the wells (6.2 ft^3/s). The remaining 0.3 ft^3/s consists of a reduction in ground-water evapotranspiration and small roundoff and model mass-balance errors. Total streamflow depletion calculated for the Hunt River Basin is 4.1 ft^3/s; for the Cocumcossuc River Basin is less than 0.1 ft^3/s; for the Annaquatucket River Basin is 1.4 ft^3/s; and for the Pettaquamscutt River Basin is 0.3 ft^3/s. The streamflow-depletion rates indicate that before withdrawals began at the public water-supply wells and the industrial well (IW), average streamflow at the five outflow measurement sites (excluding direct runoff within the HAP stream-aquifer system) are estimated to have been about 46.4 ft^3/s for the Hunt River, 3.0 ft^3/s for Cocumcossuc Brook, 0.6 ft^3/s for Queens Fort Brook, 15.2 ft^3/s for Annaquatucket River, and 10.0 ft^3/s for Pettaquamscutt River.

Model-calculated streamflows and streamflow depletions for the Hunt and Annaquatucket Rivers as a function of distance along each stream are shown in figures 14*A* and 14*B*, respectively. River mile 0.0 on each figure is the uppermost reach (model cell) of each of the simulated streams (fig. 12). Calculated streamflows are shown for the calibrated model and for the simulation in which withdrawals were specified only at the fish-hatchery wells. Differences in the calculated streamflows between the two simulations are shown by the streamflow-depletion curves.

Natural stream-channel losses are calculated for the uppermost reach of the Hunt River, where Scrabbletown Brook enters the HAP stream-aquifer system from till and bedrock upland areas (fig. 14*A*). The river loses flow until about mile 0.6, at which point ground-water discharge causes the river to become gaining. The river remains mostly gaining until the area of large ground-water withdrawals just below the confluence with Fry Brook (about river mile 4.0). In this area, the streamflow-depletion rate increases sharply, and streamflow losses result from induced infiltration. Below the area of withdrawals, the river again mostly gains flow except along the downgradient end of Potowomut Pond.

Natural stream-channel losses are calculated for the first 2.0 mi of the Annaquatucket River, extending from the headwaters of the river at the fish hatchery to the upgradient end of Belleville Pond (fig. 14*B*). Ground-water discharge to Belleville Pond is substantial; as a result, there are large gains in streamflow through the pond. These calculated gains are consistent with those measured during this investigation (table 3). Natural streamflow losses are calculated on the downgradient end of Belleville Pond. Streamflow depletions begin at about river mile 2.1, and are largest near the supply wells (river mile 3.0–3.1).

Contributing Areas and Sources of Water to Supply Wells

Contributing areas and sources of water were delineated for the public water-supply wells and fish-hatchery wells 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). The land area that directly overlies the contributing area is often protected from uses that could cause contamination of the underlying water table. Potential sources of water to wells in the HAP stream-aquifer system are precipitation and wastewater recharge, streamflow leakage from natural channel losses, streamflow leakage caused by induced infiltration, and lateral ground-water inflow from till and bedrock 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

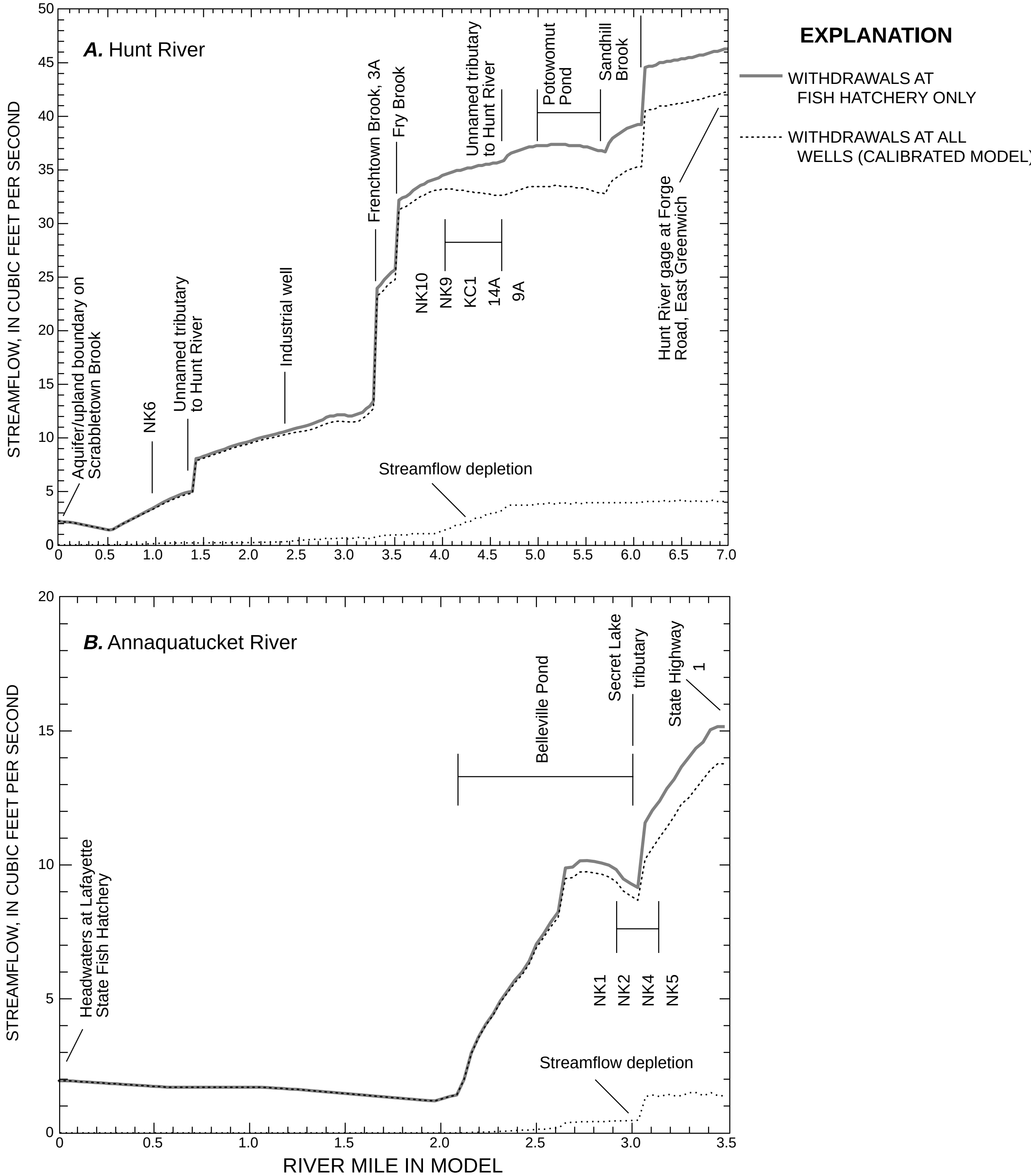


Figure 14. Model-calculated steady-state streamflows and streamflow depletions for (*A*) the Hunt River and (*B*) the Annaquatucket River, Rhode Island. (Streamflows calculated for model cells along the center line of Potowomut and Belleville Ponds were used.)

ground-water-flow system, and to calculate the time of travel of these particles 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 by the model. This value is based on measurements of porosity 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. This value did not affect the analysis, however, because all contributing areas delineated for the supply wells are upgradient to simulated ponds and lakes.

The contributing area to each well was delineated by overlaying a 2 × 2 array of particles onto the simulated water table. Particles then were tracked from the water table to their points of discharge from the simulated HAP aquifer. The origin of those particles that were captured by each simulated well defined the contributing area to that well. Contributing areas shown in this report were delineated with the option in MODPATH to stop particles at cells containing weak internal sinks. In the HAP model, internal sinks are gaining streams, withdrawal wells, and areas of evapotranspiration. Cells with weak internal sinks are those in which the amount of water removed by the internal sink is less than the total amount of water that flows into the cell. Weak sinks cause some ambiguities in the delineation of contributing areas because it cannot be determined whether a particle that enters a cell with a weak internal sink should be removed by the sink or should continue through the flow system. Internal sinks are not a problem when all of the water that flows into the cell is removed by the sink (a strong internal sink). Though there are weak internal sinks in the HAP model, these sinks did not affect the delineation of contributing areas to the majority of wells, as determined by comparing contributing areas delineated for the wells with the option to stop particles at cells containing weak sinks with those delineated for the wells with the option to allow particles to pass through weak sinks. Contributing areas to NK7 and NK8, however, were strongly affected by the weak-sink problem because of the very low withdrawal rates simulated for the wells (table 5). As a consequence of the weak-sink problem, contributing areas are not presented for these two wells.

The amount of streamflow leakage contributing to each well's withdrawal was determined by tracking particles from losing stream reaches to their point of discharge from the flow system. Twenty seven particles were distributed uniformly in a three-dimensional array (3 × 3 × 3) within each losing stream cell. To estimate the amount of streamflow leakage reaching each of the supply wells, a volumetric flow rate was assigned to each particle. This volumetric flow rate was determined by dividing the streamflow-leakage rate to the aquifer in the cell in which the particle originated by the number of particles placed in each cell (27). The contribution of streamflow leakage to each supply well was then calculated by summing the individual flow rates of all particles captured by each well. The approach for determining the type of streamflow leakage within each losing stream cell—that is, either natural stream-channel losses or induced infiltration—was described in the preceding section of this report. The total amounts of natural stream-channel losses and induced infiltration contributing to each well's withdrawal (shown as a percentage of total withdrawal rate), as well as the total amount of water from other sources withdrawn from each well, are shown in table 9. The other sources of water are precipitation and wastewater recharge within the active area of the model and lateral ground-water inflow from till and bedrock upland areas outside of the active area of the model.

Contributing areas delineated for supply wells in the HAP stream-aquifer system are shown on plate 1. The areal extent of the contributing area of each well is a function of the withdrawal rate of the well, the recharge rate (or areal distribution of recharge rates) to the HAP aquifer within the contributing area, and the amount of water captured by the well from sources other than recharge. The largest contributing areas shown on plate 1 are those for wells NK9 and NK5. Although the withdrawal rate simulated for well NK9 (1.18 Mgal/d) is much greater than that simulated for well NK5 (0.49 Mgal/d), the areal extent of the contributing area to each well is nearly equal (0.39 mi^2 for well NK9 and 0.34 mi^2 for well NK5). The similarity in the size of the contributing areas delineated for these two wells is explained in part in that well NK9 captures some of its withdrawal from induced infiltration from the Hunt River; other factors that contribute to the relative size of these two contributing areas are differences in the recharge rates to the HAP aquifer

Table 9. Model-calculated streamflow leakage and other sources of water to supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well locations are shown on figure 1. **Other sources**: refers to ground-water recharge from precipitation and wastewater discharge to the Hunt–Annaquatucket–Pettaquamscutt aquifer, and ground-water recharge to till and bedrock upland areas that enters the Hunt–Annaquatucket–Pettaquamscutt aquifer by lateral ground-water inflow]

Water-supply well identifier	Source of water, as percentage of well's total withdrawal rate		
	Streamflow leakage to aquifer by natural channel losses	Streamflow leakage to aquifer by induced infiltration	Other sources
Hunt River Basin			
9A	75.9	0	24.1
14A	39.1	36.7	24.2
KC1	56.6	16.2	27.2
NK9	0	16.2	83.8
3A	94.7	0	5.3
NK6	0	0	100.0
Annaquatucket River Basin			
NK1	0	[1]0	100.0
NK2	0	0	100.0
NK4	0	0	100.0
NK5	0	0	100.0
SFH1	30.2	0	69.8
SFH2	0	0	100.0
Pettaquamscutt River Basin			
NK3	0	7.4	92.6

[1]Three particles, with a combined flow rate of less than 0.01 cubic feet per second, are captured by NK1.

within each well's contributing area and the amount of water captured by each well from lateral ground-water inflow along the boundary of the model. The smallest contributing area delineated for any of the wells is that for well 3A (pl. 1). This well captures 95 percent of its withdrawal from natural stream-channel losses along Frenchtown Brook. Streamflow losses along Frenchtown Brook are supported by water-level measurements made during this study that indicated a downward hydraulic gradient from the brook to the underlying HAP aquifer.

Some of the contributing areas do not overlie the wells (pl. 1), including those for KC1, 3A, NK6, SFH1, SFH2, and NK5. Although several hydrogeologic and well-design factors affect the location of these contributing areas, an important factor is the position of the screened interval of these wells. In each case, the screened interval is in either the second, third, or fourth layer of the model, which allows recharge in the immediate vicinity of the wells to flow above the screened interval.

Streamflow leakage was calculated to be a source of water to seven wells, all but five of which are in the Hunt River Basin (table 9). As shown in the table, induced infiltration is calculated to be a source of water to wells 14A, KC1, and NK9 in the Hunt River Basin. Induced infiltration is not a source of water to any of the wells in the Annaquatucket River Basin. This appears to be a contradiction to the conclusion that the calculated rate of induced infiltration in the Annaquatucket River Basin was 0.3 ft^3/s for the withdrawal rates simulated by the calibrated model (see previous section "Stream-Aquifer Interactions"). Most of the induced infiltration in the Annaquatucket River Basin comes from Secret Lake, downgradient of wells NK1, NK2, NK4, and NK5. The explanation for this apparent contradiction is that the induced infiltration is not captured by the wells, but discharges from the flow system at other locations; although the hydraulic stresses caused by withdrawals at these wells are large enough to induce infiltration from the lake to the HAP aquifer, the stresses are too small to cause the induced water to be captured by the wells. Newsom and Wilson (1988) refer to this induced water as "induced throughflow."

In addition to calculating particle flow paths through the simulated aquifer, MODPATH also calculates the total traveltime of each particle from its entry at the water table to its withdrawal at a supply well (pl. 1). Calculated traveltimes for particles captured by the wells for the conditions simulated by the calibrated model range from a minimum of 0.1 years to a maximum of 51.2 years. The average traveltime to most of the wells is less than 5 years, with the exception of wells KC1 (average traveltime 5.2 years), NK9 (5.9

years), NK4 (6.1 years), and NK5 (11.9 years). Considerable variation was found in the range of particle traveltimes to each of the wells, as shown on plate 1. Particle traveltimes to the wells are a function of many factors, including withdrawal rates of the wells, recharge rates to the aquifer, lateral ground-water inflow rates, and the hydraulic conductivity and porosity of the aquifer.

In conclusion, it should be noted that the contributing areas and sources of water delineated for wells in the HAP stream-aquifer system are unique to the particular set of hydrologic and well-design conditions simulated by the calibrated, steady-state flow model of the system. The areal extent and shape of the contributing areas would likely be different if changes were made to any of the model hydraulic variables or stresses, such as the distribution of hydraulic conductivity of the aquifer, withdrawal rates of the wells, or recharge rates to the aquifer.

TRANSIENT NUMERICAL MODEL

A transient model was developed to simulate average annual hydrologic conditions in the HAP stream-aquifer system. Average annual hydrologic conditions are defined as the average conditions during each of the 12 months during the 56-year period 1941–96. The primary purpose of simulating transient conditions was to quantify monthly streamflow depletions in the Hunt, Annaquatucket, and Pettaquamscutt Rivers caused by time-varying withdrawals at the supply wells. The model-calculated streamflow depletions are the basis by which the numerical model of the HAP system is incorporated into the conjunctive-management model developed for the system. 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 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. This approach was taken to ensure that withdrawal strategies determined by the conjunctive-management model could be sustained indefinitely without causing long-term reductions in aquifer storage.

Development

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, including those for hydraulic conductivity and the top and bottom elevations of each cell.

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 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 (stress conditions 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 empirically that five annual cycles (a total of 60 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 very 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.

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. 12). In the transient model, however, stress rates vary over the annual cycle. The monthly stresses specified in the transient model are described below.

Average monthly precipitation recharge rates estimated for the Hunt River Basin for the 1941–96 period (fig. 10*A*) were increased by 10 percent for consistency with the increase that was made to the average annual recharge rate during calibration of the steady-state model. The resulting monthly precipitation recharge rates specified to all areas of the model except ponds and lakes ranged from 0.6 in. for September to 4.7 in. for March, with a total annual recharge of 28.0 in. In addition to precipitation recharge, some areas of the HAP aquifer also receive recharge from wastewater disposal. Constant rates of wastewater disposal equal to those specified in the steady-state model were simulated; the total recharge rate from wastewater disposal over the entire model area was 1.2 ft^3/s. Monthly recharge rates to ponds and lakes were calculated by subtracting average monthly free-water-surface evaporation rates from average monthly precipitation rates measured from 1941–96 at the Kingston climatological station. Total free-water-surface evaporation during the May through October growing season is estimated to be 21.0 in. (Farnsworth and others, 1982, map 2). Based on the total annual free-water-surface evaporation of 28.0 in. (Farnsworth and others, 1982, map 3), this gives 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 are therefore about 3.5 in. during May through October and 1.2 in. during November through April. Net monthly recharge rates specified to ponds ranged from zero in June and July to 3.9 in. for November, with a total annual recharge rate to ponds and lakes that is slightly higher (by 0.7 in.) than the value of 19.5 in. 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 particular month. For example, a recharge rate of 4.7 in. (March) is 16.8 percent of the total average annual recharge of 28.0 in. Consequently, 16.8 percent of the total average annual lateral ground-water inflow to the HAP aquifer from upland areas was specified for March. The daily rate of inflow at each cell for each month then was determined by dividing the total monthly inflow to the cell by the number of days in the month.

Monthly evapotranspiration rates from the water table were determined by assuming 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 1996 average monthly withdrawal rates for each well. This rate was set for consistency with the 1996 average annual withdrawal rates specified in the steady-state model. Constant withdrawal rates were specified for the industrial well and each of the three supply wells at the Lafayette State Fish Hatchery (table 5). Total monthly withdrawal rates simulated for all wells ranged from 6.71 ft^3/s to 10.1 ft^3/s, and averaged 8.12 ft^3/s.

Monthly streamflow rates were specified for the first reach of each stream that enters the HAP system from till and bedrock uplands (sites A, B, F, H, and J in fig. 12*A* and site W in fig. 12*B*) and at the headwater of the Annaquatucket River (site R, fig. 12*B*). Methods used to estimate 1941–96 average monthly rates of inflow for streams that enter the system from upland areas were described in the "Hydrologic Components and Budget" section. Additionally, a constant rate of streamflow of 1.95 ft^3/s was specified at the headwater of the Annaquatucket River where ground water is discharged to the stream at the Lafayette State Fish Hatchery (table 6). Total monthly streamflows specified to the transient model ranged from a minimum of 6.6 ft^3/s in September to a maximum of 56.7 ft^3/s in March. Average annual specified streamflow at these sites was 28.1 ft^3/s, which is close to that of the steady-state model, 28.5 ft^3/s. Physical characteristics of the simulated streams (streambed conductance, streambed elevation, and so forth) were equivalent to those specified in the steady-state model.

Storage Properties of Aquifer

A uniform value of specific yield of 0.28 was specified for the stratified deposits simulated in the model. This value is the same as the median specific yield determined for 18 samples of stratified deposits from the adjacent Pawcatuck River Basin (Allen and others, 1963); it also is close to the value of 0.26 determined by Moench and others (2000) for stratified glacial deposits of western Cape Cod, Massachusetts. A specific yield equal to 1.0 was specified for the simulated ponds and lakes. A uniform value of the storage coefficient of the aquifer of 3.0×10^{-4}, which corresponds to a 30-foot saturated thickness of aquifer with a specific storage of 1.0×10^{-5} ft^{-1}, was specified for each cell in layers 2-4 of the model. The value of specific storage is based on the estimate of 1.3×10^{-5} ft^{-1} made by Moench and others (2000) for the specific storage of stratified glacial deposits of Cape Cod, Massachusetts.

Calibration and Hydrologic Budget

The model was calibrated to average monthly water-level altitudes measured at NKW-255 during the periods 1955–63 and 1966–96, and to measured or estimated average monthly streamflow of the Hunt, Annaquatucket, and Pettaquamscutt Rivers. As with the steady-state model, direct runoff is not simulated by the transient model; therefore, calculated streamflows do not reflect the highest flow rates that typically occur during storms. Observation well NKW-255 is the only well in the study area with a period of record that is long enough to be used for model calibration. Although the water-level record at the well does not extend over the full 56-year period used for model development, the record was assumed to provide a good indication of the average range of water-level altitude fluctuations at the well.

Calculated water-level altitudes at well NKW-255 are shown in figure 15*A* with the average monthly water-level altitudes measured at the well for the combined 40-year period 1955–63, 1966–96. The calculated hydrograph is shifted upward from the measured one by about 4 ft because of model error; as shown in table 7, the steady-state water-level altitude calculated for the well is 40.74 ft but the measured water-level altitude on October 8, 1996, was 36.83 ft. The annual fluctuation of the calculated hydrograph is similar to the measured hydrograph, reaching a maximum water-level altitude during April and a minimum altitude during September and October, although the calculated range in water-level altitudes over the annual cycle (3.5 ft) is greater than the observed range (2.5 ft). During the calibration process, four 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. For example, for a specific yield of 0.30, the calculated annual range was 3.2 ft. In the absence of more data on the specific yield of the HAP aquifer, however, a value of 0.28 was retained.

Average monthly measured streamflows and calculated mid-monthly streamflows for the Hunt River for the 56-year period (1941–96) are shown in figure 15*B*. In both cases, the maximum streamflow is in March and the minimum streamflow is in September. Because the model does not simulate direct runoff, the calculated streamflow hydrograph should be lower than the measured hydrograph, which is the case for all months except May through July. Average annual streamflow calculated for the river by the transient model is 42.0 ft^3/s, which is close to the value of 42.3 ft^3/s calculated by the steady-state model. Calculated maximum and minimum streamflows for the Annaquatucket River are 16.9 ft^3/s in April and

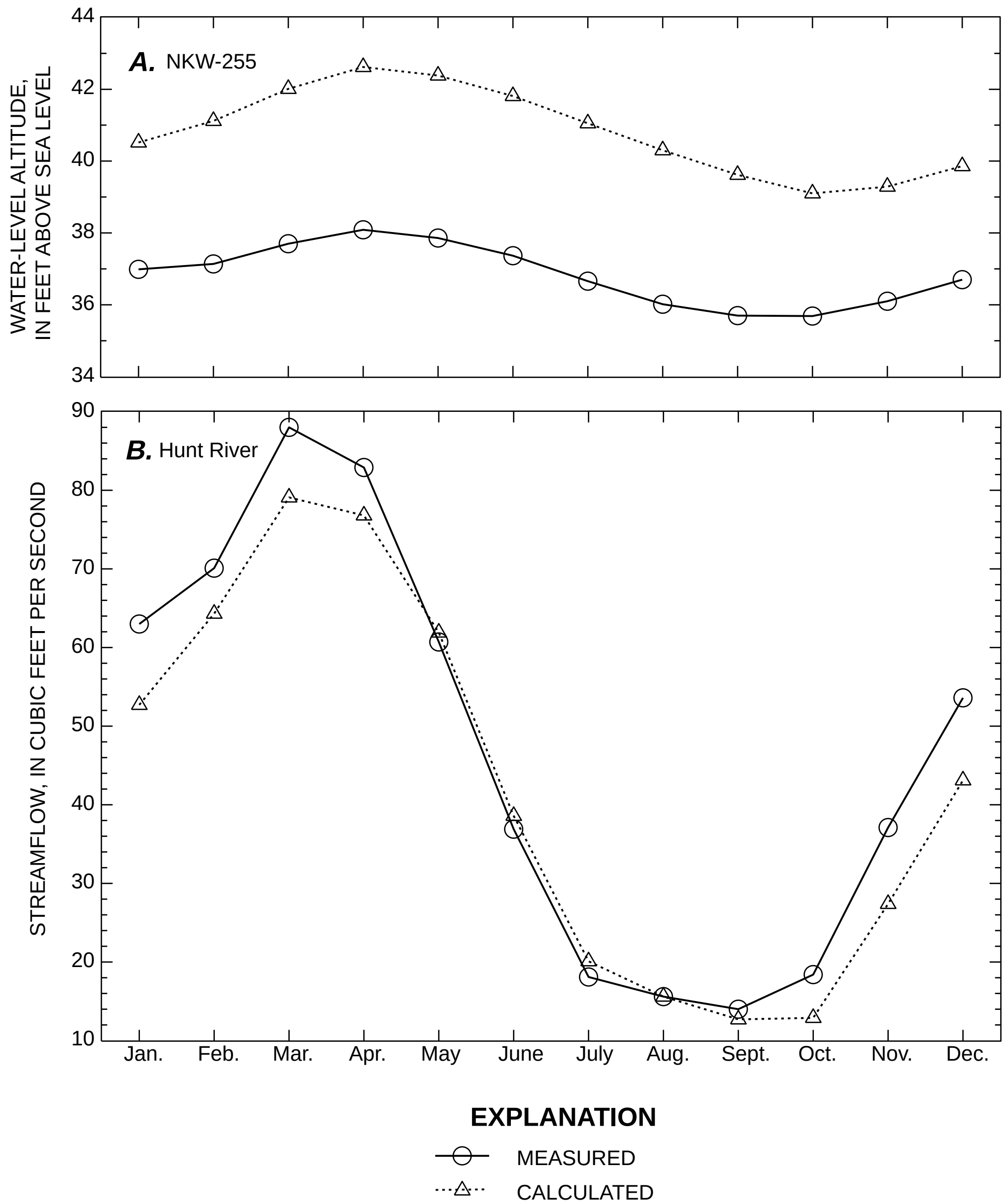


Figure 15. Average monthly measured and model-calculated mid-monthly (*A*) water-level altitudes at well NKW-255 and (*B*) streamflow at the Hunt River gaging station, Rhode Island.

11.4 ft^3/s in October, which are close to the estimated maximum and minimum average monthly streamflows for the river of 20 ft^3/s in March and April and 11.5 ft^3/s in August through October. Calculated maximum and minimum streamflows for the Pettaquamscutt River are 15.1 ft^3/s in April and 5.4 ft^3/s in October, which also are close to the estimated maximum and minimum average monthly streamflows for the river of 15.0 ft^3/s in March and April and 4.5 ft^3/s in August through October.

Although improvements between measured and calculated water-level altitudes and streamflows might have been made by modifying the specified rates of recharge, streamflow from upland areas, or lateral ground-water inflow from upland areas, this was judged to be inappropriate given the limited availability of data for these variables.

The average annual hydrologic budget for the HAP stream-aquifer system calculated with the calibrated transient model is shown with that for the steady-state budget in table 10. Overall, good agreement was found between the several hydrologic components of the two models. The average rate of inflow to and outflow from aquifer storage is 13.2 ft^3/s over the annual cycle (table 10).

Table 10. Model-calculated steady-state and transient average annual hydrologic budgets for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Budget components are in cubic feet per second and, in parentheses, million gallons per day; budget components shown schematically in figure 7]

Hydrologic budget component	Steady-state model		Transient model	
Inflow				
Recharge				
Precipitation (R_{PR})	34.3	(22.2)	34.3	(22.2)
Wastewater return flow (R_{WW})	1.2	(.8)	1.2	(.8)
Lateral ground-water inflow (GW_I)	19.5	(12.6)	19.3	(12.5)
Streamflow from uplands (SF_I)	26.5	(17.1)	26.1	(16.9)
Ground water discharged to Annaquatucket River (Q_{AR})	2.0	(1.3)	2.0	(1.3)
Storage	0	(0)	13.2	(8.5)
Total inflow	83.5	(54.0)	96.1	(62.2)
Outflow				
Streamflow (SF_O)	69.3	(44.8)	69.3	(44.8)
Evapotranspiration (ET_{GW})	4.6	(3.0)	4.5	(2.9)
Ground-water underflow (GW_U)	1.0	(0.6)	1.0	(0.6)
Ground-water withdrawal (Q_W)	8.1	(5.2)	8.1	(5.2)
Storage	0	(0)	13.2	(8.5)
Total outflow	83.0	(53.6)	96.1	(62.0)
Budget error (inflow-outflow)	0.5	(0.4)	0	(0.2)

Stream-Aquifer Interactions

Model-calculated mid-monthly streamflows at the downstream end of the Hunt, Annaquatucket, and Pettaquamscutt Rivers for the 1941–96 period are shown in figure 16. Calculated streamflows shown in the figure are for the calibrated model and for a simulation in which withdrawals were specified only at the fish-hatchery wells. Calculated streamflow hydrographs for the Annaquatucket and Pettaquamscutt Rivers show less variability over the annual cycle than does the hydrograph for the Hunt River (fig. 16), which is consistent with measured (or estimated) streamflow variability for these streams. A statistical summary of the calculated mid-monthly streamflows for each of the three rivers, as well as the percentage of the area of each river basin that is underlain by glacial stratified deposits, are given in table 11. The statistics shown in table 11 are for the simulation in which withdrawals were specified only at the fish-hatchery wells; results similar to those in the table were obtained with simulation of the calibrated model.

The coefficient of variation of monthly streamflows (table 11) is a measure of the relative variability of monthly streamflows among the three rivers. The coefficient of variation calculated for the Hunt River exceeds those for the Annaquatucket and Pettaquamscutt Rivers (table 11). Data provided in the table also indicate that the coefficient of variation of calculated streamflows decreases as the percentage of stratified deposits that underlies each basin increases. These decreases are consistent with the results of previous studies of streamflow in the northeastern United States (see, for example, Thomas, 1966), which have shown that the variability of streamflow decreases as the percentage of stratified deposits in a basin increases. The large area of Belleville Pond in the Annaquatucket River Basin, which was simulated with a storage coefficient of 1.0, also may contribute to the relatively low variability of streamflow observed for that basin.

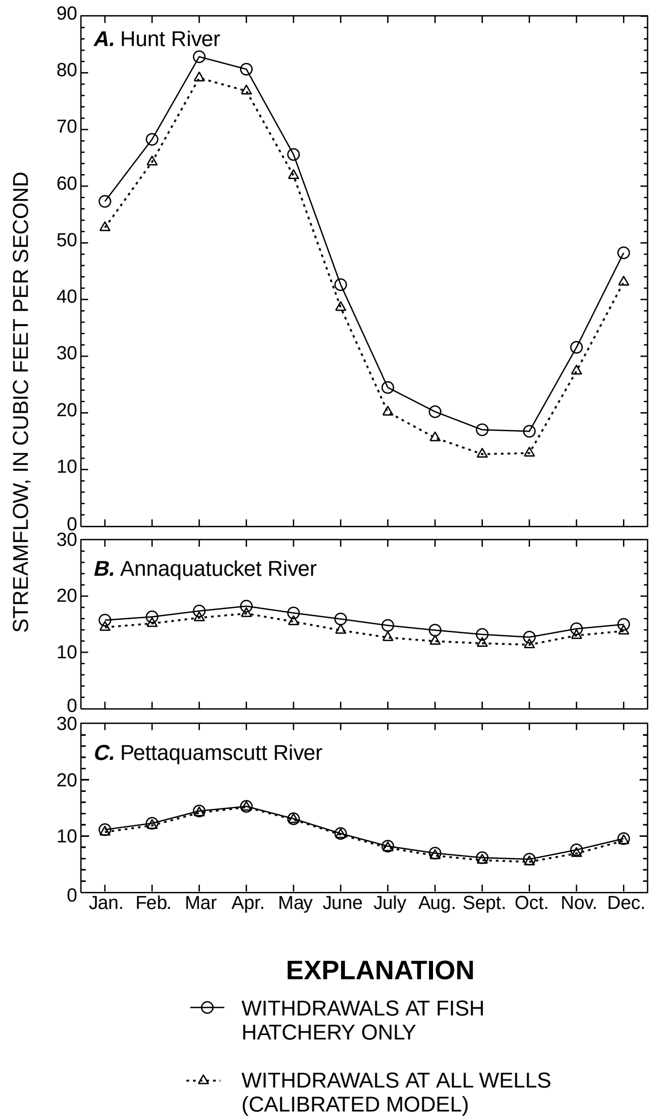


Figure 16. Model-calculated mid-monthly streamflow at the downstream end of the (*A*) Hunt, (*B*) Annaquatucket, and (*C*) Pettaquamscutt Rivers, Rhode Island.

Table 11. Summary statistics of model-calculated, mid-monthly streamflow for the Hunt, Annaquatucket, and Pettaquamscutt Rivers, Rhode Island

[Simulation conditions: withdrawals only at wells at the Lafayette State Fish Hatchery. ft^3/s, cubic foot per second]

River basin	Percentage of basin underlain by stratified deposits	Streamflow at downstream end of river			
		Range (ft^3/s)	Mean (ft^3/s)	Standard deviation (ft^3/s)	Coefficient of variation (dimensionless)
Hunt	52	16.8–82.9	46.2	24.3	0.53
Annaquatucket	75	12.7–18.2	15.4	1.7	.11
Pettaquamscutt	64	5.9–15.3	10.1	3.2	.32

As a result of these factors, streamflow in the Hunt River approaches that of the Annaquatucket River during periods of low flow, even though the drainage area for the Hunt River is more than twice that of the Annaquatucket River. This model-calculated trend is supported by streamflow measurements made during this study (table 2). For example, streamflow measured at the gage on the Hunt River (site P, fig. 6) on September 20, 1995, was 7.24 ft^3/s, while that measured at the downstream end of the Annaquatucket River (site T, fig. 6) on the same date was 7.44 ft^3/s. In contrast, during high-flow conditions (April 24, 1996), flows on the two streams were substantially different—83.6 ft^3/s for the Hunt River and 20.7 ft^3/s for the Annaquatucket River.

The difference between each pair of hydrographs shown in figure 16 is the total streamflow depletion in each river basin caused by ground-water withdrawals. Monthly streamflow depletions are largest for the Hunt River, ranging from 3.7 ft^3/s to 5.2 ft^3/s, and averaging 4.2 ft^3/s for the annual cycle. This average depletion is close to that calculated by the steady-state model of 4.1 ft^3/s. Monthly streamflow depletions in the Annaquatucket River Basin range from 1.2 ft^3/s to 2.2 ft^3/s, and average 1.5 ft^3/s for the annual cycle (compared to 1.4 ft^3/s calculated for the steady-state model); monthly streamflow depletions in the Pettaquamscutt River Basin range from 0.1 ft^3/s to 0.6 ft^3/s, and average 0.4 ft^3/s for the annual cycle (compared to 0.3 ft^3/s calculated for the steady-state model). Some of the difference between the average annual depletions calculated with the transient model and those calculated with the steady-state model are because of round-off of the calculated values.

For the average annual withdrawal and hydrologic conditions simulated with the steady-state model, each stream reach either gains water from, or loses water to, the HAP aquifer. For transient simulations, however, a stream reach can be gaining during one part of the year and losing during another part of the year. For example, along a 0.6-mile reach of the Hunt River near wells NK9, KC1, 14A, and 9A, the average annual rate of loss of streamflow calculated with the transient model is 0.69 ft^3/s. During the months of March through May, however, when streamflow is high and withdrawal rates low, the reach becomes gaining, with the largest rate of streamflow gain (0.34 ft^3/s) during April.

CONJUNCTIVE-MANAGEMENT MODEL

A conjunctive-management model was developed for the HAP stream-aquifer system to determine whether sustained ground-water withdrawals during July, August, and September could be increased over current average rates, while streamflow-depletion rates caused by ground-water withdrawals are simultaneously maintained at desired levels during the same 3-month period. These 3 months were selected because they generally coincide with the time of year when water-supply demands are largest and streamflows are simultaneously lowest. Current conditions are defined as the average monthly withdrawal rates and estimated streamflow-depletion rates during 1993–98. This reference period was selected because withdrawal records for public water-supply wells in the aquifer are complete for 1993–98 (table 12), and because the average monthly withdrawal rates for this 6-year period better reflect current average withdrawal conditions and water-supply demands than does the 1996 withdrawal record that was used for calibration of the transient model.

Current rates of streamflow depletion caused by withdrawals at the public water-supply wells were estimated for the Hunt, Annaquatucket, and Pettaquamscutt Rivers by simulation of the transient model. In a first simulation, the 1993–98 average monthly withdrawal rates were specified for each well (table 12). The annual pattern of 1993–98 monthly withdrawals was simulated for 5 years to attain dynamic equilibrium, under the assumption that the 1993–98 withdrawals would be continued indefinitely with the other stresses simulated by the transient model. A second simulation then was made in which there were no withdrawals at the public water-supply wells. Streamflow depletions were calculated by subtracting streamflows calculated in the first simulation from those calculated in the second simulation. The calculated streamflow-depletion rates at the end of July, August, and September at the downstream end of the Hunt, Annaquatucket, and Pettaquamscutt Rivers are summarized in table 13. The calculated streamflow-depletion rates are largest for the Hunt River, ranging from 4.30 to 4.75 ft^3/s; those for the Annaquatucket River range from 2.01 to 3.00 ft^3/s and those for the Pettaquamscutt River range from 0.30 to 0.64 ft^3/s (table 13). The calculated rates also are largest for the

Table 12. Average 1993–98 monthly withdrawal rates for public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize withdrawal rates for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.29	.26	.23	.24	.23	.29	.35	.21	.18	.18	.20	.20
9A	.07	.17	.11	.12	.10	.11	.19	.29	.33	.21	.13	.16
14A	.22	.32	.22	.20	.25	.29	.39	.44	.33	.32	.37	.29
NK6	.31	.32	.30	.40	.43	.43	.55	.39	.29	.23	.19	.18
NK9	.58	.64	.65	.47	.55	1.11	1.39	1.47	1.27	1.00	.88	.70
NK10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total for basin........	1.74	1.79	1.59	1.59	1.88	3.03	3.81	3.60	2.93	2.22	2.09	2.07
Annaquatucket River Basin												
NK1	.28	.27	.28	.34	.43	.59	.58	.42	.26	.22	.15	.32
NK2	.20	.14	.13	.20	.32	.34	.38	.24	.18	.17	.16	.07
NK4	.29	.28	.25	.30	.37	.50	.57	.46	.36	.33	.25	.25
NK5	.30	.27	.32	.30	.44	.63	.75	.56	.40	.34	.34	.31
Total for basin........	1.07	0.96	0.98	1.14	1.56	2.06	2.28	1.68	1.20	1.06	0.90	0.95
Pettaquamscutt River Basin												
NK3	.09	.10	.09	.06	.07	.14	.22	.20	.17	.17	.14	.11
NK7	.01	.00	.04	.05	.05	.04	.09	.06	.03	.02	.01	.01
NK8	.00	.00	.02	.03	.04	.06	.09	.08	.04	.01	.00	.01
Total for basin........	0.10	0.10	0.15	0.14	0.16	0.24	0.40	0.34	0.24	0.20	0.15	0.13
Total for all basins	2.91	2.85	2.72	2.87	3.60	5.33	6.49	5.62	4.37	3.48	3.14	3.15

Hunt River when expressed as a percentage of the pre-withdrawal streamflow calculated for each river (that is, streamflows calculated for each river with no withdrawals at the public water-supply wells)—22–28 percent for the Hunt River, 16–21 percent for the Annaquatucket River, and 5–9 percent for the Pettaquamscutt River.

Formulation of the Conjunctive-Management Model

The conjunctive-management model developed for the system was formulated and solved by use of optimization techniques. Formulation of the model refers to the process of defining the conjunctive-management problem mathematically by a set of decision variables, an objective function, and a set of constraints. The decision variables of the model were monthly withdrawal rates at each of the public water-supply wells; values for each decision variable were calculated by the optimization solution technique. Mathematically, the decision variables were expressed as $Qw_{i,t}$, which is the withdrawal rate at well i in month t. The subscript t ranges from $t = 1$ for January through $t = 12$ for December. The model had a maximum of 192 decision variables, one for each of 16 existing and hypothetic public water-supply wells (table 14) for each of 12 months.

Table 13. Model-calculated end-of-month streamflow depletions for the Hunt, Annaquatucket, and Pettaquamscutt Rivers, Rhode Island, for July, August, and September, with 1993–98 average monthly ground-water withdrawal rates

[River sites shown on figure 6. Streamflow depletion is given in cubic feet per second and, in parentheses, million gallons per day]

River (site identifier)	Model-calculated, end-of-month streamflow depletion		
	July	August	September
Hunt (P)	4.70 (3.04)	4.75 (3.07)	4.30 (3.78)
Annaquatucket (T)	3.00 (1.94)	2.59 (1.67)	2.01 (1.30)
Pettaquamscutt (V)	.64 (.41)	.46 (.30)	.30 (.19)

The objective function of the model was to maximize total ground-water withdrawals from the HAP aquifer during July, August, and September and is given as

$$maximize \sum_{i=1}^{NW} \sum_{t=7}^{9} ND_t Qw_{i,t} \ , \qquad (5)$$

where NW is the total number of wells and ND_t is the number of days in month t. Values of the objective function were in units of million gallons withdrawn during the 3-month period.

The value of the objective function was limited by a set of constraints on maximum rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers; minimum monthly water demands by each of the three water suppliers (KCWA, RIEDC, and NK); and minimum and maximum withdrawal rates at each of the wells.

Maximum rates of streamflow depletion were required to be less than or equal to specified maximum rates at streamflow constraint sites located at the most downstream model cell of each of the three rivers (sites P, T, and V shown on fig. 6):

$$Qsd_{j,t} \le (Qsd_{j,t})_{max} \ , \qquad (6)$$

where $Qsd_{j,t}$ is streamflow depletion at streamflow constraint site j in month t and $(Qsd_{j,t})_{max}$ is the maximum rate of streamflow depletion allowed at site j in month t. The downstream locations of each of the three rivers were used for the constraint sites because they are the locations where streamflow depletions are largest in each of the basins. Maximum rates of streamflow depletion specified at the three constraint sites are described in the applications of the model. Thirty-six streamflow-depletion constraints were specified in the model—one for each of the three rivers in each of the 12 months.

Table 14. Maximum withdrawal rates specified for public water-supply wells in the conjunctive-management model for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Unless otherwise noted, maximum withdrawal rates are equal to well yield based on original aquifer test at site. Withdrawal rates are million gallons per day. Well locations are shown on figure 1. KCWA, Kent County Water Authority; NK, Town of North Kingstown; RIEDC, Rhode Island Economic Development Corporation; No., number]

Well No.	Water supplier	Current well configuration		Modified well configuration	
		Water-supply well identifier	Maximum withdrawal rate	Water-supply well identifier	Maximum withdrawal rate
		Hunt River Basin			
1	KCWA	KC1	2.59	KC1	2.59
2	RIEDC	3A	1.80	3A	[a]2.80
3	RIEDC	9A	2.10	9A	2.10
4	RIEDC	14A	1.44	14A	1.44
5	NK	NK6	1.37	NK6	[a]2.37
6	NK	NK9	[b]2.21	NK9	[b]2.21
7	NK	NK10	2.16	NK10	2.16
		Annaquatucket River Basin			
8	NK	NK1	1.44	NK1	1.44
9	NK	NK2	[c]1.44	NK2	[c]1.44
10	NK	NK4	[c]1.44	NK4	[c]1.44
11	NK	NK5	1.75	NK5	1.75
12	NK			H1	[d]1.00
13	NK			H2	[d]1.00
		Pettaquamscutt River Basin			
14	NK	NK3	1.44	NK3	1.44
15	NK	NK7	[b].81	NK7	[b].81
16	NK	NK8	.40	NK8	.40

[a]Assumed increased capacity of 1.00 Mgal/d at wells 3A and NK6.
[b]Maximum withdrawal rate during 1993–98.
[c]Assumed maximum withdrawal rate equal to that of well NK1.
[d]Assumed maximum withdrawal rate.

Total monthly withdrawals from all wells in each of the three water-supply systems were required to be greater than or equal to the average monthly demands of each supplier during the 1993–98 period (table 15). This constraint was written for each supplier as

$$\sum_{i = W_L}^{W_U} Qw_{i,\,t} \geq D_{WS,\,t} \ , \qquad (7)$$

where $D_{WS,\,t}$ is the demand for supplier WS in month t, and W_L and W_U are the lowermost and uppermost well numbers in supply system WS (well numbers shown in table 14). Thirty-six water-demand constraints were specified—one for each of the three suppliers in each of the 12 months.

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

$$(Qw_{i,\,t})_{min} \leq Qw_{i,\,t} \leq (Qw_{i,\,t})_{max} \ , \qquad (8)$$

where $(Qw_{i,\,t})_{min}$ and $(Qw_{i,\,t})_{max}$ are the minimum and maximum withdrawal rates at well i in month t. The minimum withdrawal rate at all wells equalled zero and did not need to be explicitly specified in the model. The maximum withdrawal rate for each well (table 14) was assumed to be the larger of the well's yield based on the aquifer test done when the well was first installed (table 1) or the maximum withdrawal rate during 1993–98. For wells NK2 and NK4, however, a maximum withdrawal rate equal to that for nearby well NK1 (1.44 Mgal/d) was assumed. This was done because yield data for these two wells were not available, and because maximum withdrawal rates at each well during 1993–98 were low compared to maximum rates possible for nearby wells. Maximum withdrawal rates for the two hypothetical wells are discussed in the applications section. A maximum of 192 constraints for maximum withdrawal rates were specified.

Table 15. Average monthly withdrawal rates (demands) for each water supplier in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1993–98

[Withdrawal rates are million gallons per day]

Month	Kent County Water Authority	Rhode Island Economic Development Corporation	Town of North Kingstown
January	0.27	0.58	2.05
February	.08	.74	2.03
March	.08	.55	2.07
April	.16	.56	2.16
May	.32	.58	2.71
June	.80	.69	3.85
July	.94	.93	4.62
August	.80	.94	3.88
September	.53	.84	3.00
October	.28	.71	2.46
November	.32	.70	2.13
December	.54	.64	1.95

In addition to constraints on withdrawal rates for each individual well, constraints on combined withdrawal rates also were specified for two pairs of wells. First, a maximum combined withdrawal rate of 1.60 Mgal/d was specified for wells NK1 and NK2 for each month as

$$Qw_{8,\,t} + Qw_{9,\,t} \leq 1.60 \ Mgal/d \ , \qquad (9)$$

where the subscripts *8* and *9* are the well numbers given in table 14. This constraint was necessary because the yields of these wells have been observed to decrease when the combined withdrawal rate exceeds 1.60 Mgal/d.

Second, a minimum combined withdrawal rate of 0.47 Mgal/d was specified for wells NK9 and NK10 for each month as

$$0.47 \ Mgal/d \leq Qw_{6,\,t} + Qw_{7,\,t} \ . \qquad (10)$$

A minimum combined withdrawal rate from these wells is necessary for system operation; the value of 0.47 Mgal/d was the minimum combined average monthly withdrawal rate from the wells during 1993–98 (table 12). In addition, wells NK9 and NK10 cannot pump simultaneously. To explicitly address this constraint would have required use of integer variables, which would have complicated the solution procedure. Instead, a maximum combined withdrawal rate from the two wells equal to the maximum withdrawal rate of NK9 (2.21 Mgal/d, see table 14) was specified as

$$Qw_{6,\,t} + Qw_{7,\,t} \leq 2.21 \ Mgal/d \ . \qquad (11)$$

This approach is valid because the two wells are close to one another and have very similar effects on streamflow depletion in the Hunt River, as determined by simulations with the transient model. Therefore, withdrawal rates at the wells can be interchanged without affecting the streamflow-depletion constraints.

In summary, the conjunctive-management model was formulated mathematically to maximize withdrawals from wells in the HAP aquifer during July, August, and September (equation 5), subject to constraints on streamflow depletions caused by ground-water withdrawals (equation 6), water demands (equation 7), and withdrawal rates at the wells (equations 8-11).

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

The optimization method used to solve the conjunctive-management model is based on a widely applied technique for solving many types of ground-water management problems called the response-matrix technique. The basis of the technique is the assumption that the rate of streamflow depletion at each streamflow constraint site is a linear function of the rates of ground-water withdrawal at each public water-supply well. By assuming linearity, it is possible to determine total streamflow depletion at a constraint site by summation of the individual streamflow depletions caused by each well. Detailed descriptions of the response-matrix technique are given by Gorelick and others (1993) and Ahlfeld and Mulligan (2000). Specific applications of the technique to problems in stream-aquifer management are given by Maddock (1974), Morel-Seytoux and Daly (1975), Morel-Seytoux (1975a,b), Illangasekare and Morel-Seytoux (1982), Peralta and others (1988), Male and Mueller (1992), Mueller and Male (1993), and Barlow (1997a). The technique is valid as long as (1) the saturated thickness and transmissivity of the HAP aquifer do not vary substantially with changes in withdrawal rates and (2) other nonlinear effects simulated by the transient model, such as head-dependent boundary conditions, do not substantially affect the linear relation between ground-water withdrawals and streamflow depletions. The validity of these assumptions are addressed at the end of this section.

Implementation of the response-matrix technique requires calculation of characteristic streamflow-depletion responses at each of the three streamflow constraint sites to simulated unit withdrawals at each of the 16 existing and hypothetical wells. To calculate the characteristic responses, 16 simulations of the transient model were made. In each simulation, the withdrawal rate specified for one of the wells was increased from its 1993–98 rate by 0.5 Mgal/d for 1 month (the month of January was used); at the end of the month, the withdrawal rate at the well was returned to its 1993-98 rate. The single-month increase of 0.5 Mgal/d is referred to as the unit withdrawal Qw_i^* at well i. The amount of streamflow depletion resulting from the unit withdrawal was determined by subtracting streamflow rates calculated by the model with the unit withdrawal active from those calculated by the model with the unit withdrawal inactive. Streamflow-depletion responses to the unit withdrawals are defined as $Qsd_{j,t}^*$. Streamflow-depletion response coefficients ($r_{j,i,t}$) are then defined as

$$r_{j,i,t} = \frac{Qsd_{j,t}^*}{Qw_i^*} . \qquad (12)$$

The response coefficients are dimensionless and range from 0.0 to 1.0. For the assumption of linearity to be valid, the values of the response coefficients for each well/streamflow-constraint-site pair must remain constant for all simulated withdrawal and hydrologic conditions.

Response coefficients determined by the transient model for five of the well/streamflow-constraint-site pairs (fig. 17) indicate that there is substantial variability in the quantity and timing of streamflow-depletion responses to the simulated unit withdrawals. For example, the effect of the unit withdrawal at well 3A on streamflow in the Hunt River is rapid, with a large depletion of streamflow in the first month but very little depletion in the months following the unit withdrawal. This variability of streamflow responses to unit withdrawals is advantageous, because it provides flexibility in determining withdrawal schedules at the wells that increase the yield of the aquifer while meeting the streamflow-depletion constraints. Factors that affect streamflow responses are the relative positions of the wells and streamflow constraint sites (including the vertical positions of the screened interval of each well), the geometry and hydraulic properties of the aquifer, and the streambed conductance and other physical characteristics of the streams. Although not shown in figure 17, response coefficients for wells NK7 and NK8 are nearly identical to those shown for well NK3. Also, response coefficients for wells 9A, 14A, and NK10 are

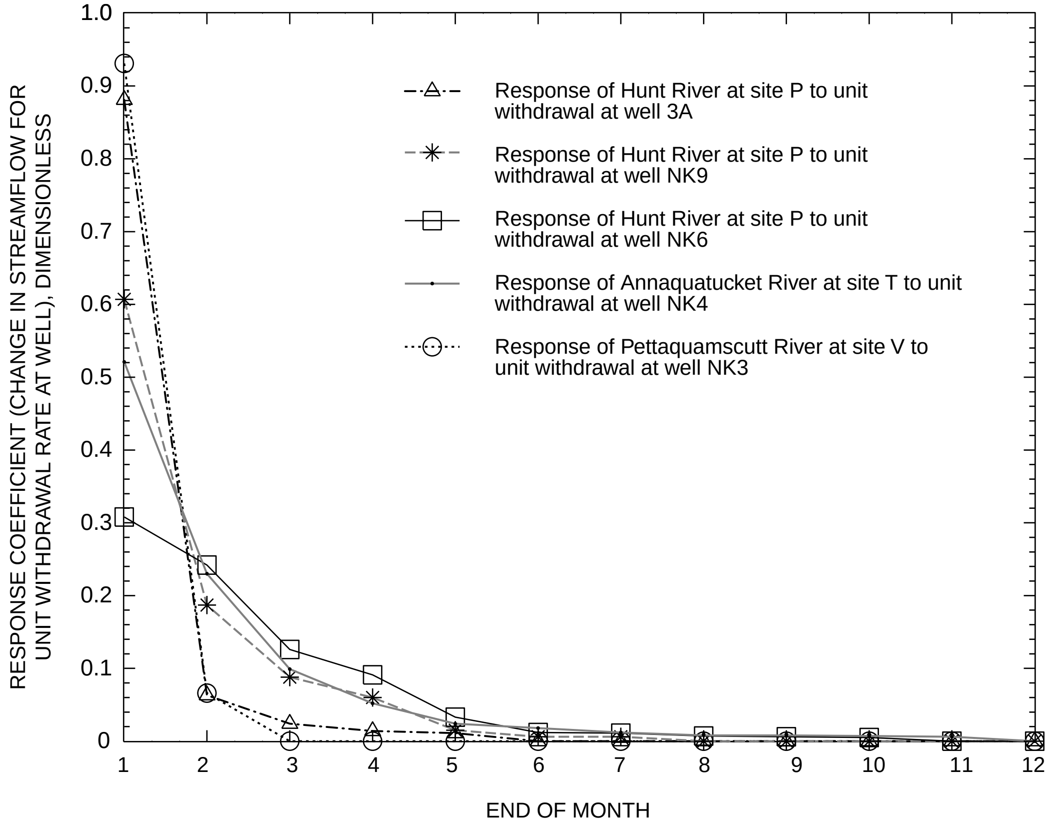


Figure 17. Selected simulated response coefficients for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island. (Unit withdrawal rate of 0.5 million gallons per day. Well locations shown on fig. 1; streamflow sites P, T, and V shown on fig. 6.)

similar to those shown for well NK9; and those for wells NK1, NK2, and NK5 are similar to those shown for well NK4.

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

$$Qsd_{j,t} = \sum_{i=1}^{NW} \sum_{k=1}^{12} r_{j,i,k} Qw_{i,k'} \ , \qquad (13)$$

where

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

The two-part definition of k' is required as a consequence of the annual cycle of withdrawals. For example, streamflow depletions in January ($t = 1$) can be affected by withdrawals in December ($t = 12$). Although the summation includes 12 terms for each well/streamflow-constraint-site pair, many of the terms equal zero, because many of the response coefficients equal zero (fig. 17).

The response coefficients are the link between the numerical and conjunctive-management models of the HAP stream-aquifer system. The response coefficients are incorporated into the conjunctive-management model by replacing the definition of $Qsd_{j,t}$ in the streamflow-depletion constraints (equation 6) by the right-hand side of equation 13. The constraints are then written as

$$\sum_{i=1}^{NW} \sum_{k=1}^{12} r_{j,i,k} Qw_{i,k'} \le (Qsd_{j,t})_{max} \ . \qquad (14)$$

Equation 14 replaces equation 6 in the conjunctive-management model.

Difficulties arose in the use of the response-matrix technique because the numerical model of the HAP stream-aquifer system is weakly nonlinear. These nonlinearities are the result of two factors. First, the HAP aquifer is unconfined, which means that the saturated thickness and transmissivity change as withdrawal rates at the wells change. Second, evapotrans–piration and streamflow leakage were simulated as piecewise-linear functions of calculated water-level altitudes. Because of these nonlinearities, the response coefficients for each well/streamflow-constraint-site pair can change as withdrawal rates change, and such changes can affect the solution of the conjunctive-management model. These types of nonlinearities have been addressed in ground-water management problems by sequential (or iterative) linearization of the nonlinear problem (Danskin and Gorelick, 1985; Danskin and Freckleton, 1989; Gorelick and others, 1993, p. 206–208; Barlow, 1997a; and Ahlfeld and Mulligan, 2000, p. 160–163). The sequential-linearization approach was not used here, however, because it is computationally intensive and because simulations with the transient model indicated that the response coefficients change very little as the simulated withdrawal conditions change. These simulations consisted of different unit withdrawal rates, different background withdrawal conditions (specifically, either the 1993–98 average monthly withdrawal condition or a condition of no withdrawal at any of the supply wells), and different months in which the unit withdrawal was active. The primary reason that the response coefficients change very little for the different withdrawal conditions is that the HAP aquifer is highly transmissive near many of the wells. As a consequence, drawdowns caused by different simulated withdrawal conditions do not cause substantial changes in the saturated thickness or transmissivity of the aquifer in these areas.

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

By assuming linearity of the streamflow responses to ground-water withdrawals, the modified conjunctive-management model defined by equations 5, 7–11, and 14 constitutes a linear program. The LINDO linear-programming computer software (LINDO Systems, 1996) was used to solve each specific application of the conjunctive-management model described in the next section. The program mathematically searches for the monthly withdrawal rates at each well that maximize the yield of the aquifer subject to the set of constraints. The validity of the response-matrix, linear-programming technique that was used in this work was evaluated for several applications of the model. The evaluations consisted of simulating the withdrawal rates calculated by LINDO with the transient model, and then ensuring that the resulting streamflow depletions calculated for July, August, and September were less than or close to the streamflow-depletion rates specified in the conjunctive-management model.

Applications of the Model

Four sets of applications of the conjunctive-management model were made for alternative definitions of the maximum rate of streamflow depletion allowed at streamflow constraint sites on the Hunt, Annaquatucket, and Pettaquamscutt Rivers (that is, alternative definitions of $(Qsd_{j,t})_{max}$ in equation 14). The purpose of varying the specified maximum rates of streamflow depletion was to quantify the amount of withdrawal that is possible during July, August, and September for different streamflow-depletion criteria. Four sets of alternatives were evaluated:

Set 1: Maintain current rates of streamflow depletion in all three rivers during July, August, and September.

Set 2: Decrease current rates of streamflow depletion in the Hunt River during July, August, and September, with current rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers.

Set 3: Maintain current rates of streamflow depletion in the Hunt River during July, August, and September, with increased rates of streamflow depletion allowed in the Annaquatucket and Pettaquamscutt Rivers.

Set 4: Decrease current rates of streamflow depletion in the Hunt River during July, August, and September, with increased rates of streamflow depletion allowed in the Annaquatucket and Pettaquamscutt Rivers.

Current rates of streamflow depletion are those determined with the transient model for the 1993–98 withdrawal rates (table 13). Note that by decreasing current rates of streamflow depletion in the Hunt River, streamflow in the river would be increased over the current estimated rates.

Streamflow depletion in the Hunt River was not allowed to increase in any of the alternatives. This was done because streamflow depletions calculated for the Hunt River for current withdrawal rates (table 13) are larger than those for either the Annaquatucket or Pettaquamscutt Rivers, both in absolute quantity and as a percentage of the pre-withdrawal streamflow calculated for each river.

For each alternative, two configurations of the public water-supply wells were tested. The first configuration (referred to as the current well configuration) consisted of the current system of 14 wells with their associated maximum withdrawal rates (table 14). The second configuration (referred to as the modified well configuration) was a modified system of 16 wells that consisted of the current 14 wells; an assumed increased capacity of 1.00 Mgal/d at wells 3A and NK6; and two additional hypothetical wells, H1 and H2 (table 14), in the Annaquatucket River Basin, each with an assumed maximum withdrawal rate of 1.00 Mgal/d. The locations of the two hypothetical wells are shown on figure 12*B*. Well sites 3A, NK6, H1, and H2 were identified in discussion with RIEDC and the town of North Kingstown as locations where increased yields from the aquifer may be possible. Further testing of these sites would be required to determine whether the model-calculated withdrawals that are in exceedance of current withdrawal rates could actually be attained at the sites. All withdrawals from well 3A were allocated to RIEDC and all withdrawals from wells NK6, H1, and H2 were allocated to the town of North Kingstown.

The value of the objective function calculated for each alternative was compared to the current, 1993–98 average total withdrawal during July, August, and September, which is 506.5 Mgal (based on data in table 15). Results of each set of alternatives are described in the following four subsections; total ground-water withdrawals calculated for all alternatives are summarized in the last subsection.

Maintain Current Rates of Streamflow Depletion During July, August, and September

The first set of alternatives was made to determine whether current withdrawal rates from the aquifer can be increased during July, August, and September without increasing current estimated rates of streamflow depletion in the Hunt, Annaquatucket, or Pettaquamscutt Rivers during these months. Maximum allowed streamflow depletions for each river from July through September are those shown in table 13. Streamflow depletions during each of the remaining 9 months of the year were constrained to be less than or equal to the calculated maximum monthly streamflow-depletion rate in each river, which was 4.75 ft^3/s for the Hunt River, 3.00 ft^3/s for the Annaquatucket River, and 0.64 ft^3/s for the Pettaquamscutt River (table 13). These constraints were designed to prevent large increases in streamflow depletion from October through June.

Total ground-water withdrawal for July, August, and September determined for the current well configuration was 546.0 Mgal, which is an overall increase of 7.8 percent from the current total withdrawal of 506.5 Mgal. The increase consists of a 12.6 percent increase over current withdrawals for July and a 10.8 percent increase over current withdrawals for September. These are modest increases that indicate little flexibility in the current configuration of wells to provide for substantial increased withdrawals while current rates of streamflow depletion are maintained in the three rivers.

The increased yield would require implementation of the monthly withdrawal rates calculated by LINDO for each well, which are given in table 16. Note that there are very small discrepancies (≤0.04 Mgal/d) between the total monthly withdrawal rates calculated for all basins for October through June (bottom row of table 16) and the 1993–98 total monthly withdrawal rates for all basins for these months (bottom row of table 12). These discrepancies result from round-off errors in the withdrawal rates of individual wells and from errors introduced by the response-matrix solution procedure.

The patterns of withdrawals calculated for the three water-supply systems indicate the following:

1. Monthly withdrawal rates calculated for well KC1 (table 16) are equal to the current withdrawal rates for the well (table 12). Because water-supply demands for KCWA in the HAP aquifer can be met only by withdrawals from their single well in the Hunt River Basin (KC1), the well must withdraw at a rate that is at least equal to each month's demand. There is, however, little opportunity for

Table 16. Monthly withdrawal rates calculated for the current configuration of public water-supply wells for 1993–98 estimated rates of streamflow depletion in July, August, and September, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	.51	.51	.00	.71	.70	.64
9A	.00	.00	.00	.00	.00	.00	.00	.43	.84	.00	.00	.00
14A	.00	.00	.00	.00	.00	.00	.92	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	1.37	1.37	1.37	.00	.00	.00
NK9	1.62	1.61	1.65	1.75	.00	.00	.47	.00	.47	.58	1.72	1.94
NK10	.00	.00	.00	.00	.55	1.69	.00	.54	.00	.00	.00	.00
Total for basin.......	2.47	2.43	2.28	2.47	1.45	3.18	4.21	3.65	3.21	1.57	2.74	3.12
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.44	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	.93	.00	1.44	.00	.00	.00
NK5	.00	.00	.00	.00	1.75	1.75	1.75	1.66	.00	.00	.00	.00
Total for basin.......	0.00	0.00	0.00	0.00	1.75	1.75	2.68	1.66	1.44	1.44	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	.00	.31	.19	.43	.41	.00
NK7	.43	.41	.41	.41	.41	.41	.42	.00	.00	.00	.00	.00
NK8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total for basin.......	0.43	0.41	0.41	0.41	0.41	0.41	0.42	0.31	0.19	0.43	0.41	0.00
Total for all basins	2.90	2.84	2.69	2.88	3.61	5.34	7.31	5.62	4.84	3.44	3.15	3.12

increased withdrawals from the HAP aquifer for the KCWA system because the system consists of a single well.

2. Calculated withdrawals from wells in the RIEDC system (table 16) are concentrated at well 3A during the months of October through June, but are distributed among wells 3A, 9A, and 14A during July through September. This withdrawal pattern differs from the current pattern of withdrawals (table 12), in which each well is active during every month. An increase of 0.50 Mgal/d (15.5 Mgal) over the current July withdrawal rate is calculated for the RIEDC system for this alternative.
3. A comparison of the calculated withdrawals for North Kingstown wells (table 16) with current withdrawal patterns (table 12) indicates (a) higher total withdrawals from the Hunt River Basin during November through April; (b) use of well NK6 only during July, August, and September, and at its maximum specified rate of 1.37 Mgal/d; (c) use of wells in the Annaquatucket River Basin only during May through October; and (d) higher total withdrawals from the Pettaquamscutt River Basin during January through June and October and November. An increase of 0.32 Mgal/d (9.9 Mgal) in July and of 0.47 Mgal/d (14.1 Mgal) in September is calculated for the town of North Kingstown water-supply system. The large increase in yield for the system, compared to the other two water-supply systems, results from the large number of wells in the system and the distribution of the wells among

the three river basins; these factors provide flexibility in the withdrawal schedules calculated for each well.

The monthly withdrawal rates calculated by the conjunctive-management model (table 16) were simulated in the transient model for a 5-year period. With this withdrawal pattern, seven of the nine streamflow-depletion constraints specified for July, August, and September were met in the fifth year of simulation (that is, at dynamic equilibrium). Of the two streamflow-depletion constraints that were not met, the maximum difference between specified and calculated streamflow-depletion rates was 0.07 ft^3/s for the Hunt River in the month of July. This value is a small difference from the specified depletion of 4.70 ft^3/s, and substantiates the response-matrix solution technique.

Because of the similarity of some of the response coefficients, it is possible to interchange calculated withdrawal rates among those wells with similar response coefficients, while still maintaining the value of the objective function and meeting the model constraints. For example, table 16 indicates that well 14A is active only during July; well NK10 in May, June, and August; well NK1 in October; and well NK3 from August through November. A simulation of the transient model was made to illustrate that there is some flexibility in the withdrawal patterns calculated by the linear program, and that, in some cases, these withdrawal patterns can be simplified. In the simulation, withdrawal rates from those wells with little activity during the year were shifted to wells within the same water-supply system that have similar response coefficients and are active during more months of the year. Specifically, as shown in table 17, the July withdrawal

Table 17. Monthly withdrawal rates specified for public water-supply wells in a simulation of the transient model of the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	.51	.51	.00	.71	.70	.64
9A	.00	.00	.00	.00	.00	.00	.92	.43	.84	.00	.00	.00
14A	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	1.37	1.37	1.37	.00	.00	.00
NK9	1.62	1.61	1.65	1.75	.55	1.69	.47	.54	.47	.58	1.72	1.94
NK10	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total for basin........	2.47	2.43	2.28	2.47	1.45	3.18	4.21	3.65	3.21	1.57	2.74	3.12
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	.93	.00	1.44	1.44	.00	.00
NK5	.00	.00	.00	.00	1.75	1.75	1.75	1.66	.00	.00	.00	.00
Total for basin........	0.00	0.00	0.00	0.00	1.75	1.75	2.68	1.66	1.44	1.44	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK7	.43	.41	.41	.41	.41	.41	.42	.31	.19	.43	.41	.00
NK8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total for basin........	0.43	0.41	0.41	0.41	0.41	0.41	0.42	0.31	0.19	0.43	0.41	0.00
Total for all basins	2.90	2.84	2.69	2.88	3.61	5.34	7.31	5.62	4.84	3.44	3.15	3.12

at well 14A was shifted to well 9A; withdrawals from NK10 were shifted to NK9; the October withdrawal at NK1 was shifted to NK4; and withdrawals from NK3 were shifted to NK7. With this modified withdrawal pattern, calculated streamflow depletions for the Hunt, Annaquatucket, and Pettaquamscutt Rivers in July, August, and September were less than or equal to the specified rates for all but one of the streamflow constraint sites during one of the months. The one exception was the streamflow depletion calculated for July for the Pettaquamscutt River, which exceeded the specified constraint value by only 0.02 ft^3/s. The transient model could be used to test whether other withdrawal patterns (with equivalent overall withdrawal rates) also could meet the model constraints.

Total ground-water withdrawal for July, August, and September determined for the modified well configuration was 596.3 Mgal, which is an overall increase of 17.7 percent from the current average total withdrawal of 506.5 Mgal. The increase consists of a 25.0 percent increase over current average withdrawals for July and a 30.0 percent increase over September withdrawals. The larger increase in total withdrawal, compared to the current well configuration, results from the larger number of wells and increased total withdrawal capacity from all wells that is provided by the modified well configuration.

Monthly withdrawal rates calculated for the modified well configuration are shown in table 18. In contrast to withdrawal patterns calculated for the

Table 18. Monthly withdrawal rates calculated for the modified configuration of public water-supply wells for 1993-98 estimated rates of streamflow depletion in July, August, and September, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	.93	.95	.00	.71	.31	.64
9A	.00	.00	.00	.00	.00	.00	.00	.00	.84	.00	.40	.00
14A	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	2.37	.89	1.89	.00	.00	.00
NK9	1.62	1.62	1.66	1.75	.00	.00	.00	.00	.47	.00	1.74	1.95
NK10	.00	.00	.00	.00	.47	1.00	.47	.47	.00	1.25	.00	.00
Total for basin.......	2.47	2.44	2.29	2.47	1.37	2.49	4.71	3.11	3.73	2.24	2.77	3.13
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.08	.69	.00	.00	.00	.80	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK5	.00	.00	.00	.00	1.75	1.75	1.75	1.21	.00	.00	.00	.00
H1	.00	.00	.00	.00	.00	.00	.24	.00	.76	.00	.00	.00
H2	.00	.00	.00	.00	.00	.00	1.00	1.00	1.00	.00	.00	.00
Total for basin.......	0.00	0.00	0.00	0.00	1.83	2.44	2.99	2.21	1.76	0.80	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	.00	.31	.19	.00	.00	.00
NK7	.43	.41	.41	.41	.41	.41	.41	.00	.00	.00	.00	.00
NK8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.41	.40	.00
Total for basin.......	0.43	0.41	0.41	0.41	0.41	0.41	0.41	0.31	0.19	0.41	0.40	0.00
Total for all basins	2.90	2.85	2.70	2.88	3.61	5.34	8.11	5.63	5.68	3.45	3.17	3.13

current well configuration (table 16), no increases in withdrawals are calculated for the RIEDC system. This appears to be caused by the increased withdrawal rate allowed at well NK6 in the modified well configuration. Relatively large withdrawals can be sustained at this well during July through September because streamflow depletion in the Hunt River reacts slowly to withdrawals from the well (fig. 17). Also, for this alternative, hypothetical well H2 withdraws at its maximum specified rate of 1.00 Mgal/d from July through September, and hypothetical well H1 withdraws during July and September.

Streamflow depletions calculated for the three rivers for July, August, and September with the withdrawal rates calculated for this alternative (table 18) were less than or equal to the specified constraint values for seven of the nine streamflow-depletion constraints in July, August, and September. Of the two constraints that were not met, the maximum difference between specified and calculated streamflow-depletion rates was 0.17 ft^3/s for the Hunt River in the month of July. This is a small difference from the specified depletion of 4.70 ft^3/s.

Decrease Current Rates of Streamflow Depletion in the Hunt River During July, August, and September, With Current Rates of Streamflow Depletion in the Annaquatucket and Pettaquamscutt Rivers

The second set of alternatives was made to determine whether estimated current rates of streamflow depletion in the Hunt River can be decreased during July, August, and September, (1) while current water-supply demands are met and (2) without increasing streamflow depletions in the Annaquatucket or Pettaquamscutt Rivers. Decreasing current rates of streamflow depletion in the Hunt River would result in increased streamflow in the river. As in the first set of alternatives, maximum allowed streamflow-depletion rates during July, August, and September for the Annaquatucket and Pettaquamscutt Rivers are constrained to be less than or equal to those calculated for 1993–98 average withdrawal rates; streamflow depletions in all rivers during each of the remaining 9 months of the year were constrained to be less than or equal to the estimated current maximum monthly rate of streamflow depletion in each river (table 13). To determine the maximum decreases in streamflow depletion in the Hunt River that could be attained during July, August, and September, the estimated current rates of streamflow depletion for each month were lowered by uniform increments of 5 percent in a series of LINDO simulations; the maximum decreases were determined when the next 5-percent increment resulted in an infeasible solution (that is, one or more of the model constraints could not be met).

For the current configuration of supply wells, the calculated maximum increases in streamflow that could be attained for the Hunt River for July, August, and September are only 5 percent of existing streamflow-depletion rates calculated for these months, or from 0.22 ft^3/s in September to 0.24 ft^3/s in August. The small increase in streamflow that is possible with the current configuration of wells is not surprising, given the small increase in total withdrawal that was calculated in the first set of alternatives for the current supply-well configuration. Total ground-water withdrawal for July, August, and September for this alternative is 526.1 Mgal, which is an overall increase of only 3.7 percent from the current average total withdrawal (506.5 Mgal). This small increase relative to that calculated for the current well configuration in the first set of alternatives is a result of the lower rates of streamflow depletion allowed for the Hunt River in this alternative.

For the modified configuration of supply wells, the calculated maximum increases in streamflow that could be attained for the Hunt River for July, August, and September are 15 percent of existing streamflow-depletion rates calculated for these months, or from 0.65 ft^3/s in September to 0.71 ft^3/s in August. Total ground-water withdrawal for July, August, and September for this alternative is 525.2 Mgal, which is an overall increase of only 3.7 percent from the current average total withdrawal (506.5 Mgal). The most significant difference between withdrawal rates calculated for this alternative (table 19) and those calculated for the modified well configuration in the first set of alternatives (table 18) is that calculated withdrawals for well NK6 during July and September are substantially lower for this alternative.

Table 19. Monthly withdrawal rates calculated for the modified configuration of public water-supply wells and a 15-percent reduction in the 1993–98 estimated rates of streamflow depletion in the Hunt River in July, August, and September, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	0.74	.55	.56	.58	.69	.99	.75	.00	.71	.33	.64
9A	.00	.00	.00	.00	.00	.00	.00	.20	.84	.00	.38	.00
14A	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	.83	.89	1.13	.00	.00	.00
NK9	1.62	1.62	1.66	1.75	.00	.00	.00	.00	.47	.00	.00	1.52
NK10	.00	.00	.00	.00	.47	.80	.47	.47	.00	.61	1.74	.00
Total for basin.......	2.47	2.44	2.29	2.47	1.37	2.29	3.23	3.11	2.97	1.60	2.77	2.70
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.08	.89	.00	.00	.00	1.44	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	.16	.00	.00	.00	.00	.00
NK5	.00	.00	.00	.00	1.75	1.75	1.75	1.21	.00	.00	.00	.00
H1	.00	.00	.00	.00	.00	.00	.00	.00	.76	.00	.00	.00
H2	.00	.00	.00	.00	.00	.00	1.00	1.00	1.00	.00	.00	.00
Total for basin.......	0.00	0.00	0.00	0.00	1.83	2.64	2.91	2.21	1.76	1.44	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	.00	.31	.19	.00	.00	.43
NK7	.43	.41	.41	.41	.41	.41	.41	.00	.00	.41	.40	.00
NK8	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total for basin.......	0.43	0.41	0.41	0.41	0.41	0.41	0.41	0.31	0.19	0.41	0.40	0.43
Total for all basins	2.90	2.85	2.70	2.88	3.61	5.34	6.55	5.63	4.92	3.45	3.17	3.13

Maintain Current Rates of Streamflow Depletion in the Hunt River During July, August, and September, With Increased Rates of Streamflow Depletion Allowed in the Annaquatucket and Pettaquamscutt Rivers

As noted previously, estimated rates of streamflow depletion are larger for the Hunt River than for either the Annaquatucket or Pettaquamscutt Rivers. The estimated average streamflow depletion in the Hunt River for the months of July through September is 25 percent of the estimated pre-withdrawal streamflows in the river, whereas those for the Annaquatucket and Pettaquamscutt Rivers are 19 percent and 7 percent, respectively. In the third and fourth sets of alternatives, specified rates of streamflow depletion for the Annaquatucket and Pettaquamscutt Rivers were allowed to increase to a maximum of 25 percent of the estimated pre-withdrawal streamflow in each river during July through September (table 20), as determined with the transient numerical model. The maximum increases in the allowed rates of streamflow depletion are 0.56 to 1.20 ft^3/s for the Annaquatucket

Table 20. Specified rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers, Rhode Island, for conditions in which streamflow depletions are allowed to increase in the two rivers

[All values are in cubic foot per second]

Month	Model-calculated pre-withdrawal streamflow	Model-calculated current rates of streamflow depletion (from table 13)	Specified rate of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers			
			25 percent of maximum allowed increase in streamflow depletion	50 percent of maximum allowed increase in streamflow depletion	75 percent of maximum allowed increase in streamflow depletion	100 percent of maximum allowed increase in streamflow depletion
			Annaquatucket River			
July	14.24	3.00	3.14	3.28	3.42	3.56
August	13.56	2.59	2.79	2.99	3.19	3.39
September	12.84	2.01	2.31	2.61	2.91	3.21
			Pettaquamscutt River			
July	7.44	.64	.94	1.25	1.55	1.86
August	6.52	.46	.75	1.05	1.34	1.63
September	5.84	.30	.59	.88	1.17	1.46

River and 1.16 to 1.22 ft^3/s for the Pettaquamscutt River (table 20). Increasing current rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers would result in decreased streamflow in these rivers.

Four sets of LINDO simulations were made for each well configuration, in which the allowed increases in streamflow depletion for the Annaquatucket and Pettaquamscutt Rivers were incrementally set at 25-, 50-, 75-, and 100-percent of the maximum allowed rates (table 20). In each simulation, streamflow depletions during the remaining 9 months of the year were constrained to be less than or equal to the maximum monthly rate, which in each case equals the July rate. Specified rates of streamflow depletion in the Hunt River were maintained at current estimated rates, as was done for the first set of alternatives.

Substantial increases in ground-water withdrawals are calculated for the several simulations, because streamflow is allowed to decrease in the Annaquatucket and Pettaquamscutt Rivers (fig. 18). For the current configuration of supply wells, total withdrawals during July through September range from a minimum of 546.0 Mgal for current rates of streamflow depletion specified for the Annaquatucket and Pettaquamscutt Rivers to a maximum of 705.1 Mgal for the maximum allowed decreases in streamflow in the two rivers (fig. 18). This is a maximum increase of 39.2 percent over the current total withdrawal of 506.5 Mgal. For the modified well configuration, total withdrawals range from 596.3 Mgal to 760.3 Mgal (fig. 18), which is a maximum increase of 50.1 percent over the current total withdrawal.

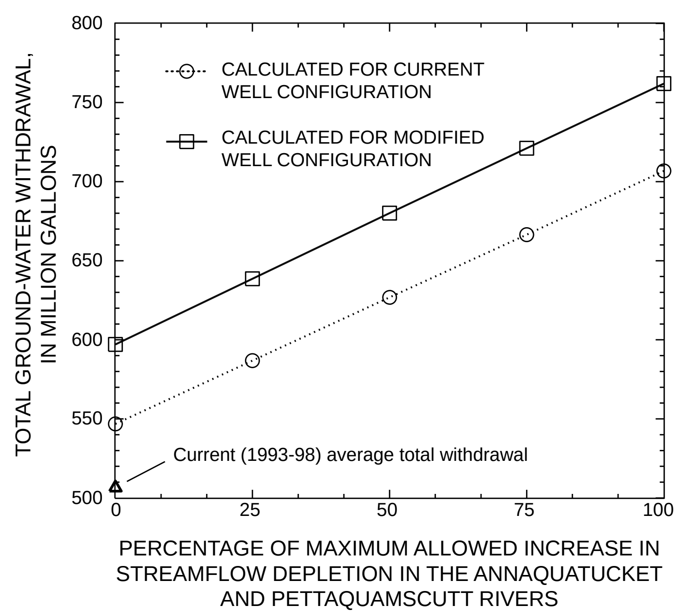


Figure 18. Total ground-water withdrawals during July, August, and September calculated with the conjunctive-management model for current rates of streamflow depletion specified for the Hunt River and increased rates of streamflow depletion specified for the Annaquatucket and Pettaquamscutt Rivers, Rhode Island.

Monthly withdrawal rates calculated for the current and modified well configurations for the maximum allowed decrease in streamflows in the Annaquatucket and Pettaquamscutt Rivers are shown in tables 21 and 22. Monthly withdrawals calculated for the current well configuration (table 21) indicate the following.

1. As with the previous alternatives, monthly withdrawal rates calculated for well KC1 remain at the 1993–98 rates.
2. Calculated withdrawals from wells in the RIEDC system are concentrated at well 3A from October through June, but are distributed among wells 3A, 9A, and 14A from July through September. Well 14A withdraws at its maximum rate (1.44 Mgal/d) during July. A net increase over the current total withdrawal rate for the RIEDC system during July of 30.4 Mgal (0.98 Mgal/d) is calculated for this alternative.
3. For the North Kingstown water-supply system, (a) well NK6 withdraws only during July, August, and September, and at its maximum specified rate of 1.37 Mgal/d; (b) withdrawals only occur in the Annaquatucket River Basin during May through September; (c) well NK4 withdraws at its maximum rate of 1.44 Mgal/d during July and September and well NK5 at its maximum rate of 1.75 Mgal/d from June through August; (d) withdrawals from the Pettaquamscutt River Basin are larger than current rates (table 12) for all months except December; and (e) well NK7

Table 21. Monthly withdrawal rates calculated for the current configuration of public water-supply wells for increased streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers and current rates of streamflow depletion in the Hunt River, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	.13	.52	.00	.71	.70	.64
9A	.00	.00	.00	.00	.00	.00	.34	.42	.84	.00	.00	.00
14A	.00	.00	.00	.00	.00	.00	1.44	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	1.37	1.37	1.37	.00	.00	.00
NK9	.00	.82	.86	.96	.00	.00	.47	.00	.47	1.46	.00	.00
NK10	.84	.00	.00	.00	.47	.90	.00	.47	.00	.00	1.32	1.95
Total for basin.......	1.69	1.64	1.49	1.68	1.37	2.39	4.69	3.58	3.21	2.45	2.34	3.13
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.26	.00	1.01	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	1.44	.61	1.44	.00	.00	.00
NK5	.00	.00	.00	.00	1.03	1.75	1.75	1.75	.00	.00	.00	.00
Total for basin.......	0.00	0.00	0.00	0.00	1.03	1.75	3.45	2.36	2.45	0.00	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	1.24	.00	.97	1.00	.00	.00
NK7	.81	.81	.81	.81	.81	.81	.00	.81	.00	.00	.41	.00
NK8	.40	.40	.40	.40	.40	.40	.00	.20	.00	.00	.40	.00
Total for basin.......	1.21	1.21	1.21	1.21	1.21	1.21	1.24	1.01	0.97	1.00	0.81	0.00
Total for all basins	2.90	2.85	2.70	2.89	3.61	5.35	9.38	6.95	6.63	3.45	3.15	3.13

Table 22. Monthly withdrawal rates calculated for the modified configuration of public water-supply wells for increased streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers and current rates of streamflow depletion in the Hunt River, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	1.03	1.20	.00	.00	.73	.64
9A	.00	.00	.00	.00	.00	.00	.00	.00	.84	.71	.00	.00
14A	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	2.37	.27	2.37	.00	.00	.00
NK9	.84	.82	.86	.96	.00	.00	.00	.00	.47	.00	1.59	1.95
NK10	.00	.00	.00	.00	.47	.90	.47	.47	.00	1.28	.00	.00
Total for basin.......	1.69	1.64	1.49	1.68	1.37	2.39	4.81	2.74	4.21	2.27	2.64	3.13
Annaquatucket River Basin												
NK1	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	.32	.00	.98	.00	.00	.00
NK5	.00	.00	.00	.00	1.03	1.75	1.75	1.75	.00	.00	.00	.00
H1	.00	.00	.00	.00	.00	.00	1.00	.00	1.00	.00	.00	.00
H2	.00	.00	.00	.00	.00	.00	1.00	1.00	1.00	.00	.00	.00
Total for basin.......	0.00	0.00	0.00	0.00	1.03	1.75	4.07	2.75	2.98	0.00	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	1.24	.00	.98	.00	.00	.00
NK7	.81	.81	.81	.81	.81	.81	.00	.81	.00	.81	.54	.00
NK8	.40	.40	.40	.40	.40	.40	.00	.20	.00	.37	.00	.00
Total for basin.......	1.21	1.21	1.21	1.21	1.21	1.21	1.24	1.01	0.98	1.18	0.54	0.00
Total for all basins	2.90	2.85	2.70	2.89	3.61	5.35	10.12	6.50	8.17	3.45	3.18	3.13

withdraws at its maximum rate from January through June and during August, and well NK8 withdraws at its maximum rate from January through June and during November. The net increases in total withdrawals from the North Kingstown system over current withdrawals are 59.2 Mgal (1.91 Mgal/d) in July, 41.2 Mgal (1.33 Mgal/d) in August, and 67.8 Mgal (2.26 Mgal/d) in September.

Monthly withdrawals calculated for the modified well configuration for the maximum allowed decrease in streamflow in the Annaquatucket and Pettaquamscutt Rivers (table 22) are similar to those calculated for the modified well configuration for the current rates of streamflow depletion in the two rivers (table 18). Because of the allowed decreases in the flow in the two rivers, however, total withdrawals from wells in the Annaquatucket and Pettaquamscutt River Basins are higher from July through September than for the alternative in which current rates of depletion were specified. Streamflow depletions calculated by the transient model for the three rivers for July, August, and September with the withdrawal rates calculated for this alternative (table 22) were less than or equal to the specified constraint values for eight of the nine streamflow-depletion constraints in July, August, and September; the constraint specified for the Hunt River in July was exceeded by 0.17 ft^3/s.

Decrease Current Rates of Streamflow Depletion in the Hunt River During July, August, and September, With Increased Rates of Streamflow Depletion Allowed in the Annaquatucket and Pettaquamscutt Rivers

The fourth set of alternatives was made to determine the amount of decrease in streamflow depletion in the Hunt River that could be attained from July through September for increased rates of streamflow depletion specified for the Annaquatucket and Pettaquamscutt Rivers. As was done in the second set of alternatives, the maximum decreases in streamflow depletion in the Hunt River that could be attained were determined in a series of LINDO simulations in which the estimated current rates of streamflow depletion for each month were lowered by uniform increments of 5 percent; the maximum decreases were determined when the next 5-percent increment resulted in an infeasible solution. For each simulation, streamflow depletion in the Hunt River during the remaining 9 months of the year was constrained to be less than or equal to the estimated current maximum monthly rate (4.75 ft^3/s). Streamflow-depletion rates in the Annaquatucket and Pettaquamscutt Rivers were allowed to increase by 50 percent and then 100 percent of the maximum allowed increases (table 20); that is, flow in the two rivers was allowed to decrease.

Total ground-water withdrawals calculated for the several simulations are summarized in table 23 and shown in figure 19. Also shown in the table and on the figure are ground-water withdrawals calculated for the previous applications of the model. The trade-off between increased total ground-water withdrawal from the aquifer during July, August, and September and decreased streamflow depletion in the Hunt River is summarized in figure 19. The shaded area of figure 19

Table 23. Summary of the model-calculated total ground-water withdrawals from the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, during July, August, and September

[Values are in million gallons. --, not simulated]

Percentage reduction in streamflow depletion in the Hunt River	Percentage of maximum allowed increases in streamflow depletions in the Annaquatucket and Pettaquamscutt Rivers									
	No increases		25 percent		50 percent		75 percent		100 percent	
	Well configuration		Well configuration		Well configuration		Well configuration		Well configuration	
	Current	Modified	Current	Modified	Current	Modified	Current	Modified	Current	Modified
0	546.0	596.3	586.8	638.6	626.8	680.1	666.5	721.1	705.1	760.3
5	526.1	573.5	--	--	607.3	--	--	--	--	--
10	infeasible	549.3	--	--	585.6	634.3	--	--	665.3	716.7
15	--	525.2	--	--	562.7	--	--	--	--	--
20	--	infeasible	--	--	537.9	586.5	--	--	621.2	669.0
25	--	--	--	--	513.4	--	--	--	--	--
30	--	--	--	--	infeasible	538.2	--	--	573.5	621.6
35	--	--	--	--	--	512.4	--	--	547.3	595.8
40	--	--	--	--	--	infeasible	--	--	infeasible	infeasible

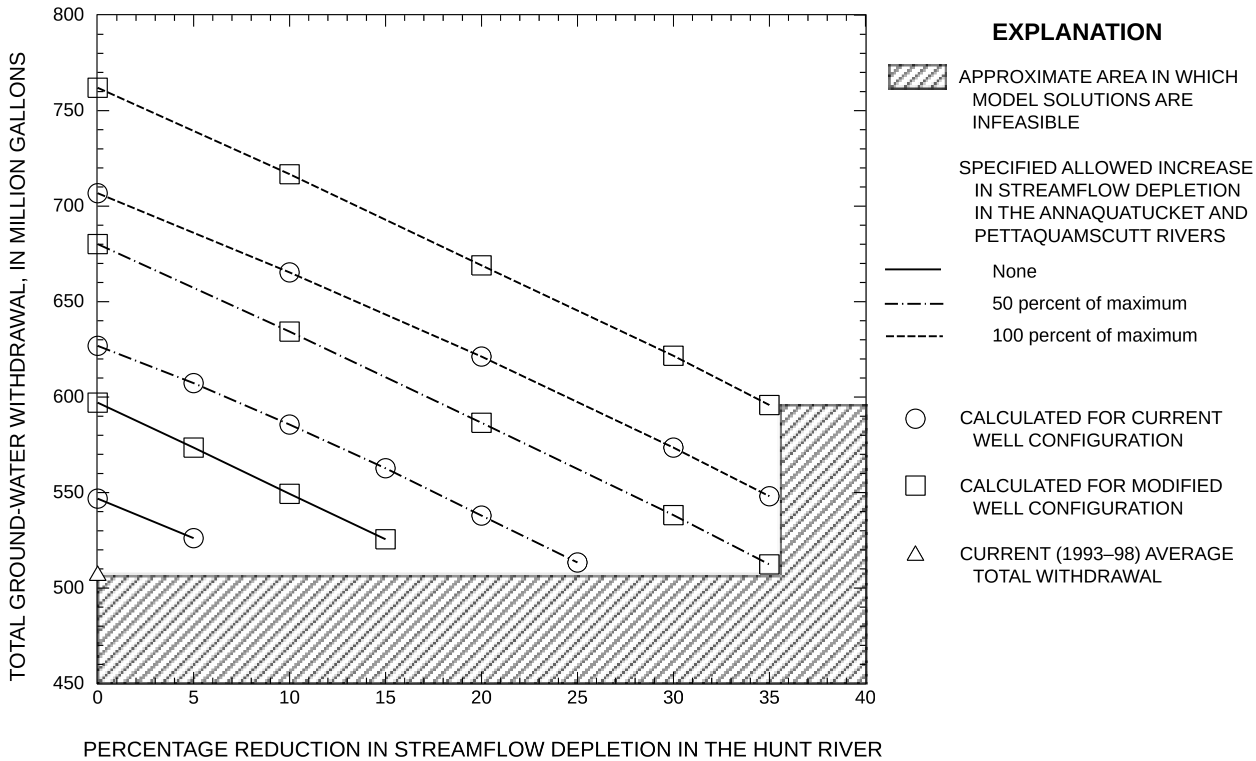


Figure 19. Total ground-water withdrawals during July, August, and September calculated with the conjunctive-management model in which streamflow depletions in the Hunt River are reduced from current estimated rates and those for the Annaquatucket and Pettaquamscutt Rivers are allowed to increase from current estimated rates, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island.

is the approximate region in which solutions to the conjunctive-management model are infeasible; that is, one or more model constraints can not be met by any combination of well withdrawals.

The calculated maximum decrease in streamflow depletion that could be attained for the Hunt River from July through September is about 35 percent of existing streamflow-depletion rates calculated for the months, or from 1.51 ft^3/s in September to 1.66 ft^3/s in August. These reductions in streamflow depletion in the Hunt River would require a maximum increase of 1.20 ft^3/s in the streamflow-depletion rate in the Annaquatucket River and of 1.22 ft^3/s in the streamflow-depletion rate in the Pettaquamscutt River. Decreases in streamflow depletion in the Hunt River greater than 35 percent would require that one or more of the following actions be taken: (1) decreases in current water-supply demands; (2) larger increases in allowed streamflow depletions in the Annaquatucket and Pettaquamscutt Rivers than were allowed in this evaluation; or (3) different configurations of wells (and of maximum withdrawal rates at the wells) than were used in this evaluation.

Monthly withdrawal rates calculated for each well for the current well configuration and for conditions of maximum allowed increases in streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers and a 35-percent depletion in streamflow depletions in the Hunt River are shown in table 24. Total withdrawal from all wells during the 3-month period is 547.3 Mgal, which is an overall increase of 8.1 percent from the current average total withdrawal of 506.5 Mgal. Total withdrawal from all wells for the same conditions but for the modified well configuration is 595.8 Mgal (table 23, fig. 19), which is an overall increase of 17.6 percent from the current average total withdrawal.

Table 24. Monthly withdrawal rates calculated for the current configuration of public water-supply wells for increased streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers and 35 percent reduction in streamflow depletion in the Hunt River, Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Withdrawal rates are million gallons per day. Well locations are shown on figure 1. Shading used to emphasize results for July, August, and September]

Water-supply well identifier	January	February	March	April	May	June	July	August	September	October	November	December
Hunt River Basin												
KC1	0.27	0.08	0.08	0.16	0.32	0.80	0.94	0.80	0.53	0.28	0.32	0.54
3A	.58	.74	.55	.56	.58	.69	.43	.25	.00	.71	.70	.64
9A	.00	.00	.00	.00	.00	.00	.00	.69	.84	.00	.00	.00
14A	.00	.00	.00	.00	.00	.00	.50	.00	.00	.00	.00	.00
NK6	.00	.00	.00	.00	.00	.00	.00	.00	.15	.00	.00	.00
NK9	.84	.82	.86	.47	.00	.00	.47	.00	.47	1.25	.00	.00
NK10	.00	.00	.00	.00	.47	.47	.00	.47	.00	.00	2.14	1.95
Total for basin	1.69	1.64	1.49	1.19	1.37	1.96	2.34	2.21	1.99	2.24	3.16	3.13
Annaquatucket River Basin												
NK1	.00	.00	.00	.49	.00	.43	.00	.00	.00	.00	.00	.00
NK2	.00	.00	.00	.00	.00	.00	.07	.00	1.01	.00	.00	.00
NK4	.00	.00	.00	.00	.00	.00	1.44	.60	1.44	.00	.00	.00
NK5	.00	.00	.00	.00	1.03	1.75	1.75	1.75	.00	.00	.00	.00
Total for basin	0.00	0.00	0.00	0.49	1.03	2.18	3.26	2.35	2.45	0.00	0.00	0.00
Pettaquamscutt River Basin												
NK3	.00	.00	.00	.00	.00	.00	.16	.25	.96	.81	.00	.00
NK7	.81	.81	.81	.81	.81	.81	.81	.81	.00	.00	.00	.00
NK8	.40	.40	.40	.40	.40	.40	.24	.00	.00	.40	.00	.00
Total for basin	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.06	0.96	1.21	0.00	0.00
Total for all basins	2.90	2.85	2.70	2.89	3.61	5.35	6.81	5.62	5.40	3.45	3.16	3.13

SUMMARY AND CONCLUSIONS

Ground-water withdrawals from the Hunt–Annaquatucket–Pettaquamscutt (HAP) stream-aquifer system in central Rhode Island exceeded 8 Mgal/d during months of peak water use during 1993–98, and additional withdrawals have been proposed to meet growing demands from within and outside of the system boundary. Nearly all of the water withdrawn, however, is derived from depletions of flow in the rivers, brooks, and ponds that overlie the HAP aquifer. Concerns by the Rhode Island Department of Environmental Management regarding the effects of ground-water withdrawals on streamflow depletions in the HAP stream-aquifer system prompted an investigation to better understand the water resources of the system and to evaluate alternatives for the conjunctive management of the ground- and surface-water resources of the system. The investigation was done from 1995 to 2000 by the U.S. Geological Survey in cooperation with the town of North Kingstown, RIDEM, Rhode Island Economic Development Corporation, and Rhode Island Water Resources Board.

The stream-aquifer system covers a 19.0-square-mile area and is defined by the HAP sand-and-gravel aquifer and the network of rivers, brooks, and ponds that overlie and are in hydraulic connection with the aquifer. Average annual flows in the three largest streams in the system during 1941–96 were measured or estimated to have been 46.4 ft^3/s for the Hunt River, 17.0 ft^3/s for the Annaquatucket River, and 9.5 ft^3/s for the Pettaquamscutt River. Ground water is withdrawn from the HAP aquifer at 18 large-capacity water-supply wells, which consist of 14 public water-supply wells, an industrial well, and 3 fisheries wells. Three water-supply systems withdraw water at the 14 public water-supply wells; these are the town of North Kingstown, Rhode Island Economic Development Corporation, and Kent County Water Authority. Total average annual withdrawal from all 18 wells was estimated to have been 7.8 ft^3/s during 1941–96, of which an estimated 4.6 ft^3/s, or 59 percent of the total withdrawal, was exported from the HAP system.

Steady-state and transient numerical models were developed to simulate ground-water flow and ground-water/surface-water interactions in the HAP stream-aquifer system. The models are representative of average withdrawal and hydrologic conditions in the HAP system during the 1941–96 period. 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 83.0 ft^3/s, which was close to the flow rate of about 88.5 ft^3/s estimated independently from hydrologic and water-use data for the system. The models do not simulate direct runoff within the HAP stream-aquifer system, which partly explains the lower flow rate calculated by the steady-state model. Estimated rates of streamflow depletion caused by ground-water withdrawals at the 14 public water-supply wells and industrial well were calculated by the models. Streamflow depletion consists of captured ground-water discharge and induced infiltration of streamflow. Monthly streamflow-depletion rates calculated by the transient model for the Hunt River ranged from 3.7 ft^3/s to 5.2 ft^3/s, and averaged 4.2 ft^3/s over the annual cycle; those for the Annaquatucket River ranged from 1.2 ft^3/s to 2.2 ft^3/s, and averaged 1.5 ft^3/s; and those for the Pettaquamscutt River ranged from 0.1 ft^3/s to 0.6 ft^3/s, and averaged 0.4 ft^3/s. Streamflow-depletion rates 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.

Contributing areas and sources of water to supply wells in the HAP stream-aquifer system were delineated by use of the steady-state model. Sources of water to the wells consisted of precipitation and waste-water recharge to the HAP aquifer, streamflow leakage from natural stream-channel losses, streamflow leakage caused by induced infiltration, and lateral ground-water inflow from till and bedrock upland areas. Streamflow leakage was calculated to be a source of water to seven wells, all but five of which are in the Hunt River Basin. Calculated traveltimes of simulated water particles from the water table to the supply wells averaged less than 5 years for most wells, but ranged from 0.1 years to 51.2 years for the conditions simulated.

A conjunctive-management model of the HAP stream-aquifer system was developed to simultaneously address the water-demand and streamflow-depletion issues. The objective of the model was to maximize total ground-water withdrawal from the HAP aquifer during July, August, and September. These three months are generally the time of year when water-supply demands are largest and streamflows are simultaneously lowest. Total withdrawal from the HAP aquifer was limited by a set of constraints specified in the model. These constraints were (1) maximum rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers; (2) minimum monthly water demands of each of the three water-supply systems that withdraw water from the aquifer; and (3) minimum and maximum withdrawal rates at each supply well.

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

Four sets of applications of the conjunctive-management model were made to determine whether total ground-water withdrawal from the HAP aquifer during July, August, and September could be increased over the current total withdrawal for alternative definitions of the maximum rates of streamflow depletion allowed in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Current conditions were defined as the average monthly withdrawal rates at each supply well, water demands of each of the three water-supply systems, and estimated streamflow-depletion rates during the 6-year period 1993–98. Total withdrawal from all wells in the system from July through September during 1993–98 was 506.5 million gallons. Estimated streamflow-depletion rates for 1993-98 were calculated by use of the transient model, with the 1993–98 average monthly withdrawal rates specified at each supply well. Streamflow-depletion rates calculated for July, August, and September averaged 25 percent of the model-calculated pre-withdrawal streamflow rates for the Hunt River, 19 percent for the Annaquatucket River, and 7 percent for the Pettaquamscutt River.

The first set of applications of the model were made with the current estimated rates of streamflow depletion in the Hunt, Annaquatucket, and Pettaquamscutt Rivers. Results of these applications indicated that total withdrawal from the HAP aquifer during July, August, and September could be increased from about 8 to 18 percent over the current total withdrawal. The increased yield would require modifications to the current annual withdrawal schedule of each supply well and, for the 18-percent increase, a modified network of supply wells that would include two new well sites in the Annaquatucket River Basin. A second set of model applications then was made to determine if current estimated rates of streamflow depletion in the Hunt River could be reduced without increasing current estimated rates of streamflow depletion in the Annaquatucket or Pettaquamscutt Rivers. Decreases in the current rates of streamflow depletion in the Hunt River would result in increased streamflow in the river during these three months. Results showed that current rates of streamflow depletion in the Hunt River during July, August, and September could be decreased from 5 to 15 percent, depending on whether the existing or modified well network was used.

Subsequent model applications indicated that substantial increases in total ground-water withdrawal from the HAP aquifer are possible, but would require increased rates of streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers. Maximum increases in the July through September yield of the HAP aquifer of from 39 to 50 percent over the current total withdrawal were calculated when streamflow-depletion rates in the Annaquatucket and Pettaquamscutt Rivers were allowed to increase from their current estimated rates to a maximum of 25 percent of the model-calculated pre-withdrawal streamflow for each river during July, August, and September. Alternatively, it was shown that current estimated rates of streamflow depletion in the Hunt River during July, August, and September could be reduced by as much as 35 percent for the maximum allowed increases in streamflow depletion in the Annaquatucket and Pettaquamscutt Rivers; maximum increased withdrawal from the HAP aquifer, however, would range from only 8 to 18 percent over the current total withdrawal for the 35-percent reduction in streamflow-depletion rates in the Hunt River.

Results of the different applications of the model demonstrate the usefulness of coupling numerical-simulation and optimization for regional-scale evaluation of water-resource management alternatives. The results of the evaluation must be viewed, however, within the limitations of the quality of data available for the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system and representation of the system with a simulation model. An additional limitation of the analysis was the use of an average annual cycle of monthly withdrawal and hydrologic conditions. Ground-water withdrawal strategies may need to be modified to meet streamflow-depletion constraints during extreme hydrologic events, such as droughts.

REFERENCES CITED

Ahlfeld, D.P., and Mulligan, A.E., 2000, Optimal management of flow in groundwater systems: San Diego, Calif., Academic Press, 185 p.

Allen, W.B., 1956, Ground-water resources of the East Greenwich quadrangle, Rhode Island: Rhode Island Development Council Geological Bulletin 8, 56 p.

Allen, W.B., Hahn, G.W., and Tuttle, C.R., 1963, Geohydrologic data for the upper Pawcatuck River Basin, Rhode Island: Rhode Island Water Resources Coordinating Board Geological Bulletin 13, 68 p.

Allen, W.B., Johnson, K.E., and Mason, R.A., 1959, Ground-water map of the Crompton quadrangle, Rhode Island: Rhode Island Water Resources Coordinating Board GWM-3, 1 sheet, scale 1:24,000.

Barlow, P.M., 1997a, Dynamic models for conjunctive management of stream-aquifer systems of the glaciated Northeast: Storrs, Conn., University of Connecticut, Ph.D. dissertation, 256 p.

_____1997b, Particle-tracking analysis of contributing areas of public-supply wells in simple and complex flow systems, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2434, 66 p.

Bent, G.C., 1995, Streamflow, ground-water recharge and discharge, and characteristics of surficial deposits in Buzzards Bay Basin, southeastern Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 95-4234, 56 p.

Cervione, M.A., Jr., Richardson, A.R., and Weiss, L.A., 1993, Low-flow characteristics of selected streams in Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 93-4046, 16 p.

Danskin, W.R., and Freckleton, J.R., 1989, Ground-water-flow modeling and optimization techniques applied to high-ground-water problems in San Bernardino, California: U.S. Geological Survey Open-File Report 89-75, 14 p.

Danskin, W.R., and Gorelick, S.M., 1985, A policy evaluation tool—Management of a multiaquifer system using controlled stream recharge: Water Resources Research, v. 21, no. 11, p. 1731–1747.

Dickerman, D.C., and Barlow, P.M., 1997, Water-table conditions and stream-aquifer interaction in the Hunt–Annaquatucket–Pettaquamscutt aquifer, central Rhode Island, October 7–9, 1996: U.S. Geological Survey Water-Resources Investigations Report 97-4167, 1 sheet.

Dickerman, D.C., and Bell, R.W., 1993, Hydrogeology, water quality, and ground-water-development alternatives in the upper Wood River ground-water reservoir, Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 92-4119, 87 p.

Dickerman, D.C., Kliever, J.D., and Stone, J.R., 1997, Hydrogeology, water quality, and simulation of ground-water-development alternatives in the Usquepaug–Queen ground-water reservoir, southern Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 97-4126, 48 p.

Dickerman, D.C., Trench, E.C.T., Russell, J.P., 1990, Hydrogeology, water quality, and ground-water development alternatives in the lower Wood River ground-water reservoir, Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 89-4031, 109 p.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration Technical Report NWS 33, 26 p.

Franke, O.L., Reilly, T.E., Pollock, D.W., and LaBaugh, J.W., 1998, Estimating areas contributing recharge to wells—Lessons from previous studies: U.S. Geological Survey Circular 1174, 14 p.

Fuss and O'Neill, Inc., 1997, Hydrogeologic investigation and assessment report for the Hunt aquifer, East Greenwich, North Kingstown, and Warwick, Rhode Island (May 1997): Manchester, Conn., various pagination.

Garabedian, S.P., LeBlanc, D.R., Gelhar, L.W., and Celia, M.A., 1991, Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts, 2. analysis of spatial moments for a nonreactive tracer: Water Resources Research, v. 27, no. 5, p. 911–924.

Gorelick, S.M., Freeze, R.A., Donohue, David, and Keely, J.F., 1993, Groundwater contamination–Optimal capture and containment: Boca Raton, Fla., Lewis Publishers, 385 p.

Guthrie, R.C., and Stolgitis, J.A., 1977, Fisheries investigations and management in Rhode Island lakes and ponds: Rhode Island Division of Fish and Wildlife Fisheries Report No. 3, 256 p.

GZA GeoEnvironmental, Inc., 1992, Phase I report, Hunt River aquifer, wellhead recharge area study (December, 1992): Providence, R.I., various pagination.

Hahn, G.W., 1959, Ground-water map of the Slocum quadrangle, Rhode Island: Rhode Island Water Resources Coordinating Board GWM-2, 1 sheet, scale 1:24,000.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Heath, D.L., 1991, The North Kingstown, RI wellhead protection area pilot project: Boston, Mass., U.S. Environmental Protection Agency, Region 1, Ground Water Management Section, various pagination.

Illangasekare, Tissa, and Morel-Seytoux, H.J., 1982, Stream-aquifer influence coefficients as tools for simulation and management: Water Resources Research, v. 18, no. 1, p. 168–176.

Jenkins, C.T., 1963, Graphical multiple-regression analyses of aquifer tests: U.S. Geological Survey Professional Paper 475-C, p. C198–C201.

Johnson, A.I., 1966, Specific yield--compilation of specific yields for various materials: U.S. Geological Survey Open-File Report (Hydrologic Laboratory, Denver, Colorado), 119 p.

Johnson, K.E., and Marks, L.Y., 1959, Ground-water map of the Wickford quadrangle, Rhode Island: Rhode Island Water Resources Coordinating Board GWM-1, 1 sheet, scale 1:24,000.

Kliever, J.D., 1995, Hydrologic data for the Usquepaug–Queen River Basin, Rhode Island: U.S. Geological Survey Open-File Report 95-305, 68 p.

Lang, S.M., 1961, Appraisal of the ground-water reservoir areas in Rhode Island: Rhode Island Water Resources Coordinating Board Geological Bulletin 11, 38 p.

LINDO Systems, Inc., 1996, LINDO user's manual: Chicago, LINDO Systems, Inc., 390 p.

Maddock, Thomas, III, 1974, The operation of a stream-aquifer system under stochastic demands: Water Resources Research, v. 10, no. 1, p. 1–10.

Male, J.W., and Mueller, F.A., 1992, Model for prescribing ground-water use permits: Journal of Water Resources Planning and Management, v. 118, no. 5, p. 543–561.

Masterson, J.P., and Barlow, P.M., 1997, Effects of simulated ground-water pumping and recharge on ground-water flow in Cape Cod, Martha's Vineyard, and Nantucket Island Basins, Massachusetts: U.S. Geological Survey Water-Supply Paper 2447, 79 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Moench, A.F., Garabedian, S.P., and LeBlanc, D.R., 2000, Estimation of hydraulic parameters from an unconfined aquifer test conducted in a glacial outwash deposit, Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 00-485, 139 p.

Morel-Seytoux, H.J., 1975a, A combined model of water table and river stage evolution: Water Resources Research, v. 11, no. 6, p. 968–972.

_____1975b, A simple case of conjunctive surface-ground-water management: Ground Water, v. 13, no. 6, p. 506–515.

Morel-Seytoux, H.J., and Daly, C.J., 1975, A discrete kernel generator for stream-aquifer studies: Water Resources Research, v. 11, no. 3, p. 253–260.

Mueller, F.A., and Male, J.W., 1993, A management model for specification of groundwater withdrawal permits: Water Resources Research, v. 29, no. 5, p. 1359–1368.

National Oceanic and Atmospheric Administration, 1998, Climatological data annual summary, New England, 1998, v. 110, no. 13, 41 p.

Newsom, J.M., and Wilson, J.L., 1988, Flow of ground water to a well near a stream—effect of ambient ground-water flow direction: Ground Water, v. 26, no. 6, p. 703–711.

Peralta, R.C., Kowalski, K., and Cantiller, R.R.A., 1988, Maximizing reliable crop production in a dynamic stream/aquifer system: Transactions of the American Society of Agricultural Engineers, v. 31, no. 6, p. 1729–1742.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 249 p.

Power, W.R., Jr., 1957, Surficial geology of the Slocum quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-106, 1 sheet, scale 1:31,680.

_____1959, Bedrock geology of the Slocum quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-114, 1 sheet, scale 1:31,680.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Quinn, A.W., 1952, Bedrock geology of the East Greenwich quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-17, 1 sheet, scale 1:31,680.

_____1963, Bedrock geology of the Crompton quadrangle, Rhode Island: U.S. Geological Survey Bulletin 1158-B, 17 p.

Rosenshein, J.S., Gonthier, J.B., and Allen, W.B., 1968, Hydrologic characteristics and sustained yield of principal ground-water units Potowomut–Wickford area, Rhode Island: U.S. Geological Survey Water-Supply Paper 1775, 38 p.

Rutledge, A.T., 1993, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records: U.S. Geological Survey Water-Resources Investigations Report 93-4121, 45 p.

_____2000, Considerations for use of the RORA program to estimate ground-water recharge from streamflow records: U.S. Geological Survey Open-File Report 00-156, 44 p.

Schafer, J.P., 1961, Surficial geology of the Wickford quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-136, 1 sheet, scale 1:24,000.

Smith, J.H., 1955, Surficial geology of the East Greenwich quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-62, 1 sheet, scale 1:31,680.

_____1956, Surficial geology of the Crompton quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle GQ-94, 1 sheet, scale 1:31,680.

Socolow, R.S., Leighton, C.R., Zanca, J.L., and Ramsbey, L.R., 1998, Water resources data, Massachusetts and Rhode Island, water year 1997: U.S. Geological Survey Water-Data Report MA-RI-97-1, 334 p.

Thomas, M.P., 1966, Effect of glacial geology upon the time distribution of streamflow in eastern and southern Connecticut: U.S. Geological Survey Professional Paper 550-B, p. B209–B212.

Williams, R.B., 1964, Bedrock geology of the Wickford quadrangle, Rhode Island: U.S. Geological Survey Bulletin 1158-C, 15 p.

APPENDIX A:
Water Levels at Observation Wells, 1995–96

Table A1. Monthly water levels and altitudes at network observation wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1995–96

[USGS well identifiers and locations are shown on figure 5. All values are in feet. MP, measuring point; USGS, U.S. Geological Survey; WL, water level]

USGS well identifier	Altitude of MP	November 21, 1995		January 17, 1996		February 14, 1996		March 13, 1996	
		WL below MP	WL altitude	WL below MP	WL altitude	WL below MP	WL altitude	WL below MP	WL altitude
WCW-29	36.27	35.05	1.22	34.90	1.37	33.99	2.28	33.65	2.62
WCW-270	44.07	22.35	21.72	24.29	19.78	23.24	20.83	23.18	20.89
EGW-2	30.15	5.75	24.40	9.10	21.05	5.70	24.45	7.78	22.37
EGW-77	49.23	6.02	43.21	5.79	43.44	5.35	43.88	5.52	43.71
NKW-45	47.62	18.91	28.71	18.70	28.92	17.33	30.29	17.10	30.52
NKW-255	45.64	8.95	36.69	9.66	35.98	8.13	37.51	7.76	37.88
NKW-452	59.07	15.07	44.00	14.75	44.32	13.09	45.98	12.59	46.48
NKW-591	61.44	8.96	52.48	8.70	52.74	7.40	54.04	7.32	54.12
NKW-641	53.47	11.96	41.51	12.27	41.20	10.37	43.10	9.82	43.65
NKW-1316	47.81	10.00	37.81	10.15	37.66	9.24	38.57	8.90	38.91
NKW-1319	99.32	34.59	64.73	34.60	64.72	32.15	67.17	32.27	67.05
NKW-1330	86.52	18.96	67.56	19.05	67.47	18.27	68.25	17.94	68.58
NKW-1333	67.41	17.29	50.12	16.65	50.76	16.32	51.09	16.31	51.10
NKW-1335	76.73	19.94	56.79	18.05	58.68	14.80	61.93	13.86	62.87

USGS well identifier	Altitude of MP	April 24, 1996		May 15, 1996		June 19, 1996		July 24, 1996	
		WL below MP	WL altitude	WL below MP	WL altitude	WL below MP	WL altitude	WL below MP	WL altitude
WCW-29	36.27	33.16	3.11	33.33	2.94	34.05	2.22	34.25	2.02
WCW-270	44.07	22.71	21.36	23.17	20.90	24.20	19.87	24.36	19.71
EGW-2	30.15	5.47	24.68	7.88	22.27	10.36	19.79	9.35	20.80
EGW-77	49.23	5.06	44.17	6.08	43.15	6.07	43.16	5.81	43.42
NKW-45	47.62	16.52	31.10	16.82	30.80	17.45	30.17	17.79	29.83
NKW-255	45.64	7.26	38.38	7.56	38.08	8.66	36.98	8.83	36.81
NKW-452	59.07	12.58	46.49	12.95	46.12	14.10	44.97	14.69	44.38
NKW-591	61.44	7.15	54.29	8.00	53.44	9.68	51.76	9.30	52.14
NKW-641	53.47	9.15	44.32	9.60	43.87	10.82	42.65	11.10	42.37
NKW-1316	47.81	8.81	39.00	9.18	38.63	10.08	37.73	10.25	37.56
NKW-1319	99.32	31.17	68.15	31.76	67.56	33.72	65.60	32.07	67.25
NKW-1330	86.52	17.46	69.06	17.43	69.09	17.75	68.77	17.87	68.65
NKW-1333	67.41	16.36	51.05	16.39	51.02	18.10	49.31	17.24	50.17
NKW-1335	76.73	12.41	64.32	12.70	64.03	14.51	62.22	15.70	61.03

USGS well identifier	Altitude of MP	August 21, 1996		September 25, 1996		October 8, 1996		November 20, 1996	
		WL below MP	WL altitude	WL below MP	WL altitude	WL below MP	WL atitude	WL below MP	WL altitude
WCW-29	36.27	34.70	1.57	34.57	1.70	34.86	1.41	34.50	1.77
WCW-270	44.07	24.75	19.32	24.38	19.69	24.49	19.58	24.03	20.04
EGW-2	30.15	9.46	20.69	9.41	20.74	9.90	20.25	12.20	17.95
EGW-77	49.23	6.42	42.81	6.74	42.49	6.07	43.16	5.96	43.27
NKW-45	47.62	18.14	29.48	18.04	29.58	18.15	29.47	17.81	29.81
NKW-255	45.64	9.41	36.23	8.64	37.00	9.33	36.31	9.02	36.62
NKW-452	59.07	15.15	43.92	14.90	44.17	15.06	44.01	14.52	44.55
NKW-591	61.44	10.20	51.24	9.05	52.39	9.32	52.12	8.68	52.76
NKW-641	53.47	11.97	41.50	11.76	41.71	12.09	41.38	11.55	41.92
NKW-1316	47.81	10.80	37.01	10.10	37.71	10.68	37.13	10.25	37.56
NKW-1319	99.32	32.57	66.75	30.88	68.44	31.68	67.64	30.81	68.51
NKW-1330	86.52	18.15	68.37	18.02	68.50	18.16	68.36	17.89	68.63
NKW-1333	67.41	17.32	50.09	16.75	50.66	17.33	50.08	16.66	50.75
NKW-1335	76.73	16.96	59.77	17.35	59.38	18.82	57.91	17.79	58.94

Table A2. Daily mean water levels at recorder observation well NKW 641 in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well location shown on figure 5. Well depth below land surface datum: 16.15 feet. --, no data available]

Day	Daily mean water level, in feet below land surface datum															
	1995	1996												1997		
	December	January	February	March	April	May	June	July	August	September	October	November	December	January	February	March
1	--	11.66	9.84	9.45	9.18	8.41	9.49	10.57	10.79	11.53	11.24	10.45	11.63	9.45	9.24	9.68
2	--	11.68	9.83	9.45	9.15	8.43	9.54	10.59	10.67	11.55	11.27	10.46	11.47	9.45	9.30	9.68
3	--	11.69	9.82	9.45	9.14	8.51	9.57	10.60	10.75	11.59	11.29	10.48	11.23	9.48	9.33	9.74
4	--	11.72	9.82	9.49	9.17	8.57	9.60	10.54	10.82	11.62	11.32	10.52	11.22	9.54	9.37	9.78
5	--	11.75	9.82	9.50	9.21	8.61	9.63	10.60	10.87	11.65	11.36	10.55	11.22	9.55	9.23	9.81
6	--	11.77	9.83	9.48	9.26	8.66	9.67	10.67	10.92	11.68	11.39	10.59	11.21	9.58	9.06	9.80
7	--	11.79	9.83	9.40	9.29	8.71	9.71	10.71	10.95	11.65	11.42	10.61	11.19	9.63	9.13	9.86
8	--	11.79	9.81	9.32	9.32	8.73	9.74	10.75	10.99	10.90	11.40	10.63	10.59	9.66	9.17	9.90
9	--	11.78	9.79	9.32	9.33	8.76	9.78	10.79	11.03	10.92	10.44	--	10.21	9.69	9.18	9.94
10	--	11.73	9.78	9.33	9.27	8.78	9.82	10.83	11.04	11.08	10.42	--	10.20	9.69	9.21	9.96
11	--	11.71	9.74	9.31	9.17	8.79	9.85	10.88	11.04	11.19	10.60	--	10.22	9.74	9.24	9.98
12	--	11.75	9.70	9.26	9.09	8.81	9.88	10.93	11.09	11.26	10.71	--	10.23	9.79	9.27	10.01
13	--	11.69	9.72	9.20	9.05	8.85	9.92	10.34	11.09	11.32	10.78	--	10.22	9.83	9.33	10.05
14	11.37	11.53	9.72	9.21	9.02	8.90	9.96	8.97	10.94	11.36	10.82	--	10.20	9.87	9.32	10.07
15	11.38	11.55	9.75	9.20	9.03	8.93	10.00	9.26	11.01	11.41	10.86	--	10.19	9.92	9.10	9.91
16	11.40	11.60	9.78	9.19	8.75	8.96	10.04	9.58	11.08	11.46	10.89	--	10.16	9.82	9.19	9.83
17	11.41	--	9.78	9.18	8.24	8.97	10.09	9.80	11.14	11.46	10.92	--	10.10	9.64	9.24	9.89
18	11.42	11.43	9.82	9.17	8.31	8.98	10.12	9.96	11.18	11.04	10.95	--	9.88	9.74	9.28	--
19	11.43	11.32	9.89	9.16	--	8.98	10.17	10.08	11.22	10.90	10.97	--	9.79	9.81	9.29	--
20	11.43	10.46	9.93	9.01	8.38	9.00	10.20	10.16	11.26	10.96	10.41	--	9.46	9.87	9.36	--
21	11.44	10.34	9.72	8.89	8.41	9.03	10.20	10.24	11.31	11.02	10.09	11.58	9.45	9.93	9.38	--
22	11.46	10.41	9.37	8.91	8.44	9.07	10.21	10.32	11.36	11.06	10.26	11.61	9.44	9.97	9.39	--
23	11.49	10.44	9.48	8.95	8.44	9.12	10.24	10.39	11.39	11.08	10.36	11.64	9.44	9.92	9.46	--
24	11.50	10.43	9.46	8.99	8.46	9.16	10.29	10.45	11.40	11.10	10.39	11.68	9.43	9.96	9.49	--
25	11.52	10.37	9.32	9.01	8.50	9.21	10.32	10.51	11.39	11.11	10.40	11.71	9.39	9.56	9.53	--
26	11.53	10.31	9.37	9.03	8.52	9.25	10.37	10.56	11.41	11.14	10.41	11.58	9.39	9.20	9.56	--
27	11.55	10.24	9.40	9.07	8.55	9.29	10.41	10.61	11.45	11.16	10.42	11.37	9.37	9.41	9.58	--
28	11.58	9.97	9.40	9.09	8.62	9.33	10.46	10.66	11.43	11.17	10.41	11.48	9.37	9.27	9.63	--
29	11.61	9.86	9.43	9.09	8.65	9.36	10.50	10.71	11.38	11.18	10.42	11.55	9.37	9.10	--	--
30	11.63	9.83	--	9.12	8.49	9.40	10.54	10.76	11.44	11.21	10.42	11.60	9.39	9.18	--	--
31	11.65	9.82	--	9.15	--	9.44	--	10.81	11.49	--	10.43	--	9.42	9.21	--	--
Mean	--	11.08	9.69	9.21	8.84	8.94	10.01	10.41	11.14	11.26	10.76	--	10.13	9.63	9.32	--
Maximum	--	11.79	9.93	9.50	9.33	9.44	10.54	10.93	11.49	11.68	11.42	--	11.63	9.97	9.63	--
Minimum	--	9.82	9.32	8.89	8.24	8.41	9.49	8.97	10.67	10.90	10.09	--	9.37	9.10	9.06	--

Table A3. Daily mean water levels at recorder observation well NKW 1319 in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island

[Well location shown on figure 5. Well depth below land surface datum: 41.70 feet. --, no data available]

Day	Daily mean water level, in feet below land surface datum, 1996									
	January	February	March	April	May	June	July	August	September	October
1	--	31.78	32.01	32.34	31.19	32.57	33.48	32.23	32.43	30.91
2	--	31.75	32.02	32.38	31.07	32.64	33.52	32.18	32.47	30.97
3	--	31.76	32.07	32.39	31.00	32.70	33.54	32.07	32.49	31.04
4	--	31.76	32.14	32.39	30.99	32.77	33.55	31.99	32.51	31.13
5	--	31.77	32.17	32.43	30.99	32.82	33.50	31.97	32.55	31.23
6	--	31.82	32.21	32.48	31.04	32.85	33.47	31.98	32.59	31.32
7	--	31.85	32.19	32.52	31.10	32.89	33.46	32.03	32.63	31.40
8	--	31.85	32.09	32.58	31.13	32.93	33.46	32.08	32.46	31.47
9	--	31.86	32.08	32.60	31.19	32.99	33.49	32.14	32.04	31.35
10	--	31.89	32.08	32.57	31.24	33.04	33.54	32.21	31.74	30.94
11	--	31.85	32.06	32.56	31.29	33.09	33.58	32.28	31.61	30.65
12	--	31.89	32.04	32.49	31.34	33.14	33.62	32.33	31.57	30.51
13	--	31.93	--	32.40	31.42	33.18	33.61	32.38	31.56	30.47
14	--	31.95	--	32.31	31.49	33.23	33.39	32.38	31.54	30.47
15	--	32.04	32.10	32.27	31.56	33.29	32.75	32.38	31.54	30.54
16	--	32.08	32.09	32.20	31.62	33.35	32.63	32.38	31.57	30.60
17	--	32.13	32.12	31.98	31.68	33.41	32.63	32.38	31.60	30.69
18	--	32.21	32.10	31.61	31.67	33.46	32.63	32.38	31.44	30.78
19	--	32.31	32.11	31.35	31.65	33.51	32.63	32.38	31.11	30.84
20	--	32.36	32.13	31.18	31.68	33.56	32.60	32.38	30.83	--
21	--	32.40	32.12	31.08	31.73	33.57	31.82	32.37	30.71	--
22	--	32.37	32.02	31.03	31.79	33.54	31.82	32.41	30.70	--
23	--	32.25	31.95	30.99	31.87	33.47	31.82	32.45	30.72	--
24	--	32.14	31.93	31.00	31.94	33.43	31.87	32.50	30.68	--
25	--	32.07	31.98	31.04	32.02	33.39	31.90	32.46	30.66	--
26	--	31.99	32.03	31.06	32.10	33.37	31.94	32.38	30.69	--
27	--	31.96	32.09	31.12	32.17	33.36	31.98	32.38	30.72	--
28	--	31.94	32.14	31.20	32.26	33.35	32.02	32.41	30.76	--
29	--	31.98	32.17	31.26	32.33	33.37	32.09	32.39	30.81	--
30	31.91	--	32.23	31.28	32.41	33.42	32.14	32.37	30.87	--
31	31.81	--	32.28	--	32.49	--	32.20	32.39	--	--
Mean	--	32.00	32.09	31.87	31.60	33.19	32.80	32.29	31.52	--
Maximum	--	32.40	32.28	32.60	32.49	33.57	33.62	32.50	32.63	--
Minimum	--	31.75	31.93	30.99	30.99	32.57	31.82	31.97	30.66	--

APPENDIX B:
Streamflow at Partial-Record Sites, 1995–96

Table B1. Instantaneous streamflow at partial-record sites in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1995–96

[Site identifiers and locations are shown on figure 6. Streamflow measurements are in cubic feet per second. --, not measured]

Stream	Site identifier	Date of streamflow measurement								
		8/16/95	9/20/95	10/18/95	11/21/95	1/17/96	2/14/96	3/13/96	4/19/96	4/24/96
Hunt River Basin										
Scrabbletown Brook......	A	0.17	0.13	0.10	2.09	2.91	3.33	3.98	6.24	4.10
Hunt River Tributary	B	.36	.24	.27	2.63	3.84	4.06	4.77	7.15	5.68
Hunt River....................	C	--	1.52	--	--	--	--	--	--	16.60
Hunt River....................	D	--	4.73	--	--	--	--	--	--	23.80
Frenchtown Brook.........	E	.73	1.24	1.76	11.60	14.90	16.20	19.00	31.40	22.10
Frenchtown Brook.........	F	--	1.75	--	--	--	--	--	--	23.70
Hunt River....................	G	--	7.57	--	--	--	--	--	--	50.80
Fry Brook	H	.05	.04	.19	5.32	13.80	6.00	9.07	16.50	8.88
Hunt River....................	I	--	5.65	--	--	--	--	--	--	64.50
Hunt River....................	J	--	5.43	--	--	--	--	--	--	62.70
Hunt River....................	K	--	5.14	--	--	--	--	--	--	61.30
Sandhill Brook	L	--	--	--	--	--	--	--	--	1.29
Sandhill Brook	M	--	.08	--	--	--	--	--	--	3.65
Sandhill Brook	N	--	.78	--	--	--	--	--	--	5.27
Sandhill Brook	O	--	.71	--	--	--	--	--	--	7.08
Cocumcossuc Brook Basin										
Cocumcossuc Brook	Q	.11	.35	.60	3.55	5.24	3.82	4.88	6.98	4.37
Annaquatucket River Basin										
Annaquatucket River.....	R	--	--	--	--	--	--	--	--	2.68
Annaquatucket River.....	S	--	--	--	--	--	--	--	--	3.84
Annaquatucket River.....	T	4.72	7.44	7.76	14.90	15.90	19.00	19.10	26.50	20.70
Pettaquamscutt River Basin										
Mattatuxet River...........	U	--	1.36	--	--	--	--	--	--	4.75
Mattatuxet River...........	V	2.65	2.68	2.08	3.74	19.70	14.30	18.10	15.20	12.00

Table B1. Instantaneous streamflow at partial-record sites in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, 1995–96—*Continued*

Stream	Site identifier	Date of streamflow measurement							
		5/15/96	6/19/96	7/24/96	8/21/96	9/7/96	9/25/96	10/8/96	11/20/96
Hunt River Basin									
Scrabbletown Brook......	A	2.73	0.65	1.40	0.16	0.50	1.43	0.54	2.17
Hunt River Tributary.....	B	3.38	1.48	1.28	.51	.69	1.41	.98	2.40
Hunt River....................	C	--	--	--	--	--	--	3.07	--
Hunt River....................	D	--	--	--	--	4.00	--	4.81	--
Frenchtown Brook.........	E	13.50	3.36	6.74	1.84	1.80	5.77	2.78	9.97
Frenchtown Brook.........	F	--	--	--	--	2.06	--	2.95	--
Hunt River....................	G	--	--	--	--	5.79	--	10.20	--
Fry Brook......................	H	5.57	1.02	1.63	.21		1.76	1.28	2.31
Hunt River....................	I	--	--	--	--	9.20	--	7.13	--
Hunt River....................	J	--	--	--	--	6.90	--	7.71	--
Hunt River....................	K	--	--	--	--	8.74	--	10.60	--
Sandhill Brook	L	--	--	--	--	.21	--	.18	--
Sandhill Brook	M	--	--	--	--	--	--	.90	--
Sandhill Brook	N	--	--	--	--	1.33	--	1.82	--
Sandhill Brook	O	--	--	--	--	2.55	--	2.15	--
Cocumcossuc Brook Basin									
Cocumcossuc Brook	Q	3.11	0.83	1.19	0.50	1.16	2.90	1.14	2.44
Annaquatucket River Basin									
Annaquatucket River.....	R	--	--	--	--	--	--	1.95	--
Annaquatucket River.....	S	--	--	--	--	1.16	--	1.36	--
Annaquatucket River.....	T	17.50	9.61	15.20	7.33	11.10	30.00	11.70	15.80
Pettaquamscutt River Basin									
Mattatuxet River...........	U	--	--	--	--	15.70	--	2.39	--
Mattatuxet River...........	V	12.20	5.51	4.12	3.73	11.80	8.42	4.00	6.95

APPENDIX C:
Withdrawals from Public-Supply Wells, 1943–98

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98

[Withdrawals are in million gallons. Record incomplete for years not shown. EDC, Rhode Island Economic Development Corporation; KCWA, Kent County Water Authority; NK, North Kingstown; Mgal/d, million gallons per day; --, before pumping began]

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Hunt River Basin													
EDC 9A (began pumping in February 1943)													
1943	--	29.4	35.7	24.5	39.4	35.8	35.7	44.6	62.5	35.4	28.0	33.0	1.11
1944	32.5	30.6	58.8	36.8	39.5	40.1	40.9	38.4	34.3	36.1	38.0	36.9	1.27
1945	38.0	33.3	41.8	39.4	40.8	39.8	41.8	43.4	41.6	50.8	13.4	19.3	1.21
1946	37.9	29.1	32.0	21.9	24.4	26.3	25.6	31.9	28.1	36.5	23.0	21.0	.93
1947	25.1	20.8	25.3	13.6	16.7	18.9	23.6	22.4	22.7	20.0	13.6	15.3	.65
1948	14.5	12.2	12.3	12.1	18.6	20.6	23.6	29.9	33.8	32.2	25.1	30.9	.73
1949	25.1	6.5	21.2	18.1	23.6	29.4	23.2	18.2	22.6	35.6	33.3	34.3	.80
1950	35.4	29.1	35.2	28.5	2.7	9.6	9.8	11.2	4.8	2.8	2.9	2.1	.48
1951	2.4	1.5	3.6	4.9	6.5	9.7	21.5	16.8	9.6	9.6	7.1	6.6	.27
1952	6.9	8.1	7.1	8.4	8.5	17.7	29.8	17.4	14.3	10.0	7.5	9.9	.40
1953	10.1	9.4	7.7	11.1	13.5	29.4	24.7	24.5	22.9	17.3	44.0	47.9	.72
1954	48.3	43.4	16.7	14.0	11.6	21.3	20.8	18.8	12.7	19.5	11.1	17.9	.70
1955	10.9	7.0	9.3	8.8	13.3	19.0	24.9	20.9	33.2	42.8	15.5	16.9	.61
1956	17.0	15.5	11.7	14.2	18.5	22.1	27.8	32.9	25.4	19.7	14.1	23.2	.66
1957	21.5	21.9	36.3	44.7	43.4	41.0	31.9	32.8	25.8	24.8	18.8	23.9	1.00
1958	21.0	22.7	21.6	21.3	26.0	25.9	33.9	26.7	27.3	16.5	9.8	11.8	.72
1959	14.4	17.1	12.4	18.3	27.5	30.4	33.1	22.0	23.6	26.8	27.0	27.2	.77
1960	24.8	27.3	26.5	20.2	27.9	26.3	19.2	20.7	20.5	19.7	23.3	23.4	.77
1961	20.2	27	27.3	21.8	16.5	25.7	37.0	30.4	31.3	30.3	25.8	22.6	.87
1970	24.8	23.8	32.6	31.5	26.4	21.0	26.4	24.8	24.0	24.8	25.5	34.1	.88
1971	29.5	25.2	37.2	25.5	29.5	33.0	34.1	24.8	21.0	12.4	12.4	15.5	.82
1972	24.8	25.2	32.6	22.5	15.5	9.0	18.6	21.0	9.0	12.4	9.0	10.9	.58
1973	12.4	9.8	14.0	16.5	14.0	12.0	10.9	0	0	0	0	0	.25
1974	0	0	0	0	0	0	1.6	3.1	6.2	4.7	4.5	6.2	.07
1975	7.8	15.4	20.2	21.0	17.1	12.0	15.5	0	0	0	0	0	.30
1993	0	0	0	0	0	0	5.8	6.0	6.3	5.3	5.3	5.7	.09
1994	0	0	0	0	0	0	.1	12.5	23.9	6.2	0	0	.12
1995	0	4.6	5.8	3.2	5.2	7.0	3.8	7.3	7.0	7.5	2.8	7.4	.17
1996	3.2	5.8	4.5	6.4	6.0	5.7	5.7	4.2	5.2	5.0	4.5	4.9	.17
1997	5.2	12.9	4.4	5.2	2.1	0	0	4.5	8.3	6.5	6.2	5.3	.17
1998	4.9	4.5	4.9	6.2	5.7	6.6	19.4	19.3	8.3	7.9	5.2	5.8	.27

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Hunt River Basin—*Continued*													
EDC 14A (began pumping in February 1943)													
1943	--	7.2	17.5	20.5	24.0	26.1	32.8	45.4	73.0	40.1	37.1	37.9	0.99
1944	64.6	38.5	68.9	37.6	40.1	39.9	40.5	59.0	36.0	37.5	38.8	43.7	1.49
1945	44.2	36.9	46.2	43.8	45.5	44.5	63.5	46.7	45.2	58.6	44.4	28.2	1.50
1946	6.9	9.7	13.2	9.2	6.3	7.1	24.7	7.1	12.2	5.9	4.0	4.1	.30
1947	3.4	2.9	3.9	10.4	11.4	12.2	18.5	22.1	19.4	16.9	15.9	17.7	.42
1948	13.7	14.9	15.6	15.5	20.5	26.2	34.8	39.7	25.0	18.6	20.7	30.1	.75
1949	28.5	41.4	33.5	32.2	21.9	37.9	44.1	48.0	29.4	9.7	9.4	10.0	.95
1950	8.5	12.9	7.2	13.9	38.5	37.4	46.2	47.8	44.5	40.1	40.6	40.8	1.04
1951	41.5	37.3	41.6	40.9	44.4	45.9	47.7	48.8	43.8	44.7	39.6	44.3	1.43
1952	45.0	40.0	47.0	40.9	44.0	45.2	46.6	43.6	42.0	44.0	41.8	45.4	1.44
1953	46.2	41.3	43.5	44.9	48.1	47.2	48.7	49.2	47.1	45.3	15.3	14.7	1.35
1954	16.0	15.2	45.1	42.9	45.2	40.1	46.2	43.5	40.8	37.6	44.6	49.4	1.28
1955	46.2	41.7	42.5	42.2	44.7	44.5	48.6	51.1	24.0	14.7	40.7	45.2	1.33
1956	48.1	48.7	52.9	50.0	49.2	50.9	52.8	52.6	49.2	50.0	49.2	43.0	1.63
1957	52.1	44.8	31.7	25.7	40.4	42.1	50.2	49.8	48.1	47.0	47.4	49.8	1.45
1958	50.1	46.3	49.5	47.2	38.5	34.9	26.7	34.7	38.0	50.2	44.7	49.4	1.40
1959	50.2	45.2	47.4	41.7	34.6	32.4	39.9	45.5	40.1	37.3	33.0	30.0	1.31
1960	32.3	26.1	23.9	26.6	30.8	30.1	42.5	50.2	40.0	34.6	27.3	38.1	1.10
1961	47.9	31.5	41.8	35.0	46.9	43.4	38.7	48.6	42.5	41.9	44.4	43.5	1.39
1970	18.6	15.4	14.0	24.0	15.5	28.5	34.1	38.8	33.0	24.8	12.0	6.2	.73
1971	21.7	19.6	31.0	21.0	20.2	27.0	38.8	38.8	37.5	37.2	40.5	38.8	1.02
1972	37.2	30.8	37.2	25.5	34.1	37.5	37.2	34.5	37.5	23.3	25.5	21.7	1.05
1973	21.7	18.2	24.8	24.0	24.8	25.5	26.4	0	0	0	0	0	.45
1974	0	0	0	0	0	0	3.1	6.2	19.5	23.3	22.5	20.2	.26
1975	18.6	16.8	7.8	1.5	6.2	4.5	6.2	0	0	0	0	0	.17
1993	0	0	0	0	0	0	10.0	12.1	9.7	5.8	8.8	4.5	.14
1994	0	0	0	0	0	0	.1	11.3	1.8	9.0	14.0	11.2	.13
1995	11.9	12.1	10.0	5.8	11.2	10.9	18.9	16.3	12.0	12.0	9.2	6.6	.38
1996	11.5	10.2	9.8	10.1	9.6	11.5	12.4	17.2	10.8	12.0	11.3	9.4	.37
1997	8.9	23.0	9.5	8.0	11.1	14.0	15.6	12.2	12.7	6.9	9.6	10.5	.39
1998	9.4	8.5	10.4	12.0	13.9	16.4	16.3	13.1	12.7	13.6	14.2	11.3	.42

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
						Hunt River Basin—*Continued*							
EDC 3A (began pumping in July 1993)													
1993	--	--	--	--	--	--	9.3	9.0	7.5	7.9	5.9	1.6	0.11
1994	19.6	17.8	18.5	16.6	19.1	23.0	24.8	6.0	.1	5.4	6.3	9.1	.46
1995	10.8	4.7	5.8	9.4	6.3	7.3	6.1	4.6	3.5	.6	6.5	6.0	.20
1996	8.0	5.2	5.5	5.0	5.7	6.1	7.4	7.3	8.7	7.0	6.5	7.1	.22
1997	8.5	9.8	6.5	6.5	6.6	11.8	16.3	11.1	6.4	10.0	6.2	6.8	.29
1998	6.3	5.8	7.0	5.8	5.7	4.4	1.2	.2	6.9	3.0	4.2	5.6	.15
KCWA 1 (began pumping in February 1965)													
1965	--	--	--	10.3	33.1	34.9	46.0	37.7	9.9	3.2	.2	16.3	.52
1966	16.1	13.5	11.8	15.3	22.4	37.8	44.2	44.3	22.4	16.4	19.1	17.4	.77
1967	19.9	16.3	9.1	25.3	11.1	41.4	39.3	33.3	38.6	25.5	11.7	22.4	.81
1968	18.3	15.4	14.3	18.1	35.6	42.8	44.9	46.9	58.7	33.8	21.3	25.5	1.03
1969	22.4	24.7	32.2	29.8	36.1	55.2	44.1	53.3	38.4	23.7	18.5	0	1.04
1970	0	0	0	20.1	25.5	25.0	54.9	54.1	48.3	35.1	18.0	37.7	.87
1971	35.4	31.6	30.9	37.4	36.8	62.1	58.2	49.8	58.4	38.7	30.3	39.6	1.40
1972	31.8	27.3	36.2	33.2	43.6	43.9	44.2	47.4	12.9	8.2	44.7	42.0	1.14
1973	49.7	54.5	55.0	44.6	57.0	58.9	56.2	67.1	47.4	43.6	34.9	34.2	1.65
1974	40.8	33.1	35.8	45.7	52.1	53.1	60.2	59.5	42.0	38.2	30.6	31.9	1.43
1975	32.0	30.2	31.1	31.6	43.5	43.2	49.5	68.7	36.3	33.8	29.0	28.2	1.25
1976	27.4	23.9	29.8	37.1	40.0	46.5	50.3	51.2	46.8	38.0	25.0	18.8	1.19
1977	14.1	11.7	12.8	17.2	43.1	33.7	23.7	20.2	15.9	12.7	12.3	40.0	.71
1978	44.6	38.7	46.1	42.9	41.0	32.0	27.8	38.7	35.5	29.6	20.9	18.7	1.14
1979	25.4	30.7	31.0	32.7	32.7	32.5	30.1	26.3	29.3	29.8	21.8	11.1	.91
1980	3.8	28.4	19.6	19.1	29.8	28.2	29.2	32.4	30.7	27.2	18.6	14.6	.77
1981	13.6	11.6	14.4	20.7	28.8	38.6	35.2	35.0	32.1	25.4	19.3	20.3	.81
1982	17.6	18.7	25.3	26.3	39.1	29.9	34.0	38.2	37.3	39.0	37.0	38.2	1.04
1983	35.5	31.6	33.4	36.3	24.7	7.4	18.7	13.0	13.4	24.4	18.3	20.9	.76
1984	21.2	15.2	25.6	23.9	28.4	27.7	30.4	30.7	26.1	19.0	13.3	14.3	.75
1985	8.6	23.3	29.4	26.9	31.1	31.0	33.0	30.0	28.4	14.3	0	0	.70
1986	2.2	17.5	18.6	19.7	24.1	26.4	28.1	21.7	17.8	16.3	16.5	12.9	.61
1987	13.4	9.9	13.2	10.6	12.2	23.7	34.3	24.3	11.4	13.4	11.9	13.7	.53
1988	11.0	10.2	9.9	10.0	14.3	26.0	24.3	28.0	6.8	0	7.9	6.3	.42
1989	7.7	7.6	7.0	4.9	10.9	10.2	14.7	12.7	7.6	.19	.18	.34	.23
1990	.32	.55	.27	.73	.73	13.4	11.2	9.6	5.6	.23	0	0	.12
1991	.26	0	.16	0	9.6	23.7	18.8	9.3	2.8	.2	0	0	.18
1992	0	.08	0	0	4.1	8.4	8.1	2.3	0	0	0	0	.06

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
							Hunt River Basin—*Continued*						
KCWA 1—*Continued*													
1993	0	0	0	0	10.8	26.0	20.9	19.6	3.1	0.5	0	0	0.22
1994	0	0	0	0	.7	22.7	18.5	2.8	.6	0	0	.3	.12
1995	.3	0	0	0	0	3.4	34.1	42.2	17.2	0	0	0	.27
1996	1.8	2.8	1.4	1.0	1.6	12.5	1.1	3.2	0	0	26.0	67.5	.32
1997	46.6	.5	.4	.3	4.8	28.4	43.9	27.8	23.6	14.7	1.9	.6	.53
1998	1.2	9.8	13.3	27.7	41.0	51.2	56.4	52.9	50.9	36.9	30.2	31.3	1.10
NK 9 (began pumping in August 1944)													
1944	--	--	--	--	--	--	--	57.8	51.6	29.8	18.7	40.5	.54
1945	46.5	29.7	26.7	18.7	22.8	28.7	32.3	35.7	33.6	30.4	5.7	15.1	.89
1946	34.8	35.4	30.0	36.0	36.6	18.7	12.3	14.9	13.0	13.3	25.2	30.1	.82
1947	29.2	25.3	26.9	26.5	25.6	22.4	28.1	37.5	30.7	28.0	29.0	26.9	.92
1948	29.9	32.4	28.5	24.7	27.8	22.6	30.9	34.1	20.1	18.4	15.1	19.5	.83
1949	18.4	18.8	18.3	16.1	17.0	23.1	19.8	14.8	12.5	16.6	15.5	16.5	.57
1950	17.5	15.2	16.7	14.5	15.8	17.9	21.3	19.8	16.5	18.4	17.8	18.6	.58
1951	19.4	17.7	19.9	18.6	19.3	19.0	18.2	19.9	16.7	22.0	23.7	22.6	.60
1952	21.3	16.6	17.6	17.9	19.1	20.1	23.1	19.5	17.3	19.5	18.8	18.5	.63
1953	19.3	16.9	18.1	17.9	18.6	23.6	20.3	16.5	16.7	17.5	17.6	16.7	.60
1954	16.9	15.2	16.4	16.0	17.0	20.6	20.9	16.3	14.8	14.1	14.4	15.1	.54
1955	15.9	15.0	14.9	15.5	15.2	16.6	21.6	17.6	15.4	16.9	15.7	17.7	.54
1956	17.4	21.3	25.7	16.5	18.7	21.7	23.4	24.7	15.5	16.8	22.0	19.7	.67
1957	18.6	16.6	17.4	18.6	18.5	26.5	17.7	9.2	6.1	16.2	16.1	16.6	.54
1958	15.4	17.0	19.1	19.0	19.6	15.3	21.6	15.7	16.9	16.8	16.2	18.1	.58
1959	20.1	16.9	9.8	12.1	17.9	17.1	15.5	24.6	14.5	20.7	14.4	16.5	.55
1960	19.4	15.8	18.8	15.4	21.7	23.3	22.7	29.2	23.9	18.6	20.0	22.7	.69
1961	23.0	22.3	20.1	20.6	21.3	24.5	23.9	22.2	16.1	17.0	19.8	20.5	.69
1962	21.0	18.5	15.3	14.0	17.4	19.4	21.0	24.3	15.2	21.3	17.1	22.3	.62
1963	21.6	20.5	23.6	21.2	17.9	24.2	28.4	24.5	22.1	37.7	12.0	20.7	.75
1964	20.6	21.5	16.3	18.1	26.5	31.3	28.0	25.1	25.1	17.1	19.4	21.8	.74
1965	22.9	19.5	23.1	9.0	13.2	13.2	15.5	25.3	30.4	25.1	25.5	16.2	.65
1966	20.3	19.5	18.9	17.1	17.9	15.6	29.0	11.0	19.0	16.2	16.9	18.0	.60
1967	18.1	13.0	16.1	16.4	29.1	12.1	14.2	12.5	14.6	23.5	24.7	19.6	.59
1968	18.3	22.2	23.4	18.6	17.8	16.8	17.4	11.7	10.0	16.2	21.6	21.3	.59

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Hunt River Basin—*Continued*													
NK 9—*Continued*													
1969	20.4	17.7	20.2	18.1	21.1	28.2	23.3	14.2	18.3	18.8	24.7	39.0	0.72
1970	38.8	33.0	36.4	19.6	28.0	37.1	20.1	18.0	0	11.8	16.7	6.4	.73
1971	4.7	8.4	9.7	7.9	10.2	34.1	31.4	19.3	6.9	6.2	8.8	8.6	.43
1972	5.9	10.5	8.2	3.2	1.3	0	0	0	0	0	0	0	.08
1973	0	0	0	0	0	.4	0	0	0	0	0	3.0	.01
1974	.2	0	0	0	.3	1.8	1.5	9.7	0	0	1.0	1.0	.04
1975	0	0	0	0	.7	1.8	4.0	12.0	2.4	0	1.2	.2	.06
1976	.1	0	0	.7	0	11.6	6.1	0	0	.5	0	0	.05
1977	0	0	0	.3	4.2	2.8	17.0	.9	0	0	0	0	.07
1978	0	0	0	2.6	.8	11.7	14.3	.1	0	0	0	1.4	.08
1979	0	0	0	0	0	6.6	14.8	1.8	.2	0	0	17.0	.11
1980	30.7	1.0	0	19.1	6.4	18.1	28.7	22.1	26.9	2.9	0	0	.43
1981	0	2.3	1.9	1.1	2.8	7.1	12.7	0	0	0	0	0	.08
1982	0	0	0	0	0	0	16.2	0	0	0	0	0	.04
1990	0	0	0	0	0	.3	1.0	1.5	0	0	0	0	.01
1991	0	0	0	0	0	0	2.9	.7	13.6	22.3	5.2	0	.12
1992	0	0	0	.6	0	0	0	0	0	0	0	0	.00
1993	0	0	0	0	4.1	36.6	47.3	51.4	42.6	36.3	31.2	23.1	.75
1994	0	0	0	0	0	33.6	44.8	38.1	38.7	38.9	34.7	31.6	.71
1995	31.0	32.1	30.4	0	12.2	36.8	41.8	42.9	33.5	6.0	3.9	0	.74
1996	20.0	26.5	28.0	23.8	34.4	44.2	49.8	58.7	44.0	34.6	33.0	34.2	1.18
1997	33.7	27.0	32.0	33.8	38.9	49.1	47.8	39.7	32.5	28.8	26.9	23.3	1.13
1998	23.5	21.3	31.0	27.6	12.1	0	27.6	43.5	37.2	35.7	29.5	17.6	.84
NK 10 (began pumping in June 1944)													
1944	--	--	--	--	--	18.4	42.8	32.2	17.1	30.6	35.7	10.1	.51
1945	15.3	26.1	28.3	37.6	32.1	35.6	43.2	37.5	21.4	10.5	33.4	24.9	.95
1946	6.0	1.8	11.4	4.6	5.4	25.8	35.5	22.1	20.8	20.1	19.4	18.3	.52
1947	19.7	18.3	19.7	18.8	15.8	19.4	14.9	5.9	11.1	16.0	10.1	15.1	.51
1948	10.5	7.8	14.1	17.0	5.7	6.6	2.9	.5	13.9	13.4	14.1	8.2	.31
1949	8.8	7.2	10.6	12.7	15.7	26.6	28.5	24.1	18.5	18.3	18.7	16.4	.56
1950	13.7	13.8	18.4	19.4	21.4	22.9	21.6	16.8	16.5	15.6	12.9	9.9	.56
1951	7.7	7.7	8.5	10.1	16.8	18.2	30.3	23.4	24.8	20.3	25.2	23.2	.59
1952	14.2	12.1	13.6	13.6	15.3	19.4	38.5	20.1	19.0	15.4	14.0	15.0	.58
1953	14.7	14.3	14.6	14.7	19.1	38.8	34.6	29.3	28.5	22.7	18.6	17.7	.73

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
							Hunt River Basin—*Continued*						
NK 10—*Continued*													
1954	17.0	15.8	18.0	17.8	19.0	27.9	29.4	24.1	24.3	25.2	19.2	19.5	0.70
1955	20.1	17.4	18.8	16.8	29.0	25.3	33.5	33.6	25.0	22.2	20.4	21.3	.78
1956	20.6	8.8	4.5	13.5	16.9	29.2	20.1	18.9	19.8	14.3	22.7	20.4	.57
1957	12.3	9.6	9.7	12.0	27.3	34.9	37.2	29.4	26.8	15.3	11.1	15.8	.66
1958	11.0	6.4	8.4	8.5	12.2	19.5	16.9	21.7	17.4	16.7	14.3	13.7	.46
1959	11.7	11.4	24.1	21.0	21.7	19.7	24.8	21.7	24.4	21.3	17.4	15.4	.64
1960	13.6	16.5	15.9	21.2	19.6	25.3	27.1	21.6	17.8	17.1	13.6	13.6	.61
1961	13.4	12.8	16.2	13.4	14.2	20.1	27.9	25.8	24.2	18.8	14.1	13.3	.59
1962	14.8	13.4	20.9	23.4	27.3	28.6	35.4	30.9	25.1	15.3	16.9	13.7	.73
1963	15.7	14.1	14.9	20.3	27.7	29.7	38.6	32.5	21.9	6.2	24.6	17.5	.72
1964	16.9	12.7	20.7	19.2	37.5	43.6	33.4	29.1	27.6	27.7	23.8	19.2	.85
1965	18.7	18.1	17.2	19.5	8.5	18.3	22.0	14.0	14.3	17.4	17.5	7.4	.53
1966	6.6	5.9	7.3	8.7	8.5	9.1	21.9	14.3	3.3	3.7	4.1	9.3	.28
1967	6.9	12.3	5.5	6.1	6.3	10.9	3.4	3.3	5.9	4.1	6.4	7.6	.22
1968	22.6	4.9	4.9	1.0	2.0	3.1	14.2	10.3	10.5	.7	3.1	4.7	.22
1969	3.9	2.5	1.1	0	0	0	11.4	2.6	8.4	6.7	3.8	0	.11
1970	0	0	0	.6	1.8	5.1	8.0	0	0	0	0	0	.04
1971	0	0	0	.1	0	10.5	10.7	3.0	1.5	.9	.8	1.4	.08
1972	.7	1.2	.7	0	.4	.3	9.0	9.6	30.0	33.4	0	0	.23
1973	.9	0	0	.9	.9	16.6	8.1	21.5	3.7	0	0	0	.14
1974	0	.4	.8	0	.3	18.1	28.6	37.8	.2	.4	0	0	.24
1975	0	0	0	0	5.2	11.9	29.8	10.4	0	.1	0	0	.16
1976	0	0	0	1.0	2.7	35.4	30.9	12.9	1.8	.3	0	.5	.23
1977	0	0	0	1.8	24.1	24.4	40.2	21.2	8.6	1.0	0	0	.33
1978	.4	.04	0	0	5.9	22.2	38.3	11.4	.2	0	0	0	.21
1979	0	3.6	.2	.8	5.2	20.4	38.1	9.9	3.6	.6	0	0	.23
1980	.4	1.1	0	5.5	2.0	10.4	30.7	2.6	3.6	0	0	0	.15
1981	0	0	1.1	0	12.9	29.2	29.7	18.0	6.3	.3	0	0	.27
1982	0	0	0	0	12.4	2.5	30.3	8.7	4.8	0	0	0	.16
1990	25.9	25.7	28.9	29.0	34.4	41.9	34.6	40.4	29.2	21.8	30.7	35.1	1.03

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Hunt River Basin—*Continued*													
NK 10—*Continued*													
1991	34.8	32.1	36.7	39.0	45.7	62.1	65.5	49.9	22.6	0	26.7	37.1	1.24
1992	35.1	34.1	37.8	34.7	43.6	45.8	48.4	20.0	0	0	0	0	.82
1993	0	0	0	0	0	0	0	0	0	0	0	0	.00
1994	0	0	0	0	0	0	0	0	0	0	0	0	.00
1995	0	0	0	0	0	0	0	0	0	0	0	0	.00
1996	0	0	0	0	0	0	0	0	0	0	0	0	.00
1997	0	0	0	0	0	0	0	0	0	0	0	0	.00
1998	0	0	0	0	0	0	0	0	0	0	0	0	.00
NK 6 (began pumping in March 1978)													
1990	19.2	16.8	15.5	19.3	20.3	19.1	19.4	18.2	17.2	17.3	4.5	0	.51
1991	0	2.7	5.9	2.1	8.5	10.5	13.1	5.4	6.1	11.1	5.1	3.1	.20
1992	1.1	1.6	1.5	.3	4.1	10.4	7.2	16.0	20.3	18.5	15.4	16.4	.31
1993	17.9	15.5	18.3	18.1	24.5	18.3	14.9	8.9	5.0	.1	0	3.5	.40
1994	16.9	15.2	17.0	15.7	18.7	20.8	18.5	8.8	7.2	1.7	.4	2.0	.39
1995	2.7	.02	1.8	15.4	11.1	8.1	17.4	17.9	11.1	16.0	13.8	16.8	.36
1996	10.1	5.9	4.6	6.7	9.5	10.8	11.7	10.2	4.9	6.4	4.0	6.1	.25
1997	6.9	8.4	7.9	7.5	.3	0	18.6	11.7	13.6	14.2	9.0	1.2	.27
1998	3.0	8.2	6.9	9.1	16.6	19.8	20.5	14.9	9.9	5.0	6.6	3.7	.34
Annaquatucket River Basin													
NK 1 (began pumping in December 1944)													
1945	6.5	6.0	6.8	6.5	5.9	7.4	8.5	8.9	7.8	5.8	5.6	6.5	.23
1946	7.8	7.7	7.2	7.2	7.1	7.0	8.4	7.0	6.6	6.5	6.1	6.3	.23
1947	6.3	5.7	6.5	6.4	7.1	7.5	8.7	9.0	7.8	7.7	7.2	7.2	.24
1948	7.1	6.6	7.2	6.9	7.3	7.5	9.7	10.6	9.0	7.9	7.2	7.5	.26
1949	7.6	7.1	8.1	8.2	8.2	12.2	13.1	11.8	9.1	9.1	8.1	7.8	.30
1950	8.2	7.3	8.2	7.9	8.4	9.5	11.5	10.1	9.0	8.4	7.7	8.1	.29
1951	8.1	7.4	8.4	8.0	8.6	9.0	11.7	10.1	7.9	7.7	0	4.7	.25
1952	8.7	8.1	8.7	8.7	9.4	11.7	17.0	11.2	10.3	10.6	10.8	11.5	.35
1953	10.5	9.1	10.6	10.2	11.4	17.5	16.8	15.7	15.5	12.7	10.9	11.4	.42
1954	11.6	10.6	12.2	11.9	12.9	16.0	18.4	14.9	12.3	11.5	11.5	12.0	.43

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Annaquatucket River Basin—*Continued*													
NK 1—*Continued*													
1955	12.2	11.1	12.7	12.7	10.4	16.7	22.4	19.9	15.1	14.2	13.2	13.9	0.48
1956	13.6	13.0	14.3	14.4	16.4	21.9	20.9	21.3	17.2	15.2	0	3.4	.47
1957	15.7	14.1	15.9	16.6	21.7	27.6	27.5	21.2	18.2	18.8	14.9	15.8	.62
1958	15.8	14.9	15.8	16.1	16.6	18.4	21.5	20.8	17.7	17.4	16.2	17.3	.57
1959	12.6	16.2	4.4	4.3	5.4	7.5	6.9	5.6	7.3	7.8	8.1	8.8	.26
1960	8.2	7.8	7.7	6.8	8.3	9.1	9.5	10.4	19.4	9.6	7.5	5.9	.30
1961	21.7	20.8	22.3	21.8	25.3	25.8	38.3	32.5	24.8	24.5	22.4	22.0	.83
1962	24.1	21.3	22.7	23.1	28.7	33.7	39.8	35.5	25.9	23.4	20.1	21.2	.88
1963	21.9	19.8	23.3	25.3	28.3	35.2	27.5	27.7	28.7	25.6	22.2	24.7	.85
1990	4.2	1.5	5.4	0	.1	15.2	20.0	13.5	15.1	11.4	12.7	14.6	.31
1991	13.7	9.2	8.3	12.9	15.5	18.1	16.1	16.1	14.2	12.3	9.6	9.1	.42
1992	8.9	7.8	7.7	11.2	15.1	15.2	17.0	19.3	17.1	16.1	13.6	14.9	.45
1993	16.6	14.5	15.6	16.1	23.9	23.5	21.1	22.6	16.1	17.8	11.6	12.6	.58
1994	16.8	15.5	17.2	15.5	18.9	21.1	20.9	8.6	.3	4.4	7.4	9.7	.43
1995	9.9	8.9	10.0	16.6	15.3	15.3	19.3	18.9	13.6	14.7	0	20.5	.45
1996	.03	0	4.8	7.6	5.0	14.2	11.7	9.1	5.8	3.3	3.8	1.3	.18
1997	0	0	0	0	1.2	15.7	17.1	6.1	5.3	0	5.0	11.5	.17
1998	8.2	7.0	3.5	5.5	15.8	16.6	17.5	13.0	6.3	0	0	2.9	.26
NK 2 (began pumping in August 1956)													
1959	4.6	8.9	12.6	12.5	16.3	13.1	16.2	18.9	13.9	11.1	9.4	9.2	.40
1960	10.1	9.8	10.9	12.7	14.0	18.1	21.2	20.7	14.9	12.0	12.1	14.4	.47
1990	0	0	0	.5	0	2.9	7.2	2.6	4.4	1.4	0	0	.05
1991	0	.02	.1	0	.9	8.7	7.1	2.5	.5	.1	0	0	.05
1992	.3	0	.03	.3	1.9	2.6	1.0	7.7	12.8	13.5	10.0	11.5	.17
1993	7.7	6.5	7.7	7.6	10.9	9.7	10.9	8.5	2.9	.2	.07	3.1	.21
1994	8.8	7.4	8.1	11.3	14.0	14.2	13.0	5.4	4.6	3.0	.3	.3	.25
1995	0	0	.7	9.0	11.1	2.0	13.8	11.4	5.3	10.5	18.4	0	.23
1996	9.1	5.4	3.7	4.9	4.2	4.1	2.9	1.9	4.0	4.3	2.9	2.7	.14
1997	3.6	4.2	3.9	3.7	9.7	17.7	16.8	8.4	8.5	9.1	2.6	7.4	.26
1998	7.5	.4	0	0	9.8	12.8	14.0	9.3	6.7	4.8	4.0	.09	.19

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
							Annaquatucket River Basin—*Continued*						
NK 4 (began pumping in May 1967)													
1990	7.6	6.5	7.8	6.4	2.8	11.1	13.8	14.4	11.4	9.2	8.3	5.2	0.29
1991	3.3	2.5	2.8	3.4	7.8	17.9	16.1	11.2	9.0	6.7	9.2	9.0	.27
1992	12.0	11.9	9.9	10.1	12.1	16.2	15.1	11.2	10.0	10.5	10.2	9.9	.38
1993	9.7	8.6	9.0	9.0	15.1	18.4	19.3	19.2	14.8	11.4	9.7	8.7	.42
1994	10.3	8.7	9.8	9.2	11.6	17.8	19.3	12.9	12.4	11.0	8.8	8.9	.39
1995	8.9	7.8	8.7	9.7	11.5	15.4	22.4	20.1	14.8	12.0	11.2	17.0	.44
1996	0	0	0	9.9	10.3	13.1	6.5	3.2	5.1	7.2	4.6	4.1	.18
1997	9.2	11.2	10.2	4.9	8.8	15.1	22.2	14.3	9.0	10.3	3.4	1.9	.33
1998	15.9	10.9	7.9	11.9	11.7	10.9	16.0	14.9	11.3	9.8	7.6	5.4	.37
NK 5 (well drilled in January 1969)													
1990	6.3	5.5	5.8	7.2	11.0	14.8	9.6	8.7	6.6	3.9	4.3	8.6	.25
1991	10.9	10.0	11.2	10.4	12.9	14.4	16.9	13.0	12.1	9.9	9.2	10.7	.39
1992	8.4	7.5	10.6	8.8	15.7	16.5	14.0	12.1	11.0	12.0	10.0	10.2	.37
1993	9.8	8.7	9.9	9.9	14.4	19.5	19.0	17.5	7.6	9.0	8.3	9.5	.39
1994	11.3	9.9	11.3	10.0	12.2	19.4	19.2	12.4	12.9	11.2	9.5	9.8	.41
1995	9.7	8.4	9.6	10.5	13.1	15.9	23.4	21.6	15.2	10.6	8.7	2.9	.41
1996	15.9	13.3	16.6	9.8	16.1	21.8	24.7	23.8	12.4	8.0	9.3	9.1	.50
1997	3.8	.5	3.6	9.7	10.9	22.5	31.7	12.0	11.5	14.4	15.6	22.8	.44
1998	4.6	4.6	7.8	3.4	14.7	15.1	21.6	17.0	12.6	10.4	10.2	3.9	.34
							Pettaquamscutt River Basin						
NK 3 (began pumping in September 1961)													
1961	--	--	--	--	--	--	--	--	3.4	.4	.3	.3	.01
1962	0	.2	.3	.4	.8	1.4	1.9	3.9	1.1	1.7	1.1	.4	.04
1963	1.3	1.1	1.1	1.3	1.4	2.7	22.4	12.0	2.4	1.1	1.4	1.3	.14
1990	0	0	0	0	0	3.0	11.2	8.5	0	0	0	0	.06
1991	0	0	0	0	0	1.0	2.6	0.1	0	0	0	0	.01
1992	0	0	0	0	.5	1.2	.4	0	0	0	0	0	.01
1993	0	0	0	0	0	4.0	5.8	4.0	5.8	5.6	3.4	1.4	.08
1994	.3	.8	2.2	2.2	2.1	7.5	11.0	4.7	0	0	0	0	.08
1995	0	0	0	0	0	0	6.6	7.4	7.9	9.3	9.0	8.7	.13
1996	7.8	6.8	5.1	1.5	1.6	3.7	5.3	9.0	7.0	6.4	5.5	5.6	.18

Table C1. Summary of monthly withdrawals from public water-supply wells in the Hunt–Annaquatucket–Pettaquamscutt stream-aquifer system, Rhode Island, 1943–98—*Continued*

Year	January	February	March	April	May	June	July	August	September	October	November	December	Average annual daily rate (Mgal/d)
Pettaquamscutt River Basin—*Continued*													
NK 3—*Continued*													
1997	5.5	3.9	4.6	3.9	5.4	5.5	7.4	6.9	5.1	4.4	3.8	0	0.15
1998	2.7	5.2	4.7	3.6	4.6	4.3	5.1	4.6	4.0	5.0	4.3	4.0	.14
NK 7 (began pumping in August 1996)													
1996	--	--	--	--	--	--	--	1.3	1.8	2.5	.6	.8	.02
1997	.9	0	.6	.9	.2	3.1	11.0	6.1	1.7	.6	0	.1	.07
1998	.4	.1	6.1	7.6	8.2	4.7	5.7	4.4	1.5	.4	.3	.3	.11
NK 8 (began pumping in August 1996)													
1996	--	--	--	--	--	--	--	.8	.5	1.0	.5	.2	.01
1997	.4	0	.4	.6	.1	2.4	7.3	3.7	1.0	.3	0	.1	.04
1998	.4	.1	3.6	5.6	7.0	7.8	9.4	9.5	5.7	.3	.3	.6	.14